Spectral line data reduction

Pedro Salas

GBO postdoc

GBT observer training workshop, May 24th, 2021

Outline

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

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

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

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

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

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

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

All quantities are frequency dependent

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

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

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

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.
(See Dave Frayer's talk).

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.

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

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

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

```
# In AstrID:
OnOff( location, referenceOffset, 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).

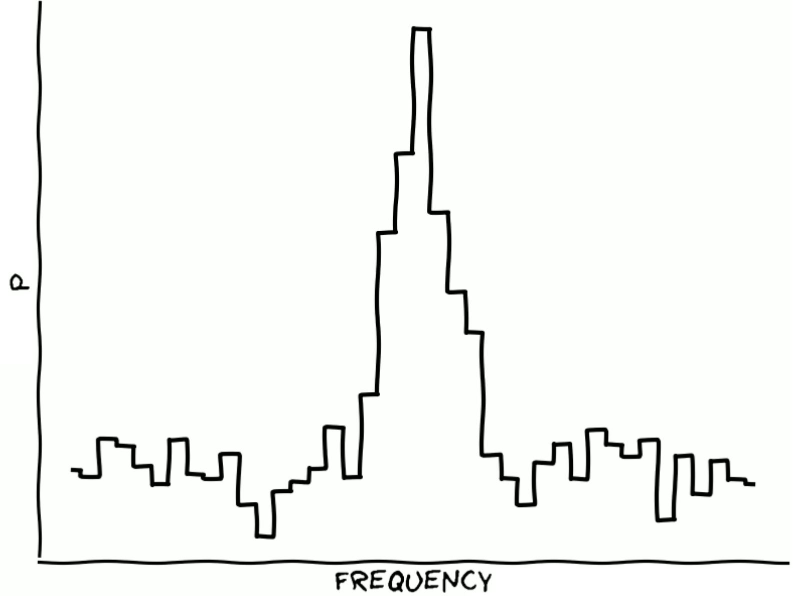
Useful for:

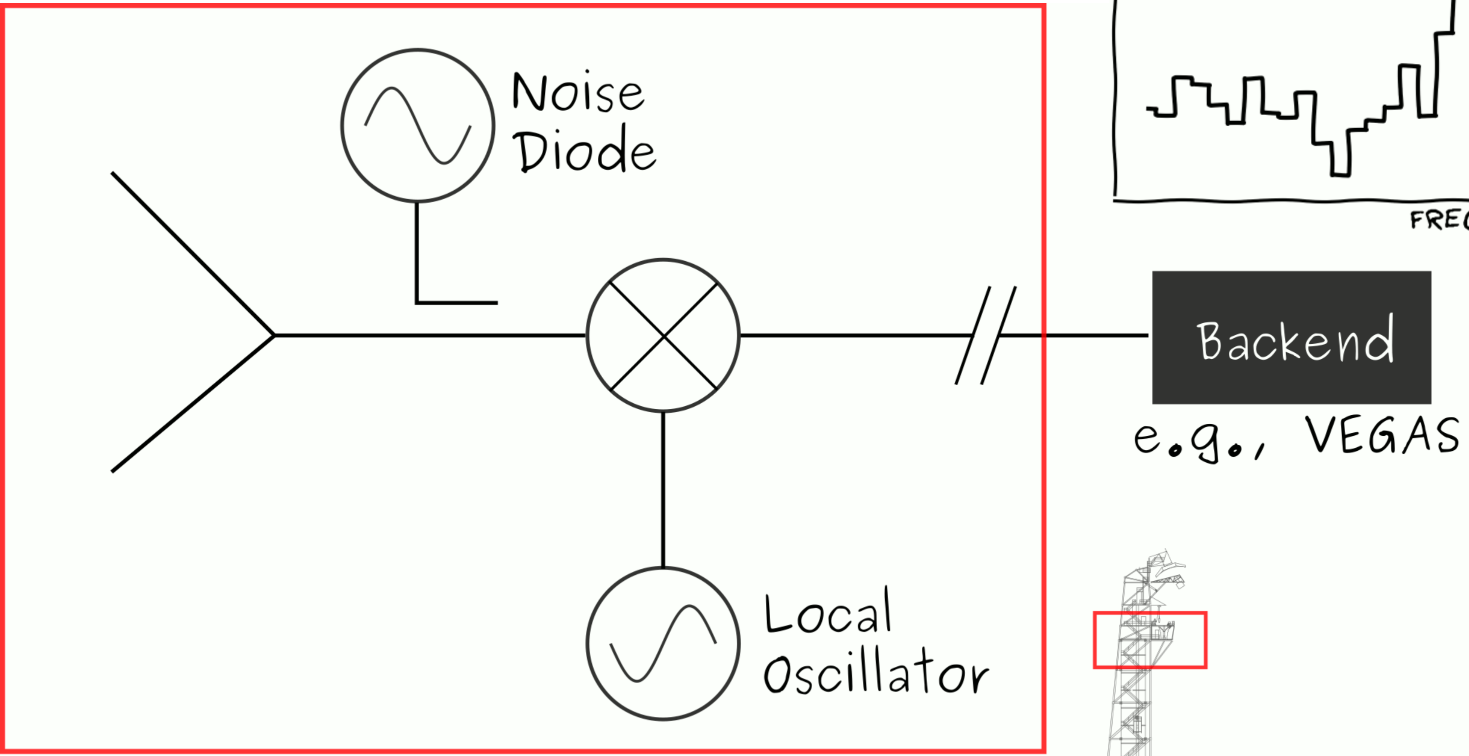
- Observations of broad (>100 km s^{-1}) spectral lines.
- Observations of sources with crowded spectrum.

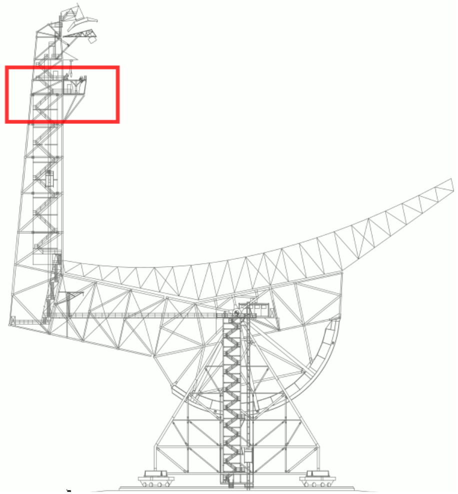
Drawbacks:

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

