Spectral line data reduction

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GBT observer training workshop, September 18th, 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

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

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

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

Changes to T_{cal} are linear in T_{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.

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

- 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).

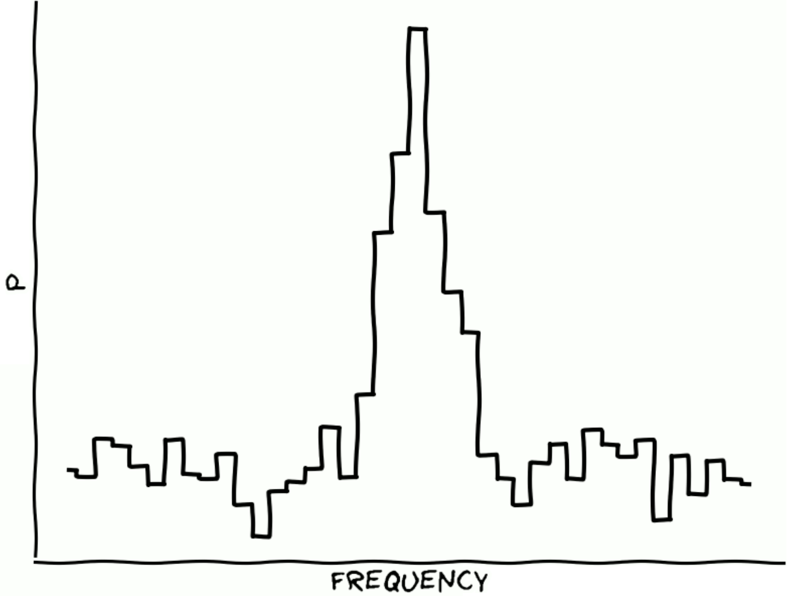
Useful for:

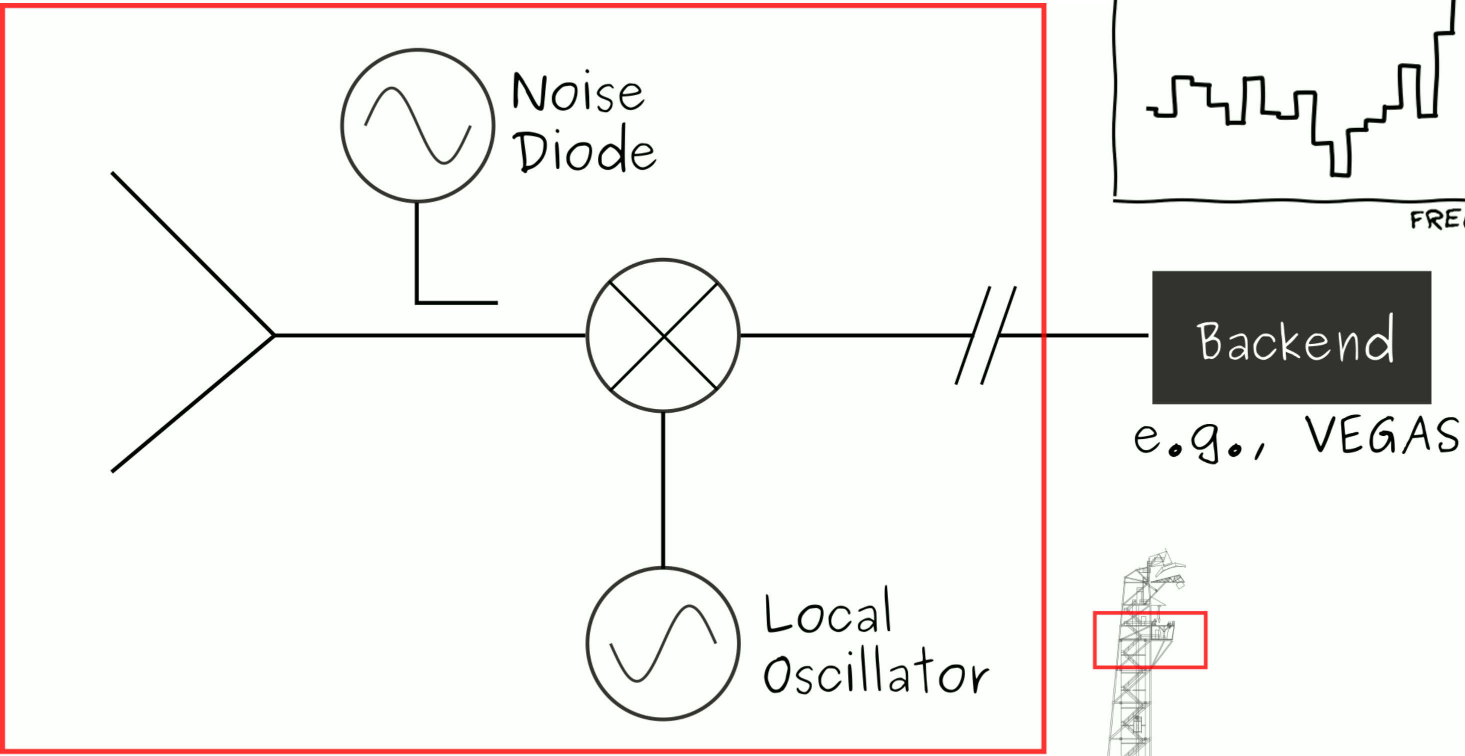
- Observations of broad (>100 km s^{-1}) spectral lines.
- Observations of sources with crowded spectrum.

