Spectral line data reduction

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GBT observer training workshop, February 16-18, 2022

Outline

- Introduction to single dish calibration.
- Tracking observations:
  - Data reduction in GBTIDL.
- Mapping observations:
  - Data reduction with the gbtpipeline.
- High-frequency calibration.
- Other tools.

A single dish telescope measures power:

$$P^{[\mathrm{cal}]}(\nu) = G(\nu)\left[T_{\mathrm{sou}}(\nu) + T_{\mathrm{sys}}^{[\mathrm{cal}]}(\nu)\right]$$

with

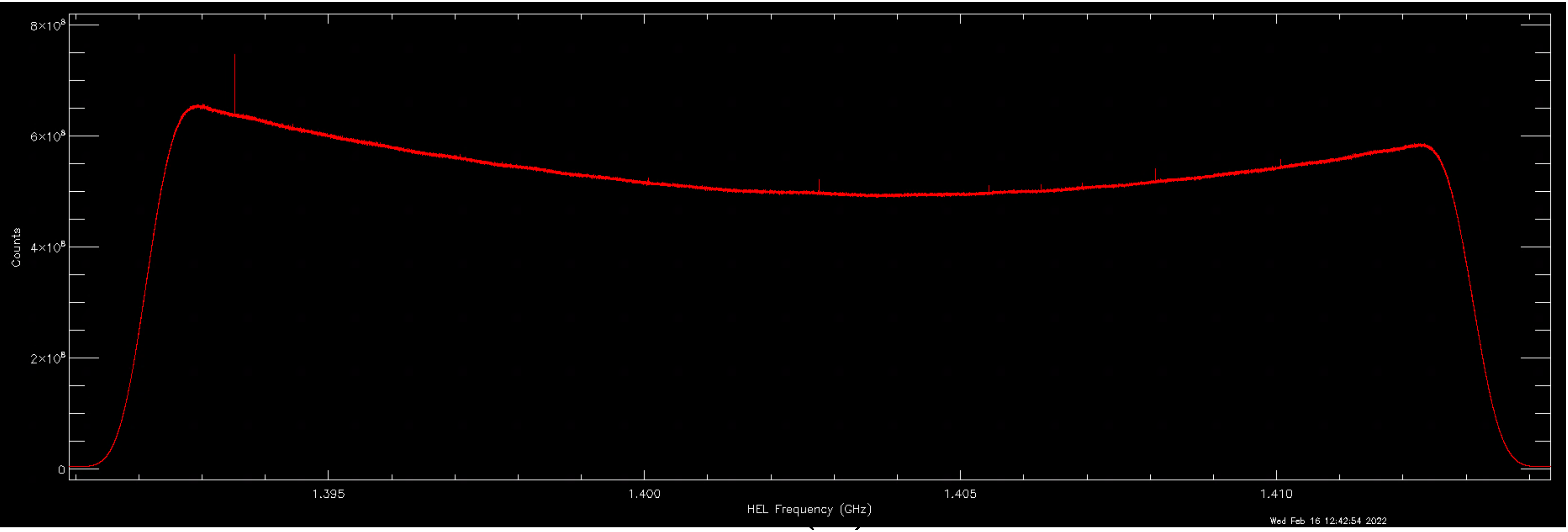
$$T_{\mathrm{sys}}^{[\mathrm{cal}]}(\nu) = T_{\mathrm{atm}} + T_{\mathrm{spill}} + T_{\mathrm{sw}} + T_{\mathrm{rx}}\left[+T_{\mathrm{cal}}\right]$$

we are after

$$T_{\mathrm{sou}}(\nu)$$

See e.g., Winkel+2012 & O'Neil 2002

A single dish telescope measures power:



See e.g., Winkel+2012 & O'Neil 2002

How do we get to $T_{\mathrm{sou}}(\nu)$ from $P^{[\mathrm{cal}]}(\nu)$?

From $P(\nu)$ to $T_{\rm sou}(\nu)$

$$P_{\rm on}^{\rm [cal]}(\nu) = G(\nu)\left[T_{\rm sou}(\nu) + T_{\rm sys}^{\rm [cal]}(\nu)\right]$$

We assume the off position is "empty":

$$P_{\rm off}^{\rm [cal]}(\nu) = G(\nu)\left[T_{\rm sys}^{\rm [cal]}(\nu)\right]$$

$$T_{\rm sou} + \Delta T_{\rm sys} = T_{\rm sys,off}^{\rm [cal]} \frac{P_{\rm on}^{\rm [cal]} - P_{\rm off}^{\rm [cal]}}{P_{\rm off}^{\rm [cal]}}$$

See e.g., Winkel+2012 & O'Neil 2002

From $P(\nu)$ to $T_{\rm sou}(\nu)$

$$T_{\rm sou} + \Delta T_{\rm sys} = T_{\rm sys,off}^{[\rm cal]} \frac{P_{\rm on}^{[\rm cal]} - P_{\rm off}^{[\rm cal]}}{P_{\rm off}^{[\rm cal]}}$$

we also need to know $T_{\rm sys,off}^{[\rm cal]}$

$$T_{\rm sys,off} = T_{\rm cal}\left[\frac{P_{\rm off}^{\rm cal}}{P_{\rm off}} - 1\right]^{-1}$$

All quantities are frequency dependent

See e.g., Winkel+2012 & O'Neil 2002

From $P(\nu)$ to $T_{\rm sou}(\nu)$

$$T_{\rm sou} + \Delta T_{\rm sys} = T_{\rm cal} \left[\frac{P_{\rm off}^{\rm cal}}{P_{\rm off}} - 1 \right]^{-1} \frac{P_{\rm on} - P_{\rm off}}{P_{\rm off}}$$

Changes to $T_{\rm cal}$ are linear in $T_{\rm sou}$ 😃

See e.g., Winkel+2012 & O'Neil 2002

Observing strategies

Position switching:

1. On-Off
2. Beam nodding
3. Sub-beam nodding

Frequency switching:

1. In band
2. Out of band

Strategy will depend on source properties and science goals.

There are other options, and you can mix these alternatives.

See e.g., Winkel+2012 & O'Neil 2002

Position switching

*It is better to keep the elevation constant

- The science target is the "On" position.

$$P_{\text{On}}^{[\text{cal}]}(\nu) = G(\nu)\left[T_{\text{sou}}(\nu) + T_{\text{sys}}^{[\text{cal}]}(\nu)\right]$$

- An "empty" region is the "Off" position.

$$P_{\text{Off}}^{[\text{cal}]}(\nu) = G(\nu)\left[T_{\text{sys}}^{[\text{cal}]}(\nu)\right]$$

```
# In AstrID:
off = Offset("AzEl", -1.0, 0.0, cosv=True)
OnOff( source, off, scanDuration, beamName )
```

Position switching

The Off region should not have emission/absorption (the Off region should be more than a beam away from your source).

The On-Off cycle should be faster than fluctuations in the telescope's gain (for narrow features ~few minutes <10 GHz, faster above).

