Spectral line & continuum data reduction

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GBT observer training workshop, February 8th, 2021

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

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

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

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

All quantities are frequency dependent

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).

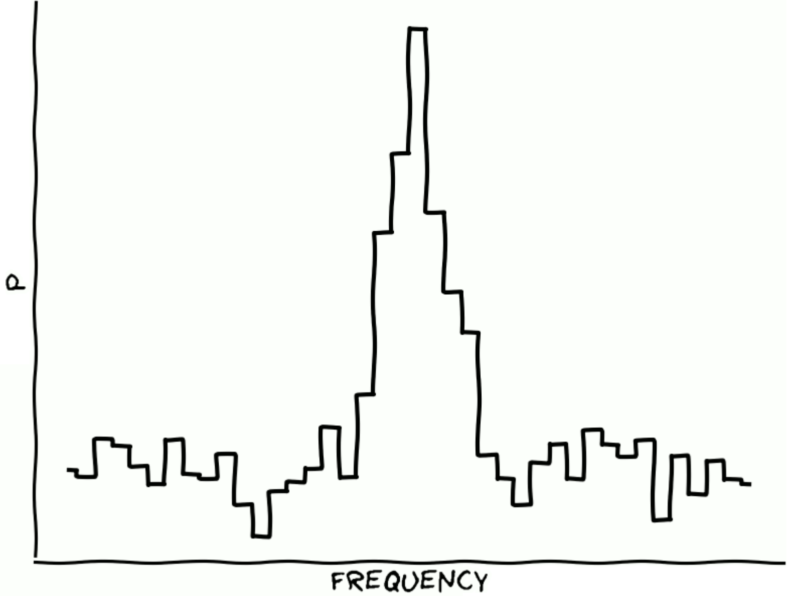
Useful for:

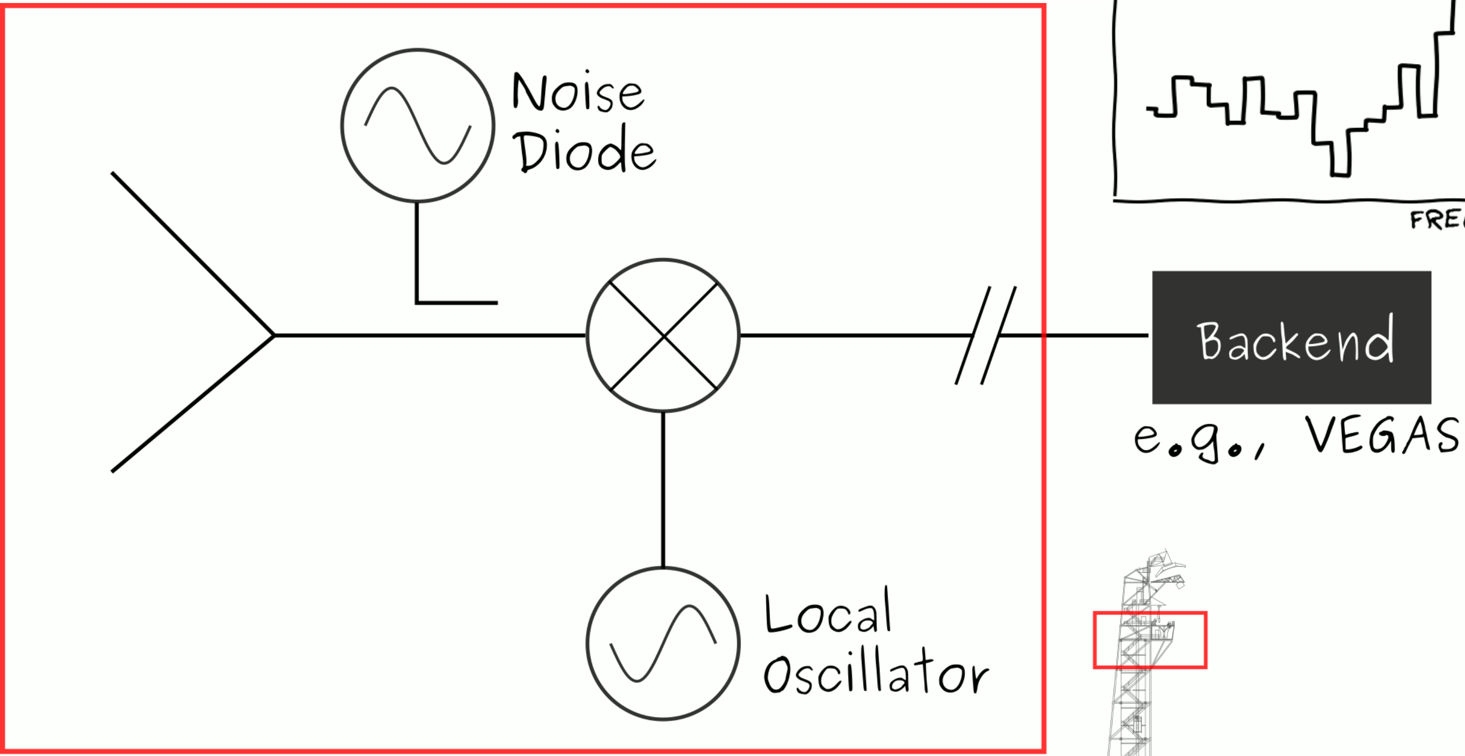
- Observations of broad (>100 km s^{-1}) spectral lines.
- Observations of sources with crowded spectrum.