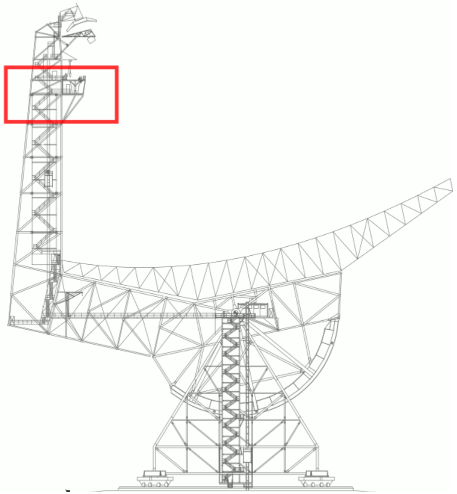
Drawbacks:

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

Frequency switching







P_{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:

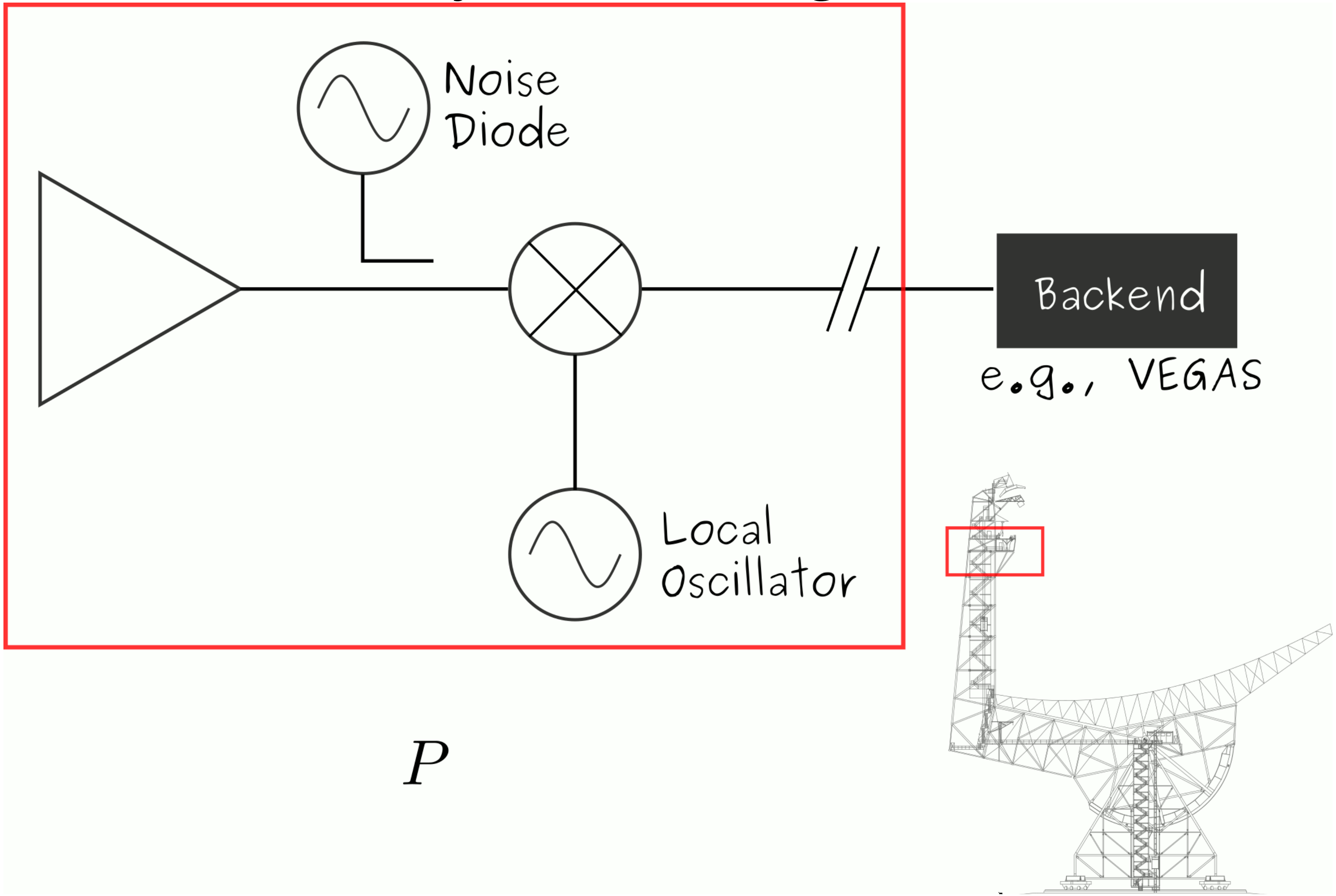
- Observations of narrow ($\leq$10 km s^{-1}) spectral lines.