Useful for:

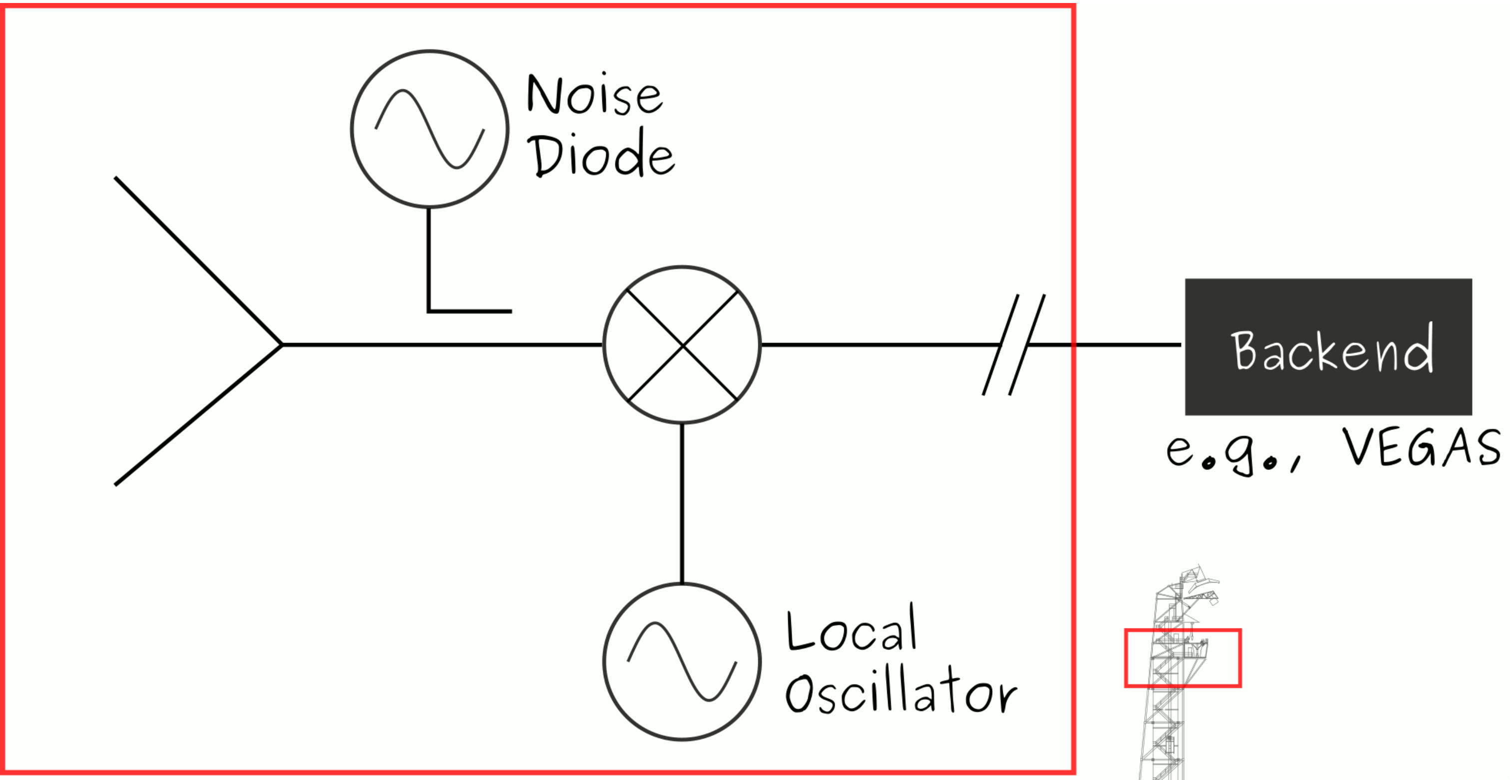
- Observations of broad (>100 km s^{-1}) spectral lines.
- Observations of sources with crowded spectrum.

Drawbacks:

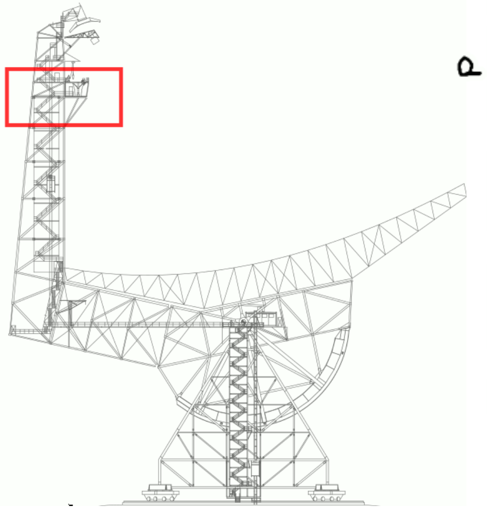
- Lost time slewing.
- Differences in P_{on} and P_{off} produce residual baselines.

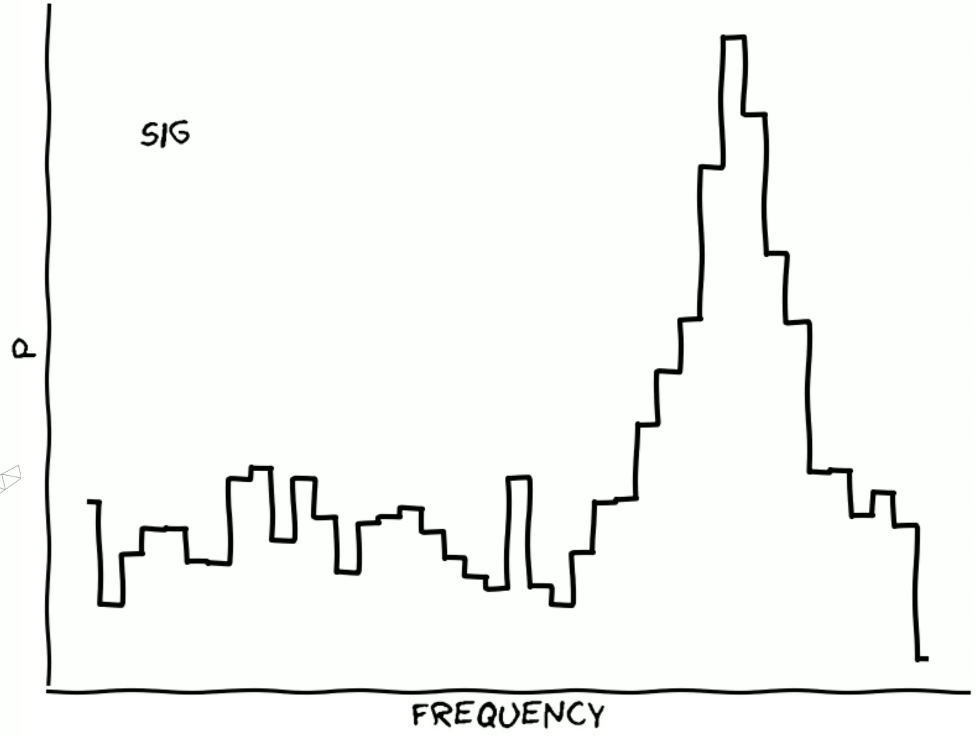
Frequency switching

The LO switches the frequency generating signal/reference pairs.