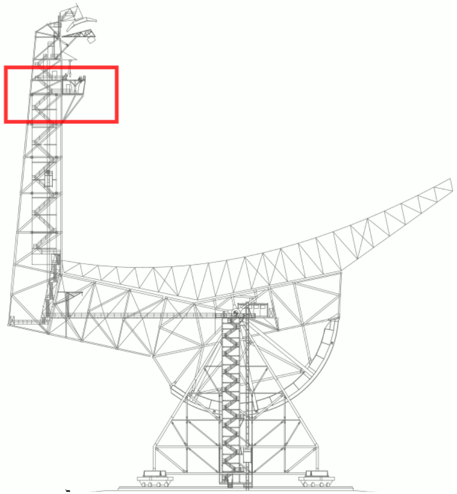
Drawbacks:

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

Frequency switching







P_{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:

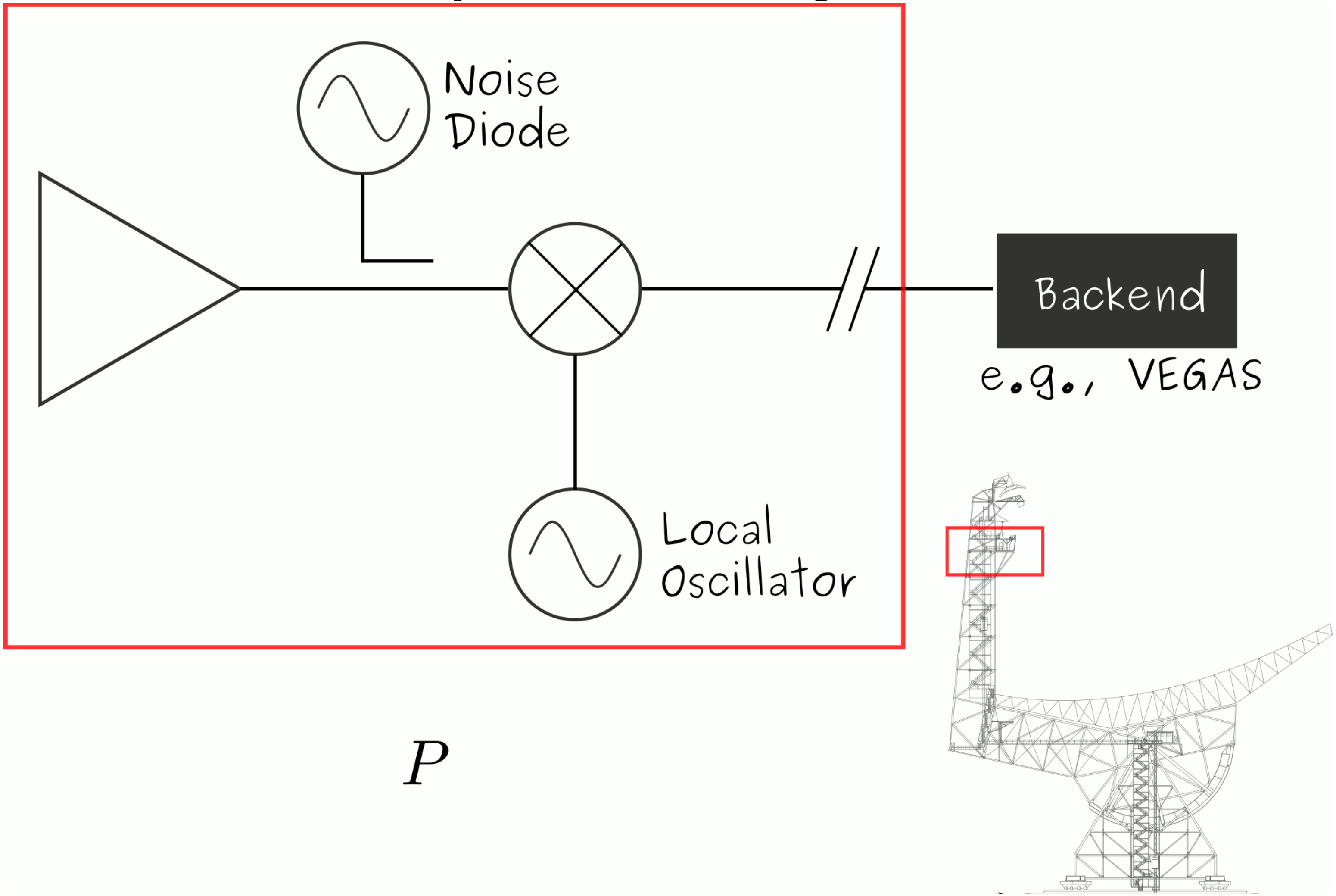