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}

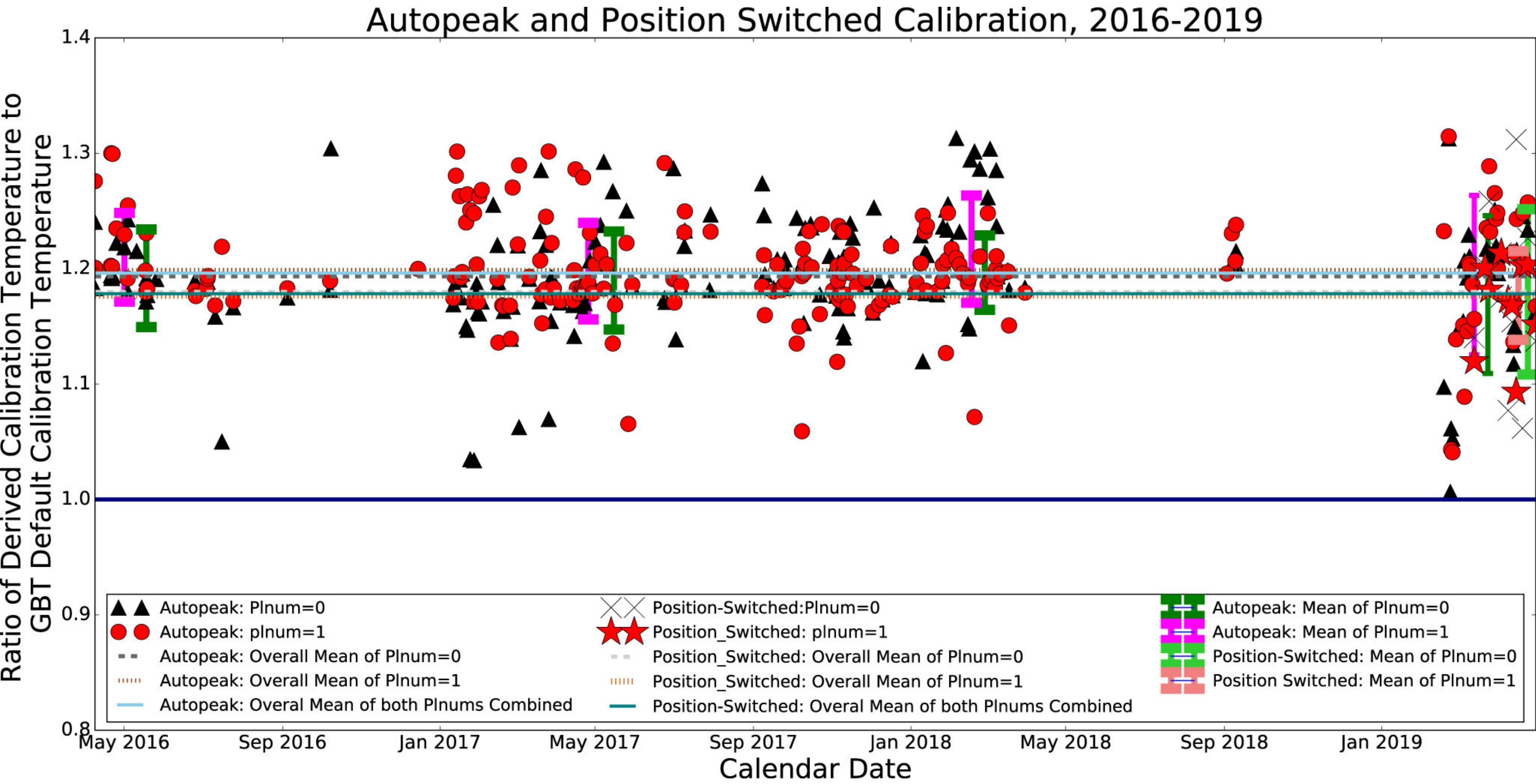
By default the metadata includes a scalar value for T_{cal}.

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_{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

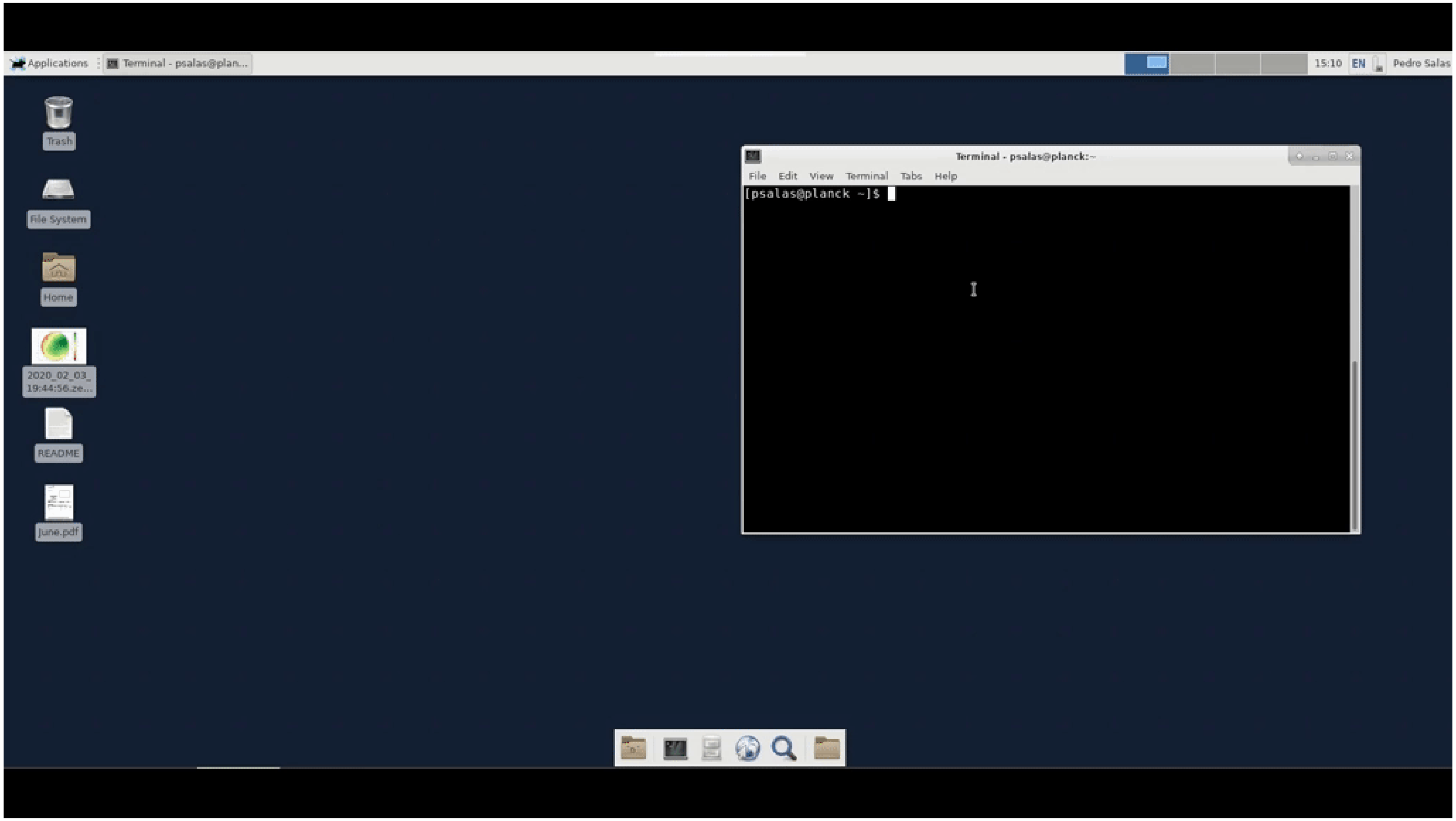
```
; Smooth spectrum in PDC by 5
; channels, keeping every 5th
; channel.

; 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.
```

