Observer's Guide

for the

Green Bank Telescope

GBT Support Staff

Version 5.0

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This guide provides essential information for the preparation
of scheduling blocks for observations with the Green Bank Telescope.

How To Use This Guide

This document provides the necessary information to perform successful observations with the Green Bank Telescope (GBT). As a new GBT user, we suggest you read Part I in its entirety. You will want to read other parts and chapters as needed for your specific project.

- In Chapter 1 we briefly outline the features of the GBT.
- in Part I we introduce you to basic observing with the GBT. This part is split in multiple chapters:
  - In Chapter 2 you learn about the Dynamic Scheduling System (DSS).
  - In Chapters 3 and 4 we provide an introduction to the The Astronomer's Integrated Desktop (AstrID) observing interface, the Control Library for Engineers and Operators (CLEO) utilities, and other observing applications.
  - In Chapter 5 we provide example Scheduling Blocks (SBs) that can be used in AstrID. We also provide detailed descriptions of the contents of SBs.
  - In Chapter 6 we provide information on recommended strategies and advanced techniques for observing with the GBT.
- In Part II you will find, in addition to a table summarizing all GBT receivers, detailed information on some of our receivers, namely.
  - Observing with the KFPA receiver (18.0-27.5 GHz; Chapter 7),
  - Observing with the W-Band receiver(68-92 GHz; Chapter 8),
  - Observing with Argus (74-116 GHz; Chapter 9).
- In Part III you will find, in addition to a table summarizing all GBT backends, information on some of our backends, namely:
  - Spectral line observing with The VErsatile GBT Astronomical Spectrometer (VEGAS) (Chapter 10),
  - Continuum observing with the Caltech Continuum Backend (CCB) (Chapter 11) ,
- In Part IV we cover special observing modes like:
  - Pulsar observations using VEGAS Pulsar Mode (VPM; Chapter 12),
  - VLBI observing with the GBT (Chapter 13),
  - Solar system radar with the GBT (Chapter 14).

  In Part V you will find information on other, relevant topics, like

  - Locations of where to find more information about RFI (In Chapter 15).
  - A discussion of the effect of weather conditions on observing (Chapter 16).

  In Part VI you will find additional information and specifal topics.

Please note, GBO staff members are actively developing an online GBT Documentation Hub https://gbtdocs.readthedocs.org. The content from this Observer's Guide will slowly move over to this online documentation system, where you will still be able to download all documentation as a single PDF file. You can make requests (using github issues) on additional documentation you would like to see added to that system.

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Glossary

A The number of air masses along the line of sight. One air mass is defined as the total atmospheric column when looking at the zenith. 204

ADC Analog to Digital Converter. A card used to convert an analog signal into a quantized digital signal. Each VEGAS Bank contains two ADC cards, one for each polarization. 30, 43, 44, 60, 117, 118, 155, 156

Analog Filter Rack A rack in the GBT IF system that contains filters to provide the DCR with signals of the proper bandwidth. 30, 147

API Application Programming Interface. A set of routines, protocols and tools that can be used when building software and applications for a specific system. 20, 30, 225

Argus Argus instrument covering 74–116 GHz. 111, 123

AS Active Surface. The surface panels on the GBT whose corner heights can be adjusted to form the best possible paraboloidal surface. 1, 28, 111

AstrID Astronomer's Integrated Desktop. The software tool used for executing observations with the GBT. i, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 29, 33, 34, 35, 37, 38, 39, 40, 42, 47, 48, 49, 61, 69, 72, 73, 89, 99, 100, 101, 116, 120, 152, 161, 190, 196, 197, 215

baseline Baseline is a generic term usually taken to mean the instrumental plus continuum bandpass shape in an observed spectrum, or changes in the background level in a continuum observation. 34, 76, 117, 203

beam switching The Ka-band (26-40 GHz) receiver is the only receiver that can perform beam switching. The switching can route the inputs of each feed to one of two "first amplifiers" which allows the short time-scale gain fluctuations to be removed from the data. This type of switching is only recommended for continuum observations. Total power mode is recommended for Ka-band dual-beam nodded observations using VEGAS as the backend. 58

beam–width The FWHM of the Gaussian response to the sky, the beam, of the GBT. 36

C–band A region of the electromagnetic spectrum covering 4–8 GHz. 59, 123, 195

CCB Caltech Continuum Backend. A wideband continuum backend designed for use with the GBT Ka-band receiver. i, 5, 114

CLEO Control Library for Engineers and Operators. A suite of utilities for monitoring and controlling the GBT hardware systems. i, 11, 14, 37, 41, 42, 43, 44, 45, 117, 152

Converter Rack A rack in the GBT IF system that receives the signal from the optical fibers (sent from the IF Rack), mixes the IF signal with LO2 and LO3 references, and then distributes the IF signal to the various backends. 61, 211, 212

DCR The Digital Continuum Receiver. A continuum backend designed for use with any of the GBT receivers. 5, 31, 50, 83, 116, 120, 161, 211

DDC Digital Down Converter. Converts a digitized real IF signal to a complex baseband signal. 189

Director's Discretionary Time Project Notes series for the Dynamic Scheduling project.. 195

DSS Dynamic Scheduling System. The DSS examines the weather forecast, equipment availability, observer availability, and other factors in order to generate an observing schedule. 9, 10, 11, 12, 14, 15, 16, 25, 118, 119, 203

Dynamic Corrections A system that uses temperature sensors located on the backup structure of the GBT to correct for deformations in the surface, and deformations that change the pointing and focus of the GBT. 27, 28

EVN European VLBI Network. A collaboration of the major radio astronomical institutes in Europe, Asia and South Africa. 189

FAA Federal Aviation Administration. The U.S. Government agency that oversees and regulates the airline industry in the U.S. 60

FEM Finite Element Model. This is a model for how the GBT support structure changes shape due to gravitational forces at different elevation angles. 28

FET Field Effect Transistor. A type of amplifier used in the receivers. 4

FPGA Field-Programmable Gate Array. An integrated circuit designed to be programmed in the field after manufacture. 30, 149, 156

frequency switching A calibration method that obtains blank sky information while keeping the telescope pointed at the object of interest. The central frequency is shifted such that the desired spectral lines appear at different locations within the bandpass shape. 29, 51, 58, 153, 154

FRM Focus Rotation Mount. A mount that holds the Prime Focus Receivers which allows the receivers to be moved and rotated relative to the focal point. The FRM has three degrees of freedom, Z-axis radial focus, Y-axis translation (in the direction of the dish plane of symmetry), and rotation. 4

FWHM Full Width at Half the Maximum. Used as a measure for the width of a Gaussian. 34, 36, 76, 90, 96, 116, 118, 120

GBT Green Bank Telescope. i, 1, 3, 5, 6, 9, 10, 11, 12, 13, 14, 15, 17, 18, 19, 20, 21, 22, 24, 25, 26, 27, 29, 30, 33, 34, 36, 37, 38, 41, 42, 43, 47, 48, 55, 56, 59, 60, 66, 74, 75, 77, 82, 83, 84, 88, 89, 98, 99, 104, 111, 116, 117, 118, 119, 120, 126, 127, 147, 149, 150, 161, 189, 190, 192, 193, 195, 196, 197, 201, 203, 204, 205, 211, 212, 213, 217

GBTIDL Green Bank Telescope Interactive Data Language. The GBT data reduction package written in IDL for analyzing GBT spectral line data. 99, 155, 157

GFM GBT Fits Monitor: The software program that provides a real time display for GBT data. 17, 33, 34, 35, 36, 37, 41, 161

GO GBT Observing. 28, 99

GUI Graphical User Interface. 17, 18, 19, 20, 21

GUPPI The Green Bank Ultimate Pulsar Procussing Instrument. A (now-retired) FPGA + GPU backend previously used for GBT pulsar observations. 5

IDL The Interactive Data Language program of ITT Visual Information Solutions. xxii

IF Intermediate Frequency. A frequency to which the Radio Frequency is shifted as an intermediate step before detection in the backend. Obtained from mixing the RF signal with an LO signal. 5, 17, 29, 39, 61, 116, 117, 118, 120, 211, 212, 215, 216, 217

IF system Intermediate Frequency system. A general name for all the electronics between the receiver and the backend. These electronics typically operate using an Intermediate Frequency (IF). 43, 47, 48, 60, 65, 75, 83, 116, 117, 149, 150, 211, 212, 213, 215

IF Rack A rack in the GBT IF system where the IF signal is distributed onto optical fibers and sent from the GBT receiver room to the GBT equipment room where the backends are located. A signal may also be sent directly to the DCR. 30, 60, 61, 83, 116, 147, 211

IF path Intermediate Frequency path. The actual signal path between the receiver and the backend through the IF system. 30, 54, 58, 77, 116, 211

ITRF International Terrestrial Reference Frame. A world spatial reference system co-rotating with the Earth in its diurnal motion in space. 193, 194

JD Julian Date. A continuous count of days since the beginning of the Julian period (12h Jan 1, 4713 BC). xxiii

K–band A region of the electromagnetic spectrum covering 18–26 GHz. 16, 60

Ka–band A region of the electromagnetic spectrum covering 26–40 GHz. 5, 58, 60, 61, 111, 114, 123, 161

KFPA The K-band Focal Plane Array receiver covering 18-26.5 GHz. 54, 58, 60, 77, 123, 125, 126, 127, 150, 166, 216

Ku–band A region of the electromagnetic spectrum from 12–18 GHz. 60, 123

L–band A region of the electromagnetic spectrum covering 1–2 GHz. 50, 51, 59, 60, 61, 123, 190

LFC Local Focus Correction. Corrections for the general telescope focus model that are measured by the observer. 28, 114, 115, 116

LO Local Oscillator. A generator of a stable, constant-frequency radio signal used as a reference for determining which radio frequency to observe. 29, 61, 157, 215, 216

LO1 The first LO in the GBT IF system. This LO is used to convert the RF signal detected by the receiver into the IF sent through the electronics to the backend. This is also the LO used for Doppler tracking. 61, 65, 153, 154, 211, 215, 221

LO2 Second LO. The second LO in the GBT IF system. This is actually a set of eight different LOs that can be used to observe up to eight different spectral windows at the same time. 30, 61, 211

LO3 Third LO. The third LO in the GBT IF system which operates at a fixed frequency of 10.5 MHz. 30

LPC Local Pointing Correction. Corrections for the general telescope pointing model that are measured by the observer. 27, 114, 115, 116

LST Local Sidereal Time. A time scale based on the Earth's rate of rotation measured relative to the fixed stars rather than the Sun. 17, 26, 42

M&C Monitor and Control. The group of software programs which control the hardware devices which comprise the GBT. 17, 20, 21, 34, 219

MJD Modified Julian Date. MJD = Julian Date (JD) - 2400000.5. 26

MUSTANG-2 The MUltiplexed SQUID TES Array at Ninety GHz bolometer receiver operating at 75-105 GHz. 5, 111, 149, 211, 220

NAD83 North American Datum of 1983. An earth-centered model for the Earth's surface based on the Geodetic Reference System of 1980. The size and shape of the earth was determined through measurements made by satellites and other sophisticated electronic equipment; the measurements accurately represent the earth to within two meters. 2, 3

NAVD88 The North American Vertical Datum of 1988. 2

noise diode A device with a known effective temperature that is coupled to the telescope system to give a measure of system temperature ($T_{\rm sys}$). When the telescope is pointed on blank sky, the noise diode is turned on and then off to determine the off-source system temperature. This device is also refered to as the "Cal". 28, 50, 51, 52, 53, 54, 58, 152, 153, 154

NRAO National Radio Astronomy Observatory. The organization that operates the VLA, VLBA and the North American part of ALMA, and formerly operated the GBT until the Green Bank Observatory became a separate entity in 2016. 3, 9, 10, 11, 12, 189, 195

NRQZ National Radio Quite Zone. An area ($\sim$34,000 km^2) around the GBT set up by the U.S. government to provide protection from RFI. 3

OMT Ortho-Mode Transducer. This is part of the receiver that takes the input from the wave-guide and separtes the two polarizations to go to separate detectors. 4

OOF Out-Of-Focus holography. A technique for measuring large-scale errors in the shape of the reflecting surface by mapping a strong point source both in and out of focus. 37, 113, 114, 116

OTF On-The-Fly. On-The-Fly mapping scans take data while the telescope pointing moves between two points on the sky. This move is usually done in a linear fashion with constant slewing speed with respect to the sky. 37, 79, 88, 89, 90, 92, 96, 112, 154, 161

P–band A region of the electromagnetic spectrum covering 300–1000 MHz. Also known as the Ultra High Frequency (UHF) band in the U.S. (Sometimes P–band is considered to be a narrow region around 408 MHz, while A–band is the region around 600 MHz). 195

PF1 The first of two prime focus receivers for the GBT. This receiver has four different bands: 290–395, 385–520, 510–690 and 680–920 MHz. 4, 123

PF2 The second of two prime focus receivers for the GBT. This receiver covers 901–1230 MHz. 4, 123

PI Principle Investigator. 10, 11, 14, 25

polarization switching This is only available for the L and X-band receivers. During an observation and at a rate of about once per second, the polarization of the observation is switched between two orthogonal linear polarizations or the two circular polarizations. This switching method is used almost exclusively for Zeeman measurements. 58

position switching A calibration method that involves observing an object of interest for a period of time, and then moving the telescope to a blank sky region to obtain the blank sky observations necessary for baseline subtraction. Nodding is a form of position switching. Position switching is done via an observing routine and is not setup in hardware unlike other switching schemes. 75

PROCNAME A GO FITS file keyword that contains the name of the Scan Type used in Astrid to obtain the data. 28

PROCSEQN A GO FITS file keyword that contains the current number of scans done of the total scans given by PROCSIZE in a given Scan Type. 28

PROCSIZE A GO FITS file keyword that contains the number of scans that are to be run as part of the Scan Type given by PROCNAME. 28

Q–band A region of the electromagnetic spectrum from 40–50 GHz.. 53, 111, 123, 156

RDBE A Roach Digital Backend, where ROACH is the core board containing a large FPGA. 189

RF Radio Frequency. The frequency of the incoming radiation detected by the GBT. 5, 30, 60, 61

RFI Radio Frequency Interference. Light pollution at radio wavelengths. i, 1, 60, 111, 149, 156, 201, 203, 217

S–band A region of the electromagnetic spectrum covering 2–4 GHz. 59, 123, 195

SB Scheduling Block. A Python script used to perform astronomical observations with the GBT. i, 14, 17, 18, 19, 21, 22, 23, 24, 25, 26, 28, 47, 48, 49, 62, 65, 66, 67, 68, 73, 74, 77, 85, 97, 98, 99, 100, 101, 102, 104, 105, 106, 109, 116, 120, 127, 161, 196, 197, 198, 217, 219, 220

τ The opacity of the atmosphere. 204

$\mathrm{T}_{\mathbf{rec}}$ The equivalent blackbody temperature brightness that the GBT receiver contributes to the detected signal. 123

$\mathrm{T}_{\mathbf{src}}$ The equivalent blackbody temperature brightness from the astronomical source. 117

$\mathrm{T}_{\mathbf{sys}}$ The total equivalent blackbody temperature brightness that the GBT sees. Depending on usage, it may or may not include T_{src}. 75, 117, 123

TLE Two-Line Element. 61, 74

total power Spectral-line observing typically requires differencing "signal" and "reference" observations so as to remove the instrumental bandpass shape. In total power observing, the reference observations are either separate scans (as acquired with, for example, Astrid's OnOff or OffOn observing directives), as separate integrations in an on-the-fly observations (for example, as edge pixels in a map), or as separate integrations in some types of subreflector nodding observations. "Switched Power", the alternative to "Total Power", provides faster switching between signal and reference observations but, in some cases, worse baseline shapes. 29, 50, 52, 53, 54, 88, 153, 154

UTC Coordinated Universal Time. The mean solar time at 0°longitude. 17, 26, 28

VEGAS The GBT spectral line backend. i, xxi, 5, 6, 30, 31, 43, 44, 51, 52, 53, 54, 55, 56, 57, 58, 59, 60, 83, 117, 118, 119, 125, 126, 149, 151, 215, 225

$\mathrm{v}_{\mathbf{relativistic}}$ The velocity of a source using the relativistic definition of the velocity–frequency relationship. 59

$\mathrm{v}_{\mathbf{optical}}$ The velocity of a source using the optical approximation of the velocity–frequency relationship. 59

$\mathrm{v}_{\mathbf{radio}}$ The velocity of a source using the radio approximation of the velocity–frequency relationship. 59

VLB Very Long Baseline: A general acronym for VLBI or VLBA. 6, 189

VLBA Very Long Baseline Array: An interferometer run by the NRAO. 5, 6, 29, 189, 190, 192

VLBI Very Long Baseline Interferometer: The use of unconnected telescopes to form an effective telescope with the size of the separation between the elements of the inteferometer. i, 15, 59, 60, 189, 190

VNC Virtual Network Computer. A GUI based system that is platform independent that allows you to view the screen of one computer on a second computer. This is very useful for remote observing. 11, 41

W–band A region of the electromagnetic spectrum covering 75–111 GHz. 37, 59, 116, 123

X–band A region of the electromagnetic spectrum covering 8–12 GHz. 52, 61, 123, 195

Chapter 1

Overview of the Green Bank Telescope

The 100 meter Green Bank Telescope (GBT) is intended to address a very broad range of astronomical problems at radio wavelengths and consequently has an unusual and unique design. Unlike conventional telescopes that have feed legs projecting over the middle of the surface, the GBT's aperture is unblocked so that incoming radiation meets the surface directly. This increases the useful area of the telescope and reduces reflection and diffraction, which ordinarily complicate a telescope's pattern of response to the sky. To keep the aperture unblocked, the design incorporates an off-axis feed arm that cradles the dish and projects upward at one edge. This requires that the figure of the telescope surface be asymmetrical. To make a projected circular aperture 100 meters in diameter, the dish is actually a 100 by 110 meter section of a conventional, rotationally symmetric 208 meter figure, beginning four meters outward from the vertex of the hypothetical parent structure (see Figure 1.1). The GBT's lack of circular symmetry greatly increases the complexity of its design and construction.

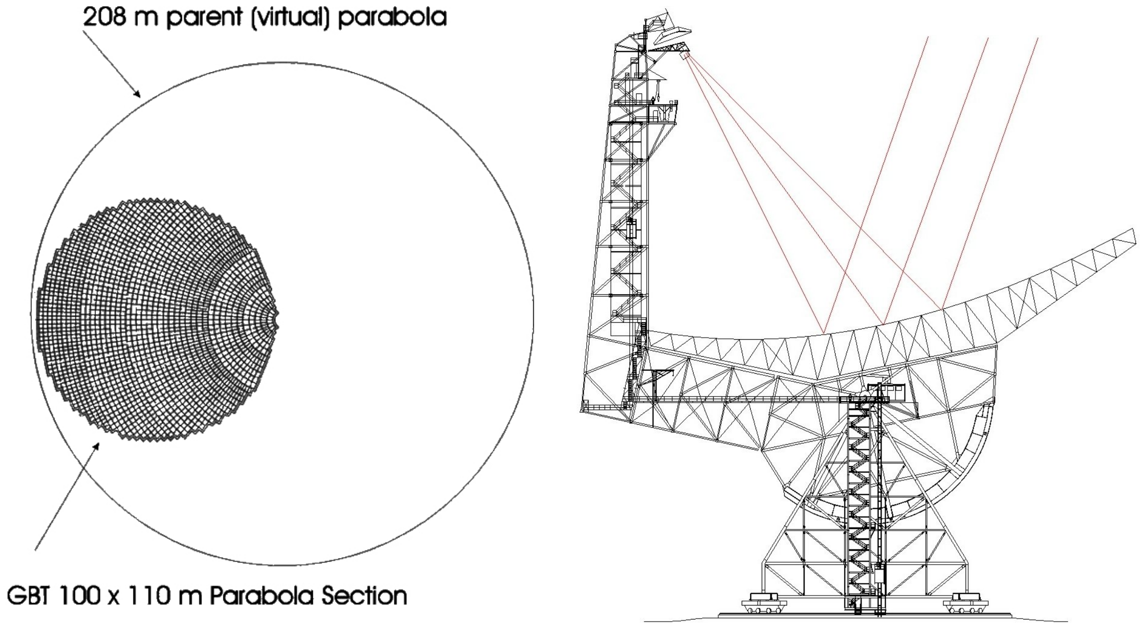
To maintain precise surface figures and pointing accuracy at high frequencies the telescope is equipped with a complex Active Surface (AS). At higher frequencies gravity distorts the surface figure of the telescope to unacceptable levels. Temperature variations and wind can also deform the figure of the dish. To compensate for these distortions, the surface of the GBT is "active" i.e. it is made up of 2004 independent panels and each of these panels are mounted on actuators at the corners, which can raise and lower the panels to adjust the shape of the dish's surface.

1.1 Main Features of the GBT

- **Fully steerable antenna**: +5° to +90° elevation range (-46.5° to +90° declination); 85% coverage of the celestial sphere. Note that observing at elevations >86° (or 80° during extremely cold weather) may fail due to the high azimuth rates required.
- **Unblocked aperture**: Reduces sidelobes, RFI, and spectral standing waves.
- **Active surface**: Compensates for gravitational and thermal distortions.
- **Frequency coverage of 290 MHz to 115+ GHz**: 3 orders of magnitude of frequency coverage for maximum scientific flexibility.
- **Location in the National Radio Quiet Zone**: Comparatively low RFI environment (See Figure 1.2).
- **Dynamic Scheduling**: Matching scientific programs to the required weather conditions.

Table 1.1: GBT Telescope Specifications.

Location	Green Bank, West Virginia, USA
Coordinates	Longitude: 79°50′23.406″ West (NAD83) Latitude: 38°25′59.236″ North (NAD83) Track Elevation: 807.43 m (NAVD88)
Optics	110 m × 100 m unblocked section of a 208 m parent paraboloid Offaxis feed arm
Telescope Diameter	100 m (effective)
Available Foci	Prime and Gregorian f/D (prime) = 0.29 (referred to 208 m parent parabola) f/D (prime) = 0.6 (referred to 100 m effective parabola) f/D (Gregorian) = 1.9 (referred to 100 m effective aperture)
Receiver mounts	Prime: Retractable boom with Focus-Rotation Mount Gregorian: Rotating turret with 8 receiver bays
Subreflector	8-m reflector with Stewart Platform (6 degrees of freedom)
Main reflector	2004 actuated panels (2209 actuators) Average intra-panel RMS 68 μm
FWHM Beamwidth	Gregorian Feed: $\sim 12.60'/f_{GHz}$ Prime Focus: $\sim 13.01'/f_{GHz}$
Elevation Limits	Lower limit: 5° Upper limit: 90°
Declination Range	Lower limit: −46.5° Upper limit: 90°
Slew Rates	Azimuth: 35.2°/min Azimuth-half (at cold temperatures $\lesssim$ 16°F): 17.6°/min Elevation: 17.6°/min
Surface RMS	Passive surface: 450 μm at 45° elevation, worse elsewhere Active surface: $\sim$ 250 μm, under benign night-time conditions
Tracking accuracy (σ_{tr})	$\sigma_{tr}^2 = \sigma_0^2 + (s/3.5)^4$ σ_0 = night:1.32″, day:2.19″; s = wind speed (ms^{-1})
Pointing accuracy	$\lesssim 10''$blind pointing accuracy



(a) (b)

Figure 1.1: The parent parabola (1.1a) and off-axis design (1.1b) of the GBT.

1.2 National Radio Quiet Zone

The National Radio Quite Zone (NRQZ) was established by the Federal Communications Commission (FCC) and by the Interdepartmental Radio Advisory Committee (IRAC) on November 19, 1958 to minimize possible harmful interference to the National Radio Astronomy Observatory (NRAO) in Green Bank, WV and the radio receiving facilities for the United States Navy in Sugar Grove, WV. The NRQZ is bounded by North American Datum of 1983 (NAD83) meridians of longitude at 78d 29m 59.0s W and 80d 29m 59.2s W and latitudes of 37d 30m 0.4s N and 39d 15m 0.4s N, and encloses a land area of approximately 13,000 square miles near the state border between Virginia and West Virginia.

- Further information on the NRQZ can be obtained at
  - https://science.nrao.edu/facilities/gbt/interference-protection/nrqz/
- Information on the West Virginia State Code Chapter 37A "Radio Astronomy Zoning Act" (WVRAZ) can be found at
  - http://www.legis.state.wv.us/WVcode/code.cfm?chap=37a&art=1

1.3 Front Ends

The GBT receivers cover several frequency bands from 0.290 - 50 GHz and 70 - 100 GHz. Table **??** lists the properties of the Prime Focus receivers and the Gregorian Focus receivers. System temperatures are derived from lab measurements or from expected receiver performance given reasonable assumptions about spillover and atmospheric contributions.

The *Proposer's Guide for the Green Bank Telescope* provides more information on GBT receivers. See also Tab. 6.2 for more details on each receiver available.

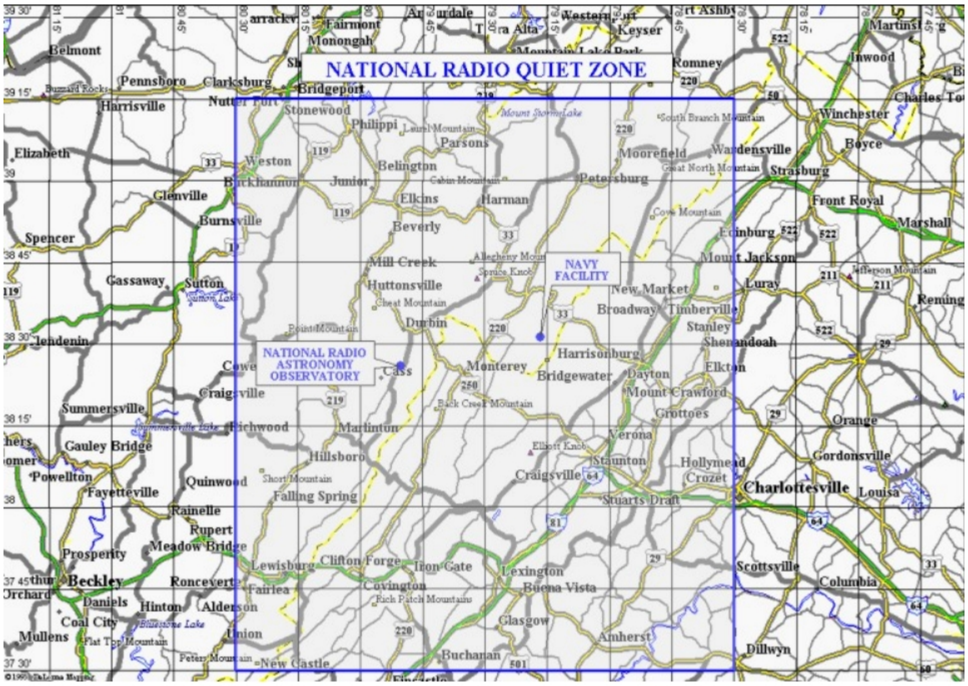


Figure 1.2: The National Radio Quiet Zone.

Prime focus receivers

The Prime focus receivers are mounted in a Focus Rotation Mount (FRM) on a retractable boom. The boom is moved to the prime focus position when prime focus receivers are to be used, and retracted when using Gregorian receivers. The FRM holds one receiver box at a time. Currently there are two receiver boxes, PF1 and PF2. A change from PF1 to PF2 receivers requires a box change, taking about 4 hours and done only during scheduled maintenance days.

The PF1 (0.29 - 0.92 GHz) receiver is divided into 4 frequency bands within the same receiver box. The receivers are cooled Field Effect Transistor (FET) amplifiers. The feeds for the lower three bands are short-backfire dipoles, and the feed for the fourth (680-920MHz) is a corrugated feed horn with an Ortho-Mode Transducer (OMT) polarization splitter. A feed change, required to switch between bands, takes 4 hours and must occur on a maintenance day. The PF2 (0.920 - 1.23 GHz) receiver uses a cooled FET and a corrugated feed horn with the OMT.

Note that the 450 MHz and 600 MHz PF1 feeds and the PF2 feed are unlikely to be considered for installation on the GBT.

Gregorian focus receivers

The Gregorian receivers are mounted in a rotating turret in a receiver room located at the Gregorian Focus of the telescope. The turret has 8 portals for receiver boxes. Up to 8 receivers can be kept cold and active at all times. Changing between any two Gregorian receivers that are installed in the turret takes about 60-90 seconds.

1.4 Backends

The GBT has two continuum backends: the The Digital Continuum Recevier (DCR) and the Caltech Continuum Backend (CCB). VEGAS is the backend for spectral line and pulsar observing. There is a single dish mode for the Very Long Baseline Array (VLBA) backend that is available for high time–resolution observations. Planetary radar uses a specialized backend.

For more information on GBT backends, please see the *Proposer's Guide for the Green Bank Telescope*.

Digital Continuum Receiver (DCR)

The DCR is the GBT's general purpose continuum backend. It is used both for utility observations such as pointing, focus, and beam-map calibrations, as well such as for continuum astronomical observations including point-source on/offs, extended source mapping, etc.

Caltech Continuum Backend (CCB)

The CCB is a sensitive, wideband backend designed exclusively for use with the GBT Ka–band (26-40 GHz) receiver. It provides carefully optimized Radio Frequency (RF) (not an Intermediate Frequency (IF)) detector circuits and the capability to beam-switch the receiver rapidly to suppress instrumental gain fluctuations. There are 16 input ports (only 8 can be used at present with the Ka–band receiver), hard-wired to the receiver's 2 feeds × 2 polarizations × 4 frequency sub-bands (26-29.5 , 29.5-33.0; 33.0-36.5; and 36.5-40 GHz). The CCB allows the left and right noise-diodes to be controlled individually to allow for differential or total power calibration. Unlike other GBT backends, the noise-diodes are either on or off for an entire integration (there is no concept of "phase within an integration"). The minimum practical integration period is 5 milliseconds; integration periods longer than 0.1 seconds are not recommended. The maximum practical beam-switching rate is about 4 kHz, limited by the needed $250\mu s$ beam-switch blanking time. Switching slower than 1 kHz is not recommended.

VEGAS

The VErsatile GBT Astronomical Spectrometer (VEGAS) is the spectral line and pulsar backend for the GBT. It consists of eight independent dual polarization spectrometers (banks) that can be configured in any one of theSpectral modes (see Tab. 10.1) or Pulsar Modes (see Tab. 12.1). VEGAS can be used with any receiver except The MUltiplexed SQUID TES Array at Ninety GHz 2 (MUSTANG-2). It provides up to 64 spectral windows as well as wide bandwidths (1000-1500 MHz). See chapters 10 and 12 for detailed information on VEGAS.

GUPPI

The Green Bank Ultimate Pulsar Processing Instrument (GUPPI) was previously the main pulsar backend for the GBT. It is retired as of January 2021 and has been replaced by VEGAS Pulsar Mode (VPM).

1.4.0.1 MUSTANG-2

For information on MUSTANG-2, please go here: https://gbtdocs.readthedocs.io/en/latest/references/receivers/mustang2.html

"VLBI"

The GBT supports Very Long Baseline (VLB) observations with a Mark6 VLBA recorder. This recorder can also be used in a "single-dish" mode to make high time–resolution observations. See Chapter 13 for more information.

Radar

Planetary radar observations are supported by the JPL radar backend. See Chapter 14 for more information.

1.5 Polarization Measurements

Measurement of Polarization and Stokes parameters is possible using VEGAS. This is an "expert user" mode: users should contact their GBT support person or the GBT helpdesk. For an introduction to polarization observations, see Heiles (2002).

Part I

GBT Observing

Chapter 2

Introduction to the Dynamic Scheduling System

This chapter gives an introduction to the Dynamic Scheduling System (DSS) for the Robert C. Byrd Green Bank Telescope (GBT). The GBT has been scheduled with the Dynamic Scheduling System (DSS) since October 1, 2009. Observers can access the DSS through this site: https://dss.gb.nrao.edu.

2.1 Overview of the DSS

The primary goal of the Green Bank Telescope Dynamic Scheduling System (DSS) is to improve the efficiency of GBT observations by matching the observing schedule to predicted weather conditions while allowing each observer to retain interactive control of the telescope. Each day the DSS will examine the weather forecast, equipment availability, observer availability, and other factors, and set an observing schedule for the 24-hour period beginning the next day. Observers will therefore get about 24-48 hours notice before their project will observe. Observers will have the opportunity to suspend their observing program, set blackout dates indicating when they are unavailable for observing, and back out of current observations if they find the observing conditions are not suitable to their science goals.

The DSS readily accommodates remote observing, but by being on site in Green Bank observers increase their likelihood of being scheduled during the period of their visit. Visits to Green Bank should be arranged in advance with the project's "Friend", and observers should ideally spend one to two weeks in Green Bank to give enough opportunity for their project to get scheduled at least once. **Projects observing at high frequencies (20 GHz and higher) typically require staying in Green Bank for two weeks or longer.**

2.2 DSS Terminology

The process of scheduling GBT observations begins with the preparation of the proposal using the NRAO Proposal Submission Tool (PST). Proposals accepted by the NRAO Time Allocation Committee become GBT projects that appear in the DSS system and are identified by an assigned project ID (e.g., GBT09A-001).

Projects are divided into sessions, which have associated parameters that define how the observation should be scheduled. These parameters include sky position, time allocated, observing frequency, and minimum and maximum durations preferred for a single, contiguous block. Sessions for monitoring observations have additional parameters describing how often to repeat the observation. The project investigators initially define the session parameters in the proposal, but the parameters may be modified by request to the helpdesk (helpdesk-gb@nrao.edu). Observers can see the most critical session parameters on the DSS web pages.

Completing the observations for a session may require scheduling multiple segments. Each contiguous block of scheduled time is called a *telescope period*.

As telescope periods are completed, the project and associated sessions will be billed for the time. If any time is lost to weather or an equipment failure, the observer may consult with the telescope scheduler (via the helpdesk) and request that the project not be billed for the lost time.

2.3 Controlling the Scheduling of a Project

Users can access their DSS account by logging in to the system at . The DSS username and password are the same as those used for NRAO Interactive Services (i.e., the Proposal Submission Tool).

From the DSS web site, users can view and manage the scheduling information for their projects. In order for a project session to enter the pool of sessions eligible for scheduling, the user is responsible for ensuring that the session is enabled in the DSS, and that a qualified observer is available to perform the observation. Sessions and observers are enabled for observing simply by clicking a check box in the DSS project page (See figure 2.2). Users can control when their project is scheduled by enabling or disabling individual sessions.

Note that astronomers intending to observe remotely must be trained and approved by GB staff before the project can be authorized and made eligible for scheduling.

Observers can enter personal blackout dates. Blackouts can be entered either as one time events (e.g., May 1, 20:00 to May 4, 05:00 UT) or as repeating events (e.g., every Monday from 15:30 to 17:30 ET). If all observers for a given project are blacked out at a given time, that project will not get scheduled. If at least one observer is not blacked out, the project is eligible for scheduling. The default time zone used for entering blackouts is set on the *Preferences* tab, which is linked at the top of every DSS web page. Observers can also override the default by selecting a time zone when making a blackout entry. Observers with more than one project will find that they need to enter blackout dates only once, and the dates will be applied to all their projects. **Those visiting Green Bank to observe should use blackout dates to mark the periods of their travel before and after the run to ensure they are scheduled only when available and ready on-site.**

Guidelines for the use of blackouts: While blackout dates give observers control of the scheduling process, efficient GBT operation requires that not too much time be blacked out or disabled. It is especially important that projects with large observing allocations not have too much time unavailable for scheduling because of blackouts. As a guideline, projects with more than 20 hours of allocated observing should limit time that cannot be scheduled to no more than 20% of the total eligible observing time over the course of a semester. If a project cannot meet this guideline, the PI is encouraged to increase observing opportunities by enlisting additional observers who are qualified for remote observing. Projects that require observers to visit Green Bank for training are excluded from this guideline until the observers are trained for remote observing.

Caution Regarding Blackouts: If a project has only one observer, that observer should be particularly conscientious of blackouts. It can be easy for an observer to inadvertently hamper observing opportunities by setting blackout dates too freely, particularly repeating blackouts. Repeating blackouts should be used with care. Targets with low declinations, such as the Galactic Center, have tightly constrained observing opportunities to begin with, so observers on such projects should be particularly careful with blackouts that would further limit their observing opportunities. Consider, as an example, a project that has a session with a 4-hour minimum duration to observe the Galactic Center. If the observer has a repeating 1-hour blackout date that intersects the window, the entire session becomes ineligible each time the blackout intersects the 4-hour window. The Green Bank Observatory is not responsible for lost observing opportunities due to excessive blackouts.

When entering blackouts, keep in mind, too, that projects do expire, so it is in the interest of the observer to keep the projects eligible for scheduling as much as possible.

2.4 Canonical Target Positions

The DSS keeps track of a project's scheduling requirements via the session parameters, which can be viewed on the project page. The PI should check that session parameters properly reflect the needs of the project. The project Friend assigned by NRAO can also offer advice on optimizing session parameters, where appropriate. In some cases, a session's target position may be representative of a group of objects clustered on the sky. As the project progresses and some of these targets are observed, this representative position may need to be updated. In this case, the PI should send an email request to the DSS helpdesk.

The DSS can automatically update the sky coordinates of common, fast-moving solar system objects, including comets. The position is updated each day prior to scheduling. On the project page under *Project Sessions*, an asterisk next to the coordinates indicates that the position for that session is automatically updated in this manner.

Many observers find it helpful to use a sky-plotting tool to help plan their observations and keep track of target locations on the sky. The CLEO Scheduler & Skyview tool, which runs on Linux systems in Green Bank and can be run remotely through Virtual Network Computer (VNC), is one such tool that allows a GBT user to plot target locations on the sky for any date and time. This application can read target coordinates from a standard astrid catalog file. Observers will find this tool handy for identifying the time of day a project may get scheduled, as well as helping to plan observations in detail after they are scheduled. To run the program, type `cleo scheduler` from the command line. See § 4.2.3 for further details on the CLEO Scheduler & Skyview application.

2.5 Contact Information and Project Notes

Observers can specify how they should be contacted, prior to and during their observations. It is critical to keep contact information current. Each observer can provide *dynamic contact* information in a free-format text box. Here the observer should provide any contact information not available through the person's (static) NRAO contact information, which is also listed on the page. Observers can also specify the order in which they should be contacted by GBT operations, in the event of any schedule changes or in case there is need to contact the observer for any reason prior to the scheduled start time. Specify the order by clicking the arrow icons next to the list of team members, on the DSS project page.

Finally, observers can record *Project Notes* on the DSS project web page. Project notes provide observers a place to store and share observing instructions. The notes are visible to all project team members as well as the GBT operations staff and schedulers. Observers who need to share instructions or other information with the GBT operator prior to the start of an observation can provide these instructions in the project notes area. Project notes are not intended to be a log for observations, but rather a place to store brief instructions or news that should be shared among observers and the GBT operator.

2.6 The DSS Software

2.6.1 The DSS Home Page

Upon logging in to the DSS system, users arrive at their DSS home page (Figure 2.1) where they see a list of active projects on which they appear as co-investigator. From the DSS home page, users can:

- Access the project page for each of their affiliated projects

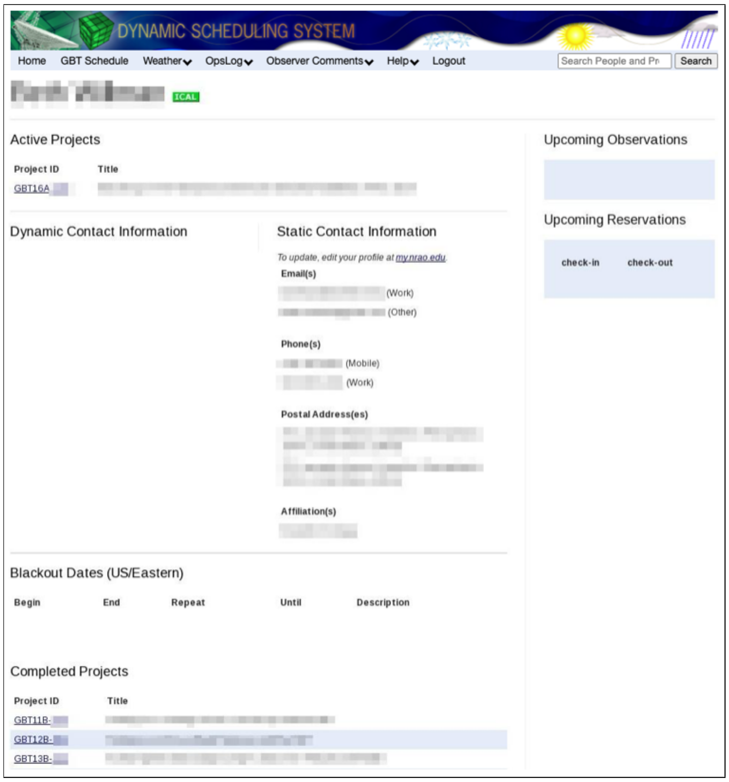


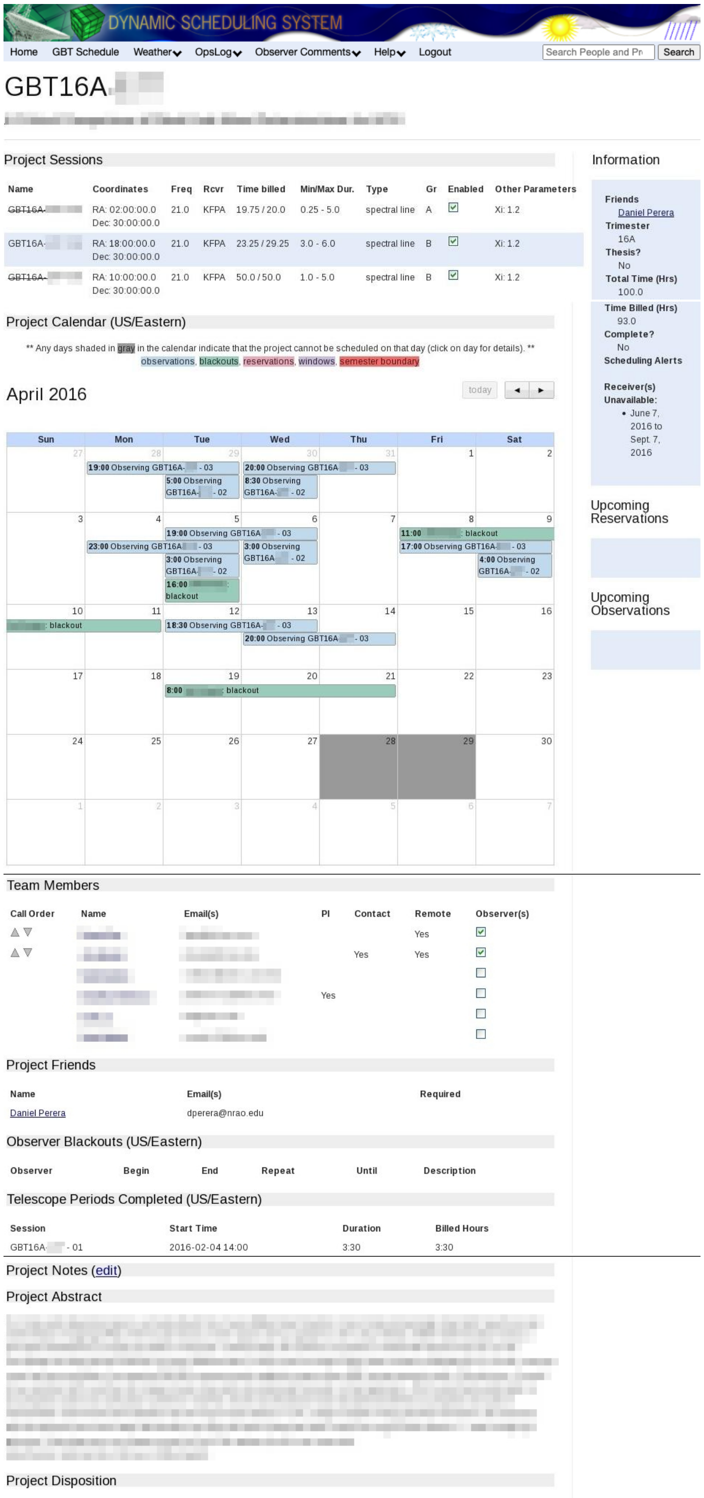
Figure 2.1: A sample DSS home page.

- See a list of upcoming observations
- See a list of upcoming Green Bank room reservations
- See their *static* contact information, as entered in the NRAO services system http://my.nrao.edu.
- Set *dynamic* contact information
- Set blackout dates
- Follow a link to the current GBT fixed schedule
- Follow a link to the weather forecasts page
- follow a link to the NRAO support center
- Set the default time zone via the Preferences link
- Access DSS documentation
- Establish an iCalendar subscription. Instructions for using iCalendar are available by hovering the mouse cursor over the iCal icon on the DSS Home Page.

2.6.2 The DSS Project Page

By selecting a project ID, observers are presented with the project page. Figure 2.2 shows what they can do on this page.

The project calendar gives observers an idea when their project is eligible for scheduling. Regardless of the weather, there will be times when a project is not eligible for scheduling, for example because of no receiver availability, observer blackouts, fixed telescope maintenance periods, and other fixed projects appearing on the GBT schedule. Times not eligible for scheduling will be grayed out on the project calendar.



- Inspect session parameters
- Enable or disable individual session
- View total allocated and billed time
- See a project calendar
- View scheduling alerts
- View receiver availability
- View upcoming reservations
- View upcoming observations
- Specify observers from the project team, and set the order they should be contacted by GBT operations
- See a list of blackout dates for all observers on the project
- See a list of completed telescope periods
- Store and share project notes
- View your abstract and disposition letter

Figure 2.2: A sample DSS project page.

The project calendar helps with planning in a number of ways. However, it is important to understand that a session's eligibility is based on ever-changing constraints, and can change from *not eligible* to *eligible* at any time. Therefore, if observers wish to take a break from observing based on the calendar outlook, they should either disable all sessions until they are ready to resume with the observing, or enter blackout dates to cover the period they do not wish to observe.

The project page includes a panel with project team members listed. Using a checkbox, team members can select or deselect those identified as observers. They can also rearrange the order observers are listed. The top observer in the list is expected to observe the next scheduled session. If there is a change in schedule, this person will be called first.

2.7 Responsibilities

Each project has a Principle Investigator (PI) and, optionally, a list of additional investigators. An investigator is eligible to be an observer for a given project if that person is qualified for remote observing or is on site in Green Bank.

It is essential that one of the observers for a scheduled project contact GBT operations at least 30 minutes prior to the start of the observation. Observers can contact the GBT operator by telephone (304-456-2341), by the CLEO chat program "Talk and Draw" (for qualified remote observers), or by showing up in the GBT control room. If the GBT operator has not been contacted before the session's start time, the operator will phone observers in the order they are listed on their project web page.

- The PI is responsible for:
  - Managing the project
  - Identifying all associated observers
  - Working with project team members and the GBT project Friend to ensure that SBs are properly and promptly prepared.
  - Enabling each session by clicking the "enable" button on the project's web page. Sessions should be enabled only if they will be ready for observing in the next 24 hours.
  - Ensuring that all associated observers have provided contact information including a current telephone number and an email address for each observer.
  - Ensuring that a project's scheduling information is current. This includes checking the hours remaining on the project and ensuring that the session parameters are up-to-date and accurate.
  - Ensuring that each scheduled telescope period has an observer who is available at least 30 minutes before the session is scheduled to begin.
- Observers are responsible for:
  - Ensuring that the DSS project web page has their current contact information. For remote observers, this includes entering telephone numbers where they can be reached at the time of observation.
  - Contacting GBT operations 30 minutes prior to the start time of an observation.
  - Attending to observations during a scheduled telescope period. The PI is responsible for "no-shows" and the ensuing reduction in their alloted time.
  - Notifying GBT operations if they find conditions unsuitable for their session.

2.8 Remote Observing

To use the GBT remotely, observers must first be trained and certified by Green Bank staff. We encourage experienced observers to request additional training from GBO staff when using instruments or observing modes unfamiliar to them.

Contact your project friend or the DSS helpdesk (helpdesk-dss@gb.nrao.edu) if you believe the DSS does not have you listed properly as a qualified remote observer.

See https://gbtdocs.readthedocs.io/en/latest/how-tos/infrastructure/remote-connection.html for more information on remote observing.

2.9 The Daily Schedule

Each day between about 7:00 and 12:00 PM ET the telescope schedule is fixed for the 24-hour period beginning 8:00 AM ET the next day. For example, by 12:00 PM Monday, the observing schedule is fixed for the period 8:00 AM Tuesday through 8:00 AM Wednesday. Each morning this daily schedule is published and can be viewed on the DSS web site by anyone. Those with projects on the 24-hour fixed schedule will be notified by email.

Observers must ensure that their blackout dates and "session enabled" flags are up to date each day by about 5:00 AM ET. Changes made after this time may not be reflected in the upcoming day's schedule.

It is possible that weather conditions may change after a schedule is published, compromising the observing efficiency for some scheduled telescope periods. The observer or GBT staff may then decide to cancel a telescope period and substitute an alternate "backup" observation in its place. Note that the observer may decide that the weather conditions are too poor even after beginning the observation. Equipment failure can also lead to cancellations. If GBT staff must change the 24-hour schedule for these reasons, affected observers will be notified immediately by email or telephone.

2.10 Backup Projects

When a scheduled telescope period is cancelled, a backup project will be scheduled on short notice. By volunteering as a backup project, observers improve their project's chances of getting observing time. Backup projects can come in two categories: observer-run and operator-run. There are several requirements that must be met before a project can be considered for backup status.

2.11 Session Types

There are four types of sessions defined for astronomy projects: open, windowed, elective, and fixed. Open sessions have no major constraints on when they can be scheduled, beyond the functional requirements that an observer is available, the source is above the horizon, and the weather is suitable. Most sessions fall into this category and provide the most flexibility in the DSS. At the other extreme are fixed sessions that have no flexibility and are prescheduled at a particular date/time; that is, their telescope periods have already been defined.

The other two types are windowed and elective sessions, which have some constraints but are not fixed on the schedule. The most common examples are monitoring and VLBI sessions, where the science demands that an object must be observed at defined intervals or times.

Windowed sessions are defined by a cadence that may be either periodic or irregular. For example, an observer may require observing a target once per month for five months, with each observation having a tolerance of plus or minus 3 days. In this example, the window size is 7 days.

Currently, windowed sessions are scheduled in the following way. The cadence information from the proposal is used to preschedule all windowed sessions whereby all of the telescope periods are temporarily fixed in what are called default periods. The user is given the window template (e.g, 8-14 January; 8-14 February; 8-14 March; 8-14 April; and 8-14 May). Within a windowed period, a windowed session will be considered like an open session. Near the end of each window range is a default period. If the session has not been selected by the time the default period arrives, the session will be scheduled in the default period. The default period may be moved manually to a later time slot within the window if the human scheduler notices a problem with the original default period. When the windowed period is scheduled, the observer will be informed 24-48 hours in advance, just like an open session. The only difference is that the observer will be provided with the window template for planning purposes.

Elective sessions are a restrictive form of windowed sessions. Here, rather than having a range of days on which the project session can be scheduled, there is a list of possible days. As with windows the list of possible days, or *opportunities*, has a default period on which the session will be scheduled if it has not run in advance of that date.

2.12 Projects that can Tolerate Degraded Weather

The DSS is designed to schedule projects in weather that is appropriate for the frequency being observed. Some projects can tolerate lesser weather conditions than the DSS would assign by default. For example, consider a project at K–band that observes many targets, each for a short duration, say 10 seconds. The observing time for this project is dominated by overheads in slewing from one position to the next, so marginal K–band weather might be acceptable. The observing team may prefer not to wait for very good K–band weather, which is rare and would delay their scheduling.

To enable more aggressive scheduling, the observer should send an email to the DSS helpdesk requesting that the project be considered for scheduling in lesser weather conditions. The DSS support team can enter a session-specific factor (ξ) that effectively elevates the score for this session in marginal opacity conditions. The ξ parameter is tunable so the observer can request that the project be scheduled very aggressively, or modestly so. The factor only affects scoring related to atmospheric opacity, so high frequency projects that are sensitive to high winds will still not get scheduled when the forecasted winds preclude accurate pointing.

The DSS support team will help observers decide if their project can tolerate lesser weather. Note that this capability will not be used to accelerate scheduling of projects that truly do benefit from the most appropriate weather.

2.13 Other DSS Control Parameters

A list of the most relevant parameters can be found in Appendix F. There are a number of additional controls and parameters that can be used within the DSS system which are fully described in O'Neil et al. (2011).

Any changes to these parameters must be requested by contacting the GBT scheduler via the DSS helpdesk (helpdesk-dss@nrao.edu).

Chapter 3

Introduction To AstrID

3.1 What Is AstrID?

The Astronomer's Integrated Desktop (AstrID) is a single, unified workspace that incorporates a suite of applications that can be used with the GBT. AstrID provides a single interface from which the observer can create, execute and monitor observations with the GBT. Some of the features of AstrID are:

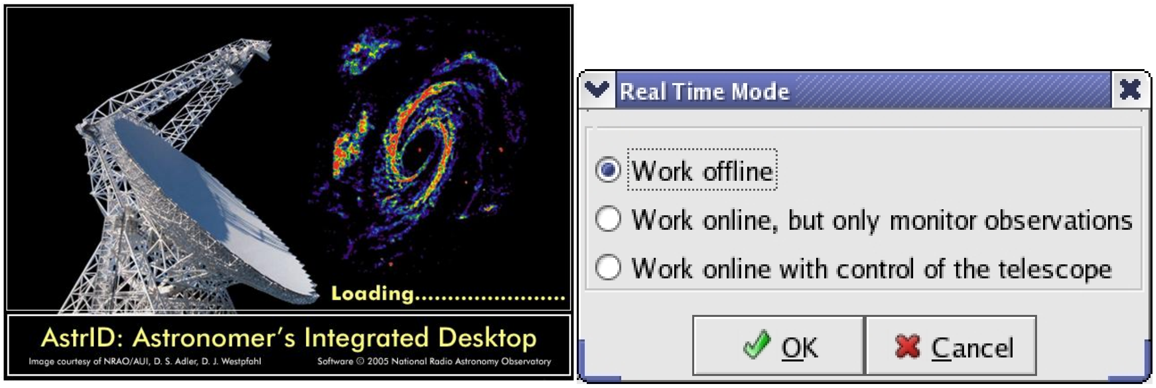
- Executes Scheduling Blocks (SBs) to perform astronomical observations.
- Provides a real time display of GBT data.
- Provides the status of the GBT.
- Provides an area to edit SBs. They may be edited offline and saved before observing.
- Allows a second observer to monitor observations in progress.

AstrID brings together many applications into a single, unified Graphical User Interface (GUI). Of particular note, AstrID provides a single point of contact to all of the Monitor and Control (M&C) software by interpreting the Python code and function in SBs. The GBT M&C systems can roughly be thought of as a group of programs - one for each hardware device - and a master program, the Scan Coordinator. The GUI places each application into its own tab window. Applications available in AstrID are:

Observation Management
AstrID interfaces with the Observing Management Application in order to execute SBs. The AstrID Edit Subtab (see § 3.4.1) provides a windows-like text editor that features syntax highlighting for Python code and allows SBs to be edited, validated, copied, and saved. SBs may be queued and executed via the AstrID Run Subtab (see § 3.4.2).

Data Display
AstrID provides a real time data display by connecting to The GBT Fits Monitor (GFM). This allows the automatic processing of pointing and focus scans that can immediately update the GBT M&C system with the determined corrections. GFM can show raw, uncalibrated continuum data as a function of time (see Chapter 4).

GBT Status
AstrID provides a screen that displays information on the real time status of the GBT. This provides meta–information such as the Local Sidereal Time (LST), Coordinated Universal Time (UTC), observer, project ID, information on the antenna such as current position, and information on the current scan and IF setup (see § 3.6).



(a) (b)

Figure 3.1: The AstrID splash screen (3.1a) and AstrID startup pop-up window (3.1b).

Table 3.1: AstrID mode features

Mode	Edit & Validate Syntax	Validate Configuration	Submit SBs	Observing Logs	Data Display
Offline	✓	Simulated			Historical[(1)]
Online (monitor)	✓	Simulated		✓	Real-time
Online (control)	✓	Real[(2)]	✓[(3)]	✓	Real-time

(1) Previously acquired data should always be viewed 'offline'.
(2) Requested configurations are validated with respect to the actual `dev_health.conf` file rather than the simulated 'ideal' universal cabling file.
(3) Only permitted when you are 'in the gateway' (the GBT operator has given you security access).

3.2 How To Start Astrid

To start AstrID, type `astrid` from the command line on any Linux computer in Green Bank. The first thing you will see is the AstrID "splash screen" which is shown in Figure 3.1a. The AstrID GUI should appear on-screen after 10-20 seconds (see Figure 3.2).

3.2.1 Astrid Modes

On startup, AstrID will automatically ask what mode to operate in via the pop-up window shown in Figure 3.1b. Once an initial mode has been set it may be changed at any time by selecting `Real Time Mode...` from the `File` drop-down menu (see § 3.3.4).

Note that observers should use `File`→`Real Time Mode...` to relinquish control of the telescope immediately after their scheduled observing session.

The features available for each mode are listed in table 3.1. Users should select the most appropriate mode for their purposes:

- **Work offline**: Primarily used to create, edit and validate SBs. It is also the preferred method to look at previously obtained data in the Data Display since online modes will continually refresh the display window with near-real-time data.

- **Work online, but only monitor observations**: May be used to view what is happening in the AstrID observing logs and Data Display for the current observations. You will not be able to submit SBs or affect observing in any manner.

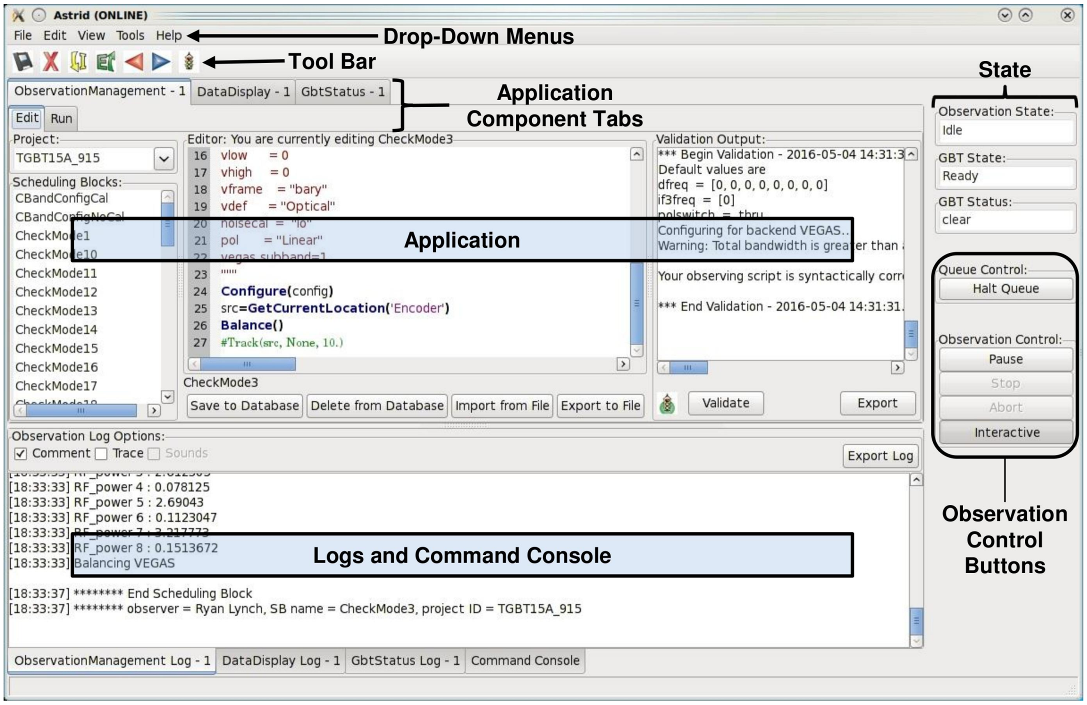


Figure 3.2: The different components on the AstrID GUI.

- **Work online with control of the telescope**: Used to perform observations with the GBT by allowing the user to submit SBs. Log information and real-time data displays are also available in this mode. **Note that working online requires the GBT operator to "put you in the gateway" (give you security access).**

3.3 Astrid GUI Composition

The AstrID GUI layout consists of several components shown in Figure 3.2 and described in the following section.

3.3.1 Resizing Astrid Display Areas

It is possible to resize some of the display areas within AstrID. If you put the mouse over the bar separating two display areas you will get a double-arrowed resize cursor. If you then hold down the left–mouse button you can use the mouse to move the border and resize the display areas.

3.3.2 Application

This comprises the majority of the space within the AstrID GUI. This shows the contents of the Application selected by the application component tabs.

3.3.3 Application Component Tabs

The application component tabs are located under the Drop-down menus and the Toolbar The top level of tabs allow users to switch between the three main AstrID applications: Observation Management, Data Display, and GBT Status. Below these are a set of subtabs that vary for each application component tab.

3.3.4 Drop–down Menus

In the top, left hand side of the AstrID GUI you will find the drop–down menus. The contents of the drop–down menus change according to which Application is currently being displayed on the AstrID GUI. We will not discuss all of the options under the drop-down menus in this document but we will provide some highlights.

File
- **New Window** Launch applications within the AstrID GUI or in an independent GUI.
- **Close Window** Close the currently displayed application in the AstrID GUI.
- **Real Time Mode...** Change between the operational modes of AstrID (see § 3.2.1).

Edit Standard "Windows" undo, redo, cut and paste options.

View Display or hide the Toolbar or view AstrID in Full Screen mode.

Tools Only active for the Data Display Application. You may use checkboxes to select various tooltips such as `info`, `pan`, and `zoom`. You can also change the "Heuristics" used during the reduction of Pointing and Focus Observations by selecting `Options...` (see § 4.1.3.3).

Help Bring up documentation for some but not all Applications.

3.3.5 Toolbar

The Toolbar is located just under the Drop–down Menus near the top of the AstrID GUI. The contents of the Toolbar change depending on which Application is being displayed in the AstrID GUI. The Toolbar options are a subset of commonly used options from the Drop–down Menus. When you leave the mouse situated over one of the Toolbar buttons for a few seconds a "pop-up" will appear that tells you what action the Toolbar button will invoke.

3.3.6 Logs

The Log Window is located in the lower portion of the AstrID GUI underneath the Application display area. Clicking on the log tabs at the very bottom of the GUI will display log information for the Observation Managament, Data Display, or GBT Status applications. Viewing a specific log will also change the application window to display the matching application.

The contents of the Observation Management application Log may be saved to an external file via the Export Log button. Note that closing or restarting AstrID will clear the Observation Management Log. If you wish to retrieve an unsaved observating log, please contact your GBT "Friend".

3.3.7 Command Console

The Command Console is a Python shell that imports the "Configuration Tool" and "Balance" Application Programming Interfaces (APIs). Both APIs will only interact with the M&C systems if the user has been granted security access and is operating AstrID from the "Work online with control of the telescope" mode (see § 3.2.1).

Observers may find the Command Console useful as a stand alone Python Shell. However, the "configuration tool" and "Balance" APIs are only intended for use by GBT staff and expert users. Note that internal AstrID commands such as those listed in Chapter 5 are not available for use without first importing all necessary AstrID modules.

3.3.8 State

Three indications of state are located in the upper right corner of the AstrID GUI.

Observation State indicates **AstrID's state.**
If AstrID is not communicating with the M&C system (such as in its "offline" mode) then you will see "Not Connected". If AstrID is communicating with the M&C system and there isn't an SB being executed then you will see "Idle" and if an SB is running (or has been paused) then you will see "SB Executing"("SB Paused").

GBT State indicates the **M&C system state.**
If the M&C system is not working properly you will see "Not In Service" or "Not Connected." "Unknown" indicates that the M&C system is working but does not know the state of any of the hardware devices. You will see the state be "Ready" when the GBT is not doing anything. It will be "Activating" or "Committed" when the GBT is preparing to perform an observation, etc. While taking data during a scan the state will be "Running". At the end of a scan you will see the state become "Stopping." If the scan is ended for any abnormal reason the state will be "Aborting."

GBT Status indicates the **error state of the M&C system.**
If the M&C system is not communicating properly with the hardware the status can be "Unknown" or "Not Connected." If the status is "Clear", "Info", or "Notice" then there are no significant problems with the GBT. If "Warning" then it is worth asking the Operator what the problem is, but it may not affect observation quality. If the status is "Error" then there is potentially something wrong that may need attention. If the status is "Fault" or "Fatal" then something has definitely gone wrong with the observations.

3.3.9 Observation Control Buttons

The Observation Control Buttons are located in the lower-right of the AstrID GUI. These buttons give the observer control of the GBT during the execution of an SB and have the following functions:

Halt Queue If this button is not activated then the SBs in the Run queue will continue to be executed in order. If this button is activated it will finish the current SB but will not allow the next SB in the Run Queue to execute until the button is returned to its default "off" state.

Pause Stop the execution of the current SB when the next line of code is encountered.

Stop Stop the current scan at the end of the next integration time. This is a nice, gentle way to stop a scan.

Abort Stop the current scan immediately. This may lead to corrupted data.

Interactive When selected, will cause AstrID to automatically answer any pop–up query. AstrID will always choose what it deems to be the safest answer. This is useful when you have to leave the control for an extended period of time (such as when you go to the cafeteria to eat, etc.).

3.4 The Observation Management Tab

The Observation Management Application consists of two sub–GUIs, the Edit Subtab and the Run Subtab (see Figures 3.3 and 3.5). In the Edit Subtab you can create, load, save, and edit SBs. You can also Validate that the syntax is correct. The Run Subtab is where you will execute GBT observations.

3.4.1 The Edit Subtab

The Edit Subtab has five major areas: a list of Project Names, SBs that have been saved into the AstrID database for that project, an editor, a Validation area, and a log summarizing the observations. This is shown in Figure 3.3. Chapter 5 covers the contents and creation of SBs.

