Spectral line & continuum data reduction

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A single dish telescope measures power:

\[ P^{[\text{cal}]}(\nu) = G(\nu) \left[ T_{sou}(\nu) + T^{[\text{cal}]}_{\text{sys}}(\nu) \right] \]

with

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

we are after

\[ T_{sou}(\nu) \]

See e.g., Winkel+2012 & O'Neil 2002
How do we get to $T_{\text{sou}}(\nu)$ from $P^{[\text{cal}]}(\nu)$?
From $P(\nu)$ to $T_{\text{sou}}(\nu)$

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

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

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

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

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

*It is better to keep the elevation constant

# In AstrID:
1 # In AstrID:
2 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

\[ P_{\text{off}} \]
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 ($\leq 10 \text{ km s}^{-1}$) spectral lines.

Drawbacks:

- Need to know source velocity \textit{a priori}.
- For larger $\Delta \nu$, larger residual baseline.
- No continuum measurements.
What is $T_{\text{cal}}$?

Is the equivalent temperature of a noise source injected to the signal.
A note on $T_{\text{cal}}$

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

Perform observations of a calibrator source!
A note on $T_{\text{cal}}$

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.

Code & documentation: [http://gbtidl.nrao.edu/](http://gbtidl.nrao.edu/)
GBTIDL example 1

```IDL
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
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
In GBTIDL:

```plaintext
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.
```
In GBTIDL:

```plaintext
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:

```
offaverage_RSCG, 6, 9
show

gsmooth, 12
show

fileout, 'rscg31_spec.fits'; Save to this fits file.
keep; Save the primary data container (PDC) to the fits file.
```
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`
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)
Continuum

Pick receiver, integration time and slew rate to minimize $\frac{1}{f}$ noise (timescale $\sim 1.4$ 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.
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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: $T_{\text{amb}}$ & $T_{\text{cold}}$.

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

W band receiver calibration wheel.
Hot & cold loads

W-band

\[ G = \frac{(T_{\text{amb}} - T_{\text{cold}})}{(P_{\text{amb}} - P_{\text{cold}})} \]

\[ T_{\text{sys}} = GP_{\text{off}} \]

\[ T_{a} = T_{\text{sys}} \frac{P_{\text{on}} - P_{\text{off}}}{P_{\text{off}}} \]
Hot & cold loads

ARGUS

\[ T^*_a = T^*_s y s \frac{P_{on} - P_{off}}{P_{off}} \]

\[ T^*_s y s (t) = \frac{T_{cal}}{\left( \frac{P_{amb}}{P_{off}} - 1 \right)} \]

\[ T_{cal} \approx (T_{atm} - T_{bg}) + (T_{amb} - T_{atm}) e^{\tau_0 A} \]

\[ T_{cal} \approx T_{amb} \]
Temperature scales

- \( T_a \): Antenna temperature.
- \( T_a' = T_a e^{\tau_0 A} \): Antenna temperature corrected for atmosphere.
- \( T_a^* = \frac{T_a'}{\eta_l} \): Forward beam brightness temperature.
- \( T_{mb} = \frac{T_a'}{\eta_{mb}} \): 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:
SDFITS

Single Dish FITS files.
Default data i/o for GBTIDL and gbtgriddler.
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
Questions?

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