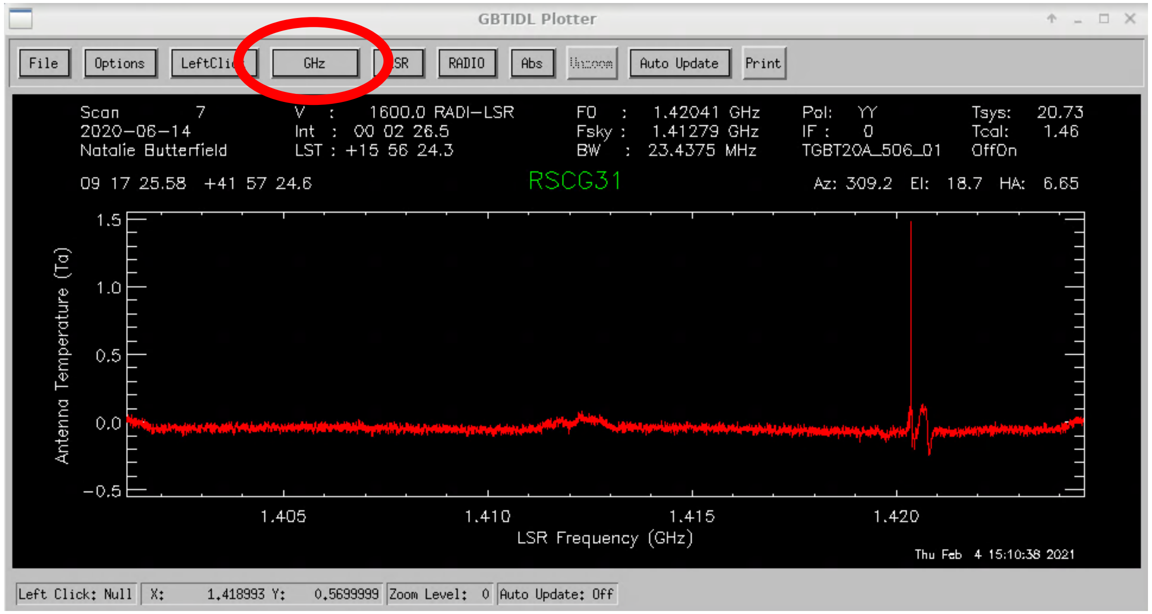


Data courtesy of A. Bonsal & N. Butterfield

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

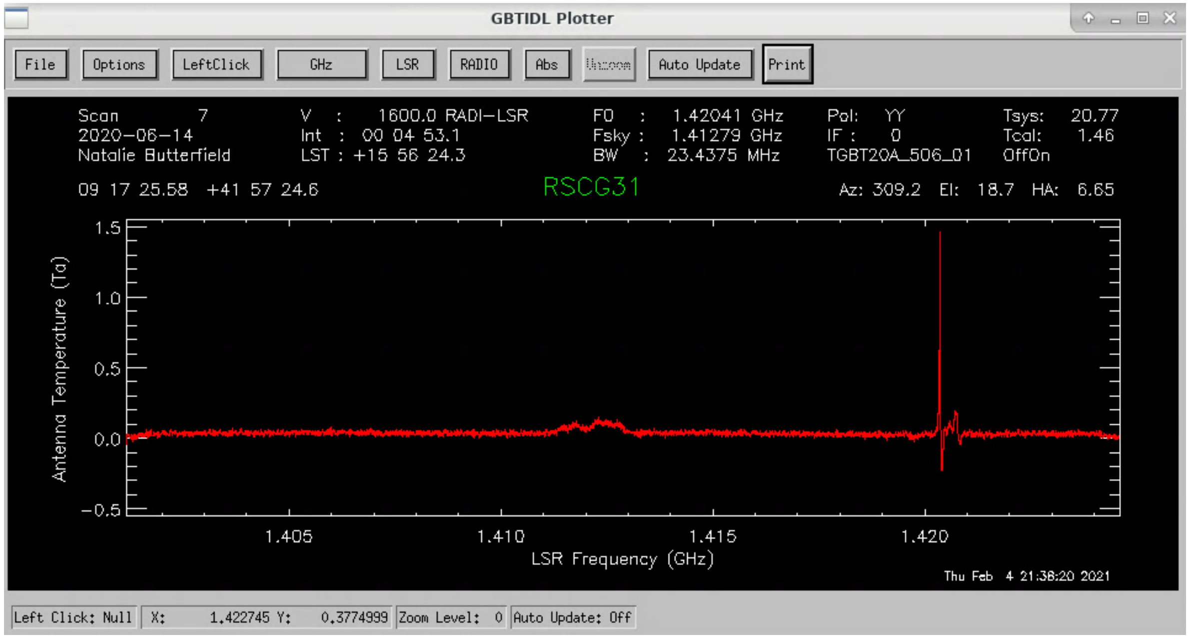
```
pro average_RSCG, scan_start, scan_end
    ; Average the position switched scans
    ; starting at scan_start and ending at
    ; scan_end, inclusive.

    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:

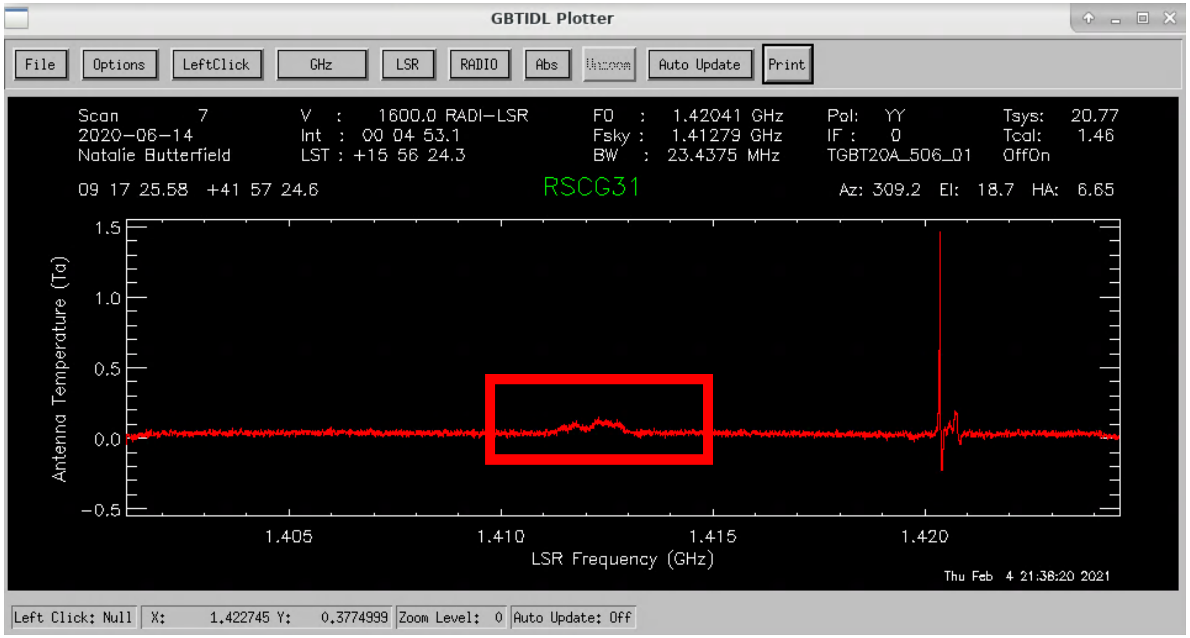
```
offline, 'TGBT20A_506_01'
.r average_RSCG
average_RSCG,6,9
show                          ; Display the averaged spectrum.
gsmooth,12                    ; Smooth using a Gaussian kernel.
show                          ; Show the smoothed spectrum.
fileout, 'rscg31_spec.fits'   ; Save to this fits file.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