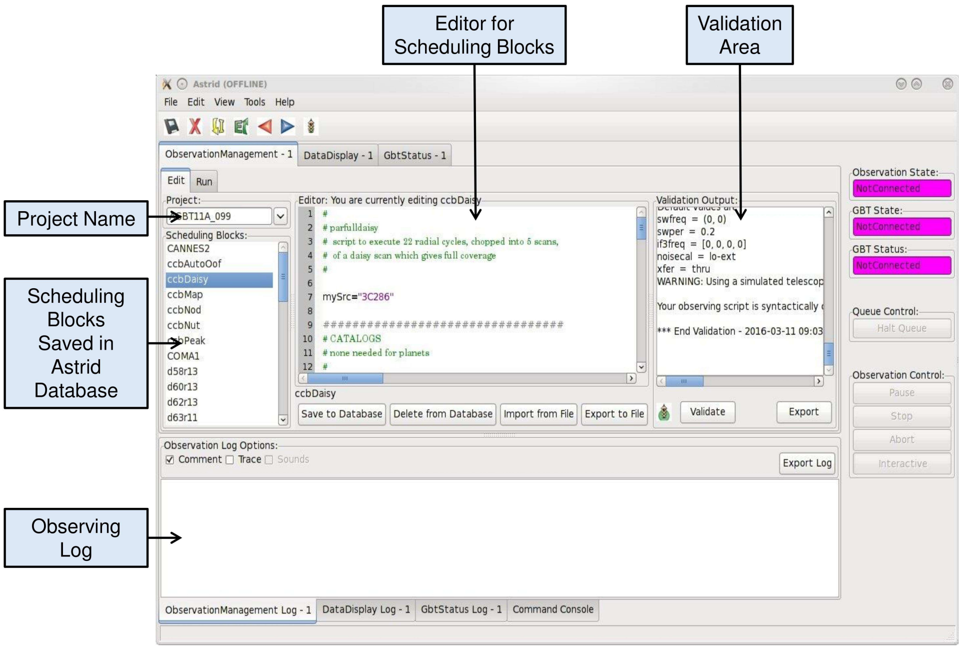


Figure 3.3: The AstrID Observation Management/Edit Subtab.

3.4.1.1 Project Name and List of Scheduling Blocks

To access scheduling blocks associated with your project, you will need to enter your Project Name in the "project" window located in the upper left part if the Edit Subtab. Your Project Name is the code that your GBT proposal was given with the prefix "AGBT", e.g., AGBT16A_001. To enter a Project Name you may either type it in directly, or use the drop–down arrows to navigate to your project through a project hierarchy as shown in Figure 3.4.

After doing this you will see in the window labeled "Scheduling Blocks" a list of SBs, if any, that have been previously saved into the AstrID database. All of the saved SBs for a given project will show up in the "Scheduling Blocks" section of the Edit Subtab. If an SB has been Validated (i.e. it is syntactically correct) then it will appear in bold–face type. This means that it can be executed. If the script has been saved but is syntactically incorrect it will appear in lighter–faced type.

3.4.1.2 Editor

You can use the Editor to create or modify an SB within AstrID. Standard Windows functions like Ctrl–X (to cut selected text), Ctrl–C (to copy selected text), and Crtl–V (to paste selected text) can be used within the editor. The editor lists the line number on the left hand side of the window and marks Python code as follows:

- **Green highlighted text** - Commented characters
- **Black highlighted text** - Standard Python commands/syntax
- **Purple highlighted text** - Strings

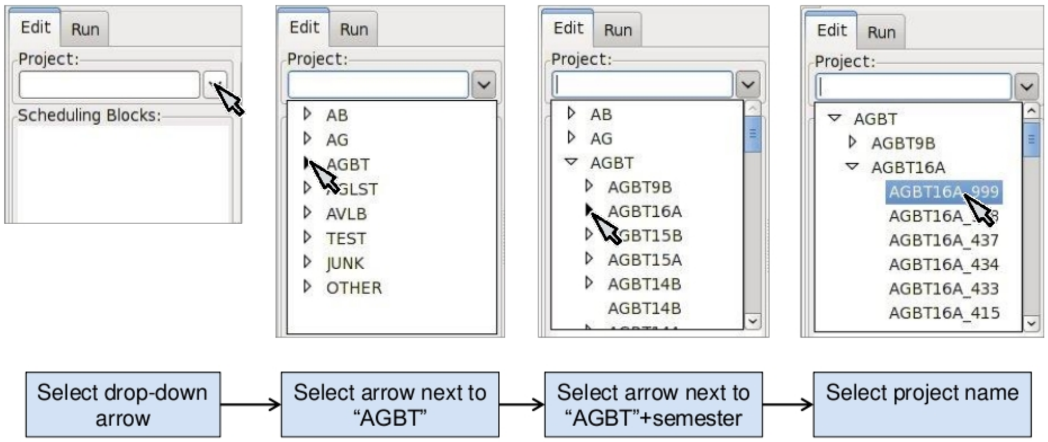


Figure 3.4: Selecting your project using the drop-down menu. Alternatively, simply type the full project code, e.g. AGBT16A_999, in the blank field below Project and hit enter.

- **Magenta highlighted text** - Triple quoted strings (used in Python to enclose strings that span multiple lines)
- **Dark blue highlighted text** - Python functions
- ⊖/⊕ - Marks the start of an indented block of Python code such as an **if** statement or **for** loop. Clicking on ⊖ will collapse the indented code block and change the symbol to ⊕. Likewise, clicking on ⊕ will expand a previously collapsed code block.

The editor also has four operational buttons:

[Save to Database] - This button will check the validation of the current SB and then save it to the AstrID database. A pop–up window will notify you if the SB did not pass Validation. A second pop-up window will allow you to set the name that the SB will be saved under in the AstrID database.

[Delete from Database] - This button will delete the currently selected SB from the AstrID database.

[Import from File] - This button will allow you to load an SB from a file on disk.

[Export to File] - This button will allow you to save the edited SB displayed in the editor to a file on a disk. This does not save the SB into the AstrID database.

The first time you select either of the [Import from File] or [Export to File] buttons you will have a pop–up window that lets you select the default directory to use. After selecting the default directory you will get a second pop–up window that shows the contents of the default directory so that you can select or set the disk file name to load from or export to.

3.4.1.3 Adding and Editing Scheduling Blocks in the Database

We will first describe how to add an SB to the "Scheduling Block" list (i.e. database) and then we will describe how to manipulate and edit SBs in the list.

Saving a Scheduling Block to the Database

If you have already created an SB outside of AstrID, you should go to the Edit Subtab in AstrID and then use [Import from File] to load your SB into the Editor. Otherwise you can just create your

SB in the Editor. To save the SB into the AstrID database you just need to hit Save to Database . This will run a validation check (see § 3.4.1.4) on your SB and then a pop–up window will appear which allows you to specify the name which you would like to use in the list for your SB.

Selecting a Scheduling Block
If you perform a single click on any SB in the "Scheduling Block" list, the contents of the selected SB will appear in the Editor. The selected SB will be highlighted with a blue background.

Mouse–button Actions on the selected Scheduling Block
If you perform a right mouse button click on the selected SB a pop–up window will appear that will let you rename, create a copy or save the SB to the AstrID database. You can also delete the SB from the AstrID database. You may also rename the SB if you perform a left mouse button double click on the script name in the list.

3.4.1.4 Validator

The Validation area is where you can check that the currently selected SB is syntactically correct. This does not check for run–time errors and thus, does not guarantee that the script will do exactly what you want it to do. For example, it can not check that you have the correct coordinates for your source. You will also see error messages, notices and warnings from the Validation in this area.

The Validator will attempt to verify that you are using a legal configuration. When run in AstrID's offline mode, the Validator can only compare your requested configuration with a simulated "ideal" model of the telescope hardware. To perform a full configuration check against the true hardware state of the telescope (modelled by the `dev_health.conf` file), you must be running AstrID from the "Work online with control of the telescope" mode.

Before an SB can be run within AstrID it first must pass Validation. To Validate a script without saving it you can just hit Validate . An SB automatically undergoes a validation check when you hit Save to Database in the editor. Any messages, etc. from the validation will appear in the "Validation Output" test area. You can export these messages to a file on disk by hitting Export in the validation area.

The state of an SB's validation is shown by the stop–light. If the script has never been validated or has been changed since the last validation the stop–light will have the yellow light on. If the SB fails validation the stop–light will turn red, while it will turn green if the SB passes validation.

Note: **for** loops with many repeats can take an extended amount of time to validate since the Validator will go through each step in the loop. Also be careful of infinite loops in the validation process. Use of time functions such as **Now()** (see Chapter 5) always return "None" in the validation.

3.4.1.5 The Observing Log

The observing log is always visible at the bottom of the Observation Management Tab. It shows information from the execution of SBs in either of the AstrID online modes. The observing log can be saved to a disk file by hitting the Export button that is just above the top right corner of the log display area. Note that closing AstrID will clear the observing log. If you wish to retrieve unsaved observing log information, please contact your GBT "friend".

3.4.2 The Run Subtab

The Run Subtab is shown in Figure 3.5. Here you will queue up SBs to perform the various observations that you desire to make. The Run Subtab has five components. Across the top of the Run Subtab you enter information that will be put into the headers associated with the observations. On the left is a list of SBs that you can execute. On the right are the "Run Queue" which holds SBs that are to be executed in the future, and the "Session History" which shows which SBs have previously been executed. At the bottom is the "Observing Log".

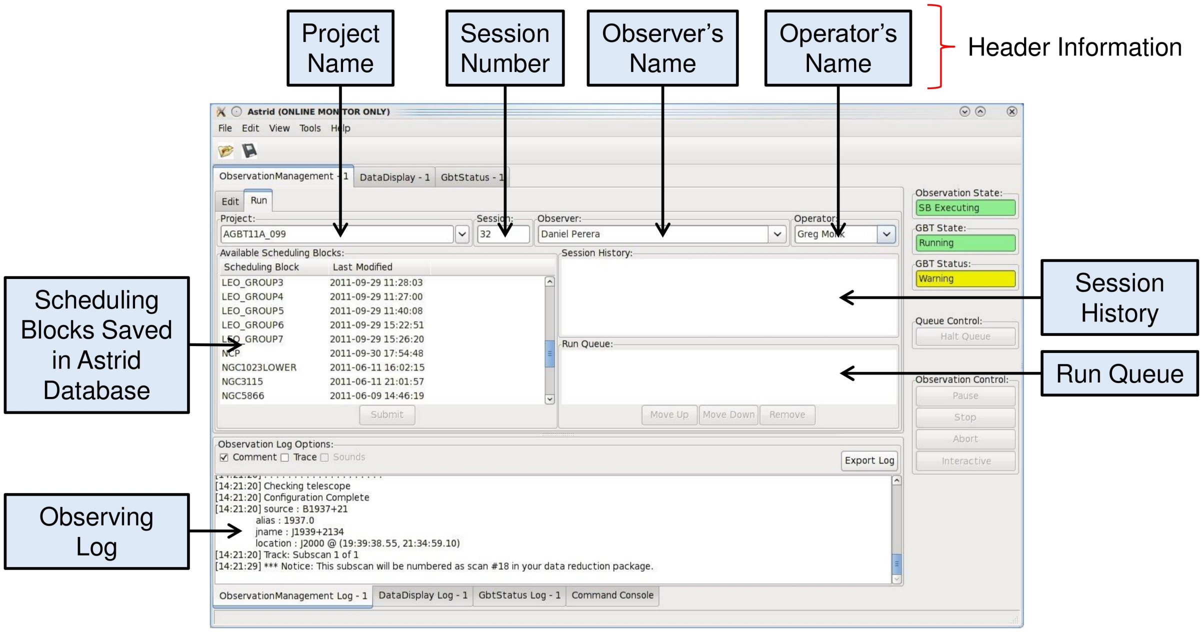


Figure 3.5: The AstrID Observation Management/Run Subtab.

3.4.2.1 Header Information Area

The following fields must have entries before an SB can be executed:

Project: Just as in the Edit Subtab you use the drop–down menu to select your Project Name. If your project is not listed, ask your GBT "friend" or the telescope Operator to add it to the database.

Session: A session is a contiguous amount of time (a block of time) for which the project is scheduled to be on the telescope. Each time a project begins observing for a new block of time it should have a new session number. The session number is usually determined by AstrID and automatically entered. However, there are cases (such as AstrID crashing) where the session number could become incorrect. You can type in the correct session number if needed. **Note that a "Session" in AstrID is equivalent to an "observing period" in the lingo of the Dynamic Scheduling System (DSS). "Session" has a different meaning in the DSS.**

Observer's Name: This is a drop–down list where you choose the observer's name. Only the PIs on a project are guaranteed to have their name in this list. If your name is not listed, ask your GBT "friend" or the telescope operator to add it.

Operator's Name: This is a drop–down list from which you pick the current operator's name at the beginning of your observations.

3.4.2.2 Submitting An SB to the Run Queue

In order to execute an SB you must:

Step 1. Select the Observation Management Tab.

Step 2. Select the Run Subtab.

Step 3. Make sure that the header information fields all have entries.

Step 4. Select the SB you wish to execute from the list of available SBs.

Step 5. Hit the Submit button below the list of SBs.

Your SB is then automatically then sent to the Run Queue. Note that double-clicking on an SB is the same as selecting the SB and then hitting Submit .

3.4.2.3 The Run Queue and Session History

When an SB is submitted for execution it is first sent to the Run Queue. This contains a list of submitted SBs that will be sequentially executed in the future.

When an SB begins execution it is moved to the Session History list. So the Session History list contains the currently executing SB on the first line and all previously executed SBs that have been run while the current instance of AstrID has been running on subsequent lines.

If there are not any SB in the Run Queue when a new SB is submitted for execution it may appear that the SB just shows up in the Session History. However it has indeed gone through the Run Queue - albeit very quickly.

3.4.2.4 The Observing Log

The observing log is always visible at the bottom of the Observation Management Tab. It shows information from the execution of SBs. The observing log can be saved to a disk file by hitting the Export button that is just above the top right corner of the log display area. Note that closing AstrID will clear the observing log. If you wish to retrieve unsaved observing log information, please contact your GBT "friend".

3.5 The Data Display Tab

The Data Display Tab provides a near–real time display of your GBT data and is discussed in Chapter 4.

3.6 The GbtStatus Tab

The GbtStatus Tab displays various GBT specific parameters, sampled values and computed values. Special care was taken to promote its use for remote observing. An Example of how the GBT Status Display appears in AstrID is shown in Figure 3.6 and 3.7.

The default status screen displays all of the currently supported items of the gbtstatus program grouped into various sections. These are:

3.6.1 General Status

Observer: The observer name.

Project ID: The data directory of the FITS files. This is your Project Name with the session as a suffix. For example, the Project ID for session 02 of AGBT16A_001 would be AGBT16A_001_02 (See § 3.4.1.1).

Status: The status of the GBT. See § 3.3.8

LST: The Local Sidereal Time (LST) of the last update.

Last Update: The local time when the database was last updated.

UTC Date: The Coordinated Universal Time (UTC) date of the last update.

UTC Time: The UTC time of the last update.

MJD: The Modified Julian Date (MJD) of the last update.

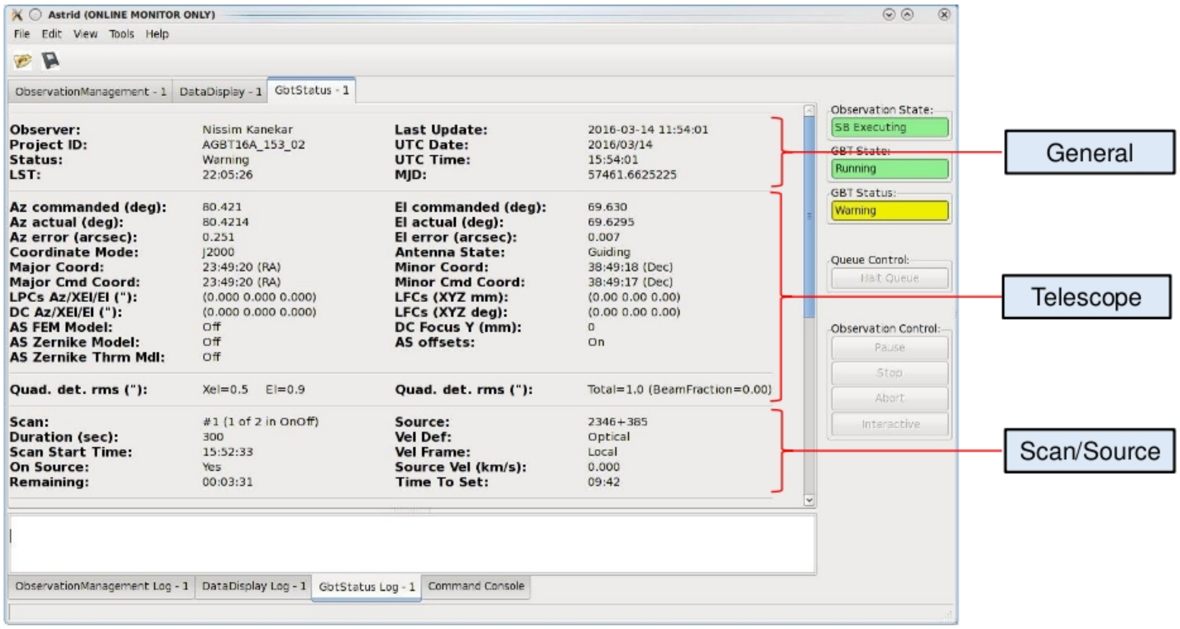


Figure 3.6: The top portion of the AstrID GbtStatus Tab. To see the rest of the status screen you will need to use the scroll bar.

3.6.2 Telescope Status

Az commanded: The commanded azimuth position of the telescope in degrees.

Az actual: The actual azimuth position of the telescope in degrees.

Az error: The difference between the commanded and the actual azimuth position of the telescope in arc-seconds. This value does not contain a cos (el) correction.

El commanded: The commanded elevation position of the telescope in degrees.

El actual: The actual elevation position of the telescope in degrees.

El error: The difference between the commanded and the actual elevation position of the telescope in arc-seconds.

Coordinate Mode: The coordinate mode used to represent a particular location on the sky. See § 5.6.1

Major and Minor Coord: The telescope position in the current Coordinate Mode.

Major and Minor Cmd Coord: The telescope position in the current commanded Coordinate Mode.

Antenna State: If the antenna software is not running the state will be "Disconnected." If the antenna software is running but with its control of the antenna turned off then the state is "Dormant." If the antenna is not moving then the state will be "Stopped." If the antenna is moving and data are being taken then the state is "Guiding" and if data are not being taken the state is "Tracking." If the antenna is moving to a new commanded position the state is "Slewing."

LPCs Az/XEl/El: The Local Pointing Correction (LPC) offsets in arc-seconds.

DC Az/XEl/El: The Dynamic Corrections values in arc-seconds. The GBT has temperature sensors attached at various points on the backup structure and the feed-arm. These are used in a dynamic model for how the GBT flexes with changing temperatures. This model is used to correct for pointing and focus changes that occur from this flexing.

LFCs (XYZ mm): The Local Focus Corrections (LFCs) for the offset focus position in millimeters. This value is determined from a Focus observation (see Chapter 5).

LFCs (XYZ deg): The subreflector tilt offset in degrees.

DC Focus Y (mm): The Dynamic Corrections Y subreflector offset in millimeters.

AS FEM Model: The state of the Finite Element Model (FEM) correction for the Active Surface (AS). The FEM predicts how the surface changes due to gravitional flexure versus the elevation angle.

AS Zernike Model: The state of the AS Zernike model correction model. The Zernike model is a set of Zernike polynomial coefficients determined from Out–Of–Focus holography that improve the shape of the AS versus the elevation angle.

AS Zernike Thrm Model: The state of the FEM correction for the AS. The FEM predicts how the surface changes due to thermal flexure.

AS Offsets: The state of the AS zero offsets. The zero offsets are the default positions for the AS. This should always be "On" if the AS is being used.

Quad. det. rms: The quadrant detector is used to detect and correct for wind-induced pointing errors. rms values in arc-seconds are reported in elevation and cross–elevation. Total rms is also given as a fraction of the beam.

3.6.3 Scan and Source Status

Scan: A scan is a command within an SB used to collect observational data. The field here is derived from the scan number and PROCNAME, PROCSIZE and PROCSEQN keywords from the GBT Observing (GO) FITS file.

Duration: The scan length in seconds.

Scan Start Time: If scan has started it is the UTC scan start time - if the scan has not started, then it is the countdown until the start of scan.

On Source: "Yes" or displays a countdown until the antenna is on source.

Remaining: The time remaining in the scan.

Source: The source name.

Vel Def: The velocity definition specifies which mathematical equation is used to convert between frequency and velocity. See Equations 5.1, 5.2, and 5.3

Vel Frame: The velocity frame or inertial reference frame. See the "vframe" keyword in § 5.2.5

Source Vel: The source velocity ($\mathrm{km\,s^{-1}}$).

Time To Set: The time till the current source sets.

3.6.4 Configuration Status

Receiver: The receiver being used.

Polarity: The receiver polarity.

Cal State: 'ON' if the noise diode is firing during the scan.

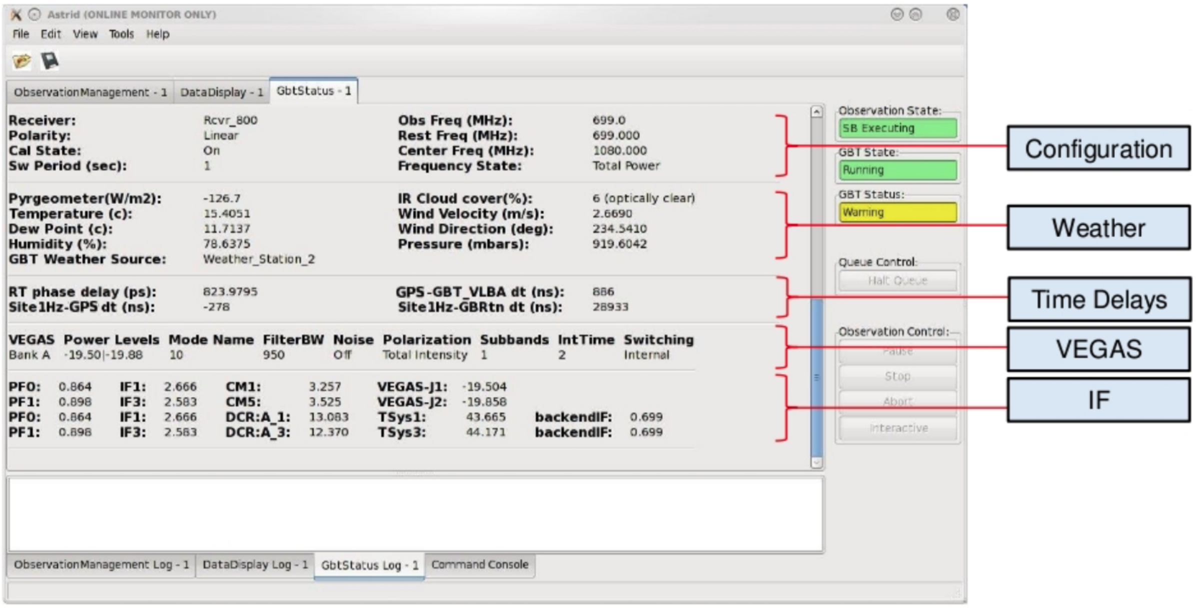


Figure 3.7: The bottom portion of the AstrID GbtStatus Tab. To see the rest of the status screen you will need to use the scroll bar.

Sw Period: The period in seconds over which the full switching cycle occurs. This is determined by the user in their configuration (see § 5.2).

Obs Freq: The observed spectral line frequency in the local frame (MHz).

Rest Freq: The spectral line frequency in the rest frame (MHz).

Center Freq: The center IF frequency set by the Local Oscillator (LO) in MHz. See Appendix B for further details.

Frequency State: The switching type. Either total power or frequency switching.

3.6.5 Weather Status

A real–time readout from one of the GBT weather stations providing information on temperature, pressure, humidity, dew point, wind direction and velocity. In addition, the pyrgeometer measures the net near-IR irradiance of the sky to give an approximate indication of cloud cover.

3.6.6 Time Delay Status

RT phase delay: This is the time delay between the timing center in the GBT equipment room and the GBT receiver room, in picoseconds, modulo 2000 ps. It is measured by comparing the phase of the 500 MHz reference signal sent to the receiver room with a copy of the signal returned to the timing center.

Site1Hz-GPS dt: Time difference between the Site1Hz (a one pulse per second signal that is locked to the hydrogen maser time standard) and a pulse from the GPS receiver.

GPS-GBT_VLBA dt: Time difference between the GPS receiver and the VLBA back end timing module.

Site1Hz-GBTRtn dt: Time delay between the Site 1Hz and a copy of the 1 Hz returned from GBT receiver room. It is twice the delay of the fiber cables. The value is about 28933 ns which means the time delay between the equipment room the the receiver room is about 14466 ns.

3.6.7 VEGAS Status

VEGAS: The VEGAS Bank (spectrometer with letter designation $A \rightarrow H$) selected in the scan coordinator.

Power Levels: The power levels at the inputs to the VEGAS Analog to Digital Converter (ADC) cards. There are two ADCs per bank, one for each polarization. The VEGAS balance API sets these values to approximately -20dBm by default.

Mode Name: Each VEGAS Bank can be configured in one of 29 Spectral Modes (see Table 10.1) or 1 of 24 Pulsar Modes (see Table 12.1).

FilterBW: The bandwidth (MHz) of the digital filter implemented in the Field-Programmable Gate Array (FPGA). Note that these values do not correspond to the bandwidths listed in Table 10.1.

Noise: The state of the noise source which can be either "On" or "Off".

Polarization: Users may specify which spectral product to record (See the "vegas.vpol" keyword in § 5.2.5). vegas.vpol="self" records "Total Intensity" products, "cross" records "Full Stokes" parameters, "self1" records the polarization inputs from the first ADC only, and "self2" records the polarization inputs from the second ADC only.

Subbands: Each VEGAS bank can select between single (subbands=1) and multiple (subbands=8) spectral windows when using VEGAS modes with a 23.44 MHz bandwidth.

IntTime: The VEGAS integration (dump) time in seconds.

Switching: Determines whether switching is controlled by VEGAS ("Internal") or another source ("External").

3.6.8 IF Status

The Intermediate Frequency path (IF path) in use is always displayed in the last section of the GBT status screen. An example screen is shown in Figure 3.7; the content displayed depends on the exact configuration. In this example, each line represents the IF path for a single polarization path from the IF Rack to the backend. Each line contains only the devices in use for the listed path. A path may include a subset of the devices and values listed below.

IF#: The # displayed is the number corresponding to the IF Rack switch in use. The value displayed is the RF power in Volts detected by the IF Rack.

CM#: The # displayed is the number corresponding to the Converter Module in use. The value displayed is the RF power in Volts coming out of the Converter Module after the Second LO (LO2) and Third LO (LO3) mixers and before the Converter Module filters.

CF#: The # displayed is the number corresponding to the Analog Filter in use. The value displayed is the RF power in Volts coming out of the Analog Filter Rack after all filters have been applied (used with 100 MHz Converters).

SG#: The # displayed is the number corresponding to the Analog Filter in use. The value displayed is the RF power in Volts coming out of the Analog Filter Rack after all filters have been applied (used with 1.6 GHz Samplers).

VEGAS-J#: The # displayed is the number corresponding to the port of VEGAS in use. The value displayed is the power level in dBFS. For best performance, it should be approximately -20 dBFS.

Radar-Port#: The # displayed is the number corresponding to the port of the Radar in use.

DCR:A_#: The # displayed is the bank and number corresponding to the port of the DCR in use. The value displayed is the total power in raw counts.

TSys#: The # displayed is the number corresponding DCR port in use. The value displayed is the system temperature as reported by the DCR (should be considered a loose approximation).

backendIF: The value displayed is the frequency of the Doppler track rest frequency as seen by the backend, in GHz.

Chapter 4

Near–Real–Time Data Displays and CLEO Utilities

4.1 The Astrid Data Display Tab

The Data Display Tab provides a real time display of your GBT data so that you can check that you are getting valid data. The Data Display is actually running an application called The GBT Fits Monitor (GFM). This application provides scan-based display and analysis of GBT data, either in real-time as the data is being collected, or in an offline mode where it can be used to simply step through the scans from an observation. Users are encouraged to run GFM offline for reanalyzing data during observations. A separate GFM application can be launched from the Linux prompt via the `gfm` command or AstrID could be switched to offline-mode.

4.1.1 Working Online

If you are using either of AstrID's "online" modes (see § 3.2.1) and have selected the "DataDisplay" tab, then the data display will update as new data are obtained. Continuum and Spectral Line data are only updated when these displays are being viewed. Pointing and Focus data are always automatically updated whether or not their displays are being shown or not. Due to this feature, clicking on previous observations while Pointing and Focus scans are in progress can confuse GFM and should be avoided. The list of scans will always automatically update.

4.1.2 Working Offline

You can look at data that have already been taken with the GBT by running AstrID in "offline" mode. To view data in this mode you need to follow these steps:

Step 1. Change the AstrID mode to "offline" (see § 3.2.1).

Step 2. Select **File**→**Open** from the drop-down menu in the Data Display Tab.

Step 3. Select a project ID from the list of project directories in `/home/gbtdata/`.

Step 4. Double-click `ScanLog.fits` to access the data.

Step 5. It may take several seconds to a few minutes to access all of your scans depending on the amount of data to load. The process is complete when you see a list of scans displayed sequentially on the left hand side of the GFM display.

Step 6. Click on a scan in the scan list window to process it.

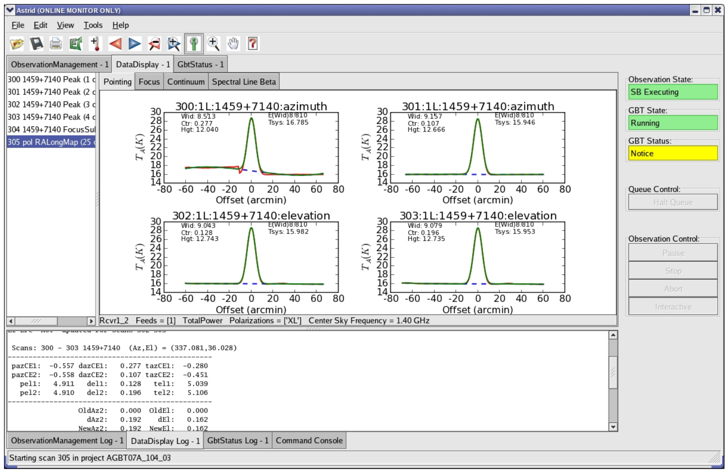


Figure 4.1: The Pointing subtab of the AstrID Data Display.

4.1.3 Pointing and Focus Data Display

Pointing scans (from Peak, AutoPeak and AutoPeakFocus – see below) will appear under the Pointing Tab. If working "Online", the data display will automatically process the pointing scans. **Note that clicking on previous scans while Pointing and Focus scans are in progress may interfere with automatic processing.** It will calibrate the data, remove a baseline and fit a Gaussian to the data. After the two azimuth scans (cross-elevation, i.e. $\mathrm{Az} \times \cos(\mathrm{Dec})$) it will then automatically update the GBT M&C system with the new azimuth pointing offset values that it determined. It will then automatically update the elevation pointing offset after the two elevation scans, unless certain criteria are not met (see § 4.1.3.1). A sample of the Data Display Application after a pointing is shown in Figure 4.1.

The measured FWHM width (Wid) is shown in arcminutes. The fitted center of the Gaussian (Ctr) is pointing offset in arcmin. The measured height of the Gaussian (Hgt) is in units of the calibrated temperature scale or raw counts (as given by the y-axis label).

The focus scan data will appear under the Focus Tab; see Figure 4.2. Again, if "Online" the data will be processed automatically. They will be calibrated, have a baseline removed and a Gaussian will be fit to the data. The focus offset will automatically be sent to the M&C system.

The details of pointing and focus observations are described in § 5.4.1.

4.1.3.1 Fitting Acceptance Options

GFM has several levels of determining whether or not the pointing and focus solutions will be updated in the M&C system. The expected Full Width at Half the Maximum (FWHM) of the Gaussian fitted to the observed pointing data as the GBT slews across the source should be $\sim 748/\nu_{\mathrm{GHz}}$ arc–seconds where ν_{GHz} is the observing frequency in GHz.

For a focus scan the resulting data should approximate a Gaussian with a FWHM of 1080 ν_{GHz}, in mm. The default behavior for observations below 27 GHz is to assume that a pointing fit is bad if the FWHM differ from the expected value by more than 30% or if the pointing correction is more than twice the FWHM in magnitude; for observations above 27 GHz, the fit is bad if the FWHM differ from the expected value by more than 50% or if the pointing correction is more than three times the FWHM in magnitude. The default for a bad focus scan is if the FWHM is more than 30% from the expected value. Users may change fitting acceptance criteria by:

Step 1. Select the Pointing or Focus Subtab in the Data Display.

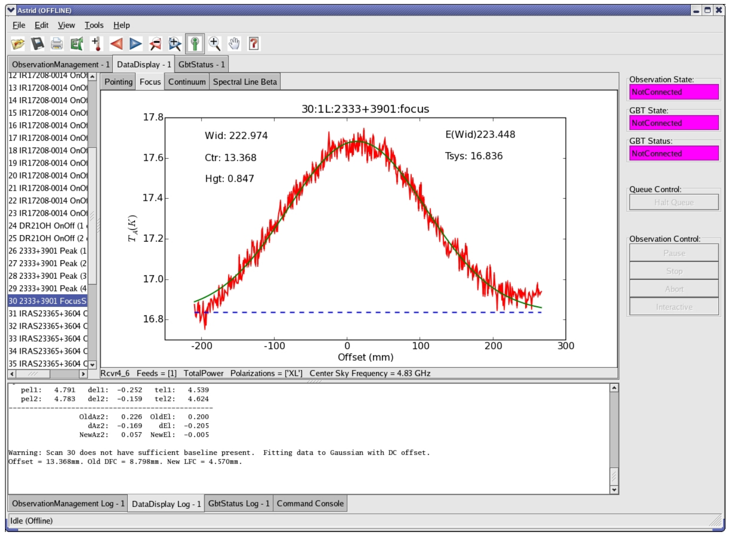


Figure 4.2: The Focus subtab of the AstrID Data Display.

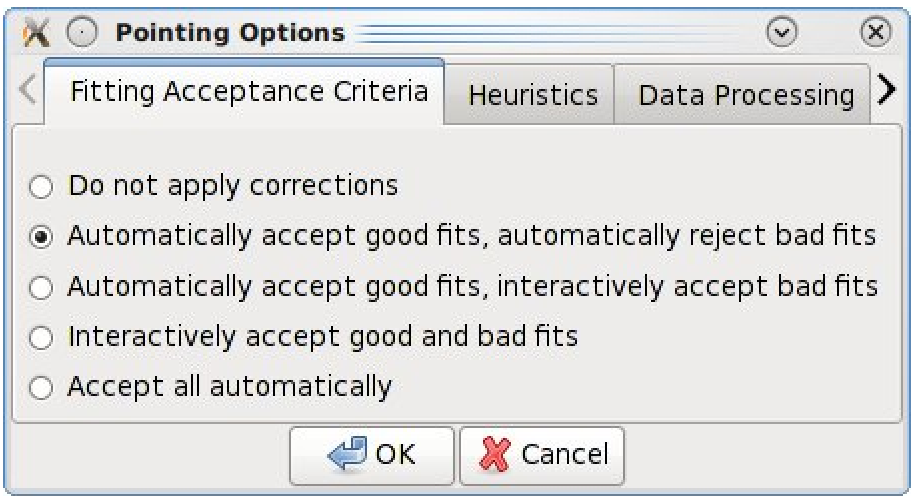


Figure 4.3: The pop–up menu to change the pointing and focus fitting acceptance criteria.

Step 2. Select `Tools→Options...` from the drop–down menu.

Step 3. Select the new mode in the "Fitting Acceptance Criteria" tab of the pop–up window.

NOTE: Options must be set independently for both Pointing and Focus **before** each type of observation in order to take effect.

GFM recognizes the fitting acceptance criteria shown in Figure 4.3 only when AstrID is in one of its online modes. The default setting is to "Automatically accept good fits, automatically reject bad fits". Users may also choose to never apply corrections or interactively accept bad and/or good fits. There is also an option to "Accept all automatically" which can be very dangerous and should only be used by experts.

4.1.3.2 Data Processing Options

The user may change the data processing strategy, beams, and/or polarizations used by GFM in reducing pointing or focus scans. This is not needed typically since the software picks the proper default settings

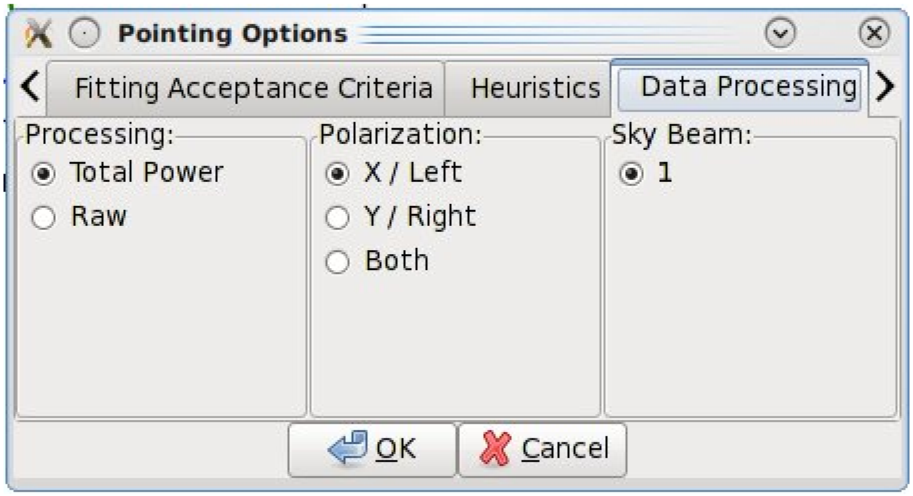


Figure 4.4: The pop–up menu to change the polarization and calibration used in pointing and focus fitting.

under normal conditions. However, for example, if the X polarization channel is faulty for some reason, one can use the Y channel instead. This can be done by:

Step 1. Select the Pointing or Focus Subtab in the Data Display.

Step 2. Select `Tools`→`Options...` from the drop–down menu.

Step 3. Make new data processing selections in the Data Processing Tab of the pop–up window (see Figure 4.4).

NOTE: Options must be set independently for both Pointing and Focus **before** each type of observation in order to take effect.

4.1.3.3 Heuristics Options

Heuristics is a generic term used at the GBT to quantify the "goodness of fit" of the pointing and focus data reduction solutions. Based on the known properties of the GBT , parts of the solution, such as the beam–width in pointing data, should have certain values within measurement errors. The Heuristics define how large these errors can be. The user may change the Heuristics by:

Step 1. Select the Pointing or Focus Subtab in the Data Display.

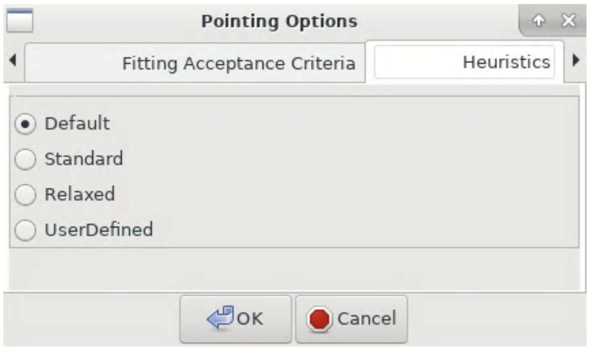
Step 2. Select `Tools`→`Options...` from the drop–down menu.

Step 3. Select the new mode in the Heuristics tab of the pop–up window (see Figure 4.5a).

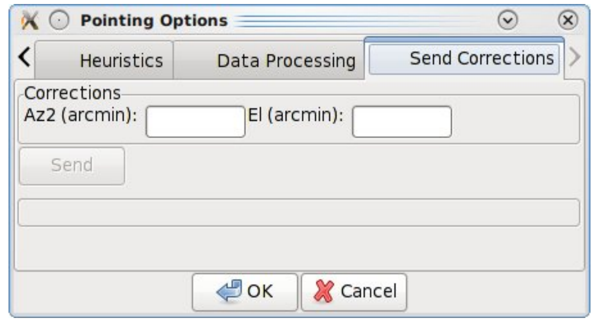
NOTE: Options must be set independently for both Pointing and Focus **before** each type of observation in order to take effect.

GFM allows the observer to switch between "default", "standard", "relaxed", and "user-defined" heuristics. The meaning of "standard" and "relaxed" heuristic values are predefined and cannot be changed by the user. The "standard" heuristics expect that the fitted Gaussians have a FWHM within 30% of the expected values and that the pointing solution is within twice the FWHM of the nominal location of the source. For the "relaxed" heuristics this becomes within 50% of the expected FWHM of the Gaussian fits and three times the FWHM for the pointing correction.

The "default" option is the software default, and at low frequency (< 27 GHz) it is equivalent to "standard" heurisitics, while at high frequency (> 27 GHz) the "default" mode corresponds to "relaxed"



(a) Pointing and Focus heuristics pop-up.



(b) Send Corrections pop-up.

Figure 4.5: Figure 4.5a shows the pop–up menu to change the pointing and focus fitting heuristics. Figure 4.5b shows The pop–up menu to manually send pointing corrections to the telescope.

heursitics. Under normal observing conditions, the observer should expect to use the "default" values. Under marginal weather conditions "relaxed" heuristics may be appropriate even at low frequencies (below 27 GHz). The "user-defined" heuristic values should only be used by experts. If you wish to use "user-defined" heuristics then you should contact your GBT project friend.

4.1.3.4 Send Corrections

For most observations, GFM processing produces good fits, and the solutions are automatically sent to the telescope using the default settings. However, at high frequencies (especially W–band 68-92 GHz Receiver), fits may fail, and the user may want to manually send the corrections to the telescope. The user may tell the operator to enter a solution, or they can send the corrections themselves using the Send Corrections tab. Note that corrections show up instantly within the CLEO status window (see § 4.2), but do not take effect until the start of the next scan. This can be done by:

Step 1. Select the Pointing or Focus Subtab in the Data Display.

Step 2. Select `Tools`→`Options...` from the drop–down menu.

Step 3. Select the Send Corrections Tab in the pop–up window (if not visible use arrow button on the right, the Send Corrections tab is farthest to the right)

Step 4. Enter the corrections in the text box, and click Send to send the solutions to the telescope. (see Figure 4.5b).

4.1.4 OOF Data Display

Out-Of-Focus holography (OOF) is a technique for measuring large-scale errors in the shape of the reflecting surface by mapping a strong point source both in and out of focus. The procedure derives surface corrections which can be sent to the active surface controller to correct surface errors. The procedure is only recommended for observing at frequencies of 40 GHz and higher.

The AutoOOF procedure will obtain three On-The-Fly (OTF) maps, each taken at a different focus position. Processing will begin automatically upon completion of the third map, the status of which can be viewed in the progress bar under "AutoOOF Processing Status" on the right–hand–side of the screen. Once complete, the result will be displayed in the OOF subtab of the AstrID Data Display (see Figure 4.6).

Once processing is complete, the default solution displayed in AstrID is the fifth-order Zernike fit (z5). The most aggressive fit is z6, while z3 is less aggressive. Solutions may be selected and viewed via the radio buttons in the upper–right section of the screen. Derived Local Pointing Corrections (LPCs) in

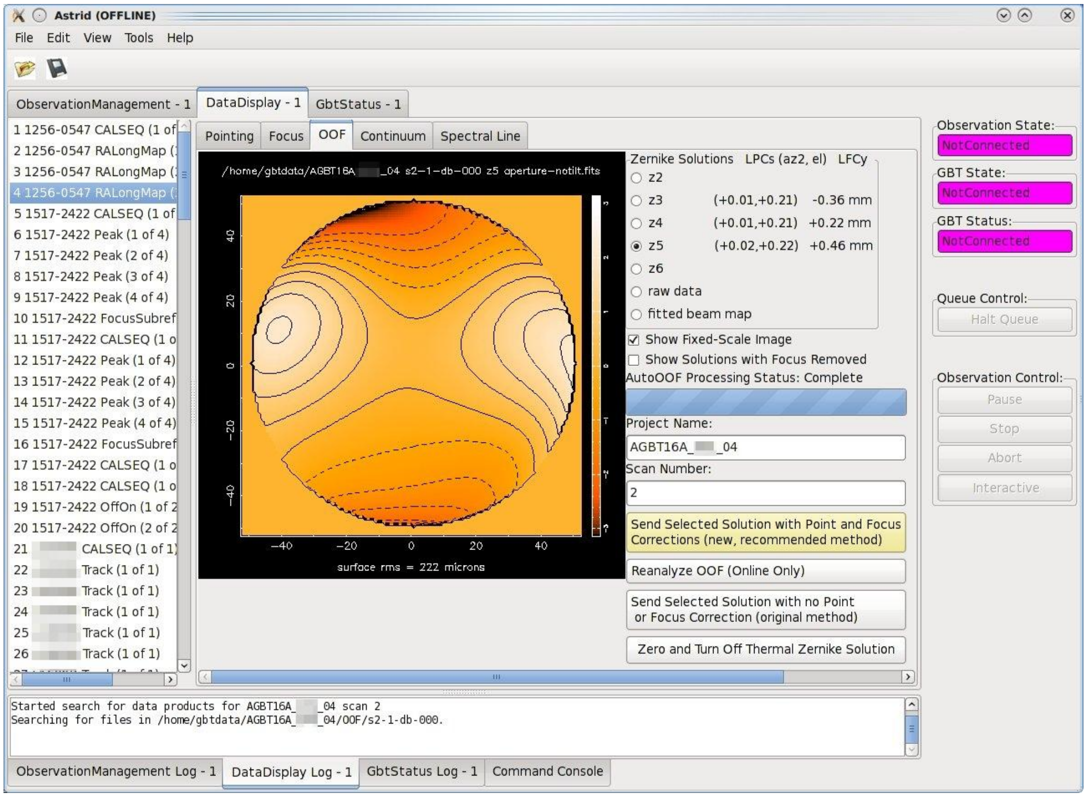


Figure 4.6: The OOF subtab of the AstrID Data Display.

arcminutes, and Local Focus Corrections (LFCy) in millimeters are displayed to the right of each radio button. Raw AutoOOF data at each focus position can be viewed as a timestream and map by selecting the "raw data" radio button. The "fitted beam map" radio button will display fitted beam map images and reduced χ^2 values for the three highest orders of Zernike fits (z3, z4, and z5 by default).

Solutions must be chosen by the observer and manually sent to the active surface. Therefore, it is essential that the Zernike fits and raw AutoOOF data are examined carefully before deciding upon a solution. Steps for validating and discerning appropriate solutions can be found in the following sections.

See Sec. 6.2 for more information on the AutoOOF procedure.

4.1.5 Continuum Data Display

Continuum data taken with the GBT that are not part of pointing and focus scans will show up in plots under the Continuum Tab (see Figure 4.7). This will show the uncalibrated continuum data as a function of time only.

4.1.6 Spectral Data Display

The Spectral Line Display was a tool originally designed for browsing the previous GBT Spectrometer spectral line data.

When viewing data online, the most recent integration is plotted automatically. Individual integrations may be selected and viewed offline. See Figure 4.8 for an example of the spectral line data display. The spectra displayed are raw data and no calibration has been applied to them. As spectra are plotted, information about each plot is printed in the console window. Each line is color coded to match the color

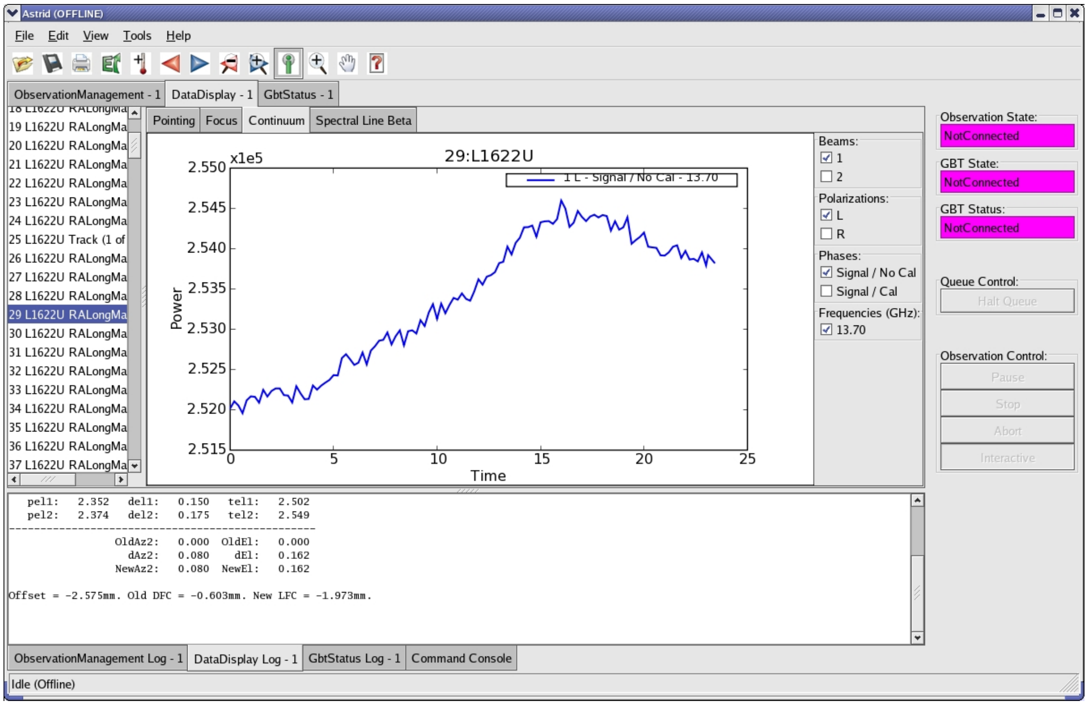


Figure 4.7: The Continuum subtab of the AstrID Data Display.

of that spectrum in the plotting window. In addition, some of the information for the very first spectra are used to annotate the plot. The plot title is parsed as project_name:scan_number:integration_number. For offline usage, the desired integration can be selected either using the up/down arrows, or by typing in a value in the edit box.

All user interaction for this plugin occurs in the right-hand side options panel. The check boxes allow selection of spectra to plot via astronomical variables: Beams, Polarizations, IF Numbers, and Phases. The options panel also includes three buttons and a radio box for plot viewing. The "Views" radio box offers options for plotting the bandpass vs. Channels or Sky Frequency. The Keep Zoom toggle button will maintain the current zoom, even as new spectra are plotted. Using the unzoom command (mouse right-click, or via the tool bar) will return the plot to its original scale. The Overlay toggle button can be used to overplot spectra from different integrations or scans. Finally, the Clear button erases the plot.

4.1.7 The Data Display Plotting Panel Toolbar

The plotting panel toolbar allows user interactions with plots in the display window and is located near the top of the Astrid Screen. The following features are available:

Open: Allows the user to open a previously saved session. This has the same functionality as file → open described in § 4.1.2.

Save: Allows the user to save output from the data display log as a text file.

Print (DO NOT USE): Please use the "export" function instead.

Export: Allows the user to save the figure displayed in the plotting panel to a file. The name must have an extension of either .png, .ps or .eps.

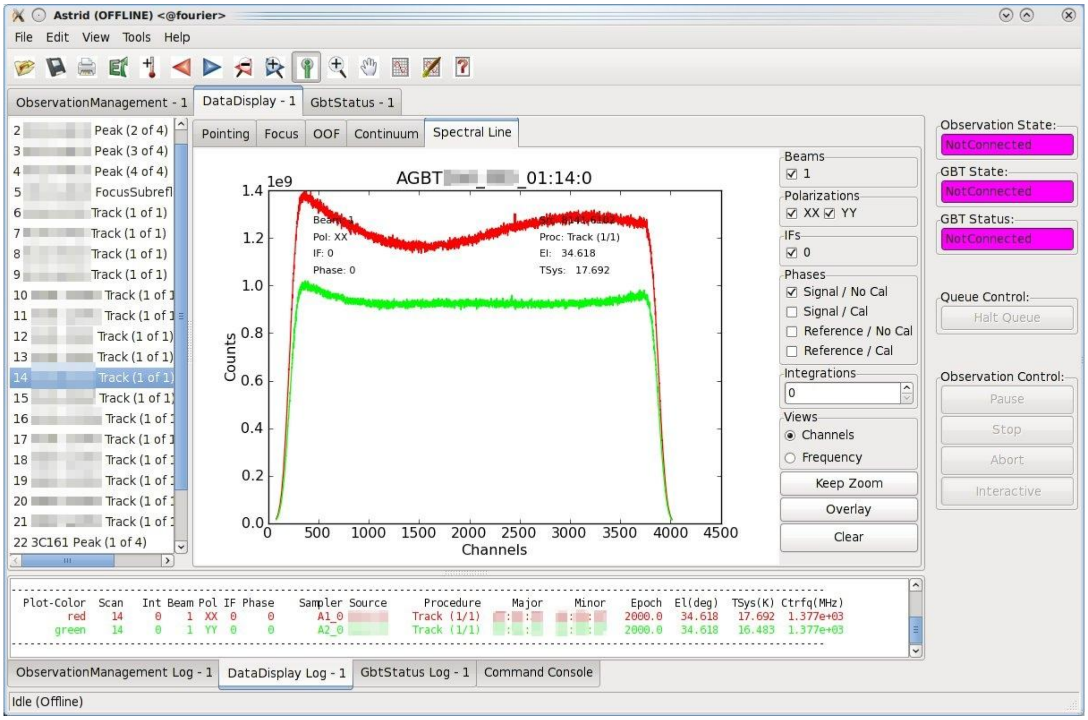


Figure 4.8: The Spectral Line subtab of the AstrID Data Display.

Unfreeze: Not applicable to Astrid general use. Unfreezes the processing of commands via the command line and intended for use in conjunction with the "freeze" command.

Undo: Undoes your last command.

Redo: Redoes your last command.

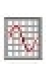
Unzoom: Undoes a previously executed zoom.

Rezoom: Redoes a previously executed zoom.

Info Tool: Selecting the info tool allows the user to use the mouse pointer to focus in/out among the available subplots (e.g., peak scans). Left-clicking the mouse brings a subplot into focus (hiding the other subplots). Right-clicking the mouse on the focused plot will show all subplots. If there is only one subplot, the info tool simply displays the mouse xy coordinates.

Zoom Tool: Selecting the zoom tool allows the user to use the mouse pointer for zooming in on a particular area of the plot. Left-clicking the mouse will zoom in. Right-clicking the mouse will zoom out.

Pan Tool: Allows the user to use the mouse pointer to pan around the selected subplot. Left-clicking the mouse and holding the left button down will pan around the subplot. Right-clicking restores the original view.



Grid Tool: Turns on the plot grid.

Plot Edit Tool: Allows the user to edit plot labels, colors, and title. Clicking on "Advanced Options" brings up an additional dialog which contains options for transparency, legend placement, and ordering of plots. Colors may be entered as hex codes or selected by clicking on the colored button to the right of the text field. Plots can only be reordered within their subplot - i.e., Y1 lines will always be below Y2 lines. Legend location can be specified with simple strings (e.g., "upper right") or coordinates 0-1 along the plot edges. If a string is chosen it will be used in place of any coordinates.

User Manual: Displays the Data Extraction and Analysis Program (DEAP) user manual.

4.1.8 Use of Plotting Capabilities

A User Manual is available http://deap.sourceforge.net/help/index.html that describes all the plotting functionality available in GFM. There is also a plotting Tutorial that illustrates the plotting capabilities by example which is available at http://deap.sourceforge.net/tutorial/index.html.

4.2 The CLEO Utilities

The Control Library for Engineers and Operators (CLEO) system provides a large number of utilities for monitoring and controlling the GBT hardware systems. Some of these are quite useful for observers, although most are intended for expert users and GBT staff.

Useful help messages pop up when you hover the mouse over any CLEO widget for a few seconds. Documentation is also available on the following web pages, but is somewhat out of date, so its best to consult your GBT "friend" for details.

- http://www.gb.nrao.edu/∼rmaddale/GBT/CLEOManual/index.html
- http://www.gb.nrao.edu/∼rmaddale/GBT/CLEOManual/tableofcontents.html.

The following section describes just a few CLEO utilities that are useful for observers.

4.2.1 Starting CLEO

To start CLEO, log in to any Linux workstation in Green Bank, open a terminal window, and type `cleo`. A "Cleo Launcher" window will appear (see Figure 4.9). Click on the **`Launch`** menu to get a list of programs that can be run. Remote observers working via VNC may prefer to use "Cleo Container" which launches and displays CLEO applications as tabs within a single window. Cleo Container can be opened from the terminal by typing `cleo cleocontainer` or from the Cleo Launcher via **`Launch`** → **`Cleo Container...`**

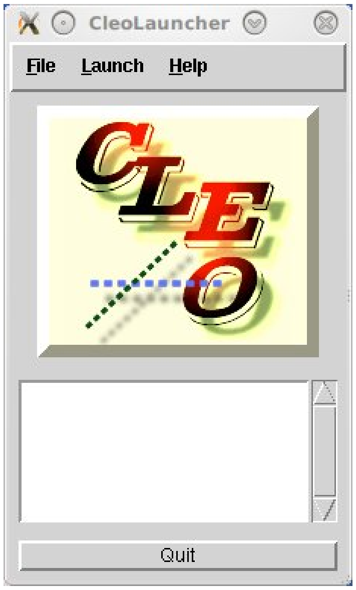


Figure 4.9: The Cleo Launcher.

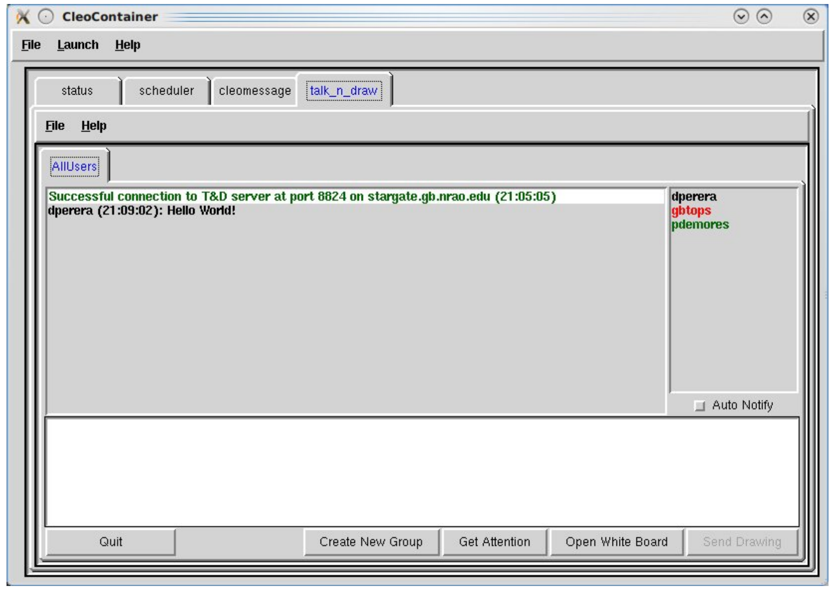


Figure 4.10: The CLEO Talk and Draw application launched as a tab of the Cleo Container.

4.2.2 Talk and Draw

`Launch` → `Observer Tools` → `Talk and Draw`

Launching “Talk and Draw” will open a window that allows communication with all other users of the same application including the GBT operator (see Figure 4.10). Messages typed in the white text box near the bottom of the screen will become visible to other users after pressing the “Enter” key.

Users may also create private groups via the `Create New Group` button and inviting other users to join. The private session will be accessible through a new tab next to the default “AllUsers” tab. Users may then send messages within their newly created group or to “AllUsers” (including the operator) by selecting the relevant tab and entering a message.

4.2.3 Scheduler and Skyview

`Launch` → `Observer Tools` → `Scheduler & Skyview...`

This displays a plot of the sky in Az/El coordinates as viewed from Green Bank as shown in Figure 4.11. One can import a catalog of source positions to be displayed, or display one of the lists of standard calibration sources. By default it displays solar system objects. For example, to display sources listed in the standard AstrID “xband_pointing” catalog press

- `Catalog...` → `Add/Select/DeSelect Catalogs...` → `xband_pointing` → `Apply` → `OK`

If one selects `Schedule` (button at upper right), one may enter a date and time and display the sky for that time. It shows the corresponding LST, and moving the cursor on the plot displays the RA/Dec and Az/EL under the cursor. This is very useful for planning observations. There is also a `Real Time` option in which the location of objects and the direction the GBT is pointed are displayed for the current time.

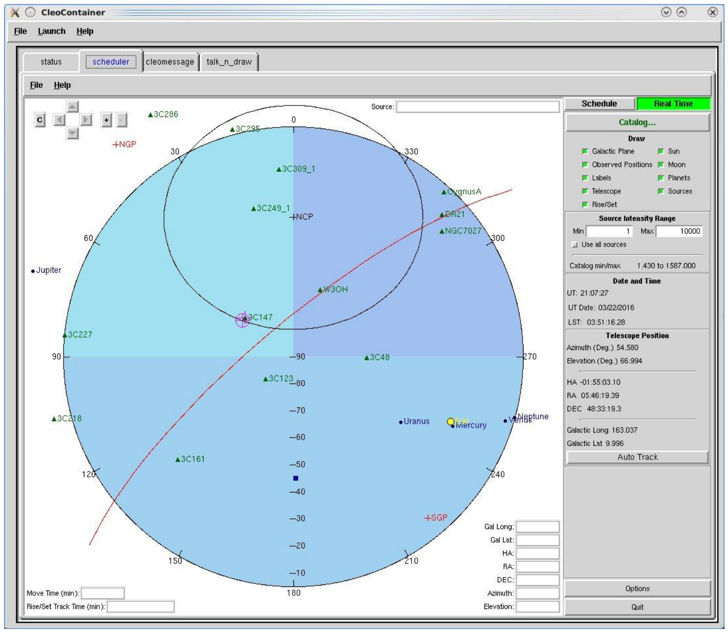


Figure 4.11: The CLEO Scheduler & Skyview application.

4.2.4 Status

Launch → **Status...**

This displays the status of many GBT systems all on one screen as shown in Figure 4.12.

4.2.5 Messages

Launch → **Messages...**

This shows all system status messages as shown in Figure 4.13. It's often useful to identify problems that might arise with any of the GBT devices.

4.3 VEGAS Monitoring Tools

4.3.1 The VEGAS CLEO screen

This can be launched via **Launch** → **Backends** → **VEGAS...** from the CLEO launcher (see § 4.2). An example of the VEGAS CLEO screen is shown in Figure 4.14.

The VEGAS CLEO screen follows standard CLEO conventions, and is fairly self-explanatory. As for all backend screens, Intermediate Frequency system (IF system) information for a selected bank can be displayed by clicking on the blue square to the right of the Bank label.

The VEGAS CLEO screen can be used to launch the VEGAS Data Monitor (described in the next section) by clicking on the `VEGAS Power Monitor...` button.

4.3.2 VEGAS Data Monitor

The VEGAS Data Monitor (VEGASDM) provides a real-time display of the currenttotal power level as measured by the VEGAS ADCs, as well as a histogram of the distribution of ADC counts. VEGASDM may be launched by:

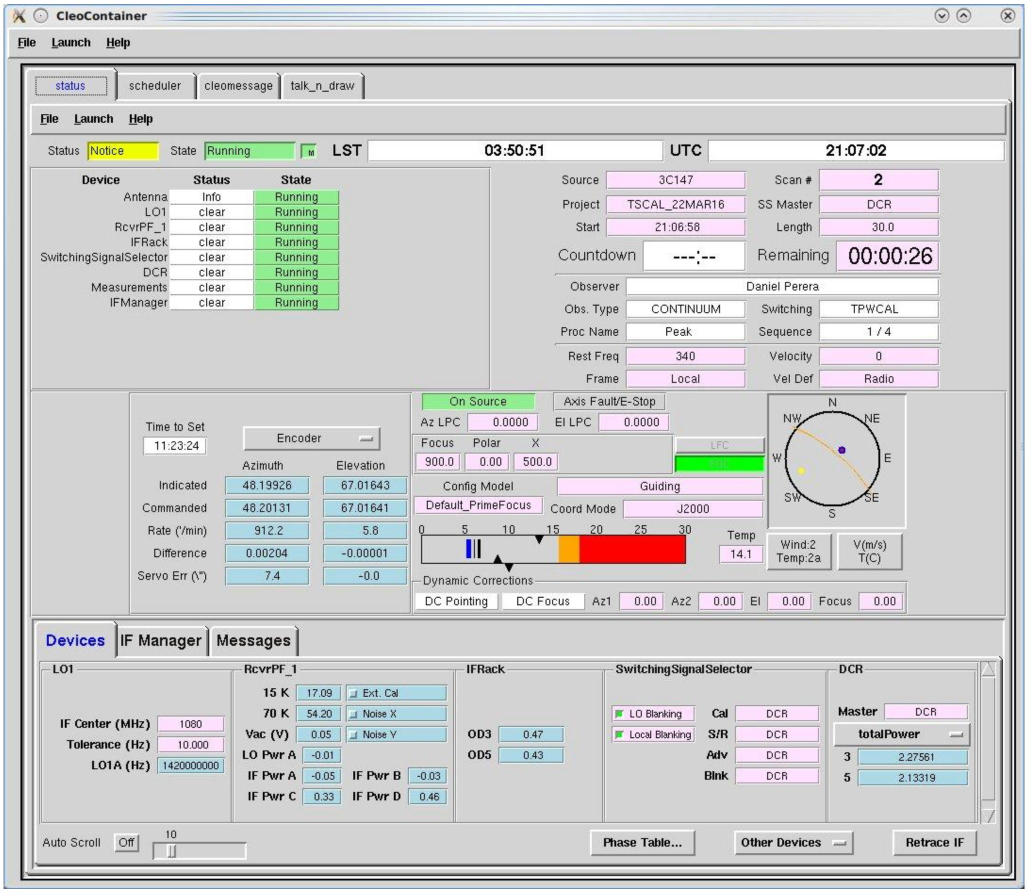


Figure 4.12: The CLEO Status application.

```
% source /home/gbt/gbt.bash (or .csh)
% VEGASDM
```

or by clicking the `VEGAS Power Monitor...` button from the VEGAS CLEO screen. The VEGASDM display will appear as in Figure 4.15

VEGASDM has nine tabs, one for each Bank, and one overview tab. If a Bank is active, the tab label will be green, otherwise it will be red. Each Bank tab shows whether the Bank is in the running state, and what mode it is in. The upper plot shows the total power from each polarization as a function of time, while the lower two plots show the distribution of ADC counts for each polarization. If VEGAS is balanced correctly, the ADC counts should be approximately Gaussian, centered around zero, with a full-width half maximum of approximately 25–50 counts. If the ADC counts are very centrally peaked, there is not enough power going into VEGAS, while if the ADC counts have peaks at +/- 127 counts, VEGAS is being over-driven.

The final tab of VEGASDM gives an overview plot of the total power for all eight banks on a single screen.

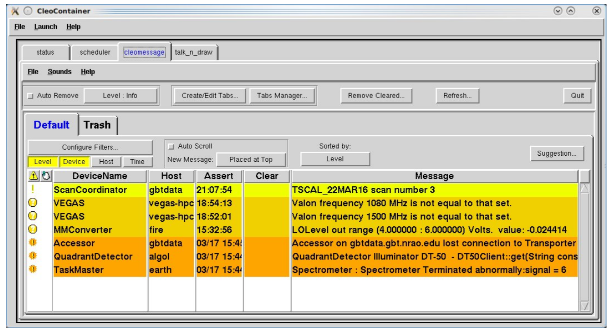


Figure 4.13: The CLEO Messages application.