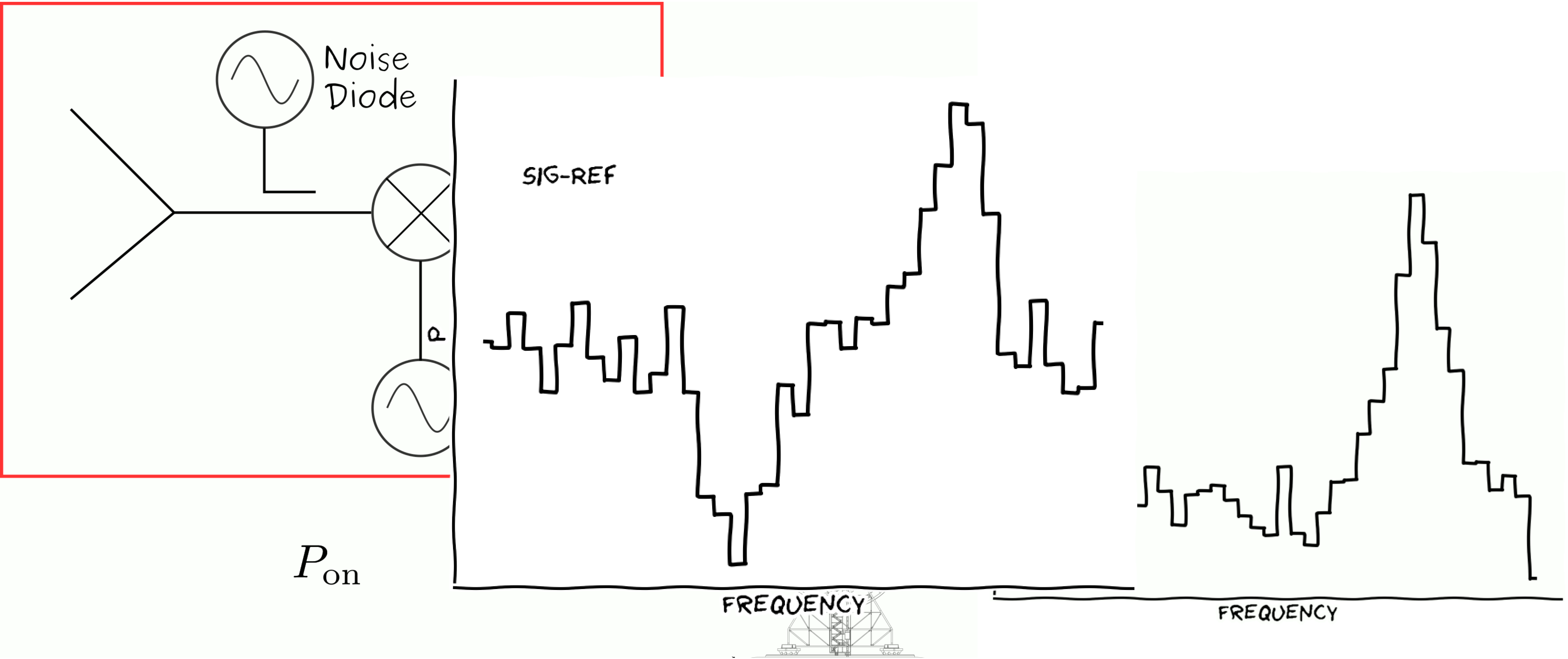
P_{on}





Frequency switching

The LO switches the frequency generating signal/reference pairs.



Frequency switching

The Off "region" should not have emission/absorption.

Be aware of the RFI environment (you do not want to switch to a region with RFI).

Useful for:

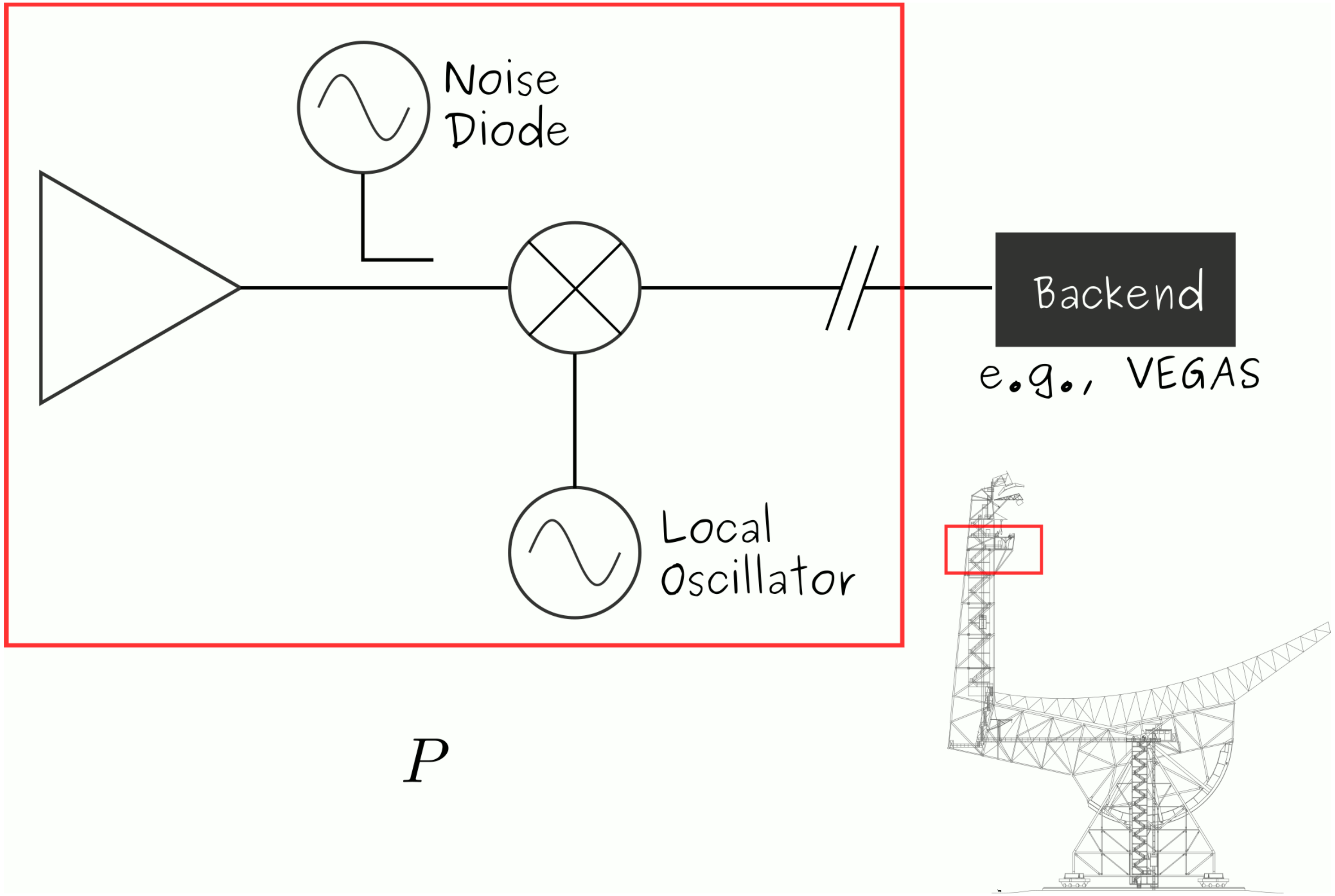
- Observations of narrow ($\leq$10 km s^{-1}) spectral lines.