- Observations of narrow ($\leq$10 km s^{-1}) spectral lines.

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}

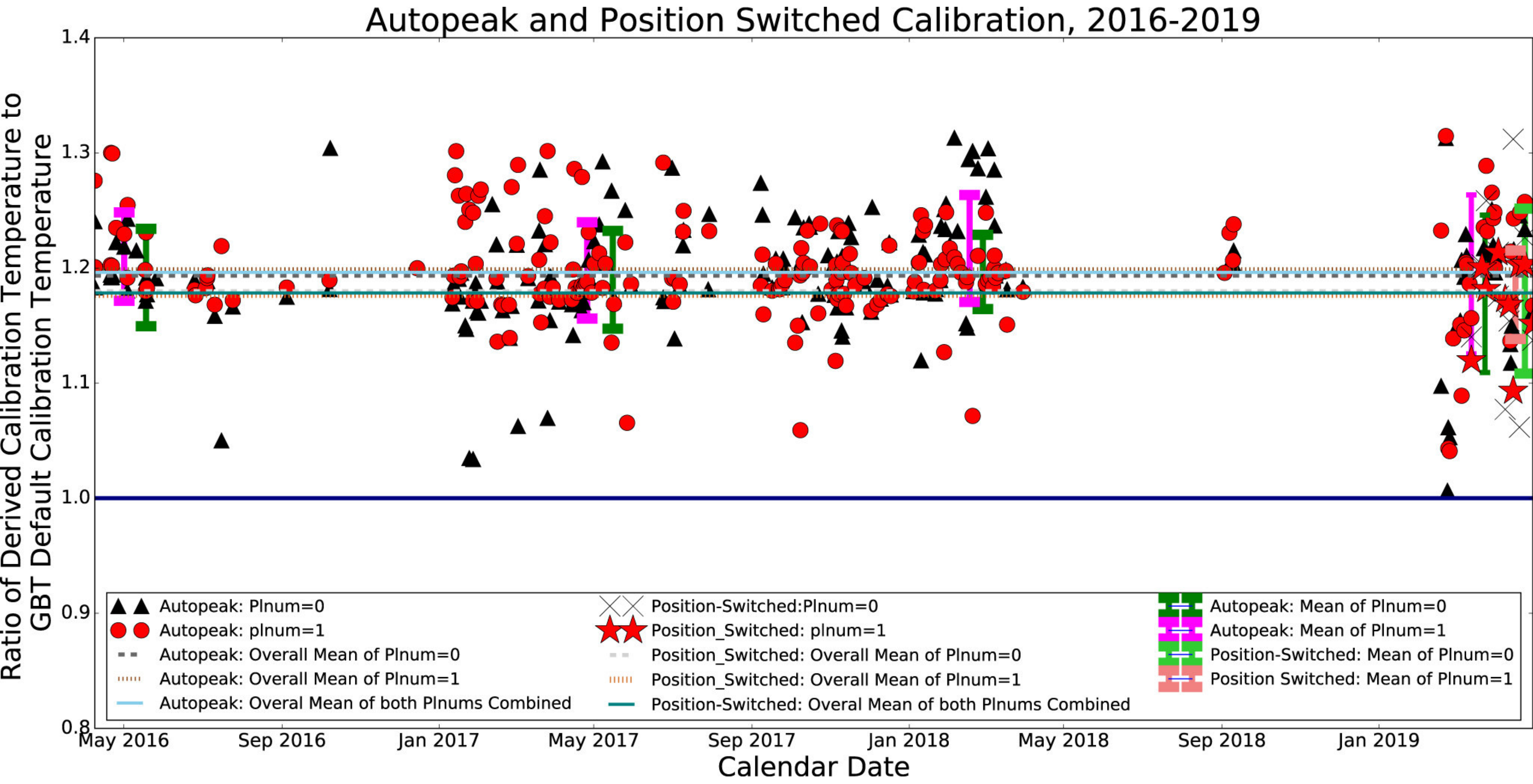
By default the metadata includes a scalar value for T_{cal}.