Figure 4.14: The VEGAS CLEO Screen

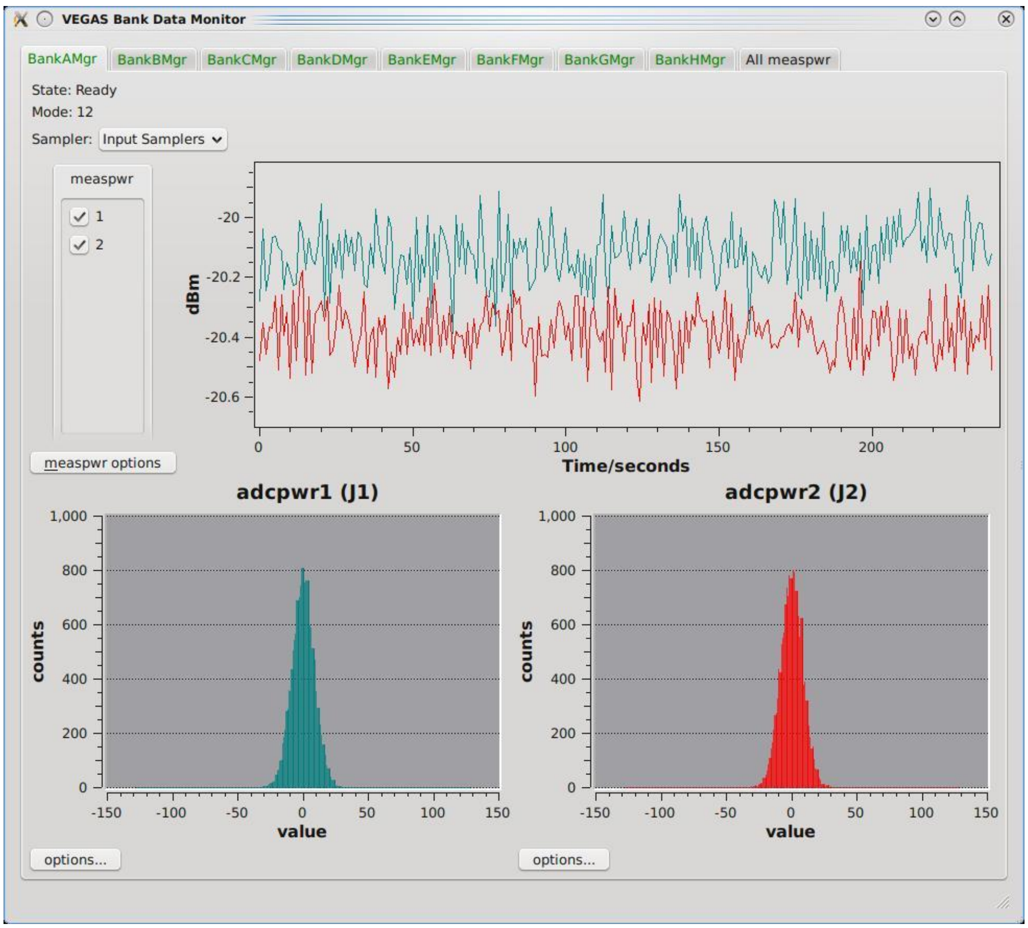


Figure 4.15: The VEGAS Data Monitor screen

Chapter 5

Scheduling Blocks

At the GBT, we use Scheduling Blocks (SBs) to perform astronomical observations. The SB can contain information for configuring the telescope, balancing the IF system, and other commands to "tweak" the telescope system (observing directives) along with the commands (scan types) to collect observational data. AstrID interprets SBs via Python, specifically Python 2.7.2. Thus SBs should follow Python syntax rules (such as indentation for loops) and can also contain or make use of any Python commands. Here is an example of a simple SB:

```
#load the configurations file
execfile('/mypath/myconfigurations.txt')

# load catalogs file
Catalog('/mypath/mycatalog.cat')

# configure the GBT
Configure(myconfig)

# slew to the source
Slew('B0329+54')

# balance the IF system
Balance()

# now observe the source for ten minutes
Track('B0329+54',None,600)
```

Script 5.1: A simple SB

- **execfile** loads definitions for configuring the GBT's receivers, IF system and backends for the observations. This is described in § 5.2.
- **Catalog** loads a catalog containing information (such as positions and radial velocity, etc.) on the sources to observe. This is described in § 5.3.
- **Configure** runs the configuration defined in `myconfigurations.txt` to select the receiver and backend and set switches and frequencies. This is described in § 5.2.
- **Slew** moves the telescope to the desired source (see § 5.4).
- **Balance** balances the power levels in the IF system and backend so that they should be in their linear regime (see § 5.4.1.9).
- **Track** performs and aquires data for the desired observation. Track and other pre-defined scans are described in § 5.4.

5.1 Making A Scheduling Block

Scheduling Blocks must be created well prior to your telescope time. We suggest that you review SBs with your project friend.

SBs can be written using AstrID's "Observation Management" Edit subtab (see § 3.4.1), which contains a simple text editor reminiscent of Notepad (MS Windows), or you can choose to write your SB outside of AstrID and use the "Observation Management" Import facility in AstrID to upload it into the database; see § 3.4.1.2 for details.

For the database, you should choose a descriptive name for your SB, such as "map_G11.0" or "pointfocus", which will remind you of the science you are trying to accomplish by running that block. Names such as "test" or "turtle.p" are not descriptive and should be avoided. The name you choose can be up to 96 characters long, and can contain white spaces, so you may have an SB name that consists of a few words (such as "K-band frequency-switched spectroscopy"). You do not need to add a suffix to your SB name (*.sb or *.py).

5.1.1 Components of a Scheduling Block

A typical Scheduling Block will include:

A) A configuration of the system (see § 5.2).

B) Specification of the sources via a catalog (see § 5.3).

C) A slew to the source and then balancing the power levels, and maybe other commands (see § 5.5).

D) Observational scan type commands (see § 5.4).

In the following sections we discuss each of these components.

5.2 Configuration of the GBT IF System

5.2.1 Overview

The routing of signals through the GBT system is controlled by many electronic switches which eliminate the need to physically change cables by hand. The GBT's electronically configurable IF system allows many, and more complicated paths for the signals to co-exist at all times. Configuring the GBT IF system can usually be accomplished in under one minute.

5.2.2 Defining and Executing A Configuration

Configurations are defined as sets of keyword–value pairs within a single string variable. To execute a configuration, this variable is passed as an argument into the **Configure()** command in an SB. Configurations may be defined in two ways:

1. The configuration definition may reside on a text file external to the SB. It can then loaded into the SB via the **execfile()** command (see script 5.3).

2. The configuration may be explicitly defined within the SB (see script 5.4).

We usually recommend that configuration definitions reside on text files external to the SB. This allows for configurations to be changed on the file without the need to re-validate and re-save the SB (see § 3.4.1.4). It also allows for simple SBs without clutter. Note that you should always use **execfile** rather than **import**, as **import** will not reread the file and miss any changes that you may have made.

Explicitly defining configurations within SBs allows users to easily edit and view their configuration from AstrID. If this method is chosen, users **must** re-validate and re-save the SB if any changes are made. Examples of both methods can be seen in scripts 5.3 and 5.4.

If using multiple configurations, it is recommended that you define them all in one text file and load them into the SB via a single **execfile** command. You may then use **Configure()** to execute each configuration as necessary.

```
#the configuration file syntax.py

myconfiguration = '''
# This is a comment (ignored by software)
primarykeyword1 = your primarykeyword value
primarykeyword2 = your primarykeyword value
. . .
. . .
primarykeywordN = your primarykeyword value
'''
```

Script 5.2: A text file containing an example of basic configuration syntax.

```
#  An SB to configure only

#  Configuration is defined
#    in an external file.

execfile('mypath/syntax.py')
Configure(myconfiguration)
```

Script 5.3: An SB using **execfile()** to load the contents of Script 5.2 into AstrID. "myconfiguration" can then be used as an argument to **Configure()** to configure the system.

```
# An SB to configure only - Configuration is defined here

myconfiguration = '''
# This is a comment (ignored by software)
primarykeyword1 = your primarykeyword value
primarykeyword2 = your primarykeyword value
. . .
. . .
primarykeywordN = your primarykeyword value
'''
Configure(myconfiguration)
```

Script 5.4: An SB that explicitly defines all configuration keywords within triple quotes as the parameter "myconfiguration". This parameter is then used as an argument to **Configure()** in order to configure the system. This SB will perform exactly the same function as the text file and SB shown in Scripts 5.2 and 5.3.

5.2.3 Basic Configuration Syntax

An example of the basic configuration syntax is shown in scripts 5.2 and 5.4. Configurations are passed into **Configure()** as a string argument. For each configuration, all keywords and values (§ 5.2.5) exist as line separated keyword=value pairs, all enclosed within a single set of triple-quotes.

5.2.4 Example Configurations

The best way to learn about how to define and perform configurations is through examples. Keywords available for use in a configuration definition will be discussed in § 5.2.5 and all examples have been placed in the directory /home/astro-util/projects/GBTog/configs/

5.2.4.1 Continuum Observations

```
# configuration definition for continuum observations

continuum_config='''
receiver  = 'Rcvr1_2'
beam      = '1'
obstype   = 'Continuum'
backend   = 'DCR'
nwin      = 1
restfreq  = 1400
bandwidth = 80
swmode    = 'tp'
swtype    = 'none'
swper     = 0.2
tint      = 0.2
vframe    = 'topo'
vdef      = 'Radio'
noisecal  =  'lo'
pol       = 'Linear'
'''
```

Script 5.5: An example continuum configuration.

The above configuration definition (script 5.5) has been given the name 'continuum_config' and can be used for pointing and focusing observations or for continuum mapping. We have configured for the following:

- The single beam L–band (1 to 2 GHz) receiver [receiver='Rcvr1_2'; beam='1']
- Total power, continuum observations [obstype='Continuum'; swmode='tp'; swtype='none'].
- The DCR as the backend detector [backend='DCR']
- Take data using a single band centered on 1400 MHz with a 80 MHz bandwidth [nwin=1; restfreq=1400; bandwidth=80]
- Go through a full switching cycle in 0.2 seconds [swper=0.2]
- Record data with the DCR every 0.2 seconds [tint=0.2]
- Disable doppler tracking for continuum observations [vframe='topo'; vdef='Radio'].
- Use a low-power noise diode [noisecal='lo']
- Linear polarization [pol='Linear']

5.2.4.2 Spectral Line, Frequency Switching Observations

```
# configuration definition for spectral line observations
# using frequency switching

fs_config='''
receiver  = 'Rcvr1_2'
obstype   = 'Spectroscopy'
backend   = 'VEGAS'
restfreq  = 1420
bandwidth = 23.44
nchan     = 65536
vegas.subband = 1
swmode    = 'sp'
swtype    = 'fsw'
swper     = 2.0
swfreq    = 0, -5.0
tint      = 10
vframe    = 'lsrk'
vdef      = 'Radio'
noisecal  = 'lo'
pol       = 'Linear'
'''
```

Script 5.6: An example frequency switched, spectral line configuration.

The above example (script 5.6) will configure for the following:

- The single beam L–band (1 to 2 GHz) receiver [receiver='Rcvr1_2']. Note that not specifying 'beam' defaults to [beam='1'].
- Frequency switching, spectral line observations [obstype='Spectroscopy'; swmode='sp'; swtype= 'fsw'].
- VEGAS as the backend detector using linear polarization without cross-polarization products [backend='VEGAS'; pol='Linear'].
- Take data using a single band using VEGAS mode 11 (see Table 10.1) defined by a 23.44 MHz bandwidth, 65536 channels, and one band per spectrometer. [bandwidth=23.44; nchan=65536; vegas.subband=1], centered on 1420 MHz [restfreq=1420].
- Go through a full switching cycle in 2 seconds [swper=2.0]. Over one cycle, the frequency switching states will be centered on the line, and then be shifted by -5 MHz [swfreq=0,-5.0].
- Record data with VEGAS every 10 seconds [tint=10]
- Doppler track the spectral line with the rest frequency 1420 MHz in the commonly used Local Standard of Rest velocity with the radio definition of Doppler tracking [vframe='lsrk'; vdef='Radio'].
- Use a low-power noise diode [noisecal='lo']

5.2.4.3 Multiple Spectral Lines, Total Power Observations

```
# configuration definition for multiple spectral line observations
# using total power switching
tp_config='''
```

```
receiver  = 'Rcvr8_10'
obstype   = 'Spectroscopy'
backend   = 'VEGAS'
restfreq  = 9816.867, 9487.824, 9173.323, 8872.571,
            9820.9, 9821.5, 9822.6, 9823.4, 9824.6
dopplertrackfreq = 8873.1
bandwidth = 23.44
nchan     = 8192
swmode    = 'tp'
swtype    = 'none'
swper     = 1.0
tint      = 30
vframe    = 'lsrk'
vdef      = 'Radio'
noisecal  = 'lo'
pol       = 'Circular'
'''
```

Script 5.7: An example total power, spectral line configuration.

The above example (script 5.7) will configure for the following:

- The single beam X–band (8 to 10 GHz) receiver. [receiver='Rcvr8_10']. Note that not specifying 'beam' defaults to [beam='1'].
- Total power, spectral line observations [obstype='Spectroscopy'; swmode='tp'; swtype='none'].
- VEGAS as the backend detector using circular polarization without cross-polarization products [backend='VEGAS'; pol='Circular'].
- Mode 21 of VEGAS (see Table 10.1). This mode is defined by a bandwidth of 23.44 Mhz, 8192 spectral channels in the eight subband mode of VEGAS [bandwidth=23.44; nchan=8192]. Note that not specifying 'vegas.subband' for a bandwidth of 23.44 MHz will default to vegas.subband=8.
- 9 spectral windows, each of which centered on one of the 9 frequencies (in MHz) listed under restfreq [restfreq=9816.867, 9487.824, 9173.323, ...].
- Go through a full switching cycle in 1 second [swper=1.0] and record data with VEGAS every 30 seconds [tint=30].
- Doppler track the spectral line with the rest frequency 8873.1 MHz [dopplertrackfreq=8873.1] in the commonly used Local Standard of Rest velocity [vframe='lsrk'] with the radio definition of Doppler tracking [vdef='Radio'].
- Use a low-power noise diode [noisecal='lo'].

5.2.4.4 Multiple Spectral Lines, Multi-beam, Total Power Observations

```
# configuration definition for spectral line observations
# using a multi-beam receiver
tp_config_multi_beam = '''
receiver  = 'Rcvr40_52'
beam      = '1,2'
obstype   = 'Spectroscopy'
backend   = 'VEGAS'
```

```
restfreq  = 44580, 43751, 45410, 46250
deltafreq = 0,100,0,0
bandwidth = 1500
nchan     = 16384
swmode    = 'tp'
swtype    = 'none'
swper     = 1.0
tint      = 10
vframe    = 'lsrk'
vdef      = 'Radio'
noisecal  =  'lo'
pol       = 'Circular'
'''
```

Script 5.8: An example total power, spectral line configuration for a multi-beam receiver.

The above example (script 5.8) will configure for the following:

- The dual beam Q–band (40 to 52 GHz) receiver using both beams [receiver='Rcvr40_52'; beam='1,2'].
- Total power, spectral line observations [obstype='Spectroscopy'; swmode='tp'; swtype='none'].
- VEGAS as the backend detector using circular polarization without cross-polarization products [backend='VEGAS'; pol='Circular'].
- Mode 2 of VEGAS (see Table 10.1). This mode is defined by a bandwidth of 1500 Mhz with 16384 spectral channels [bandwidth=1500; nchan=16384].
- 4 spectral windows, each of which centered on one of the 4 frequencies (in MHz) listed under restfreq [restfreq=44580, 43751, 45410, 46250].
- Shift the window centered on 43751 MHz by 100 MHz in the local (topocentric) frame. Thus, this window will now be centered on 43851 MHz [deltafreq=0,100,0,0]. deltafreq should be defined in the same manner as restfreq: This example uses 4 comma separated values.
- Go through a full switching cycle in 1 second [swper=1.0] and record data with VEGAS every 10 seconds [tint=10].
- Doppler track the spectral line with the rest frequency 44580 MHz (default is the first specified rest frequency) in the commonly used Local Standard of Rest velocity [vframe='lsrk'] with the radio definition of Doppler tracking [vdef='Radio'].
- Use a low-power noise diode [noisecal='lo'].

5.2.4.5 Multiple Spectral Lines, KFPA Observations

```
#configuration definition for spectral line obs. using the KFPA
kfpa_config='''
receiver  = 'RcvrArray18_26'
beam      = 'all'
obstype   = 'Spectroscopy'
backend   = 'VEGAS'
restfreq  = {24600:'1,2,3,4', 23900:'5,6,7', 25500 : '-1',
             'DopplerTrackFreq': 24700}
deltafreq = {24600:-100, 23900:0, 25500:0}
bandwidth = 187.5
```

```
nchan      = 32768
swmode     = 'tp'
swtype     = 'none'
swper      = 1.0
tint       = 30
vframe     = 'lsrk'
vdef       = 'Radio'
noisecal   = 'lo'
pol        = 'Circular'
vegas.vpol= 'cross'
'''
```

Script 5.9: An example total power, spectral line configuration for the K-band Focal Plane Array (KFPA).

The above example (script 5.9) will configure for the following:

- The KFPA (18 to 26 GHz) receiver using all 7 beams [receiver='RcvrArray18_26'; beam='all'].
- Total power, spectral line observations [obstype='Spectroscopy'; swmode='tp'; swtype='none'].
- VEGAS as the backend detector with circular cross-polarization products [backend='VEGAS'; vegas.vpol='cross'; pol='Circular'].
- Mode 4 of VEGAS (see Table 10.1). This mode is defined by a bandwidth of 187.5 Mhz with 32768 spectral channels [bandwidth=187.5; nchan=32768].
- 3 spectral windows centered on 24600, 23900, and 25500 MHz. Data will be recorded for beams 1→4 using the first window (24600 MHz) while beams 5→7 will use the second window (23900 MHz). An additional IF path will be routed from beam 1 to the window centered on 25500 MHz. This is known as the "7+1" mode of the KFPA (see Chapter 7) [restfreq=24600:'1,2,3,4',23900:'5,6,7', 25500:'-1','DopplerTrackFreq': 24700].
  - Note that doppler tracking the center (24700 MHz) of the full frequency range (25500 - 23900 + bandwidth) is necessary in this example. The maximum frequency separation limitation of the KFPA is 1.8 GHz when using multiple beams (see Chapter 7). The Radio definition of doppler tracking has been used in the Local Standard of Rest Velocity [vframe='lsrk'; vdef=Radio]
- Shift the window centered on 24600 MHz by -100 MHz in the local (topocentric) frame. Thus, this window will now be centered on 24500 MHz [deltafreq=24600:-100, 23900:0, 25500:0]. deltafreq should be defined using the same syntax as restfreq: This example uses Python dictionary syntax.
- Go through a full switching cycle in 1 second [swper=1.0] and record data with VEGAS every 30 seconds [tint=30].
- Use a low-power noise diode [noisecal='lo'].

5.2.4.6 Advanced Use of the Restfreq Keyword

```
# Example for the advanced usage of restfreq
adv_restfreq_config='''
receiver = 'Rcvr12_18'
beam = '1,2'
obstype = 'Spectroscopy'
backend = 'VEGAS'
swmode = 'tp'
```

```
swtype = 'none'
swper = 1.0
tint = 10
vframe = 'lsrk'
vdef = 'Radio'
noisecal = 'lo'
pol = 'Circular'
bandwidth = 23.44
nchan = 32768
dopplertrackfreq = 13500.0
restfreq = [
 {'restfreq':14000,'bank':'A','bandwidth':1500,'nchan':1024,'beam':'1'},
 {'restfreq':14000,'bandwidth':1500,'nchan':1024,'beam':'2'},
 {'restfreq':13000,'bandwidth':187.5,'nchan':32768,'beam':'1'},
 {'restfreq':13100,'bandwidth':187.5,'nchan':32768,'beam':'2',
                     'vpol':'cross','deltafreq':1},
 {'restfreq':13200,'bank':'C','bandwidth':23.44,'res':0.7,'beam':'1',
                     'subband':8},
 {'restfreq':13300,'bank':'C','bandwidth':23.44,'res':0.7,'beam':'1',
                     'subband':8},
 {'restfreq':13400,'bank':'C','bandwidth':23.44,'res':0.7,'beam':'1',
                     'subband':8},
 {'restfreq':13400,'bandwidth':23.44,'res':0.7,'beam':'2',
                     'subband':1},
 {'restfreq':13500,'bandwidth':100,'nchan':32768,'beam':'1'},
 {'restfreq':13500,'bandwidth':100,'nchan':32768,'beam':'2'}]
'''
```

Script 5.10: An example showing advanced use of the restfreq keyword.

The above example (Script 5.10) uses the advanced restfreq syntax (an array of Python dictionary terms) to more precisely configure the GBT system. Note that this is an example of usage only and it is not recommended that users attempt to manually route beams to specific VEGAS banks.

When using the advanced restfreq syntax, it is important to be aware of the following details in the main configuration block:

- Key values specified in the restfreq dictionary term override key-values pairs in the main configuration. If no values for a key have been specified, a default value will be used if available.
- **bandwidth** and **nchan** must always be specified in the main configuration block outside of restfreq. This is required for the configuration to pass validation, even if such values are redundant [bandwidth=23.44; nchan=32768].
- **dopplertrackfreq** must be set by the user [dopplertrackfreq=13500.0] since there is no default doppler tracking frequency for the advanced restfreq syntax.

The following points give details on the usage of the advanced restfreq syntax in this example:

- Multiple rest frequencies (or windows centered on a rest frequency) are input as an array of Python dictionary terms. The '**restfreq**' dictionary key is the minimum required entry for each dictionary term and specifies the center of each window. Each bank may also be configured with different resolution, bandwidth, and number of spectral windows. However, the integration time, switching period and frequency switch must be the same for all banks.
- Each window may be routed to a specific bank (VEGAS spectrometer) with the '**bank**' dictionary key (see the first window of this example). By omitting 'bank', the system will attempt to route

windows to available banks automatically (recommended). Note that certain restrictions exist when routing multi-beam receivers to VEGAS banks. See § 10.3 and § 7.1 for further information.

- The '**beam**' dictionary key specifies which beam is used for the window. Omitting 'beam' defaults to beam 1 ['beam':'1'].
- VEGAS modes are set for a window by defining valid combinations of bandwidth and resolution, and the number of sub-bands if using a 23.44 MHz bandwidth (see Table 10.1). If these values are not defined as dictionary keys, then values defined in the main configuration block or default values will be used. It is worth noting the following points in this example:
  - Bank C has been split into 3 subbands and uses VEGAS mode 23 defined by 23.44 MHz bandwidth, 8 subbands, and 0.7 kHz resolution ['bank':'C', 'bandwidth':23.44, 'res':0.7, 'subband':8].The 3 windows are centered on 13200, 13300, and 13400 MHz. **Note that all sub-bands within a single bank must use identical VEGAS settings apart from the center frequency and offset**.
  - A second window has been centered around 13400 MHz using a bandwidth of 23.44 MHz with 0.7 kHz resolution. However, this window is configured to use beam 2 and mode 10 of VEGAS with a single sub-bank ['restfreq':13400,'bandwidth':23.44,'res':0.7,'beam':'2','subband':1]
  - The window centered at 13100 MHz gives an example of the other dictionary keys available. This window has been shifted +1 MHz in the local frame ['deltafreq':1] to be centered on 13101 MHz. Data will be recorded with full Stokes polarization products ['vpol':'cross']. All other windows will record data with total intensity polarization products [vegas.vpol='self' (the default setting)]

5.2.5 Configuration Keywords

5.2.5.1 Keywords That Must Always Be Present

The following keywords do not have default values and must be present in all configuration definitions.

receiver This keyword specifies the name of the GBT receiver to be used. The names and frequency ranges of the receivers can be found in Table **??**. The value of the receiver keyword is a string and should therefore be placed within quotes when used.

backend This keyword specifies the name of the backend (data acquisition system) to be used. The value for this keyword is a string. Valid backends are listed in Table 9.1.

obstype This keyword specifies the type of observing to be performed. The allowed values are one of the following strings: 'Continuum', 'Spectroscopy', 'Pulsar', 'Radar', 'VLBI'.

bandwidth This keyword gives the bandwidth in MHz to be used by the specified backend. The value of the keyword should be a float. Possible values depend on the receiver and backend that are chosen (see Table 9.2 and Table 10.1).

restfreq This keyword specified the rest frequencies for spectral line observations or the center frequencies for continuum observations. There are three available syntaxes for restfreq:

1. **Simple**

```
restfreq  = 1420, 1661, 1667
deltafreq = 0, 5, 0
```

The above example sets 3 rest frequencies and offsets the second window (1661 MHz) by +5 MHz in the local (topocentric) frame using deltafreq. Rest frequencies may be specified as a list of comma separated float values (MHz). This syntax should be used when all beams (including single beam receivers) are configured to observe the same rest frequencies and VEGAS does not need to use an advanced configuration (see "Advanced" below). Note that:

- **deltafreq** can also specified using the same syntax as restfreq, a single global offset, or omitted to use the default value of zero.
- If **dopplertrackfreq** is not set in the main configuration block then the first rest frequency listed using this syntax will be doppler tracked by default.

2. **Multi-beam**

```
restfreq={24000:'1,2,3,4',23400:'5,6',25000:'7',
          'dopplertrackfreq':24200}
#deltafreq must be specified with this syntax - even when zero
deltafreq = {24000:0, 23400:0, 25000:0}
```

The above example specifies a rest frequency of 24000 MHz for beams 1–4, 23400 MHz for beams 5 and 6, and 25000 MHz for beam 7. Different feeds of multi-beam receivers may be tuned to different rest frequencies. Rest frequencies and delta frequencies are input as Python dictionaries. Further information on this syntax and example can be found in Appendix B. Note that:

- **deltafreq** must **always** be specified as a separate Python dictionary, even when zero.
- **dopplertrackfreq** must **always** be specified in the restfreq Python dictionary.

3. **Advanced**

```
bandwidth = 23.44
nchan     = 32768
dopplertrackfreq = 1420.0
restfreq = [{'restfreq':1420.0},
            {'restfreq':1420.0,'deltafreq':-20.0},
            {'restfreq':1667.0,'bandwidth':11.72,'nchan':65536}]
```

The above example will configure VEGAS to use 3 rest frequencies. The first two windows are centered on 1420 MHz with mode 23 of VEGAS using bandwidth=23.44 and nchan=32768 from the main configuration block (8 subbands are selected by default for bandwidth=23.44). However, deltafreq has been used as a dictionary key to offset the second window by -20 MHz in the local topocentric frame. A third window is centered on 1667 MHz with mode 16 of VEGAS using the 'bandwidth' and 'nchan' dictionary keys to override values from the main configuration block.

This syntax may be used to more precisely configure VEGAS observations and specifies restfreq as an array of Python dictionaries. See script 5.10 for a more detailed example of this syntax. Note that:

- Available dictionary keys are: '**restfreq**', '**bandwidth**', '**nchan**', '**res**', '**deltafreq**', '**tint**', '**vpol**', '**bank**', '**beam**', and '**subband**'.
  - '**restfreq**' takes a float value in MHz and is the only required key for each dictionary term.
  - '**res**' is the spectral resolution (kHz) and can be used as an alternative to the 'nchan' restfreq dictionary key or the 'nchan' keyword in the main configuration block to select the VEGAS mode. Allowed values are floats and listed in Table 10.1.
  - '**bank**' specifies which VEGAS bank to use. Allowed values are the string letters 'A'→'H'. The default is to let the configuration tool select which bank should be used (recommended).
  - All other keys have the same meaning as the standard configuration keywords.

- Key-value pairs specified in the dictionary override configration keywords specified in the main configuration block which in turn override any default values.
- **dopplertrackfreq** must **always** be set in the main configuration block.
- **deltafreq** may still be specified as a single global offset in the main configuration block or ommitted to use the default value of zero.
- **nchan** must **always** be set in the main configuration block, even if that value is overridden by 'nchan' in the restfreq dictionary.

5.2.5.2 Keywords With Default Values

swmode This keyword specifies the switching mode to be used for the observations. This keyword's values are given as a string. The switching schemes are

- **'tp':** (Total Power With Cal) - The noise diode is periodically turned on and off for equal amounts of time. **(Default value)**
- **'tp_nocal':** (Total Power Without Cal) - The noise diode is turned off for the entire scan.
- **'sp':** (Switched Power With Cal) - The noise diode is periodically turned on and off for equal amounts of time while another component is in a signal state and then again in a reference state. This is used in frequency switching where the signal state is one frequency and the reference state is another frequency. Similarly beam switching and polarization switching change the beams or polarizations so that their signals are sent down two different IF paths.
- **'sp_nocal':** (Switched Power Without Cal) - The noise diode is turned off while another component is switched between a signal and reference state.

swtype This keyword is only used when swmode='sp' or swmode='sp_nocal', and specifies the type of switching to be performed. This keyword's values are 'none', 'fsw' (frequency switching), 'bsw' (beam switching) and 'psw' (polarization switching). **Default values are 'fsw' for all receivers except receiver='Rcvr26_40'. The default for receiver='Rcvr26_40' is swtype='bsw'.**

swper This keyword defines the period in seconds over which the full switching cycle occurs. See Table 10.2 for recommended minimum switching periods for each VEGAS mode. The value is a float. **Default values are 0.2 for obstype='continuum', 0.04 for obstype='pulsar', and 1.0 for any other value for the obstype keyword**.

swfreq This keyword defines the frequency offsets used in frequency switching (swtype='fsw'). The value consists of two comma separated floats which are the pair of frequencies in MHz. The best values for swfreq are bandwidth/2^n where n is an integer so that the frequency switch will be an integer number of channels giving less artifacts in data reduction. **Default values are swfreq=-0.25*Bandwidth, +0.25*Bandwidth for swtype='fsw', and swfreq=0,0 otherwise.**

tint This keyword specifies the backend's integration (dump) time. The value is a float with units of seconds. See Table 10.1 for minimum integration times with VEGAS. **Default values are 10.0 for obstype='continuum', tint=swper for obstype='spectroscopy' and 30.0 of any other value for the obstype keyword.**

beam This keyword specifies which beams are to be used for observations with multi-beam receivers. The keyword value is a string of comma separated integers. For example beam='2' would record data for the second beam and beam='3,7' would record data for beams 3 and 7. When using the KFPA, beam='all' can be used to record data from all seven beams. This 'beam' configuration keyword has a different meaning to the 'beamName' in observing scans which usually specifies a tracking beam, not which beams to record data for. **The default value is '1'**.

Note: The Ka–band dual-beam single-polarization 26–40 GHz receiver ('Rcvr26_40').

nwin This keyword specifies the number of frequency windows that will be observed for backends other than VEGAS. The value for this keyword is an integer with a maximum value that is backend and receiver dependent, see § 1.4. The number of values given for the restfreq keyword must be the same as nwin. **The default value is 1**.

Note: 'nwin' does not need to be specified for VEGAS configurations.

deltafreq This keyword specifies offsets in MHz for each spectral window so that the restfreq is not centered in the middle of the spectral window. 'deltafreq' can be specified as a single float offset which will be applied across all windows or in the same manner as 'restfreq'. For examples of using deltafreq with different types of restfreq syntax, see Scripts 5.8, 5.9, and 5.10. More details on deltafreq can be found in Appendix B. **The default value is 0.0**.

vframe This keyword specifies the velocity frame (the inertial reference frame). The keyword value is a string. Allowed values are 'topo' (topocentric, i.e. Earth's surface), 'bary' (Barycenter of solar system), 'lsrk' (Local Standard of Rest kinematical definition , i.e. typical LSR definition), 'lsrd' (Local Standard of Rest dynamical definition – rarely used), 'galac' (center of galaxy), 'cmb' (relative to Cosmic Microwave Background). **The default value is 'topo'.**

vdef This keyword specifies which mathematical equation (i.e. definition) is used to convert between frequency and velocity. The keyword value is a string. Allowed values are 'Optical', 'Radio', 'Relativistic'. **The default value is 'Radio'.**

$$\mathrm{v_{radio}} = c\left[1 - \frac{\nu}{\nu_o}\right] \tag{5.1}$$

$$\mathrm{v_{optical}} = c\left[\frac{\nu_o}{\nu} - 1\right] \tag{5.2}$$

$$\mathrm{v_{relativistic}} = c\left[\frac{\nu_o^2 - \nu^2}{\nu_o^2 + \nu^2}\right] \tag{5.3}$$

5.2.5.3 Backend and Receiver Dependent Keywords

Some configuration keywords depend on which backends and receivers are being used. Some observations may require one of these keywords while for other observations none may be needed.

nchan An integer. This keyword is used to determine the number of spectral channels that VEGAS will provide. Available values are listed in Table 10.1.

- The following string values designed for use with the now obsolete GBT spectrometer may still be used: 'low', 'medium-low', 'medium', 'medium-high', and 'high'. These string values may be used to distinguish between up to 5-levels of resolution for a given bandwidth. For example, mode 18 of VEGAS could be set by setting bandwith=11.72 and nchan=262144 or nchan='medium-high'.

dopplertrackfreq A float specifying the rest frequency in MHz used to compute the velocity for doppler tracking. When using the simple restfreq syntax, the default is the first listed restfreq value.

pol Each of the prime focus receivers, L–band, S–band and C–band receivers have a hybrid that can output either linear or circular polarization. Additionally, W–band is linear when using two beams and ciruclar when using one beam. The "pol" keyword specifies whether linear or circular polarization is desired for these receivers. The keyword value is a string. Allowed values are 'Linear' and 'Circular'. **The default value is 'Circular' for the VLBI and Radar back ends, and 'Linear' otherwise.**

noisecal All receivers below 12 GHz have two noise diodes for calibration signals – one with an equivalent brightness temperature at roughly one tenth the system temperature ('lo' value) and one nearly equal to the system temperature ('hi' value). This keyword is a string which specifies which noise diode is to be used. Allowed values[1] are 'lo', 'hi' and 'off'. **The default value is 'lo' except for the Radar backend for which the default values is 'off'.**

For the Ka–band (26-40 GHz) receiver there are three additional choices. These are 'L', 'R', or 'LR'. The Ka–band receiver has two 'lo' noise diodes, one for each polarization for each of the two beams. The 'L', 'R', and 'LR' options specify which of these noise diodes are to be used.

notchfilter There is a notch filter covering roughly 1200–1310 MHz in the L–band receiver that filters out an Federal Aviation Administration (FAA) radar signal. This keyword determines if this notch filter is in place and used by the system or is removed from the receiver's RF path. The keyword value is a string with allowed values of 'In' or 'Out'. **The default value is 'In'.**

vegas.vpol Keyword to specify which spectral product to record in the FITS file. It assumes the following values:

- **'self':** Record the total intensity polarization products. **(Default value)**
- **'cross':** Record the full Stokes polarization products.
- **'self1':** Record the polarization from the first Analog to Digital Converter (ADC) card only. There are two ADCs per VEGAS bank, one for each polarization.
- **'self2':** Record the polarization from the second ADC only.

vegas.subband Keyword used by config tool to select between 23.44 MHz VEGAS modes with single and multiple spectral windows (see Table 10.1). It assumes values 1 or 8. **The default value is 8.**

vlbi.phasecal This expert keyword turns the VLBI phase cals on or off. The phase cals can can run at 1 MHz ('M1') or 5 MHz ('M5'). The keyword value is a string. Allowed values are 'off', 'M1' or 'M5'.

broadband This keyword is used to activate the "broadband" 7.5 GHz maximum instantaneous mode of the KFPA by setting `broadband=1`. This may only be used with single beam configurations using either beam 1 or beam 2. The default is "off" (`broadband=0`).

5.2.5.4 Expert Keywords

These keywords should only be used by very experienced observers who have expert knowledge of how a given backend works or in how the GBT IF system works.

vlow and **vhigh** These keywords specify the minimum and maximum velocity to be observed from a group of sources. The value is a float and is in units of km s^{-1} for velocities. See Appendix C for more details on the use of vlow and vhigh. The use of vlow and vhigh is not recommended for frequencies where there can be large amounts of RFI. **The default value is 0.0.**

iftarget This keyword specifies the target voltage level to use when balancing the IF Rack. The keyword value is a float. The nominal range of the IF Rack is 0.0–10.0 and the linear range is 0.1–5.0.

xfer This expert keyword sets the beam switch for the Ku–band, K–band and Ka–band receivers. The keyword is a string. Allowed values are 'ext', 'thru', or 'cross'. The default values are 'ext' when swtype='bsw' and 'thru' otherwise.

[1]There are expert values of 'on-mcb', 'on-ext', 'lo-mcb', 'hi-mcb', 'lo-ext' and 'hi-ext' whose use is beyond the scope of this document. Please contact a support person about the use of these values.

polswitch This expert keyword sets the polarization switch for the L–band and X–band receivers. The keyword value is a string. Allowed values are 'ext', 'thru', and 'cross'. The default value is 'ext' if swtype='psw' and 'thru' otherwise.

ifbw This expert keyword sets the minimum IF bandwidth to be used in filters within the receiver and in the IF Rack. The keyword value is float with units of MHz.

if0freq This expert keyword is used to set the center frequency of the IF after the mixing the RF signal with the first LO. The keyword value is a float with units of MHz.

lo1bfreq This expert keyword is used to set the frequency of the synthesizer used for the alternative The First LO (LO1), LO1B. This keyword is only to be used with the Ka–band receiver. The keyword value is a float with units of MHz.

lo2freq This expert keyword is used to set the frequency values of the eight LO2 synthesizers within the Converter Rack. The keyword values are a comma separated list of floats with units of MHz.

if3freq This expert keyword is used to set the IF input frequency of the backend. The keyword value is a comma separated list of floats with units of MHz.

5.2.6 Resetting The Configuration

The configuration tool in AstrID remembers all the keyword values defined during a session. This feature occasionally results in AstrID being unable to validate an otherwise correct configuration because of previously set values or hardware being configured improperly. To reset the configuration parameters to their default state, you can issue the **ResetConfig**() command in a script before another **Configure**(). This command will reset the configuration tool values to their defaults.

5.3 Catalogs

The Source Catalog system in AstrID provides a convenient way for the user to specify a list of sources to be observed, as well as a way to refer to standard catalogs of objects. At a minimum for each source there must be a name and a location (Ra/Dec or Glat/Glon, etc). Other parameters may be set, such as radial velocity. An example of a simple Catalog is:

```
# My source list
format=spherical
coordmode=J2000
HEAD = NAME   RA          DEC
Object1  09:56:16.98  +49:16:25.5
Object2  10:56:16.98  +50:16:25.5
Object3  11:56:16.98  +51:16:25.5
Object4  12:56:16.98  +52:16:25.5
```

Script 5.11: A simple catalog.

There are three formats of catalogs:

- **SPHERICAL** A fixed position in one of our standard coordinate systems, e.g., RA/DEC, AZ/EL, GLON/GLAT, etc.
- **EPHEMERIS** A table of positions for moving sources (comets, asteroids, satellites, etc.)
- **NNTLE NASA/NORAD** Two-Line Element (TLE) sets for earth satellites.

In addition, the following solar system bodies may be referred to by name: "Sun", "Moon", "Mercury", "Venus", "Mars", "Jupiter", "Saturn", "Uranus", "Neptune", and "Pluto". These names are case-insensitive and may be given to any Scan Type function (see § 5.4). No catalog needs to be invoked for the system to understand these names.

To use the catalog system, observers invoke the **Catalog()** command within SBs and pass names of the desired objects to any of the scan functions (§ 5.4). All sources named in all the catalogs that have been invoked are available within an SB. If the same name appears in two or more catalogs, the name from the most recently invoked catalog will prevail. Name comparisons are case-insensitive, hence "b2322+16" and "B2322+16" are equivalent.

5.3.1 Getting Your Catalog Into Astrid

Although one can include any number of Catalogs in an SB, the standard practice is to put all the Catalogs into separate files that are then brought into the SB via multiple calls to the **Catalog()** command. This: a) keeps SBs simple and without clutter; and b) allows changes to be made to a Catalog without having to validate and re-save the SB.

The best way to learn about how to bring Catalogs into an SB is through an example. Let's suppose that there are two Catalogs that you need for your observations. These two catalogs are in the following files:

```
/home/astro-util/projects/GBTog/cats/sources.cat
/home/astro-util/projects/GBTog/cats/pointing.cat
```

These catalogs may be loaded into the SB as shown in the following example:

```
#first load the catalog with the flux calibrators
cata=Catalog('/home/astro-util/projects/GBTog/cats/sources.cat')

#now load the catalog with the pointing source list
catb=Catalog('/home/astro-util/projects/GBTog/cats/pointing.cat')

#Objects defined in loaded catalogs may now be used in scan functions
#Object1 is in source.cat and 0006-0004 is in pointing.cat
Track('Object1',None, 60)
Slew('0006-0004')
```

Script 5.12: Loading two catalogs into an SB, then using objects defined in those catalogs as inputs to scan functions

All sources from all catalogs are available and referenced by name within the scope of the SB, with the exception that for duplicate source names only the last entry of that name will be recognized. After loading a Catalog any scan function may be run by giving it the source name as shown above (Script 5.12).

5.3.2 The Format of the Catalog

A Catalog typically has two sections: a header section followed by a table of information for all the sources. The header section consists of "KEYWORD = VALUE" pairs. The "KEYWORD = VALUE" pairs tell the Scheduling Block interpreter how to read the information in the table section of the Catalog. Once a keyword value is given, its value will persist until re-set or the end of the Catalog is reached. The keywords are case-insensitive. The values for a keyword must not contain any embedded blanks (except source names in NNTLE format).

A Catalog can contain comments with the beginning of a comment being denoted by the hash symbol, "#". All information on a line after the hash symbol is considered to be part of the comment. After the header, each source in the Catalog occupies a single line. You should not use the hash symbol in source names.

5.3.2.1 Catalog Header Keywords

Catalog Header Keywords are used to define how the catalog entries should be read. The keywords and their values are case insensitive. The example shown in Script 5.13 will be used to describe some of the Catalog Header Keywords. Unless mentioned otherwise, the following keywords should be listed as column headings under "HEAD":

```
# My source list
format=spherical
HEAD = NAME COORDMODE   RA  DEC         RESTFREQ   VELDEF      VEL  type
Object1  J2000  09:56:16.9  +49:16:25  1420.405  VRAD-LSR   -25.3  HII
Src_A    J2000  10:56:16.9  +50:16:25  1665.401  VOPT-BAR   100.9  Gal
```

Script 5.13: An example catalog using additional header keywords

FORMAT This tells the type of catalog and **must be the first line in any catalog**. Possible values are "spherical", "ephemeris" and "nntle". For the SPHERICAL format, the first line would contain "FORMAT=SPHERICAL". This is the default format, hence the "FORMAT=SPHERICAL" may be omitted.

HEAD This gives the header for tabular data, and consists of a list of any keywords. This should appear as the last line in the header before lines giving information about the sources in the catalog. You can also create your own header keyword, such as the "type" column in the above example. The default header is "HEAD = NAME RA DEC VELOCITY". In the above example we have added more entries than the default. We have also created a new keyword named "type".

NAME The source name is any string up to 32 characters long. The name should not contain any embedded blanks or hashes.

COORDMODE The default is J2000. Possible values are: J2000, B1950, JMEAN (mean coordinate of date given by EQUINOX), GAPPT (geocentric apparent coordinates of date), GALACTIC, HADEC, AZEL, ENCODER. In the above example we put the COORDMODE keyword in the HEAD line since we have sources whose positions are given in different coordinate modes (J2000 and B1950). This keyword may be given as either a header keyword or columnn heading under "HEAD".

VEL or **VELOCITY** The radial velocity in km/sec. The Default is to use any previous setting or 0.0 if there is none.

VELDEF Velocity definition in the FITS convention, e.g. "VOPT-BAR", "VRAD-LSR", etc. (see https://safe.nrao.edu/wiki/bin/view/GB/Data/VelDefFits). The default is the velocity definition or reference frame that was previously set. In the above example we put the VELDEF keyword in the HEAD line since we have sources whose velocity definitions are different. This keyword may be given as either a header keyword or columnn heading under "HEAD". This value will also override the velocity definition in the configuration (see § 5.2.5).

RESTFREQ The rest frequency, in MHz. The default is to use the previous setting. Again we put the RESTFREQ keyword in the HEAD line since we are defining two different spectral line rest frequencies for each source. Note that this is an "expert" keyword as one has to be aware of any conflicts with the hardware configuration. This keyword may be given as either a header keyword or columnn heading under "HEAD".

RA, HA, DEC, AZ, EL, GLON, GLAT A pair of coordinates must be given: RA/DEC, HA/DEC, AZ/EL, or GLON/GLAT. Angle formats may be either in sexagesimal with colons (e.g. dd:mm:ss.ss) or in decimal format. RA and HA are always in hours regardless of decimal or sexagesimal notation, while all other coordinates use degrees of arc in both formats.

EQUINOX Used if the Coordmode is "JMEAN". The value is a float (e.g. 2006 December 1, 12:00 UT would be 2006.919178082192). This keyword may be given as either a header keyword or columnn heading under "HEAD".

```
# My source list
format=spherical
coordmode=jmean
equinox=2007.123456
HEAD = NAME     RA         DEC
Object2  10:56:16.98  +50:16:25.5
```

Script 5.14: An example catalog using the equinox header keyword.

- Additional keywords used when the Ephemeris format is active are (see § 5.3.5 for examples):

DATE The UTC date, either "2005-06-23" or "2005-Jun-23" form. This keyword may be given as either a header keyword or columnn heading under "HEAD".

UTC The UTC time in the form "hh:mm:ss".

DRA, DHA, DDEC, DAZ, DEL, DLON, DLAT The coordinate rate keywords given in arcsec per hour.

DVEL The radial velocity rate in km/sec/hour.

- Additional keywords used by the NNTLE format are (see § 5.3.6 on NNTLE format below for examples):

FILE For use in NNTLE format only. This keyword value may refer to a file or a URL containing a 2-line element set. This keyword may not be listed as a column name under "HEAD".

USERADVEL For use in the NNTLE format only. If this is set to 1, then the radial velocity tracking will be performed. Otherwise, if this is set to 0 or is missing then radial velocity tracking will not be performed. This keyword may not be listed as a column name under "HEAD".

5.3.2.2 SPHERICAL format Examples

–Here is an example of a simple catalog.

```
# My source list
format=spherical
coordmode=J2000
HEAD = NAME   RA         DEC
Object1  09:56:16.98  +49:16:25.5
Object2  10:56:16.98  +50:16:25.5
Object3  11:56:16.98  +51:16:25.5
Object4  12:56:16.98  +52:16:25.5
```

Script 5.15: A simple catalog.

–Because all the keyword values use the defaults, the following is equivalent:

```
# My source list
Object1  09:56:16.98  +49:16:25.5
Object2  10:56:16.98  +50:16:25.5
Object3  11:56:16.98  +51:16:25.5
Object4  12:56:16.98  +52:16:25.5
```

Script 5.16: A simple catalog using default header keywords and columns.

–Here is an example catalog that specifies the radial velocities of the sources.

```
# My source list with radial velocities
format=spherical
coordmode = B1950
head = name   ra       dec          velocity
Object1  09:56:16.98  +49:16:25.5  27.23
Object2  08:56:16.98  +48:16:25.5  28.24
Object3  07:56:16.98  +47:16:25.5  29.25
Object4  06:56:16.98  +45:16:25.5  30.26
```

Script 5.17: A catalog using the "velocity" column to specify radial velocity in km/sec.

–Here is an example Catalog where one may omit the "format=" line, but not the "coordmode=" line.

```
# A list of HII regions
coordmode=Galactic
head= NAME GLON        GLAT     vel       restfreq
G350+.07   350.107    +0.079    42.2235   9816.867
G351+.17   351.613     0.172   -15.553    9487.824
G352-.17   352.393    -0.176   -52.227    9173.323
G352-.36   353.4219   -0.3690   22.335    9487.824
```

Script 5.18: A catalog using the "Galactic" coordinate mode and omitting "format=".

Warning: setting the velocity or rest frequency in a catalog only changes the values in the LO1 manager. If either value is changed by a large amount, the receiver selection or bandpass filters or the frequency spacing between spectral windows may change. Thus one should re-configure the IF system for a large change in velocity or frequency. The user should be wary of how much the velocity or rest frequency can change for a particular configuration.

–Finally we show an example Catalog with user-defined keywords. The user may create custom keywords (or equivalently column headings). These are available within an SB, but are otherwise ignored.

```
# a list of pointing references
format=spherical
coordmode=j2000
head= name    ra           dec          BMIN BMAX  S20    S6
0011-1434 00:11:40.40   -14:34:04.7    15  45   0.17   0.20
0012-3321 00:12:17.96   -33:21:57.8    15 180   0.85   0.18
0012+6551 00:12:37.80   +65:51:10.5    15 360   1.20   0.55
0012+2702 00:12:38.14   +27:02:40.7    15 180   0.60   0.21
0012+3353 00:12:47.3826 +33:53:38.459   0  45   0.08   0.08
0012-3954 00:12:59.9080 -39:54:25.836   0  45   0.49   1.5
```

Script 5.19: A catalog with user–defined keywords

Table 5.1: The following Catalogs are present as of April 2022. The flux densities of pointing calibrators vary by up to a factor of two on time scales of years at frequencies higher than 8 GHz, so the pointing calibrators will never be good flux calibrators. The main reason for updating their flux densities is to make sure the observer gets a strong-enough pointing calibrator. For genuine flux-density calibration, we recommend observers use the flux densities of 3C123, 3C286, and 3C295 (See Perly and Butler, 2017, ApJS, 230, 7).

Catalog	Description
fluxcal	Calibrators with well-determined flux densities. U. S. Government Printing Office (Usgpo) 2006, The Astronomical Almanac for the year 2006, Washington: U.S. Government Printing Office (USGPO), 2006, U.S. Naval Observatory (USNO), Royal Greenwich Observatory (RGO).
pointing	Condon's master pointing catalog for the GBT[a]
pf_pointing	Extracted from pointing catalog for the 50 cm band (0.6GHz).
lband_pointing	Extracted from pointing catalog for the 21 cm band (1.4GHz).
sband_pointing	Extracted from pointing catalog for the 10 cm band (3GHz).
cband_pointing	Extracted from pointing catalog for the 6 cm band (6GHz).
xband_pointing	Extracted from pointing catalog for the 3.5 cm band (9GHz).
kuband_pointing	Extracted from pointing catalog for the 2 cm band (14GHz).
kband_pointing	Extracted from pointing catalog for the 1.5 cm band (20GHz).
kaband_pointing	Extracted from pointing catalog for the 9 mm band (32GHz).
qband_pointing	Extracted from pointing catalog for the 7 mm band (43GHz).
wband_pointing	Extracted from pointing catalog for the 3.5mm band (86GHz).
mustang_pointing	Extracted from pointing catalog for the 3.3mm band (90GHz).
HI_strong	Galaxies with strong HI lines, extract from Rich Fisher's database[b]
pulsars_all	All 1533 pulsars in the ATNF database as of 26 Aug 2005.
pulsars_all_GBT	All 1054 pulsars visible from Green Bank.
pulsars_brightest_GBT	The brightest pulsars, visible from Green Bank.
pulsars_bright_MSPs_GBT	Bright millisecond pulsars visible from Green Bank.

[a] https://safe.nrao.edu/wiki/bin/view/GB/PTCS/PointingFocusCatalog
[b] http://www.gb.nrao.edu/~{}rfisher/GalaxySurvey/galaxy_survey.html

5.3.3 Standard Catalogs

Several "standard" catalogs listed in Table 5.1 are available for use within the Green Bank computing system. They are all ASCII files in the directory `/home/astro-util/astridcats`.

Note that for convenience, these standard catalogs may be referred to within Astrid simply by name, without the ".cat" extension. e.g.:

```
c = Catalog(kaband_pointing)
```

Script 5.20: Loading standard catalogs into an SB

The GBT pointing catalog has been updated several times to include better positions and more recent flux densities. These changes are described in the PTCS project notes posted at https://safe.nrao.edu/wiki/bin/view/GB/PTCS/ProjectNotes

- PTCS/PN/58 introduces PCALS4.1 and "gold standard" pointing calibrators for use at higher frequencies

- PTCS/PN/66 introduces PCALS4.4, a catalog upgrade incorporating high-frequency flux densities from WMAP5 and accurate positions from the VLBA calibrator surveys through VCS6
- PTCS/PN/72 introduces PCALS4.5 with high-frequency flux densities updated by WMAP7, the Planck "'Early Release Compact Source Catalog", and the Australia Telescope AT20G survey.
- PCALS 4.7 adds new 30, 44, 70, and 100 GHz flux densities from the final Planck Catalogue of Compact Sources (Planck Collaboration, 2013, arXiv:1303.5088) and 20 GHz fluxes from Righini, S., Carretti, E., Ricci, R. et al. 2012 MNRAS, 426, 2107 "A 20 GHz bright sample for delta > +72°: I. Catalogue". There is no PTCS/PN describing this release.

5.3.4 Catalog Functions

Two useful catalog functions are available.

5.3.4.1 c.keys()

Acts like a Python function that returns a list of all the source names in the Catalog loaded into the variable 'c' [i.e. via c=**Catalog**('mycatalog')]. The value returned can be used in the SB to automatically loop through all the sources in a catalog. Here is an example of how to do this:

```
c = Catalog(HI_strong)
sourcenames = c.keys()
for s in sourcenames :
    Nod(s,'1','2',120)
```

Script 5.21: Using c.keys() to create an array of source names in the SB

5.3.4.2 c['sourcename']['keyword']

Returns the value of the keyword for the named source in the Catalog loaded into the variable 'c'. This function can be used to pass information in the Catalog on to the SB (e.g. specifying different map sizes for different sources/directions).

The c['sourcename']['keyword'] function can be used to get information out of the "keyword" column of the Catalog for use within the SB. In the following example we get the source's Declinations and only observe those sources above 20° Declination (note that the coordinates are always returned in degrees):

```
c = Catalog(lband_pointing)
sourcenames = c.keys()
for s in sourcenames :
    print c[s]['dec']
    if c[s]['dec'] > 20 :
        Nod(s,'1','2',120)
```

Script 5.22: An example SB that retrieves the declination of each source in the catalog and prints it to screen. If the declination of the source is above 20° then the SB will proceed to perform a **Nod()** scan.

The c["sourcename"]["keyword"] function can also be used to execute more complicated observing strategies. In the following example we have many sources to observe and we desire a different amount of total integration time for each source. To accomplish this we add two new columns to the Catalog. We will call these columns "sourcetime" and "status". A few lines of the Catalog (let's call it mycatalog.cat) would look like:

```
head= name ra dec velocity sourcetime status
SrcA  00:01:02  -03:04:05  -22.0  300  done
SrcB  06:07:08  +10:11:12  +56.3  120  waiting
```

Script 5.23: An example catalog with user–defined columns.

The SB would look like:

```
c = Catalog('mycatalog.cat')
sourcenames = c.keys()
for s in sourcenames :
    if c[s]['status'] == 'waiting' :
        dwelltime = float(c[s]['sourcetime'])
        Track(s,None,dwelltime)
```

Script 5.24: An example SB that retrieves information for each source from user-defined columns in the catalog shown in Script 5.23.

Note that c[‘sourcename’][‘keyword’] will return a string value. Thus, we convert “dwelltime” in Script 5.24 to a float value in order to use it as a suitable time argument in the **Track** scan function.

5.3.5 EPHEMERIS : Tables for moving objects

A Catalog can also be used as an Ephemeris for the position of a moving object, such as a comet or asteroid. To make the Catalog into an Ephemeris the first non-comment line of the Catalog must contain:

```
FORMAT = EPHEMERIS
```

The header of the Catalog for an Ephemeris can also contain the NAME, COORDMODE, VELDEF and HEAD keywords. The “data lines” in the Catalog must contain at least the date, the time, and a pair of coordinates for an Ephemeris. Optional parameters are coordinate rates, radial velocity and radial velocity rate. User-defined parameters may also be added.

The dates and times are required to be in UTC. The dates and times can be specified in any legal python form, for example: a) ’YYYY-MM-DD hh:mm:ss’ where MM is month number (e.g August = 09); or b) ’YYYY-MMM-DD hh:mm:ss’ where MMM is the abbreviated month name such as Jan, Feb, etc.

The ephemeris table should contain enough entries to cover a period longer than that required by a particular observing session with sufficient time resolution for the expected motion with respect to the telescope’s beam size. The observing system selects the portion of the table needed for the current scan start time and duration.

5.3.5.1 Example Ephemeris Catalogs

```
FORMAT    = EPHEMERIS
NAME      = MyMovingObject
COORDMODE = J2000
VELDEF    = VRAD-LSR
#-------------------------------------------------------------------
2004-07-16 00:10:00  09:56:16.98  +49:16:25.5  27.234234
2004-07-16 00:20:00  09:56:17.76  +49:16:36.2  27.456345
2004-07-16 00:30:00  09:56:18.55  +49:16:46.9  27.568233
```

```
2004-07-16 00:40:00  09:56:19.32  +49:16:57.6  27.623423
2004-07-16 00:50:00  09:56:20.10  +49:17:08.3  27.723456
#---------------------------------------------------------------------
```

Script 5.25: A simple ephemeris catalog. Note that the "HEAD=" line has been omitted because the default is "DATE UTC RA DEC VEL"

```
FORMAT = EPHEMERIS
VELDEF = VRAD-TOP
COORDMODE = J2000
HEAD = date utc ra dec dra ddec vel
# 1: soln ref.= JPL#153
NAME = 2008CM
2015-Dec-30 05:00 09:00:46.65 +13:13:58.0 -1045.1405 -1344.9600 4.8196
2015-Dec-30 05:10 09:00:35.06 +13:10:13.7 -1044.8328 -1344.5100 4.8595
2015-Dec-30 05:20 09:00:23.47 +13:06:29.5 -1044.4856 -1344.0600 4.8997
2015-Dec-30 05:30 09:00:11.88 +13:02:45.3 -1044.0885 -1343.6000 4.9405
2015-Dec-30 05:40 09:00:00.30 +12:59:01.2 -1043.6313 -1343.1400 4.9815
2015-Dec-30 05:50 08:59:48.72 +12:55:17.2 -1043.1244 -1342.6900 5.0230
2015-Dec-30 06:00 08:59:37.15 +12:51:33.3 -1042.5679 -1342.2200 5.0648
```

Script 5.26: A more complicated ephemeris catalog for a comet that specifies the coordinate rates.

```
# PRN14 tracking table (angles in degrees)
# visible 01:30 to 3:00 UT

format    = ephemeris
name      = PRN14
coordmode = azel
head=date  utc       az         el
#-----------------------------------------
2004-05-16 01:30:06  103.1822   43.0174
2004-05-16 01:30:14  103.2464   42.9721
2004-05-16 01:30:22  103.3105   42.9268
2004-05-16 01:30:30  103.3745   42.8814
#-----------------------------------------
```

Script 5.27: A ephemeris catalog for tracking a satellite.

5.3.5.2 Comets

Tracking a comet which does not track at the sidereal rate will require the use of an external file generated from the NASA JPL Horizons website which holds a database of all the orbital parameters of all major and minor bodies in the solar system. First you must download the ephemeris file for your object of interest from the website: https://ssd.jpl.nasa.gov/horizons/app.html. Then you will have to convert the file into the CATALOG format for AstrID.

When you go to https://ssd.jpl.nasa.gov/horizons/app.html you should see something like what is shown in Figure 5.1.

Your entries should be:

Ephemeris Type: Observer Table

Target Body: SELECT YOUR OBJECT. Clicking on the blue "Edit" button will open a form to search for the object of interest.

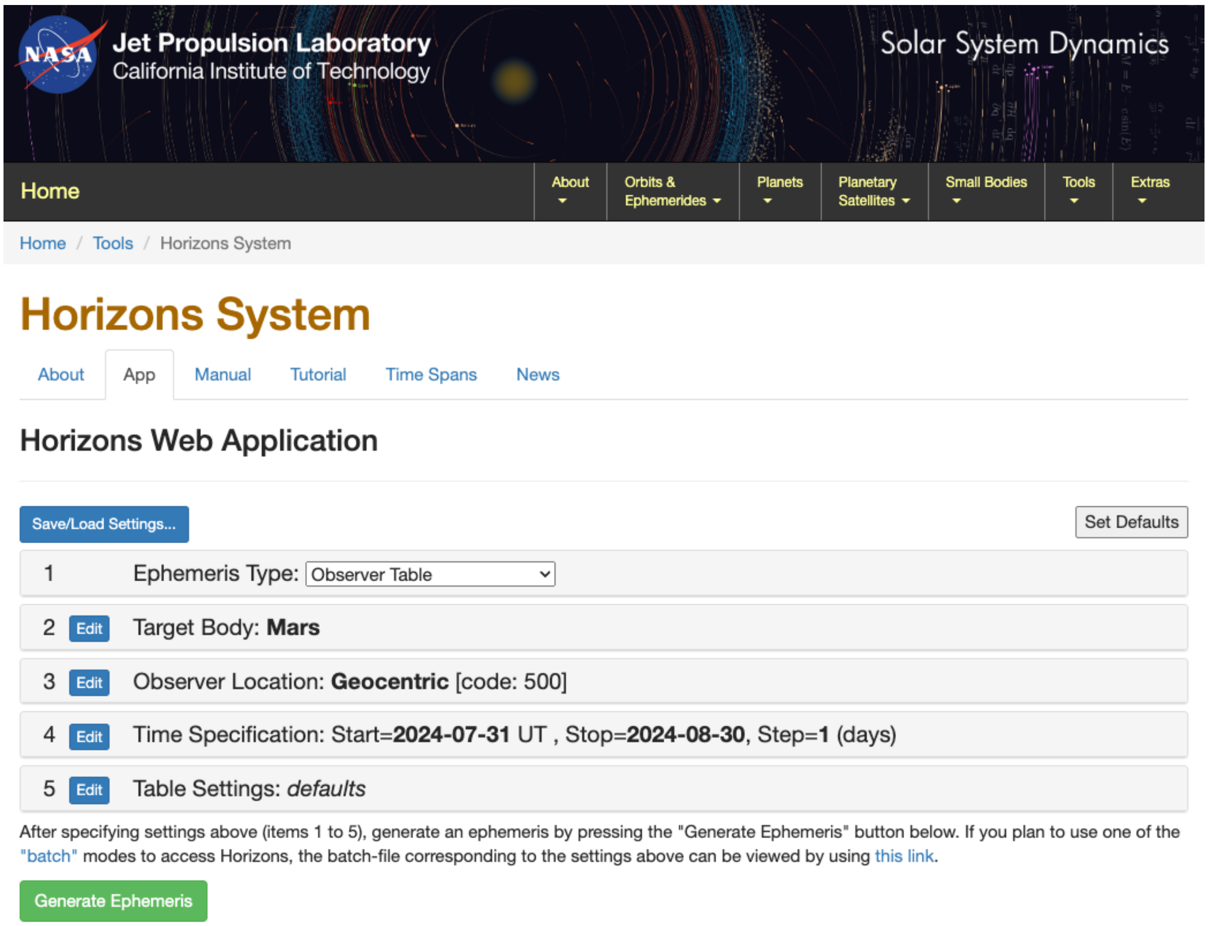


Figure 5.1: The JPL Horizons website

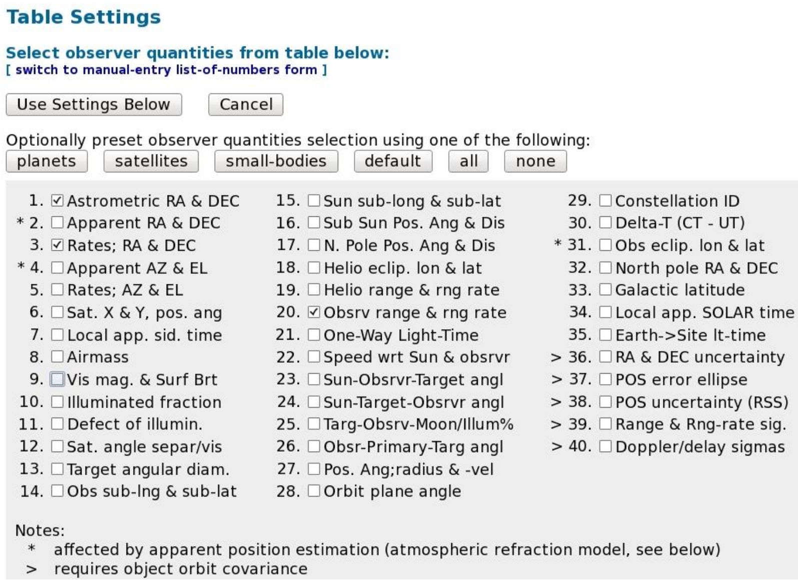


Figure 5.2: Selecting quantities to generate an ephemeris.

Observer Location: Green Bank (GBT) [-9] (radar) (280° 09' 36.7"E, 38° 25' 59.1"N, 873.10 m). To set the location to Green Bank, first click "Edit", then type -9 in the search bar and press Search; the correct location should now appear.

Time Specification: CHOOSE YOUR RANGE. The ephemeris table should contain enough entries to cover a period longer than that required by a particular observing session. The observing system selects the portion of the table needed for the current scan start time and duration. If the position of the comet is changing rapidly, you should select a "step" range of 5 mins or shorter. If the comet is further out in the solar system and is not moving as rapidly with respect to the sidereal rate, a "step" range of 10-15 mins may be adequate to track the comet. Consult your observatory friend if you are unsure of the step range you should choose.