Drawbacks:

- Need to know source velocity *a priori*.
- For larger $\Delta\nu$, larger residual baseline.
- No continuum measurements.

What is T_{cal}?

Is the equivalent temperature of a noise source injected to the signal path.



A note on T_cal

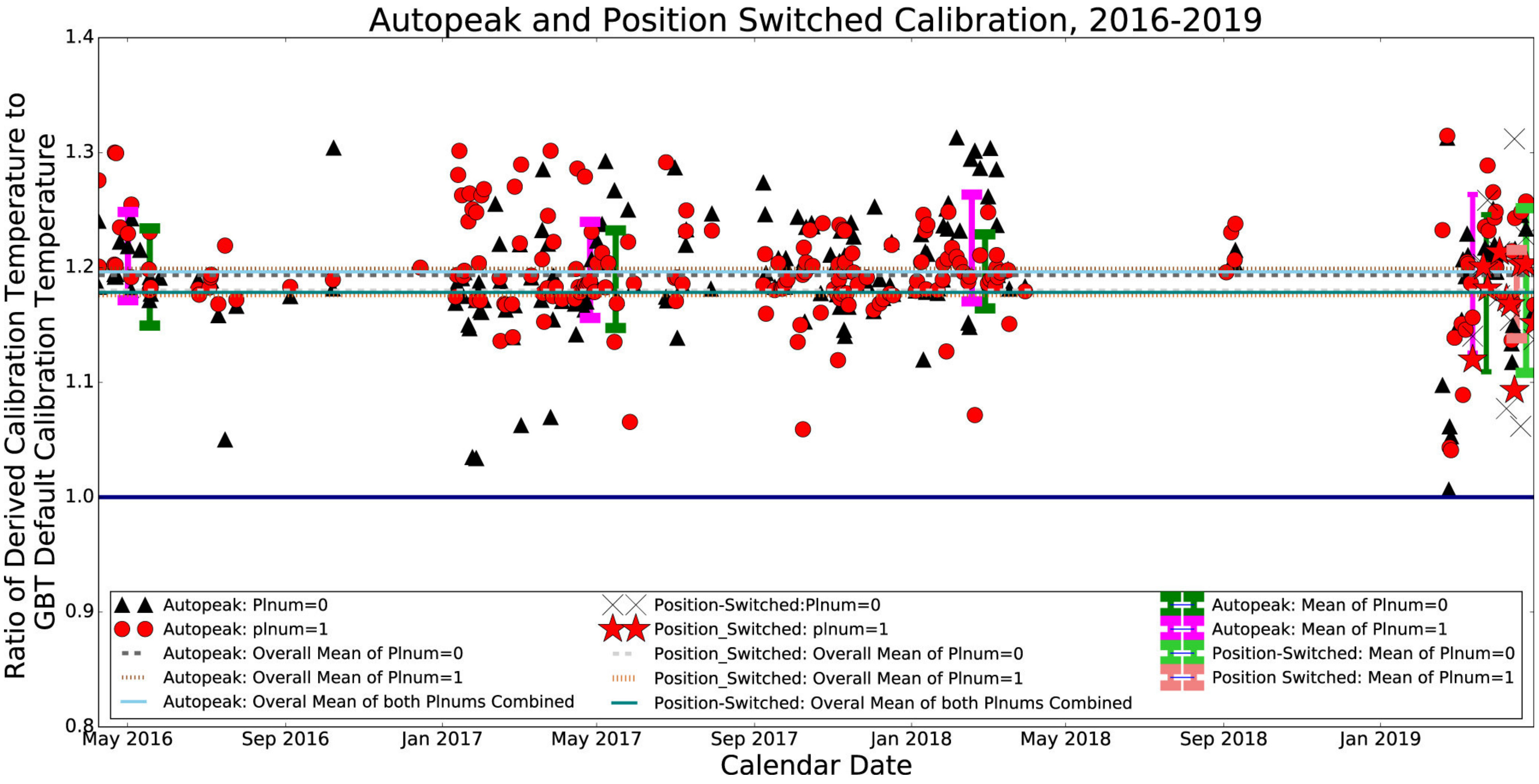
By default the metadata includes a scalar value for T_cal.

However,

- It is a scalar (good approximation for some receivers).
- You don't know when it was measured (the temperature of the noise diodes drifts).

➔ **Perform observations of a calibrator source!**

A note on $T_{\rm cal}$



Goddy+2020

➔ Perform observations of a calibrator source!

A note on T_{cal}

Calibrators should:

- Have a known flux density at your observing frequency.
- Be stable in time (or you should know its flux density at the time of your observation, e.g. check the ALMA calibrator database).
- Be point-like (or you should have a model of their brightness distribution).

Standard calibration sources and their properties:

- Perley & Butler 2017
- Ott et al. 1994

GBTIDL

- GBO supported data reduction software.
- Written in IDL.
- Locally available:

```
user@planck$ gbtidl
```

- Supports spectral line data reduction.
- Knows about most spectral line observing modes, e.g., On-Off, Track, frequency switching, beam nodding.

```
GBTIDL -> getps, 1
GBTIDL -> getfs, 10
```

Code & documentation:

http://gbtidl.nrao.edu/

GBTIDL: getting help

```
GBTIDL -> usage,'show'                ; Lists optional arguments.
GBTIDL -> usage,'show', /verbose ; Describes the command.
GBTIDL -> usage,'show', /source  ; Show source code.
```

GBTIDL: data access

```
GBTIDL -> online                      ; To access the active project.
GBTIDL -> offline, 'AGBT16B_037_04'   ; To access a project in /home/sdfits.
GBTIDL -> filein, 'mySDFITS.fits'     ; To access an SDFITS file in
                                      ; another location.
```

GBTIDL: data containers

GBTIDL stores the data in containers (array like structures). There are 16 of them, and the first (0) is called the primary data container (PDC).

```
; Save the contents of the third row of an SDFITS
; to variable `x`.
GBTIDL -> getrec,3        ; Read the third row into the PDC.
GBTIDL -> x = getdata() ; Copies the PDC into `x`.
; Zero the first 500 elements of x.
GBTIDL -> x[0:500] = 0
```