Frequency switching







$$P_{\text{off}}$$

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:

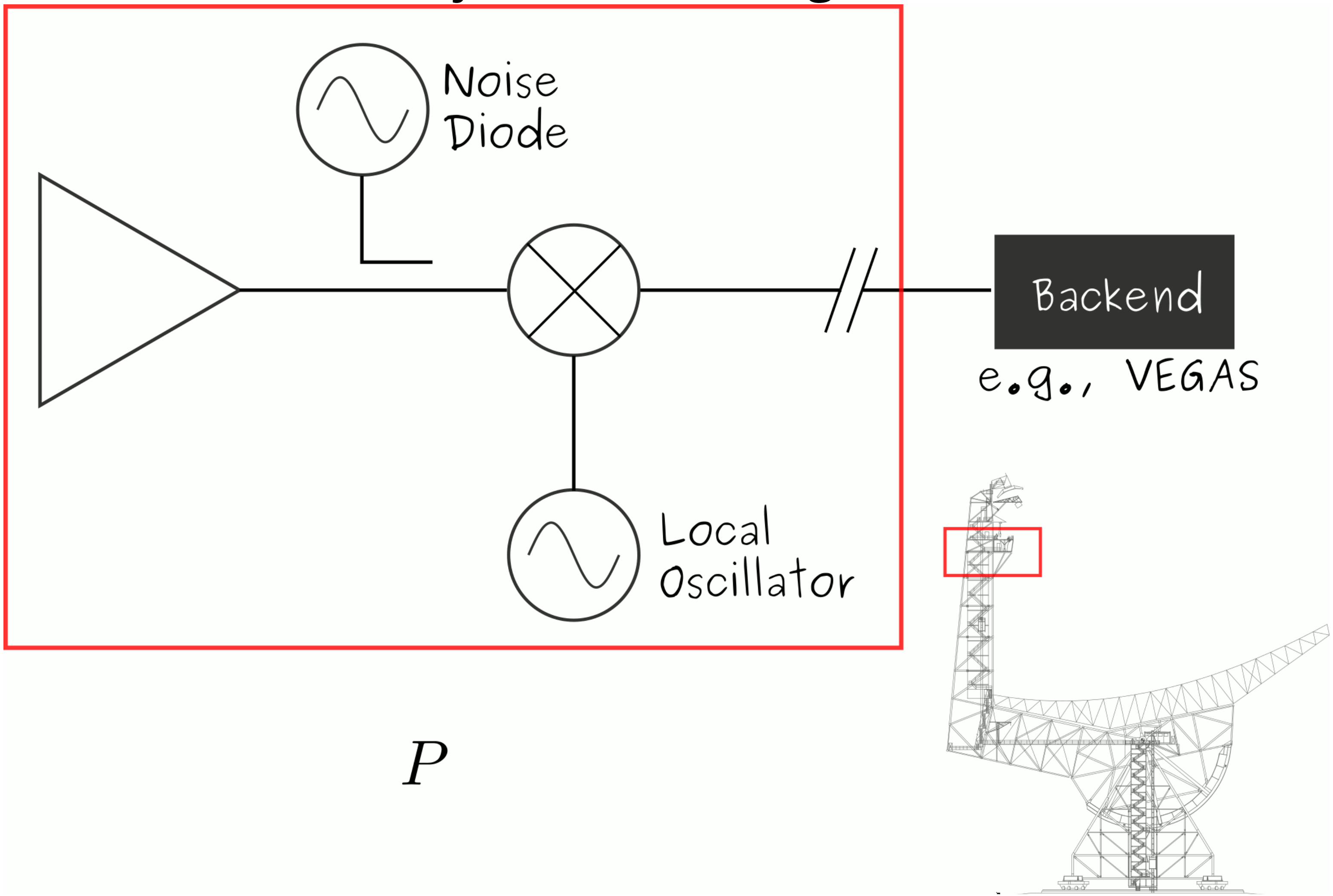
- Observations of narrow ($\leq$10 km s^{-1}) spectral lines.

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.



A note on T_{cal}

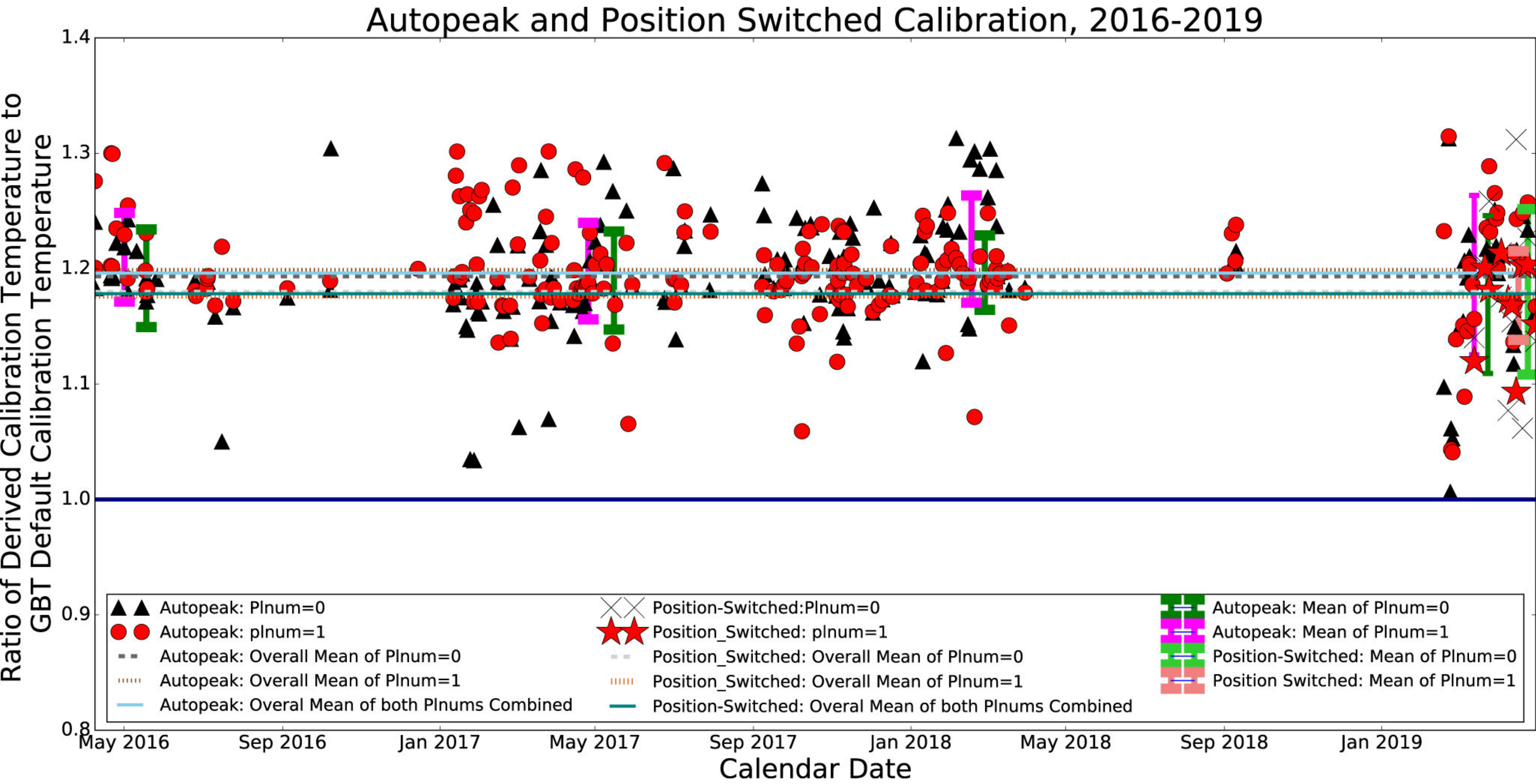
By default the metadata includes a scalar value for T_{cal}.

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 $T_{\rm cal}$

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).
- Be point-like.

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

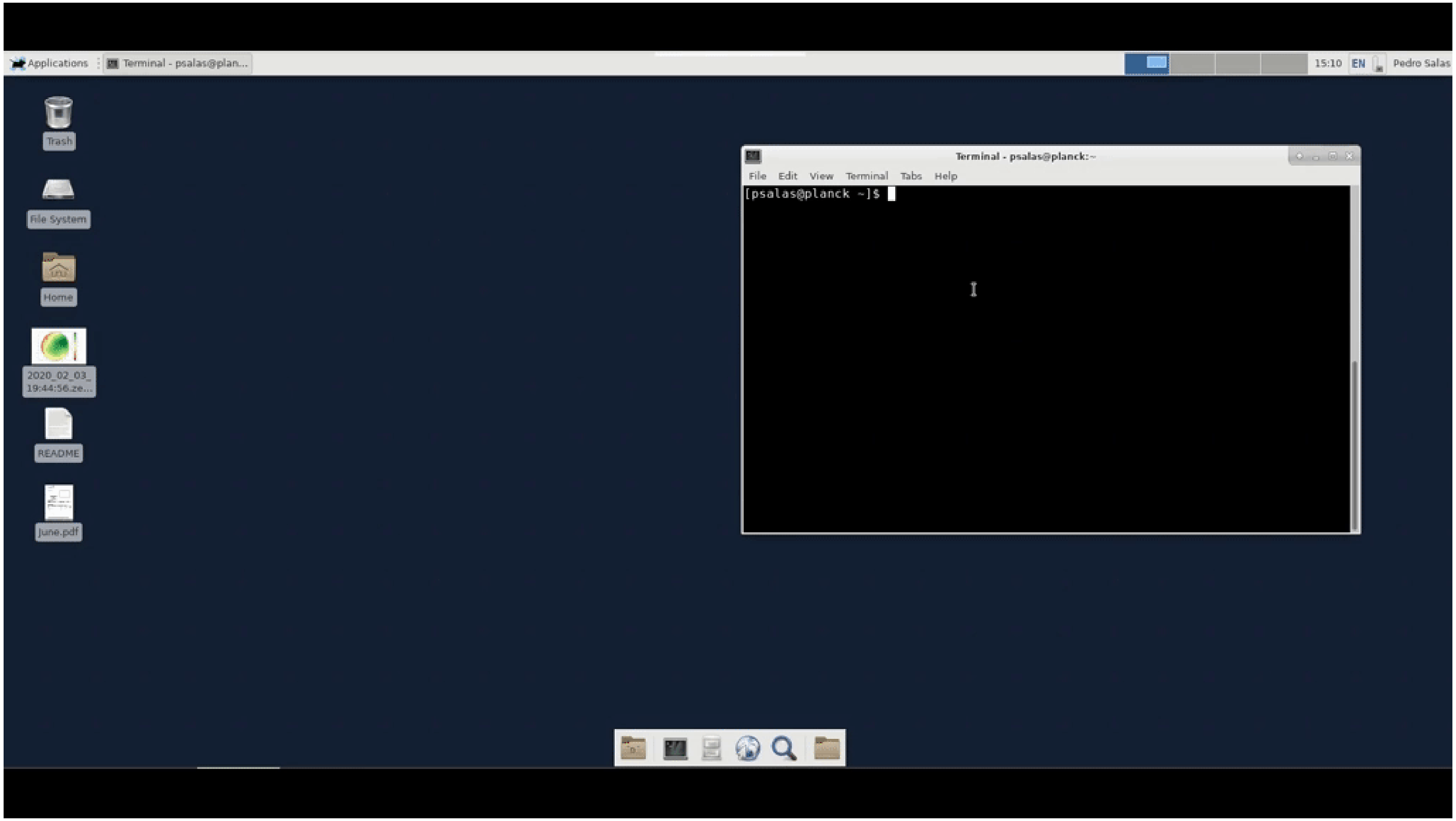
```
; Smooth spectrum in PDC by 5
; channels, keeping every 5th
; channel.