Table Settings: QUANTITIES=1,3,20. Figure 5.2 shows the quantities that should be selected through the web interface to properly generate an ephemeris for tracking a comet. NOTE: The dates and times are required to be in UTC. The dates and times can be specified in any legal python form, for example: a) 'YYYY-MM-DD hh:mm:ss' where MM is month number (e.g August = 09); or b) 'YYYY-MMM-DD hh:mm:ss' where MMM is the abbreviated month name such as Jan, Feb, etc. (see below)

After clicking "Generate Ephemeris", you should save the file to a directory in your area in Green Bank. The ephemeris file will begin with a large amount of header information followed by lines containing the date, time and pairs of coordinates as shown in Script 5.28. Optional parameters are coordinate rates, geocentric distance and geocentric radial velocity.

```
*******************************************************************************
JPL/HORIZONS                   103P/Hartley 2             2016-Apr-05 07:53:21
Rec #:900870 (+COV)   Soln.date: 2014-Nov-10_13:49:39   # obs: 6506 (1986-2013)

FK5/J2000.0 helio. ecliptic osc. elements (au, days, deg., period=Julian yrs):

  EPOCH=  2456981.5 ! 2014-Nov-20.0000000 (TDB)    RMSW= n.a.
   EC= .6937804720128784   QR= 1.064195154203179   TP= 2457863.8230300969
   OM= 219.7487450736021   W= 181.3222857728302    IN= 13.6042724340803
   A= 3.475268743304754    MA= 225.7701522441      ADIST= 5.886342332406328
   PER= 6.4787437937458    N= .152132314           ANGMOM= .023095142
   DAN= 5.88279            DDN= 1.06431            L= 41.0339546
   B= -.310996             MOID= .0720049          TP= 2017-Apr-20.3230300969

Comet physical (GM= km^3/s^2; RAD= km):
```

```
   GM= n.a.                RAD= .800
   M1=  14.7     M2=  n.a.     k1=  8.     k2= n.a.     PHCOF= n.a.

COMET comments
1: soln ref.= JPL#252, data arc: 1986-03-15 to 2013-05-14
2: k1=8.;
*******************************************************************************


*******************************************************************************
Ephemeris / WWW_USER Tue Apr  5 07:53:22 2016 Pasadena, USA      / Horizons
*******************************************************************************
Target body name: 103P/Hartley 2                  {source: JPL#252}
Center body name: Earth (399)                     {source: DE431}
Center-site name: Green Bank (GBT)
*******************************************************************************
Start time      : A.D. 2016-Apr-05 00:00:00.0000 UT
Stop  time      : A.D. 2016-Apr-06 00:00:00.0000 UT
Step-size       : 5 minutes
*******************************************************************************
Target pole/equ : No model available
Target radii    : 0.8 km
Center geodetic : 280.160200,38.4330940,0.8760930 {E-lon(deg),Lat(deg),Alt(km)}
Center cylindric: 280.160200,5003.37558,3943.7589 {E-lon(deg),Dxy(km),Dz(km)}
Center pole/equ : High-precision EOP model        {East-longitude +}
Center radii    : 6378.1 x 6378.1 x 6356.8 km     {Equator, meridian, pole}
Target primary  : Sun
Vis. interferer : MOON (R_eq= 1737.400) km        {source: DE431}
Rel. light bend : Sun, EARTH                      {source: DE431}
Rel. lght bnd GM: 1.3271E+11, 3.9860E+05 km^3/s^2
Small-body perts: Yes                             {source: SB431-BIG16}
Atmos refraction: NO (AIRLESS)
RA format       : HMS
Time format     : CAL
RTS-only print  : NO
EOP file        : eop.160404.p160626
EOP coverage    : DATA-BASED 1962-JAN-20 TO 2016-APR-04. PREDICTS-> 2016-JUN-25
Units conversion: 1 au= 149597870.700 km, c= 299792.458 km/s, 1 day= 86400.0 s
Table cut-offs 1: Elevation (-90.0deg=NO ),Airmass (>38.000=NO), Daylight (NO )
Table cut-offs 2: Solar Elongation (  0.0,180.0=NO ),Local Hour Angle( 0.0=NO )
*******************************************************************************
Initial FK5/J2000.0 heliocentric ecliptic osculating elements (au, days, deg.):
  EPOCH=  2456981.5 ! 2014-Nov-20.0000000 (TDB)    RMSW= n.a.
   EC= .6937804720128784   QR= 1.064195154203179   TP= 2457863.8230300969
   OM= 219.7487450736021   W= 181.3222857728302    IN= 13.6042724340803
Comet physical (GM= km^3/s^2; RAD= km):
   GM= n.a.                RAD= .800
   M1=  14.7     M2=  n.a.     k1=  8.     k2= n.a.     PHCOF= n.a.
**********************************************************************************************
 Date__(UT)__HR:MN     R.A._(ICRF/J2000.0)_DEC dRA*cosD d(DEC)/dt            delta      deldot
**********************************************************************************************
$$SOE
 2016-Apr-05 00:00 C   18 27 00.30 -13 25 32.9 12.40954  9.786338 3.50004632213965 -36.1740593
 2016-Apr-05 00:05 C   18 27 00.37 -13 25 32.0 12.40419  9.784071 3.49997377062988 -36.1812496
                                         ...........
                                           .......
                                             ...
```

Script 5.28: A JPL ephemeris file

Now that you have your ephemeris, it needs to be converted to a form that AstrID can read. You can do this by running the Python script `jpl2astrid` from any directory in your area on the Green Bank computer system. If you just type “jpl2astrid”, and give it no arguments, it lists instructions, like this:

```
Usage:  jpl2astrid cometfilename.txt [vel]
    If 'vel' is blank,  do not write the radial velocities.
    If 'vel' is non-blank,  do write the radial velocities.
    output will have '.astrid' extension.
    Include in Astrid with, e.g. Catalog(fullpath/cometfile.astrid )

    If '-h' or '-help' instead of 1st argument, print help message

 Access the JPL Horizons web interface: http://ssd.jpl.nasa.gov/horizons.cgi
 Set up Horizons web-interface as follows
   ephemeris type:   OBSERVER
   target body:      [select the object]
```

```
   Observer Location:   Green Bank (GBT) [select from list of observatories]
   Time Span:         [put in desired values]
   Table Settings:    QUANTITIES=1,3,20
        i.e., (1)Astrometric RA&Dec, (3)rates RA&Dec, and (20)Range and range rate
   Display/Output:    plain text

 Use the web browser file menu to save the output file as (for example) cometfilename.txt
```

Script 5.29: jpl2astrid usage

If you give it a file name, say by typing "jpl2astrid jplephemfile.txt", it produces another file in the form for AstrID Catalogs. You should verify that the first non-comment line of the resulting catalog file contains:

```
FORMAT = EPHEMERIS
```

You now have a valid catalog file that AstrID will be able to use. When you load the catalog into AstrID, make sure you have the correct path and that the name of the comet is exactly what is in the .astrid catalog file in "quotations". The catalog file should look something like this:

```
FORMAT = EPHEMERIS
VELDEF = VRAD-TOP
COORDMODE = J2000
HEAD = date utc ra dec dra ddec
# 1: soln ref.= JPL#252
NAME = 103P/Hartley
2016-Apr-05 00:00 18:27:00.30 -13:25:32.9 12.7582 9.7863
2016-Apr-05 00:05 18:27:00.37 -13:25:32.0 12.7527 9.7841
2016-Apr-05 00:10 18:27:00.44 -13:25:31.2 12.7469 9.7818
2016-Apr-05 00:15 18:27:00.52 -13:25:30.4 12.7409 9.7796
```

Script 5.30: An AstrID ephemeris catalog generated by running jpl2astrid on Script 5.28

Note: You may wish to edit the "NAME =" line to rename the object. The name of the object will be used in SBs as an argument to scan functions such as **Track**.

5.3.6 NNTLE : Tracking Earth satellites

"NNTLE" stands for NASA/NORAD Two-Line Elements. This refers to a standard NASA format for orbital elements for Earth satellites.

The first non-comment line of the Catalog must contain

```
FORMAT = NNTLE
```

If the FILE keyword is used then one should only give the name of the object in the Catalog as the elements of the orbit are retrieved from the file or URL. Note that the full path name of the file must be given, and the file must have world read permission.

The remainder of the non-comment lines contain the names for one or more satellites and their orbital elements in the NASA/NORAD Two-Line Element format.

An example of a valid file is as follows (data taken from the AMSAT URL listed above):

```
FORMAT = NNTLE
USERADVEL = 1      # optional keyword
#
OSCAR10
1 14129U          88230.56274695 0.00000042           10000-3 0   3478
2 14129  27.2218 308.9614 6028281 329.3891   6.4794  2.05877164 10960
GPS-0008
1 14189U          88230.24001475 0.00000013                   0   5423
2 14189  63.0801 108.8864 0128028 212.9347 146.3600  2.00555575 37348
```

Script 5.31: An example of a valid NNTLE format Catalog file

When implementing an NNTLE catalog, the scantype function will pass the 3 lines to a program that will calculate positions for the antenna, given the scan start time and duration. The source name is the string that appears on the first of the three lines, and that is what one would pass to the scan function.

It may also be convenient to use TLEs on a file or website as shown in Scripts 5.32 and 5.33.

```
FORMAT    = NNTLE
USERADVEL = 0
FILE      = /home/astro-util/projects/GBTog/other/gps-ops.txt
Name      = 'GPS BIIR-2'
```

Script 5.32: An example NNTLE format Catalog file using the "FILE" keyword

```
FORMAT    = NNTLE
USERADVEL = 0
URL       = http://www.celestrak.com/NORAD/elements/gps-ops.txt
Name      = 'GPS BIIR-2'
```

Script 5.33: An example NNTLE format Catalog file using the "URL" keyword

The first set of orbital elements whose name matches the name listed in the file will be used for calculating the satellite position. Note that the generation of tracks for satellites is based on "pyephem", an implementation of xephem in Python.

5.4 Scan Types

A Scan is a pattern of antenna motions that when used together yield a useful scientific dataset. This section describes the various scan types that are available for use within GBT SBs. Each scan type consists of one or more scans, which are the individual components of the antenna's motion on the sky. The scan types listed below are the functions within your SB where data will be obtained with the GBT.

Please note that the syntax for all Scan Types is case-sensitive. Location, Offset, Horizon, and Time objects are defined in § 5.6 while Catalogs are defined in § 5.3. Seldom used scan types are discussed in Appendix D.2. Nearly all scans use the following parameters:

Location
: Most Scan commands require a "location" parameter. This may be either a Location object (see § 5.6 and § 5.6.1), or it may be the name of a radio source given in a Catalog (see § 5.3).

beamName
: Most Scan commands use a "beamName" parameter. This should not be confused with the **beam**

Table 5.2: Utility Scan Types available for the GBT.

Scan Type	Observing Type	Description
AutoPeakFocus	Continuum	Selects and observes a nearby calibration source and updates the pointing and focus corrections.
AutoPeak	Continuum	Selects and observes a nearby calibration source and updates the pointing corrections.
AutoFocus	Continuum	Selects and observes a nearby calibration source and updates the focus correction.
AutoOOF	Continuum	Selects and observes a nearby calibration source with different focus settings to create an out-of-focus holography map to update the surface.
Focus	Continuum	Performs a focus observation.
Peak	Continuum, Line	Performs a pointing or cross observation.
Tip	Continuum, Line	Performs an observation to derive T_{sys} vs. elevation.
Slew	Continuum, Line, Pulsar	Slews the telescope to the specified source or Location.
Balance	Continuum, Line, Pulsar	Balances the IF system so that each device is operating in its linear response regime
BalanceOnOff	Continuum, Line, Pulsar	Move from a source to a reference position and balance the IF system at the mid-point of the two power levels.

keyword in Configurations (see § 5.2.5). This indicates the "tracking beam" i.e., the beam that is pointed at the specified location. It may have values '1', '2', '3', up to the maximum beam number for the specified receiver. The beam numbers and their relative locations depend on the receiver. A value of 'C' means the center of the array or receiver box, where there may or may not be a feed. Syntax such as 'MR12' means halfway between beams 1 and 2, which is used only for subreflector nodding.

scanDuration

A float value specifying the length of a scan in seconds. Note that scan type procedure may consist of a series of subscans. In these cases "scanDuration" refers to the length of each subscan, not the time required to complete the full scan type procedure. For example, the **OnOff** scan type, typically used for position switching observations, will perform a pair of subscans: one 'on'-source, and one 'off'-source. If scanDuration is set to 60.0, then the full procedure will require 2 minutes to complete (60 seconds for the 'on' scan and then 60 seconds for the 'off' scan).

5.4.1 Utility Scans

Utility scans generally describe procedures that are used to calibrate some aspect of the system such as pointing, focus, or power levels. Nearly every observing session will require the use of one or more of the utility scans described in the following section and listed in table 5.2.

AutoPeakFocus, **AutoPeak**, **AutoFocus** and **AutoOOF** automatically execute their own default continuum configurations unless "configure=False" has been supplied as an optional argument (only recommended for expert users). After running one of these **Auto*** procedures, one needs to reconfigure for their science observations.

5.4.1.1 AutoPeakFocus

The intent of this scan type is to automatically peak and focus the antenna for the current location on the sky and with the current receiver. Therefore it should not require any user input. However,

Table 5.3: Default values for performing peak and focus observations.

Receiver	ν (MHz)	$\Delta\nu$ (MHz)	Beam -refBeam	Peak: Beam FWHM	Peak: Length (')	Peak: Time (sec)	Focus: Focus FWHM	Focus: Length (mm)	Focus: Time (sec)	Notes
Rcvr_342	340	20	1	36'	180	30	3.2 m	—	—	A,C
Rcvr_450	415	20	1	30'	180	30	2.6 m	—	—	A,C
Rcvr_600	680	20	1	18'	90	15	1.6 m	—	—	A,C
Rcvr_800	770	20	1	16'	80	15	1.4 m	—	—	A,C
Rcvr_1070	970	20	1	13'	65	15	1.1 m	—	—	A,C
Rcvr1_2	1400	80	1	8.8'	130	30	76 cm	480	60	B,D,E
Rcvr2_3[a]	2000	80	1	6.2'	90	30	54 cm	480	60	B,D,E
Rcvr4_6[a]	5000	80	1	2.5'	40	30	22 cm	480	60	B,D,E
Rcvr8_10[a]	9000	80	1	1.4'	16	24	12 cm	480	60	B,D,E
Rcvr12_18[a]	14000	320	1-2	53"	18	30	76 mm	320	60	B,D,F
RcvrArray18_26	25000	800	4-6	30"	9	30	43 mm	240	60	B,D,F
Rcvr26_40	32000	320	1-2	23"	8	24	32 mm	180	60	B,D,F
Rcvr40_52[a]	43000	320	1-2	17"	6	30	25 mm	120	60	B,D,F
Rcvr68_92	77000	320	1-2	10"	3	30	14 mm	100	60	B,D
RcvrArray75_115	86000	320	10-11	8.6"	3	30	12 mm	100	60	B,D

[a] Please note that this receiver name no longer correlates exactly with the actual frequency range of the receiver.

A Prime Focus: Peak Lengths are chosen to be 5 x FWHM with a scan time of 15 seconds to have good sampling across the beam.

B Gregorian Focus: Peak Rates are chosen to give 2 seconds across the FWHM, Peak Times to give a scan time of 30 seconds (to allow vibrations to settle).

C Prime Focus: Axial focus measurements are not recommended for prime focus receivers since the gain changes only slightly over the entire focus range.

D Gregorian Focus: The optimal focus length is 2 x FWHM, but to allow for varying baselines we currently recommend $\sim$ 3 x focus FWHM, plus 40mm at each end to allow for the fact that focus measurement is done with respect to focus tracking curve, not last offset. The Focus Rate is then chosen to give a 60sec scan time. This is a trade-off between completing the focus scan quickly, and allowing any potential scan-start anomalies to die away.

E Focus rates and lengths are conservative limits set by subreflector hardware (the absolute maximum would be 600mm/min and 600mm).

F Multi-beam receivers use a larger peak length to accomodate the beam separation in azimuth.

by setting any of the optional arguments the user may partially or fully override the search and/or procedural steps as described below.

AutoPeakFocus() should not be used with Prime Focus receivers. The prime focus receivers have pre-determined focus positions and there is not enough travel in the feed to move them significantly out of focus.

AutoPeakFocus() will execute its own default continuum configuration unless "configure=False" is supplied as an optional argument, which is not recommended in general unless one knows the system well.

SYNTAX:

AutoPeakFocus(source, location, frequency, flux, radius, balance, configure, beamName, elAzOrder, gold)

source A string. It specifies the name of a particular source in the pointing catalog or in a user-defined Catalog. The default is None. Specifying a source bypasses the search process. Please note that NVSS source names are used in the pointing catalog. If the name is not located in the pointing catalog then all the user-specified catalogs previously defined in the Scheduling Block are searched. If the name is not in the pointing catalog or in the user defined catalog(s) then the procedure fails.

location A Catalog source name or Location object (see § 5.6.1). It specifies the center of the search radius. The default is the antenna's current beam location on the sky. Planets and other moving objects may **not** be used.

frequency A float. It specifies the observing frequency in MHz. The default is the rest frequency used by the standard continuum configurations, or the current configuration value if "configure=False" (see Table 5.3).

flux A float. It specifies the minimum acceptable calibration flux in Jy at the observing frequency. The default is 20 times the continuum point-source sensitivity.

radius A float. The routine selects the closest calibrator within the radius (in degrees) having the minimum acceptable flux. The default radius is 10 degrees. If no calibrator is found within the radius, the search is continued out to 180 degrees and if a qualified calibrator is found the user is given the option of using it [default], aborting the scan, or continuing the scheduling block without running this procedure.

balance A Boolean. Controls whether after slewing to the calibrator the routine balances the power along the IF path and again to set the power levels just before collecting data. Allowed values are True or False. The default is True.

configure A Boolean. This argument causes the telescope to configure for continuum observing for the specified receiver. The default is True. **Note: because AutoPeakFocus() is self-configuring when set to True, one must re-configure the GBT IF path for your science observations after the pointing and focus observations are done.** If set to False, then no configuration is done, and the observer must ensure that the system is properly configured first before running the command.

beamName A string. It specifies which receiver beam will be the center of the cross-scan. beamName can be 'C', '1', '2', '3', '4', etc, up to '7' for the KFPA receiver. This keyword should not be specified unless there is an issue with the default beams used for pointing (5.3).

refBeam A string. It specifies which beam will be the reference beam for subtracting the sky contribution for the pointing observations. The name strings are the same as for the **beamName** argument. This keyword should not be specified unless there is an issue with the default beams used for pointing (5.3). The KFPA and Argus have backup beam pairs that can be used for pointing and focus if there is an issue with one of the default beams. The valid beam pairs for the KFPA are beamName='4', refBeam='6' (default beam pair) or beamName='3', refBeam='7' (backup beam pair), while the valid beam pairs for Argus are beamName='10', refBeam='11' (default beam pair) or beamName='14', refBeam='15' (backup beam pair).

elAzOrder A Boolean. If True, the elevation peak scans will be done first before the azimuth peak scans. This can be helpful for high-frequency observations (> 40GHz) to provide more successful initial pointing solutions, since the elevation pointing offsets are typically larger than the azimuth offsets. The default is False, for which the azimuth pointing scans will be done before the elevation scans.

calSeq A Boolen. If True, then for 'Rcvr68_92' the observations will be proceeded by calibration calSeq observations, or for 'RcvrArray75_115' the calibration "vanecal" observations. If False, then the calibration vanecal or calSeq observations will be skipped. This keyword is only applicable for receivers operating above 66 GHz, and the associated calibration observations depend on the receiver ('Rcvr68_92', 'RcvrArray75_115', and 'Rcrv_PAR') and the particular Auto utilty procedure (see the individual receiver chapters for specifics). The default value is True.

gold A Boolean. If True then only "Gold standard sources" (.i.e. sources suitable for pointing at high frequencies) will be used by AutoPeakFocus(). This parameter is ignored if the "source" parameter is specified.

AutoPeakFocus will use the default scanning rates and lengths listed in Table 5.3. The sequence of events done by **AutoPeakFocus()** in full automatic mode, i.e, with no arguments are:

1. Determine the appropriate receiver based on the selection in the scan coordinator.
2. Determine the recommended beam, antenna/subreflector motions, and duration for peak and focus scans.
3. Get current antenna beam location from the control system.
4. Configure for continuum observations with the current receiver.
5. Run a balance (see § 5.4.1.9) to place the IF power levels appropriately.
6. Determine the source as specified by the user or as chosen by software using the minimum flux, observing frequency, location, and search radius. If no pointing source is found within the specified radius, then provide the observer the option to use a more distant source (default), and if none found either aborting (second default) or continuing the scheduling block.
7. Slew to source.
8. Run another balance to set the power levels at the location of the source.
9. Run a set of four pointing scans using the Peak command.
10. Run a scan using the Focus command.

USAGE:

Script 5.34 gives examples demonstrating the expected use of AutoPeakFocus:

```
#Configure for correct receiver at start of session...
execfile('/home/astro-util/projects/GBTog/configs/tp_config.py')
Configure(tp_config)

#Default (fully automatic)
AutoPeakFocus()
#point and focus on 3C286
AutoPeakFocus('3C286')
# find a pointing source near ra=16:30:00 dec=47:23:00
AutoPeakFocus(location=Location('J2000','16:30:00','47:23:00'))

#AutoPeakFocus has executed its own configuration
```

```
#Reconfigure for science observations
Configure(tp_config)
```

Script 5.34: Examples demonstrating the expected use of AutoPeakFocus.

5.4.1.2 AutoPeak

AutoPeak() is the same as **AutoPeakFocus()** except that it does not perform a focus scan.

SYNTAX:
AutoPeak(source, location, frequency, flux, radius, balance, configure, beamName, refBeam, elAzOrder, calSeq, gold)

Parameter descriptions: See **AutoPeakFocus**()

USAGE: See **AutoPeakFocus**()

5.4.1.3 AutoFocus

AutoFocus() is the same as **AutoPeakFocus()** except that it does not perform pointing scans.

AutoFocus() should not be used with Prime Focus receivers. The prime focus receivers have pre-determined focus positions, and there is not enough travel in the feed to move these receivers significantly out of focus.

SYNTAX:
AutoFocus(source, location, frequency, flux, radius, balance, configure, beamName, refBeam, calSeq, gold)

Parameter descriptions: See **AutoPeakFocus**()

USAGE: See **AutoPeakFocus**()

5.4.1.4 AutoOOF

"OOF" (Out-Of-Focus holography) is a technique for measuring large-scale errors in the shape of the reflecting surface by mapping a strong point source both in and out of focus. The procedure derives surface corrections which can be sent to the active surface controller to correct surface errors. The procedure is recommended when observing at frequencies of 40 GHz and higher. Recommended strategies for using AutoOOF can be found in § 6.2.

AutoOOF() can only be used for observations above 26 GHz. Receiver choices are limited to 'Rcvr26_40', 'Rcvr40_52', 'Rcvr68_92', 'RcvrArray75_115', and 'Rcvr_PAR' (MUSTANG).

SYNTAX:
AutoOOF(source, location, frequency, flux, radius, balance, configure, beamName, refBeam, calSeq, gold)

Parameter descriptions: **AutoOOF** uses the same parameters as **AutoPeakFocus** with a few minor changes:

- **receiver** choices are limited to 'Rcvr26_40', 'Rcvr40_52', 'Rcvr68_92', 'RcvrArray75_115', and 'Rcvr_PAR'
- **nseq** is an optional parameter for use with 'Rcvr_PAR'. It is used to specify the number of OTF maps made with **AutoOOF** and may take values of 3 or 5.

- **calSeq** The default value is True which will run a set of calibration scans before the OOF map scans for 'Rcvr68_92' and 'RcvrArray75_115'. This keyword is only applicable for receivers operating above 66 GHz and the associated calibration observations depend on the receiver ('Rcvr68_92', 'RcvrArray75_115', and 'Rcrv_PAR'; see the individual receiver chapters for specifics).

USAGE:

AutoOOF is used in a similar manner to **AutoPeakFocus**. The command should normally be run without any arguments, since the default options are handled best by the OOF processing software. It is important to only OOF on bright sources (at least 3-4 Jy). A basic example is shown in Script 5.35:

```
#Specifying a source for AutoOOF
AutoOOF('2253+1608')
```

Script 5.35: Example demonstrating the use of AutoOOF.

This example OOF command is applicable for all recievers, and users should refer to the individual reciever chapters to understand the specifics on how the OOF data are calibrated via the calSeq keyword.

For Ka-band, the default backend for the AutoOOF procedure is the CCB. Besides the much higher sensitivity provided by the CCB (a fast beam-switching backend designed for continuum measurements), the larger beam at lower frequency makes the surface solutions less affected by winds. Since the Ka+CCB system provides the most accurate measurements of the surface parameters, it should be used whenever possible.

Users should refrain from using non-standard defaults for the AutoOOF measurements since the processing software is customized per receiver based on the default parameters (e.g., avoid running an AutoOOF at a non-default frequency or pre-configuring and running with the configuration=False keyword).

5.4.1.5 Focus

The Focus scan type moves the subreflector or prime focus receiver (depending on the receiver in use) through the axis aligned with the beam. Its primary use is to determine focus positions for use in subsequent scans and is used almost exclusively with continuum observing.

SYNTAX: Focus(location, start, focusLength, scanDuration, beamName, refBeam **)**

location A Catalog source name or Location object. It specifies the source upon which to do the scan.

start A float. It specifies the starting position of the subreflector (in mm) for the Focus scan. See Table 5.3 for the recommended value for each receiver.

focusLength A float. It specifies the ending position of the subreflector relative to the starting location (also in mm). See Table 5.3 for the recommended value for each receiver.

scanDuration A float. It specifies the length of each scan in seconds. See Table 5.3 for the recommended value for each receiver.

beamName A string. It specifies the receiver beam to use for the measuring the focus. The default for each receiver is listed in Table 5.3. Make sure that you configure with the same beam with which you Focus.

refBeam A string. It specifies the reference receiver beam to use for receivers with more than one beam. The default for each receiver is listed in Table 5.3. Make sure that you configure with the same beam with which you Focus.

USAGE: The only required parameter for **Focus()** is location. In the following example a focus of the subreflector is performed from -200 to +200mm at 400mm/min using beam 1:

```
#Focus using default settings
Focus('0137+3309')

#Focus from -200 to +200mm at 400mm/minute with beam 1
Focus('0137+3309', -200.0, 400.0, 60.0, '1')
```

Script 5.36: Focus() example.

5.4.1.6 Peak

The Peak scan type sweeps through the specified sky location in the four cardinal directions. Its primary use is to determine pointing corrections for use in subsequent scans. Note that the hLength, vLength and scanDuration should be overridden as a unit since together they determine the rate.

SYNTAX: **Peak(** location, hLength, vLength, scanDuration, beamName, refBeam, elAzOrder**)**

location A Catalog source name or Location object. It specifies the source upon which to do the scan.

hLength An Offset object. It specifies the horizontal distance used for the Peak. **hLength** values may be negative. The default value is the recommended value for the receiver (see Table 5.3).

vLength An Offset object. It specifies the vertical distance used for the Peak. **vLength** values may be negative. The default value is the recommended value for the receiver (see Table 5.3).

scanDuration A float. It specifies the length of each scan in seconds. The default value is the recommended value for the receiver (see Table 5.3).

beamName A string. It specifies the receiver beam to use for the scan. The default for each receiver is listed in Table 5.3. Make sure that you configure with the same beam with which you Peak.

refBeam A string. It specifies the reference receiver beam to use for receivers with more than one beam.

elAzOrder A Boolean. If True, the elevation peak scans will be done first before the azimuth peak scans. This can be helpful for high-frequency observations (> 40GHz) since the elevation pointing offsets are typically larger than the azimuth offsets. The default is False, for which the azimuth pointing scans will be done before the elevation scans.

USAGE: The only required parameter for **Peak()** is location. The following example does a Peak in encoder coordinates with 90 minute lengths and a 30 second scan duration using beam 1.

```
#Peak using default settings
Peak('0137+3309')

#Peak using encoder coordinates with scans of 90' length in 30 sec
Peak('0137+3309',Offset('Encoder','00:90:00',0),
                 Offset('Encoder',0,'00:90:00'),30,'1')
```

Script 5.37: Peak() example.

5.4.1.7 Tip

The Tip scan moves the beam on the sky from one elevation to another elevation while taking data and maintaining a constant azimuth. It is recommended to tip from 6° to 45° as the atmosphere will not change significantly above 45°.

SYNTAX: Tip(location, endOffset, scanDuration, beamName, startTime, stopTime**)**

location A Catalog source name or Location object. It specifies the start location of the tip scan. The Location must be in AzEl or encoder coordinates.

endOffset An Offset object. It specifies the beam's final position for the scan, relative to the location specified in the first parameter. The Offset also must be in AzEl or encoder coordinates. **WARNING:** Ensure that you do not slew below 6° elevation.

scanDuration A float. It specifies the length of each scan in seconds.

beamName A string. It specifies the receiver beam to use for the scan. beamName can be 'C' (center), '1', '2', '3', '4' or any valid combination for the receiver you are using such as 'MR12' (i.e., track halfway between beams 1 and 2). The default value for beamName is '1'.

startTime A time string with the following format: 'hh:mm:ss'. It allows the observer to specify a start time for the Tip. See the following section on Observing Scans with the "Track()" command to see more details on startTime.

stopTime A time string with the following format: 'hh:mm:ss'. It allows the observer to specify a stop time for the Tip. See the following section on Observing Scans with the "Track()" command to see more details on stopTime.

USAGE: Scan timing may be specified by either a scanDuration, a stopTime, a startTime plus stopTime, or a startTime plus scanDuration. The following example tips the GBT from 6° in elevation to 45° in elevation over a period of five minutes using beam 1:

```
#Tip from 6 to 80 degrees elevation over 5 minutes with beam 1
Tip(Location('AzEl',1.5,  6.0),
      Offset('AzEl',0.0, 39.0), 300.0, '1')
```

Script 5.38: Tip() example.

5.4.1.8 Slew

Slew moves the telescope beam to point to a specified location on the sky without collecting any data. Note that once **Slew()** is complete, the location will continue to be tracked at a sidereal rate until a new command is issued.

SYNTAX: Slew(location, offset, beamName**)**

location A Catalog source name or Location object. It specifies the source to which the telescope should slew. The default is the currentlocation in "J2000" coordinate mode.

offset An Offset object. It moves the beam to an optional offset position that is specified relative to the location specified in the location parameter value. The default is None. See § 5.6 for information on Offset objects.

beamName A string. It specifies the receiver beam to use for the scan. beamName can be 'C', '1', '2', '3', '4' or any valid combination for the receiver you are using such as 'MR12'. The default is '1'.

USAGE: Slew does the following based on the arguments provided:

1. If only a location is given the antenna slews to the indicated position.
2. If a location and offset are given, the antenna slews to the indicated position plus the offset.
3. If only an offset is given, the antenna slews to the current location plus the specified offset.

The following example slews to 3C 48 using the center of all the receiver's beams:

```
Slew('3C48',beamName='C') #Slew to 3c48 using the center of all beams
```

Script 5.39: Slew() example.

5.4.1.9 Balance

The **Balance()** command is used to balance the electronic signal throughout the GBT IF system so that each device is operating in its linear response regime. **Balance()** will work for any device with attenuators and for a particular backend. Individual devices can be balanced, such as the Prime Focus receivers, the IF system, the DCR, and VEGAS (The Gregorian receivers lack attenuators and do not need to be balanced). If the argument to**Balance()** is blank (recommended usage), then all devices for the current state of the IF system will be balanced.

RECOMMENDED SYNTAX: **Balance**()

ADVANCED SYNTAX: **Balance(** 'DeviceName', {'DeviceKeyword':Value})

Parameter descriptions See Appendix E for details on the advanced use of Balance().

USAGE: Without any arguments, the**Balance()** command uses the last executed configuration to decide what hardware will be balanced. Strategies for balancing the hardware in the GBT IF system are discussed in § 6.3. The following script gives a simple example showing the expected use of **Balance()**:

```
execfile('/home/astro-util/projects/GBTog/configs/tp_config.py')
Configure(tp_config) #Execute the desired configuration
Slew('3C286')  #Slew so that you may balance 'on-source'
Balance() #Balance the IF and devices for your configuration
```

Script 5.40: Balance() example.

5.4.1.10 BalanceOnOff

When there is a large difference in power received by the GBT between two positions on the sky, it is advantageous to balance the IF system power levels to be at the mid-point of the two power levels. Typically this is needed when the "source position" is a strong continuum source. This scan type has been created to handle this scenario; one should consider using it when the system temperature on and off source differ by a factor of two or more.

BalanceOnOff() slews to the source position and then balances the IF system. It then determines the power levels that are observed in the IF Rack. Then the telescope is slewed to the off position and the power levels are determined again. The change in the power levels is then used to determine attenuator settings that put the balance near the mid-point of the observed power range. Note that the balance is determined only to within ±0.5 dB owing to the integer settings of the IF Rack attenuators.

SYNTAX: BalanceOnOff(location, offset, beamName**)**

location A Catalog source name or Location object. It specifies the source to which the telescope should slew. The default is the current location in "J2000" coordinate mode.

offset An Offset object. It moves the beam to an optional offset position that is specified relative to the location specified in the location parameter value. The default is None. See § 5.6 for information on Offset objects.

beamName A string. It specifies the receiver beam to use for the scan. beamName can be 'C', '1', '2', '3', '4' or any valid combination for the receiver you are using such as 'MR12'. The default is '1'.

USAGE: The following example balances on 3C 48 and remeasures 1° off:

```
execfile('/home/astro-util/projects/GBTog/configs/tp_config.py')
Configure(tp_config) #Execute the desired configuration
BalanceOnOff('3C48', Offset('J2000', 1.0, 0.0))
```

Script 5.41: BalanceOnOff() example.

5.4.2 Observing Scans

Observing scan types will aquire scientific datasets by performing one or more scans at specific locations on the sky. Available GBT observing scans are listed in Table 5.4 and are described in the following section.

5.4.2.1 Track

The Track scan type follows a sky location while taking data.

SYNTAX:
Track(location, endOffset, scanDuration, beamName, startTime, stopTime, fixedOffset **)**

location A Catalog source name or Location object. It specifies the source which is to be tracked.

endOffset An Offset object (see § 5.6 for information on Offset objects).
Supplying an endOffset object with a value other than **None** will track the telescope across the sky at constant velocity. The scan will start at the specified **location** and end at **(location+endOffset)** after **scanDuration** seconds. If you wish to only track a single location rather than slew the telescope between two points, use **None** for this parameter.

scanDuration A float. This specifies the length of the scan in seconds.

Table 5.4: Observing Scan Types available for the GBT.

Scan Type	Observing Type	Description
Track	Continuum, Line, Pulsar	Takes data at a single position or while moving with constant velocity.
OnOff	Continuum, Line	Observe a source and then a reference position.
OffOn	Continuum, Line	Observe a reference position and then a source.
OnOffSameHA	Continuum, Line	Observe a source and then a reference position using the same hour angle as the source observations.
Nod	Continuum, Line	Observe a source with one beam and then with another beam.
SubBeamNod	Continuum, Line	Moves the subreflector alternately between two beams.

beamName A string. It specifies the receiver beam to use for the scan. beamName can be 'C', '1', '2', '3', '4' or any valid combination for the receiver you are using such as 'MR12'. The default value for beamName is '1'.

startTime A time object. This specifies when the scan begins in Universal Time (UT). If **startTime** is in the past then the scan starts as soon as possible with a message sent to the scan log. If **(startTime+scanDuration)** is in the past, then the scan is skipped with a message to the observation log. The value may be:

- **A time object** Note, if startTime is more than ten minutes in the future then a message is sent to the observation log. See § 5.6 for information on time objects.
- **A Horizon object** The following script implicitly calculates the **startTime** using Horizon():

```
Track('VirgoA', None, 120.0, startTime=Horizon())
```

Script 5.42: Track() example using startTime=Horizon(). If the source never rises then the scan is skipped and if the source never sets then the scan is started immediately. In either case a message is sent to the observation log. See § 5.6 for information on Horizon objects.

stopTime A time object (see § 5.6 for information on time objects). This specifies when the scan completes. If **stopTime** is in the past then the scan is skipped with a message to the observation log. The value may also be:

- **A Horizon Object** When a Horizon object is used, the stop time is implicitly computed. The following lines in an SB would track VirgoA from rise to set using a horizon of 20°:

```
horizon = Horizon(20.0)
Track('VirgoA', None, 120.0, startTime=horizon, stopTime=horizon)
```

Script 5.43: Track() example using a Horizon object in startTime and stopTime. If the source never sets, then the scan stop time is set to 12 hours from the current time. See § 5.6 for information on Horizon objects.

fixedOffset An Offset object (see § 5.6 for information on Offset objects). **Track** follows the sky location plus this fixed Offset. The **fixedOffset** may be in a different coordinate mode than the **location**. If an **endOffset** is also specified, **Track** starts at **(location+fixedOffset)**, and ends at **(location+fixedOffset+endOffset)**. The **fixedOffset** and **endOffset** must be both of the same coordinate mode, but may be of a different mode than the **location**. The **fixedOffset** parameter may be omitted.

USAGE: location and **endOffset** are required parameters. Scan timing must be specified by either a scanDuration, a stopTime, a startTime plus stopTime, or a startTime plus scanDuration. Examples of **Track** are shown in Script 5.44:

```
#Example 1 - track 3C48 for 60 seconds using the center beam
Track('3C48', None, 60.0)

#Example 2 - track a position offset by 1 degree in elevation
Track('3C48', None, 60.0, fixedOffset=Offset('AzEl', 0.0, 1.0) )

#Example 3 - scan across the source from -1 to +1 degrees in azimuth
Track('3C48', Offset('AzEl', 2.0, 0.0), 60.0,
  fixedOffset=Offset('AzEl',-1.0, 0.0))
```

Script 5.44: Examples of the Track() scan function.

5.4.2.2 OnOff

The **OnOff** scan type performs two scans. The first scan is on source, and the second scan is at an offset from the source location used in the first scan.

SYNTAX: OnOff(location, referenceOffset, scanDuration, beamName **)**

location A Catalog source name or Location object. It specifies the source upon which to do the "On" scan.

referenceOffset An Offset object. It specifies the location of the "Off" scan relative to the location specified by the first parameter.

scanDuration A float. It specifies the length of each scan in seconds.

beamName A string. It specifies the receiver beam to use. The default value for beamName is '1'.

USAGE: The following example does an **OnOff** scan with reference offsets of 1 degree of arc in Right Ascension and 1 degree of arc in Declination and a 60 second scan duration (120 seconds total), using beam 1:

```
OnOff('0137+3309', Offset('J2000', 1.0, 1.0, cosv=False), 60, '1')
```

Script 5.45: OnOff() example.

5.4.2.3 OffOn

The **OffOn** scan type is the same as the **OnOff** scan except that the first scan is offset from the source location.

SYNTAX: OffOn(location, referenceOffset, scanDuration, beamName **)**

Parameter descriptions: See **OnOff**

USAGE: The following example does an **OffOn** scan with reference offsets of 1 degree of arc in Right Ascension and 1 degree of arc in Declination and a 60 second scan duration (120 seconds total), using beam 1:

```
OffOn('0137+3309', Offset('J2000', 1.0, 1.0, cosv=False), 60, '1')
```

Script 5.46: OffOn() example.

5.4.2.4 OnOffSameHA

The OnOffSameHA scan type performs two scans. The first scan is on the source, and the second scan follows the same HA track used in the first scan.

SYNTAX: OnOffSameHA(location, scanDuration, beamName **)**

location A Catalog source name or Location object. It specifies the source upon which to do the On scan.

beamName A string. It specifies the receiver beam to use for both scans. The default value for beamName is '1'.

scanDuration A float. It specifies the length of each scan in seconds.

USAGE: The following example does an **OnOffSameHA** scan with a 60 second scan duration (120 seconds total), using beam 1:

```
OnOffSameHA('0137+3309', 60, '1')
```

Script 5.47: OnOffSameHA() example.

5.4.2.5 Nod

The Nod procedure does two scans on the same sky location with different beams. **Nod should only be used with multi-beam receivers.**

SYNTAX: Nod(location, beamName1, beamName2, scanDuration **)**

location A Catalog source name or Location object. It specifies the source upon which to do the Nod.

beamName1 A string. It specifies the receiver beam to use for the first scan. beamName1 can be '1', '2' or any valid beam for the receiver you are using.

beamName2 A string. It specifies the receiver beam to use for the second scan. beamName2 can be '1', '2' or any valid beam for the receiver you are using.

scanDuration A float. It specifies the length of each scan in seconds.

USAGE: The following example does a **Nod** between beams 3 and 7 of the KFPA receiver with a 60 second scan duration (120 seconds total).

```
Nod('1011-2610', '3', '7', 60.0)
```

Script 5.48: Nod() example.

5.4.2.6 SubBeamNod

For multi-beam receivers**SubBeamNod** causes the subreflector to tilt about its axis between two feeds at the given periodicity. The primary mirror is centered on the midpoint between the two beams. The beam selections are extracted from the scan's beamName, i.e., 'MR12'. The "first" beam ('1') performs the first integration. The periodicity is specified in seconds (float) per nod (half-cycle). A subBeamNod is limited to a minimum of 4.483 seconds for a half cycle.

SYNTAX: SubBeamNod(location, scanDuration, beamName, beam1, beam2, nodLength, nodUnit **)**

location A Catalog source name or Location object. It specifies the source upon which to do the nod.

scanDuration A float. It specifies the length of each subscan in seconds.

beamName A string. It specifies the receiver beam pair to use for nodding. beamName can be e.g. 'MR12'. Either beamName or beam1 and beam2 need to be specified.

beam1 A string. It specifies the first receiver beam to use for nodding. Beam1 and beam2 have to be on the same elevation.

beam2 A string. It specifies the second receiver beam to use for nodding. Beam1 and beam2 have to be on the same elevation.

nodLength Type depends on value of **nodUnit**: integer for 'integrations', and float or integer for 'seconds'. It specifies the half-cycle time which is the time spent in one position plus move time to the second position.

nodUnit A string, either 'integrations' or 'seconds'. The default is 'seconds'.

USAGE: The following examples both do a **SubBeamNod** between beams 1 and 2. The first uses the default 'seconds' **nodUnit** and the second sets the **nodLength** in units of the primary backend's integration time (see **tint** in § 5.2.5).

```
#Example 1 - nodLength units in seconds (default)
SubBeamNod('3C48', scanDuration=60.0, beamName='MR12',
           nodLength=4.4826624)

#Example 2 - nodLength units are "tint" as set in the configuration
SubBeamNod('3C48', scanDuration=60.0, beamName='MR12',
           nodLength=3, nodUnit='integrations')
```

Script 5.49: SubBeamNod() example.

The scan will end at the end of the scanDuration (once the current integration is complete) regardless of the phase of the nod cycle. When the subreflector is moving the entire integration during which this occurs is flagged. It takes about 0.5 seconds for the subreflector to move between beams plus additional time to settle on source (total time is about ~ 1.5 second).

For example, if we had previously configured for Rcvr26_40 and an integration time of 1.5 seconds (tint=1.5 in the configuration), example 2 in script 5.49 would blank roughly one out of every three integrations in a half-cycle (nodLength=3) while the subreflector was moving between beams. If nodLength=5, then only one in five integrations would be blanked. A resonable compromise in terms of performance and to minimize the amount of data blanked is to use subBeamNod with an integration time of 0.2 s and a nodLength=30 (6 sec nodding between beams). It is important to use a small tint value to avoid blanking too much data (e.g., 0.5 sec or less).

The subBeamNod mode is useful to produce good baselines for the measurement of broad extragalactic lines. For Ka-band, Q-band, and Argus, the performance of subBeamNod is signficantly better than Nod observations. For W-band and the KFPA, the beams are farther apart and the subBeamNod technique does not work as well, and users are recommended to use Nod observations.

The antenna uses the average position of the two beams for tracking the target, and SDFITS reports the positions of the beams relative to the tracking position. Although the SDFITS header postion will not match the target position, **SubBeamNod** successfully nods between the two beams during the scan. Control of the subreflector may be done with any scan type using the submotion class. This should only be done by expert observers. Those observers interested in using this class should contact their GBT "Friend".

5.4.3 Mapping Scans

Mapping scan types will record data over specified areas of the sky. The GBT mapping procedures are described in the following section and listed in table 5.5.

- **On-The-Fly (OTF) mapping**: Data are recorded while the telescope slews across a region of the sky using a specified trajectory (also known as raster scanning). OTF mapping is described in Mangum, Emerson, and Greisen (2007, A&A 474, 679). This is more efficient than point mapping, and may also minimize changes in the system and atmosphere by slewing rapidly across the sky.
- **Point mapping**: A region of the sky is divided into a grid of discrete positions. Data will then be recorded at each of these locations for a specified amount of time. This method is more simple than OTF mapping and may be suitable when data are required for a few specific locations.

Most GBT mapping procedures have versions that allow for periodic reference observations. These may be used to correct for the instrumental bandpass shape in total power observations during data

Table 5.5: Mapping Scan Types available for the GBT.

Scan Type	Observing Type	Description
RALongMap	Continuum, Line	Make an OTF raster map by moving along the major axis of the coordinate system.
RALongMapWithReference	Continuum, Line	Make an OTF raster map by moving along the major axis of the coordinate system and making periodic reference observations.
DecLatMap	Continuum, Line	Make an OTF raster map by moving along the minor axis of the coordinate system.
DecLatMapWithReference	Continuum, Line	Make an OTF raster map by moving along the minor axis of the coordinate system and making periodic reference observations.
PointMap	Continuum, Line, Pulsar	Make a map using individual pointings.
PointMapWithReference	Continuum, Line, Pulsar	Make a map using individual pointings with periodic reference observations.
Daisy	Continuum, Line	Make an OTF map in the form of daisy petals.

reduction. For OTF mapping, some observers may prefer to use the edge pixels of the map as a reference position if they are suitably "off-source".

The GBT mapping calculator is a useful tool for planning mapping observations. It may be used to provide AstrID commands and parameters for many of the mapping scan types. The mapping calculator can be found at http://www.gb.nrao.edu/ rmaddale/GBT/GBTMappingCalculator.html. An important restriction on mapping with the GBT is that the raster scan legs or petal lengths should be at least 30 s so that the telescope only turns around a maximum of twice per minute (to minimize the stresses on the telescope).

5.4.3.1 RALongMap

A Right Ascension/Longitude (RALong) map performs an OTF raster scan centered on a sky location. Scans are performed along the major axis of the selected coordinate system. One can map in a variety of corrdinate systems, including J2000, Galactic, and AzEl. The selected coordinate system is defined by the coordinateMode keyword for the Offset object (5.6.2). The starting point of the map is defined as (-hLength/2, -vLength/2) from the specified center location.

SYNTAX: RALongMap(location, hLength, vLength, vDelta, scanDuration, beamName, unidirectional, start, stop **)**

location A Catalog source name or Location object. It specifies the center of the map.

hLength An Offset object. It specifies the horizontal width of the map (i.e., the extent in the longitude-like direction). **hLength** values may be negative.

vLength An Offset object. It specifies the vertical height of the map (i.e., the extent in the latitude-like direction). **vLength** values may be negative.

vDelta An Offset object. It specifies the distance between map rows. **vDelta** values must be positive.

scanDuration A float. It specifies the length of each scan in seconds.

- **Note**: Observers should limit **scanDuration** so that no more than 2 scans (or accelerations) are performed per minute. Overhead is ∼20 seconds per scan.

beamName A string. It specifies the receiver beam to use for the scan. beamName can be 'C', '1', '2', '3', '4' or any valid combination for the receiver you are using such as 'MR12'. Default is '1'.

unidirectional A Boolean. It specifies whether the map is unidirectional (True) or boustrophedonic[2] (False). Default is False.

start An integer. It specifies the starting row for the map. The default value for start is 1. This is useful for doing parts of a map at different times. For example, if map has 42 rows, one can do rows 1-12 by setting "start=1, stop=12", and later finishing the map using "start=13, stop=42".

stop An integer. It specifies the stopping row for the map. The default value for stop is None, which means "go to the end".

USAGE:
Script 5.50 produces a map with 41 rows each 120' long, using a row spacing of 3' and scan rate of 20'/min with beam 1 (default). A plot showing the actual trajectory of the antenna on the sky when script 5.50 was executed is shown in figure 5.3. Note that the blue dots in figure 5.3 mark timestamps of the data sampled along the trajectory.

Observers should ensure that they are sampling sufficiently in the scanning direction when using OTF mapping. In this example data were recorded every 5 seconds (tint=5.0 in the configuration). This results in one sample every 1.67' in the scanning direction using the above scan rate of 20'/min. This is suitable for observations at 1420 MHz, where the FWHM of the beam is 8.8'.

```
RALongMap('NGC4258',                              # center of the map
     Offset('J2000', 2.0, 0.0,cosv=True),   # 120' width
     Offset('J2000', 0.0, 2.0,cosv=True),   # 120' height
     Offset('J2000', 0.0, 0.05,cosv=True), #   3' row spacing
     360.0)                                     # 6 minutes per row
```

Script 5.50: RALongMap() example.

5.4.3.2 RALongMapWithReference

RALongMap with periodic reference observations.

SYNTAX: **RALongMapWithReference**(location, hLength, vLength, vDelta, referenceOffset, referenceInterval, scanDuration, beamName, unidirectional, start, stop)

Parameter Descriptions See **RALongMap**. The following additional parameters are used to define the periodic reference observations:

- **referenceOffset**: An Offset object. It specifies the position of the reference source on the sky relative to the **Location** specified by the first input parameter.
- **referenceInterval**: An integer. It specifies when to do a reference scan in terms of map rows. For example, setting referenceInterval=4 will periodically perform one scan on the reference source followed by 4 mapping scans.

USAGE: Script 5.51 produces a map with 120' long and 60' wide, using a row spacing of 3' and scan rate of 4'/s. A reference position will be observed once before every 3 rows. The sequence of scans will be: reference → rows 1-3 → reference → rows 4-6...

```
RALongMapWithReference('CygA',              # center of map
   Offset('J2000', 2.0, 0.0, cosv=True),   # 120' length
   Offset('J2000', 0.0, 1.0, cosv=True),   #  60' height
   Offset('J2000', 0.0, 0.05, cosv=True),  #   3' row spacing
   Offset('J2000', 2.0, 0.0, cosv=True),   # 2 degree ref offset in RA
   3, 30.0)               # ref before every 3 rows, 30 second scan duration
```

Script 5.51: RALongMapWithReference() example.

[2] from the Greek meaning "as the ox plows" i.e. back and forth

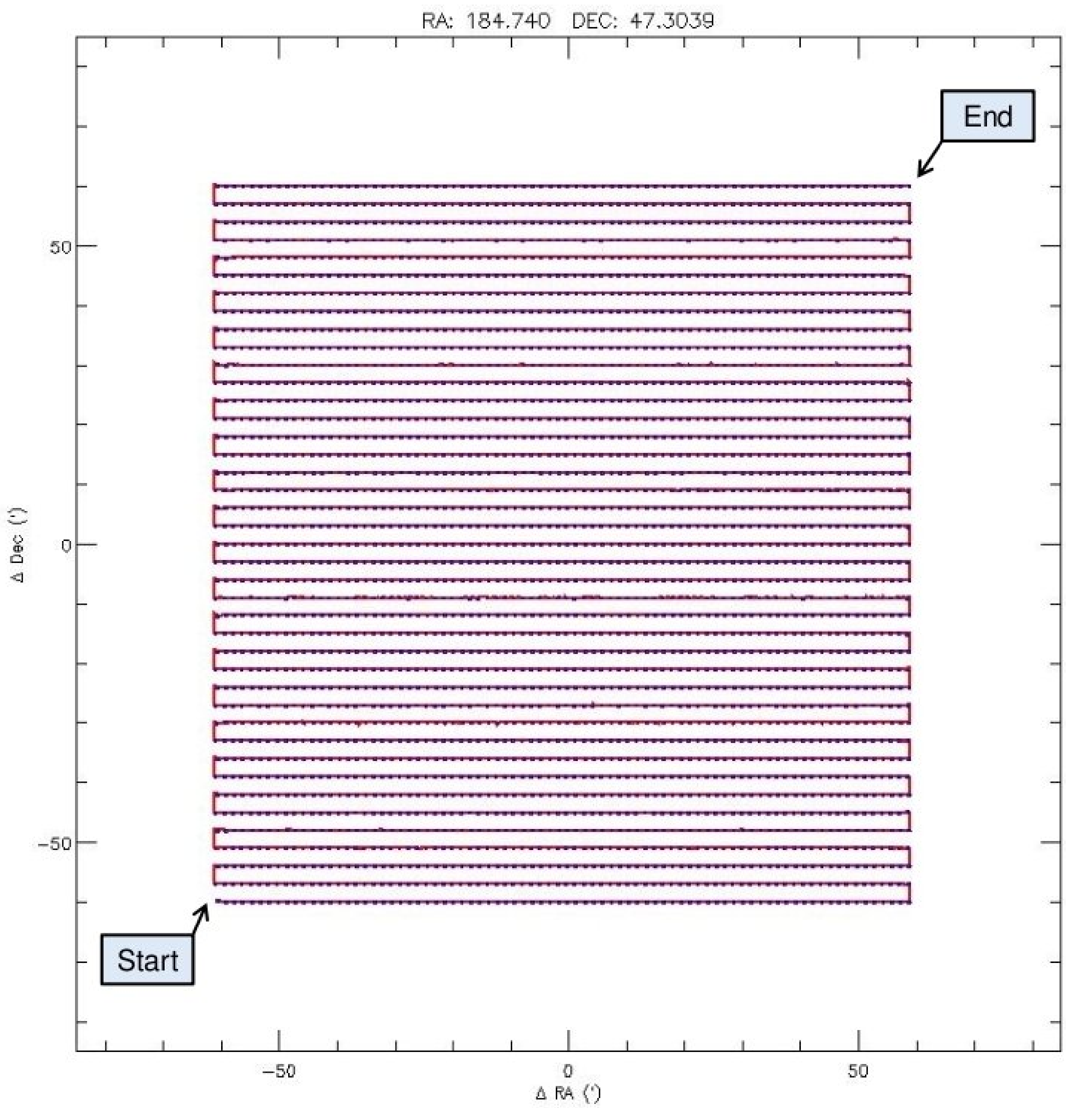


Figure 5.3: The actual GBT antenna trajectory (red) generated by executing script 5.50. Blue dots mark timestamps of sampled data. (sampling frequency is set via **tint** in the configuration). Please note, the RA axis is inverted.

5.4.3.3 DecLatMap

A Declination/Latitude map performs an OTF raster scan centered on a sky location. Scans are performed in declination, latitude, or elevation coordinates depending on the desired coordinate system. The starting point of the map is defined as (-hLength/2, -vLength/2) from the specified center location.

SYNTAX: **DecLatMap**(location, hLength, vLength, hDelta, scanDuration, beamName, unidirectional, start, stop)

Parameter Descriptions See **RALongMap** with the following difference:

- **hDelta**: An Offset object. Similar to **vDelta** in **RALongMap**. It specifies the horizontal distance between map columns. **hDelta** values must be positive.

USAGE: Script 5.52 produces a map with 41 columns each 120' tall, using a column spacing of 3' and scan rate of 20'/min with beam 1 (default). A plot showing the actual trajectory of the antenna on the sky when script 5.52 was executed is shown in figure 5.4. Note that the blue dots in figure 5.4 mark timestamps of the data sampled along the trajectory.

```
DecLatMap('NGC4258',                           # center of the map
     Offset('J2000', 2.0, 0.0,cosv=True),   # 120' width
     Offset('J2000', 0.0, 2.0,cosv=True),   # 120' height
     Offset('J2000', 0.05,0.0,cosv=True),   #   3' column spacing
     360.0)                                 # 6 minutes per column
```

Script 5.52: DecLatMap() example.

5.4.3.4 DecLatMapWithReference

DecLatMap with periodic reference observations.

SYNTAX: **DecLatMapWithReference**(location, hLength, vLength, hDelta, referenceOffset, referenceInterval, scanDuration, beamName, unidirectional, start, stop)

Parameter Descriptions See **RALongMap** with the following difference:

- **hDelta**: An Offset object. Similar to **vDelta** in **RALongMap**. It specifies the horizontal distance between map columns. **hDelta** values must be positive.

The following parameters are used to define the periodic reference observations:

- **referenceOffset** An Offset object. It specifies the position of the reference source on the sky relative to the **Location** specified by the first input parameter.
- **referenceInterval** An integer. It specifies when to do a reference scan in terms of map columns. For example, setting referenceInterval=4 will periodically perform one scan on the reference source followed by 4 mapping scans.

USAGE: Script 5.53 produces a map 120' long and 60' wide using a column spacing of 3' and scan rate of 4'/min. A reference position will be observed once before every 3 columns. The sequence of scans will be: reference → columns 1-3 → reference → columns 4-6...

```
DecLatMapWithReference('CygA',             # center of map
   Offset('J2000', 1.0, 0.0, cosv=True),   #   60' width
   Offset('J2000', 0.0, 2.0, cosv=True),   #  120' length
   Offset('J2000', 0.05, 0., cosv=True),   #    3' column spacing
   Offset('J2000', 2.0, 0.0, cosv=True),   # 2 degree ref offset in RA
   3, 30.0)          # ref before every 3 columns, 30 second scan duration
```

Script 5.53: DecLatMapWithReference() example.

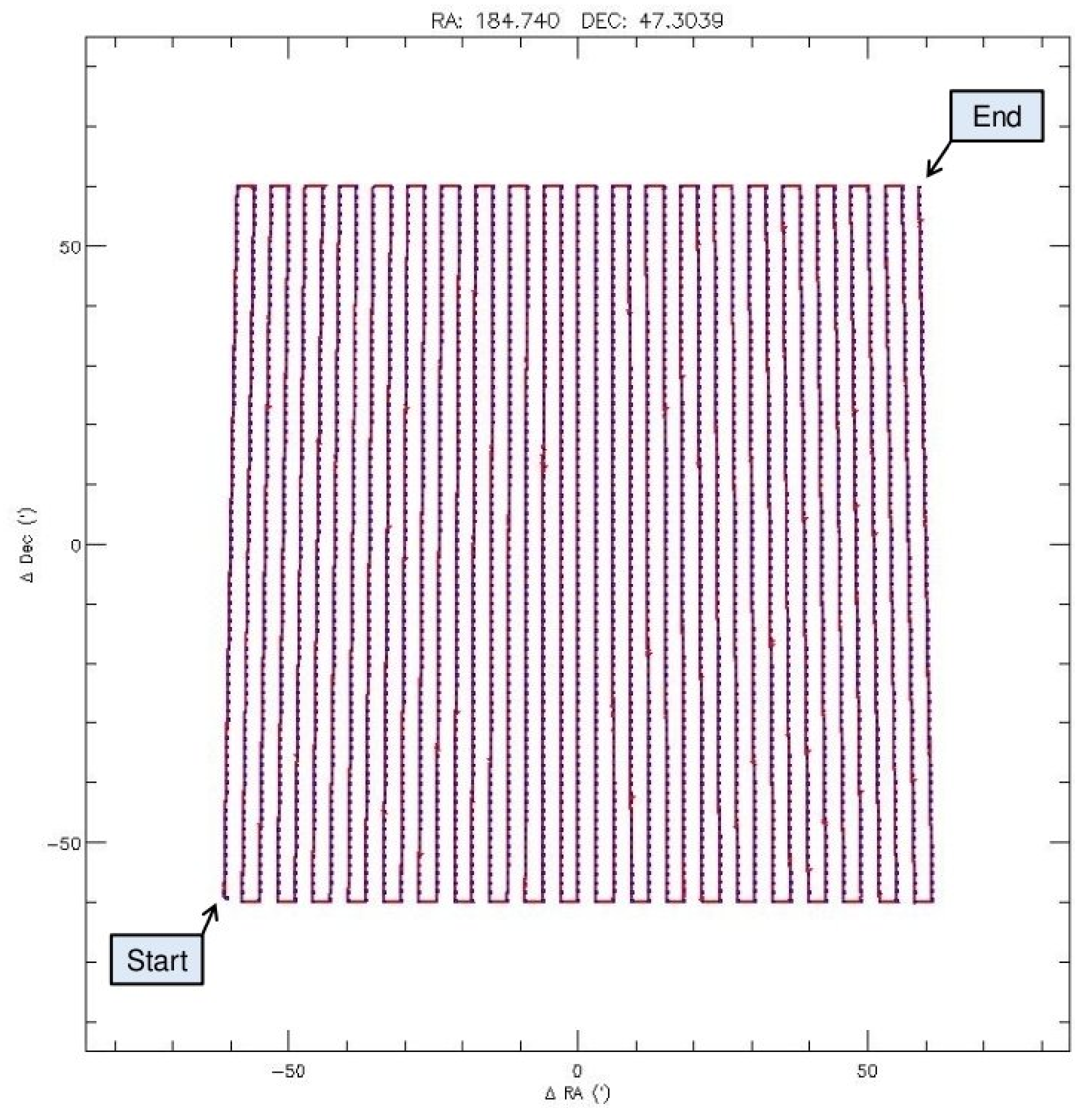


Figure 5.4: The actual GBT antenna trajectory (red) generated by executing script 5.52. Blue dots mark timestamps of sampled data. (sampling frequency is set via **tint** in the configuration). Please note, the RA axis is inverted.

5.4.3.5 PointMap

A PointMap() constructs a map by sitting on fixed positions laid out on a grid. The starting point of the map is defined as (-**hlength**/2,-**vLength**/2).

SYNTAX:
PointMap(location, hLength, vLength, hDelta, vDelta, scanDuration, beamName, start, stop **)**

location A Catalog source name or Location object. It specifies the center of the map.

hLength An Offset object. It specifies the horizontal width of the map. **hLength** values may be negative.

vLength An Offset object. It specifies the vertical height of the map. **vLength** values may be negative.

hDelta An Offset object. It specifies the horizontal distance between points in the map. **hDelta** values must be positive.

vDelta An Offset object. It specifies the vertical distance between points in the map. **vDelta** values must be positive.

scanDuration A float. It specifies the length of each scan in seconds.

beamName A string. It specifies the receiver beam to use for the scan. **beamName** can be 'C', '1', '2', '3', '4' or any valid combination for the receiver you are using such as 'MR12'. Default is '1'.

start An integer. It specifies the starting point for the map. The default value for **start** is 1. Note in **PointMap** this counts points, not stripes.

stop An integer. It specifies the stopping point for the map. The default value for **stop** is None, which means "go to the end".

USAGE: Script 5.54 produces a 9 point map using a 3×3 grid. Points are separated by 10 arc-seconds in RA and 10 arc-seconds in Dec. Each point will be observed for 30 seconds using beam 1 (default). A plot showing the actual trajectory of the antenna on the sky when script 5.54 was executed is shown in figure 5.5. Note that the black crosses mark the average positions of sampled data at each point.

```
PointMap('W75N',                                   # center of map
  Offset('J2000', 20.0/3600.0, 0.00, cosv=True), # 20" width
  Offset('J2000', 0.00, 20.0/3600.0, cosv=True), # 20" height
  Offset('J2000', 10.0/3600.0, 0.00, cosv=True), # 10" horizontal spacing
  Offset('J2000', 0.00, 10.0/3600.0, cosv=True), # 10" vertical spacing
     30.0)                                         # 30 second scan length
```

Script 5.54: PointMap() example.

5.4.3.6 PointMapWithReference

PointMap with periodic reference observations.

SYNTAX: **PointMapWithReference(** location, hLength, vLength, hDelta, vDelta, referenceOffset, referenceInterval, scanDuration, beamName, start, stop **)**

Parameter Descriptions See **PointMap**. The following additional parameters are used to define the periodic reference observations:

- **referenceOffset**: An Offset object. It specifies the position of the reference source on the sky relative to the **Location** specified by the first input parameter.

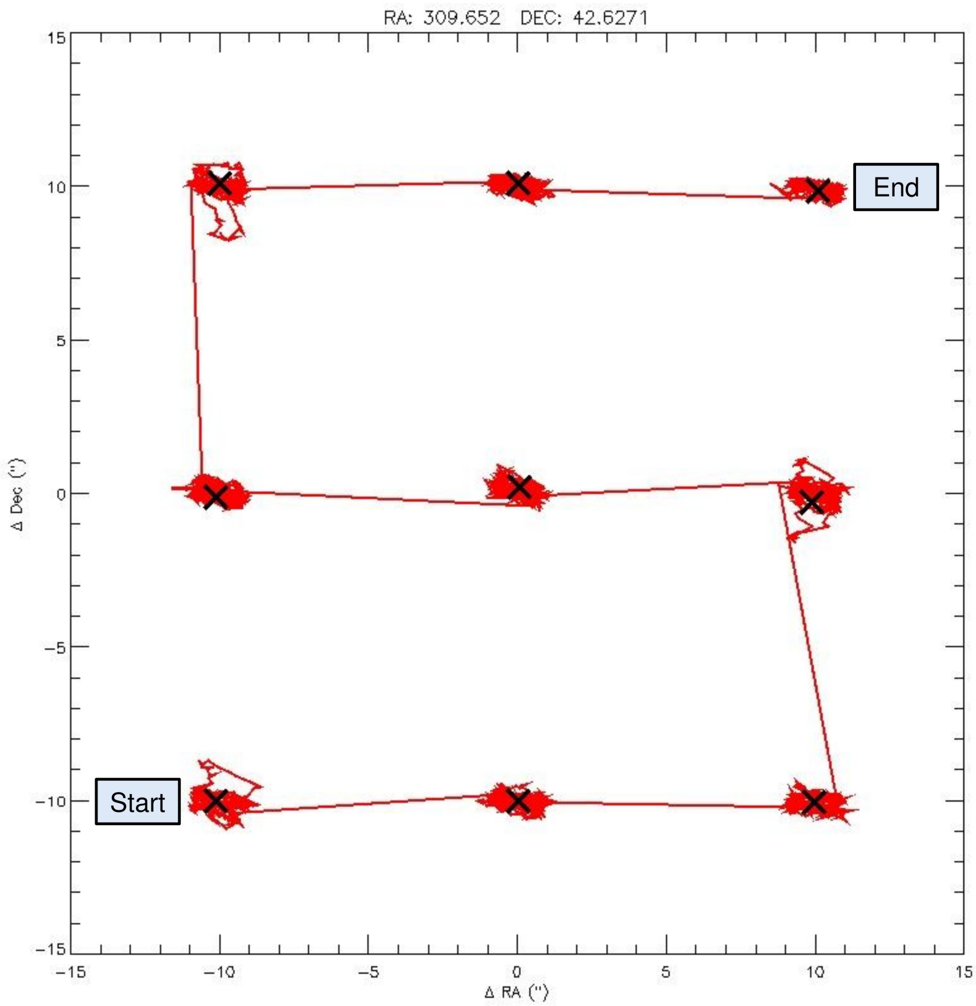


Figure 5.5: A plot of the actual GBT antenna trajectory (red) generated by executing script 5.54. The average positions of data sampled at each point are marked with black crosses. Please note, the RA axis is inverted.

- **referenceInterval**: An integer. It specifies when to do a reference scan in terms of map points. For example, setting referenceInterval=4 will periodically perform one scan on the reference source followed by 4 pointed scans.

USAGE: Script 5.55 produces a 4×4 point map using beam 1 (default). A reference position will be observed before every 2 points. The sequence of scans will be: reference(r) $\rightarrow$ points 1 and 2 ($P_{1,2}$)$\rightarrow r \rightarrow P_{3,4} \rightarrow r \rightarrow P_{5,6} \rightarrow r \rightarrow P_{7,8} \rightarrow r \rightarrow P_{9,10} \rightarrow r \rightarrow P_{11,12} \rightarrow r \rightarrow P_{13,14} \rightarrow r \rightarrow P_{15,16}$.

```
PointMapWithReference('2023+2223',       # center of map
   Offset('B1950', 1.5, 0.0, cosv=True), # 90' width
   Offset('B1950', 0.0, 1.5, cosv=True), # 90' height
   Offset('B1950', 0.5, 0.0, cosv=True), # 30' horizontal step spacing
   Offset('B1950', 0.0, 5.0, cosv=True), # 30' vertical step spacing
   Offset('J2000', 3.0, 0.0, cosv=True), # 3 degree ref offset in RA
   2, 2.0)            # ref before every 2 points, 2 second scan duration
```

Script 5.55: PointMapWithReference() example.

5.4.3.7 Daisy

The Daisy scan type performs an OTF scan around a central point in the form of daisy petals. It is a useful observing mode for focal plane arrays, allowing more integration time in the central field of view.

The **Daisy** scan will produce an approximately closed circular pattern on the sky after 22 radial oscillation periods (see figure 5.6b). For beam-sizes of 20″ FWHM or so, the circular area mapped will be fully sampled if the map radius is less than 6′. It is not an especially useful observing mode for general-purpose single-beam mapping, since the largest "hole" in the map is $\sim 0.3\times$ the map radius.