GBTIDL example 2

In GBTIDL:

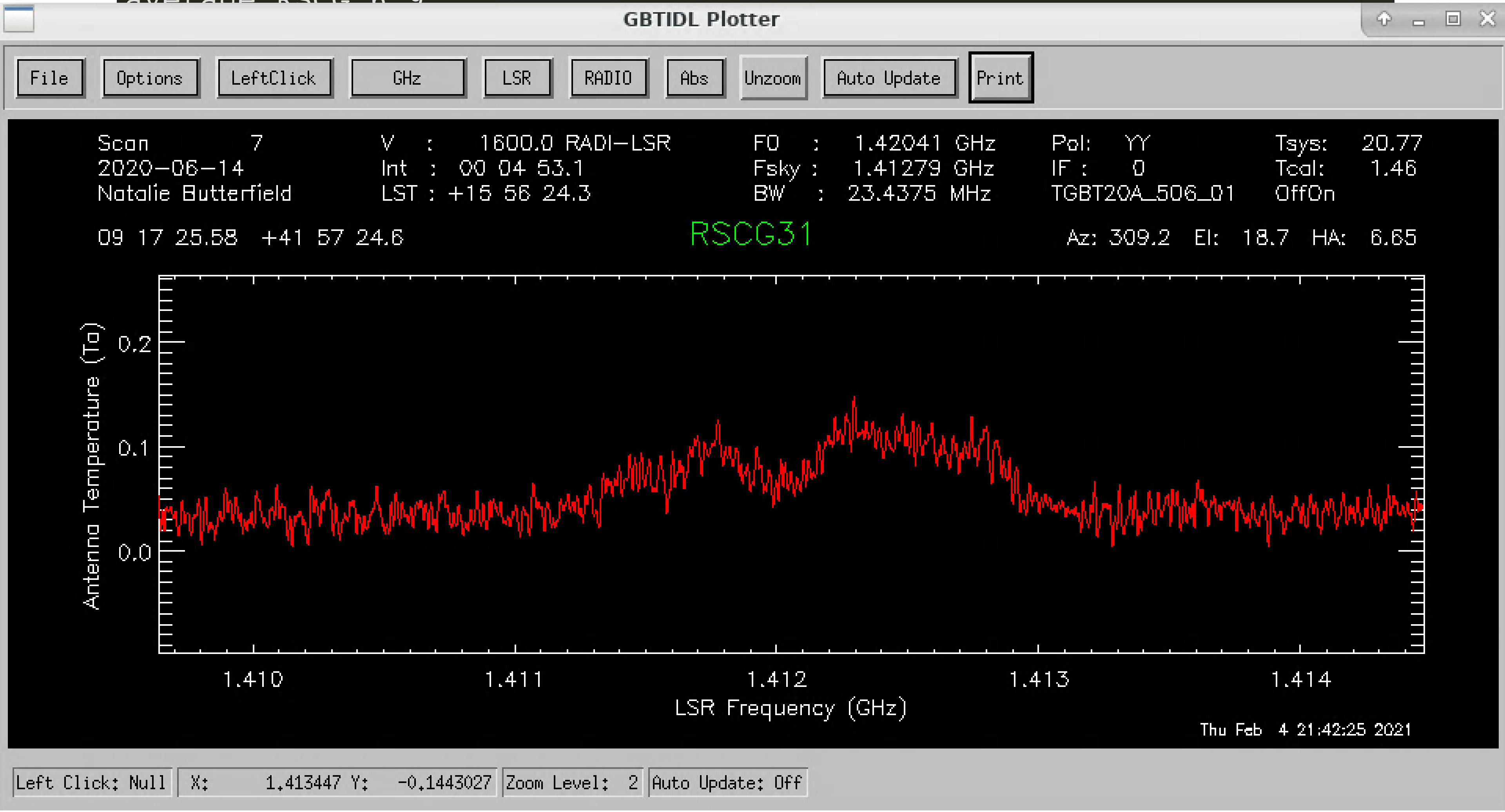
```
offline, 'TGBT20A_506_01'
.r average_RSCG
average_RSCG,6,9
show                          ; Display the averaged spectrum.
gsmooth,12                    ; Smooth using a Gaussian kernel.
show                          ; Show the smoothed spectrum.
fileout, 'rscg31_spec.fits'   ; Save to this fits file.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