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
```

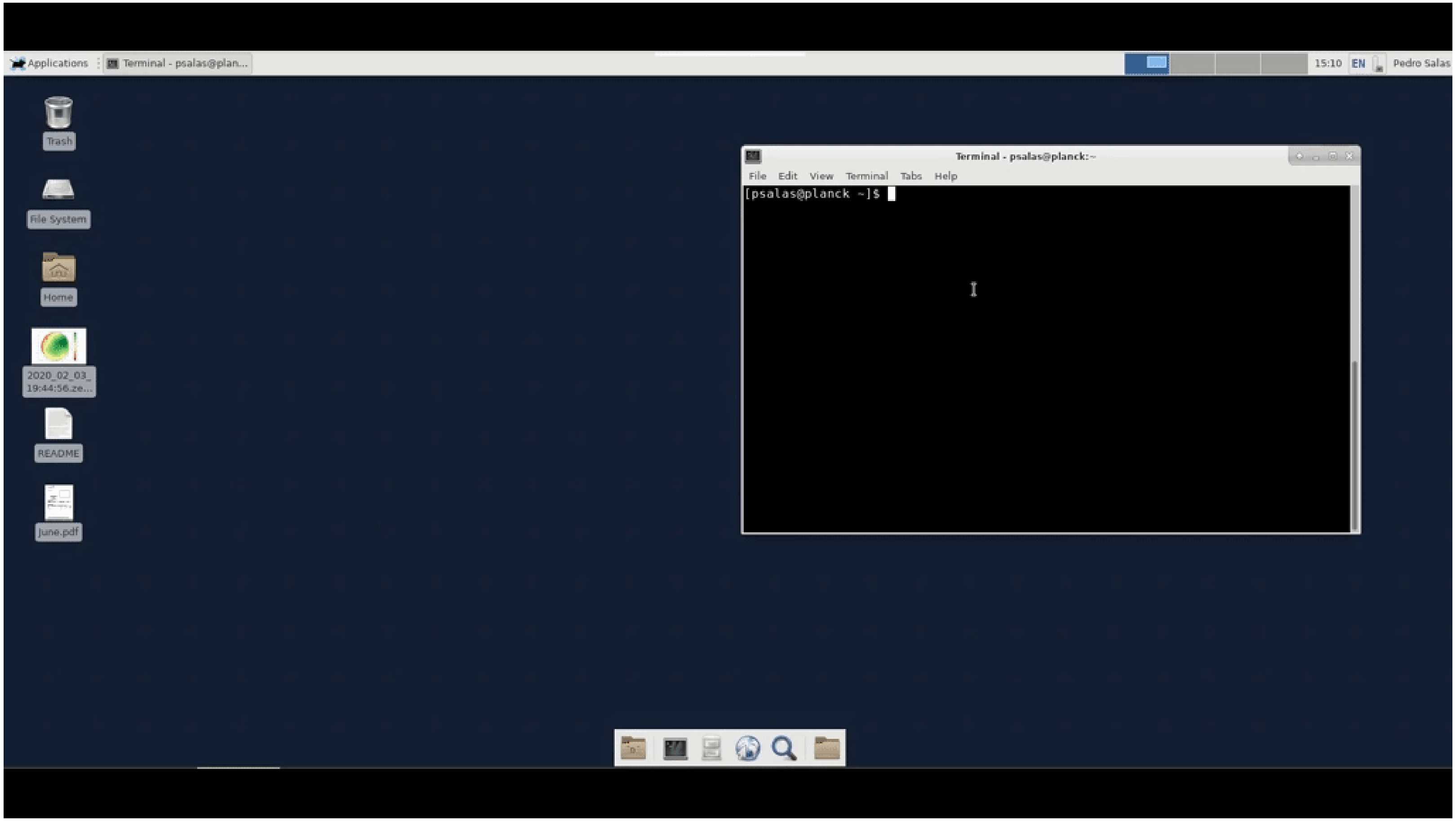
- Supports spectral line data reduction.
- Knows about most spectral line observing modes, e.g., On-Off, Track, frequency switching, beam nodding.

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

Code & documentation:
http://gbtidl.nrao.edu/

GBTIDL 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.
```