; 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, 'TGBT20A_506_01' ; Connect to project TGBT20A_506 session 01.
summary                   ; List the contents of the sdfits file.
getps,6                   ; Get position switched data for scan 6.
gsmooth,10                ; Smooth the data using a Gaussian kernel 10 channels wide.
```

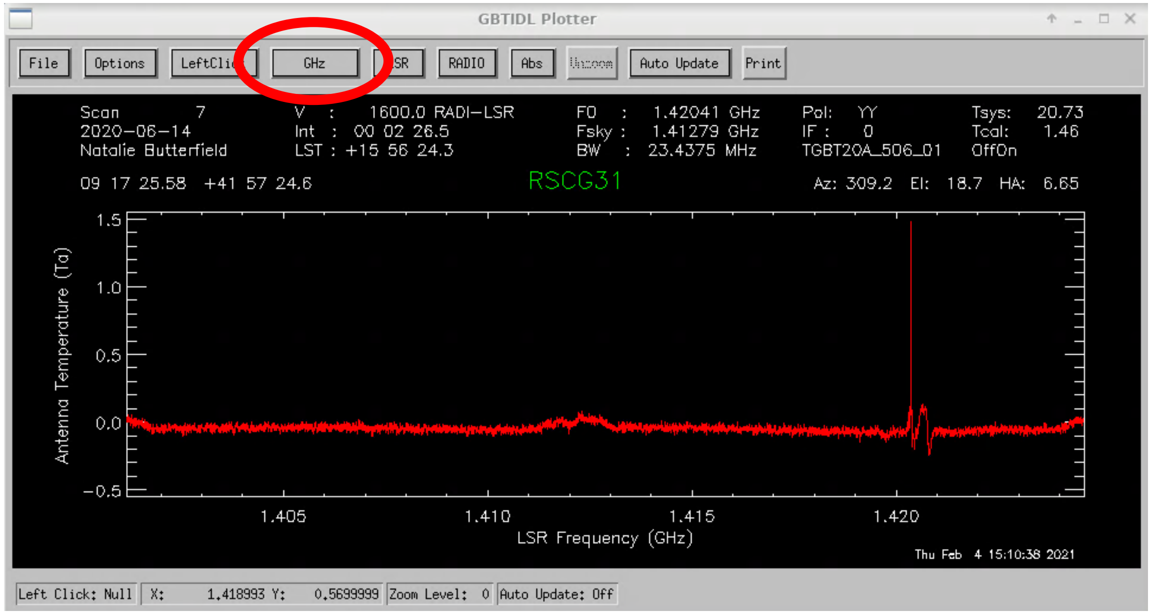


Data courtesy of A. Bonsal & N. Butterfield

GBTIDL example 1

Try it yourself:

- Open GBTIDL, load the data for this example, TGBT20A_506_01, and plot the spectrum.
- Convert the frequency axis into velocity.
- What is the velocity of the object?
- Does it agree with the optically derived velocity? (see Barton+1996)



GBTIDL example 2

average_RSCG.pro

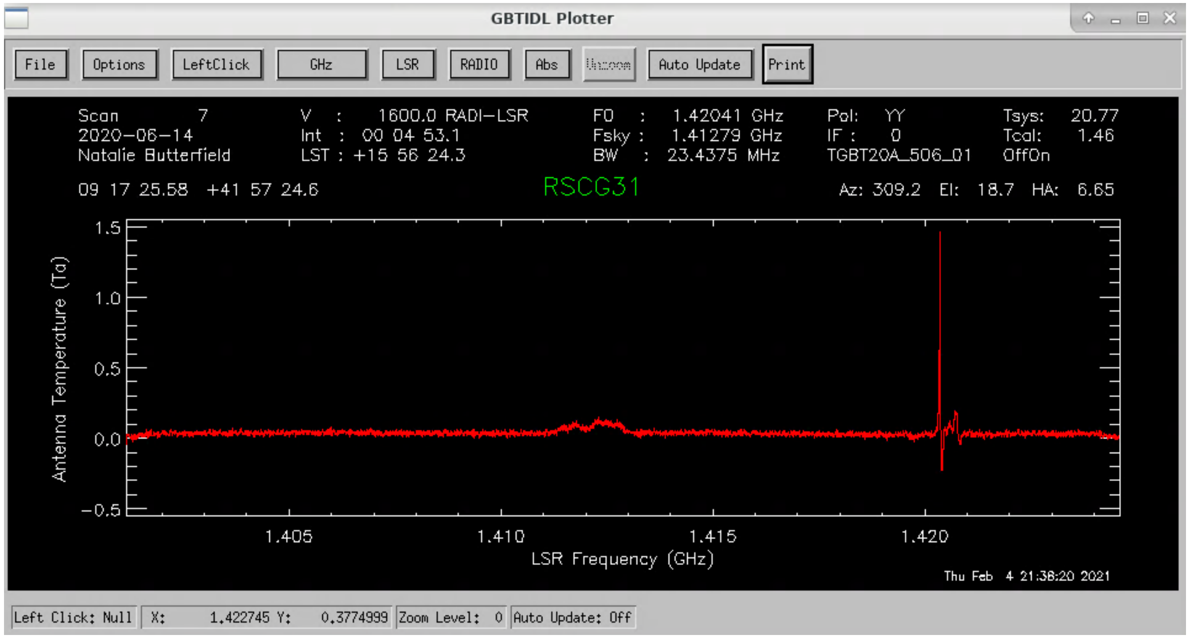
```
pro average_RSCG, scan_start, scan_end
    ; Average the position switched scans
    ; starting at scan_start and ending at
    ; scan_end, inclusive.