GBTIDL example 2

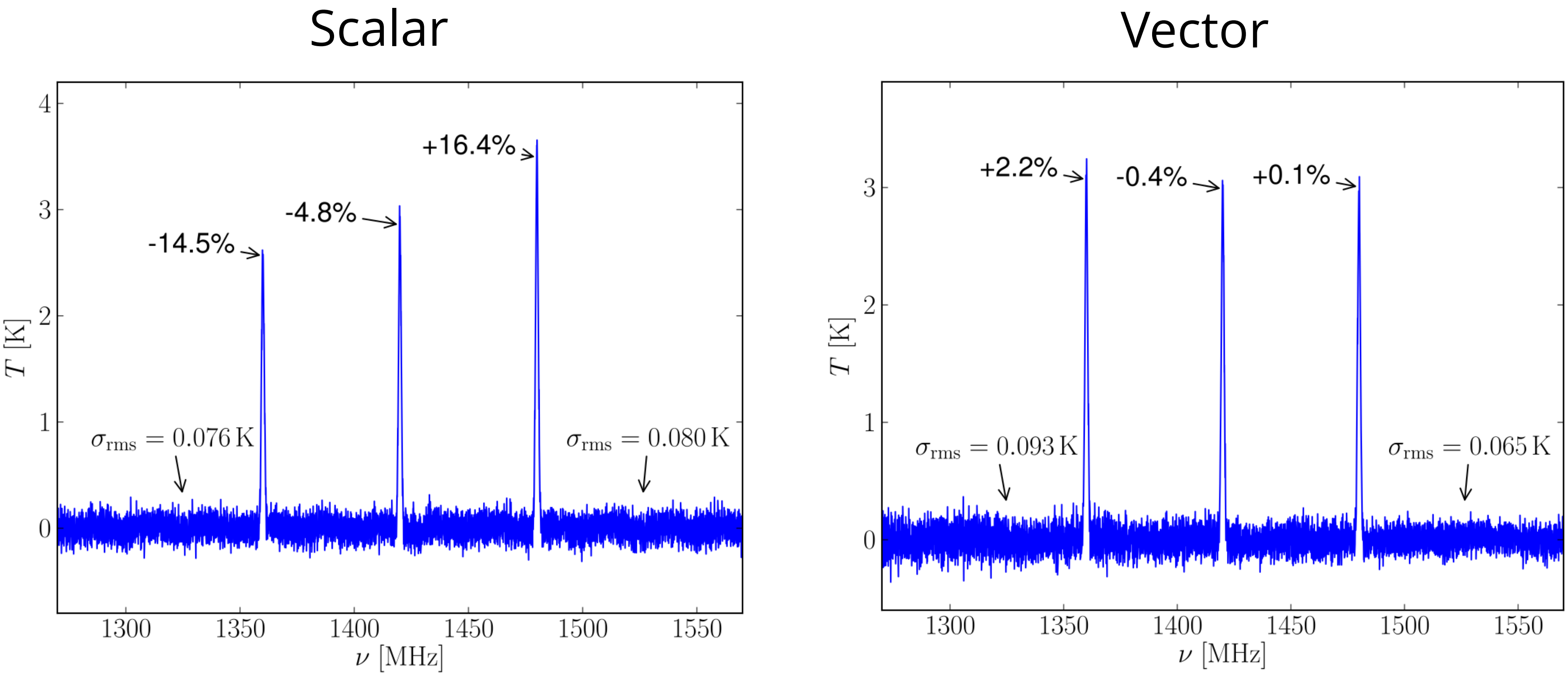
In GBTIDL:

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



Scalar vs vector calibration

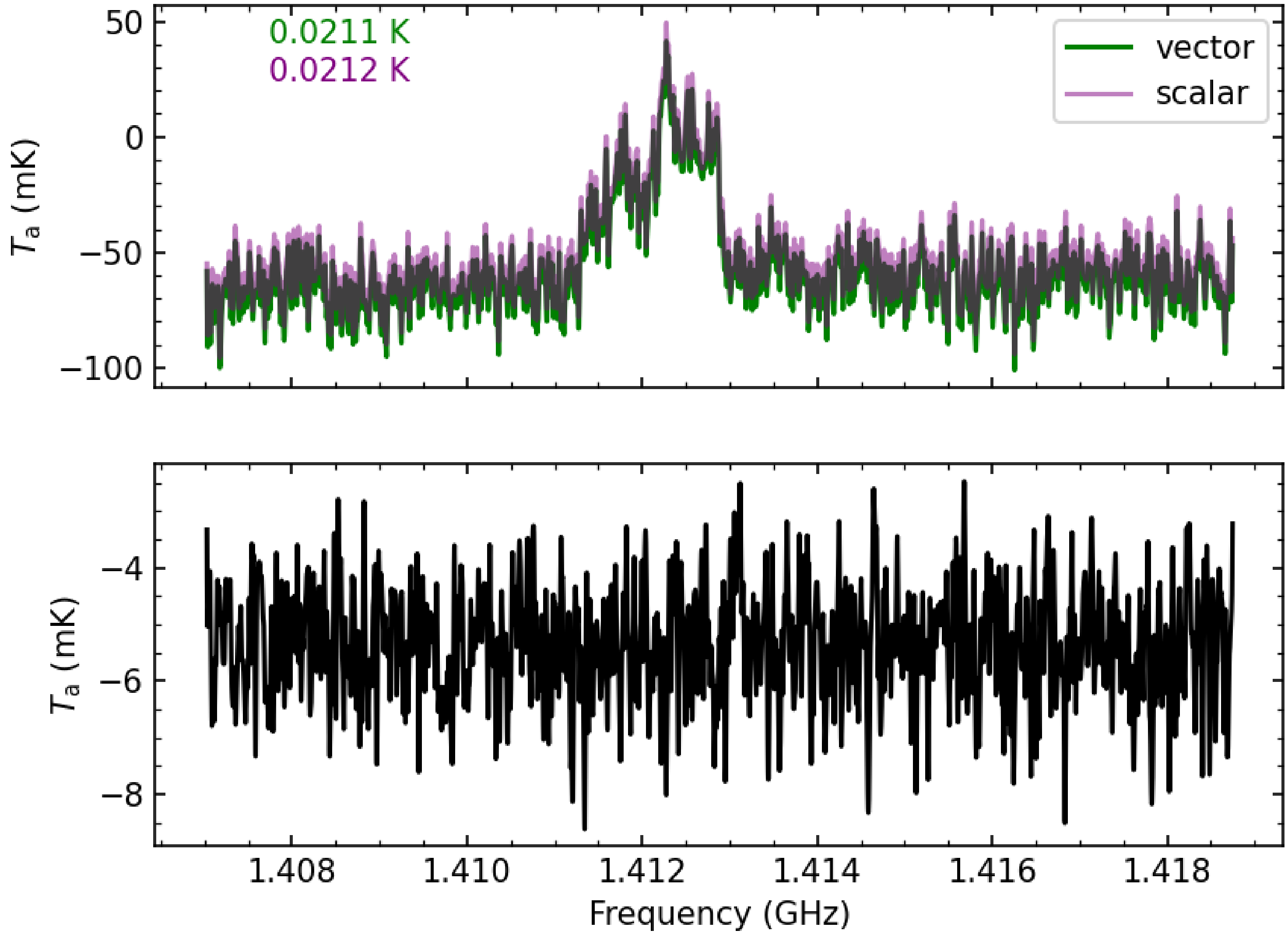
Using averages while calibrating introduces biases, particularly if there are standing waves and/or a non-flat frequency response (e.g., power law in T_{cal}).



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):