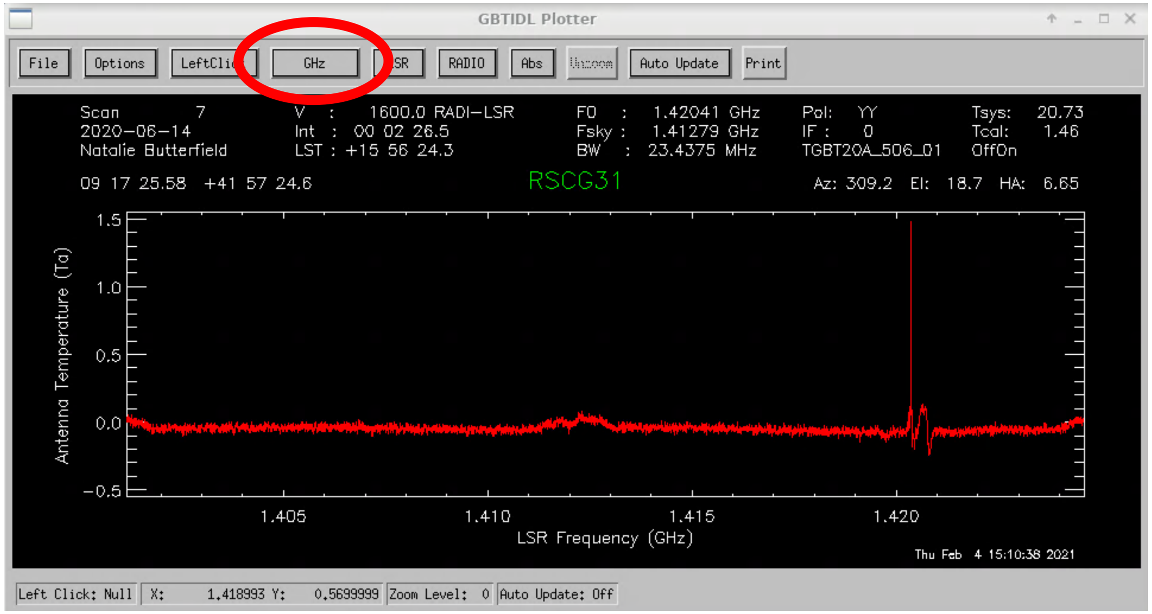


Data courtesy of A. Bonsal & N. Butterfield

GBTIDL example 1

Try it yourself:

- Open GBTIDL, load the data for this example 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

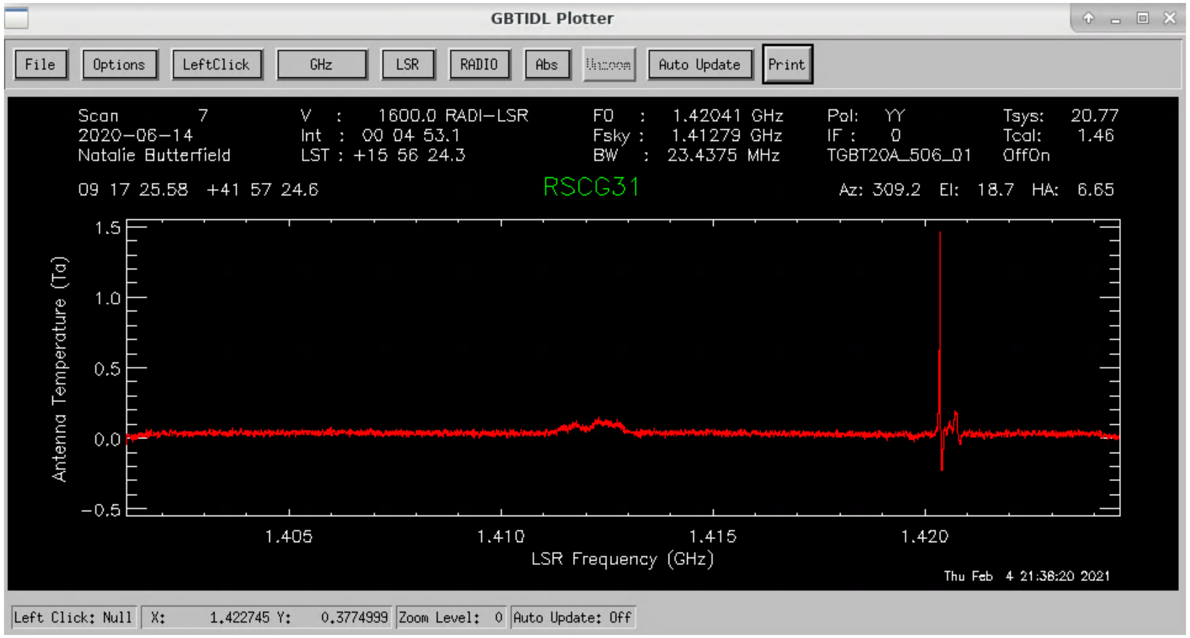
```
pro average_RSCG, scan_start, scan_end
    ; Average the position switched scans
    ; starting at scan_start and ending at
    ; scan_end, inclusive.

    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:

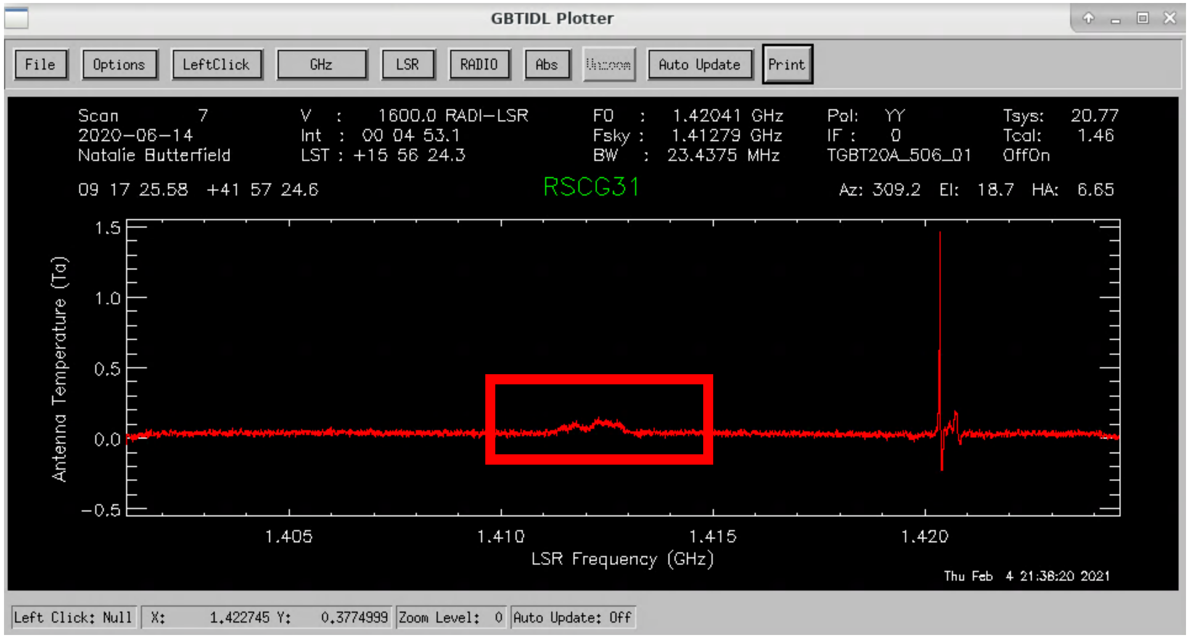
```
offline, 'TGBT20A_506_01'
.r average_RSCG
average_RSCG,6,9
show                        ; Display the averaged spectrum.
gsmooth,12                  ; Smooth using a Gaussian kernel.
show                        ; Show the smoothed spectrum.
fileout, 'rscg31_spec.fits' ; Save to this fits file.
keep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