Trajectories are generated according to:

$$\Delta\hat{x}(t) = \frac{r_0 \sin(2\pi t/\tau + \phi_1)\cos(2t/\tau + \phi_2)}{\cos(\hat{y}_0)} \tag{5.4}$$

$$\Delta\hat{y}(t) = r_0 \sin(2\pi t/\tau + \phi_1)\sin(2t/\tau + \phi_2) \tag{5.5}$$

$\hat{x}$ and $\hat{y}$ are then major and minor coordinates of a sperical coordinate system, t is the time, r_0 is the map radius, τ is the radial oscillation period, ϕ_1 and ϕ_2 are the radial and rotational phases, and $\hat{y}_0$ is the minor coordinate of the map center.

SYNTAX: Daisy(location, map_radius, radial_osc_period, radial_phase, rotation_phase, scanDuration, beamName, cos_v, coordMode, calc_dt **)**

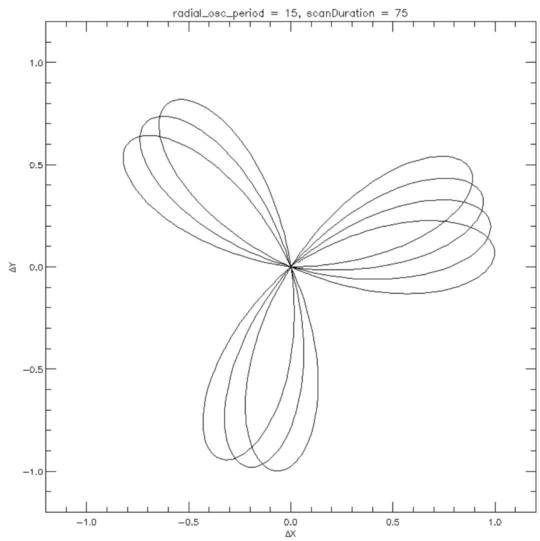
location A Catalog source name or Location object. It specifies the center of the map.

map_radius r_0 in equations 5.4 and 5.5. A float which specifies the radius of the map's "daisy petals" in arc-minutes.

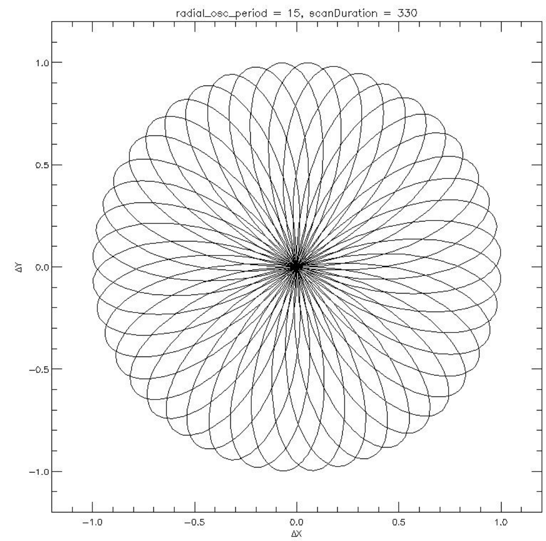
radial_osc_period τ in equations 5.4 and 5.5. A float which specifies the period of the radial oscillation in seconds.

–**Note:** not to be less than 15 sec $\times\sqrt{r_0/1.5'}$ for radii $> 1.5'$ and in no case under 15 seconds.

radial_phase ϕ_1 in equations 5.4 and 5.5. A float which specifies the radial phase in radians.



(a) Daisy scan with scanDuration = 5×radial_osc_period.



(b) Daisy scan with scanDuration = 22×radial_osc_period.

Figure 5.6: Figure 5.6a shows the Daisy trajectory after 5 radial oscillations. Figure 5.6b shows an approximately closed pattern after 22 radial oscillations

rotation_phase ϕ_2 in equations 5.4 and 5.5. A float which specifies the rotational phase in radians.

scanDuration A float. It specifies the length of the scan in seconds.

beamName A string. It specifies the receiver beam to use for both scans. **beamName** can be 'C', '1', '2', '3', '4' or any valid combination for the receiver you are using such as 'MR12'. The default value is '1'.

cos_v A Boolean. It specifies whether secant minor corrections (the $\cos(\hat{y}_0)$ term in equation 5.4) should be used for the major axis of the coordinate system. The default is True.

coordMode A string. It specifies the coordinate mode for the radius that generates the map. The default is 'AzEl'.

calc_dt A float. It specifies time sampling used by the control system to calculate a path. Values should be between 0.1 and 0.5. Calculating many points for a long daisy scan can significantly increase overhead at scan startup. The default is 0.1.

USAGE: It takes approximately 22 radial oscillation periods to complete a closed Daisy pattern. However, **radial_oscillation_period** is typically set to be in the range of 15–60 seconds depending on the radius being used. As an example, 22 ocillations of 20 seconds would take 440 seconds. If a long trajectory such as this is sent to the antenna manager, intrinsic inefficiencies in the array handling mechanism can significantly increase overhead at the start of a scan. Therefore one should try to keep individual scans to 5 minutes or less.

Script 5.56 will do 22 radial periods over 5 scans lasting 110 seconds each. The **rotation_phase** and **radial_phase** arguments are used so that each scan starts where the previous scan finished. This will produce the closed Daisy pattern shown in figure 5.7. The entire SB should take approximately 10 minutes to complete.

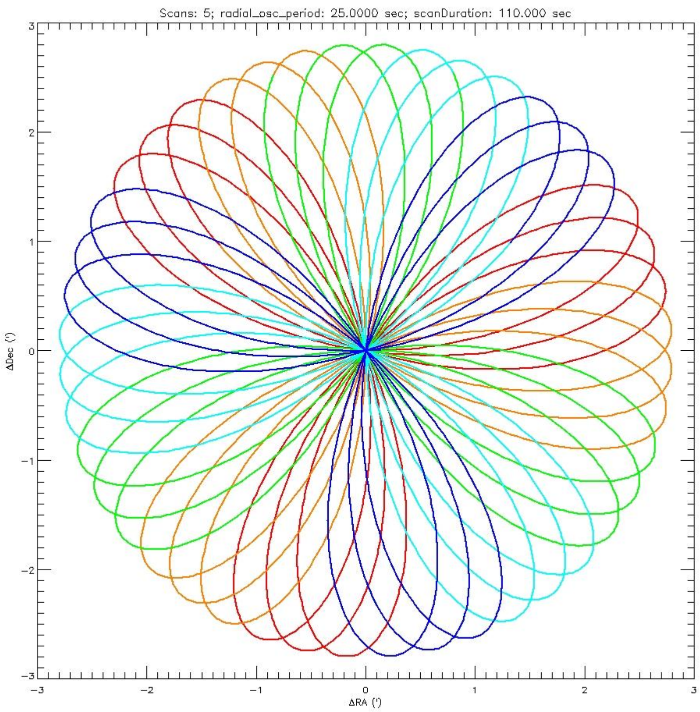


Figure 5.7: A plot of the GBT antenna trajectory executed with script 5.56. Each scan is plotted using a different color.

```
nosc              = 22.0 # 22 radial oscillations for closed Daisy pattern
map_radius        = 2.8  # arc-minutes
radial_osc_period = 25.0 # seconds
n_scans           = 5    # split 22 oscillations over 5 scans
scanDuration      = nosc * radial_osc_period / n_scans
phi2              = 2.0 * nosc / n_scans
phi1              = 3.14159265 * phi2
#NOTE - increment rotation_phase by phi2 each scan
#     - increment radial_phase by phi1 each scan
for i in range(n_scans):
  Daisy('3C123',map_radius,radial_osc_period,i*phi1,i*phi2,scanDuration,
        beamName='1',coordMode='J2000',cos_v=True,calc_dt=0.2)
```

Script 5.56: Daisy() example.

5.5 Utility Functions

Utility functions are used in SBs to control various aspects of the GBT other than data-taking scans. This includes such things as changing power levels, pausing the SB, or waiting for a source to rise. Please note that the syntax for all utility functions is case-sensitive. Advanced utility functions are found in Appendix D.

5.5.1 Annotation

The **Annotation()** function allows you to add any keyword and value to the GO FITS file. This could be useful if there is any information you would like to record about your observation for later data processing, or for record keeping. Note that the information in a FITS KEYWORD created via the **Annotation()** function will be ignored by the standard GBT data reduction package GBTIDL.

SYNTAX: **Annotation**(KEYWORD, Value)

KEYWORD A completely uppercase string of eight characters or less. Do not use any standard FITS keywords.

Value A string value for **KEYWORD**.

USAGE: An example use of the **Annotation()** function is if you wish to specify what type of source you are observing. Your sources might include H II regions and Planetary Nebulae for example. You could specify each type with

```
Annotation('SRCTYPE','HII')
Annotation('SRCTYPE','PNe')
```

Script 5.57: Annotation() example.

5.5.2 Break

The **Break()** function inserts a breakpoint into your SB and gives the observer the choice of continuing or terminating the SB. When a breakpoint is encountered during execution, your SB is paused and a pop-up window is created. The SB remains paused for a set amount of time or until you acknowledge the pop-up window and tell AstrID to continue running your script.

The **Break()** function can take two optional arguments, a message string and a timeout length. Why have a timeout? If an observer walks away from the control room during his or her observing session (e.g. to go to lunch or the bathroom) and a breakpoint is reached, it would be counterproductive to pause the observation indefinitely. This will help save valuable telescope time.

SYNTAX: **Break**(message, timeout)

message A string. Displayed in the pop-up dialog with a default of "Observation paused"

timeout A float. The number of seconds to get user-input before continuing the SB. If you wish for the timeout to last forever then use None. The default is 300 seconds, or 5 minutes.

USAGE:

```
Break('This will time out in 5 minutes, the default.')
Break('This will time out after 10 minutes.',600)
Break('This will never time out.', None)
```

Script 5.58: Break() example.

5.5.3 Comment

The **Comment()** function allows you to add a comment into the AstrID observing process which will be echoed to the observation log during the observation. What's the difference between this, and just writing comments with the pound (#) sign in your SB? When you use the pound sign to write your comments, they will not appear in the observation log when your SB is run. Using the **Comment()** function directs your comment to the output in the observation log.

SYNTAX: **Comment**(message)

message A string. Text to display during the observation.

USAGE:

```
# now slew to the source
Comment('Now slewing to 3C 286')
Slew('3C286')
```

Script 5.59: Comment() example.

5.5.4 GetUTC

SYNTAX: **GetUTC**()

Return Value: A float. The current UTC time in decimal hours since midnight.

WARNING: If AstrID is in "offline" mode, then **GetUTC()** will return a value of None. Attempting to validate Script 5.60 without checking the return value is not equal to None while "offline" will result in an infinite loop.

USAGE: The following example will repeatedly perform **Track** scans until the UTC time is past 12.0 hours.

```
while GetUTC() < 12.0 and GetUTC() != None:
    Track('0353+2234',None,600.)
```

Script 5.60: GetUTC() example.

5.5.5 GetLST

SYNTAX: **GetLST**()

Return Value: A float. The current Local Sidereal Time in decimal hours.

WARNING: If AstrID is in "offline" mode, then **GetLST()** will return a value of None. Attempting to validate Script 5.61 without checking the return value is not equal to None while "offline" will result in an infinite loop.

USAGE: The following example will repeatedly perform **Track** scans on the source "1153+1107" until the LST is past 13.5 hours when the source "1712+035" will be observed once.

```
while GetLST() < 13.5 and GetLST() != None:
    Track('1153+1107',None,600.)
Track('1712+036',None,600.)
```

Script 5.61: GetLST() example.

5.5.6 Now

SYNTAX: Now()

Return Value: A UTC time object (see § 5.6.4) containing the UTC time and date.

WARNING: If AstrID is in "offline" mode, then **Now()** will return a value of None. Attempting to validate Script 5.62 without checking the return value is not equal to None while "offline" will result in an infinite loop.

USAGE: The following example will repeatedly perform **Track** scans on the source "1153+1107" until 09:54:12 UTC on 12 June 2016.

```
while Now() < '2016-06-12 09:54:12' and Now() != None:
    Track('1153+1107',None,600.)
```

Script 5.62: Now() example.

5.5.7 WaitFor

WaitFor() pauses the SB until the specified time is reached. The expected wait time is printed in the observation log including a warning if the wait is longer than 10 minutes. **WaitFor()** will immediately return if the specified time has already passed and is within the last 30 minutes. While **WaitFor()** has the SB paused, it does not prevent the user from aborting. However if the user chooses to continue once the abort is detected, then the **WaitFor()** abandons the wait and returns immediately.

SYNTAX: **WaitFor(** Time_object **)**

Time_object A valid time object (see § 5.6.4).

- **Note:** If a value of None is used as an argument to **WaitFor()**, the SB will abort with a message to the observation log. This can occur when passing a value from Horizon().GetRise() or Horizon().GetSet() when such an event may never occur, such as the rise time for a circumpolar source.

USAGE: The following example will pause the SB until a Local Sidereal Time of 15:13, then wait for the source "1532_3421" to rise above 10° elevation, and finally wait for the Sun to set below 5° elevation.

```
#Wait for 15:13 LST
WaitFor('15:13:00 LST')

#Wait until source is above 10 deg elevation
WaitFor(Horizon(10.0).GetRise('1532+3421'))

#Wait for the Sun to set below 5 deg elevation
WaitFor(Horizon(5.0).GetSet('Sun'))
```

Script 5.63: WaitFor() example.

5.5.8 ChangeAttenuation

ChangeAttenuation() allows the observer to change all the attenuators in the IF Rack or the Converter Rack by the same amount.

SYNTAX: **ChangeAttenuation(** devicename, attnchange **)**

devicename A string that can be either 'IFRack' or 'ConverterRack'. This specifies the device in which the attenuators will be changed.

attnchange A float. This specifies how much the attenuators should be changed. This value can be either positive or negative.

- **Note:** if any new attenuator setting is less than zero or exceeds the maximum value, 31 for the IF Rack and 31.875 for the Converter Rack, then the attenuator setting is made to be the appropriate limiting value.

USAGE: The Following example adds 1 to the attenuation value in the IF rack and subtracts 0.5 from the attenuation value in the converter rack.

```
ChangeAttenuation('IFRack', 1.0)
ChangeAttenuation('ConverterRack',-0.5)
```

Script 5.64: ChangeAttenuation() example.

5.6 Scheduling Block Objects

Scheduling Block Objects are Python objects that are used to contain multiple pieces of information within a single variable. These are used with positions (requiring a major and minor axis value along with an epoch), times (requiring the date and the time of day), and for defining a horizon for the minimum elevation below which you would not want to observe.

5.6.1 Location Object

A Location object is used to represent a particular location on the sky.

SYNTAX: **Location(** coordinateMode, value1, value2 **)**

coordinateMode A string. The following modes are allowed: 'J2000', 'B1950', 'RaDecOfDate', 'HaDec', 'ApparentRaDec', 'Galactic', 'AzEl', and 'Encoder'

value1, value2 May be a float, or sexagesimal quoted as a string (i.e. 'hh:mm:ss.s'). A location must be specified by these two values, the meanings of which are dependent on the both the chosen coordinate mode and value type of each unit:

- **float values**: will always denote units in degrees of arc, regardless of the coordinate mode.
  - This should not be confused with decimal use in Catalogs (see § 5.3) which denote decimal hours for RA and HA, and degrees of arc for all other angles.
- **sexagesimal value1**: Represents units of time for J2000, B1950, ApparentRaDec, and RaDecOfDate and degrees of arc for HaDec, Galactic, AzEl and Encoder.
- **sexagesimal value2**: Represents degrees of arc.

USAGE:

```
# RA is in units of *time*, Dec is in degrees
location = Location('J2000', '16:30:00', '47:15:00')

# Same location - RA is in degrees, Dec is in degrees
location = Location('J2000', 247.5, 47.25)

# Az is in degrees, El is in degrees
location = Location('AzEl', '45:00:00', '72:30:00')
```

Script 5.65: Specifying Location Objects.

5.6.2 Offset Object

An Offset is a displacement from the position of a source or from the center position of a map. Offset objects may be added to other offset objects with the same coordinate mode and cosv correction. Offset objects may be added to Location objects with the same coordinate mode. **Note that such addition is not commutative and must be of the form** (**Location+Offset**). **Offset+Location** will produce a validation error.

SYNTAX: **Offset**(coordinateMode, value1, value2, cosv)

coordinateMode A string. The following modes are allowed: 'J2000', 'B1950', 'RaDecOfDate', 'HaDec', 'ApparentRaDec', 'Galactic', 'AzEl', and 'Encoder'

value1, value2 May be a float, or sexagesimal quoted as a string (i.e. 'hh:mm:ss.s'). An offset must be specified by these two values, the meanings of which are dependent on the both the chosen coordinate mode and value type of each unit:

- **float values**: will always denote units in degrees of arc, regardless of the coordinate mode.
  - This should not be confused with decimal use in Catalogs (see § 5.3) which denote decimal hours for RA and HA, and degrees of arc for all other angles.
- **sexagesimal value1**: Represents units of time for J2000, B1950, ApparentRaDec, and RaDecOfDate and degrees of arc for HaDec, Galactic, AzEl and Encoder.
- **sexagesimal value2**: Represents degrees of arc.

cosv A Boolean. It specifies whether secant minor corrections in equation 5.7 should be used for the major axis of the coordinate system (i.e. $h/\cos(v)$ is the offset value in the direction of h). The default is True. Since coordinate distances and angular separations are not equivalent for spherical coordinate systems, the following approximations may be used for small separations:

$$\Delta v = v_1 - v_2 \tag{5.6}$$

$$\Delta h = (h_1 - h_2) \cdot cos(v), \tag{5.7}$$

where h is the value of the major coordinate axis and v is the value of the minor coordinate axis. For example, setting cosv=True with J2000 coordinate offsets will apply a $\cos(Dec)$ term from equation 5.7 to make maps appear rectangular if plotted with ΔRA vs. ΔDec relative to a central location.

USAGE: Script 5.66 gives examples of adding Offset objects to Location and other Offset objects. The resulting coordinates are printed to screen.

```
start_location = Location('J2000','12:00:00','45:00:00')
offset1        =   Offset('J2000','00:04:00','01:00:00',cosv=False)
offset2        =   Offset('J2000', 2.0      , 2.0      ,cosv=False)
```

```
offset3        = offset1 + offset2

loc1 = start_location + offset1  #loc1 (RA,Dec) = (12:04:00, 45:00:00)
loc2 = start_location - offset2  #loc2 (RA,Dec) = (11:52:00, 43:00:00)
loc3 = start_location + offset3  #loc3 (RA,Dec) = (12:12:00, 48:00:00)
print 'RA,Dec of loc3 = (%s,%s)'%(loc3.GetH(),loc3.GetV())
```

Script 5.66: Adding Offset objects to Location objects and other Offset objects.

5.6.3 Horizon Object

Observing Scripts allow an observer to specify a definition of the horizon. The user defined horizon can be used to begin an observation when an object "rises" and/or end the observation when it "sets" relative to the specified elevation of the "horizon". The Horizon object may be used to obtain the initial time that a given source is above the specified horizon (including an approximate atmospheric refraction correction).

SYNTAX: **Horizon**(elevation)

FUNCTIONS: **Horizon**(elevation)**.GetRise**(location)
Horizon(elevation)**.GetSet**(location)

location A Catalog source name or Location object using a spherical coordinate mode. **Horizon**() will not work with planets and ephemeris tables.

elevation A float. The Horizon elevation in degrees. The default is 5.25 (the nominal GBT horizon limit).

Return Value: A UTC time object (see § 5.6.4) containing the UTC time and date.

- **GetRise**(source) will return the most recent rise time if the source is currently above the horizon, or the next rise time if the source has not yet risen. **GetRise**(source) will return **None** if the source never rises and the current time if the source never sets.
- **GetSet**(source) will return the next set time of the source. **GetSet**(source) will return **None** if the source never sets and the current time if the source never rises.

USAGE: Any Horizon object may be substituted as a start or stop time in scan types, such as **Track**(). Script 5.67 will display the time when VirgoA rises above 20° elevation. Depending on the position of the source at the time of execution, the SB would then either begin a **Track**() scan immediately or wait for VirgoA to rise above 5.25° elevation before beginning the scan. In both cases, the SB would terminate the next time VirgoA sets below 5.25° elevation.

```
print Horizon(20.0).GetRise('VirgoA')

h = Horizon() #default horizon of 5.25 degrees elevation
Track('VirgoA',None,startTime=h,stopTime=h)
```

Script 5.67: Using Horizon Objects.

5.6.4 Time Object

The Time Object is primarily used for defining scan start or stop times. The time may be represented as either a sexegesimal string or in a python mxDateTime object. You can learn more about mxDateTime at http://www.egenix.com/files/python/mxDateTime.html [3].

SYNTAX:

The Time Object can be expressed in either UTC or LST. The time can be either absolute or relative. An absolute or dated time specifies both the time of day and the date. An absolute time may be represented by either a sexagesimal string, i.e., "yyyy-mm-dd hh:mm:ss" or by a DateTime object. Relative or dateless times are specified by the time of day for "today". "WaitFor" will treat a dateless time that is more than 30 minutes in the past as being in the future, i.e., the next day. Relative times may be represented by either a sexagesimal string, i.e., "hh:mm:ss" or a DateTimeDelta object.

For UTC times, the sexagesimal representation may include a "UTC" suffix. Note that mxDateTime objects are always UTC. LST time may only be used with relative times and the sexagesimal representation must include a "LST" suffix.

Time Objects can have slightly varying formats and can be created in a few different ways. Some examples are:

"2006-03-22 15:34:10" Absolute time in UTC represented by a string.

DateTime.TimeDelta(12, 0, 0) Relative time in UTC as a mxDateTime object.

"2006/03/22 15:34:10 UTC" Absolute time in UTC represented by a string.

"22:15:48 LST" Relative time in LST as a string.

DateTime.DateTime(2006, 1, 21, 3, 45, 0) Absolute time in UTC as a mxDateTime object.

USAGE: In this example we will continue to do one minute observations of srcA until Feb 12, 2016 at 13:15 UTC when we will then do a ten minute observations of srcB.

```
from mx import DateTime

switchTime=DateTime.DateTime(2016,2,12,13,15,0) # Feb 12, 2016, 13:15 UTC

while Now() < switchTime and Now() != None:
    Track(srcA,None,60)

Track(srcB,None,600)
```

Script 5.68: Using Time Objects.

5.7 Example Scheduling Blocks

For the following SB examples we will use the configuration examples from § 5.2. All configurations, catalogs and scripts are available within the Green Bank computing environment at

`/home/astro-util/projects/GBTog/`

[3]Note, one must access the python DateTime module directly from an observation script to generate time objects, i.e., using mx import DateTime.

The following catalog (sources.cat) will be used for all examples:

```
# My source list with radial velocities
format=spherical
coordmode = B1950
head = name    ra          dec          velocity
Object1  09:56:16.98  +49:16:25.5  27.23
Object2  08:56:16.98  +48:16:25.5  28.24
Object3  07:56:16.98  +47:16:25.5  29.25
Object4  06:56:16.98  +45:16:25.5  30.26
```

Script 5.69: The `sources.cat` catalog used for the SB examples in this section.

5.7.1 Frequency Switched Observations Looping Through a List of Sources

In this example we perform frequency switched observations of the HI 21 cm line towards several different sources. This example is available as `/home/astro-util/projects/GBTog/SBs/example1.py`.

```
# Frequency Switched Observations where we loop through a list of sources

# first we load the configuration file
execfile('/home/astro-util/projects/GBTog/configs/fs_config.py')

# now we load the catalog file
c = Catalog('/home/astro-util/projects/GBTog/cats/sources.cat')

# now we configure the GBT IF system for frequency switch HI observations
Configure(fs_config)

# get the list of sources
sourcenames = c.keys()

# now loop the sources
for src in sourcenames:
    Slew(src)            # Slew to each source
    Balance()            # Balance power levels
    Track(src,None,600.) # Observe each source for 10 minutes
```

Script 5.70: SB Example 1 – Frequency switched observations looping through a list of sources.

5.7.2 Position-switched observations repeatedly observing the same source

In this example we perform position switched observations of a single source. We observe the source for two minutes and the off position for two minutes. This is repeated twenty times. This example is available as `/home/astro-util/projects/GBTog/SBs/example2.py`.

```
# Position Switched Observations to repeatedly observe the same source

# load the configuration file
execfile('/home/astro-util/projects/GBTog/configs/tp_config.py')

# load the catalog file
Catalog('/home/astro-util/projects/GBTog/cats/sources.cat')
```

```
# configure the GBT IF system for position switch HI observations
Configure(tp_config)

# specify which source we wish to observe
src = 'Object1'

# specify how far away from the source the off position should be
# offset two minutes of time in Right Ascension
myoff=Offset("J2000","00:02:00",0.0)

#Slew to the source and then balance the power levels
Slew(src)
Balance()
# now we use a Break() so that we can check the IF system
Break('Check the Balance of the IF system')

# specify how many times to observe the source
numobs = 20

# observe 'on' source for 2 minutes and 'off' source for 2 minutes
# and then repeat
for i in range(numobs):
    OnOff(src,myoff,120.)
```

Script 5.71: SB Example 2 – Position switched observations repeatedly observing the same source.

5.7.3 Position Switched Observations of Several Sources and Using the Horizon Object

In this example we perform position switched observations of three sources. We observe the first source until the second source rises above 20° elevation. Then we observe the second source until it goes below 20° elevation at which point we observe a third source.

This example is available as /home/astro-util/projects/GBTog/SBs/example3.py.

```
# Load the configuration file and the catalog file
execfile('/home/astro-util/projects/GBTog/configs/tp_config.py')
Catalog('/home/astro-util/projects/GBTog/cats/sources.cat')

# now we configure the GBT IF system for position switched observations
Configure(tp_config)

# define which sources to observe
srcA = 'Object4'
srcB = 'Object3'
srcC = 'Object1'
myoff=Offset('J2000','00:02:00',0.0) # Off position of 2min time in RA
h=Horizon(20.0) # specify a horizon of 20 degrees elevation

riseSrcB = h.GetRise(srcB) # now get rise and set times of srcB
setSrcB = h.GetSet(srcB)

#print the rise and set times of srcB
risesetstring='20 deg elev. rise = %s and set = %s'%(riseSrcB,setSrcB)
```

```
Comment(risesetstring)

# observe srcA until srcB has risen above 20 deg elevation
Slew(srcA)
Balance()
while Now() < riseSrcB and Now() != None:
    OnOff(srcA,myoff,120.)

# now observe srcB until it sets
Slew(srcB)
Balance()
while Now() < setSrcB and Now() != None:
    OnOff(srcB,myoff,120.)

# now observe srcC five times
numobs=5
Slew(srcC)
Balance()
for i in range(numobs):
    OnOff(srcC,myoff,120.)
```

Script 5.72: SB Example 3 – Position switched observations of several sources and using the Horizon object.

5.7.4 Frequency Switched On-The-Fly Mapping

In this example we perform frequency switched observations of the HI 21 cm line to map a 5×5° region of the sky. We use pixels that are 3′ in size and have an integration time of 2 seconds per pixel.We do not observe the whole map in this example.

This example is available as `/home/astro-util/projects/GBTog/SBs/example4.py`.

```
# Frequency Switched Observations where we perform on-the-fly (OTF) mapping

# Load the configuration file
execfile('/home/astro-util/projects/GBTog/configs/fs_config.py')

# Load the catalog file
Catalog('/home/astro-util/projects/GBTog/cats/sources.cat')

# now we configure the GBT IF system for freq switched HI observations
Configure(fs_config)

# now we set the parameters for the map
src       = 'Object2'                    # location of the map center
majorSize = Offset('Galactic',5.0,0.0)   # 5 degrees in galactic longitude
minorSize = Offset('Galactic',0.0,5.0)   # 5 degrees in galactic latitude
rowStep   = Offset('Galactic',0.0,0.05)  # 3 arcminutes between map rows

# the time to scan each row
# time = majorSize / rowStep * integration time per pixel
scanTime = 5.0/0.05*2. # 2 seconds per pixel

# Balance power levels
Slew(src)
```

```
Balance()
Break('Check power levels')

# only do part of the map here
rowStart = 10
rowStop  = 20

# now observe for the map
RALongMap(src,majorSize,minorSize,rowStep,scanTime,
          start=rowStart,stop=rowStop)
```

Script 5.73: SB Example 3 – Frequency switched On-The-Fly mapping.

5.8 What Makes a Good Scheduling Block

Rarely does an observing session exactly follow one's plans. A useful philosophy is to consider the work that would be involved in editing an SB if something were to go wrong during its execution and you wanted to resume its execution where you left off. You should break apart any long scripts into smaller individual scripts to reduce the need for edits.

During your observing, you will make decisions as to how to proceed with the next observations. You should break apart large scripts to increase your flexibility in being able to react to the circurmstances that arise during your observing.

We recommend that the following should be avoided within a single SB, as it will make the block too long:

- **Multiple Configurations**: Multiple configurations (peak/focus and science observations) should optimally be perfomed with separate SBs.
- **Changing Receivers**: You should only use a single receiver within an SB.
- **Multiple Maps**: You should perform only a single map within any SB.

Chapter 6

Observing Tactics and Recommendations

This chapter provides common tactics and recommendations for GBT observing. You will find information on

- When and how to use the Active Surface (Sec. 6.1)
- How to run AutoOOF scans (Sec. 6.2)
- How to Balance the IF system (Sec. 6.3)
- How to Calibrate your data (Sec. 6.4)
- How to point and focus the GBT (Sec. 6.5)
- Strategies for spectral configurations (Sec. 6.6)
- How to run mapping observations (Sec. 6.7)
- What to consider for high-frequency observing (Sec. 6.8)
- What to consider when observing strong continuum sources (Sec. 6.9)

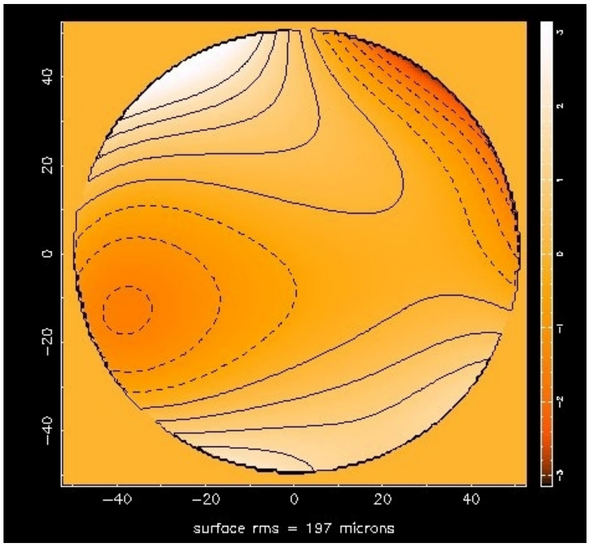
6.1 Active Surface (AS) Strategies

If you are observing at a frequency of 8 GHz or higher then you should use the Active Surface (AS). At frequencies below 8 GHz the AS does not provide any improvements to the efficiency of the GBT. Due to RFI considerations the AS may be turned off for lower frequency observations.

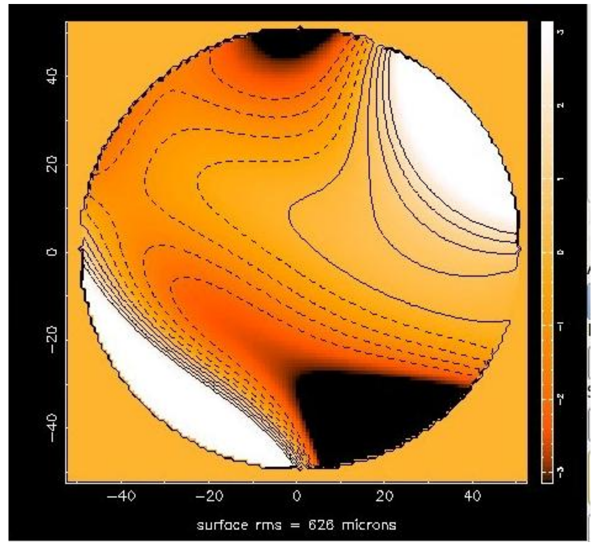
You do not need to do anything to turn on or off the use of the glsAS.The GBT telescope operator performs these tasks.

6.2 AutoOOF Strategy

AutoOOF is recommended for observing at frequencies of 40 GHz and higher and only available for use with Rcvr26_40 (Ka–band), Rcvr40_52 (Q–band), Rcvr68_92 (Wband), RcvrArray75_115 (Argus), and Rcvr_PAR (MUSTANG-2). For the associated data display, see Section 4.1.4. It is important to note the following points when using AutoOOF:



(a) Acceptable OOF solution.



(b) Unacceptable OOF solution.

Figure 6.1: Figure 6.1a shows broad features (±1.5 radians of phase) with a surface rms of 197 μm. Figure 6.1b shows steep contour lines (±15 radians of phase) and a surface rms of 626 μm. This is likely the result of poor quality raw data and should not be used.

Since the Ka-band receiver with the default CCB backend provides the most accurate measurements of the surface parameters, users should consider using this whenever possible, except for Mustang users who prefer using the Mustang system. Besides the high sensitivity provided by the CCB, the larger beam at the lower frequency makes the surface solutions less affected by winds.

Choose a bright calibrator: preferably at least 7 K in the observed band, which is about 4 Jy at Q-band. You should not rely on the catalog flux to be accurate as it is often many years out of date. The ALMA Calibrator Source Catalogue has an extensive record of the flux densities for many of the bright 3 mm sources (https://almascience.eso.org/sc/). If you are not sure then run a point/focus scan on the calibrator first in order to confirm its strength. Remember, you need to be able to detect the source when the subreflector is out of focus which reduces its peak intensity significantly.

Allow approximately 25 minutes for an AutoOOF: The AutoOOF procedure will obtain three OTF maps (each map takes 5–6 minutes) at a different focus position.

Use AutoOOF to derive pointing and focus offsets: The processing is launched automatically upon completion of the third map, and the result is displayed in the OOF plug-in tab of Astrid. It is incumbent upon the user to examine the solutions, and click the button (in the Astrid DataDisplay tab) to send the selected solution to the active surface. It is recommended that when sending the solutions, you use the button in the OOF display tab labeled "After selecting the Zernike solution above, click this button to send the solutions to the telescope".

AutoOOF is not necessary for extended sources: Extended sources may be observed without the AutoOOF corrections if the science is not impacted by the primary beam variations.

AutoPeakFocus may be run as a sanity check on the AutoOOF solution. If Peak/Focus scans were performed before AutoOOF, then source amplitude should be greater after the AutoOOF than what was seen before the surface correction was sent. Additionally, AutoPeakFocus pointing and focus corrections should agree with values derived by AutoOOF.

6.2.1 How long does the solution remain valid?

- **Nighttime**: A general rule of thumb is if the corrections are measured at least two hours after sunset, then the solutions should be good for about four hours. This depend on how rapidly the backup structure cools off after sunset and how sunny the day was. If the OOF is taken after midnight, the structure has typically stabilized by then, and the solutions may be good until after sunrise.

- **Daytime**: During the daytime, this is a difficult question to answer, as it depends on the position of the telescope with respect to the Sun and cloud cover. The answer can be anything from less than 30 min to 4 hours.

- **Periodically Examine Peak Scans**: A new AutoOOF may be necessary if the following characteristics are seen:
  - Significant sidelobes begin to appear.
  - The beam size increases by more than 10%.
  - Source amplitude decreases systematically by 15% or more.

6.2.2 AutoOOF Solutions

Figure 6.1 shows examples of acceptable and unacceptable OOF solutions. Good solutions have the following characteristics:

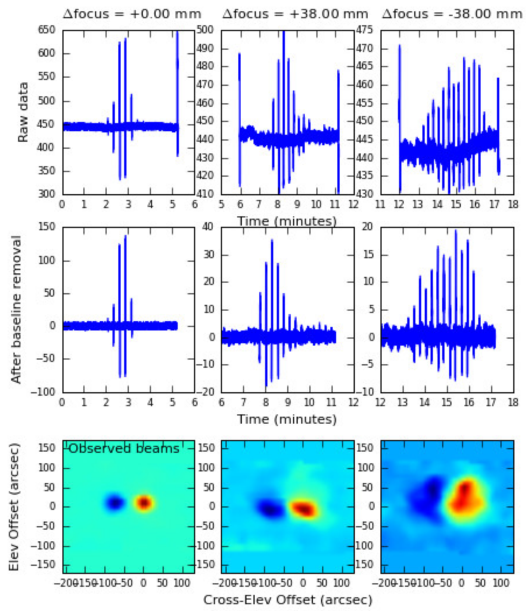
- Broad features of less than ±1.5 radians of phase in early to mid-morning to a few radians in the afternoon. Note that you may uncheck “Show Fixed Scale Image” to view the full data range in the color bar.
- Surface rms residuals $< 400\ \mu$m. (less than 500 microns if starting withe the default gravity-zernike model)

6.2.3 AutoOOF Raw Data

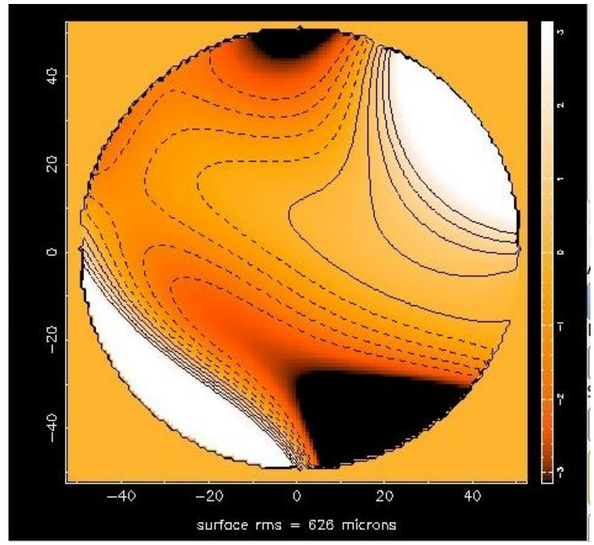
Although an OOF solution may appear to be reasonable (e.g., Figure 6.1a) it may also be invalid if it was derived from a bad set of raw data. Sending such a solution to the active surface could degrade performance. Therefore, observers should always check the quality of the raw AutoOOF data in order to determine whether their derived solutions are valid. For a set of raw data to be considered valid, it should show the following characteristics:

- Clear detections of the source in the raw data timestream at all focus positions.
- Symmetrical left/right positive/negative pattern in all three raw data images.
- Smooth features in all three raw data images. Sharp edges or stripes indicate hardware/software glitches or excessive winds.

The AutoOOF raw data can be viewed by selecting the “raw data” radio button in the upper–right section of the OOF Subtab of the Data Display. Each column represents one focus position. The top row is the raw timestream data from the receiver, the second row has the baselines removed, and the bottom row shows the corresponding beam maps. See Figure 6.2 for a comparison of acceptable and unacceptable raw AutoOOF data.



(a) A plot of the raw OOF data on a fairly clean Ka–band/CCB dataset.



(b) A plot of raw OOF data on a source which is too faint.

Figure 6.2: A comparison of acceptable and unacceptable AutoOOF raw data.

6.2.4 Selecting the Zernike order to fit

By default, AutoOOF will halt processing after the fifth-order Zernike (z5) solution has been computed. The z5 solution is suitable for most conditions and is generally what observers should expect to use. A more agressive sixth-order (z6) fit may also be derived at the cost of a few additional minutes of processing time. This is usually unnecessary and should only be done on bright calibrators under favorable weather conditions. See § 6.2.6 for information on how to change the maximum order of fit to process.

Occasionally, it may be necessary to occasionally drop to a lower order of fit if the following features are seen:

- **Large excursions** over a significant area of the dish edge in the OOF solution.
- **Regularly spaced features** around the circumference of the dish at higher order fits in the OOF solution.
- **Anomalous values in the pointing/focus LPC/LFCs** for one particular solution, or a significant jump in LPCs above a certain Zernike fit order. For example, if the focus (LPCy) values for the z3–z4 solutions are around $-3mm$, then abruptly jump to $+10mm$ for the z5 solution, then it would be prudent to assume that some or all of the solutions may be invalid. It may be possible to determine which solutions are valid by examining the fitted beam maps for obvious artifacts or deviations from the observed beams (see Figure 6.3).

6.2.5 Sending a Solution to the Active Surface

When you are ready to accept the solution being displayed it will need to be manually sent to the active surface. It is recommended that when sending the solutions, you use the yellow button labeled

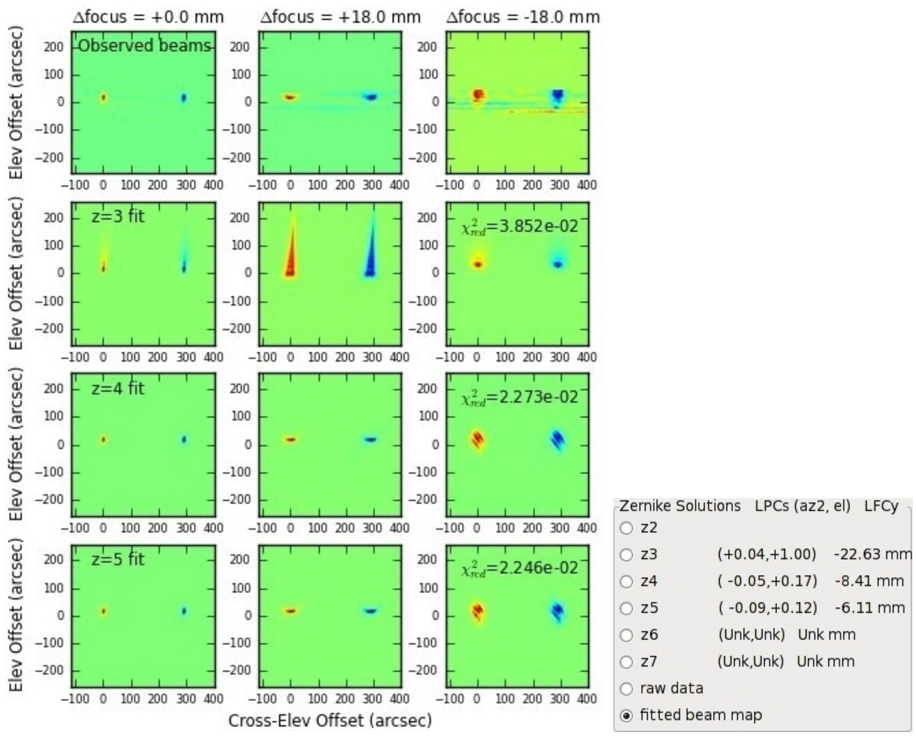


Figure 6.3: *Left:* The AutoOOF fitted beam maps. The observed beams are plotted on the top row with the z3, z4 and z5 fits to the observed beams plotted below. The z3 solution (2^{nd} row down) shows an obvious artifact and should not be used. *Right:* Zernike Solutions. Note the significant jump in LPCs and the LFC between the z3 and z4 solutions.

Send Selected Solution with Point and Focus Corrections . If you use this option, you do not have to perform a Peak or Focus after an AutoOOF. It is still good practice to Peak and Focus at the beginning of your observing session unless you are using the W–band 68–92 GHz receiver (see Chapter 8). Subsequent pointing and focus corrections may be computed via AutoOOF.

Many high frequency observers will perform Peak scans immediately following an AutoOOF to verify the surface solution (see § 6.2). If the solution is satisfactory the LPCs and LFC from Peak/Focus scans should agree with values from the OOF solution, there should be no significant sidelobes visible in the peak scans, and Peak scans should also yield the expected beam FWHM. If in doubt, you may disable OOF corrections by pressing Zero and Turn Off Thernal Zernike Solution in order to compare Peak scans with and without OOF corrections.

6.2.6 OOF Processing Options

Deriving the sixth-order Zernike (z6) solution will require a few additional minutes of processing time and for the user to manually change the maximum order of fit to process in the following way:

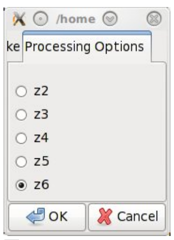


Figure 6.4: OOF Processing Options.

Step 1. Select the OOF Subtab of the Data Display.

Step 2. Select `Tools→Options...` from the drop–down menu.

Step 3. Select the maximum order of fit to process from the "Processing Options" tab of the pop–up window (Figure 6.4).

NOTE: All changes must be made **before submitting the SB** containing the **AutoOOF()** function in order to take effect. You may also repeat processing after making any changes by pressing Reanalyze OOF (Online Only) .

More information on AutoOOF can be found at
https://safe.nrao.edu/wiki/bin/view/GB/PTCS/AutoOOFInstructions

6.3 Balancing Strategies

The GBT IF system has many ways to add gain and/or attenuation in the IF path, depending upon the desired configuration. Before taking data with the GBT, the observer must ensure that all components along the IF path have optimum input power levels; this process is referred to as "balancing". This will ensure for example that no components saturate and that amplifiers are in the most linear part of their dynamic range. The system automatically adjusts power levels to optimum values when you issue the **Balance()** command in AstrID. The following discussion gives guidelines for when and how often to use the **Balance()** command.

Strategies for balancing the IF power levels depend upon the backend, the observing frequency, the observing tactics, the weather and the objects being observed. The DCR has a dynamic range of about 10 [1] in its ability to handle changes in the brightness of the sky as seen by the GBT. The sky brightness can change because of continuum emission of a source or a maser line as you move on and off the source. It can also change due to changes in the atmosphere's contribution to the system temperature as the elevation of the observations change or due to the weather.

[1] From about 0.5 to 5 Volts of IF power in the IF Rack.

Whenever you **Balance()** you almost always change the variable attenuator. Each attenuator setting has a unique bandpass shape. So if you change attenuators then you will likely see changes in the bandpasses and baselines of the raw data.

There are not any set–in–stone rules for when an observer should balance the GBT IF system. However there are some guidelines which will allow you to determine when you should balance the IF system. Here are the guidelines:

1. You should balance the IF system after performing a configuration.
2. You should minimize the number of times you balance when observing.
3. If you know T_{sys} + T_{src} will change by more than a factor of two (3 dB[2]) when you change sources (not between and on and off observation) you should consider balancing.
4. Try to avoid balancing while making maps.
5. Never balance between "signal" and "reference" observations (such as during an on/off observation).
6. If you are observing target sources and calibration sources then try not to balance between observations of the targets and calibrators.

Note:

- If during your observing you expect to see a change in power levels on the sky that are roughly equivalent to the GBT system temperature, then you should contact your GBT support person to discuss balancing strategies. There are no global solutions and each specific case must be treated independently.
- If the system temperature between "signal" and "reference" observations differ by a factor of two or more, **BalanceOnOff()** (see § 5.4.1.10) should be used in place of **Balance()**. This will balance the IF power levels at the midpoint of the two power levels at each sky position.

6.3.1 Balancing VEGAS

There are two aspects to VEGAS balancing that will produce separate error messages, so the user should check the origin carefully:

1. **Adjusting IF power levels upstream of the VEGAS ADC**: Power levels upstream of the VEGAS ADCs are balanced so that the power going into an ADC is at an acceptable level.
   - **Balancing will fail if the input IF power levels to VEGAS is more than ±2 dB from the target value of -20 dBFS**. VEGAS has a much higher range than that, but it is extremely rare that the observation/equipment combination should prevent the balancing algorithm from meeting the target. A conservative limit was chosen since a failure normally means that some part of the system is not configured correctly, or that there is hardware failure. If an IF balancing failure occurs, the user (or operator) should look for errors in the IF system and can view the actual IF power levels in the VEGAS CLEO screen (see § 4.3.1). If they are significantly different from -20 dBFS, there is a problem somewhere in the IF chain.

[2] A change in power from P_1 to P_2 can be represented in dB by $10 \log_{10}(P_1/P_2)$

- **If the power levels are different from -20 dBFS, but close to it, there may not be a real problem**. In some cases, the IF balancing will fail due to an exceptional, but acceptable circumstance; for example, looking at an extremely bright source, or using a spectral window close to the edge of the receiver passband. The IF balancing failure does not cause an abort, and it is often acceptable to continue observing under these circumstances.

  The useable dynamic range of VEGAS is actually > 20 dB. It is set at a low level by quantization effects, and at high levels by saturation. If the IF power level looks reasonable, the next check is to look at the ADC histogram counts. As long as the histogram looks like a Gaussian distribution, with a a FWHM around 20 counts or larger, but with no counts approaching ±127, then the IF level into VEGAS is acceptable (see Figure 4.15). Make sure you monitor the ADC histogram through all phases of your observation (e.g. switching on and off a bright source).

2. **Adjusting the "digital gain" inside the VEGAS processing firmware**: There should be no circumstances (e.g. an FFT overflow) which result in lost precision.

   - **The digital gain should never fail to balance**. It is a property of the firmware design of each mode, not the IF input. A failure of the digital gain balancing indicates a serious problem, and engineering support should be called.

6.4 Calibration Strategies

For best flux density calibration of spectra, it is recommended that you should observe continuum flux density calibration sources at least once during an observing session. To do this, do a Peak/Focus on the calibrator, followed by an observation in the same spectral line setup used for the program sources. This will give the relation of flux density to antenna temperature as a function of frequency that can be applied to the program spectra.

Of course, there may be other outstanding reasons to perform calibration observations more often. If you have concerns over how often you should observe a calibrator you should get into contact with your GBT support person.

Flux density histories for many of the bright 3mm point sources can be found in the ALMA Calibrator Source Catalogue (https://almascience.eso.org/sc/).

6.5 Pointing and Focusing Strategies

How often you need to point and focus the GBT depends on the frequency of your observations, the weather conditions, whether or not it is day or night-time, and the amount of flux error that your experiment can tolerate from pointing and focus errors. See Table 6.1 for guidelines on how often to Point/Focus. Note that spacings between Point/Focus observations may be increased if results appear stable, especially during the night.

Within the DSS, the tracking error σ_{tr} (arc seconds) as a function of wind speed s in units of m s^{-1} is given by

$$\sigma_{tr}^2 = \sigma_0^2 + \left(\frac{s}{3.5}\right)^4, \tag{6.1}$$

where $\sigma_0 = 1.32''$ at night and $\sigma_0 = 2.19''$ during the day, and is the tracking and pointing error with no winds. The DSS will only schedule observations if the tracking error is smaller than a specified fraction ($f < f_{max}$) of the beam FWHM (σ_{beam}) given by

$$f = \frac{\sigma_{tr}}{\sigma_{beam}} = \frac{\sigma_{tr}\nu}{748}, \tag{6.2}$$

Table 6.1: Observing wind limits using DSS default parameters and suggested time periods between Point and Focus observations.

		Wind limit (ms^{-1})		Recommended Point/Focus spacing	
Receiver	ν (GHz)	Day	Night	Day	Night
Rcvr_342	0.340	73.4	73.4	— Initial Peak only —	
Rcvr_450	0.415	66.5	66.5	— Initial Peak only —	
Rcvr_600	0.680	52.0	52.0	— Initial Peak only —	
Rcvr_800	0.770	48.8	48.8	— Initial Peak only —	
Rcvr_1070	0.970	43.5	43.5	— Initial Peak only —	
Rcvr1_2	1.4	36.2	36.2	— Initial Peak and Focus only —	
Rcvr2_3	2.0	30.3	30.3	— Initial Peak and Focus only —	
Rcvr4_6	5.0	19.1	19.1	Hourly on hot afternoons	Every 2-3 hours
Rcvr8_10	10.0	13.5	13.5	Hourly on hot afternoons	Every 2-3 hours
Rcvr12_18	15.0	11.0	11.0	Hourly	Every 1-2 hours
RcvrArray18_26	25.0	8.3	8.5	Hourly	Every 1-2 hours
Rcvr26_40	32.0	7.1	7.4	Hourly	Hourly
Rcvr40_52	43.0	5.5	6.1	Every 30-60 minutes	Hourly
Rcvr68_92	80.0	–	4.4	Every 30-60 minutes	Every 30-60 minutes
Rcvr_PAR	90.0	5.5	6.1	Every 30-60 minutes	Every 30-60 minutes
Rcvr75_115	95.0	–	–	-[a]	Every 30-45 minutes

[a] It is not recommended to observe with Argus during the day.

where ν is the observing frequency in GHz. Values for f_{max} in the DSS are currently set at 0.2 for receivers below 50 GHz, 0.22 for receivers above 50 GHz (Rcvr68_92) and 0.4 for filled arrays (Rcvr_PAR). An f_{max} value of 0.2 assures observers that their flux uncertainty due to tracking errors is no more than 10%, assuming they are observing a point source.

Table 6.1 provides wind limits using default DSS parameters. Observers may wish to alter some parameters in the DSS to better suit their observing requirements. For example, pointing may be relaxed for extended sources (i.e. set $\theta_{src} > 0$ in the DSS), or more tightly constrained (a value of $f_{max} = 0.14$ in the DSS assures no more than 5% flux uncertainty due to tracking errors). You may request changes to DSS control parameters by contacting your GBT "friend" and emailing helpdesk-dss@nrao.edu.

For further information on DSS control parameters see Appendix F. See DSS Project Note 18.1 (R. J. Maddalena and Frayer, 2014) for tracking performance and parameters used in Equation 6.1.

6.6 Spectral Configurations

It is good practice for the observer to schedule a short observation towards a strong spectral line source at the beginning of each observing session. The observer should process and check the spectra before proceeding with the observations to confirm the spectral configuration. It is also important to check the system temperatures for each beam. Poor configuration choices for the backend will sometimes be detected as anomalous system temperatures.

6.7 Mapping Strategies

The sky should be sampled five times across the beam (i.e., the scan rate and integration times should be set such that there are five integrations recorded in the time the telescope scans across an angle equal to the beam FWHM) and there should be four switching periods per integration (see Mangum, Emerson, and Greisen 2007 A&A, 474, 679 for details). For VEGAS, minimum recommended integration times and switching periods are listed in Table 10.1 and § 10.4. The DCR has a minimum integration time of 100 ms.

The GBT Mapping Calculator is a useful tool for planning mapping observations and may be used to provide AstrID commands and parameters for many of the mapping scan types. The mapping calculator can be found at http://www.gb.nrao.edu/∼rmaddale/GBT/GBTMappingCalculator.html.

It is important to take account of the overheads involved with mapping scans. For example, it takes approximately 25 seconds to start a **RALongMap** mapping scan. So observers scheduling scans much shorter than 1 minute will lose a large fraction of their observing time to overheads. Using Daisy pattern scans are more efficient for scheduling small maps, as a region can be mapped in a single scan. However there is an additional delay in starting a **Daisy** procedure, as the system computes the antenna trajectories. As a rule of thumb, maps larger than about 10–20 beam FWHM in size should use the **RALongMap** or **DecLatMap** scan types while smaller maps should use **Daisy** scans. For practical reasons, it is often best to keep the scan length under about 15 minutes.

Observers wishing to use the GBT mapping pipeline may periodically wish to include reference scans into their Scheduling Blocks. Further information on using the pipeline can be found at https://safe.nrao.edu/wiki/bin/view/GB/Gbtpipeline/PipelineRelease.

6.8 High Frequency Observing Strategies

When observing at frequencies above 10 GHz you should be aware that additional calibration measurements may be necessary. The telescope efficiency can become elevation dependent, atmospheric opacities are important and the opacities can be time variable. You should contact your GBT support person to discuss these issues.

All the GBT high frequency receivers have at least two beams (pixels) on the sky. You should make use of both of these during your observations if possible. For example, if you are doing position switched observations and your source is not extended then you can use the AstrID **Nod()** procedure to observe (see § 5.4.2).

6.9 Observing Strategies For Strong Continuum Sources

Spectral line observations of strong continuum sources leads to a great amount of structure (i.e. ripples) in the observed spectra. So observations of strong continuum sources requires careful consideration of the observing setup and the techniques used.

If you are trying to observe weak broad spectral lines (wider than ∼100 MHz) toward a source with strong continuum emission (more than 1/10th the system temperature), then you should consider using double position switching. This technique is discussed in an Arecibo memo (Ghosh and Salter, 2002).

Another issue is finding a proper IF balance that allows both the "on" and "off" source positions to remain in the linear range of the backend being used. This means that one must find the IF balance in both the "on" and "off" position and then split the difference – assuming that the difference in power levels between the "on" and "off" do not exceed the dynamic range of the backend. The **BalanceOnOff()** procedure in AstrID can be used to accomplish this type of balancing (see § 5.4.1).

Part II

Frontends

Table 6.2: Properties of the Prime Focus and Gregorian Focus Receivers.

	Name	ν Range (GHz)	Polarization	Beams	Polns/ Beam	T_{rec} (K)	T_{sys} (K)
— Prime Focus Receivers —							
PF1	Rcvr_342	0.290-0.395	Lin/Circ	1	2	12	46
PF1	Rcvr_450	0.385-0.520	Lin/Circ	1	2	22	43
PF1	Rcvr_600	0.510-0.690	Lin/Circ	1	2	12	22
PF1	Rcvr_800	0.680-0.920	Lin/Circ	1	2	21	35
PF2	Rcvr_1070	0.910-1.230	Lin/Circ	1	2	10	17
— Gregorian Focus Receivers —							
L–band	Rcvr1_2	1.15-1.73	Lin/Circ	1	2	6	20
S–band	Rcvr2_3	1.73-2.60	Lin/Circ	1	2	8-12	22
C–band	Rcvr4_6[a]	3.95-7.8	Lin/Circ	1	2	5	18
X–band	Rcvr8_10[a]	7.80-12.0	Circ	1	2	17	27
Ku–band	Rcvr12_18	12.0-15.4	Circ	2	2	14	30
KFPA	RcvrArray18_26	18.0-27.5	Circ	7	2	15-25	30-45
Ka–band	Rcvr26_40 (MM-F1)	26.0-31.0	Lin	2	1	20	35
Ka–band	Rcvr26_40 (MM-F2)	30.5-37.0	Lin	2	1	20	30
Ka–band	Rcvr26_40 (MM-F3)	36.0-39.5	Lin	2	1	20	45
Q–band	Rcvr40_52	39.2-50.5	Circ	2	2	40-70	67-134
W–band	Rcvr68_92 (FL1)	67-74	Lin/Circ	2	2	50	160
W–band	Rcvr68_92 (FL2)	73-80	Lin/Circ	2	2	50	120
W–band	Rcvr68_92 (FL3)	79-86	Lin/Circ	2	2	50	100
W–band	Rcvr68_92 (FL4)	85-93	Lin/Circ	2	2	60	110
Argus	RcvrArray75_115	74-116	Lin	16	1	50	110
MUSTANG-2		75-105	–	223	-	–	–

[a] Please note that this receiver name no longer correlates exactly with the actual frequency range of the receiver.

Chapter 7

K-band Focal Plane Array, KFPA (18-27.5 GHz)

The K-band Focal Plane Array has seven beams total, each with dual circular polarization. Each beam covers the 18-27.5 GHz frequency range with fixed separations on the sky with nominal offsets listed in Table 7.1. The feeds have cooled polarizers producing circular polarization. The only internal switching mode is frequency switching. The seven feeds are laid out in a hexagon with one central feed as shown in Figure 7.1. The hexagon is oriented such that the central feed is not at the same cross-elevation or the same elevation as any of the other beams. Beam pairs (3,7) and (4,6) are at equal elevations and are appropriate choices for nodding and peak/focus observations.

Unlike other receivers, the KFPA uses variable noise diodes for each beam (∼10% of the system temperature) that can change, so it is very important for observers to calibrate their data every session. The maximum instantaneous bandwidth for the receiver, in normal observing modes, is currently 1.8 GHz. A "broadband" mode has been developed for the KFPA in which it is possible to route 7.5 GHz of bandwidth from beam 1 of the receiver to the VEGAS backend. Alternatively, using this mode allows for 4 GHz of bandwidth to be routed from both beams 1 and 2 simultaneously. Advice should be sought from a staff scientist if this mode is desired.

7.1 Configuration

7.1.1 Beam selection with VEGAS banks

Observers can use all 7 KFPA beams simultaneously, or select a only subset of them. To maximize versatility and observing efficiency when mapping, most observers will want to use the full set of 7 beams paired with the observations with the VEGAS backend.

An equal number of beams must be routed to Converter Rack Modules A and B, imposing the following constraints on mapping beams to VEGAS banks:

- A single beam may be routed to any or all of the VEGAS banks A→H.
- Dual-beam configurations allow each beam to be routed to a maximum of 4 VEGAS banks.
- When using 3–4 beams, each beam may be routed to up to a maximum of 2 VEGAS banks.
- When using more than 5 beams, each beam may only be routed to a single VEGAS bank.

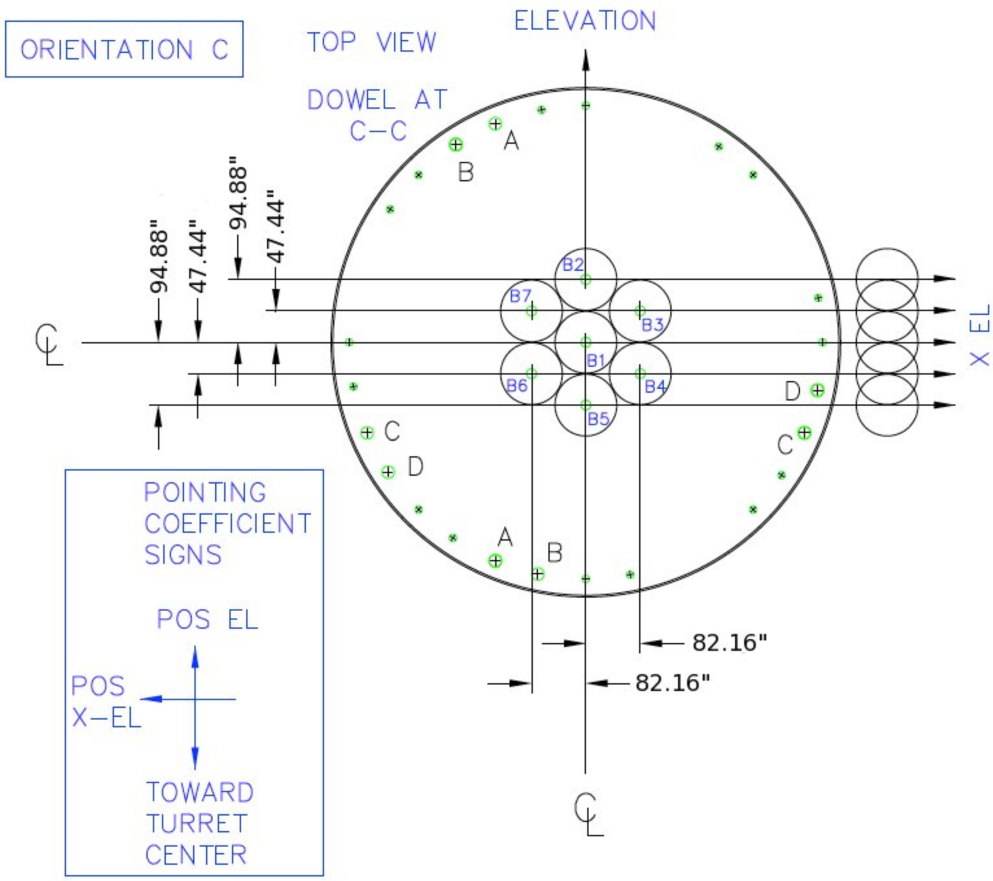


Figure 7.1: Orientation of the KFPA feeds on the GBT

- When using all 7 beams, each beam may be routed to a single VEGAS bank with an optional second copy of beam 1 being routed to the remaining VEGAS bank. This is known as the “7+1” mode of the KFPA.

An example configuring for the 7+1 mode of the KFPA is given in Script 5.9.

7.1.2 Instantaneous Bandwidth

- **Narrowband mode** is the default setting and must be used with any KFPA multi-beam configuration. In this mode all frequencies must have a maximum frequency separation of 1.8 GHz and lie within 900 MHz of the doppler tracking frequency.
- **Broadband mode** allows the system to process up to 7.5 GHz of bandwidth. This mode is only available for single beam observations using beam 1 and is achieved by setting `broadband=1` in the configuration (see § 5.2.5).

7.2 Calibration

The KFPA receiver has variable noise-diodes that can change so it is important that users calibrate their data for every session. The diodes have effective temperatures that can drift slowly over time or change after a thermal cycle of the cyrostat.

Table 7.1: Nominal beam offsets for each feed of the KFPA at orientation C.

Beam	ΔX-El (″)	ΔEl (″)
1	0.00	0.00
2	0.00	94.88
3	-82.16	47.44
4	-82.16	-47.44
5	0.00	-94.88
6	82.16	-47.44
7	82.16	47.44

We currently recommend that users calibrate their data by carrying out **Nod/OnOff** observations on a known flux calibrator using the same configuration that they would use for their science observations. An example SB for performing this type of calibration using all 7 beams of the KFPA is shown in Script 7.1.

It is also possible to use the sky at different elevations to "flat-field" the relative gains of the beams and then absolute calibrate the data with an **OnOff/Nod** observation of one reference beam using a known flux calibrator. Calibration using resolved sources such as planets or the Moon adds the requirement for an accurate temperature model of the source plus a model for coupling the GBT beam to the planet disk. Observers wishing to use such methods should consult their project friend to devise the best strategy for calibration.

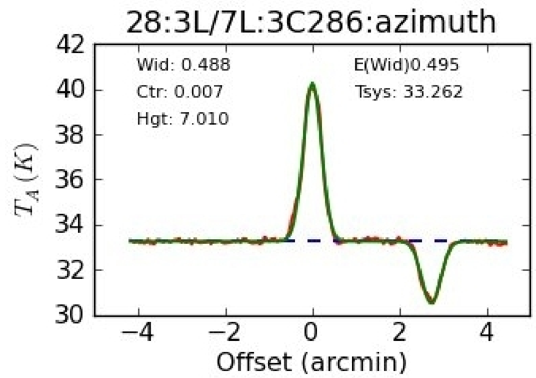
```
execfile('/home/astro-util/projects/GBTog/configs/kfpa_config.py')
Catalog(fluxcal)
Catalog(kband_pointing)
src = '3C286'           # Do not use extended 3C sources

Configure(kfpa_config) # Configure for KFPA receiver
AutoPeakFocus(src)      # Automatically slews, balances,
                        # and configures for continuum.

Configure(kfpa_config) # Reconfigure for VEGAS + KFPA using
Slew(src)               # the same configuration you would use
Balance()               # for your science observations....

Nod(src, '3', '7', scanDuration=30.0) # This combination covers all
Nod(src, '2', '6', scanDuration=30.0) # 7 beams - edit as necessary
Nod(src, '4', '1', scanDuration=30.0) # for other beam configurations.
Nod(src, '1', '5', scanDuration=30.0)
```

Script 7.1: An example SB used to calibrate KFPA noise diodes for all 7 beams.