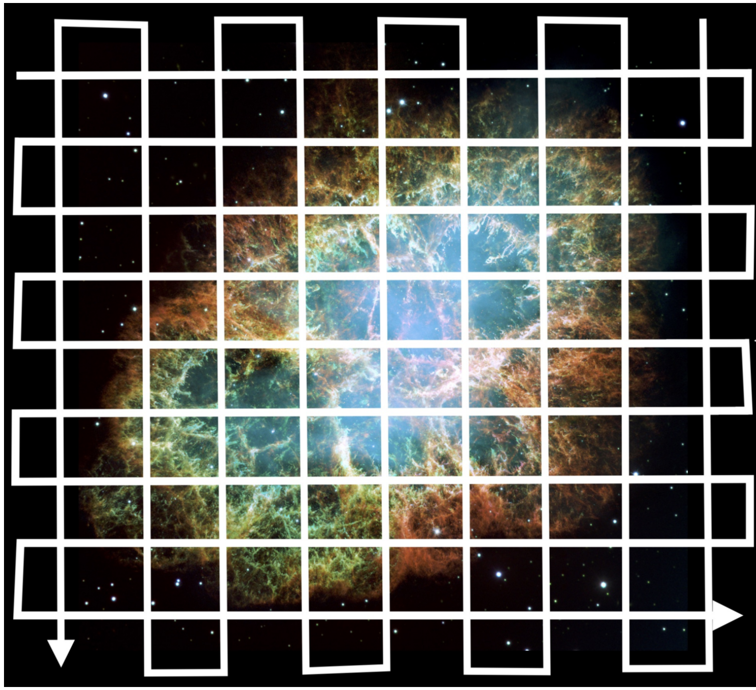
- RaLongMap, DecLatMap
- Daisy

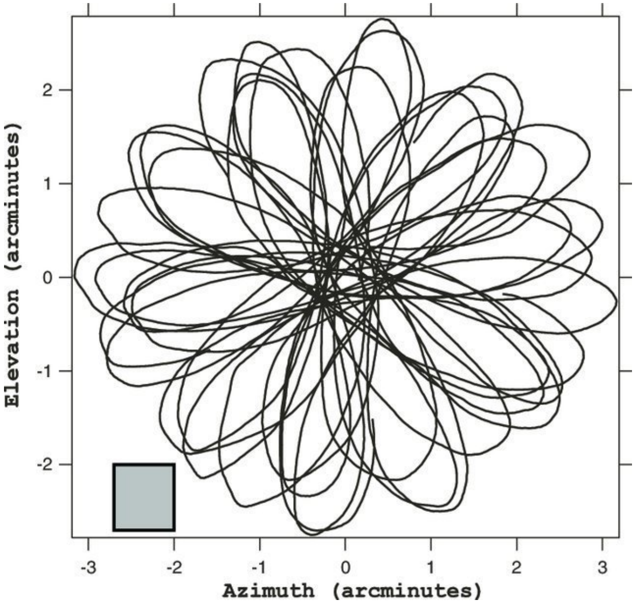
Grid:

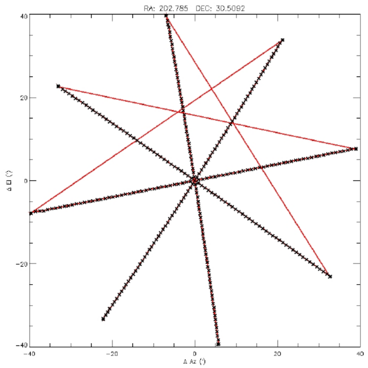
- PointMap

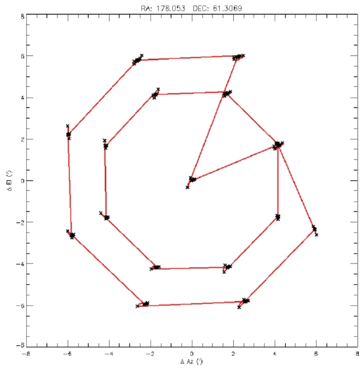
Others:

- Spider
- Z17



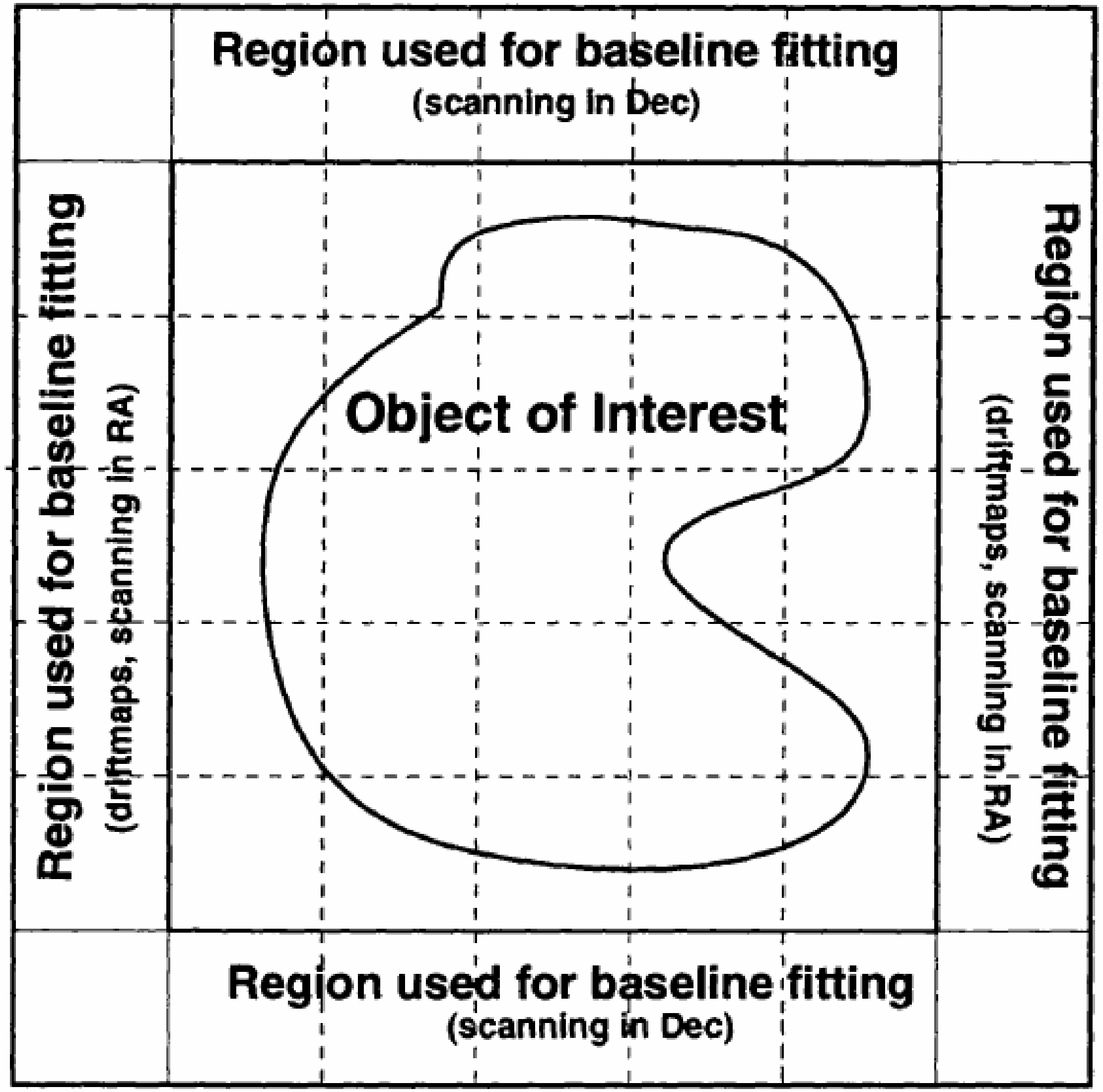






Mapping

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

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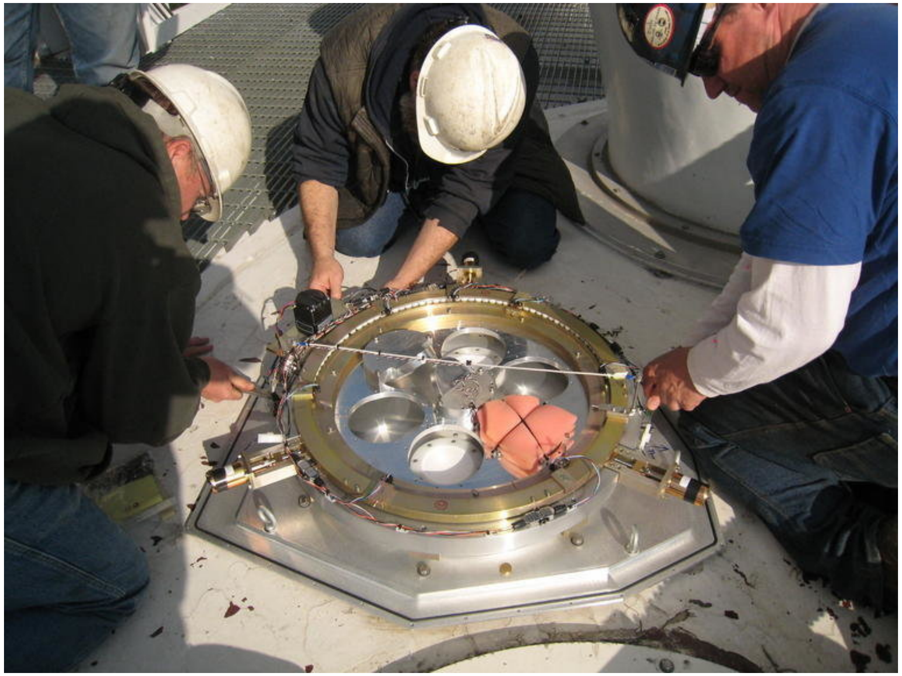
Hot & cold loads

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

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

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

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

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

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

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