GBTIDL example 2

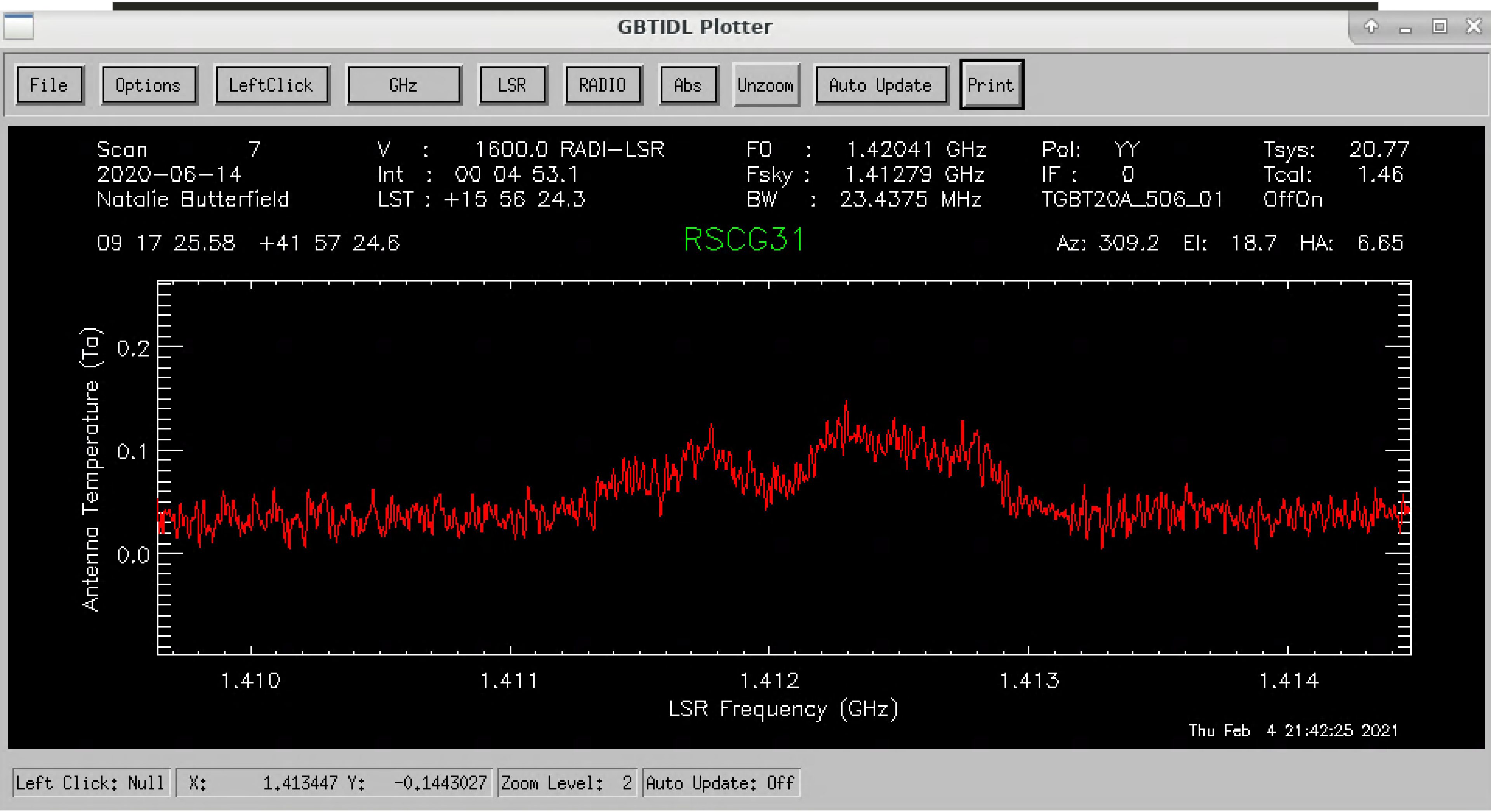
In GBTIDL:

```
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:



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.
```