Container arithmetic

```
; Add data containers 10 and 11 and save into 12
GBTIDL -> add,10,11,12
; Subtract data containers 10 and 11 and save into 12
GBTIDL -> subtract,10,11,12
; Divide data containers 10 and 11 and save into 12
GBTIDL -> divide,10,11,12
```

GBTIDL: observation information

```
GBTIDL -> summary ; Summary of loaded session.
GBTIDL -> header  ; Metadata of container 0
GBTIDL -> list    ; List the contents of each
                  ; row in the SDFITS.
```

GBTIDL: baseline fitting

```
GBTIDL -> setregion ; Define region for baseline fitting.
GBTIDL -> nfit,3     ; Set polynomial order.
GBTIDL -> bshape     ; Fit polynomials to selected ranges.
GBTIDL -> baseline   ; Subtract baseline.
```

GBTIDL: smoothing

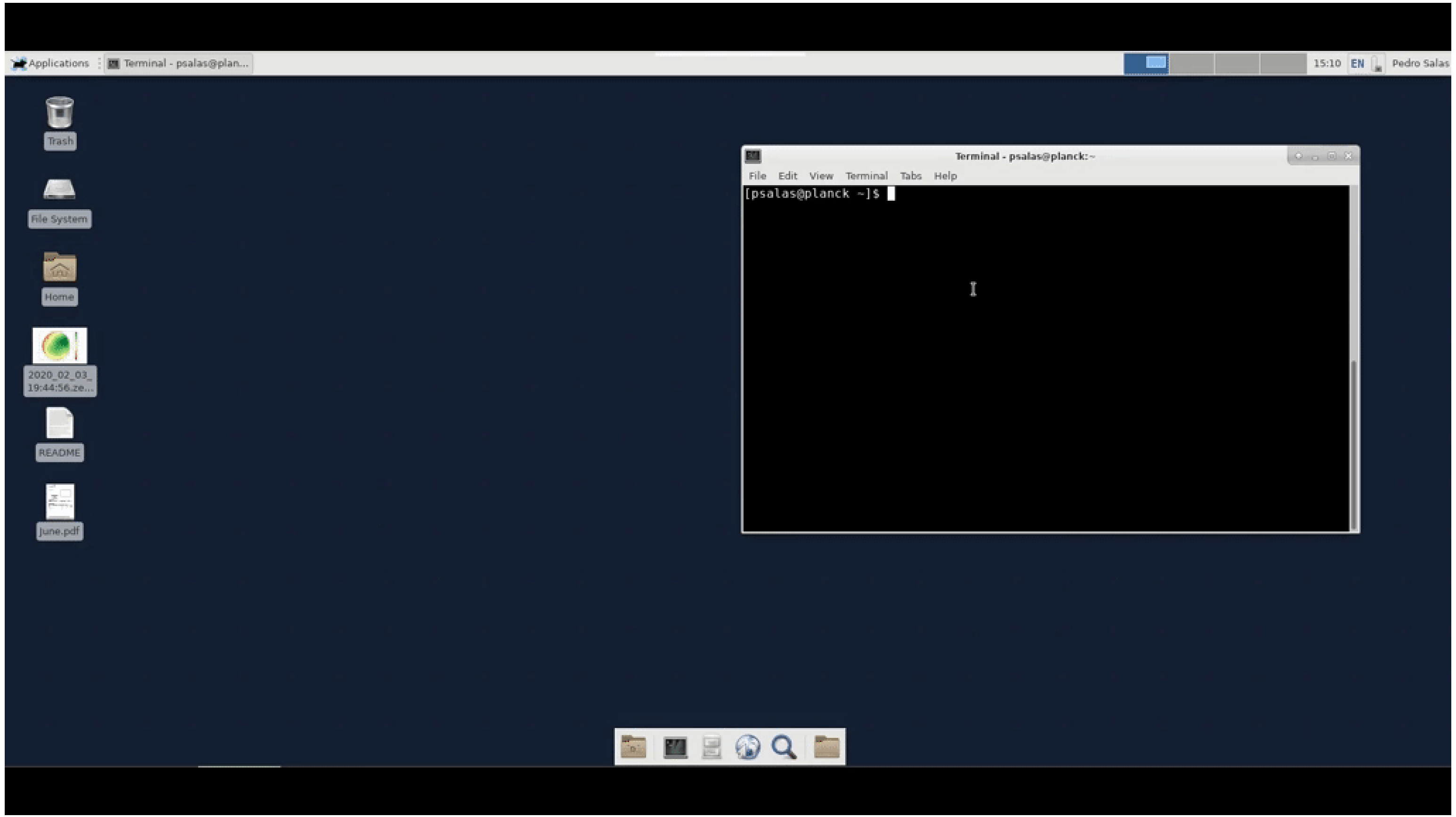
```
; Smooth spectrum in PDC by 5
; channels, keeping every 5th
; channel.

; Using a Gaussian kernel.
GBTIDL -> gsmooth,5,/decimate
; Using a boxcar kernel.
GBTIDL -> boxcar,5,/decimate
```

GBTIDL: Gaussian fitting

```
; Fit a Gaussian to the spectrum
; on display. You will specify the
; region to be fitted and starting
; guesses using the GUI.
GBTIDL -> fitgauss
```