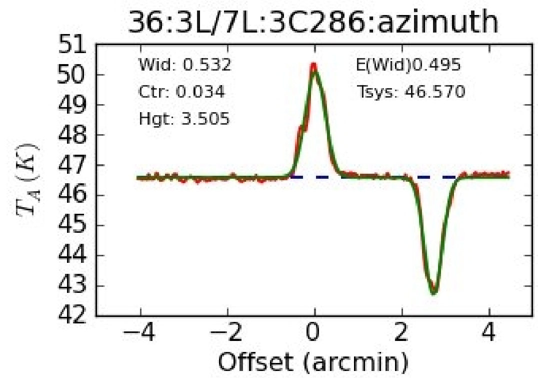
7.2.1 Realigning the Noise Diodes

Sometimes the effective temperature of the noise diodes can suddenly change by significant amounts due to firmware configuration glitches that may occur after resetting the manager, updates to receiver parameters, and power failures. A large change the effective temperature of a noise diode could result in unusual $T_{\rm sys}$ values or a large difference between the amplitude of beams in azimuth Peak scans as shown in Figure 7.2a.

If you suspect that the noise diode temperatures have drifted and need to be aligned, let the GBT operator know to contact the on-duty support scientist who can examine the data and realign the noise



(a) KFPA azimuth pointing scan where noise diode temperatures have drifted. The amplitude of beam 3 is approximately 3 times that of beam 7.



(b) KFPA azimuth pointing scan after realigning the noise diodes. Beam amplitudes are approximately equal.

Figure 7.2: KFPA azimuth pointing scans before and after noise diode realignment

diodes if necessary. Figure 7.2b shows a repeat of the scan shown in Figure 7.2a after the noise diodes were realigned.

Chapter 8

W-band receiver (68-92 GHz)

8.1 Overview

The 4 mm receiver ("W-band") is a dual-beam, dual-polarization receiver which covers the frequency range of approximately 67-92 GHz. A key difference between the 4 mm receiver and other GBT receivers is that there are no noise-diodes for the 4 mm receiver. This impacts the observing and calibration techniques for the receiver. Users need to take a calibration sequence whenever the configuration changes or whenever the IF system is balanced for any data that needs to be calibrated. The receiver has an optical table with an ambient and cold load that is used for calibration (Figure 8.1). The optical table can also convert linear polarization into circular polarization using a 1/4-wave plate in front of one of the beams for VLBI observations. The two beams are separated by 286″ in the cross-elevation direction on the sky (i.e., along azimuth).

In this chapter, we present information for carrying out W-band observations. We concentrate on items specific to W-band, and assume the user is familiar with the other chapters of the observing guide. Contact Green Bank Observatory support scientists if you have questions.

8.2 Configuration

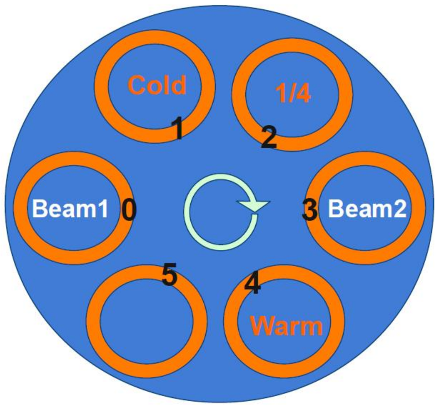
The 4mm Receiver uses the standard config-tool software that automatically configures the GBT IF system based on user input (e.g., frequency and bandwidth). Example W-band configuration files are given in /home/astro-util/projects/4mm/. The 4mm system is broken into four separate bands:

- FL1: 67-74 GHz
- FL2: 73-80 GHz
- FL3: 79-86 GHz
- FL4: 85-92 GHz,

You can only use one of these bands at a time (i.e., you cannot simultaneously observe lines in more than one band). The millimeter down-converter filters of the system limits the instantaneous bandwidth to 4 GHz for 73-92 GHz (filters FL2, FL3,FL4), while up to 6 GHz of total bandwidth is available for 67-74 GHz (filter FL1).

The configuration items specific to the 4mm receiver are the following:

- receiver = 'Rcvr68_92' (name of the receiver)



	Wheel Position (defined wrt Beam1)	Beam 1	Beam 2
0	Observing	Sky	Sky
1	Cold1	Cold	Warm
2	Position2	1/4wave circ	Sky
3	Position3	Sky	Sky
4	Cold2	Warm	Cold
5	Position5	Sky	1/4wave Circ

Figure 8.1: Diagram showing the positions of the 4mm Calibration wheel. The wheel is rotated above the cryostat, and the location of the beams are separated by 180 degrees on the wheel. In the Observing position, both beams see the sky. In the Cold1 position, beam-1 sees the cold load and beam-2 sees the ambient load, while for the Cold2 position, beam-2 sees the cold load and beam-1 sees the ambient load. The 1/4-wave plate can be placed over only one of the beams at a time.

- beam = 'B12', 'B1', or 'B2' (dual beam receiver)
- swmode = "tp_nocal" or "sp_nocal". There are no noise diodes with this receiver.
- polarization = "linear" or "circular" (Default is linear). If user selects circular, then the 1/4-wave plate is placed in front of the chosen beam. There is only one 1/4-wave plate, so users can have circular polarization for only one of the beams.

8.3 Observing

To maximize the telescope efficiency for targets smaller or similar in size to the beam ($\sim 10''$), observations should be carried out during the night under stable thermal conditions. During the daytime, the effective point-source aperture efficiency decreases significantly since the beam shape increases in size. Depending on the science goals, successful daytime observations are possible for extended sources.

- Start the project with an AutoOOF (unless observing extended sources during the day). This sets the active surface, including the thermal corrections, as well as getting initial pointing and focus corrections. For AutoOOF, it is recommended to use the brightest point source in the sky between 25–80 degree (25–75 degree at half-slew rate) elevation. If the Ka-band receiver is available, run the AutoOOF at Ka-band instead of W-band for more accurate surface corrections. The S/N ratios observed with the Ka+CCB system are much higher than is possible at W-band, and the winds affect the Ka-band data to a lesser degree due to the larger beam-size. After the AutoOOF solutions are applied, run a point and focus at W-band.
- After configuration and balancing, check the RF power levels in the IF rack to confirm that power is going through the channels and that the power levels are not saturated (< 10). Beam-1 uses channels 1 and 3, and beam-2 uses channels 5 and 7. The target power level for W-band is 1.5, and the software adjusts theattenuation to reach this level.

- Users must run the CalSeq procedure to calibrate the data (see § 8.3.1). During the calibration sequence, users can watch the movement of the calibration wheel from the Rcvr68_92 CLEO page (Figure 8.2).

8.3.1 CalSeq

The CalSeq procedure is used to calibrate W-band data. This procedure should be run after every configuration and balance. This is needed to convert instrumental counts into antenna temperatures. The syntax for the CalSeq command is the following:

CalSeq(type, scanDuration, [location, beamName, fixedOffset, tablePositionList, dwellFractionList]), where the arguments in [ ] are optional.

- type: string keyword to indicate type of calibration scan: manual, auto, autocirc
  - "manual" – A separate scan will be done for each table position. The user can input a list of calibration table wheel positions with the tablePositionList argument.
  - "auto" – default dwell fraction =(0.33, 0.33, 0.34) and default three positions = (Observing, Cold1, Cold2). The user can specify a list of positions and dwell times with the tablePostionList and dwellFractionList arguments.
  - "autocirc" – dwell fraction =(0.25, 0.25, 0.25, 0.25) and four positions = (Observing, [Position2 for beamName='1' or Position5 for beamName='2' for use with circular VLBI observations], Cold1, Cold2).
- scanDuration: scan exposure time, in seconds. For manual mode, each specified position will be observed for the scan exposure time (i.e., separate scans for each position). For auto modes, the total scan exposure time will be divided between positions based on the dwell fractions (i.e., one scan for all positions).
- location: a Catalog source name or Location object; default is None (use current location).
- beamName: Beam name associated with pointing location. This argument is a string. Default beam is '1'.
- fixedOffset: offset sky position (used in cases when observing a bright source and want to measure the system temperature of the sky off-source). This argument should be an Offset object. Default sky offset is 0.
- tablePositionList: user-specified, variable-length ordered list of cal table positions for the manual or auto modes. The default sequence is ['Observing', 'Cold1', 'Cold2'].
- dwellFractionList: user-specified, ordered list of dwell fractions associated with the tablePositionList for use only with the auto mode. By using auto mode with tablePositionList and dwellFractionList, expert users can control the wheel in any order of positions and dwell fractions. This input is not needed for autocirc or manual modes and is ignored in these modes if given.

Example usage of the CalSeq command:

- CalSeq("auto",45.0). This command can be used for most observations, which uses the default tablePositionList=['Observing', 'Cold1', 'Cold2'].
- CalSeq("auto",45.0,fixedOffset=Offset("J2000", "00:00:00", "00:02:00")). This command can be used for bright objects where one wants a system temperature measurement on blank sky. In this example, the offset is $2'$ to the north. If observing a large object, one can increase the offset size to move off-source for the blank-sky measurement.

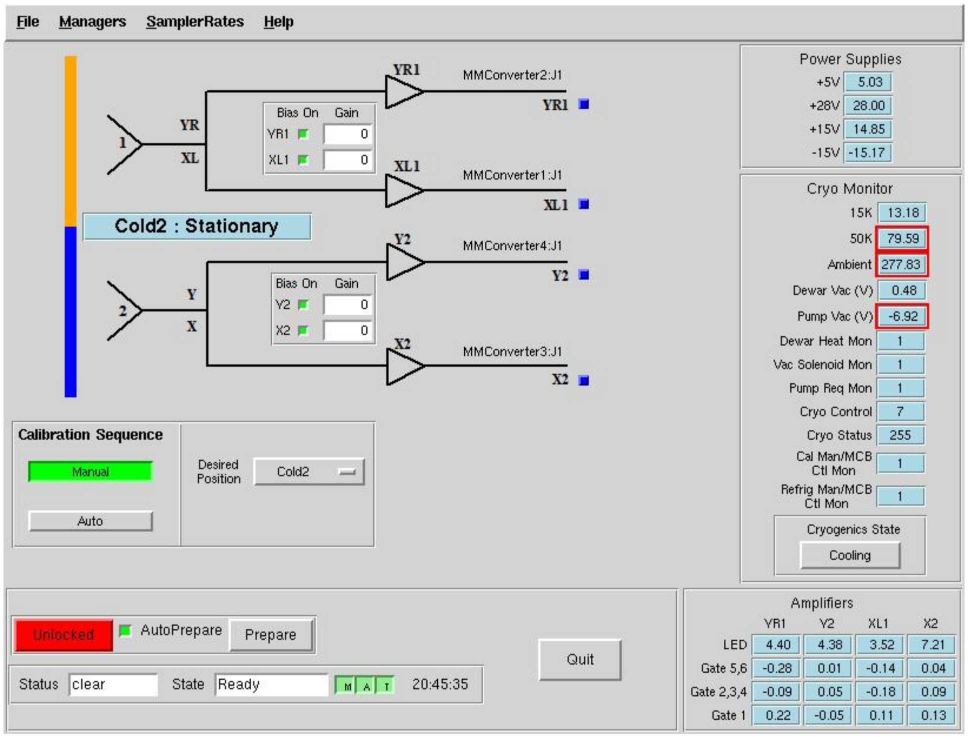


Figure 8.2: The 4mm Receiver CLEO window. Users can manually move the wheel by using the "Desired Position" button. The temperature of the ambient load used for calibration is given by the "Ambient" temperature sensor value shown at the right (277.83 K in this example).

- CalSeq("manual",10.0,tablePositionList=['Position2', 'Observing', 'Cold1', 'Cold2']). This is an example command for calibration of VLBI observations with beam-1 circular polarization. We can only observe the cold and ambient loads with linear polarization. The calibration from linear to circular requires observations of the same sky with both linear and circular polarization (Observing and Position2, respectively, in this example).

8.3.2 AutoOOF Thermal Corrections

Optimal point-source observations should be carried out with regular AutoOOF measurements (every 2-4 hours) during the nighttime when the thermal stability of the dish is best. The AutoOOF corrections can improve the point-source aperture efficiency by 30–100% at W-band. Application of the AutoOOF corrections during the day are typically not practical at W-band given the thermal environment of the dish is generally not sufficiently stable. During the day, the measured beam sizes can vary significantly (e.g., 10–14″), but the main-beam shape typically remains fairly symmetric and Gaussian. Although the variation of beam size has a direct impact on the point-source aperture efficiency (η_a), it has less of an impact on the effective main-beam efficiency (η_{mb}) used for the calibration of extended sources. Therefore, extended sources may be observed during the day without the AutoOOF corrections if the science is not impacted by the primary beam variations.

8.3.3 Pointing and Focus

Blind pointing at the start of the observing run may not be successful since the blind pointing errors can be similar to the beam size, and the source may be missed in the simple Az-El scans used by the Peak procedure. Initial pointing offsets can be found with the AutoOOF procedure, or users may want

Table 8.1: 4mm Channel Definitions

Channel	Polarization	Beam
ch1	beam1 (fdnum=0)	X or L (plnum=0)
ch3	beam1 (fdnum=0)	Y or R (plnum=1)
ch5	beam2 (fdnum=1)	X or L (plnum=0)
ch7	beam2 (fdnum=1)	Y or R (plnum=1)

Table Notes: The GBT IF channel numbers 1,3,5,7 and their corresponding beam and polarization definitions. The parameters fdnum and plnum are GBTIDL keywords.

to point first with X-band. If pointing is problematic at W-band, e.g., observations during the day, or in periods of marginal weather, or in cases where the pointing source is too weak, observers can point and focus in X-band and use these telescope corrections for their W-band observations. Pointing and focus for W-band requires special attention, and users should not blindly accept the default solutions provided by the software system. Users can enter solutions manually as needed as discussed in Section 4.1.3.4.

8.4 Calibration and Data Reduction

For calibration of the antenna temperature scale, users need to run a CalSeq for each set of source data. For absolute flux calibration, a source of known flux density should be observed. The ALMA Calibrator Source Catalog has an extensive record of the flux density histories for many of the bright 3mm point sources (https://almascience.eso.org/sc/). By using ALMA flux density values as a function of time, ∼10% absolute calibration uncertainties can be obtained for W-band data.

The standard GBTIDL scripts (getps, getnod, getfs) do not work since these assume a noise diode for calibration. Example W-band scripts for the reduction of spectral line data can be found at /home/astro-util/projects/4mm/PRO. Users can use the calseq.pro within GBTIDL to derive the gains for each of the channels. After deriving the gains, users can reduce the spectra-line data, for example, using wonoff_gain.pro.

The equations and methods for calibrating W-band data are given in GBT Memo #302.

8.5 Documentation

- W-Band Web Page: http://www.gb.nrao.edu/4mm
- GBT Calibration Memo: Frayer et al. (2019)
- W-band configuration and observing scripts: /home/astro-util/projects/4mm
- GBTIDL reduction scripts: /home/astro-util/projects/4mm/PRO
- ALMA Source Catalog: https://almascience.eso.org/sc/

Chapter 9

Argus (74-116 GHz)

9.1 Overview

The Argus instrument is a 16 element focal-plane-array operating from 74 GHz to 116 GHz. The feeds are configured in 4×4 array and are each separated by 30.4 arcsec on the sky (Figure 9.1). Argus has an absorber vane that can be placed over the entire array for calibration. The 16 Argus beams can be connected to the 16 separate VEGAS channels (VEGAS has 8 banks each of which have two channels [A1, A2, B1, B2, C1,C2... H1, H2]). Each of the 16 beams only measure one polarization (linear "X"). Argus uses an IQ-mixer scheme to separate the USB and LSB (Figure 9.2), and the side-band isolation is approximately 15-20 dB.

The instantaneous bandwidth for Argus is approximately 1.5 GHz which is similar to the VEGAS spectrometer bandwidth. Users can observe multiple lines simultaneously using the VEGAS sub-banding modes (modes 20-29) for lines separated by less than the ~ 1.25 effective bandwidth of an individual VEGAS bank. For spectral-line mapping experiments, Argus is typically configured with each of the Argus beams connected to an individual VEGAS channel. Beams 9-16 use the regular GBT IF system and can be configured with multiple VEGAS banks, or the DCR for pointing, focus and OOF. Beams 1-8 have dedicated IF paths that are only connected to specific VEGAS banks.

For the chopper-vane calibration technique that Argus adopts, the natural temperature scale measured is T_A^* (GBT Memo#302).This temperature scale has the advantage of correcting for atmospheric attenuation while its derivation is nearly independent of opacity. Users need to take a vane calibration sequence whenever the configuration changes or whenever the IF system is balanced to calibrate the data.

9.2 Configuration

The Argus RcvrArray75_115 receiver uses the standard config-tool software that automatically configures the system based on user input (e.g., frequency and bandwidth). Example Argus configuration files are given in /home/astro-util/projects/Argus/OBS. The configuration keywords specific to Argus are the following:

- receiver = "RcvrArray75_115" (name of the receiver)
- beam = "all" (for all 16 beams), or list the beams separately, e.g., beam =”10,11”
- swmode = "tp_nocal" or "sp_nocal". There are no noise diodes with this receiver.
- polarization = "linear"
- sideband = "LSB" (for best performance, use LSB below 112 GHz and USB at higher frequencies)

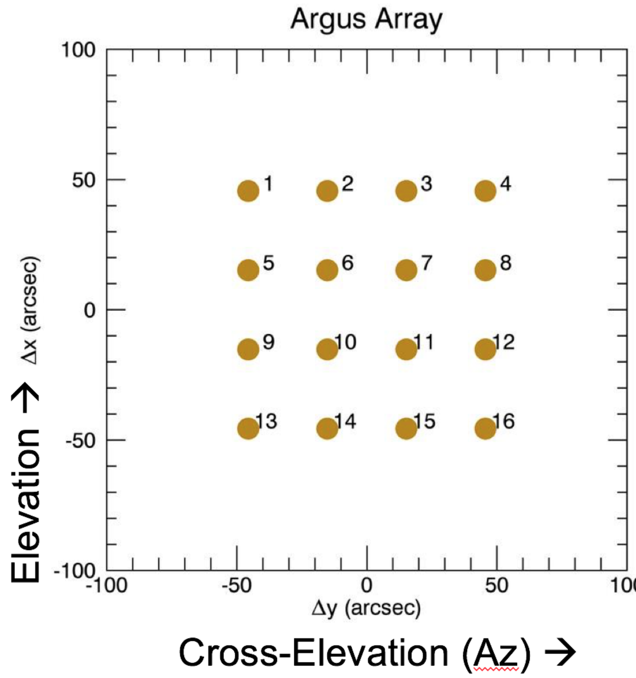


Figure 9.1: The relative orientation of the 16 beams in the Argus array as seen on the sky. The beam separation is 30.4 arcsec in the elevation and cross-elevation directions.

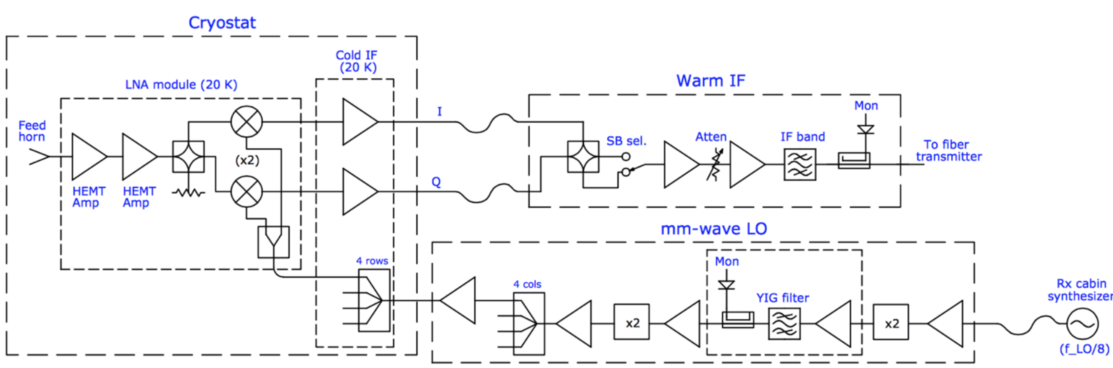


Figure 9.2: The block diagram for the Argus array showing one channel. The input LO signal goes through a 50 MHz YIG filter and is split down 16 paths for each of the individual beams. The system uses an IQ-mixer to separate USB and LSB, and only one side-band can be selected at a time. The output IF signal that is transmitted down the optical fiber system to the GBT equipment room (VEGAS) is centered on 1.525 GHz.

9.3 Observing

The observing strategies for Argus are similar to those presented for the 4mm Receiver (Chapter 8). To maximize the telescope efficiency for targets smaller or similar in size to the beam ($\sim 8''$), observations should be carried out during the night under stable thermal conditions. Depending on the science goals, successful daytime observations are possible for extended sources, where accurate beam shapes are not as crucial. Example Argus observing scripts are located at /home/astro-util/projects/Argus/OBS. The recommended observing procedures are the following:

- Startup Astrid and go online (with control of the telescope, when given permission by the operator). (Section 4.1.3.3).
- Run the argus_startup script. This script script checks the instrument status, turns ON the instrument if it is currently OFF, and pre-configures the instrument for the default 90 GHz parameters.
- At the start of the observing session, run an AutoOOF to optimize the surface, unless the exact beam shape is not important for your science goals [astrid command: AutoOOF(source)]. This procedure will correct the surface for the current thermal conditions and derive the initial pointing and focus corrections. For AutoOOF, it is recommended to use the brightest point source inthe sky between 25–80 degree elevation. If the Ka-band receiver is available, run the AutoOOF at Ka-band instead of Argus for more accurate surface corrections[1]. After the AutoOOF solutions are applied, run a point and focus with Argus to confirm the telescope collimation offsets after the application of the OOF solutions. When running AutoOOF with Argus, it is recommended to avoid using the the calSeq=False keyword so the data will be properly calibrated in fitting for the surface model. The Astrid ObservationManagement Log will report the system temperatures on the sky from the initial vanecal scans. The same Astrid command "AutoOOF(source)" can be used for any of the receivers that use AutoOOF (i.e., Ka, Q, W, Argus), and the software will adopt the appropriate defaults for each band.
- For Argus, run autopeak_focus with a bright pointing source ($>$ 1.5 Jy) within $\sim$30 deg of the target region; brighter sources are better than closer sources since the GBT pointing model is fairly accurate. Choose a frequency that is the approximate frequency of your science frequency since the YIG filter system can take time to adjust to large frequency shifts. For the best science results, autopeak_focus should be run every 30 - 50 minutes depending on conditions (point more often during the day and after sunrise and sunset). Avoid pointing in the "key-hole" (el>80 deg). Since the elevation pointing offsets can be larger than those observed typically in azimuth, use the elAzOrder=True keyword to observe the elevation Peak scans first. An example pointing command showing the usage of the frequency, calSeq, and elAzOrder keywords is AutoPeak(source, frequency=90000., calSeq=False, elAzOrder=True).
- If pointing is problematic with Argus, e.g., observations during the day, or in periods of marginal weather, or in cases where the pointing source is too weak, observers can point and focus in X-band and use these telescope corrections for their Argus observations. Also, if there are no nearby bright sources to point with Argus and the telescope is at slow slew rate (at cold temperatures), it can be faster to switch receivers for pointing than to slew far away and point with Argus. Pointing and focus using Argus requires special attention, and users should not blindly accept the default solutions provided by the software system. Users can enter solutions manually as needed as discussed in Section 4.1.3.4. If you are unsure of the Argus pointing results, point in X-band (which is adjacent to Argus in the turret).
- After configuration and balancing VEGAS for science observations, check the power levels in the system. The VEGAS levels should be $\sim -20 \pm 3$dBm (Fig. 9.4). The target power levels in the IF rack (for beams 9-16) are 1.5 Volts. The YIG LO power level going into the instrument should

[1]The focus position of the Ka-band receiver is -6 mm offset from the nominal focus position used by the other receivers, including Argus. If using a local focus correction (LFC) solution from Ka-band, add 6 mm to the LFC value to be applicable for Argus.

range from ∼ 0.2–0.6 Volts (above 84 GHz). The power coming out of the warm electronics of Argus should read about ∼ 1.0–1.4 for beams 1-8 and ∼ 0.5–0.9 for beams 9-16 (under the TP column of the WIF section of the Argus CLEO window, see Fig. 9.3).

- Users must run the argus_vanecal procedure to calibrate the data (/users/astro-util/projects/Argus/OBS/argus_vanecal) after each configuration and/or balance for observations that need to be calibrated. The vane calibration is stable over longer periods than is needed for pointing and focusing, so only one argus_vanecal procedure is required for each set of VEGAS observations between the pointing and focus observations. Under stable temperature conditions, the vane calibration is consistent over several hours while it is recommended to point and focus every 30–50 minutes for Argus.
- It is best to observe similar frequencies together in time since it can take a few minutes for the YIG system to adjust to large frequency jumps. If you need to switch by a large amount in frequency (e.g., > 4 GHz), configure and wait a couple of minutes before observing. If the YIG LO power is low after a large frequency shift (e.g., < 0.2), re-configure again.
- Only beams 9-16 that go through the GBT IF Rack can be configured with the DCR. All 16 beams can be configured with VEGAS using the 8 dedicated optical fibers for Argus beams 1-8.
- Beam-8 has very little sideband rejection and will show higher noise when using the LSB at high frequency (e.g., when the O_2 atmospheric line is in the USB).
- The "Auto" procedures will run vanecal observations by default. For pointings/focus scans that do not need to be calibrated, observers can use the calSeq=False keyword, e.g., AutoPeak(source, frequency=90000., calSeq=False). The use of the calSeq=False keyword will save a minute or two of time. However, it is recommended to run the vanecal observations while pointing between science blocks of observations in order to track the performance of the system from the calibrated peak scans. If your frequency is not specified, the default frequency for the Argus Auto procedures is 86000 MHz.
- Beam 10 is the default signal beam and beam 11 is the default reference beam for pointing, focus, and OOF observations.
- The instrument performance using VEGAS can be checked by running the vanecal.pro procedure within GBTIDL. Example Argus data reduction scripts are located at /users/astro-util/projects/Argus/PRO.
  The vanecal.pro routine uses the getatmos.pro procedure which derives the opacities and atmospheric conditions from the Green Bank Weather database.
- For absolute calibration carryout PEAK scans after applying good surface, pointing, and focus corrections for a source of known flux density (e.g., ALMA source catalog (https://almascience.eso.org/sc/).
  The ALMA calibrator catalog can also be used to check the strength of your pointing/focus source. The calibration methods and performance of the telescope are presented in GBT Memo#302.

9.4 Argus Monitoring and Diagnostics

9.4.1 Argus CLEO

The Argus CLEO window can be used to monitor the status of the instrument (Figure 9.3). This tool can be started from the CleoLauncher under the Receivers tab labeled "75-115 GHz 16-pixel". The CLEO window can be used for running basic instrument commands, such as "Startup" or the vane control (buttons within the **Commands** section of the CLEO window). Before issuing a command, you must unlock the CLEO window by clicking the Green "Locked" button to "Unlocked" (red). The

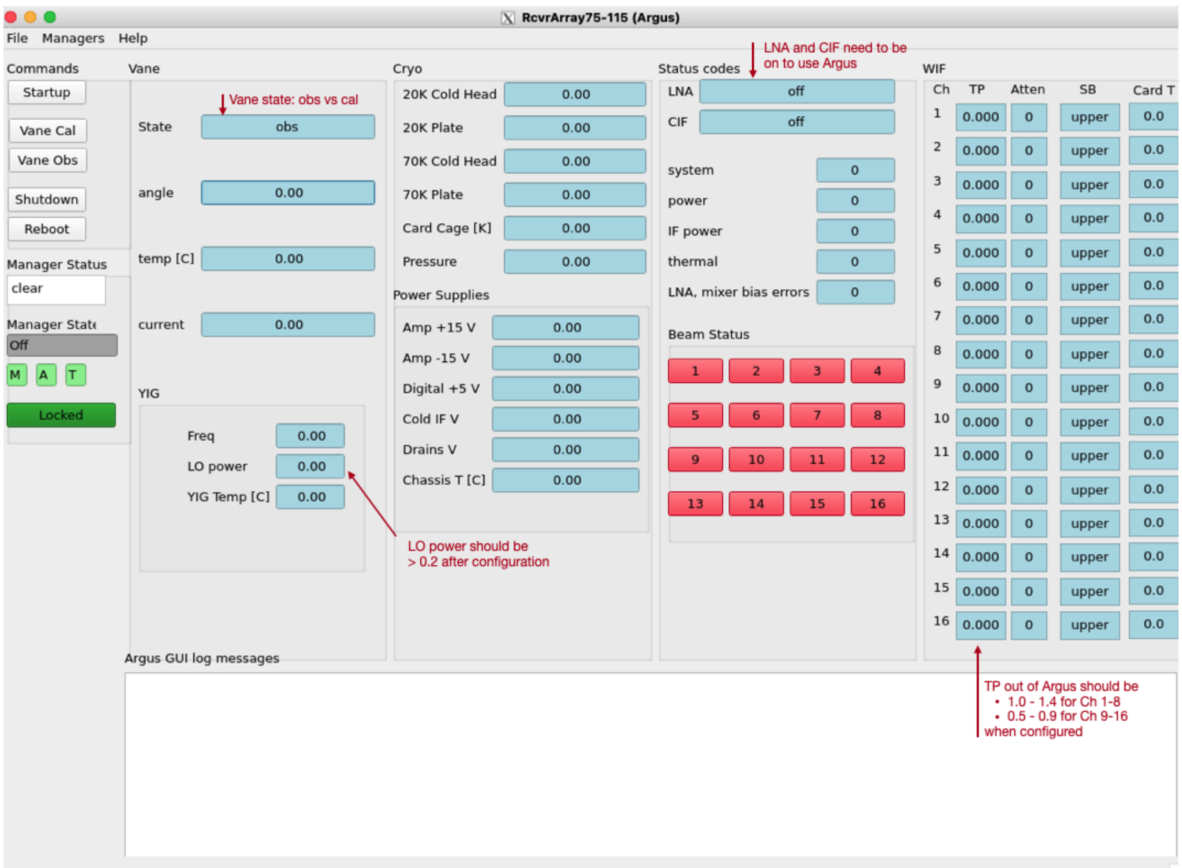


Figure 9.3: The Argus CLEO window can be started from the CleoLauncher under the Receivers tab labeled “75-115 GHz 16-pixel”. The tool can be used to monitor and carry out simple commands with the instrument.

Figure 9.4: The VEGAS CLEO window with all 16 beams connected to Argus. The VEGAS power levels should be $\sim -20 \pm 3$dBm when balancing on blank sky. When observing the vane, the associated levels would be ~ -15dBm since the ambient vane temperature is ~ 3 times the typical sky level. In this example, VEGAS Bank H1 which is connected to Argus beam-6 is not in range.

instrument parameters shown by CLEO for Argus are updated after a configuration, at the start of each scan during observing, and every 30 minutes when not observing. Updated instrument values can be obtained by issuing a "Prepare" command, which is done under the top Managers tab (prepare) or the Prepare button under the Reboot button 9.3.

The **Beam Status** buttons are color coded, where green means the signal associated with the beam is good and red indicates a potential issue with a beam. If a beam is red, the data may still be usable depending on the system temperature associated with the beam.

The **Vane** state is "obs" when the Argus feeds are looking at the sky (with an angle of ~ 3.4) and "cal" when the vane is covering Argus during the VANE calibration scan (angle of ~ 1.6).

The LNA and CIF (low noise amplifiers and cold IF electronics) need to be in the on state to carry out observations. After configuration, the YIG LO power (listed under the **YIG** section) should be ~ 0.2–0.6 [Volts]. The total power levels of the WIF (warm IF electronics) should read about ~ 1.0–1.4 for beams 1-8 and ~ 0.5–0.9 for beams 9-16 after configuration and while observing.

9.4.2 Argus IF Routing

The mapping between the VEGAS channels, Converter Modules, IF channels, and the VEGAS beams is shown in Figure 9.5. Observers should verify the VEGAS power levels are $\sim -20 \pm 3$dBm via the VEGAS CLEO window (e.g., Figure 9.4). As an example shown by Figure 9.4, the VEGAS channel H1 is -33 dBm which is too low to yield useful data. The H1 VEGAS bank corresponds to VEGAS channel J15, converter module CM12, dedicated fiber "6", and Argus beam 6. In this example, the data associated with Beam-6 from Argus would be bad and would show non-physical system temperatures.

Mapping Argus Beams to VEGAS and IF Channels

VEGAS Bank	VEGAS (J)	Argus Beam	Converter Module CM	IFrack Optical Driver OD	Dedicated Fibers
A1	1	9	1	1	-
A2	2	11	5	3	-
B1	3	10	2	2	-
B2	4	12	6	4	-
C1	5	1	3	-	1
C2	6	3	7	-	3
D1	7	2	4	-	2
D2	8	4	8	-	4
E1	9	13	9	5	-
E2	10	15	13	7	-
F1	11	14	10	6	-
F2	12	16	14	8	-
G1	13	5	11	-	5
G2	14	7	15	-	7
H1	15	6	12	-	6
H2	16	8	16	-	8

Figure 9.5: The mapping between Argus beams, VEGAS, and the GBT IF system.

9.4.3 Argus Troubleshooting Guide

The Argus CLEO window can be used to troubleshoot Argus issues, which can be launched from cleo under the Receivers tab by selecting ”75-115 GHz 16-pixel”

- To control the instrument unlock the system by selecting the green button ”Locked” on left to unlock the window (it turns red when unlocked).
- To get the current status of the instrument click the ”Prepare” button which is the last Command listed in the upper left.
- When done, lock the system to avoid accidently issuing a command by clicking the red unlocked button to green (locked).

- Confirm that the CIF and LNA are both on. If off, then run the Argus startup script.
- Make sure the vane is in the desired position (e.g., obs for looking at the sky). If the vane is “stalled” or in an unknown state, click the Vane Obs button to move the vane to the obs position. If the vane is not already in the obs position, a configuration will also command the vane to the obs position. If the vane fails to move have the operator contact a support scientist.
- Confirm there is LO power from YIG after configuration.
- The status of the instrument is checked before each scan, and the scan will be aborted if there is not enough YIG LO power, or for other major issues. If the YIG power is too low, or the WIF power levels are low, and/or if one or more of the beam Status colors are red, reconfigure. If one or more the beams are bad, observations with the remaining beams can continue, but one must have sufficient YIG LO power to carry out Argus observations.
- Sometimes the GBT M&C system will report old Argus errors when everything is working. You can ignore and continue observing, or try to clear the lingering error messages with the following procedure.
  - Click ”Prepare” to retrieve updated instrument paramaters which may clear the error.
  - If the error persists, turn the manager off and back on from the Managers pull-down menu at the top of the CLEO window. Click off, wait a couple of seconds, and then click on.
  - This usually clears the error messages. Sometimes the error message(s) need to be cleared manually from the messageMux system by the software group.
- If Argus communication errors occur (e.g., Netburner time out error), then the recent commands given to Argus may not have been done and you may need to re-configure and re-issue your observing script. Within the Argus CLEO window, click the “Prepare” button to collect the current state of the instrument. If the LNA/CIF are off under the **Status Codes**, run the Startup script and then reconfigure. Turn the manager off and back on again to clear the Netburner errors.
- If Argus is in a “fault” state after configuration and you are unable to collect data after multiple attempts then:
  - Turn manager off and back on again (under the Managers tab at the top of the Argus CLEO window) and reconfigure.
  - If cycling the manager does not work, have the operator restart turtle and/or “grail” and reconfigure.
  - If neither of the above work, then have the operator contact a support scientist.

9.5 Argus Data Reduction

Argus is calibrated on the T_a^* antenna temperature scale. Observations need to run a set of vanecal observations for each set of science data. For absolute flux calibration, a source of known flux density should be observed. The ALMA Calibrator Source Catalog has an extensive record of the flux density histories for many of the bright 3mm point sources (https://almascience.eso.org/sc/). By using ALMA flux density values as a function of time, ∼10% absolute calibration uncertainties can be obtained for Argus data. The methods and equations for calibrating Argus data are presented in GBT Memo# 302.

The standard GBTIDL scripts (getps, getnod, getfs) do not work with Argus data, since these assume a noise diode for calibration. Example Argus scripts for the reduction of spectral line data can be found at /home/astro-util/projects/Argus/PRO. Users can use the vanecal.pro procedure within GBTIDL to derive the Tcal value and the system temperatures for each of the Argus beams. Frequency switched data can be reduced using argus_fsw.pro, and position switch data can be reduced using argus_onoff.pro.

9.6 Documentation

- **Argus Web Page:** http://www.gb.nrao.edu/argus/
- **GBT Calibration Memo:** Frayer et al. (2019)
- **Argus configuration and observing scripts which are used in Astrid:** /home/astro-util/projects/Argus/OBS
  - **argus_startup:** Script that turns Argus on if it is not already on. The script configures the instrument with the default settings. This is run at the start of an Argus observing session.
  - **argus_vanecal:** Script that runs the vanecal observations. It observes with the vane over the array as well as blank sky scan with a default 6 arcmin offset from the commanded position to avoid a bright calibrator object. If observing the Moon or a very bright extended continuum source, one can use the argus_vanecal_bigoffset2 or argus_vanecal_bigoffset to observe blank sky.
  - **autooof:** Script that runs the AutoOOF observations. The sources listed are the brightest W-band sources in the sky.
  - **autopeak_focus:** Script that runs pointing and focus observations. The pointing observations are run first, and then the script issues a break to allow the user to enter the solutions manually into the system before the focus scan.
  - **autopeak_calibrate:** Calibration script to run on a known calibrator to compute the aperture and main-beam efficiency of the telescope after good pointing and focus corrections have been applied.
  - **argus_config_example:** Example total power configuration (tp_nocal) for Argus.
  - **mapRA:** Example frequency switching (sp_nocal) observing script for a RA/Dec map.
- **GBTIDL reduction scripts:** /home/astro-util/projects/Argus/PRO
  - **getatmos.pro:** Script that returns the atmospheric opacity and effective atmospheric noise and temperature for a specific time and frequency from the Green Bank Observatory weather database. This needs to be run on a Green Bank computer since using special code that only runs locally.
  - **vanecal.pro:** Script that computes the system temperature for each of the Argus beams from the vanecal observations. The script uses getatmos.pro to compute the Tcal value (see GBT Memo#302).
  - **argus_fsw.pro:** Script that calibrates a frequency switched observation.
  - **argus_onoff.pro:** Script that calibrates a position switched observation.
- **ALMA Source Catalog:** https://almascience.eso.org/sc/

Part III

Backends

Table 9.1: GBT backends.

Name	Notes
DCR	The Digital Continuum Receiver directly from the IF Rack. One frequency available.
DCR_AF	The Digital Continuum Receiver from the Analog Filter Rack Four/two frequencies maximum for single/dual beam receivers.
VEGAS	Spectral line backend with up to 524288 channels and 64 frequencies with various bandwidths.
VLBA_DAR	Very Long Baseline Array Data Acquisition Recorder.
Radar	For bi-static radar observations. Private backend.
CCB	CalTech Continuum Backend

Table 9.2: Allowable bandwidths for backends.

Backend	Receiver	Possible Bandwidths (MHz)
VEGAS	Any	1500, 1000, 187.5, 100, 23.44, 16.9, 11.72
DCR, VLBI, or Radar	Prime Focus	20, 40, 80, 240
DCR, VLBI, or Radar	Rcvr1_2, Rcvr4_6, Rcvr8_10, Rcvr12_18	20, 80, 320, 1280
DCR, VLBI, or Radar	Rcvr2_3, RcvrArray18_26, Rcvr40_52	80, 320, 1280
DCR_AF	Any	12.5, 50, 200, 800
CCB	Rcvr26_40	600

Chapter 10

VEGAS

10.1 Overview

The The VErsatile GBT Astronomical Spectrometer (VEGAS) is an Field-Programmable Gate Array (FPGA) based spectrometer that can be used with any receiver except MUSTANG-2. It consists of eight independent spectrometers (banks) that can be used simultaneously. Eight-bit samplers and polyphase filter banks are used to digitize and generate the spectra – together they provide superior spectral dynamic range and RFI resistance. For details on the design of VEGAS, please consult http://www.gb.nrao.edu/vegas/report/URSI2011.pdf.

Observers can use between one and eight dual-polarization spectrometers (or "banks") at the same time (see Fig. 10.1). Each bank within VEGAS can be configured with a different spectral resolution, bandwidth, and number of spectral windows (subbands). However, the integration time (tint), switching period (swper), and the frequency switching offset (swfreq) values **must** each be the same for all banks. The resolution and bandwidth of all subbands in a single VEGAS bank must be identical, but the center frequencies may be set independently (within limits).

Although the individual banks could be arranged to cover 10 GHz of total bandwidth, the maximum bandwidth is typically limited to 4-6 GHz by filters in the GBT IF system (see your project friend for more information). All banks have the same switching signal (i.e., same switching period, same integration time, same frequency switching offset), which is controlled by spectrometer bank "A". Each bank can be configured in one of the 29 modes listed in Table 10.1.

- **Modes 1-19** provide a single subband per bank. Modes 1–3 have the following constraints on useable bandwidth:
  - **Modes 1-2**: Have a useable bandwidth of 1250 MHz within the baseband bandwidth of 1500 MHz. The useable baseband frequency range is 150–1400 MHz.
  - **Mode 3**: Has a useable bandwidth of 800 MHz within the baseband bandwidth of 1080 MHz. The useable baseband frequency range is 150–950 MHz.
- **Modes 20-29** provide up to eight subbands per bank. To use more than one subband, set subband=8, and the actual number of subbands used is then defined by the number of frequencies provided. All subbands must have equal bandwidths and be placed within the total bandwidth processed by that bank:
  - **Modes 20-24**: Have a useable bandwidth of 1250 MHz within the baseband bandwidth of 1500 MHz. The useable baseband frequency range is 150–1400 MHz.
  - **Modes 25-29**: Have a useable bandwidth of 800 MHz within the baseband bandwidth of 1080 MHz. The useable baseband frequency range is 150–950 MHz.

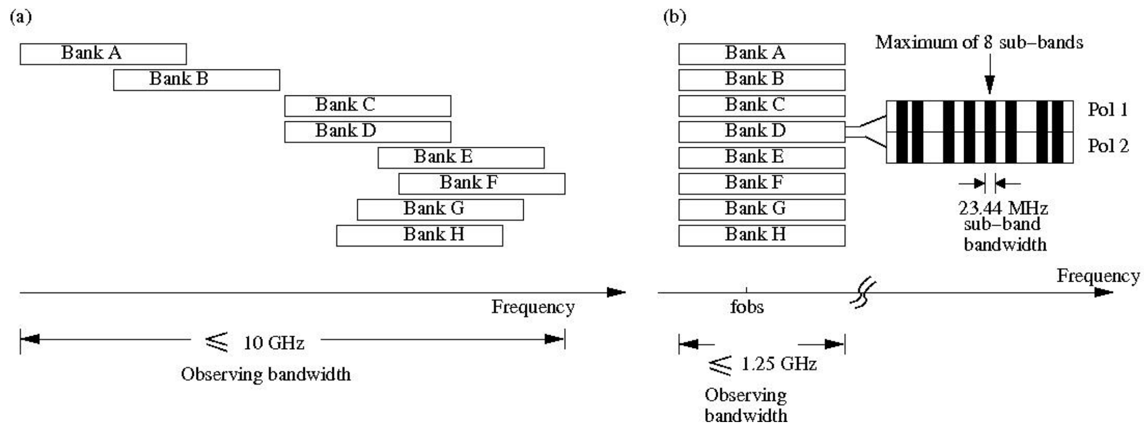


Figure 10.1: Examples of two basic VEGAS setups. Since each bank can be configured independently, these setups can be mixed and matched with the restriction that all banks have the same switching signal. (a) *Wide band, single beam, dual polarization observations.* The 8 banks can be tuned to a different frequencies where each bank produces a single spectral window. (b) *Narrow band, multiple beam, dual polarization mode.* Each bank can provide a maximum of 8 spectral windows (subbands).

Each mode provides the polarization products XX, YY, and optionally XY,YX necessary for observations of polarized emission without requiring a reduction in the number of channels or sampling speed. VEGAS can also record only a single polarization for single-polarization receivers.

10.2 Data Rates

The data rate for an individual bank can be calculated using

$$\text{Data Rate (GB/hr)} = 1.34 \times 10^{-5} \cdot \frac{n_{\text{channels}} \times n_{\text{spw}} \times n_{\text{stokes}} \times n_{\text{states}}}{t_{\text{int}}(\text{seconds})}, \tag{10.1}$$

where n_{channels} is the number of channels per spectral window, n_{spw} is the number of spectral windows, n_{stokes} is the number of stokes parameters (2 for dual polarization, 4 for full polarization), n_{states} is the number of switching states (4 for frequency switching and 2 for total power), and t_{int} is the integration time. The total data rate for a project can be calculated by adding the data rates for each bank together.

10.3 IF Configuration

The GBT IF system introduces some constraints on routing signals from the receivers to VEGAS.

- Single beam receivers or a multi-beam receiver that has been configured to use a single beam may be routed to any or all of the VEGAS banks A→H. No spectral resolution is gained with VEGAS by only using one beam of a multi-beam receiver.
- Dual-beam configurations allow each beam to be routed to a maximum of 4 VEGAS banks.
- When using 3–4 beams, each beam may be routed to up to a maximum of 2 VEGAS banks.
- When using more than 5 beams, each beam may only be routed to a single VEGAS bank.
- When using all 7 beams of the KFPA, each beam may be routed to a single VEGAS bank with an optional second copy of beam 1 being routed to the remaining VEGAS bank. This is known as the “7+1” mode of the KFPA.

Table 10.1: VEGAS Modes, including blanking, supported by each of the 8 VEGAS spectrometers.

Mode	Bandwidth (MHz)	Channels	Spectral resolution (kHz)	Minimum int. time[b] (ms)	Max data rate[a] at minimum int. time (MBs^{-1})
Single Sub-band modes					
1[c]	1500	1024	1465.00	1	32
2[c]	1500	16384	92.00	2	187
3[d]	1080	16384	66.00	4	130
4	187.5	32768	5.70	11	52
5	187.5	65536	2.90	22	52
6	187.5	131072	1.40	35	69
7	100	32768	3.10	12	51
8	100	65536	1.50	25	51
9	100	131072	0.80	40	69
10	23.44	32768	0.70	16	93
11	23.44	65536	0.40	33	93
12	23.44	131072	0.20	72	75
13	23.44	262144	0.10	134	93
14	23.44	524288	0.04	246	125
15	11.72	32768	0.40	27	93
16	11.72	65536	0.20	55	93
17	11.72	131072	0.10	123	62
18	11.72	262144	0.04	223	93
19	11.72	524288	0.02	447	93
8 Sub-band modes[e]					
20[c]	23.44	4096	5.70	6	12
21[c]	23.44	8192	2.90	12	12
22[c]	23.44	16384	1.40	35	8
23[c]	23.44	32768	0.70	51	12
24[c]	23.44	65536	0.40	97	13
25[d]	16.9	4096	4.10	8	9
26[d]	16.9	8192	2.10	17	9
27[d]	16.9	16384	1.00	47	6
28[d]	16.9	32768	0.51	69	9
29[d]	16.9	65536	0.26	132	10

[a] Maximum data rate is calculated for recording full polarization and all channels at the minimum integration period for one spectrometer. Each spectral value is represented by 4 bytes.

[b] The integration per switching state should be $\geq$ the minimum integration. For example, if an observation uses 2 switching states, then the minimum integration will be 2 times the value listed in the table.

[c] For modes 20→24 the subbands can be placed within the baseband bandwidth of 1500 MHz (see note *d*) and for modes 25→29 the subbands can be placed within 1000 MHz.

[d] The actual usable frequency range for modes 1 & 2 as well as 20→24 is 1250 MHz and for mode 3, as well as 25→29 is 800 MHz.

[e] To use more than one subband, set subband=8, and the actual number of subbands used is then defined by the number of frequencies provided.

10.4 Blanking

While the observing system is switching between states (such as switching the noise diodes on or off, switching frequencies, running doppler updates, etc...) the collected data is not valid, and thus must be 'blanked' by VEGAS. VEGAS allows the user to switch states frequently enough that the required blanking time can become a non-negligible percentage of the total observing time. For efficient observing, it is important to choose switching periods that are long enough for the total amount of blanking to be negligible. The amount of blanking per switching signal is dependent on the VEGAS mode used. Conservative values are shown in Tables 10.2 and 10.3 for values with the noise diode turned either on or off. For a more thorough description of the appropriate switching periods for a given amount of blanking, and more accurate estimates of the minimum switching periods we refer the interested reader to Kepley, R. Maddalena, and R. (2014).

10.5 Monitoring VEGAS observations

The Spectral Line tab in the AstrID Data Display (See § 4.1.6) is not fully capable of displaying VEGAS observations in real time (it will display passbands at the end of a scan, and may be used in offline mode). Rather, there are four monitoring tools that are useful with VEGAS:

- the VEGAS CLEO screen (See § 4.3.1).
- VEGASDM – the VEGAS Data Monitor (See § 4.3.2).
- vegas_status – the VEGAS shared memory display.

The first two items are generally useful while observing with VEGAS and are described in S 4.3, while `vegas_status` is for specialized problem diagnosis only.

10.6 The Online Filler and Filling VEGAS data using SDFITS

VEGAS writes "Engineering" FITS files. Once a scan is over, the "Filler" reads these files, combines the data with metadata from the Antenna and other FITS files, and produces a single-dish (SDFITS) file. This can be done automatically, by the on-line filler, or manually by the Observer. Due to the significantly higher data rate, and some other features of VEGAS, the filling process requires some oversight by the user.

10.6.1 The Online Filler

The online filler will make every attempt to fill the SDFITS file automatically. In this case, a file will be produced in `/home/sdfits/<project>` and GBTIDL can connect to it automatically using the "online", or "offline, <project>" commands. There are some caveats, however.

- Because of the way VEGAS writes its data, the filler cannot start filling until the scan has finished.
- For "large" scans, the filler could potentially fall behind the data acquisition process. To avoid this, the filler will skip scans that it cannot keep up with. The rule is:

```
If (integrationTime / totalNumberOfSpectraPerIntegration) < 0.00278s
    skip the scan
Except if (integrationLength >= 0.9s) it will be filled
```

Table 10.2: Minimum recommended switching periods (swper) with VEGAS for observations that **use a noise diode**.

	Total power (`tp`)	**Frequency switching**[a] (`sp`)		
Mode	Nominal[b] swper (sec)	Nominal[c] swper (sec)	$\nu_{min}{}^{d}$(GHz) swper=1.52 sec	Mapping[e] swper (sec)
1	0.01	0.4	115.0	0.4
2	0.028	0.4	115.0	0.4
3	0.04	0.4	115.0	0.4
4	0.028	0.4	115.0	0.4
5	0.0559	0.4	115.0	0.4
6	0.1118	0.4318	115.0	1.52
7	0.0524	0.4	115.0	0.4
8	0.1049	0.4249	115.0	1.52
9	0.2097	0.5297	59.6	1.52
10	0.2237	0.5437	54.4	1.52
11	0.4474	0.8948	16.5	1.52
12	0.8948	1.7896		1.7896
13	1.7896	3.5791		3.5791
14	3.5791	7.1583		7.1583
15	0.4474	0.8948	16.5	1.52
16	0.8948	1.7896		1.7896
17	1.7896	3.5791		3.5791
18	3.5791	7.1583		7.1583
19	7.5383	14.3166		14.3166
20	0.028	0.4	115.0	0.4
21	0.0559	0.4	115.0	0.4
22	0.1118	0.4318	115.0	1.52
23	0.2237	0.5437	54.4	1.52
24	0.4474	0.8948	16.5	1.52
25	0.0388	0.4	115.0	0.4
26	0.0777	0.4	115.0	1.52
27	0.1553	0.4753	89.7	1.52
28	0.3107	0.6307	33.8	1.52
29	0.6214	1.2428	8.6	1.52

[a] When frequency switching, switching periods must always be >0.4 seconds due to the settling time of the LO1.

[b] Recommended minimum switching period (`swper`) for total power observations with noise diodes (`swtype='tp'`). These values will yield less than 10% blanking overall.

[c] Recommended minimum switching period for frequency switching observations with noise diodes (`swtype='sp'`). These values will yield less than 10% blanking in the first state of the switching cycle as well as less than 10% blanking overall.

[d] The minimum recommended switching period is 1.52 seconds **when Doppler tracking** frequencies above ν_{min}.

[e] Recommended minimum switching period (`swper`) for **Doppler-tracked**, frequency switching observations with noise diodes (`swtype='sp'`). These values will yield less than 10% blanking in the first state of the switching cycle as well as less than 10% blanking overall. This switching period will result in less than 10% of the data being blanked. These values assume that the maps are sampled at twice Nyquist in the scanning direction and that there are four integrations per switching period **when Doppler tracking**.

Table 10.3: Minimum recommended switching periods (swper) with VEGAS for observations that **do not use a noise diode**.

	Total power (`tp_nocal`)		**Frequency switching**[a] (`sp_nocal`)		
Mode	Nominal[b] swper (sec)	Mapping[c] swper (sec)	Nominal[d] swper (sec)	ν_{min}[e] (GHz) swper=0.76 sec	Mapping[f] swper (sec)
1	0.0005	0.001	0.4	115.0	0.4
2	0.0014	0.0028	0.4	115.0	0.4
3	0.002	0.004	0.4	115.0	0.4
4	0.01	0.0114	0.4	115.0	0.4
5	0.0199	0.0227	0.4	115.0	0.4
6	0.0301	0.0357	0.4	115.0	0.76
7	0.0102	0.0128	0.4	115.0	0.4
8	0.0203	0.0256	0.4	115.0	0.76
9	0.0301	0.0406	0.4	115.0	0.76
10	0.0056	0.0168	0.4	115.0	0.76
11	0.0112	0.0336	0.4474	33.1	0.76
12	0.028	0.0727	0.8948		0.8948
13	0.0447	0.1342	1.7896		1.7896
14	0.0671	0.2461	3.5791		3.5791
15	0.0056	0.028	0.4474	33.1	0.76
16	0.0112	0.0559	0.8948		0.8948
17	0.0336	0.123	1.7896		1.7896
18	0.0447	0.2237	3.5791		3.5791
19	0.0895 or[g] 0.38	0.4474	7.1583		7.1583
20	0.0051	0.0065	0.4	115.0	0.4
21	0.0101	0.0129	0.4	115.0	0.4
22	0.0301	0.0357	0.4	115.0	0.76
23	0.0405	0.0517	0.4	115.0	0.76
24	0.0755	0.0979	0.4474	33.1	0.76
25	0.007	0.009	0.4	115.0	0.4
26	0.0141	0.018	0.4	115.0	0.76
27	0.0398	0.0476	0.4	115.0	0.76
28	0.0544	0.0699	0.4	68.6	0.76
29	0.101	0.132	0.6214	17.1	0.76

[a] When frequency switching, switching periods must always be >0.4 seconds due to the settling time of the LO1.

[b] Recommended minimum switching period (`swper`) for total power observations that do not use noise diodes (`swtype='tp_nocal'`). This value is equivalent to the hardware exposure value for VEGAS.

[c] Recommended minimum switching period (`swper`) for total power OTF mapping observations that do not use noise diodes (`swtype='tp_nocal'`) **when Doppler Tracking**. These values will yield less than 10% blanking overall and assume that the maps are sampled at twice Nyquist in the scanning direction and that there are four integrations per switching period.

[d] Recommended minimum switching period for frequency switching observations that do not make use of noise diodes (`swtype='sp_nocal'`). These values will yield less than 10% blanking in the first state of the switching cycle as well as less than 10% blanking overall.

[e] The minimum recommended switching period is 0.76 seconds **when Doppler tracking** frequencies above ν_{min}.

[f] Recommended minimum switching period (`swper`) for **Doppler-tracked**, frequency switching OTF mapping observations without noise diodes (`swtype='sp_nocal'`). These values will yield less than 10% blanking in the first state of the switching cycle as well as less than 10% blanking overall. This switching period will result in less than 10% of the data being blanked. These values assume that the maps are sampled at twice Nyquist in the scanning direction and that there are four integrations per switching period.

[g] For mode 19 this value is 0.0895/0.38 seconds for observations below/above 10.3 GHz **when Doppler tracking**.

The total number of spectra per integration is the total across all banks. So, for example, 2 banks, 8 subbands, 2 polarizions and 4 switching states (e.g. frequency switching with calibration) will produce 2*8*2*4 = 128 spectra, and so if the integration time is < 0.356s the online filler will not fill that data. The 0.9s limit is because for that integration time the online filler can almost keep up even in the worst case, and interscan latencies, pauses for pointing and focus scans, and so on will nromally allow it time to catch up. The online filler prints a summary in `/home/sdfits/<project>/<project>.log` indicating what scans were filled, had problems and were skipped, and if any data was skipped because the data rate was too fast.

The decision on whether to fill or not is made independently for each bank. For cases where the integration time is close to the limit it's possible that some banks might be filled while others are not filled for the same scan if the number of subbands or the number of polarizations vary across the banks. The summary log file will indicate when this happens.

If observers are concerned about the interpolation across the center channel (see § 10.7.1) they can turn that off in sdfits by using the "-nointerp" option.

10.6.2 Filling Offline

You may wish to (re-) fill your data offline. In this case, you may use the SDFITS filler program in the standard manner. Note however, that the actual VEGAS data is stored to a high-speed ("lustre") file system. For a current list of lustre client machines please see
https://greenbankobservatory.org/portal/gbt/processing/#data-reduction-machines

If you try to fill data without being logged into a lustre client, the filler will fail with the error message:

```
VEGAS data expected but not found, this workstation is not a lustre client.
For a list of public lustre client workstations see:
http://www.gb.nrao.edu/pubcomputing/public.shtml
```

–In this case, ssh to a lustre client (using the domain `.gb.nrao.edu`), and fill your data there.

Filling using sdfits directly (instead of the output online sdfits) might also be useful if there are a lot of spectra to be processed in GBTIDL simply because it improves the response times in GBTIDL if there are not as many spectra to search through. So if there's a convenient way to divide up the scans, then this sort of syntax works (sdfits -help for more details):

```
sdfits -backends=vegas -scans=<scan-list> <PROJECT_SESSION> <OUTPUT_PREFIX>
```

- `scan-list` is a list of comma separated scans to fill using colons to denote ranges e.g., `-scans=1,4:6,10:` would fill scans 1,4,5,6 and all scans from 10 onwards.
- `<PROJECT_SESSION>` is what you'd expect, e.g. "AGBT14A_252_04".
- `<OUTPUT_PREFIX>` is the leading part of the output directory name, e.g. `scan5to25` would result in a directory named `scan5to25.raw.vegas`

10.7 Instrumental Features and their Cure

The architecture of the VEGAS hardware, specifically the architecture of the Analog to Digital Converter (ADC), results in some characteristic features in the VEGAS spectrum. Specifically, these are:

- a strong spurious single-channel wide spike at the exact center of the ADC passband – the so-called "center spike".
- weak single-channel wide spurs at various locations in the bandpass – the 32 spurs.

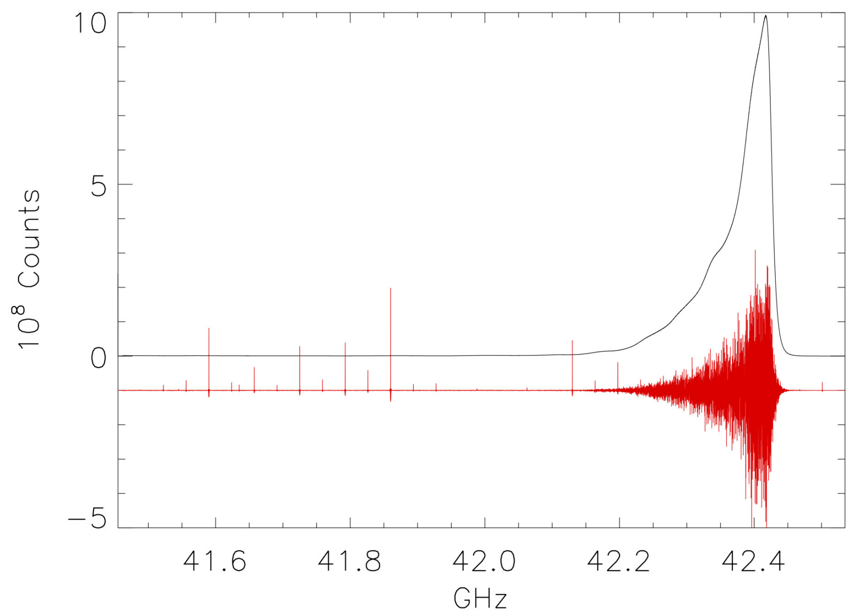


Figure 10.2: Spectra of a noise source centered near 42.4 GHz (black). A high pass filtered version of the data (offset by -1 and scaled by a factor of 100 for visibility) is shown in red, showing the spurs.

10.7.1 The Spike

The center spike is caused by the FPGA clock. By default, the center spike is interpolated over by the SDFITS filler by taking the mean of the adjacent channel on either side of the spike. The center spike is also interpolated-over by the real-time spectrum display. We have chosen to interpolate over this spike as it is omnipresent, and can cause problems for data reduction (such as system temperature calculations). If you are concerned about this process, you may shift your line from the center of the passband using the deltafreq keyword in your astrid script.

10.7.2 The Spurs

When attempting to search for RFI with VEGAS by running a high-pass filter through the data, significantly more spikes/spurs were found than naively expected. These spurs could be found in the same bins in relatively RFI free wavelengths, such as Q–band. The spurs appear at the same location (in bin space) for a given mode and have relatively stable amplitudes. These faint spurs are not always directly visible in the data, but became clear when high-pass filtered, as shown in Figure 10.2. After significant testing, it was determined that these spurs are below the spurious-free dynamic range of -60dBc specified by the manufacturer, and cannot be fully removed. In overly simplistic terms, the spurs are caused by the leaking of the FPGA clock into the four interleaved ADCs.

These spurs are relatively stable and will remain constant (for a given mode) and the magnitude of the spurs is relatively constant. These features are also quite small by most standards (Spurious Free Dynamic Range no more than -60dBc), but nevertheless can be problematic when looking for faint narrow features. The stability of these features allows them to be removed by standard data practices (such as position and/or frequency switching), but they are an added noise source which can bleed through to the final product. Due to the limited and often negligible effect of these spurs, we do not automatically interpolate across them, but let the user decide how to handle those channels.

10.8 Known Bugs and Features

10.8.1 Data is not filling

The online filler checks for project changes when it is not actively filling a scan. This means that if the previous project was a VEGAS one and it ended on a long scan, the filler may still be filling that project when the VEGAS scan has finished in your project. If you suspect that this is the case, the only solution is to ask the Operator to restart the online filler task.

— All data can still be accessed in GBTIDL by running SDFITS offline (see § 10.6.2).

10.8.2 There is a "square wave" and/or divot in my VEGASDM display

The samples which are taken to produce the VEGASDM total power display run asynchronously to the switching signals. Hence, the sampling may occur during the "Cal on" phase at one point in time, and then drift into the "Cal off" phase sometime later. This may produce an apparent square wave in the VEGASDM output, with an amplitude of a few tenths of a dB, and a period of seconds.

Similarly, it is possible for the VEGASDM data to be acquired when the LO is updating (e.g. during a Doppler track). These data are blanked in the true VEGAS spectral data acquisition, but may cause drop-outs in the VEGASDM samples.

Chapter 11

The CalTech Continuum Backend (CCB)

The Caltech Continuum Backend (CCB) is a dedicated continuum backend for the GBT Ka-band receiver, built in collaboration with A.C.S. Readhead's radio astronomy instrumentation group at Caltech and commissioned on the GBT in 2006. The driving consideration behind its design is to provide fast electronic beam switching in order to suppress the electronic gain fluctuations which usually limit the sensitivity of continuum measurements with single dish radio receivers. To further improve stability, it is a *direct detection* system: there are no mixers before the conversion from RF to detected power. The Ka-band receiver provides *eight* simultaneous, directly detected channels of RF power levels to the CCB: one for each feed, times four frequency channels (26-29.5 GHz; 29.5-33 GHz; 33-36.5 GHz; and 36.5-40 GHz). Astronomical information and labels for these 8 channels (or "ports" in GBT parlance) are summarized in Table 11.1.

The following sections outline the process of observing with, and analyzing the data from, the CCB. Much of the information in this chapter is also maintained at `/users/bmason/ccbPub/README.txt` which is convenient, for instance, for cutting and pasting data analysis commands. Template scheduling blocks are also in this directory.

Table 11.1: CCB Port labels and the astronomical quantities they measure.

Port	Beam	Polarization	Frequency
9	1	Y	38.25
10	1	Y	34.75
11	1	Y	31.25
12	1	Y	27.75
13	2	X	38.25
14	2	X	34.75
15	2	X	31.25
16	2	X	27.75

11.1 Observing with the CCB

11.1.1 Configuration

Configuration of the CCB is straightforward, and for most purposes the only two configurations needed are provided in the two configuration files:

- /users/bmason/ccbPub/ccb.conf
- /users/bmason/ccbPub/ccbbothcalslong.conf

These differ only in the duration of the integrations: the former configures for 5 millisecond integrations, which is useful for estimating the scatter in the samples to obtain meaningful χ^2 values in the analysis of science data; the later configures for 25 millisecond integrations, which is useful in peak/focus observations to speed up processing of the data (see Chapter 4, section 4.1.3). `ccb.conf` is reproduced and explained below.

The following keywords tell ASTRID to expect beam-switched continuum observations with Ka and the CCB:

```
receiver    = 'Rcvr26_40'
beam        ='B12'
obstype     ='Continuum'
backend     ='CCB'
nwin        =4
restfreq    =27000,32000,35000,38000
deltafreq   =0,0,0,0
bandwidth   =600,600,600,600
swmode      ='sp'
swtype      ='bsw'
pol         ='Circular'
vdef        ='Radio'
frame       ='topo'
```

They do not have any practical effect on the actual instrument configuration but are necessary to set up internal variables and ensure the recorded FITS files are accurate.

```
ccb.cal_off_integs  =20
ccb.XL_on_integs    =2
ccb.both_on_integs  =2
ccb.YR_on_integs    =2
ccb.bswfreq         =4
tint                =0.005
```

The meaning of these keywords is as follows:

- The first four specify the cal firing pattern.
- `ccb.bswfreq` specifies the beam switching frequency in kHz. 4 kHz is standard; the "> 10% blanking" warning which results is also standard and may be safely ignored.
- `tint` is the integration time in seconds.

11.1.2 Pointing & Focus

The online processing of pointing and focus data is handled by GFM (which runs within the Astrid Data Display window) similarly as for other GBT receivers and the DCR. A few comments:

- because the Ka–band receiver currently only has one polarization per beam, GFM will by default issue some complaints which can be ignored. These can be eliminated by choosing "Y/Right" polarization in the AstrID Data Display window (see Chapter 4, section 4.1.3.2) under Tools → Options → Data Processing.
- in the same menu (Tools → Options → Data Processing), choosing "31.25 GHz" as the frequency to process, instead of the default 38.25 GHz, can improve robustness of the result.
- The results shown in the Astrid Display are in *raw counts*, not Kelvin or Janskys.
- Processing the data with "Relaxed" heuristics is also often helpful, which is the default processing option for Ka-band (Section 4.1.3.3).

There is a template pointing and focus SB for the CCB in `/users/bmason/ccbPub` called `ccbPeak.turtle`. This scheduling block does a focus scan, four peak scans, and a symmetric nod (for accurate photometry to monitor the telescope gain).