    sclear ; Clears the default global accumulator.
    freeze ; Turn off the plotter’s auto-update feature.

    ; Loop over scans, getting the position switched data,
    ; storing it in an accumulator for averaging.
    for i=scan_start, scan_end, 2 do begin
        getps, i
        accum
    endfor

    ave

    show
    return
end
```

Save as a text file in ${HOME}/gbtidlpro

GBTIDL example 2

In GBTIDL:

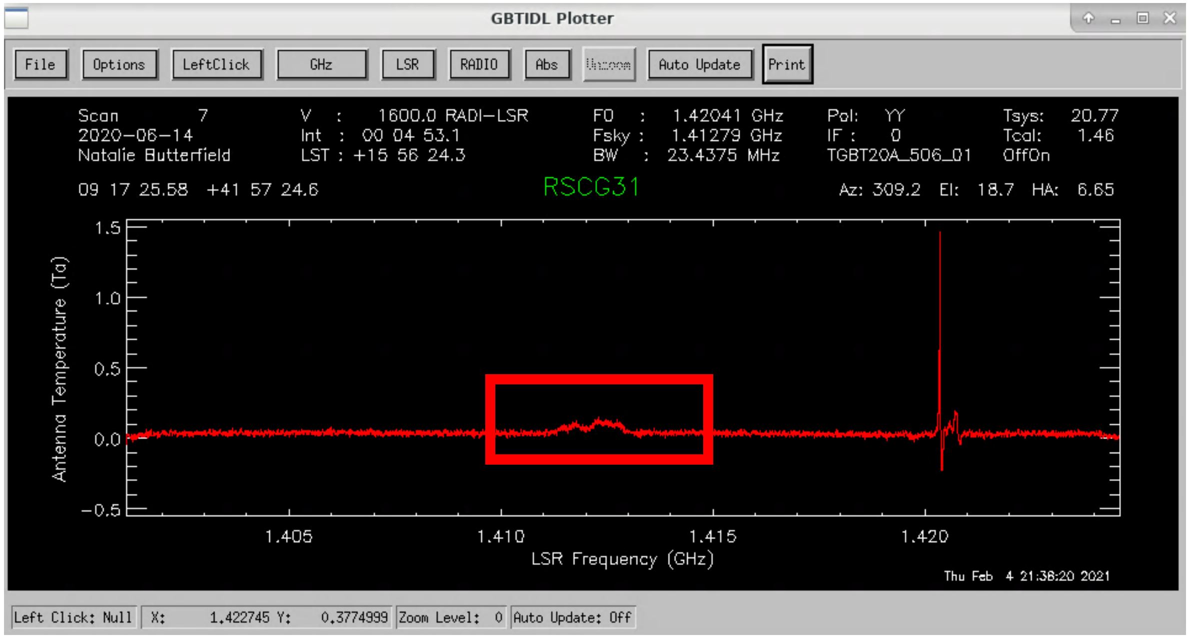
```
offline, 'TGBT20A_506_01'
.r average_RSCG
average_RSCG,6,9
show                          ; Display the averaged spectrum.
gsmooth,12                    ; Smooth using a Gaussian kernel.
show                          ; Show the smoothed spectrum.
fileout, 'rscg31_spec.fits'   ; Save to this fits file.
keep                          ; Save the primary data container (PDC)
                              ; to the fits file.
```



GBTIDL example 2

In GBTIDL:

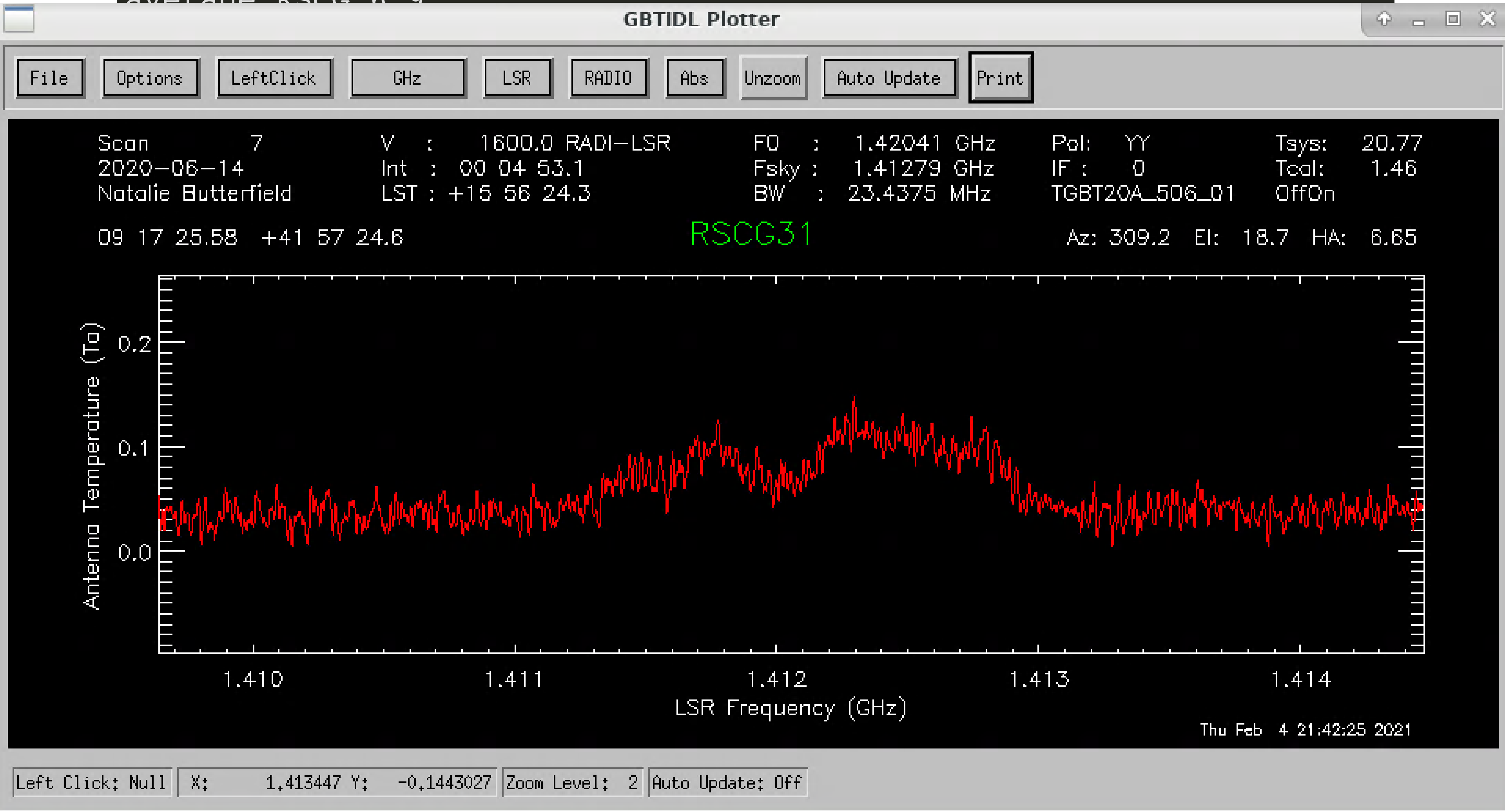
```
offline, 'TGBT20A_506_01'
.r average_RSCG
average_RSCG,6,9
show                            ; Display the averaged spectrum.
gsmooth,12                      ; Smooth using a Gaussian kernel.
show                            ; Show the smoothed spectrum.
fileout, 'rscg31_spec.fits'     ; Save to this fits file.
keep                            ; Save the primary data container (PDC)
                                ; to the fits file.
```



GBTIDL example 2

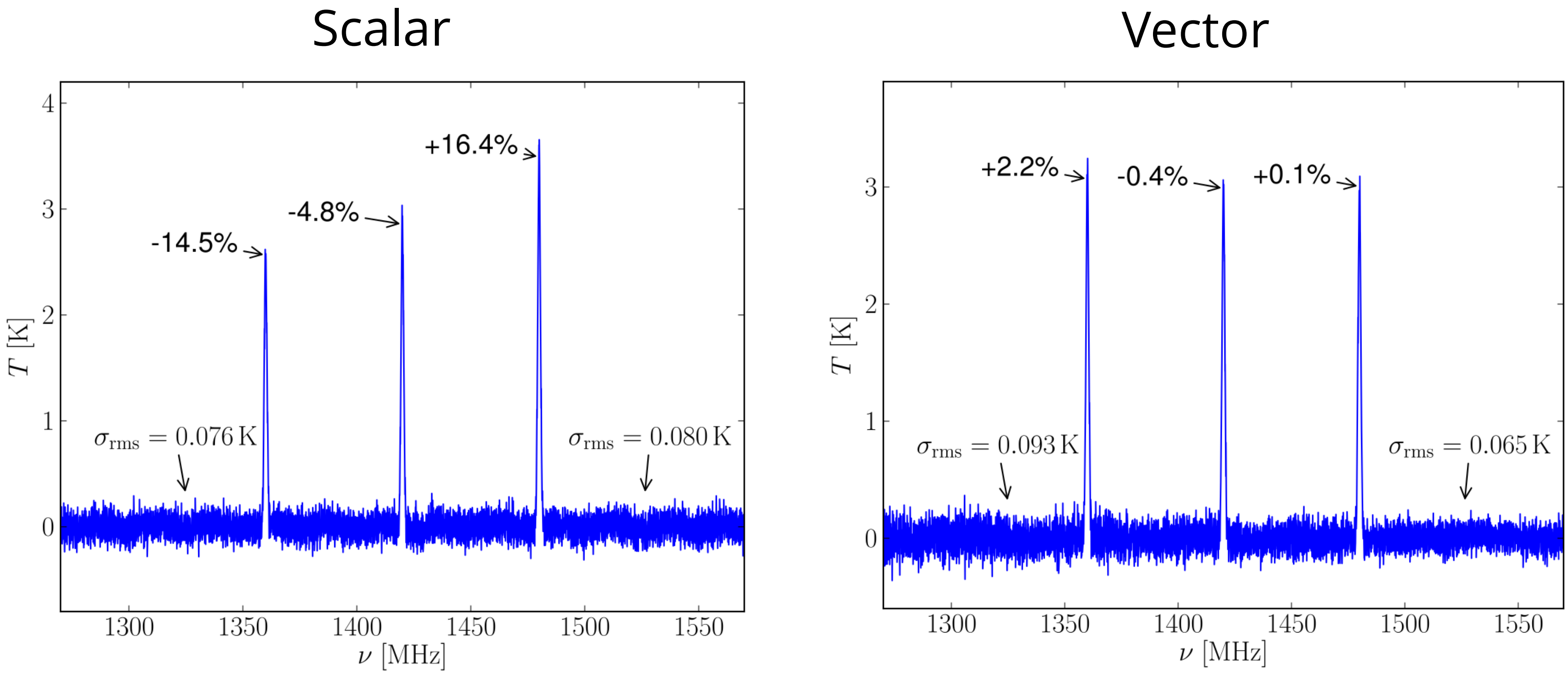
In GBTIDL:

```
offline, 'TGBT20A_506_01'
.r average_RSCG
average_RSCG 6 9
```



Scalar vs vector calibration

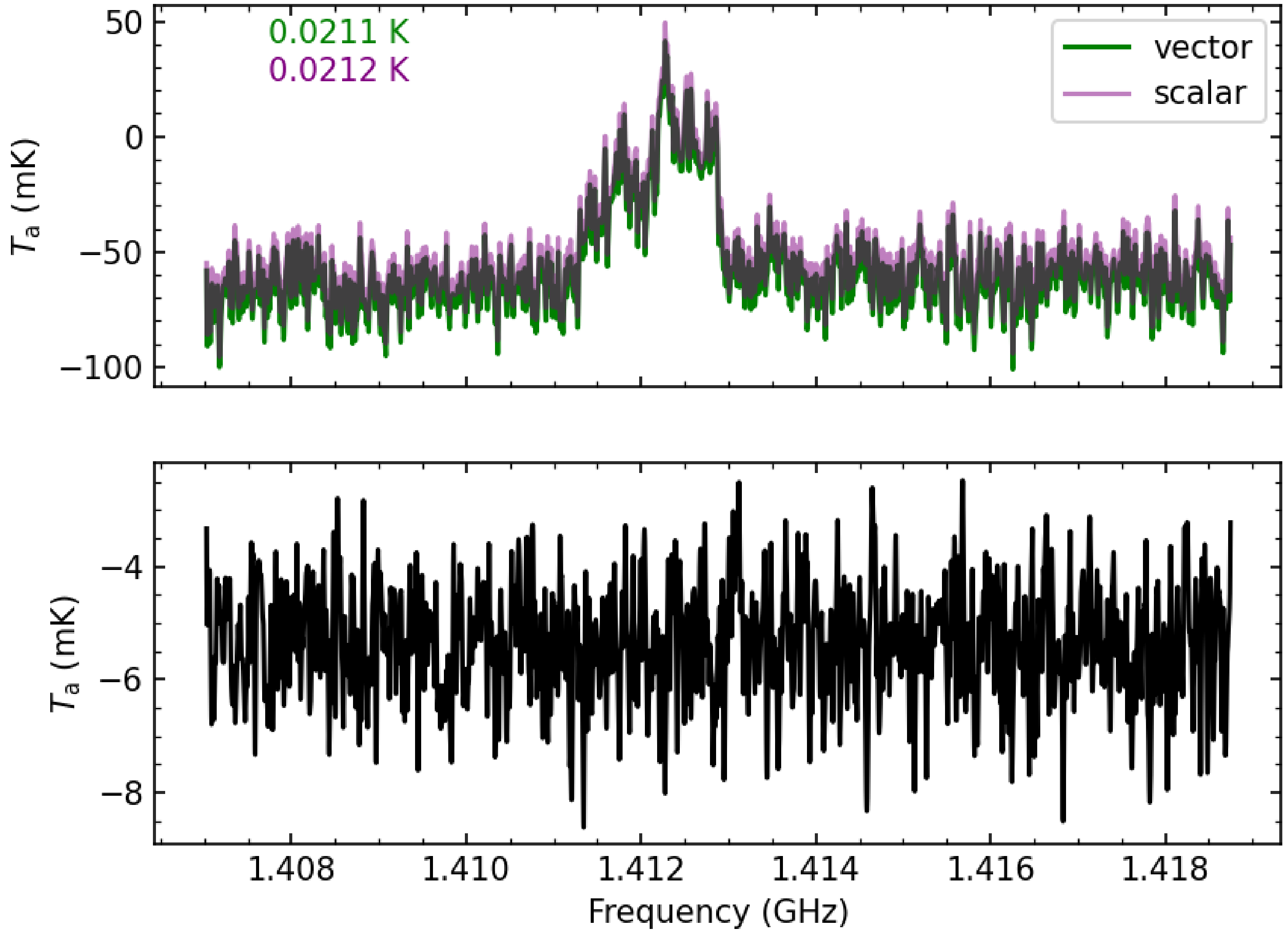
Using averages while calibrating introduces biases, particularly if there are standing waves and/or a non-flat frequency response (e.g., power law in $T_{\rm cal}$).



Winkel+2012

Scalar vs vector calibration

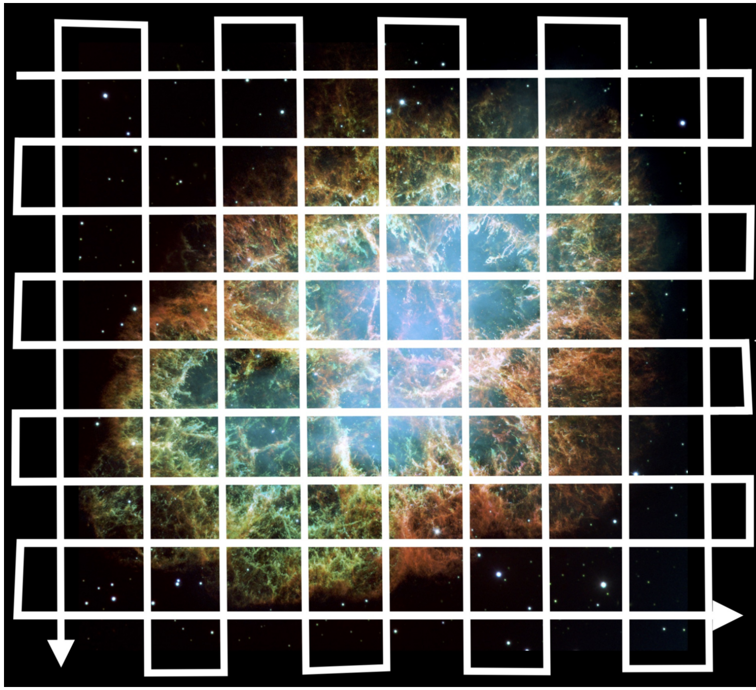
GBTIDL uses averages, but the GBT has an unblocked aperture :)



Mapping