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.

Questions?

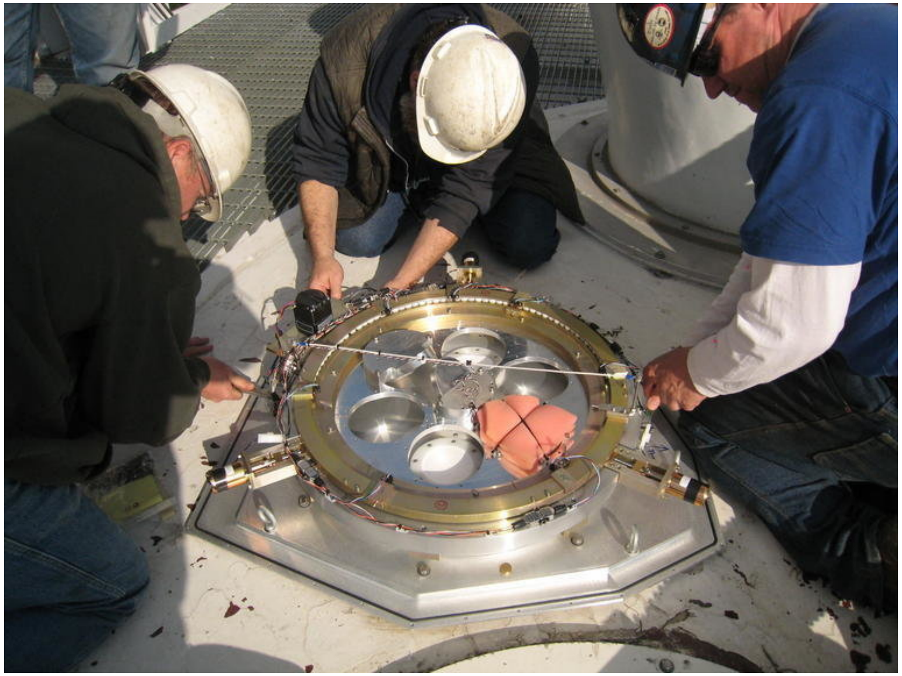
The Green Bank Observatory is a facility of the National Science Foundation
operated under cooperative agreement by Associated Universities, Inc.

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

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

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

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

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

Frayer 2019, GBT memo #302

Temperature scales

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

GBT pipeline

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.

Example:

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

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

Documentation:

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

Source code:

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

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

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