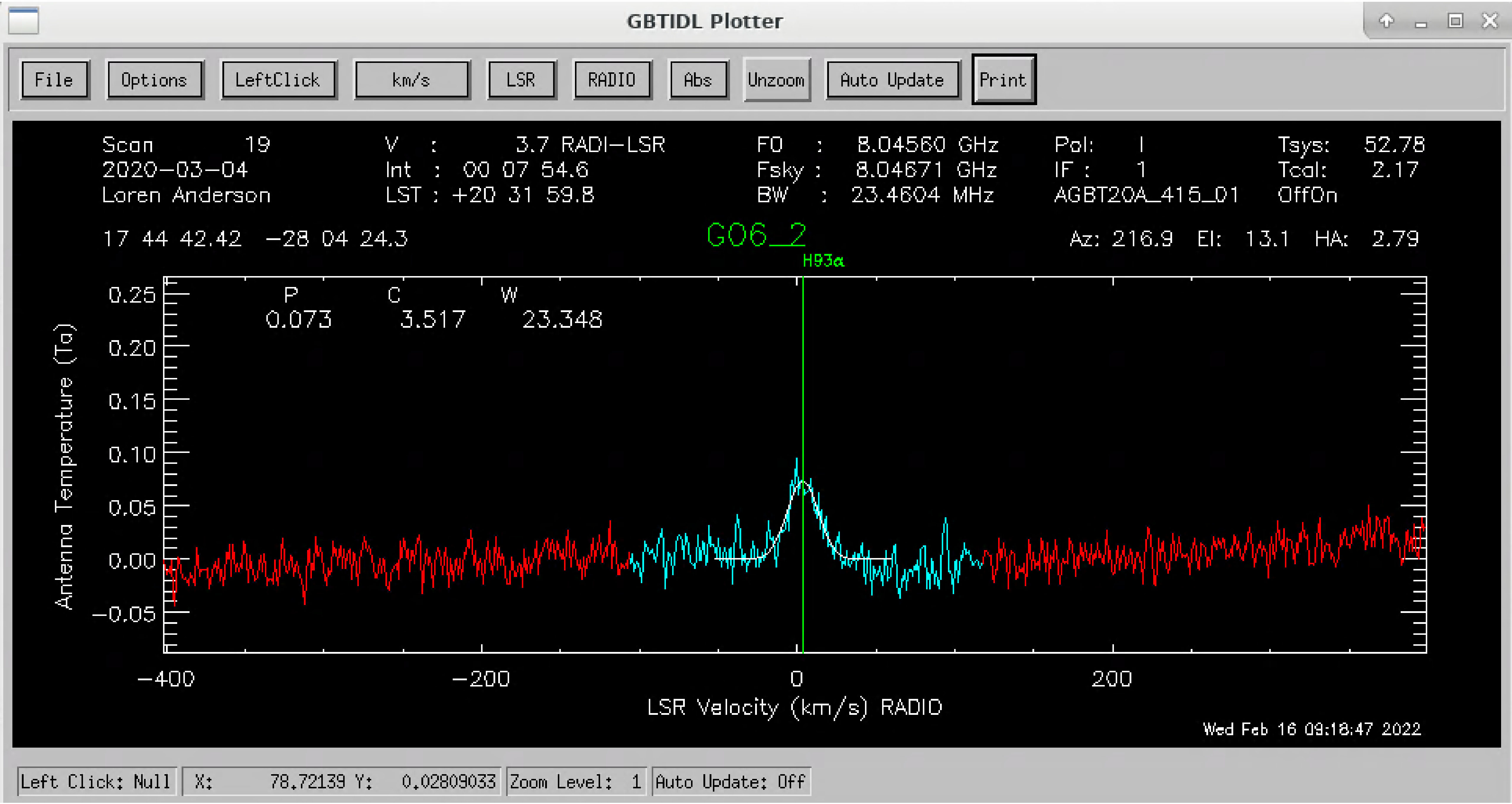
GBTIDL: example 1

```
offline, 'TGBT21A_501_11'  ; Connect to project TGBT21A_501 session 11.
summary                    ; List the contents of the SDFITS file.
getps,152                  ; Get position switched data for scan 152.
gsmooth,5,/decimate        ; Smooth the data using a Gaussian kernel 5 channels wide.
```



GBTIDL: example 2

```
; Load a SDFITS file from your scratch area.
filein,'/home/scratch/psalas/obs_training/tutorials/rrl/AGBT20A_415_01.raw.vegas.fits'
summary                   ; List the contents of the SDFITS file.
for s=18,22,4 do begin for p=0,1 do begin getps,s,ifnum=1,plnum=p & accum & endfor & endfor
ave
; Fit and remove a baseline over line free channels.
setregion
nfit,1                    ; Use an order 1 polynomial.
bshape                    ; Display the best fit.
baseline                  ; Remove the baseline.
; Now fit a Gaussian to the line.
fitgauss
; Save the spectrum on display.
fileout,'H93a.fits'
keep
```


GBTIDL Plotter
File
Options
LeftClick
km/s
LSR
RADIO
Abs
Unzoom
Auto Update
Print
Scan 19
2020-03-04
Loren Anderson
V : 3.7 RADI-LSR
Int : 00 07 54.6
LST : +20 31 59.8
F0 : 8.04560 GHz
Fsky : 8.04671 GHz
BW : 23.4604 MHz
Pol: I
IF : 1
AGBT20A_415_01
Tsys: 52.78
Tcal: 2.17
OffOn
17 44 42.42 -28 04 24.3
G06_2
Az: 216.9 El: 13.1 HA: 2.79
H93α
P C W
0.073 3.517 23.348
Antenna Temperature (Ta)
0.25
0.20
0.15
0.10
0.05
0.00
-0.05
-400
-200
0
200
LSR Velocity (km/s) RADIO
Wed Feb 16 09:18:47 2022
Left Click: Null
X: 78.72139 Y: 0.02809033
Zoom Level: 1
Auto Update: Off

Mapping

The telescope "scans" an area while tracking the map center.

Mapping

There are different mapping patterns/strategies.

On-the-fly (see e.g., Mangum+2000):

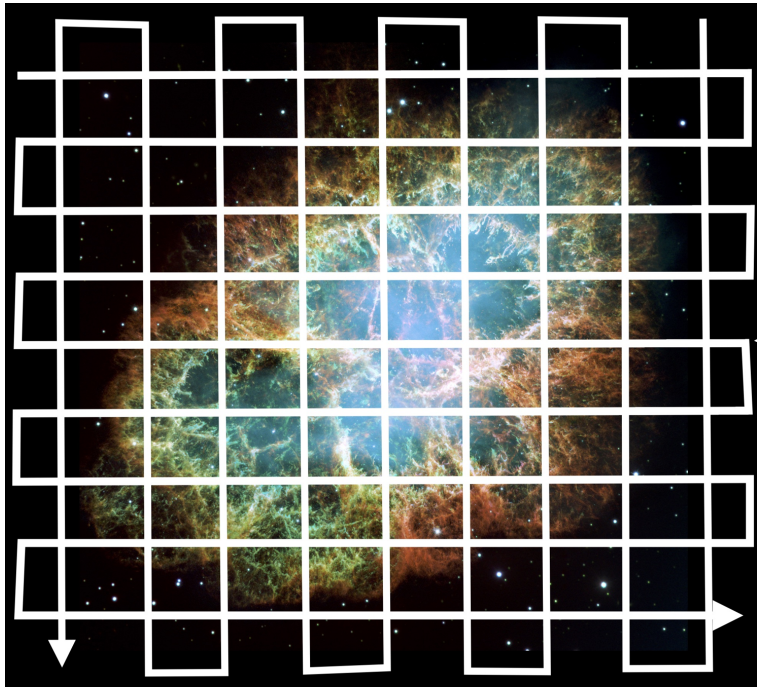
- RaLongMap, DecLatMap
- Daisy

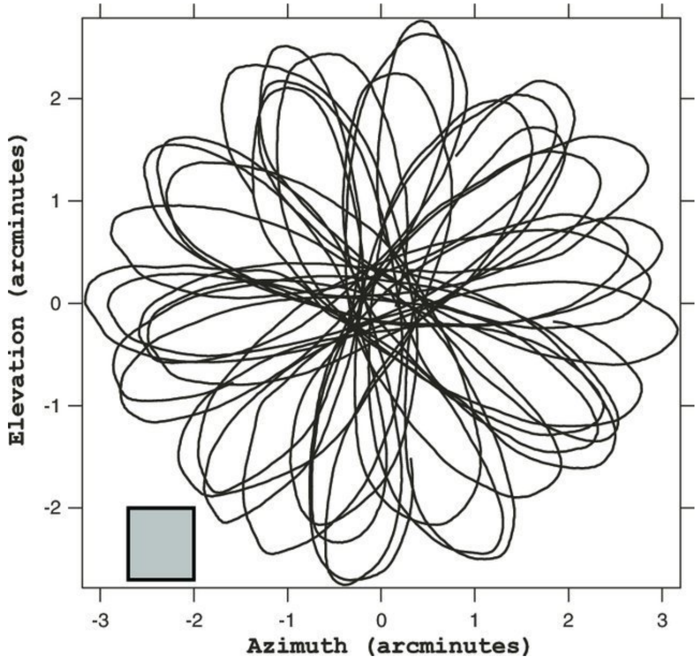
Grid:

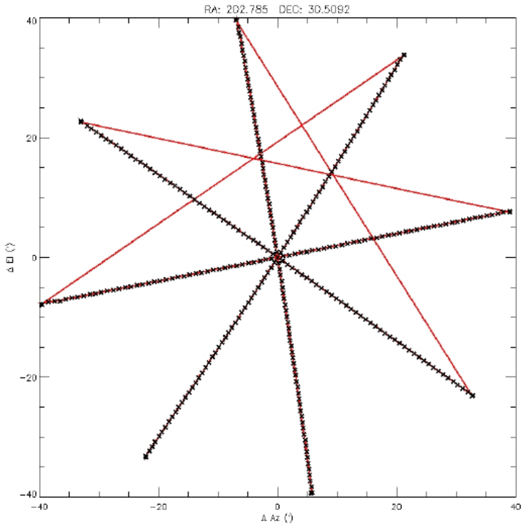
- PointMap

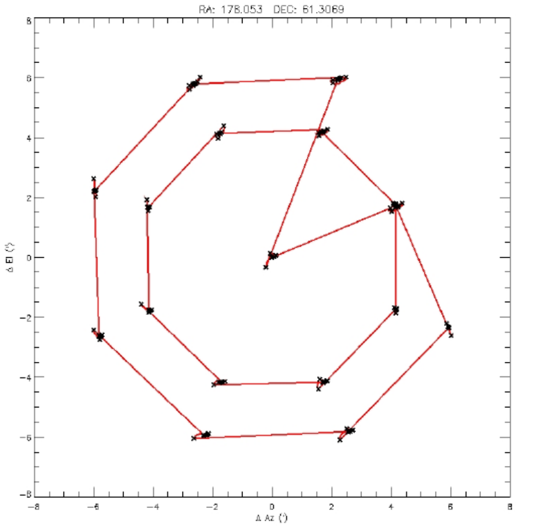
Others:

- Spider
- Z17



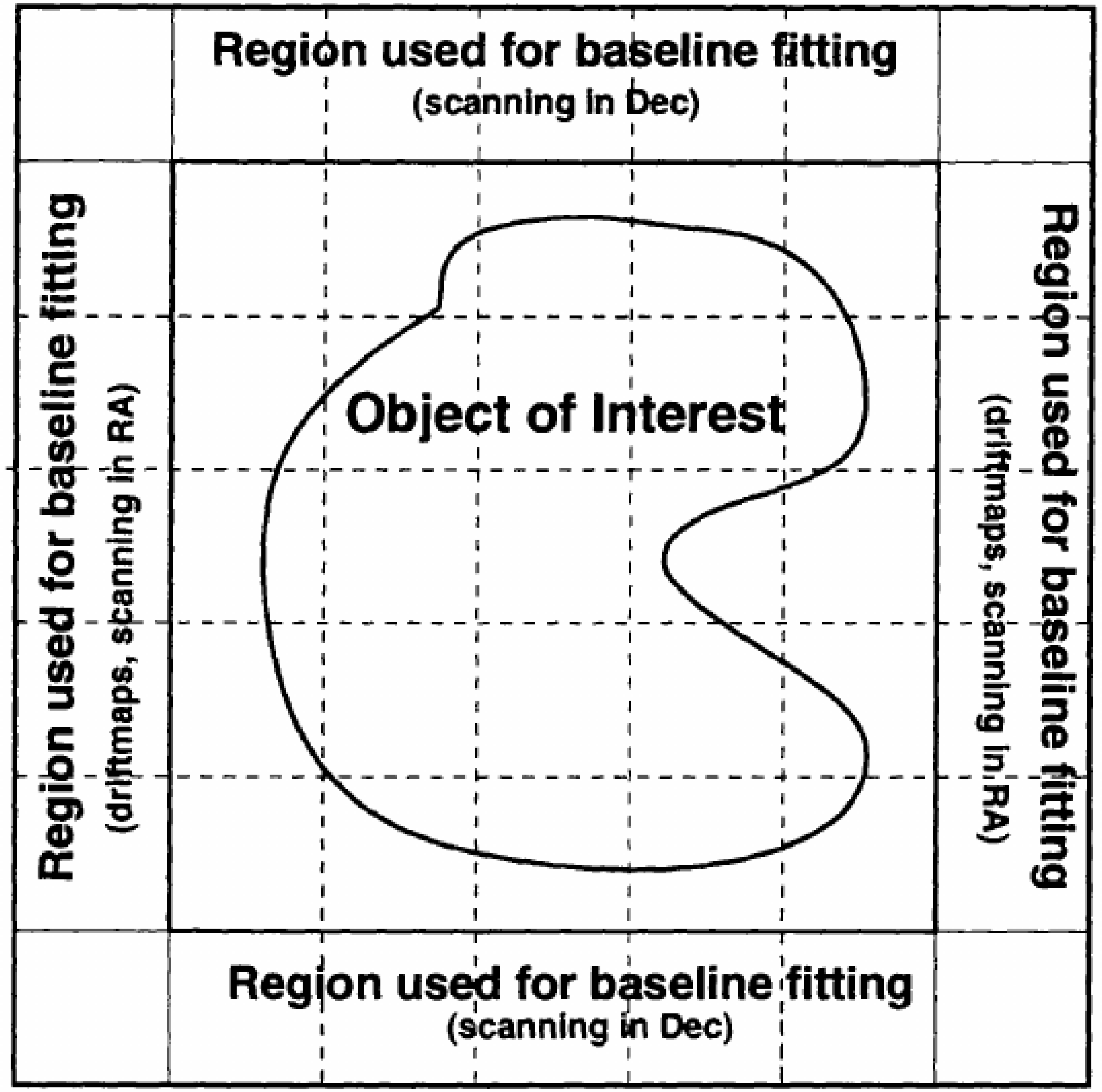






Mapping

If there are regions free of emission in the mapped area, you can use these as Off positions.