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

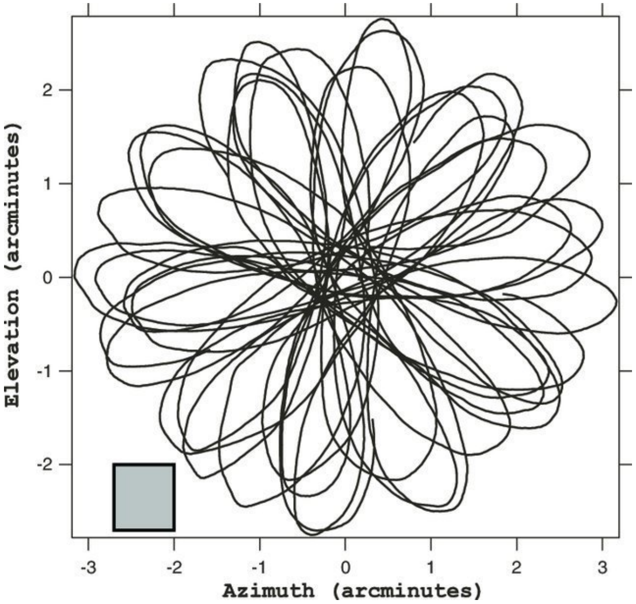
Mapping



There a re different mapping patterns.

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

- RaLongMap, DecLatMap
- Daisy

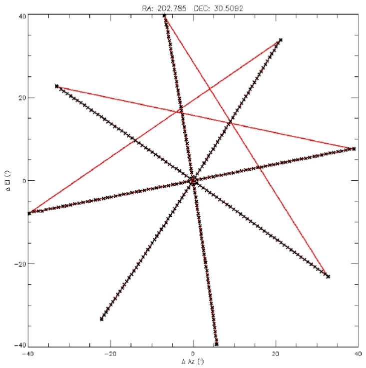


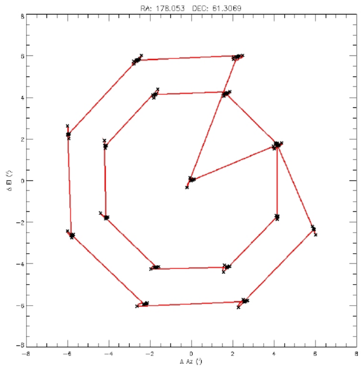
Grid:

- PointMap

Others:

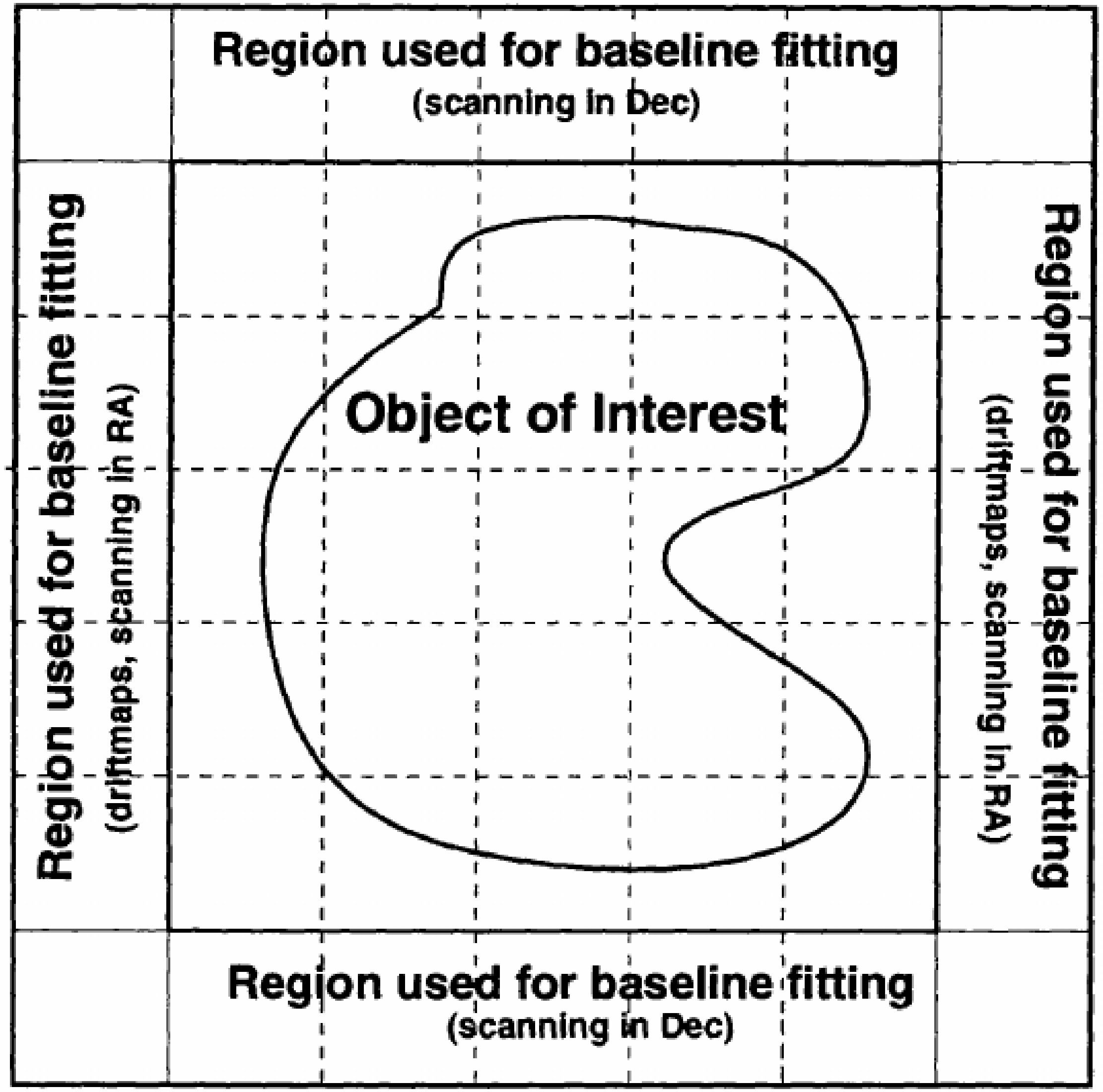
- Spider
- Z17





Mapping

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



O'Neil 2002

GBTIDL example 3

to_ta.pro