11.1.3 Observing Modes & Scheduling Blocks

Science projects with the CCB typically fall into two categories: mapping, and point source photometry. The majority of CCB science is the latter, since this is what, by design, it does best. Template scheduling blocks for both are in `/users/bmason/ccbPub`.

Observers and support scientists are strongly encouraged to use these template scheduling blocks as the basis for their CCB observing scripts and make only the changes that are required! Relatively innocuous changes can make the data difficult or impossible to calibrate with existing analysis software.

The basic template SBs are:

- `ccbObsCycle.turtle`: perform photometry on a list of sources.
- `ccbRaLongMap.turtle`: perform a standard `RALongMap` on a source (see 5.4.3).
- `ccbMap.turtle, ccbMosaicMap.turtle`: make maps using longer, single-scan, custom raster maps. Your project friend will help tailor these to your project's needs, should you choose this approach.

Point source photometry is accomplished with an OTF variant of the symmetric NOD procedure described in 5.4.2. This procedure, which we refer to as the OTF-NOD, alternately places the beam in each of the two beams of the Ka–band receiver in a B1/B2/B2/B1 pattern. This sequence cancels means and gradients in the atmospheric or receiver emission with time. Plotting the beamswitched data from this sequence produces a sawtooth pattern shown in Figure 11.1; this is discussed more in § 11.1.5. Each NOD is 70 seconds long (10 seconds in each phase, with a 10 second slew between beams and an initial 10 second acquire time).

Note: OTF-NOD is not one of the standard scan types; it is implemented in the scripts mentioned here (e.g., "ccbObsCycle.turtle").

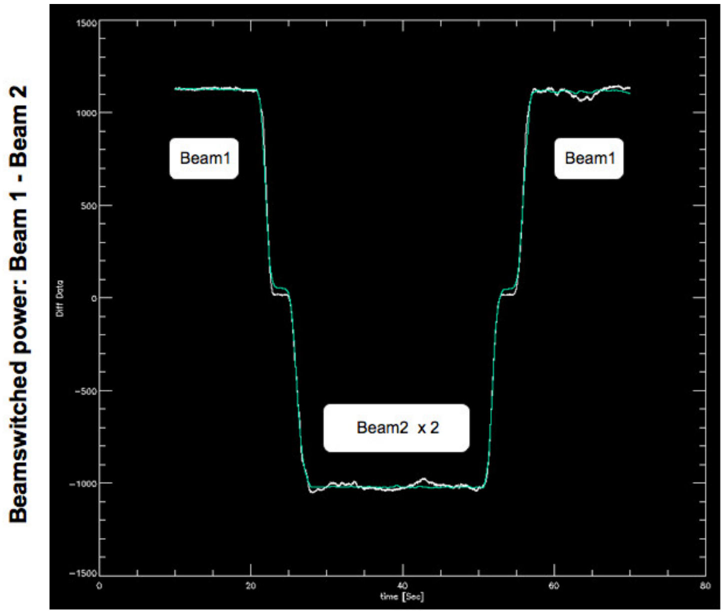


Figure 11.1: Data from a CCB, beamswitched OTF-NOD, showing data and model versus time through one B1/B2/B2/B1 scan. The white line is the CCB beam-switched data and the green line is the fit for source amplitude using the known source and telescope (as a function of time) positions.

11.1.4 Calibration

If at all possible, be sure to do a peak and focus, and perform photometry (an OTF-NOD, as implemented in `ccbObsCycle.turtle` or `ccbPeak.turtle`) on one of the following three primary (flux) calibrators: 3c48, 3c147, or 3c286. This will allow your data to be accurately calibrated (our calibration scale is ultimately referenced to the WMAP 30 GHz measurements of the planets). If this is not possible the calibration can be transferred from another telescope period (observing session) within a few days of the session in question.

11.1.5 Online Data Analysis

It is important to assess data quality during your observing session. There are a set of custom IDL routines for analyzing CCB data; if you use the observing procedures and config files described here, your data should be readily calibratable and analyzable by them. To use the IDL code, start IDL by typing (from the GB UNIX command line)

```
/users/bmason/ccbPub/ccbidl
```

Example OTF-NOD data for bright sources (under good and poor conditions) and a weak source (under good conditions) are shown in Figures 11.2 through 11.5.

Here is an example data reduction session that provides a quick look at your data:

```
; set up global variables
;  don't write files or plots to disk...
proj='AGBT06A_049_09'
setccbpipeopts,gbtproj=proj,ccbwritefiles=0,\$
  gbtdatapath='/home/archive/science-data/tape-0016/'
; to use postprocessing scripts, set ccbwritefiles=1
```

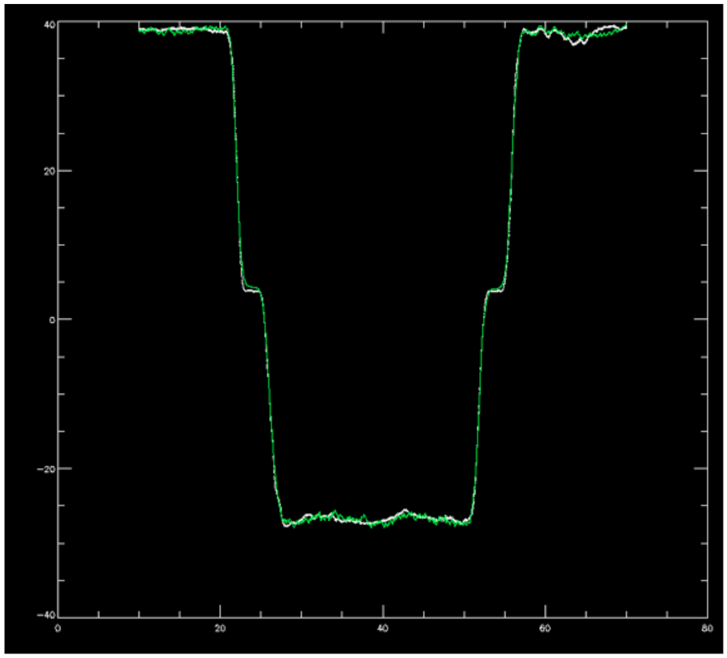


Figure 11.2: CCB data from an OTF-NOD observation of a bright source, showing data and model versus time through one B1/B2/B2/B1 scan. The white line is the CCB beam-switched data and the green line is the fit for source amplitude using the known source and telescope (as a function of time) positions. The close agreement between the data and the fit indicate that neither fluctuations in atmospheric emission nor pointing fluctuations (typically due to the wind on these timescales) are problems in this data.

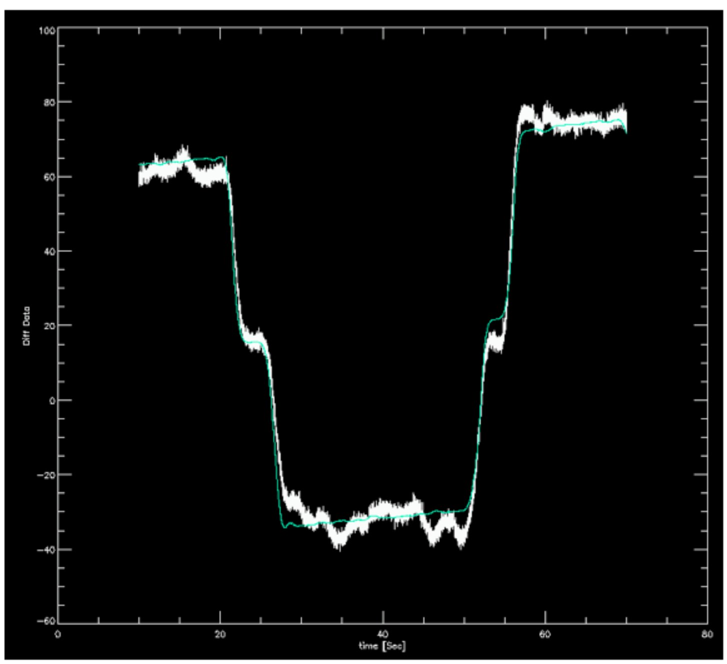


Figure 11.3: CCB OTF-NOD data on a bright source under marginal conditions.The differences between the data and the model are clearly larger in this case.

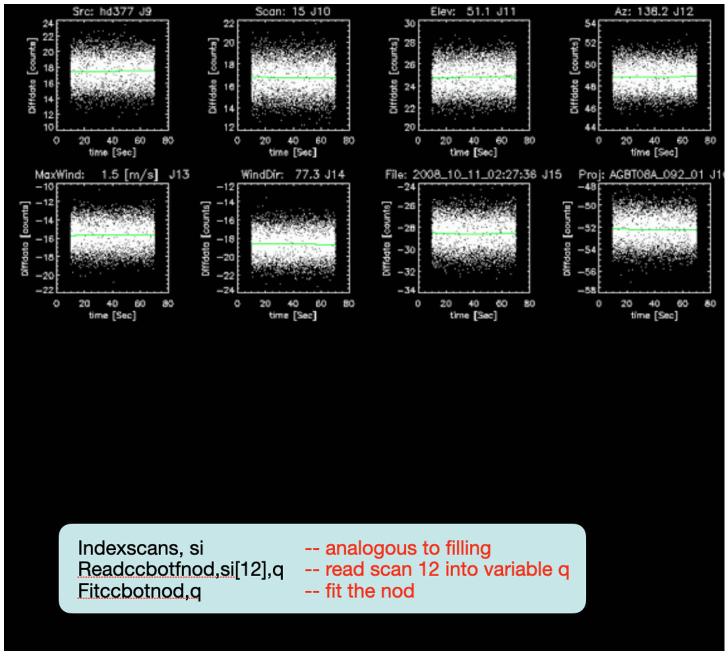


Figure 11.4: CCB OTF-NOD measurement of a weak (mJy-level) source under good conditions. The IDL commands used to obtain this plot are shown inset.

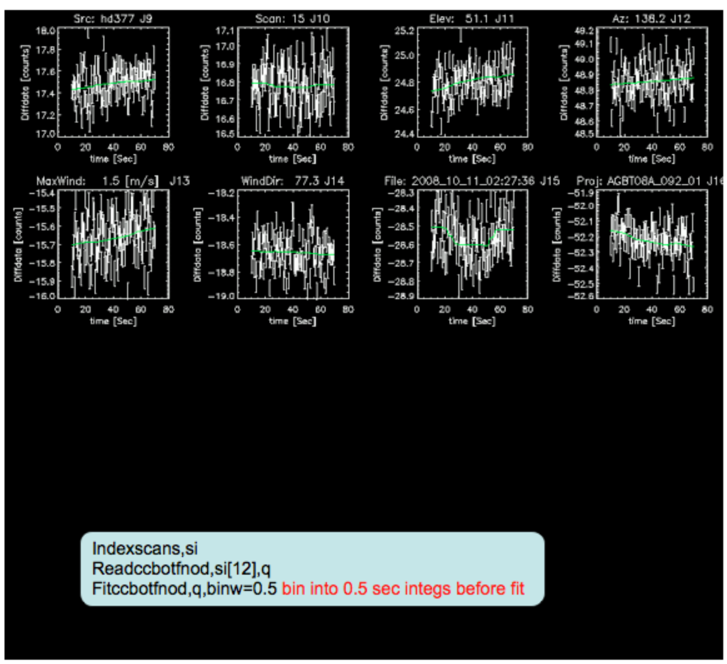


Figure 11.5: The same weak-source data, this time with the individual integrations binned into 0.5 second bins (using `fitccbotfnod`'s `binwidth` optional argument in seconds) so the thermal-noise scatter doesn't dominate the automatically chosen y-axis scale. This better shows any gradients or low-level fluctutions in the beamswitched data (due, for instance, to imperfect photometric conditions). In this data they are not significant.

```
; a good color table for the plots:
loadct,12

; create an array indexing scan numbers
;  to file name
indexscans,si

; summarize the project
summarizeproject

; read a nod observation from scan 12
readccbotfnod,si[12],q
; fit the data, binning integrations to 0.5sec bins
fitccbotfnod,q,qfit,bin=0.5
; the resulting plot shows the differenced
;  data (white) and the fit to the data (green)
;  for each of 16 CCB ports. (the first 8 are blank)

; look at the next nod that just came in
;  this time calibrate to antenna temperature
;  before plotting
; First you need to derive a calibration, which
;  requires a scan with both cals firing independently.
; /dogain tells the code to solve for the calibration;
;  the results are stored in calibdat, which we can
;  pass into subsequent invocations of the calibration.
indexscans,si
readccbotfnod,si[13],q
calibtokelvin,q,/dogain,calibdat=calibdat
fitccbotfnod,q

; the scan index si must be updated to read in scans
;  collected after it was first created
indexscans,si
readccbotfnod,si[14],q
; and calibrate to kelvin using the information
;  we just derived
calibtokelvin,q,calibdat=calibdat
; fit/plot
fitccbotfnod,q

; et cetera...
```

Script 11.1: An example CCB reduction session.

Mapping data can also be imaged using the IDL tools:

```
; make a map from scans 7-10 using port 11 data
;  (note the port must be specified; valid ports are
;   9-16)
img=makedcrccbmap([7,8,9,10],/isccb,port=11)
; replot the map
plotmap,img,/int
; make a png copy of it
grabpng,'mymap.png'
```

```
; save the map in standard FITS format—
saveimg,img,'mymap.fits'
```

Script 11.2: An example CCB reduction session.

This will be a *beam-switched* map. The beam-switching can be removed by an EKH[1] deconvolution algorithm also implemented in the code. Your project friend will help you with this, if needed.

11.2 Performance

Tests under excellent conditions show a sensitivity of 150 μJy (RMS) for the most sensitive single channel (34 GHz), or 100 μJy (RMS) for all channels combined together. These are the RMS of fully-calibrated, 70-second OTF-NODs on a very weak source. Typical "reasonable-weather" conditions are a factor of two worse.

11.3 Differences Between the CCB/Ka System and other GBT Systems

There are a few differences between the CCB/Ka system and other GBT receiver/backend systems which users familiar with the GBT will want to bear in mind.

- Because it is a direct detection system, the GBT IF system does not enter into observing.
- The Ka/CCB gains are engineered to be stable (10% - 20% over months), so no variable attenuators are in the signal chain. Consequently there is no `Balance()` step.
- To optimize the RF balance (for spectral baseline and continuum stability), the OMT's have been removed from the Ka band receiver. It is therefore sensitive to *one linear polarization per feed.* The two feeds are sensitive to orthogonal linear polarizations (X and Y).
- Feed orientation is 45° from the Elevation/cross-Elevation axes. All other receivers have feed separations that are parallel to the Elevation or cross-Elevation axes (except for the KFPA).
- There are two cal diodes (one for each feed), and they are separately controlled (*i.e.*, it is possible to turn one on and not the other). Cals are ON or OFF for an entire integration; they are not pulsed ON and OFF within a single integration.

[1]Emerson, Klein, Haslam 1979 A&A **76**,92.

Part IV

Special Observing Modes

Chapter 12

VEGAS Pulsar Modes

12.1 Overview

VEGAS can be used in pulsar observing modes (VEGAS pulsar modes, or VPM). VEGAS consists of eight CASPER ROACH2 FPGA boards (named vegasr2-1 through vegasr2-8)and twenty-four high performance computers (HPCs) equipped with nVidia RTX 2080 GPUs (labeled A-X). VPM offers many combinations of observing modes, dedispersion modes, numbers of spectral channels, bandwidths, and integration times. Data are written in `PSRFITS`.

12.1.1 Observing Modes

VPM can operate in one of three **observing modes**. All three modes can be used with **coherent** or **incoherent dedispersion**.

- **search:** This mode is used to record spectra with very high time resolution (typically $< 100\ \mu$s) and moderate frequency resolution (> 200 kHz). It is most often used when searching for new pulsars, observing known pulsars when a timing solution is not yet available, observing multiple pulsars simultaneously, or when resolution of individual pulses is required.
- **fold:** This mode is used to phase-fold spectra modulo the instantaneous pulsar period. *This requires a user-supplied pulsar timing solution that can be used by `TEMPO1` in prediction mode* (i.e., to generate "polycos"). Fold-mode is most often used for pulsar timing observations of individual pulsars.
- **cal:** This mode is used for polarization and flux calibration observations of the GBT noise diodes. It is actually a specialized fold-mode in which data are phase-folded at a constant frequency of 25 Hz (or a period of 40 ms). *This requires that the GBT noise diodes be turned on and set to a switching period of 0.04 s* (see §12.2.1 below).

12.1.2 Dedispersion Modes

VPM can operate in **incoherent** or **coherent dedispersion** modes. When using incoherent dedispersion, spectra are written without any removal of intrachannel dispersive smearing, and dedispersion must be performed offline (i.e. incoherently). When using coherent dedispersion, the intrachannel dispersive delay is removed prior to detection, providing higher effective time resolution.

When operating in incoherent dedispersion modes, eup to eight ROACH2 boards can be paired with one HPC each, forming an independent spectrometer bank. We refer to the bandwidth processed by a single ROACH2 board as a spectral window. The center frequency of each spectral window can be tuned independently, and each can cover a bandwidth of 100, 200, 800, or 1500 MHz, though filters in the IF system limit the *maximum usable bandwidth to 1250 MHz per window*. The center frequencies of each window can thus be arranged to contiguously cover up to 8×1250 MHz = 10 GHz, though, once again, IF limitations generally limit the maximum available bandwidth from any receiver to ≤ 4 GHz (up to 8 GHz is available for certain receivers; see Chapter 1.3 for details).

When operating in coherent dedispersion modes, one ROACH2 board sends output to either one, two, or eight HPCs, depending on the bandwidth being processed. With 24 HPCs, up to three ROACH2 boards can be used simultaneously, i.e. up to three spectral windows can be used. When using one spectral window, the bandwidth can be 100, 200, 800, or 1500 MHz (1250 MHz of which is usable). In wide-band coherent dedispersion modes, two or three spectral windows are used, each with an effective bandwidth of 1250 MHz, allowing one to cover up to 3750 MHz instantaneously. In these wide-band modes we refer to the combination of a ROACH2 board and eight HPCs as a data map. Figures 12.1–12.3 show the the possible combinations of ROACH2 boards and HPCs for different dedispersion modes and bandwidths.

Generally speaking, incoherent dedispersion is only recommended in the following use cases:

1. Blind searches for new pulsars
2. Observations at frequencies higher than 4 GHz (i.e., C-Band), when > 1250 MHz of bandwidth is desired.
3. Observations of long-period pulsars in which very high time resolution is not needed (i.e., intra-channel dispersive delays can be tolerated).

Observations of known pulsars, especially for high-precision timing, observations of multiple pulsars with similar dispersion measures (e.g. globular cluster MSPs), and pulsar searches for which a good estimate of the dispersion measure is available should usually use coherent dedispersion.

12.1.3 Available VPM Modes

All configurations are subject to a maximum data rate of 400 MB/s per bank. The data rate per bank can be calculated as

$$R = 8 \text{ bits} \times \frac{n_{\text{pol}} n_{\text{chan}}}{t_{\text{int}}}, \tag{12.1}$$

where n_{pol} is the number of polarization products (4 for full Stokes parameters, 1 for total intensity), n_{chan} is the number of spectral channels, and t_{int} is the integration time (i.e. sampling time). Table 12.1 lists all currently supported VPM modes.

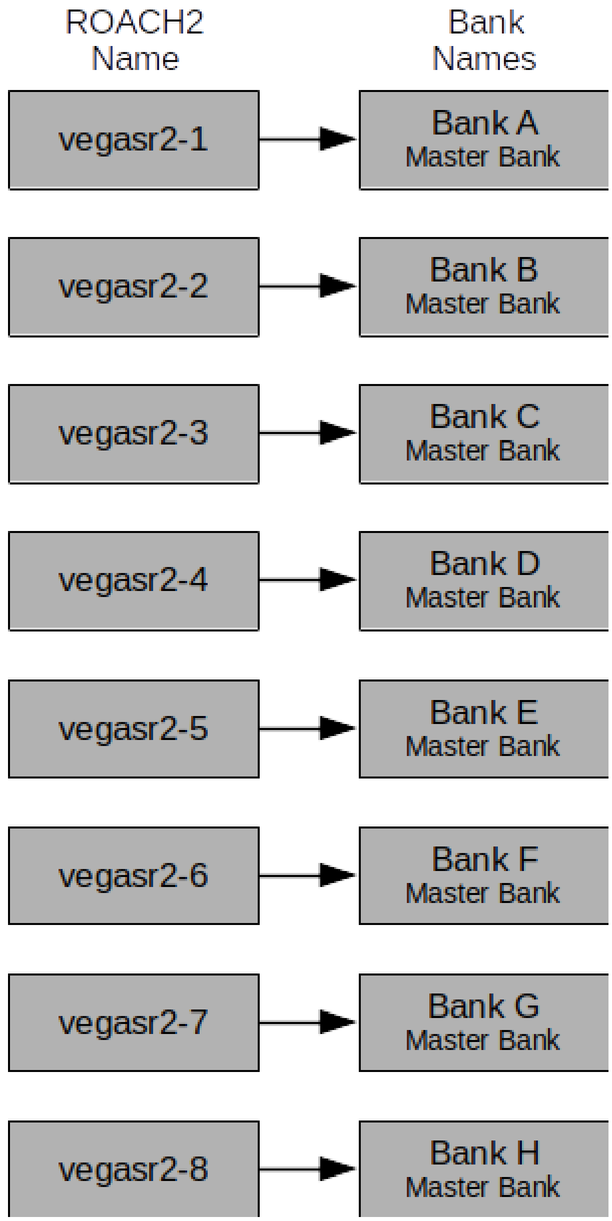


Figure 12.1: Combinations of ROACH2 boards and HPCs when VPM is used in incoherent dedispersion modes. Anywhere from one to eight ROACH2+HPC pairs can be used. The maximum usable bandwidth per ROACH2+HPC pair is 1250 MHz.

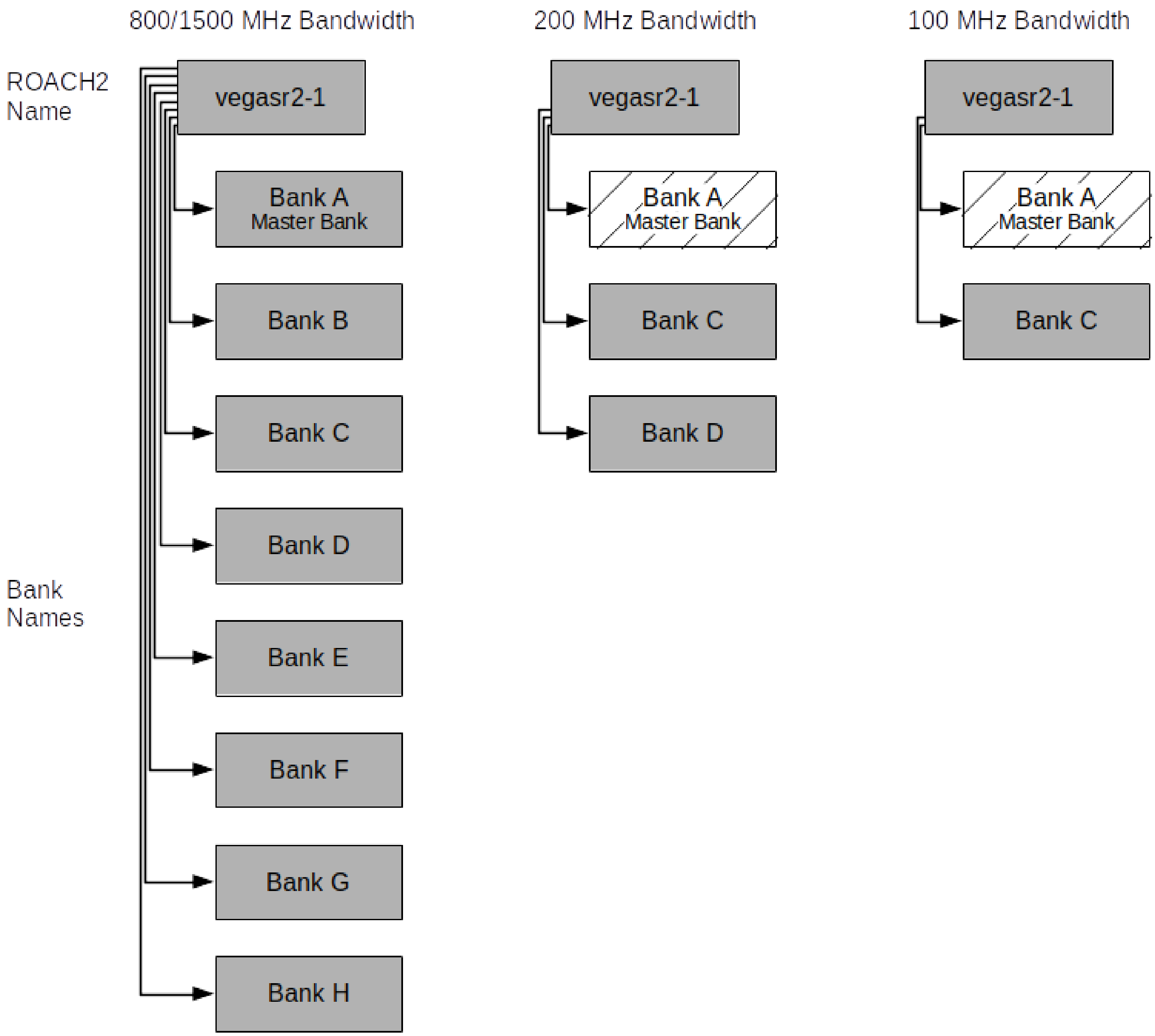


Figure 12.2: Combinations of ROACH2 boards and HPCs when VPM is used in coherent dedispersion modes with one spectral window. One ROACH2 board is paired with one, two, or eight HPCs to cover 100, 200, 800, or 1250 MHz effective bandwidths.

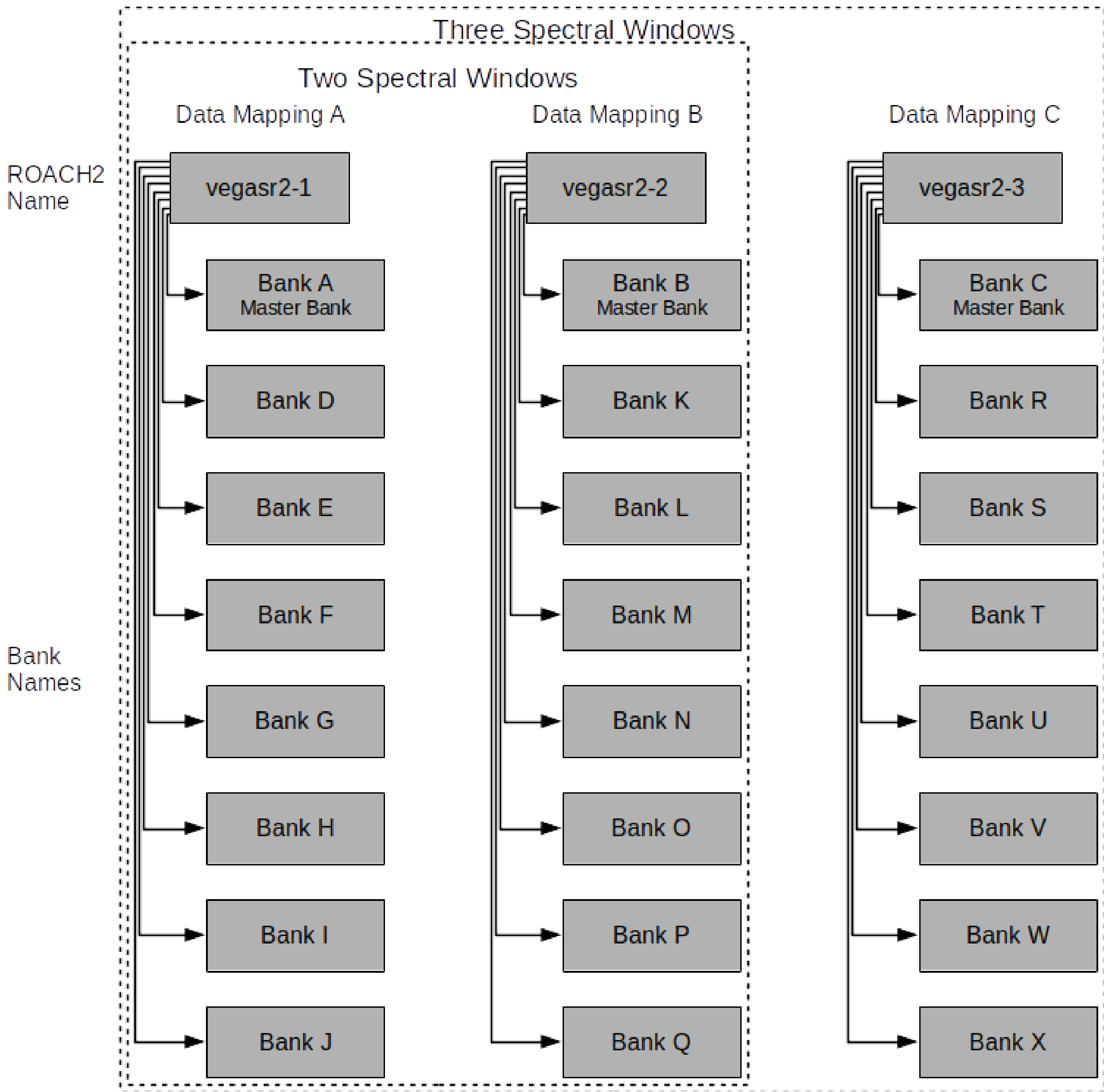


Figure 12.3: Combinations of ROACH2 boards and HPCs when VPM is used in ultra-wideband coherent dedispersion modes. Two or three ROACH2 boards are paired with eight HPCs each to cover up to 3750 MHz effective bandwidth.

12.2 Configuring VEGAS Pulsar Modes

12.2.1 Configuration Keywords

VPM is configured using the standard Astrid keyword/value configuration block, which is discussed in detail in Chapter 5.2. Here we review only those keywords relevant for VPM.

- **obstype** will always be **Pulsar**.
- **backend** will be **VEGAS**.
- **bandwidth** will be either **100, 200, 800 or 1500**. Note that this is the bandwidth of a spectral window
- **ifbw** will be **80** if bandwidth is 100, otherwise ifbw will be **0**
- **tint** is very flexible. Under the hood, it is controlled by the hardware accumulation length, so that $t_{\mathrm{int}} = \mathrm{acc\_len} \times n_{\mathrm{chan}}/\mathrm{BW}$. acc_len can take on values from 4 to 1024. However, we strongly recommend using an integration time corresponding to acc_len ¡ 64 in incoherent dedispersion modes, and equal to 16 in coherent dedispersion modes.
- **swmode** will either be **tp** for calibration scans or **tp_nocal** for pulsar scans.
- **swper** will always be **0.04**.
- **noisecal** will be **lo** for calibration scans (this uses the low-power noise diodes) and **off** for pulsar scans.

The following keywords are VPM specific.

- **vegas.obsmode** controls both the dedispersion and observing mode. Allowed values are
  - **search:** Incoherent dedispersion search-mode
  - **fold:** Incoherent dedispersion fold-mode
  - **cal:** Incoherent dedispersion cal-mode
  - **coherent_search:** Coherent dedispersion search-mode
  - **coherent_fold:** Coherent dedispersion fold-mode
  - **coherent_cal:** Coherent dedispersion cal-mode
- **vegas.polnmode** controls whether full Stokes or total intensity data are recorded. Allowed values are **full_stokes** and **total_intensity**, though total intensity can only be used in incoherent search-mode.
- **vegas.numchan** sets the number of spectral channels. See Table 12.1 for allowable values.
- **vegas.outbits** controls the number of bits used for output values. The only allowed value is **8** in standard observing modes.
- **vegas.scale** controls the VPM internal gain so that the output data is properly scaled for 8-bit values. This value is typically chosen from experience with the observing set-up. Contact your project friend for advice on which value to use.
- **vegas.dm** controls the DM used for coherent dedispersion search-mode. It is not used by any other modes.
- **vegas.fold_parfile** specifies the path to the ephemeris (parfile) used for either incoherent or coherent dedispersion fold-modes. *The parfile must be compatible with `TEMPO1` prediction mode.*

Table 12.1: Summary of Available VEGAS Pulsar Modes

Name	Dedispersion Mode	Bandwidth per Window Spectral Window [MHz]	Max. Spectral Windows	n_{chan}
c0100x0064	Coherent	100	1	64
c0100x0128	Coherent	100	1	128
c0100x0256	Coherent	100	1	256
c0100x0512	Coherent	100	1	512
c0200x0064	Coherent	200	1	64
c0200x0128	Coherent	200	1	128
c0200x0256	Coherent	200	1	256
c0200x0512	Coherent	200	1	512
c0200x1024	Coherent	200	1	1024
c0800x0032	Coherent	800	1	32
c0800x0064	Coherent	800	1	64
c0800x0128	Coherent	800	1	128
c0800x0256	Coherent	800	1	256
c0800x0512	Coherent	800	1	512
c0800x1024	Coherent	800	1	1024
c0800x2048	Coherent	800	1	2048
c0800x4096	Coherent	1500	3	4096
c1500x0032	Coherent	1500	3	32
c1500x0064	Coherent	1500	3	64
c1500x0128	Coherent	1500	3	128
c1500x0256	Coherent	1500	3	256
c1500x0512	Coherent	1500	3	512
c1500x1024	Coherent	1500	3	1024
c1500x2048	Coherent	1500	3	2048
c1500x4096	Coherent	1500	3	4096
i0100x0512	Incoherent	100	8	512
i0100x1024	Incoherent	100	8	1024
i0100x2048	Incoherent	100	8	2048
i0100x4096	Incoherent	100	8	4096
i0100x8192	Incoherent	100	8	8192
i0200x1024	Incoherent	200	8	1024
i0200x2048	Incoherent	200	8	2048
i0200x4096	Incoherent	200	8	4096
i0200x8192	Incoherent	200	8	8192
i0800x0032	Incoherent	800	8	32
i0800x0064	Incoherent	800	8	64
i0800x0128	Incoherent	800	8	128
i0800x0256	Incoherent	800	8	256
i0800x0512	Incoherent	800	8	512
i0800x1024	Incoherent	800	8	1024
i0800x2048	Incoherent	800	8	2048
i0800x4096	Incoherent	800	8	4096
i0800x8192	Incoherent	800	8	8192
i1500x0032	Incoherent	1500	8	128
i1500x0064	Incoherent	1500	8	128
i1500x0128	Incoherent	1500	8	128
i1500x0256	Incoherent	1500	8	256
i1500x0512	Incoherent	1500	8	512
i1500x1024	Incoherent	1500	8	1024
i1500x2048	Incoherent	1500	8	2048
i1500x4096	Incoherent	1500	8	4096

- **vegas.fold_bins** controls the number of pulse phase bins used for either incoherent or coherent dedispersion fold- or cal-modes. Enough bins should be used to fully resolve fine profile structure. Typical values are **256** in incoherent dedispersion modes and **2048** in coherent dedispersion fold- or cal- modes.
- **vegas.fold_dumptime** controls the length of a sub-integration in either incoherent or coherent dedispersion fold- or cal-modes. The value is specified in seconds, with **10** s being typical. It must be shorter than the total scan length.
- **vegas.subband** is always **1** for pulsar observing

Experienced observers will recognize that these keywords are very similar to those used by GUPPI, the GBT's previous, now-retired backend. This is by design. Note that the **guppi.datadisk** keyword has no analog in VPM.

12.2.2 Example Configurations

The following scripts illustrate some common VPM configurations. The first example configures a single VPM bank for incoherent dedispersion search-mode.

```
config_vpm_single= """
obstype = 'Pulsar'
# 'receiver' can be any GBT receiver except MUSTANG.  Here, we use Rcvr1_2,
# aka L-Band
receiver = 'Rcvr1_2'
restfreq = 1500.0
nwin = 1
pol = 'Linear'
backend = 'VEGAS'
bandwidth = 800.0
# tint is highly flexible but subject to data rate limits. The true tint
# will be rounded to the nearest value of acc_len * nchan / bw
# where acc_len is an integer that controls the hardware
# accumulation length
tint = 40.96e-6
deltafreq = 0.0
# For 'swmode', choose 'tp' for calibration, 'tp_nocal' for pulsar
# observation
swmode = 'tp_nocal'
swtype = 'none'
swper = 0.04
swfreq = 0
# For 'noisecal' choose 'lo' for calibration, 'off' for pulsar observation
noisecal = 'off'
vlow = 0.0
vhigh = 0.0
vframe = 'topo'
vdef = 'Radio'
# The following keywords are VEGAS specific
# 'vegas.obsmode' can be search, cal, fold, coherent_search,
# coherent_cal, or coherent_fold
vegas.obsmode = 'search'
# 'vegas.polnmode' Can be full_stokes or total_intensity for search mode.
# All other modes require full_stokes.
vegas.polnmode = 'total_intensity'
# 'vegas.numchan' can be any power of 2 between 128 and 4096
vegas.numchan = 2048
# 'vegas.scale' is configuration specific.  Ask your project friend for
# suggestions.
vegas.scale = 10000
vegas.outbits = 8
# These parameters are only used in cal, fold, coherent_cal, or
# coherent_fold modes
vegas.fold_bins = 256
vegas.fold_dumptime = 10.0
vegas.fold_parfile = '/home/gpu/tzpar/B1937+21.par'
# 'vegas.dm' only used in coherent_search mode
vegas.dm = 0.0
"""
```

Script 12.1: VPM single-bank configuration

The next configuration uses multiple banks to cover a wider bandwidth.

```
config_vpm_multi= """
obstype = 'Pulsar'
# 'receiver' can be any GBT receiver except MUSTANG.  Here, we use Rcvr4_6,
# aka C-Band
receiver = 'Rcvr4_6'
# Use the restfreq dictionary format to configure multiple banks
restfreq = [{'bank': 'A', 'restfreq': 4312.5},
          {'bank': 'B', 'restfreq': 5437.5},
          {'bank': 'C', 'restfreq': 6562.5},
          {'bank': 'D', 'restfreq': 7687.5}] ]
dopplertrackfreq = 6000.0 # Required even without doppler tracking
nwin = 4 # Must match number of entries in restfreq dictionary
pol = 'Linear'
backend  = 'VEGAS'
# 'bandwidth' is per spectrometer bank.  In this case the total bandwidth
# is larger.
bandwidth = 1500.0
# tint is highly flexible but subject to data rate limits. The true tint
# will be rounded to the nearest value acc_len * nchan / bw
# where acc_len is an integer that controls the hardware
# accumulation length
tint = 40.96e-6
deltafreq = 0.0
# For 'swmode', choose 'tp' for calibration, 'tp_nocal' for pulsar
# observation
swmode = 'tp_nocal'
swtype = 'none'
swper  = 0.04
swfreq = 0
# For 'noisecal' choose 'lo' for calibration, 'off' for pulsar observation
noisecal = 'off'
# observation
vlow = 0.0
vhigh = 0.0
vframe = 'topo'
vdef = 'Radio'
# The following keywords are VEGAS specific
vegas.obsmode = 'search' # search, cal, fold
# 'vegas.polnmode' Can be full_stokes or total_intensity for search mode.
# All other modes require full_stokes.
vegas.polnmode = 'total_intensity'
# 'vegas.numchan' can be any power of 2 between 128 and 4096
vegas.numchan = 2048
vegas.scale = 10000
vegas.outbits = 8
# These parameters are only used in cal, fold
vegas.fold_bins = 256
vegas.fold_dumptime = 10.0
vegas.fold_parfile = '/home/gpu/tzpar/B1937+21.par'
"""
```

Script 12.2: VPM multi-bank configuration

Note the use of the dictionary format to manually specify the center frequencies of each bank in the above multi-bank configuration. A simple, comma-separated list of values can also be used. The **nwin** parameter must match the number of rest frequencies, i.e. the number of banks being used. **dopplertrackfreq** must also be specified when using the dictionary format, even though pulsar observers will not typically use Doppler tracking (i.e., **vframe** is set to **topo**).

12.2.3 Example Scheduling Blocks

Scheduling blocks are described in detail in Chapter 5. Here we describe only the most typical steps for pulsar observers. These are:

1. Load an Astrid catalog using the **Catalog** command.
2. Define a configuration block as described in §12.2.2
3. Configure the GBT using the **Configure** command.
4. Slew to a source using the **Slew** command.
5. Update the pointing and focus corrections using an **AutoPeakFocus**. Note that this is *essential* to do if observing with C-Band or higher frequency receivers to ensure good efficiency. If observing with S-Band and lower frequency receivers, it is not as important, since the default pointing and focus models are already very good, and most pulsar observers choose to avoid the overhead time. However, it never hurts to start with peak and focus scans. *Always remember to reconfigure after an AutoPeakFocus*, otherwise you won't be set up for pulsar observing.
6. Balance the IF system using the **Balance** command.
7. Take data via one of several observing directives, such as **Track** or **OnOff**.

The following example scheduling block demonstrates a simple polarization calibration and pulsar observation. Note that we assume that the configuration blocks are already defined.

```
# Load one of the built-in Astrid catalogs
msps = Catalog(pulsars_bright_MSPs_GBT)

# Define some variables to be used elsewhere in the script
source = "B1937+21"
scanLength = 605.0

# Slew to the source of interest
Slew(source)

# Update pointing and focus corrections (optional at S-Band and below)
# We'll also slew back to the main source when done.
AutoPeakFocus()
Slew(source)

# Always remember to reconfigure after an AutoPeakFocus!

# Configure for the calibration scan.  We assume the configuration block
# has already been defined.
Configure(config_vpm_cal)

# Balance the IF system
Balance()

# Take a 65 second calibration scan
Track(source, None, 65.0)

# Now configure for the pulsar scan
Configure(config_vpm_psr)

# And take the main scan.  Note that we do *not* balance again
Track(source, None, scanLength)
```

Script 12.3: VPM calibration/pulsar scan example.

There are a couple of things to take note of in this example.

1. We do *not* issue a second Balance command after the polarization calibration scan, but instead immediately reconfigure and take our main pulsar scan. If we did rebalance, the conversion factor between counts and antenna temperature/flux density could change and our calibration scan would not be valid for the pulsar scan.

2. We add 5 seconds to the scan length in cal- and fold-mode scans to ensure that the last sub-integration is always written to disk.

If you want to take drift-scan data, you can use the current encoder position as your “source” but still issue a Track command—the telescope will not actually track, but will remain at the position specified by the encoder.

```
# Use the current Encoder position for a drift scan observation
source = GetCurrentLocation("Encoder")

# Configure and balance
Configure(config_vpm_search)
Balance()

# And take a 1-hour drift scan
Track(source, None, 3600.0)
```

Script 12.4: VPM drift scan example.

If your science goal requires absolute flux calibration, you will probably want to perform an on/off scan sequence on a standard calibrator source.

```
# Load one of the built-in Astrid catalogs
fluxcal = Catalog(fluxcal)

# Define some variables to be used elsewhere in the script
source = "3C43"

# Slew to the source of interest
Slew(source)

# Configure for the calibration scan.  We assume the configuration block
# has already been defined.
Configure(config_vpm_cal)

# Balance the IF system
Balance()

# Take a on/off scan.  Each scan will last 65 seconds, and our off
# position scan will be 1 degree away in declination from our
# on-source position
OnOff(source, Offset("J2000", 1.0, 0.0, cosv=False), 65.0)
```

Script 12.5: VPM flux calibration example.

Chapter 5 has lots of other useful observing tricks. Note that since Astrid is written in python, one can write scripts that iterate over sources and automate a lot of the observing setup. Contact your project friend if you'd like help with more advanced scripting.

12.3 VPM Observing Tools

Once you start observing you will want to check the quality of your data and make sure that things run smoothly. A number of tools have been designed to facilitate this.

12.3.1 The VEGAS CLEO Screen

VEGAS has its own CLEO application that can be used for spectral line and pulsar observing modes (see §4.2 for more information on CLEO). There are two ways to launch the VEGAS CLEO application:

1. From the main CLEO launcher, go to **Backends** and select **VEGAS**.

Figure 12.4: The VEGAS CLEO screen when operating in pulsar modes. In this case VPM is configured for coherent dedispersion, so all eight banks are active and configured in the same way. However, only the power monitor for Bank A will be in use. Note the VEGAS Power Monitor button on the right-hand side.

2. Type `cleo vegas` from any command prompt.

Figure 12.4 shows an example of the VEGAS CLEO screen when in pulsar mode. The upper panels display information about setup on individual banks. The most relevant parameters for pulsar observers are the mode and integration time. The bottom panels show the state of the VEGAS managers on each bank.

When using incoherent dedispersion, anywhere from one to eight banks may be active, depending on how the system was configured. *In this case, it is completely normal for inactive banks to be configured for a different mode (possibly a spectral line mode) and/or to be in an off state.* In coherent dedispersion modes only the FPGA on Bank A is active, but all the managers and HPCs will be used and configured in the same way. However, the power monitors on other banks will *not* be in use (because they are tied to the inactive FPGAs), and may not be near the target value of −20 dB (see §12.3.2).

12.3.2 The VEGAS Data Monitor

The VEGAS data monitor is used to check the input power levels for each bank. There are two ways to launch the data monitor:

1. From the VEGAS CLEO application, click on the **VEGAS Power Monitor...** button (see Figure 12.4).

2. Type `vegasdm` from any command prompt.

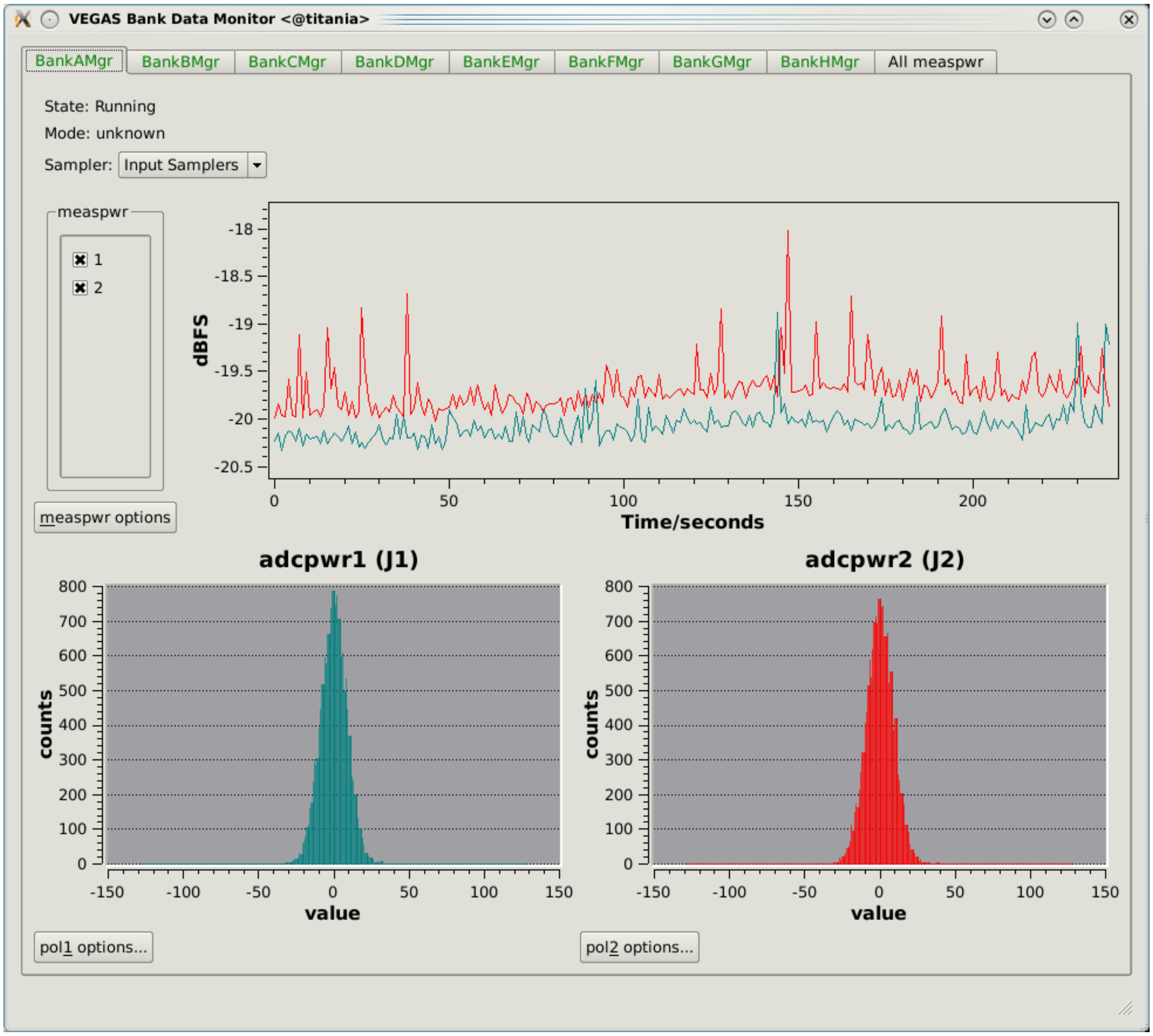


Figure 12.5: The VEGAS Data Monitor screen. Data for Bank A is selected in this example, but all eight banks are active. The chart recorder shows proper input values of approximately −20 dB. The histograms of 8-bit ADC output values are also in an acceptable range, with a FWHM of approximately 30 counts.

Figures 4.15 and 12.5 show the data monitor. The top panel shows the input power level in chart recorder form for both polarization channels. *The target power level is* -20 ± 1.5 dB. The plot is auto-scaling, so if the power levels change (e.g., during balancing) the plot may change abruptly. Note that there are separate tabs at the top of the application for each bank, though only active banks will update. The "All measpwr" tab shows the chart recorder for each bank. The bottom two panels show a histogram of 8-bit values from each ADC, one for each polarization channel. *These should have zero mean and a FWHM of approximately 30 counts once the system is balanced.*

12.3.3 The vpmStatus Tool

VPM makes use of shared memory to pass configuration parameters between the managers and data acquisition programs. To check the status shared memory type `vpmStatus` at the command prompt *while logged into one of the VEGAS HPCs*. These HPCs are named `vegas-hpc11` for Bank A, `vegas-hpc12` for Bank B, etc. Shared memory will only be properly configured on banks that are in use.

12.3.4 The vpmHPCStatus Tool

When using a multi-bank incoherent dedispersion mode or coherent dedispersion mode it is useful to check the status of all the active banks at once. This is done by typing `vpmHPCStatus` at the command prompt of *any* computer on the GBO network. This tool displays the center frequency, status of various processing threads (network communication and dedispersion), the current data block index, and a fractional running total of any dropped packets. It also displays the last few lines from the manager logs.

Note that inactive banks may have values like “Unk” (for unknown). This may occur if those banks are configured for spectral line observing. Inactive banks also will not update during data taking. *This is normal behavior. You need to only pay attention to the status of banks currently in-use.* However, for coherent dedispersion modes, this will be all eight HPCs. Figure 12.6 shows an example status screen.

12.3.5 The VPM Data Display Webpage

Data from each HPC that is collected in coherent dedispersion fold- or cal-modes is displayed on a public webpage: www.gb.nrao.edu/vpm. The page refreshes every few seconds and should reflect the most recently written scan in close to real-time. The source name and modification time are displayed at the top of the page. The first column shows observing frequency vs pulse phase summed over the entire data file. The middle column shows frequency vs pulse phase for the most recent sub-integration. The last column shows observing time vs pulse phase summed over all frequencies. *Note that long scans will be broken into multiple output files, and when a new file is opened the S/N may seem to suddenly drop.* This is expected and the S/N should recover as more data is written to that file. Also note that under certain browsers (e.g. Chrome) the page not always automatically refresh. If VPM seems to be running but the plots are not updating, first try clearing your browser’s cache and then reopening the page. If it still is not updating ask the GBT operator to make sure that the VPM coherent dedispersion autoplotting script is still running.

12.3.6 The VPM Monitor Webpage

When operating in incoherent dedispersion mode, bandpass plots are displayed on a public webpage: www.gb.nrao.edu/vpm/vpm_monitor. The page refreshes every few seconds and so should be close to real-time. Note that there is a separate panel for each bank, but only active banks will display data. The red curve shows the mean and the blue curves show the minimum and maximum values for the current data block. The average value should be around 30-40 counts and can be adjusted using the **vegas.scale** parameter. The relationship is linear for incoherent dedispersion modes. This page can also be used to monitor the RFI environment.

If you wish, you can run the same tool manually for more current data. To do this, type `vpmMonitor` at the command prompt *while logged into one of the VEGAS HPCs.* VPM must be taking data at the time. Use of the webpage is preferred.

12.3.7 Monitoring the VEGAS Manager Output

Output from the VPM data acquisition programs (as well as the spectral line programs) is captured by the VEGAS managers and written to log files. These log files can be found in

`/home/gbt/etc/log/vegas-hpcN`,

where `N` is the bank number, e.g. `vegas-hpc1` for Bank A. You can access these files from any GBO computer. A new log is started each time the VEGAS managers are started, so type `ls -tr` in the appropriate directory to find the name of the most recent log. Once you have this, you can follow the output by typing `tail -f <logName>`, where you replace `<logName>` with the appropriate file name.

Users typically will not have to check the logs unless they are trying to diagnose a problem.

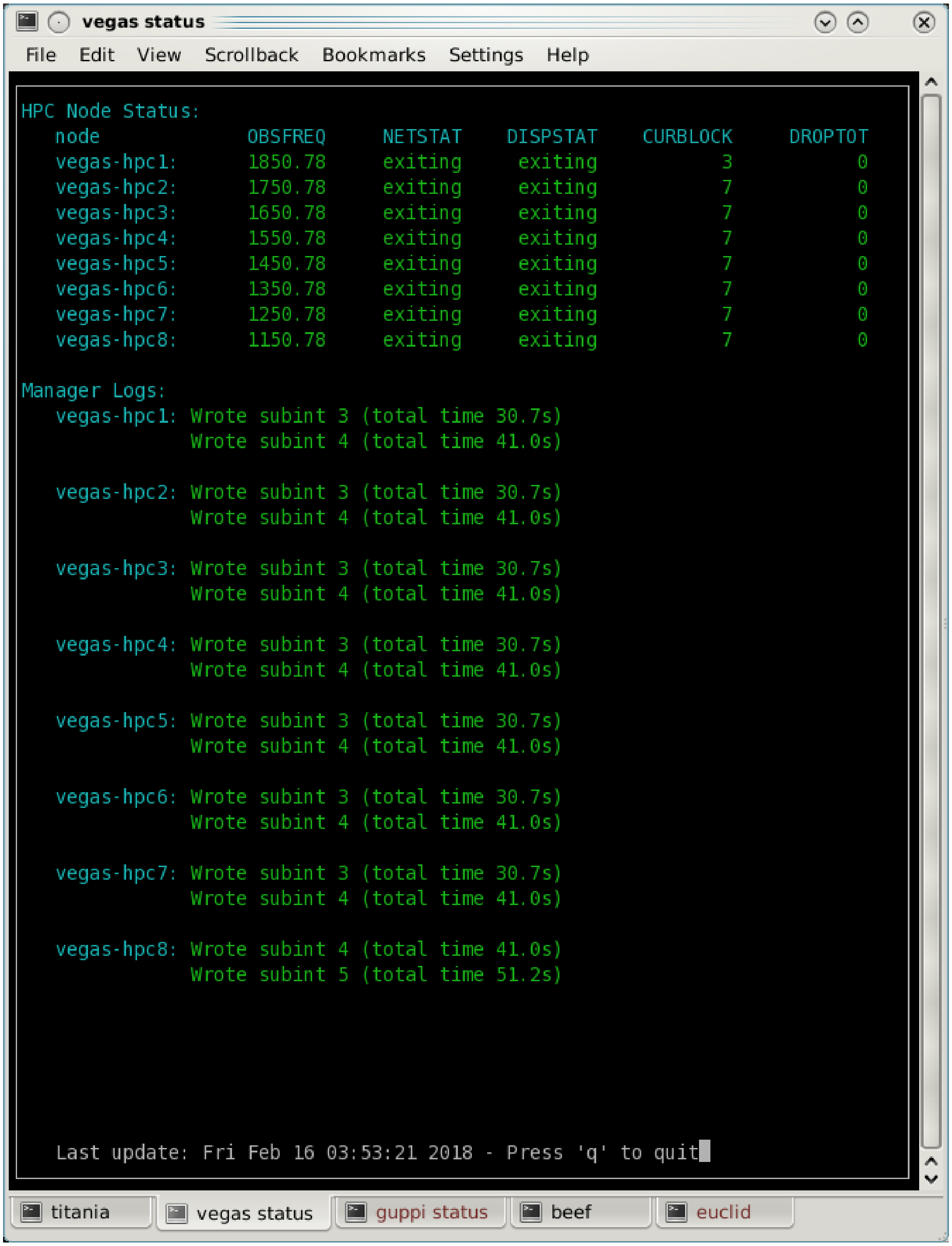


Figure 12.6: The vpmHPCStatus screen. VPM is configured for coherent dedispersion at L-band in this example. Please note, that the HPCs have recently been renamed: vegas-hpc1, is now vegas-hpc11, vegas-hpc2 is now vegas-hpc12 etc.

12.4 Accessing Your Data

VPM data are written directly to the beegfs file system, and can be accessed from any of the machines listed as lustre clients at www.gb.nrao.edu/pubcomputing/public.shtml (e.g. euclid or thales).

In coherent dedispersion modes data are written to

`/stor/gbtdata/<projectID>/VEGAS_CODD/<bankID>`

where `<projectID>` is your GBT project code with the session number in Astrid appended, e.g. `AGBT18A_100_01`, and `<bankID>` is the one-letter bank name (A–H).

In incoherent dedispersion modes data are written to

`/stor/gbtdata/<projectID>/VEGAS/<bankID>`.

File names follow the forms:

`vegas_<MJD>_<secUTC>_<sourceName>_<scanNumber>_<fileNumber>.fits`(fold- and search-modes)

`vegas_<MJD>_<secUTC>_<sourceName>_cal_<scanNumber>_<fileNumber>.fits` (cal-mode)

where `<MJD>` is the modified Julian date of the observation, `<secUTC>` is the number of seconds after midnight UTC at the start of the scan, `<sourceName>` is the source name as identified from the Antenna manager, `<scanNumber>` is the scan number within the current Astrid session, and `<fileNumber>` is the file number within the current scan (long scans are broken across multiple files to avoid any one file from being very large). `<secUTC>` is a zero-padded five-digit integer and `<scanNumber>` and `<fileNumber` are zero-padded four-digit integers. Example file names are

```
vegas_58150_05400_B1937+21_0001_cal_0001.fits
vegas_58150_05490_B1937+21_0002_0001.fits
```

Data are recorded in the `PSRFITS` standard, which can be processed by all common pulsar data analysis packages (e.g. PRESTO[1], PSRCHIVE[2], and DSPSR[3]). Data in all modes are recorded in the `/stor/gbtdata` file store.

Fold- and cal-mode data will be archived per typical GBO data archiving policies. Due to large data volumes, search-mode data will not be included in the long-term archive. *Please make arrangements to move large data sets off of the lustre file system as quickly as possible.* Data can be transferred over internet (preferred) or shipped on hard disks. Please contact your project friend or the NRAO helpdesk if you need help managing data.

12.5 Putting it All Together

In summary, a typical VPM observing session will consist of the following steps.

1. Create scheduling blocks *well in advance of being scheduled*. Contact your project friend if you have questions.
2. At the beginning of your observing session:
   (a) Launch the CLEO VEGAS and VEGAS Data Monitor applications.
   (b) Launch the `vpmHPCStatus` tools.
   (c) Log in to a beegfs client and prepare to navigate to your data output directory (the directory will only be made once data start being recorded).

[1] http://www.cv.nrao.edu/~sransom/presto/
[2] http://psrchive.sourceforge.net/
[3] http://dspsr.sourceforge.net/

(d) Navigate to www.gb.nrao.edu/vpm to monitor coherent dedispersion fold- and cal-mode observations and www.gb.nrao.edu/vpm/vpm_monitor to check the bandpass for incoherent dedispersion observations.

3. Once VEGAS has configured, check that the observing mode and various parameters are set properly using the VEGAS CLEO application and the `vpmStatus` and/or `vpmHPCStatus` tools.

4. Once VEGAS has balanced, check the input power and ADC output using the Data Monitor.

5. Once you have started recording data, check your fold- or cal-mode scans using the online viewers or by accessing data directly on disk. You should also check the bandpass using the VPM monitor webpage or the `vpmMonitor` tool.

6. Once you have started your main science scans, keep an eye on the output data and the data-taking status using the status monitors.

7. Start processing large data sets as soon as possible after your sessions ends.

12.6 Tips and Tricks

- Before writing scheduling blocks from scratch, ask your project friend if there are any already available from other projects that might suit your needs. This minimizes the possibility of an incorrect set-up or scheduling block.

- If you are searching for pulsars or observing a new source, consider observing a well known pulsar as a test source at the start of your session to make sure that things are working properly. A cal-mode scan can also be used.

- If the system seems to be having trouble balancing, or you experience other issues, ask the operator to cycle the VEGAS managers off/on, or do so yourself if you know how. This is usually sufficient to resolve any odd states that could arise out of a partial or incorrect configuration. If this fails, ask the operator to fully restart (stop/start) the VEGAS managers. If this still doesn't work, ask the operator to contact the on-duty support scientist.

- The GBT noise diodes are stable over short-to-medium time scales, and a number of continuum flux calibration scans are available for common observing set-ups (this is especially true of 820 MHz and L-band NANOGrav set-ups because NANOGrav observes flux calibrators at least once a month). If your project requires flux calibration, consider contacting your project friend to see if appropriate calibration data already exist.

- If you are observing multiple sources with relatively short scan lengths, and the operator needs to take control for a wind-stow or snow-dump, ask if you can let the current scan finish and then use Pause to let the operator take control. Once control is released back to you, you can simply un-pause and pick up where you left off. But if the operator needs to take control immediately, abort your scan and let them take over.

Chapter 13

VLBI Observing using the GBT

13.1 Proposals

The GBT has a VLBA-compatible data acquisition system. Proposals requesting GBT participation in VLBA or global VLBI observations should be submitted to the VLBA only, not to the GBT.

Proposals requesting the GBT participation in a Very Long Baseline (VLB) experiment that includes no other NRAO telescopes should be submitted to the VLBA as well as to the GBT and other agencies as appropriate, such as the European VLBI Network (EVN).

References for VLBA proposals: https://science.nrao.edu/facilities/vlba/proposing

General information about the VLBA: https://science.nrao.edu/facilities/vlba/

13.2 VLBA-compatible recording

The data acquisition system is similar to those at the VLBA stations: two Roach Digital Backend (RDBE) units and a Mark6 recorder are in use, allowing wide-band recording up to 4 Gbits/sec. Two modes are available, "PFB" mode provides 16, 32-MHz channels and a total recording rate of 2 Gbits/sec. In the "DDC" mode, each RDBE allows up to 4 channels of bandwidth 1 to 128 MHz. With two RDBEs available, up to 8 Digital Down Converter (DDC) channels may be used.

The SCHED default frequency setups should be correct for writing schedules for the new system.

The old data acquisition system with the DAR rack and Mark5A recorder have been retired. The Mark5C recorder is also not in use anymore. Consequently, no proposals should request those hardware systems.

13.3 Schedule Preparation

Scheduling is done through the VLBA analysts in Socorro.

- Schedules are prepared with the SCHED program. (refer to: http://www.aoc.nrao.edu/software/sched/index.html)
- The GBT uses the standard VLBA schedule files (`*.key` and `*.vex` files).
- The user needs to prepare a `.key` file for SCHED and send it to the VLBA analysts.

- Use **GBT_VLBA** as the station name, except for cold weather in which case use **GBT_COLD**. Refer to pointing and weather sections, below.
- In general, use **GBT_COLD** during the months of December, January, and February.

The schedules, either `.vex` or `.key` files, are processed by the VLBA analysts to produce schedule scripts for each VLBA telescope, including one for the GBT. These scripts are interpreted at the GBT by a process called "RunVLBI" which generates the configuration and pointing commands for the GBT. The same script runs in the VLBA backend to drive the recording and backend frequency setup. The GBT telescope operator runs these experiments. The user does not need to know anything about GBT-specific script details, i.e, the AstrID configurations, catalogs, and scheduling blocks.

There are, however, several GBT-specific details which the user needs to take into consideration when designing the observing schedule. These are described in the next few sections.

13.4 Special considerations when using the GBT

- Allow about 15-30 minutes setup time at the beginning of a session before VLBI recording begins. For the 3mm and 7mm VLBA bands (W-band and Q-band, respectively), allow for 45 minutes to one hour of setup time.
- Changing between Gregorian receivers requires rotating the turret. The telescope operator initiates this rotation. At least 5 minutes should be allowed in the schedule to change from one Gregorian receiver to another.
- Changing between Gregorian and prime focus requires about 10 minutes; that is the time required to extend or retract the prime focus boom. Changing from one prime focus receiver to another requires about 4 hours, because one feed must be physically removed and replaced with another.
- The prime focus receivers include 50 cm and 90 cm bands; whereas L–band and all higher frequencies ($\nu > 1.2$ GHz) use the Gregorian focus (with the exception of the upcoming Ultrawideband Receiver (UWBR), which is a prime focus receiver and will cover a frequency range of 0.7 - 4.0 GHz).
- One needs to include enough pointing/focus updates – see below.
- There are some weather-related restrictions – see below.

13.5 Available Receivers and Bands

The receivers and frequency bands are listed in table 13.1. Note that some bands are available on the GBT but not on the VLBA. Note also the time it takes to change receivers, as described above. For more information, consult

- The GBT proposers guide, chapter 4, for antenna and receiver performance.
- Gain curves, see https://safe.nrao.edu/wiki/bin/view/GB/Observing/GainPerformance

Table 13.1: VLBA bands and GBT receivers.

VLBA Band	VLBA Frequency Range (GHz)	GBT Frequency Range (GHz)	GBT Receiver AstrID Name	GBT Receiver Common Name	Net Side-band	Primary Beam FWHM	Est. SEFD (Jy)	Typical Tsys (K)
90 cm	0.312-0.342	0.290-0.395	Rcvr_342 (PF1)	P-band	lower	36′	25	20-70
—	—	0.385-0.520	Rcvr_450 (PF1)	400-MHz	lower	27′	22	20-50
50 cm	0.596-0.626	0.510-0.690	Rcvr_600 (PF1)	600-MHz	lower	21′	12	20-35
—	—	0.680-0.920	Rcvr_800 (PF1)	800-MHz	lower	15′	15	18-25
—	—	0.910-1.230	Rcvr_1070 (PF2)	PF2	lower	12′	10	18-22
18/21 cm	1.35-1.75	1.1-1.8	Rcvr1_2	L-band	lower	9′	10	15-18
13 cm	2.15-2.35	1.68-2.60	Rcvr2_3	S-band	lower	5.8′	12	18
6 cm	3.9-7.9	3.95-8.0	Rcvr4_6	C-band	lower	2.5′	10	23
4 cm	8.0-8.8	7.8-12.0	Rcvr8_10[a]	X-band	lower	1.4′	15	27
2 cm	12.0-15.4	11.8-18.0	Rcvr12_18	Ku	upper	54″	20	27
1 cm	21.7-24.1	18.0-27.5	RcvrArray18_26	KFPA	lower	32″	25	40
—	—	26.0-40.0	Rcvr26_40	Ka	upper	22″	20-40	40
7 mm	41.0-45.0	40.0-50.0	Rcvr40_52	Q-band	upper	16″	60	80
3 mm	80.0-90.0	68-92	Rcvr68_92	W-band	upper	10″	100	110

[a] Please note that this receiver name no longer correlates exactly with the actual frequency range of the receiver.
- Receivers with "PF1" or "PF2" are at the prime focus; the others are at the Gregorian focus.
- Rcvr26_40 has linear polarization only; 2 beams but one polarization state per beam; all other receivers can receive dual circular polarizations.
- Pulse Cal (or phase cal) is injected in receivers of 2 cm wavelength and longer; pulse cal is injected in the 7mm receiver after the first mix; other receivers have no pulse cal injection.
- The 4 mm receiver (Rcvr68_92) has no noise cal or pulse cal injection. See the section below for how calibration is done.