O'Neil 2002

GBTGRIDDER

Observatory supported gridding software.

```
gbtgridder -h # get help on input options.
# Example:
gbtgridder --channels 81:4014 --average 1 \
--output mycube \
my_reduced_sdfits.fits another_reduced_sdfits.fits
```

Source code at: https://github.com/GreenBankObservatory/gbtgridder

GBT pipeline

Calibrates and grids the data.

It uses the gbtgridder for gridding.

Works for receivers with noise diodes.

Designed for processing KFPA observations.

Default values suitable for KFPA observations.

Documentation:
https://safe.nrao.edu/wiki/bin/view/GB/Gbtpipeline/PipelineRelease

Source code:

https://gbt-pipeline.readthedocs.io/en/latest/#

GBT pipeline

Some options:

```
-i              # Input SDFITS.
-m              # Mapping scans.
--refscan       # Scans to use as reference.
-w              # Spectral window to process.
-c              # Channels to grid.
--beam-scaling # Multiply Tcal by this value.
--imaging-off  # If you do not want to grid.
```

Example:

```
gbtpipeline -i my.sdfits.raw.vegas -m 14:24 --refscan 13,26
```

Map scans: 14 to 24, reference scans 13 and 26

GBT pipeline: example 1

```
gbtpipeline -i "/home/scratch/dfrayer/DATAdemo/TGBT17A_506_11.raw.vegas" \
-m "14:26" --refscan 27 -w 0
```

Questions?

Send feedback to: warmentr@nrao.edu
bgregory@nrao.edu
psalas@nrao.edu

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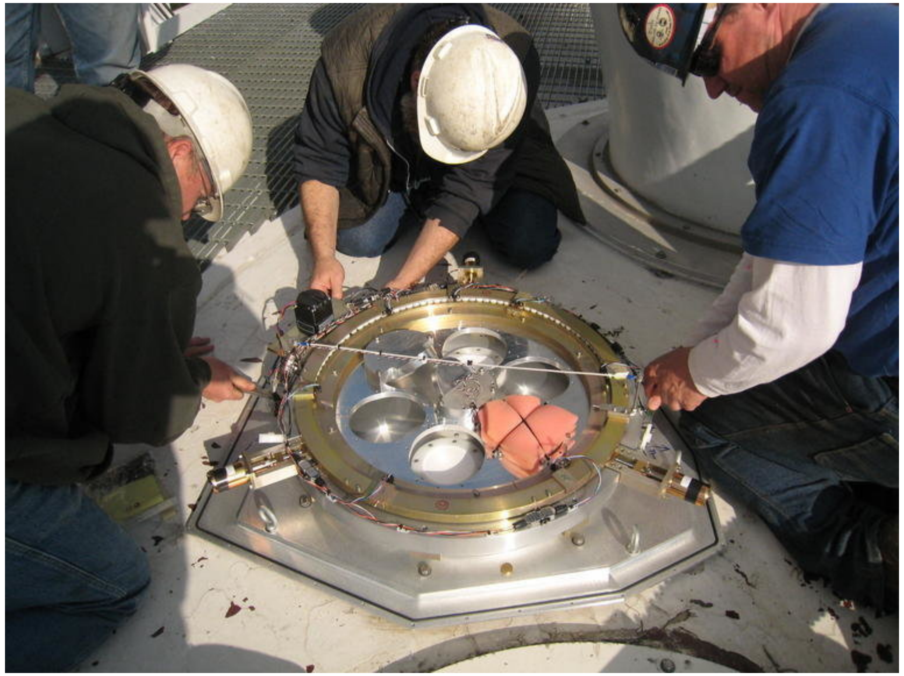
Hot & cold loads

ARGUS and the W-band receiver do not use noise diodes, they use hot and cold loads.

The W band receiver can see two loads: T_{amb} & T_{cold}.

ARGUS can see one load : T_{amb}



W band receiver calibration wheel.

Hot & cold loads

W-band

$$G = \frac{(T_{\rm amb} - T_{\rm cold})}{(P_{\rm amb} - P_{\rm cold})}$$

$$T_{\rm sys} = G P_{\rm off}$$

$$T_{\rm a} = T_{\rm sys} \frac{P_{\rm on} - P_{\rm off}}{P_{\rm off}}$$

Frayer 2019, GBT memo #302

Hot & cold loads

ARGUS

$$T_{\mathrm{a}}^{*} = T_{\mathrm{sys}}^{*} \frac{P_{\mathrm{on}} - P_{\mathrm{off}}}{P_{\mathrm{off}}}$$

$$T_{\mathrm{sys}}^{*}(t) = \frac{T_{\mathrm{cal}}}{\left(\frac{P_{\mathrm{amb}}}{P_{\mathrm{off}}} - 1\right)}$$

$$T_{\mathrm{cal}} \simeq (T_{\mathrm{atm}} - T_{\mathrm{bg}}) + (T_{\mathrm{amb}} - T_{\mathrm{atm}})e^{\tau_0 A}$$

$$T_{\mathrm{cal}} \approx T_{\mathrm{amb}}$$

GBTIDL data reduction scripts: /home/astro-util/projects/Argus/PRO

Frayer 2019, GBT memo #302

Temperature scales

- T_{a} : Antenna temperature.
- T'_{a}=$T_{\mathrm{a}}e^{\tau_0 A}$: Antenna temperature corrected for atmosphere.
- T^*_{a}=$\frac{T'_{\mathrm{a}}}{\eta_l}$: Forward beam brightness temperature.
- T_{mb}=$\frac{T'_{\mathrm{a}}}{\eta_{mb}}$: Main beam antenna temperature.

For the GBT:

- $\eta_l \simeq 0.99$, GBT memo #16 & #19
- $\eta_{mb} = 0.44 \pm 0.04$ @ 86 GHz, GBT memo #302

  $\eta_{mb} = 0.94$ @ 5 GHz

SDFITS

Single Dish FITS files.

Default data i/o for GBTIDL and gbtgridder.

VEGAS and DCR data stored as SDFITS.

Definition: https://fits.gsfc.nasa.gov/registry/sdfits.html

Details: https://safe.nrao.edu/wiki/bin/view/Main/SdfitsDetails

Note: even with a well documented definition there are multiple flavors of SDFITS, e.g., Parkes vs GBT.

Community developed data reduction tools

- GAS: KFPA ammonia survey (https://gas.readthedocs.io/en/latest/)
- DEGAS: ARGUS survey (https://github.com/GBTSpectroscopy/degas)
- TMBIDL: general use (https://github.com/tvwenger/tmbidl)
- groundhog: general use (https://github.com/astrofle/groundhog)
- SDgridder: gridder (https://github.com/tvwenger/sdgridder)
- HCGrid: gridder (https://github.com/HWang-Summit/HCGrid)
- sdpy: ??? (https://github.com/keflavich/sdpy)

*"**It takes a community to develop robust data reduction tools**" - ancient proverb*

Questions?

Send feedback to: warmentr@nrao.edu

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psalas@nrao.edu

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