```
pro to_ta, file_out, scan_ref, scan_start, scan_end, int_start, int_end, if_num
    ; Process mapping scans and save them to file_out.
    ; It uses scan_ref as reference scan.
    ; Starts with scan_start scan and ends at scan_end scan, inclusive.
    ; Process each integration individually, starting at int_start and
    ; ending at int_end, inclusive.
    ; Only process data for spectral window if_num.

    freeze ; Turn off the plotter’s auto-update feature.
    fileout, file_out

    ; Loop over scans, converting to antenna temperature
    ; using the reference position. It saves each integration
    ; into a new fits file.
    for i=scan_start, scan_end, 1 do begin
        for j=int_start, int_end, 1 do begin
            getsigref, i, scan_ref, intnum=j, ifnum=if_num
            keep
        endfor
    endfor

    return
end
```

Save as a text file in ${HOME}/gbtidlpro

GBTIDL example 3

Once the data is calibrated use the *gbtgridder* to produce a data cube.

```
gbtgridder -c 11000:11251 -a 7 --noline --nocont -o output input.fits
```

This will produce a data cube *output_cube.fits* with channels 11000 to 11251 averaged by a factor of 7.

Also, a map of weights *output_weight.fits.*

Source code at:

https://github.com/GreenBankObservatory/gbtgridder

(No documentation available)

```
gbtgridder -h ; get help on input options.
```

GBT pipeline

Calibrates and grids the data.

It uses the gbtgridder for gridding.

Works for receivers with noise diodes.

Designed for processing KFPA observations (it has been tested with L band data as well).

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

Continuum

Pick receiver, integration time and slew rate to minimize $\frac{1}{f}$ noise (timescale ~1.4 s at C and K band, see e.g., Harper+2015).

There is no observatory supported continuum data reduction package.

Contact your project friend if you are interested in doing continuum science.

Continuum: example

How to fill continuum data?

See: https://github.com/GreenBankObservatory/gbtcal-nb/blob/master/gbtcal.ipynb

Contact your project friend if you are interested in doing continuum science.

Questions?

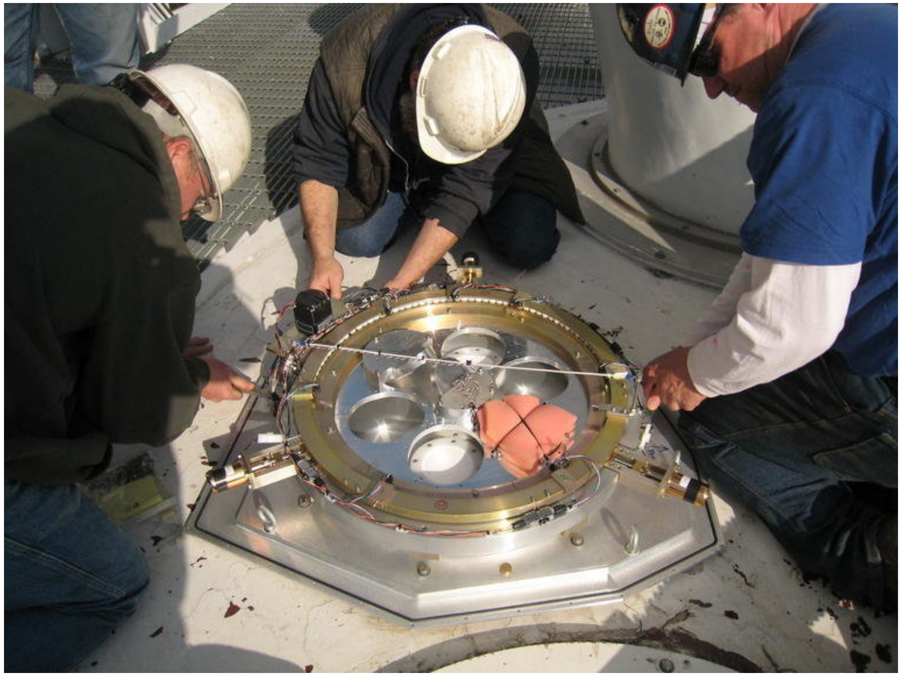
Send feedback to: warmentr@nrao.edu
psalas@nrao.edu

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: $T_{\rm amb}$ & $T_{\rm cold}$.

ARGUS can see one load : $T_{\rm amb}$



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

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

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

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

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

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

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)

Questions?

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