Table 13.2: GBT pointing and focus checks with VLBA observations.

Frequency Band	Interval between pointing scans
4–10 GHz	4–5 hours
12–18 GHz	3–4 hours
18–26 GHz	1.5–2 hours
40–90 GHz	30–60 minutes

13.6 Include Pointing and Focus Checks

It is recommended to allow for pointing and focus touch-ups when observing at the higher frequencies. Recommendations are listed in table 13.2.

Notes:

- The observer should select a strong continuum source (flux density > 0.5 Jy, or > 1.0 Jy for $\nu >$ 20 GHz).
- Allow about 6 minutes for the pointing/focus check, except for the 3mm VLBA band (W-band receiver) for which you should allow 8 minutes in order to include the temperature calibration.
- For observing at frequencies below 5 GHz, include one pointing scan at the beginning of the session.
- The telescope operator will usually do a point/focus scan at the beginning of an observing session, during the startup time.

To include a point/focus scan in your schedule, put commands into your `.key` file similar to the following:

```
comment='GBT pointing scan'
peak=1
stations=gbt_vlba
source= 'J0920+4441' dwell=06:00  vlbmode='VA' norecord /
nopeak
```

Script 13.1: Example additions to the `.key` file for GBT point and focus observations

It is important to specify only the GBT (`stations=gbt_vlba` or `stations=gbt_cold`) when putting in `peak=1`. Otherwise it may do a reference pointing for the whole VLBA, and if the pointing source is under about 5 Jy, it can produce bad results. Refer to the SCHED manual for details of schedule preparation at http://www.aoc.nrao.edu/software/sched/index.html.

13.6.1 4 mm Receiver (68-92 GHz) calibration

System Temperature (T_{sys}) calibration with this receiver uses a calibration wheel that can place hot and cold loads in front of the feed. There is no noise injection as happens with the other receivers. A "cal sequence" procedure is done before and after each peak/focus to provide a T_{sys} measurement. A cal sequence is inserted automatically with the peak/focus; the user does not have to specify it explicitly. A cal sequence takes about one minute, and will happen before and after a peak/focus. The user should use a dwell time of 8 minutes for the pointing scan, and that will include the cal sequences. Pointing Sources for high frequency observing should be strong, i.e., stronger than 3 Jy if possible.

13.7 Weather Considerations

At the higher frequencies, windy conditions can degrade the pointing. Refer to recommended wind limits for observing at https://safe.nrao.edu/wiki/bin/view/GB/PTCS/PointingFocusGeneralStrategy.

- For sustained winds of $>$ 35 MPH or gusts $>$ 40 MPH, the telescope is stowed for safety.
- Ambient temperature $<$ 17F (-8.3°C) : the maximum azimuth slew rate is reduced to 18°/min.
- Ambient temperature $<$ -10F (-23°C) : the antenna is shut down.

If your project will run in December, January, or February you should use the lower azimuth slew rate of 18°/min when making the schedule. This is accomplished by using `stations=gbt_cold` in your `.key` file, instead of `stations=gbt_vlba`.

13.8 Telescope Move times and limits

Move Limits:

- Elevation: $5° \rightarrow 90°$
- Azimuth: $-90° \rightarrow +450°$, i.e, $180° \pm 270°$

Calculating time to change sources:

- **Maximum Azimuth slew rate**: 36°/min (18°/min at low temperature)
- **Maximum Elevation slew rate**: 18°/min
- **Acceleration**: $0.05° \text{sec}^{-2}$
- **Overhead**: 20 seconds to settle
- Allow a minimum of 30 seconds for a source change, even for short moves.

13.9 High Frequency (40-90 GHz) active surface considerations

When using the 40-50 or 68-92 GHz receivers, one should tune up the active surface by doing an "AutoOOF" procedure. This is so-called "Out of focus holography" in which a strong point source is observed both in and out of focus, and large-scale deviations of the surface can be derived. The surface corrections are applied to the active surface model. This improves the aperture efficiency by a factor of 2 at 86 GHz. One should do an AutoOOF, which takes about 30 minutes, at the beginning of any high-frequency observing. The user does not have to specify this in the observing file; the operator or telescope friend will do an AutoOOF calibration prior to starting the observing, during the setup.

When observing with the 68-92 GHz receiver, one should repeat the AutoOOF about every 3-4 hours. This means that the user should allow a 30 minute gap in the schedule about every 3-4 hours. The user does not have to specify anything about an AutoOOF in the schedule; just allow the 30 minute gap. The operator or telescope friend will do the calibration.

13.10 GBT Coordinates

The geodetic position for the GBT (as of Jan 2000), based on a local survey referred to a standard NGS survey marker on the Green Bank site in the NAD83 system is

- longitude = $79°50'23.406''W$
- latitude = $38°25'59.236''N$
- Height of Track: NAVD88 height: 807.43 m (wrt ellipsoid: 776.34 m)
- Height of elevation axle: NAVD88 height: 855.65 m (wrt ellipsoid: 824.55 m)

The surveyed height refers to the top of the azimuth track. The phase center (intersection of azimuth and elevation axes) is 48.22m above the top of the azimuth track. The average geoid height = -31.10m with respect to the ellipsoid. The estimate uncertainty is $0.04''$.

The Earth-centered International Terrestrial Reference Frame (ITRF) coordinates for the phase center of the GBT were derived from a "TIES" run with the GBT and 20-meter telescopes in December 2002.

The solution as of Oct 2007 is:

$$x = 882589.638 \text{ meters}$$
$$y = -4924872.319 \text{ meters}$$
$$z = 3943729.355 \text{ meters}$$

Based on the ITRF solution, the best NAD83 geodetic position is:

$$\begin{aligned} \text{Latitude} &= 38°25'59.266''N \ (38.433129°N) \\ \text{Longitude} &= 79°50'23.423''W \ (79.839840°W) \\ \text{Height above the ellipsoid} &= 824.36 \ m \\ \text{Height above the geoid} &= 855.46 \ m \end{aligned}$$

13.10.1 Further Information:

More information about running VLBI observations at the GBT is available at https://www.gb.nrao.edu/~gbvlbi/vlbinfo.html.

Chapter 14

Solar System Radar with the GBT

14.1 Introduction

The GBT participates in radar observations of near-Earth asteroids and comets, as well as Lunar and planetary mapping and rotation studies. These are done in collaboration with JPL/Goldstone at (X–band) or (C–band), and formerly with the Arecibo Telescope, which could transmit at 2380 MHz (S–band) or 430 MHz (P–band) before its unfortunate collapse in 2020.

Anyone wishing to do radar studies should collaborate with scientists at NASA/JPL to plan the experiment. Observing time with a transmitting antenna should be secured independently from a proposal to receive with the GBT. Opportunities for radar observations can arise on short notice, in which case proposers can make use of Director's Discretionary Time proposals if the normal proposal process is not timely enough. Use the NRAO proposal submission tool to submit all proposals, and indicate the proposal is for "DDT"; these proposals will be reviewed and responded to within a few working days.

14.2 Data Acquisition Backends

There are two data acquisition backends:

1. JPL Radar backend
2. VEGAS baseband modes

At present, the best choice is the JPL system which can be configured flexibly under computer control for a wide choice of bandwidths and sampling rates. Sample rates and bandwidths are listed in table 14.1. For the rest of this chapter, we will explain the usage of the JPL Radar backend. The VEGAS baseband modes will function similarly to the incoherent pulsar modes described in Chapter 12, but consult with your project friend to ensure correct and efficient usage.

Table 14.1: Radar data acquisition backends.

Backend	Sample rates	Bandwidths
JPL	6.25–400 MHz	0.31–73 MHz
VEGAS	100–800MHz	100–800MHz

14.3 GBT Scheduling Blocks

The following configuration works for the JPL backend. It should be noted that the data recording is not controlled through the GBT user interface (AstrID). The SB tracks the object, but the user has to run the data acquisition process independently. Consult with your project friend for specific instructions about using the JPL backend data acquisition process.

Here is an example script for 8560 MHz observations.

```
# Astrid setup script for X-band planetary radar
ResetConfig()
Catalog('/home/astro-util/GBTog/cats/asteroidephemexample.astrid')
obj = '1999JV6'

Xsetup = '''
receiver  = 'Rcvr8_10' # select receiver
obstype   = 'Radar'    # select observing type
backend   = 'Radar'    # select type of backend
nwin      = 1
restfreq  = 8560       # observing frequency
bandwidth = 80         # see note below
swmode    = 'tp_nocal'
swper     = 0.2
tint      = 0.2        # see note below
vframe    = 'topo'     # see note below
vdef      = 'Radio'
noisecal  = 'off'
pol       = 'Circular'
'''

Configure(Xsetup)
Slew(obj)
AutoPeakFocus()
Break('Check peak')

Configure(Xsetup)    # need to configure after the AutoPeakFocus
Slew(obj)
Balance() # adjust power levels
Break('Set Radar Levels')

# when tracking the object, adjust power levels in the back end.
Track(obj, None, 3600) # track object for one hour
Track(obj, None, stopTime='2016-01-09 07:00:00') # Track until UT stop time
```

Script 14.1: Example SB for radar observations.]Example SB for radar observations] Example SB for radar observations.

The ephemeris file referred to in the **Catalog()** command, above, gives the coordinates for the object, as described in the next section. The object name, in this case "1999JV6" is defined in the file referred to in the **Catalog** command.

The bandwidth is applied before the optical driver step in the signal path, and can take on the values listed in Table 9.2, with the caveat that the final filter going into the JPL backend is 500 MHz wide. The JPL backend itself has an output filter that can be configured to be between 0.31 and 73 MHz wide. The integration time does not have any affect on data acquisition, and can be kept at 0.2. The velocity frame should be kept as topocentric, as doppler shifting is typically done by the transmitting telescope.

Refer to Chapter 5 for more information on GBT configurations and SBs.

14.4 Tracking moving objects

Here is an example of an ephemeris file for an asteroid. Refer to § 5.3.5 for description of the "Ephemeris format".

```
# ephemeris format example for Astrid
FORMAT = EPHEMERIS
VELDEF = VRAD-TOP
COORDMODE = J2000
HEAD = date utc ra dec dra ddec
# 1: soln ref.= JPL#178
NAME = 1999JV6
2016-Jan-09 04:00 07:15:34.38 -23:41:33.7 -317.1984 1123.6330
2016-Jan-09 04:01 07:15:34.02 -23:41:15.0 -317.2251 1123.6110
2016-Jan-09 04:02 07:15:33.67 -23:40:56.3 -317.2518 1123.5900
2016-Jan-09 04:03 07:15:33.31 -23:40:37.6 -317.2763 1123.5680
2016-Jan-09 04:04 07:15:32.96 -23:40:18.8 -317.3008 1123.5460
2016-Jan-09 04:05 07:15:32.60 -23:40:00.1 -317.3231 1123.5250
2016-Jan-09 04:06 07:15:32.25 -23:39:41.4 -317.3454 1123.5030
2016-Jan-09 04:07 07:15:31.90 -23:39:22.7 -317.3667 1123.4820
2016-Jan-09 04:08 07:15:31.54 -23:39:04.0 -317.3868 1123.4610
# etcetera ...
```

Script 14.2: Example ephemeris file for an asteroid.

Consult § 5.3.5.2 for a description of obtaining ephemeris data from the NASA/JPL "Horizons" website and converting it for use with AstrID. Here is a brief description of the process:

- Access the JPL Horizons web interface: http://ssd.jpl.nasa.gov/horizons.cgi
- Set up Horizons web-interface as follows:

  ephemeris type: Observer Table

  target body: [select the object]

  Observer Location: Green Bank (GBT) [click "Edit", then type -9 in the search bar and press "Enter".]

  Time Specifications: [put in desired values]

  Table Settings: QUANTITIES=1,3,20
  (1) Astrometric RA&Dec, (3)rates in RA&Dec, and (20) Range and range rate

- Click "Generate Ephemeris"
- Use the web browser file menu to save the output file as (for example) `cometfilename.txt`
- Run the program `jpl2astrid cometfilename.txt`
  A new file with an `.astrid` extension will be created. An example of such a file is shown in Script 14.2.

The resulting `.astrid` file is used as an argument to the AstrID **Catalog()** command.

If you wish to track the velocity, use:

- `jpl2astrid cometfilename.txt vel`

This will put the velocity in the `.astrid` file. This option is usually not necessary because the relative velocity of the object is compensated by the transmitter, i.e., the transmitted frequency at Arecibo or Goldstone is programmed to result in a constant frequency received at Green Bank.

Note: the coordinate rates, columns 5 and 6 in the above example, as given by the Horizons listing, are:

- $dRA * cosD$
- $d(DEC)/dt$

In converting to the `.astrid` result, `jpl2astrid` divides the RA rate by cosine(Declination) so that it is the rate in the RA, rather than in $RA * cos(Dec)$. The units in both coordinates are arcseconds per hour.

The `jpl2astrid` program often does not fill in the object's name correctly. One should edit the NAME in the `.astrid` file to be something meaningful, and one should make sure the object name in the SB matches that in the ephemeris table.

Part V

Other Topics

Chapter 15

Radio Frequency Interference

Radio Frequency Interference (RFI) can be a significant problem for some observations. The most up to date information on the RFI environment at the GBT can be found at:

- http://www.gb.nrao.edu/IPG/

Useful resources, referenced from the above web page include a list of known sources of RFI:

- https://safe.nrao.edu/wiki/bin/view/GB/Projects/RFIReportsTable

and plots of RFI monitoring data:

- http://www.gb.nrao.edu/IPG/rfiarchivepage.html

Additionally, the GBT RFI GUI is now available. This is a new software tool that generates RFI spectrum plots for a receiver and time frame specified by the user; to run it, log into any Green Bank Linux machine, open a terminal window, and type gbt-rfi-gui. More information is available here:

- https://greenbankobservatory.org/about/interference-protection/rfi-gui-user-guide

Every observer should check for known RFI around their observing frequencies. If you suspect that this could have a significant impact on your observations you should contact your scientific support person to decide on an appropriate course of action.

15.1 Mitigation of known RFI signals

In some cases, it is possible to turn off a known RFI source. For example, there is an amateur transponder at about 432 MHz, which we can request be shut down. If there are known RFI signals, the user should discuss them with the scientific support person. Given enough advance warning (days to weeks), we may be able to have them shut down during the observing.

Chapter 16

Weather Effects on Observations

The weather affects observations in three ways: winds affect the telescope pointing, differential heating and cooling affect the telescope pointing and efficiency, and atmospheric opacity affect the received signal and the system temperature.

16.1 Winds

Winds can set the feed arm into motion. The current recommendations for wind limits can be found in § 6.5 (specifically in Table 6.1). The fraction of time when wind speeds are low is illustrated in Figure 16.1 which shows the cumulative percentages when wind speeds are below a certain value (Figure 16.1 is from Ries, PTCS project Note 68.1). The Dynamic Scheduling System (DSS), (see Chapter 2) uses forecasted wind speeds when it determines what projects are suitable for scheduling, so one should rarely see any negative impacts from winds.

16.2 Time of Day

Differential heating and cooling of the telescope alters the surface of the telescope, resulting in degradation of telescope efficiencies, and 'bends' the telescope, resulting in pointing changes. At high frequencies, these effects are important. The current recommendations are that, for best work, observing above 40 GHz should only be done at night, from 3 hours after sunset to 2 hours after sunrise. At 40 GHz and above it is recommended to use **AutoOOF()** (see 5.4.1.4) at the start of an observing session.

Low frequency observers may want to consider night time observing for two reasons. RFI is usually lower at night; and, in some cases, the sun has a slight negative impact on baseline shapes. By default, we assume that daytime observing will be acceptable for all observations below about 16 GHz.

Figure 16.2 depicts the range of UT, EST, and LST for our definition of "night-time" observing.

16.3 Atmospheric Opacities

The frequency range covered by the GBT extends from low frequencies where the opacity is relatively low (∼0.008 nepers) to high frequencies where opacity is very high (> 1 nepers). Atmospheric opacity hits observing twice – it attenuates the astronomical signal and it increases the system temperature, and thus the noise in the observation, due to atmospheric emission.

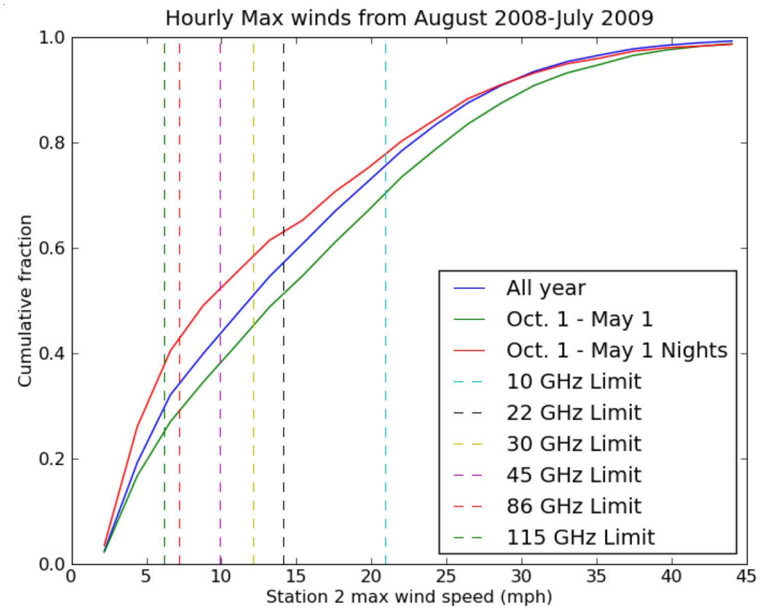


Figure 16.1: The cumulative fraction when wind speeds are below a certain value. Data from August 2008 to July 2009 are shown in blue; green shows winter data, and red shows winter nights.

Figure 16.4 shows opacities, atmospheric contributions to the system temperature and number of air masses[1] the astronomical signal must pass through vs. elevation under three typical weather conditions as calculated using the method described on the GBT "High Frequency Weather Forecasts" web page (). Typical total system temperatures are shown in Figure 16.3.

The opacities shown in Figure 16.4 are for planning purposes only and observers should not use them at high frequencies for calibrating data. Instead, one should use the actual opacities and the air mass from the bottom of Figure 16.4 to approximate the amount of attenuation a signal will experience at the expected elevation of the observation. The signal is attenuated by:

$$\exp^{\tau A}, \tag{16.1}$$

where τ is the opacity and A is the total number of air masses. Since opacity is very weather dependent, please consult with a local support staff on how best to determine opacities for your observing run.

During the cold months, high frequency observers can expect to be observing with opacities that are at or below the average (50 percentile) winter conditions for Green Bank. Thus, high frequency observers can anticipate that the typical weather conditions under which they will observe will be best represented by the top 25 percentile conditions. In contrast, low-frequency, winter observers should expect they will observe under conditions that are worse than the 50 percentile and more like those of the 75 percentile conditions.

During the warm season (June through September), high-frequency observing is much less productive and we almost exclusively schedule low frequency observing. During these months, low frequency observers can plan on observing under the average, 50 percentile conditions.

16.4 GBT Weather Restrictions

During weather conditions that pose a risk for the safety of the GBT, the GBT operators will cease all observations and take the appropriate action to ensure the safety of the GBT. The operator is fully

[1]The airmass curve in Figure 16.4 is a better approximation than the csc(elevation) approximation which is only correct above about 20° elevation.

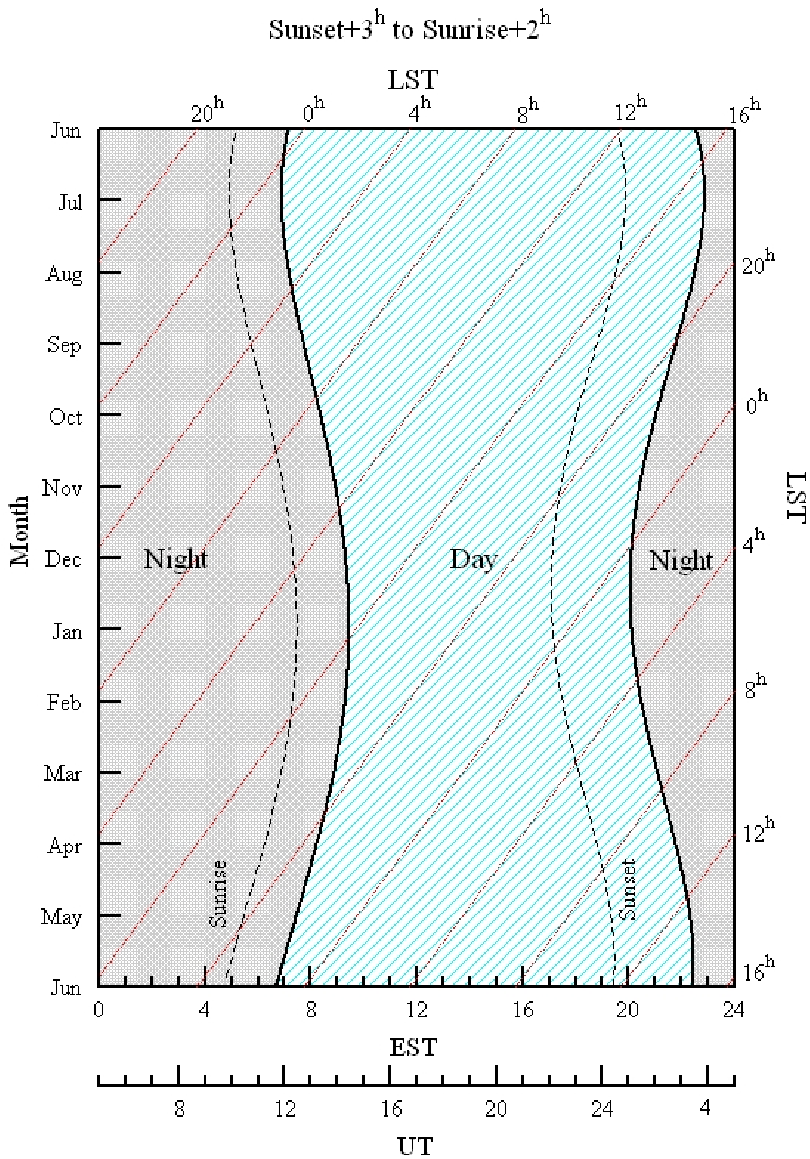


Figure 16.2: The range of UT, EST, and LST used in the GBT definition for "night-time" observing.

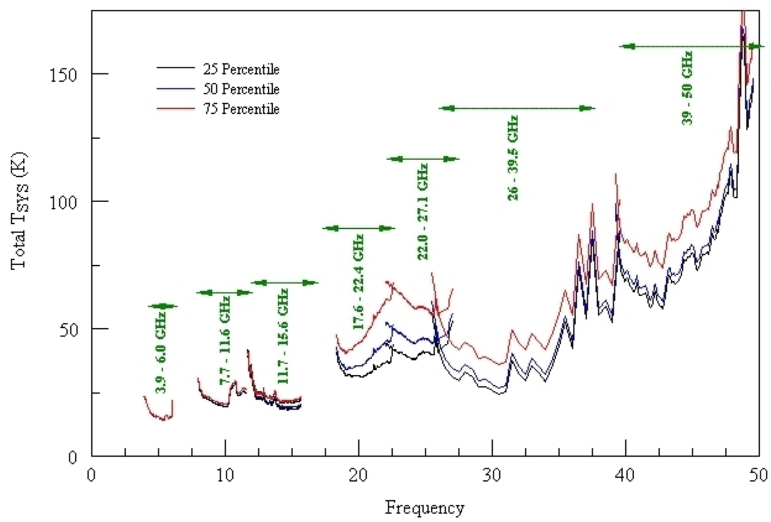


Figure 16.3: The zenith system temperatures for typical weather conditions.

responsible for the safety of the GBT and their judgement is final. The operators decisions should not be questioned by the observer.

16.4.1 Winds

The following guidelines exist for periods of high winds. If the average wind speed exceeds 35 MPH (15.6 ms^{-1}) over a one minute period, the operator will stop antenna motion. If wind gusts exceed 40 mph (17.9 ms^{-1}), or if winds are expected to exceed 40 mph for a period of time, the operator will move the antenna into the survival position. Only after the wind speeds have been below these criteria for 15 minutes will observations be allowed to resume.

Safety measures for high winds will take precedence over those for snow and ice.

16.4.2 Snow

If snow is sticking to any of the GBT structure, the operator will move the GBT to the "snow-dump" position. The decision to halt and resume observations is solely the responsibility of the GBT operator. If dry snow appears to be accumulating, the operator may periodically interrupt operations to dump snow, and then resume observations.

16.4.3 Ice

If ice is accumulating on any part of the GBT structure, the operator will move the GBT to the survival position. The decision to halt and resume observations is solely the responsibility of the GBT operator.

16.4.4 Temperature

When the air temperature drops to 16° Fahrenheit (-8.9°C), the Azimuth slew rate of the GBT will be reduced to half of its normal rate. (This is due to the changing properties of the grease used in the Azimuth drive bearings.) Half rate speed (18°/min instead of 36°/min) will be utilized until the temperature returns above 17° Fahrenheit (-8.3°C). When the temperature drops below -10° Fahrenheit (-23.3°C) observations will cease until the temperature is above 0° Fahrenheit (-17.8°C) and the operator has determined that the Azimuth drive motors are ready for use.

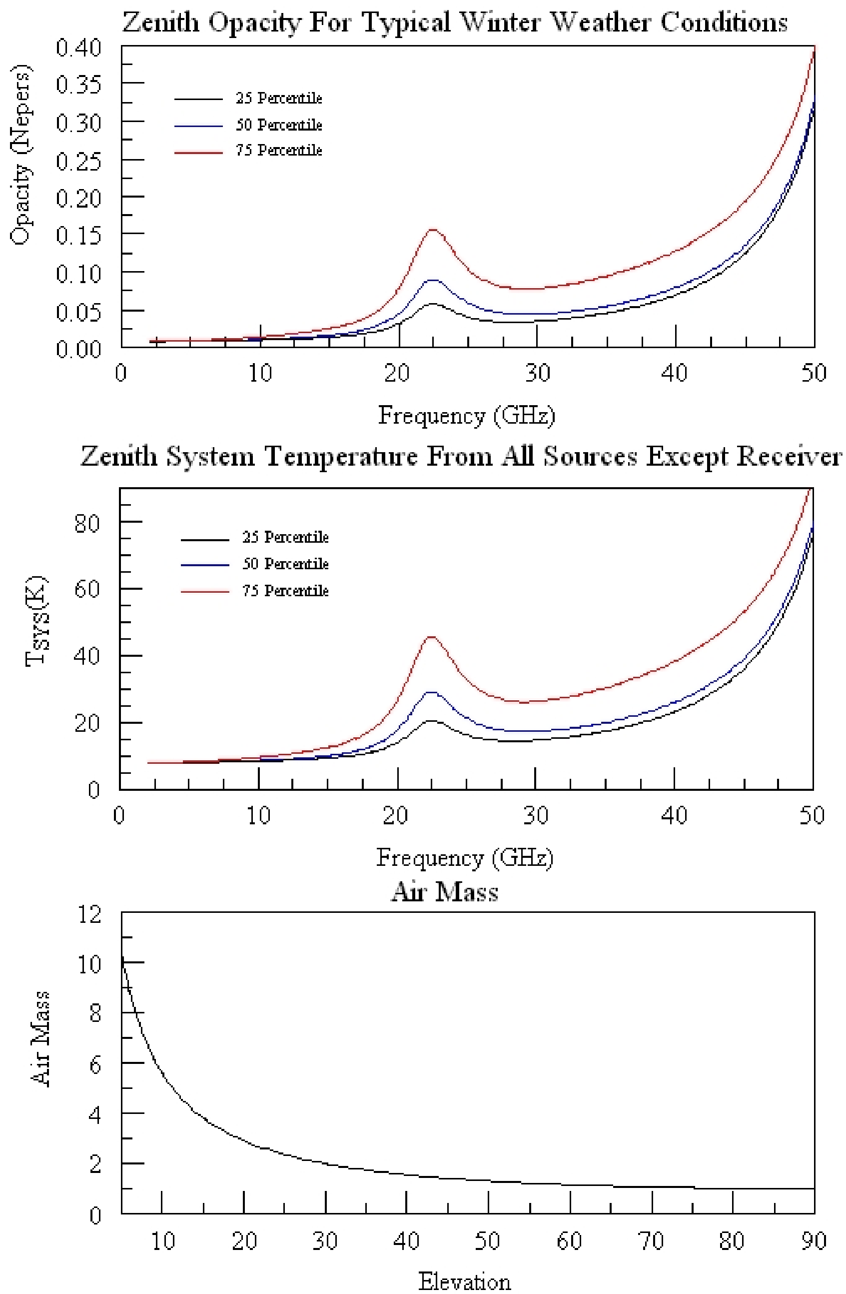


Figure 16.4: The top panel shows opacities under three typical weather conditions. The black, blue, and red curves represent the opacity under the best 25, 50, and 75 percentile weather conditions. (The 'average' opacity over the winter months is best described by the 50 percentile graph.) The middle panel is an estimate of the contribution to the system temperature at the zenith from the atmosphere, spillover, and cosmic microwave background. The bottom panel shows the number of air masses the astronomical signal must pass through as a function of elevation.

16.4.5 Feed Blowers

The feed blowers blow warm air over the radomes of the feeds to prevent condensation and frost. Although beneficial for most receivers, they produce vibrations that contaminate the MUSTANG data. Thus, users of MUSTANG can request that the operator turn off the feed blower at the start of their observing session. One hour before the end of a MUSTANG observing session, the operator will decide whether or not the blower needs to be turned back on in order to ensure the feeds for all receivers are in good shape for the next observer. The operators use the criteria that the blowers will be turned back on for the last hour if either: (1) the dew point is within 5° Fahrenheit of the air temperature, or (2) the air temperature went from above to below freezing anytime during the MUSTANG run.

Part VI

Appendix

Appendix A

GBT IF System

In this appendix we provide a general outline of the GBT IF system. Figures A.1 and A.2 give a simplified overview of the GBT IF path and will guide our discussion. We will not cover MUSTANG-2 as it is a direct detection system. Note that during each frequency mix, each polarization pair is mixed with a signal from the same synthesizer. All synthesizers are locked to our H-maser frequency standard.

A.1 From the Receiver to the IF Rack

The frequency that is observed is given by F_{sky}. Within the receiver the detected signal at F_{sky} is mixed with the LO1 signal. The LO1 frequency is derived from a synthesizer and can vary in time when Doppler tracking the velocity of a spectral line. The result of the mixing of F_{sky} and LO1 is the IF frequency, IF 1. The typical IF 1 center frequencies are 1080, 3000 and 6000 MHz. Filters limit the bandwidth in the receivers both before and after the LO1 mix. There are also filters in the IF Rack that limit the bandwidth. The resulting allowed bandwidths are 20, 80, 320, 1280 MHz and "All Pass" (i.e. no filtering other than the response of the receiver).

Before the IF Rack each signal is split into two (single beam receivers only) copies of the original signal. Each signal in the IF Rack is detected and then sent to the DCR (as used during pointing and focus observations). Each signal is also sent as an analog signal over optical fiber to the Jansky Lab to the Converter Rack.

A.2 From the Converter Rack to the Backend

When the signal reaches the Converter Rack it is split into four separate copies. This allows up to eight different copies of the received signal for single beam receivers and four copies of each received signal for dual beam receivers.

In the Converter Rack the signal is mixed with the LO2 signal. Each copy of the signal can be mixed with a different LO2 since there are eight different LO2 synthesizers. The resultant signals are then sent through a filter to make sure it has a bandpass of no more than 1.85 GHz. A final mix with a fixed frequency of 10.5 GHz then gets the signal within the input band-passes of the backends. There is a final set of filters that ensures the signal has the correct bandwidth for the backend.

A.3 KFPA Combined IF

The KFPA receiver, with 7 beams, is the first GBT receiver with more IF signals than there are Optical Fibers from the GBT to the Jansky Lab. In order to bring the IF signals to the control room, pairs of

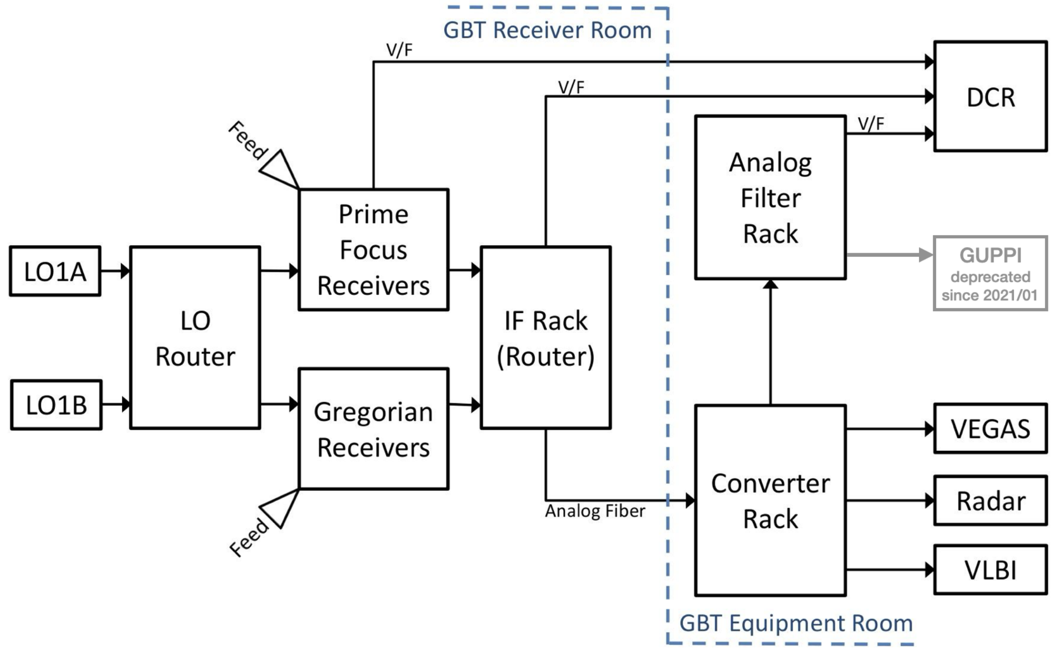


Figure A.1: A simplified flow diagram of the GBT IF system routing.

signals from different beams were duplexed on single fibers. The signal combination was accomplished by an analog addition of the IFs of pairs of beams. Beams 1, 2, 3 and 4 have IF signals centers at 6800 MHz. The IF signals from beams 5, 6 and 7 are down converted to 2100 MHz center frequency. Beam 2 is paired with 6, beam 3 with 7 and beam 4 with 5 (See Figure A.3).

At the Converter Rack one of the two beams is selected by appropriately setting the converter rack LO frequency. Beams 2, 4, 5 and 6 are routed to Converter Rack A and beams 1, 3 and 7 to Converter Rack B. This constrains certain multi-beam observing modes, as is described in Chapter 7.

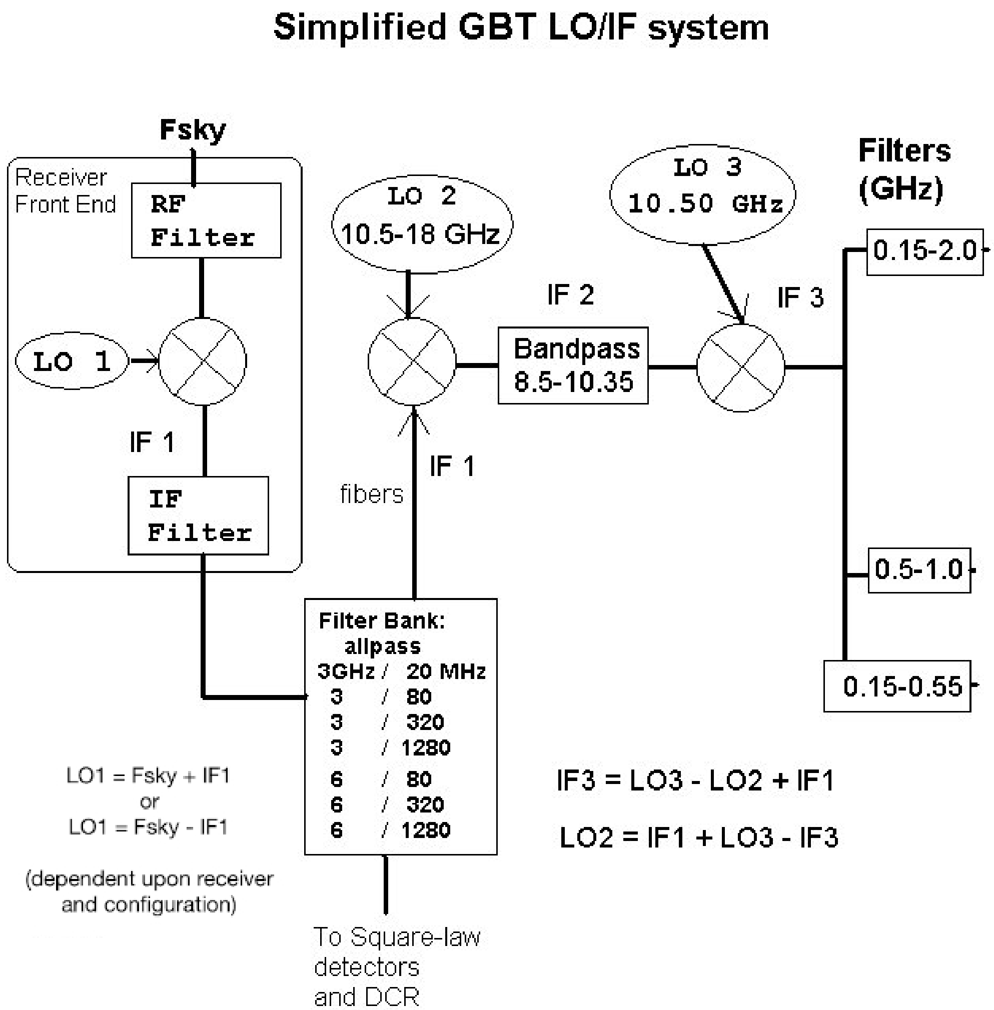


Figure A.2: A simplified flow chart of the GBT IF system.

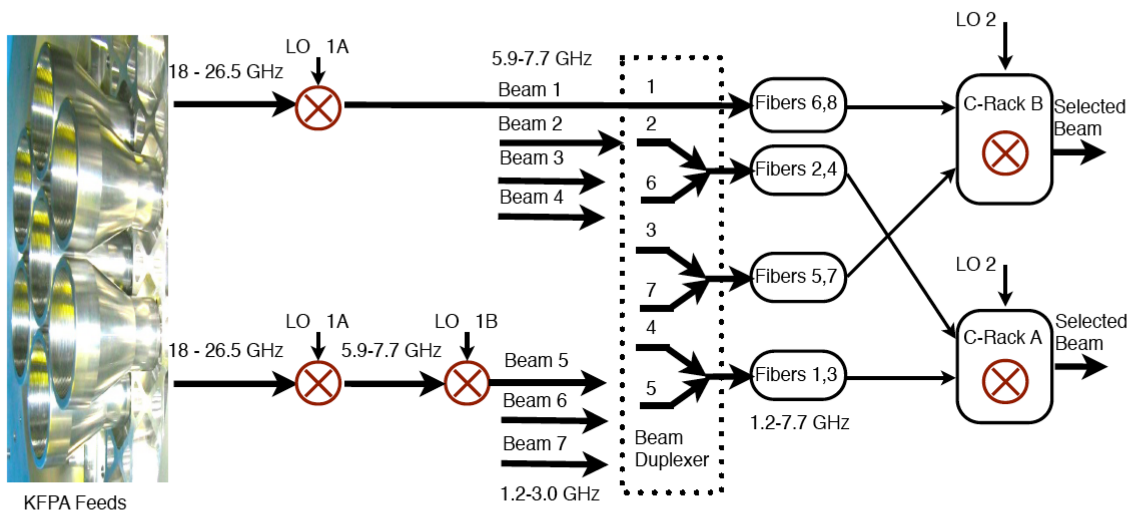


Figure A.3: A simplified KFPA diagram showing the combination of beams onto fiber modems and their selection in the Converter Rack Modules A and B.

Appendix B

Introduction to Spectral Windows

Several simultaneous frequency bands may be specified with a list of rest frequencies and offsets (keywords **restfreq**, **deltafreq**, see § 5.2.5). If using a backend other than VEGAS, the **nwin** (number of spectral windows) keyword will also need to be specified. Each spectral window includes both polarizations. i.e., if you specify one window, you get two IF systems routed to the back end device, one for each polarization; if you specify two windows, you get IFs, and so forth.

The configuration software tries to put the midpoint of the total frequency range spanned by all windows at the center of the nominal IF1 band so as to use the narrowest IF bandpass filters that will pass the desired range of frequencies. In some uncommon cases this is not possible, so the IF bandwidth must be increased to pass the desired range of frequencies.

The user specifies the rest frequencies (**restfreq** keyword) and may also specify a range of radial velocities (**vlow** and **vhigh** keywords, see Appendix C). The various IF filters are set to include the range of frequencies in the local frame required by the radial velocity range. The configuration software predicts the local frequency for each spectral window based on the rest frequencies and the radial velocity. During observing the tracking LO will correctly track the doppler tracking frequecy set by the **dopplertrackfreq** keyword. If **dopplertrackfreq** is not provided, the default value will be the first spectral window specified by the **restfreq** keyword (if not using the advanced restfreq syntax). Because there is only one tracking LO, the other spectral windows are set up with frequency offsets in the local frame with respect to the doppler tracking frequency. When observing at a variety of high velocities, one should run a configuration for each change of velocity (i.e., do not rely on just changing the velocity in the LO1 manager), and one should set **vlow**=**vhigh**.

Note that the **deltafreq** keyword gives frequency offsets that are applied in the local (or topocentric) frame i.e., it is applied as an offset in the IF system. For example, if V_{frame} is velocity of the reference frame, V is source velocity in that frame, ν_{rest} is the rest frequency of the line and we use the Radio definition of velocity then the topocentric frequency will be

$$\nu_{topo} = \nu_{rest}\left(1 - \frac{(V + V_{\mathrm{frame}})}{c}\right) + \mathrm{deltafreq} \tag{B.1}$$

Finally note that the expert user may specify any of the IF system conversion frequencies and total IF system bandwidth, overriding the calculations done by the configuration software (**ifbw**, **if0freq**, **lo1bfreq**, **lo2freq**, and **if3freq** keywords). This option may be needed in some peculiar cases. Of course one needs a good knowledge of the IF system to make use of this option.

B.1 Array Receiver Spectral Windows

Array Receivers can be configured with a variety of spectral windows. The `configtool`, part of AstrID, sets up these spectral windows, and a new syntax was required to specify more complex configurations.

Each feed has the potential to be tuned to a different rest frequency. For the KFPA receiver, a special "all" beam mode is defined which uses all 7 beams, plus one beam tuned to a second, different spectral window. This stretches the syntax of the `configtool` **restfreq** and **deltafreq** keywords. In order to support these modes within the `configtool`, expanded values and intepretations of **nwin**, **deltafreq** and **restfreq** were implemented.

The syntax uses a python dictionary for the **restfreq** and **deltafreq** keyword values for KFPA configurations. The **restfreq** dictionary maps beams and frequencies of the spectral windows. The delta frequency is a map of **deltafreq** to **restfreq**. The list of values syntax continues to be supported for simpler modes. When the dictionary is used to specify the rest frequencies, this dictionary must contain a key named 'DopplerTrackFreq'. The value assigned to this key is the rest frequency that will be used by the LO as the Doppler tracking frequency.

The following examples show how to specify `configtool` frequency settings:

- **Example 1**: Requests that beams 1,2,3 and 4 have a rest frequency of 24000 MHz, that beams 5,6,7 have a rest frequency of 23400 MHz and the 2nd beam 1 IF band has a rest frequency of 25000 MHz. There are no delta frequencies used in this observation. For non zero delta frequencies, the **deltafreq** values should be specified in the same manner as the **restfreq**.

```
beam = 'all'
restfreq = {24000:'1,2,3,4', 23400:'5,6,7', 25000:'-1',
            'DopplerTrackFreq':24200}
deltafreq = {24000:0, 23400:0, 25000:0}
```

- **Example 2**: For simple configurations the syntax for the existing receivers would also be supported. This results in the routing of 4 beams, 2 polarizations with each tuned to a rest frequency of 24000 MHz.

```
beam     = '1,2,3,4'
restfreq = 24000
```

- **Example 3**: Comparison of two configtool inputs where **restfreq** is a list, and input with the dictionary syntax. The two configurations are equal.

```
beam     ='1,2'
restfreq =23706.3,24139.417
deltafreq=0,0
```

```
beam     ='1,2'
restfreq ={23706.3:'1,2',24139.417:'1,2',
          'DopplerTrackFreq': 23706.3 }
deltafreq={23706.3: 0, 24139.417: 0}
```

- **Example 4**: 8 different rest frequencies specified.

```
restfreq = {23706.3  :'1', 24139.417:'2', 24139.417:'3', 24706.3:'4',
            24149.4:'5',24122:'6',23899:'7',24876.1:'-1',
            'DopplerTrackFreq': 24876}
```

- **Example 5**: A configuration that specifies delta frequencies.

```
beam     = 'all'
restfreq = {24000:'1,2,3,4', 23400:'5,6,7',
            25500:'-1','DopplerTrackFreq': 24876}
deltafreq= {24000:0, 23400:-500, 25500 : 0}
```

Appendix C

Usage of vlow and vhigh

The configuration keywords **vlow** and **vhigh** give the range of velocities of all sources to be observed. This information is used to set various filters in the system that will simultaneously cover the required range of velocity. Setting the velocity for each specific source is done later in the SB. For galactic sources where the range of velocities is rather small it is usually best to set both vlow and vhigh to zero.

When strong RFI is present is it best not to use vlow and vhigh. The use of vlow and vhigh can cause the GBT IF system to have a larger IF bandwidth than is necessary for a single source. This can let parts of the IF system be unnecessarily affected by RFI. The observers might need to reconfigure after each source if the change in velocity is larger than the bandwidth of a filter.

An example of how vlow and vhigh can be used is as follows. Suppose that you are looking for water masers in extragalactic AGN. Furthermore, let's say that you are looking at 100 candidates with velocities from $1000\,\mathrm{km\ s^{-1}}$ to $40000\,\mathrm{km\ s^{-1}}$. Then you would set vlow=1000.0 and vhigh=40000.0 and will not change the IF configuration when you change sources.

Note that if **vdef**="Red" (i.e., redshift), then you must give the redshift parameter "z" as the values for "vlow" and "vhigh" instead of velocity.

Your project friend can help you decide if you should use **vlow** and **vhigh**.

Appendix D

Advanced Functions

There are a few advanced functions that one can use in a Scheduling Block (SB).

D.1 General Functions

D.1.1 GetValue()

The **GetValue()** function can be used to retrieve any parameter or sampler value within the Monitor and Control (M&C) system.

SYNTAX: value = **GetValue(** 'manager', 'parameter, parameter_field')

- **value** A string. If you need the return value to be another data type such as an integer or float, please consult your favorite Python manual to find out how to use conversion operators.
- **manager** A manager in the M&C system such as 'scanCoordinator'
- **parameter** The name of the parameter or sampler value to retrieve.
- **parameter_field** The name of the parameter or sampler field value to retrieve.

USAGE: Please consult with your project friend.

```
current_source = GetValue('ScanCoordinator','source')
current_El_lpc = GetValue('Antenna','localPointingOffsets,elOffset')
```

Script D.1: GetValue() example.

D.1.2 SetValues()

The **SetValues()** function can be used to directly set any of the parameters within the M&C system. As a result, it is used to support complex configurations and expert observations. Please note that **SetValues()** does not always issue a "prepare" on the M&C Manager containing the parameter. If you wish to do a "prepare", you can also use **SetValues()** to do that as well.

SYNTAX: **SetValues(** 'manager', **{**'parameter, parameter_field: value'**}**)

- **manager** The manager containing the parameter in the M&C system.
- **parameter** The name of the parameter.

parameter_field The name of the parameter field.

value The actual value to set. Data types depend on the parameter.

USAGE: Please consult with your project friend.

```
lfcValues = {
  'local_focus_correction,Y': -7.469,           # in mm
  'localPointingOffsets,azOffset2': 9.8902e-06, # in radians
  'localPointingOffsets,elOffset': 7.27221e-05} # in radians

SetValues('Antenna', lfcValues)
SetValues('Antenna', {'state': 'prepare'})
```

Script D.2: SetValues() example.

D.1.3 DefineScan()

If you have written your own scan type using the Python language, the **DefineScan()** function is used to load your new scan type into the current SB. Once loaded, it can be referred to by name, just like any other scan type.

SYNTAX: **DefineScan(** scanName , filepath **)**

scanName A string specifying a name for the scan.

filepath A string specifying the full filepath to the scan.

USAGE: The following example defines and then executes a scan used primarily with MUSTANG-2 observations.

```
DefineScan('boxtraj','/users/bmason/gbt-dev/scanning/ptcsTraj/boxtraj.py')
boxtraj(mySrc,x0=x0,y0=y0,taux=taux,tauy=tauy,
        scanDuration=scandur, dx=dx ,dy=dy)
```

Script D.3: DefineScan() example.

D.1.4 GetCurrentLocation()

Given a coordinate mode, **GetCurrentLocation()** returns a Location object

SYNTAX: value = **GetCurrentLocation(** coordinateMode **)**

value A Location object (see § 5.6.1) containing the coordinates of the currently selected receiver beam's position on the sky (as selected in the most recent scan type).

coordinateMode A string specifying the coordinate mode of the Location object in the return value. Available coordinate modes are 'J2000', 'B1950', 'RaDecOfDate', 'HaDec', 'ApparentRaDec', 'Galactic', 'AzEl', and 'Encoder'.

USAGE: The following example prints the current coordinates in azimuth and elevation. Note that GetH() and GetV() return float values for the major and minor axis coordinates of Location and Offset objects.

```
location = GetCurrentLocation('AzEl')
print 'Az = %s, El = %s'%(location.GetH(),location.GetV())
```

Script D.4: GetCurrentLocation() example.

D.1.5 SetSourceVelocity()

The **SetSourceVelocity()** function sets the LO1 source velocity directly, in units of km/s.

SYNTAX: value = **SetSourceVelocity(** velocity **)**

velocity The source velocity in km/s.

USAGE: If you include the velocities in your catalog (see § refsec:catalogs) then you do not need to use this function.

```
SetSourceVelocity(10.5)
```

Script D.5: SetSourceVelocity() example.

D.2 Specialty Scan Types

D.2.1 Spider

Spider() executes the specified number of slices of duration **scanDuration** through the specified location. Each slice is of length 2***startOffset**. The argument startOffset also specifies the angle of the initial slice. The user may specify unidirectional or bidirectional subscans of length **calDuration** and when to run calibration subscans relative to each slice, i.e., at 'begin', 'end', or 'both'.

SYNTAX:
Spider(location, startOffset, scanDuration, slices, beamName, unidirectional, cals, calDuration **)**

location A Catalog source name or Location object. It specifies the source which is to be tracked.

startOffset An Offset object. It specifies the 1/2 length of the subscans and the angle from location of the initial subscan.
For example, if startOffset = **Offset(** 'AzEl', '00:40:00','00:00:00',cosv=True **)** then the first leg of the scan would start at +40′ in azimuth (from the location) and would complete at -40′ in AZ. If instead you used startOffset = **Offset(** 'AzEl', '00:40:00','00:40:00',cosv=True**)** the first leg would start at AZ=+40′, EL=+40′, and would go to the opposite (AZ=-40′, EL=-40′).

scanDuration A float. It specifies the length of the subscans in seconds.

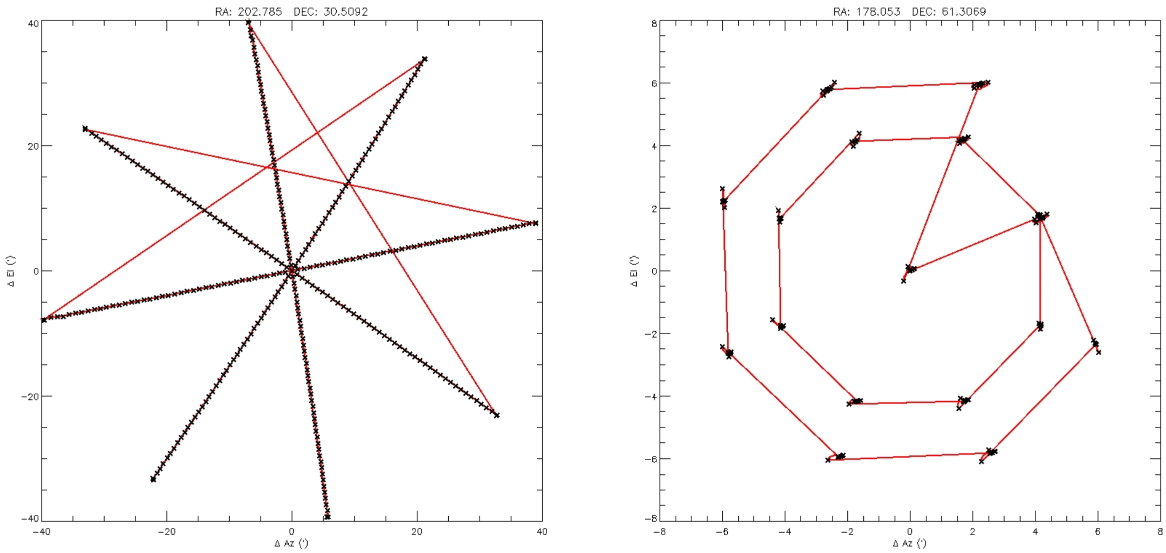
slices An integer. It specifies the number of subscans through location. The default is 4 (making a spider shape – i.e eight legs).

beamName A string. It specifies the receiver beam to use for the scan. beamName can be 'C', '1', '2', '3', '4' or any valid combination for the receiver you are using such as 'MR12'. The default is '1'.

unidirectional A Boolean. It specifies whether each slice is scanned once in one direction or twice in both directions. The default is True (one direction).

cals A string. It specifies the order of calibration subscans, i.e., at the beginning of the slice subscan ('begin'), at the end of the slice subscan ('end'), or both ('both'). The default is 'both'.

calDuration A float. It specifies the length of the calibration subscans in seconds. The default is 10.0.



(a) [Spider() GBT Antenna Trajectory.

(b) Z17() GBT Antenna Trajectory.

Figure D.1: Figure D.1a shows the actual Spider() trajectory (red) on the sky generated by executing script D.6. Crosses mark timestamps of sampled data. (sampling period is set via **tint** in the configuration). Figure D.1b shows the actual Z17() trajectory (red) on the sky generated by executing script D.7.

USAGE:

Script D.6 generates subscans through 3C 286 starting the first leg 40′ from the source's "right". A plot showing the actual trajectory on the sky when the script was executed is shown in figure D.1a. Black crosses mark timestamps of data sampled along the red trajectory.

```
Spider('3C286', Offset('AzEl','00:40:00',0.0,cosv=True),80)
```

Script D.6: Spider() example.

D.2.2 Z17

Z17() executes two circles of point subscans around location at 45° intervals. The first circle with a radius of **startOffset** and the second circle at a radius of $\sqrt{2}\cdot$ **startOffset**. The initial subscan is at the angle specified by the **startOffset**. After circling twice, the procedure executes a subscan on location. The entire set of 17 subscans each of length **scanDuration**, is sandwiched between two cal subscans of lengths **calDuration** which consist of equal parts calibration noise signal on and off.

SYNTAX:

Z17(location, startOffset, scanDuration, beamName, calDuration **)**

location A Catalog source name or Location object. It specifies the source which is to be tracked.

startOffset An Offset object. It specifies the angle from location of the initial subscan as well as the radius of the inner circle.

scanDuration A float. It specifies the length of the subscans in seconds.

beamName A string. It specifies the receiver beam to use for the scan. beamName can be 'C', '1', '2', '3', '4' or any valid combination for the receiver you are using such as 'MR12'. The is '1'.

calDuration A float. It specifies the length of the calibration subscans in seconds. The default is 10.0.

USAGE: Script D.7 generates subscan points around G135.1+54.4 starting the first circle at the source's "right". A plot showing the actual trajectory on the sky when the script was executed is shown in figure D.1b. Black crosses mark timestamps of data sampled along the red trajectory.

```
Z17('G135.1+54.4', Offset("AzEl","00:04:30","00:00:00",cosv=True), 10)
```

Script D.7: Z17() example.

Appendix E

Advanced Use of the Balance() Command

You can specify which devices are to be balanced. This overrides the default behavior of **Balance()** and should only be used when absolutely necessary.

SYNTAX: **Balance**(device, **{** option : value **}**)

device A string that may take the following values: 'IFRack', 'DCR_AF', 'GUPPI', 'vlbi', 'VEGAS', 'RcvrPF_1', and 'RcvrPF_2'.

{option : value} An optional parameter to the **Balance()** function can be a Python dictionary containing one or more of the balancing options listed below. Items which are not in the dictionary are assigned their default values and non-applicable options are ignored.

option is a string used to control the balancing. The allowed **value** types depend on the option:

- **'target_level' :** The target balancing level for the specified **device**.
  value is a float. Default values vary by **device**.
- **'port' :** Used to specify which ports to balance.
  value is an integer list (e.g., [1,2,9,10]). VEGAS ports are in the range of 1–16. The default is to balance all ports.
- **'sample_time' :** Only applicable when balancing the prime focus receivers. The prime focus balance API will try and balance the receiver over a period of **sample_time** seconds. This will be repeated a maximum of 6 times or until the power level is within 20% of the **target_level**.
  value is an integer between 1 and 41 seconds. The default is 2.
- **'cal' :** Turns the noise diodes on or off when balancing the prime focus receivers.
  value can be either 'on' or 'off'. The default is 'on'.

USAGE:

```
Balance('RcvrPF_1',{'sample_time':5,'cal':'on'})
Balance('VEGAS',{'target_level':-20})
```

Script E.1: Advanced Balance() example.

Appendix F

DSS Control Parameters

- **Required Minimum Duration**: Minimum time for scheduling a session
- **Required Maximum Duration**: Maximum time for scheduling a session
- **Time Between Sessions**: Time which must elapse between the end of one scheduled session period and the start of the next, typically used to allow the observer to sleep or reduce data.
- **Minimum Effective System Temperature (ξ)**: Some observers may wish to have their project scheduled even if the weather is not ideal. For example, projects that use very short integration times are dominated by overheads, not the radiometer equation, and so they may wish to get a scoring boost in order to allow observing under a wider range of weather conditions. To implement this desire, we allow observers to modify the minimum effective system temperature, $T_{sys}^{'}e^{\tau^{'}}$. This value usually has a default set by the DSS, and depends on observing frequency. Here, T_{sys} is the atmospheric system temperature and τ is the opacity. Recall the atmospheric observing efficiency is

  $$\eta_{atm} = \left(\frac{T_{sys}^{'}e^{\tau^{'}}}{T_{sys}e^{\tau}}\right)^2, \tag{F.1}$$

  where the prime denotes the minimum value. The minimum effective system temperature can be scaled by a factor ξ to either improve or degrade the atmospheric conditions for a particular session. The default is $\xi = 1.0$. The user needs to use caution when modifying this parameter, especially because it will have a different effect at different frequencies. For example, doubling the minimum effective system temperature will have a much larger effect at Ku-band than at K-band.

  The parameter ξ enters into the scoring in two ways. It affects the computation of overall observing efficiency, $\eta_{\rm total} = \eta_{\rm atm} \times \eta_{\rm tracking} \times \eta_{surface}$ and it also enters by modifying the threshold, minimum value.

- **Tracking Error Threshold, Source Size, and Tracking Efficiency:** To control the effect of the expected tracking error on scheduling a session, the observer should be able to modify either of two values:

  - f_{max}: the tracking error limit in units of HPBW (default 0.22 for Rcvr68_92, 0.4 for Rcvr_PAR and 0.2 for all other receivers)
  - θ_{src}: the nominal source size in units of arc seconds (default 0.0)

  The tracking error is called f, and the tracking error limit is called $f_{\rm max}$. If $f > f_{\rm max}$ the observation is too inefficient and does not get scheduled. Keep in mind that the tracking error f comes into play not only in regard to the limit, but also in the scoring equation. The value of f is ultimately a function of wind speed and observing frequency:

$$f = \frac{\sigma}{\theta_b}, \tag{F.2}$$

where

$$\left(\frac{\sigma}{\text{arcsec}}\right) \simeq \sqrt{\sigma_0^2 + \left(\frac{|v|}{3.5\ \text{m s}^{-1}}\right)^4} \quad \text{(see Eq. 1, (R. J. Maddalena and Frayer, 2014))} \tag{F.3}$$

and

$$\left(\frac{\theta_b}{\text{arcsec}}\right) \simeq \frac{748}{\nu} \tag{F.4}$$

with θ_b being the HPBW, σ_0 being the rms tracking error in the absence of wind, equal to $1.32''$ at night and $2.19''$ during the day, and ν being the observing frequency in GHz.

A value $f_{\rm max} = 0.2$ assures observers that their flux uncertainty due to tracking errors will be no more than 10%, assuming they are observing a point source ($\theta_{\rm src} = 0.0$). Observers who wish to do better than 10% may decide to specify a smaller value of $f_{\rm max}$. For example $f_{\rm max} = 0.14$ assures no more than 5% flux uncertainty due to tracking errors.

Some observers may wish to relax the tracking restrictions because their source is extended, not point-like. So the most natural way for them to ease the constraint is to specify a source size: $\theta_{\rm src}$. The default value is $\theta_{\rm src} = 0.0''$. If the user specifies $\theta_{\rm src}$ then the tracking error f should be calculated as follows:

$$f = \frac{\sigma}{\theta_{\rm obs}}, \tag{F.5}$$

where

$$\theta_{\rm obs} = \sqrt{\theta_{\rm src}^2 + \theta_{\rm b}^2} \tag{F.6}$$

This new value for the tracking error must then be used in calculating the tracking efficiency, $\eta_{\rm tr}$. So changing the source size impacts the scoring equation through both the tracking efficiency and the tracking error limit.

To summarize, most observers will not need to modify $f_{\rm max}$ or $\theta_{\rm src}$. If they do, it would be most sensible to modify only one or the other. If observing point sources, the observer may wish to change f_{max} to tighten or loosen the requirements. If observing extended sources, the observer should stick with $f_{\rm max} = 0.2$ and change the value of $\theta_{\rm src}$.

Specifying both $f_{\rm max}$ and $\theta_{\rm src}$ need not be forbidden by the software, but it is probably not the best approach.

- **Irradiance**: Section 3.4.5 of DSPN5 describes the concept of irradiance, an important concept for continuum observations above 2 GHz. Most continuum observations prefer the default values of irradiance (300 W M^{-2}), there are times when the value should be tunable, and any value of irradiance may be used for the DSS.

- **Elevation Limit**: This parameter allows the observer to modify the frequency dependent hard elevation limit, and instead set it to any value (in degrees). When using this parameter, the hour angle scoring factor will be set to zero when the source for a session is less than the minimum allowed elevation and set to one otherwise.

- **Solar Avoidance**: The angle by which the project must avoid the sun. The default here is 0.

- **Time of Day**: Time of day restrictions for this session. Options are: Any Time of Day (default); RFI (8pm - 8am); and PTCS (sunset – sunrise+2hours).

- **Transit**: The central coordinates of this session must pass through transit, with at least 25% of the session on either side of the transit window.

- **LST Exclude/Include:** This allows the session to exclude/include LST ranges when scheduling. More than one range can be given, but they must be listed sequentially.

- **Keyhole Limit**: Boolean to set a maximum elevation, specified by the sessions primary (first in list) receiver. When set to true, sessions not requiring Mustang will not be scheduled when their source will be above 80 degrees in elevation during the duration of the telescope period; Mustang observations will not be scheduled when the source will be above 78 degrees in elevation during the duration of the telescope period.

- **Good Atmospheric Stability (GAS)**: The atmospheric stability limit, $\ell_{\rm st}$, is a factor in the scoring algorithm (see DSPN 5). It is used only for continuum observations which are sensitive to atmospheric fluctuations. Currently, a forecast downward irradiance, $I_{\rm down}$, threshold value of 300 W/mi^2, is used to derive $\ell_{\rm st}$. However, a different metric has been developed for the 90 GHz Bolometer array, MUSTANG, that uses the atmospheric system temperature (including hydrosols) at the target position elevation. GAS is used to set the value of $\ell_{\rm st}$ for MUSTANG only and is ignored for all other receivers, as follows:

  For MUSTANG **only** derive the atmospheric stability limit by first calculating the zenith atmospheric system temperature at 90 GHz. (This includes hydrosols, the default in the CLEO command line interface, and is described in equation 7 in DSPN 5.) The atmospheric system temperature is the last term on the right hand side of the equation,

$$T_{\rm sys}^{\rm atm}(El = 90°) = T_{\rm k}\left(1 - e^{(EL=90°)}\right). \tag{F.7}$$

  then derive the low opacity atmospheric system temperature

$$T_{\rm sys}^{\rm atm}(El = 90°)/Sin(El) \tag{F.8}$$

  For MUSTANG, assume a frequency of 90 GHz.

$$\text{GAS is TRUE ("good")}, i.e. \begin{cases} T_{\rm sys}^{\rm atm}(El = 90°)/Sin(El) < 35K & \rightarrow \quad \ell_{\rm st} = 1 \\ \text{otherwise} & \rightarrow \quad \ell_{\rm st} = 0 \end{cases} \tag{F.9}$$

$$\text{GAS is FALSE ("usable")}, i.e. \begin{cases} T_{\rm sys}^{\rm atm}(El = 90°)/Sin(El) < 50K & \rightarrow \quad \ell_{\rm st} = 1 \\ \text{otherwise} & \rightarrow \quad \ell_{\rm st} = 0 \end{cases} \tag{F.10}$$

  For all other receivers derive the atmospheric stability limit as usual:

$$\ell_{\rm st} = \begin{cases} 1 & \text{if } I_{\rm down} < 300\text{W/mi}^2 \\ 0 & \text{else} \end{cases} \tag{F.11}$$