SPIRE Spectrometer Data Processing (The Pipeline)

Nanyao Lu
NHSC/IPAC
(on behalf of the SPIRE ICC)

Goals

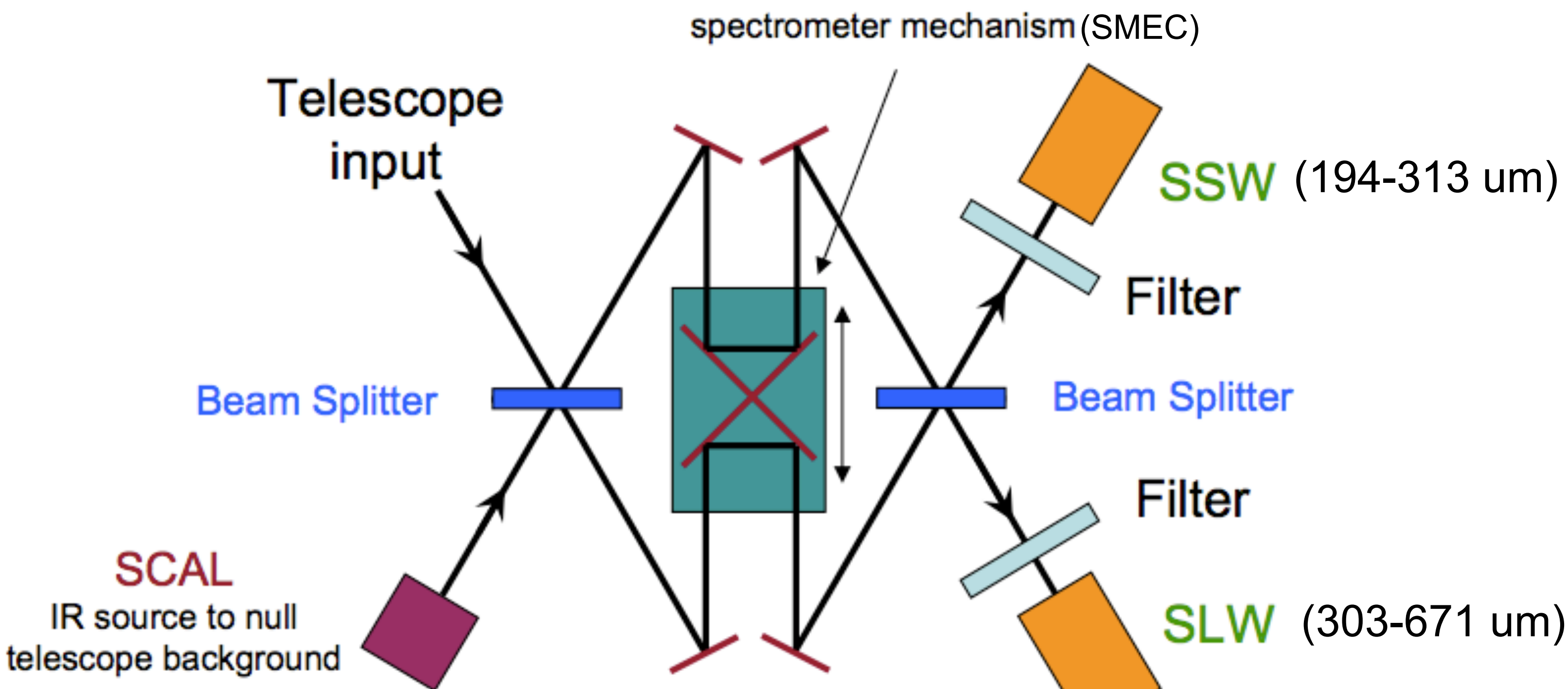
- Overview of SPIRE FTS spectrometer.
  - How photons are registered as bolometer voltages.
- Overview of the standard FTS pipeline by flow charts, and some mix of calibrations and data examples.
  - How a measured voltage interference pattern (interferogram) in time is transformed to the source spectrum.

Helpful Resources at Your Fingertips

- HIPE -> Help contents:
  - SPIRE Data Reduction Guide (SDRG):
    - Sect. 6. SPIRE spectroscopy mode cookbook.
    - Sect. 3. SPIRE observational context data structure.
    - Sect. 4. SPIRE calibration data.
  - SPIRE Pipeline Specification Manual
    - Useful for looking up some details of a pipeline module.
  - SPIREinstrument and calibration page
    - Up-to-date SPIRE information at HSC.
    - SPIRE Observer's Manual.

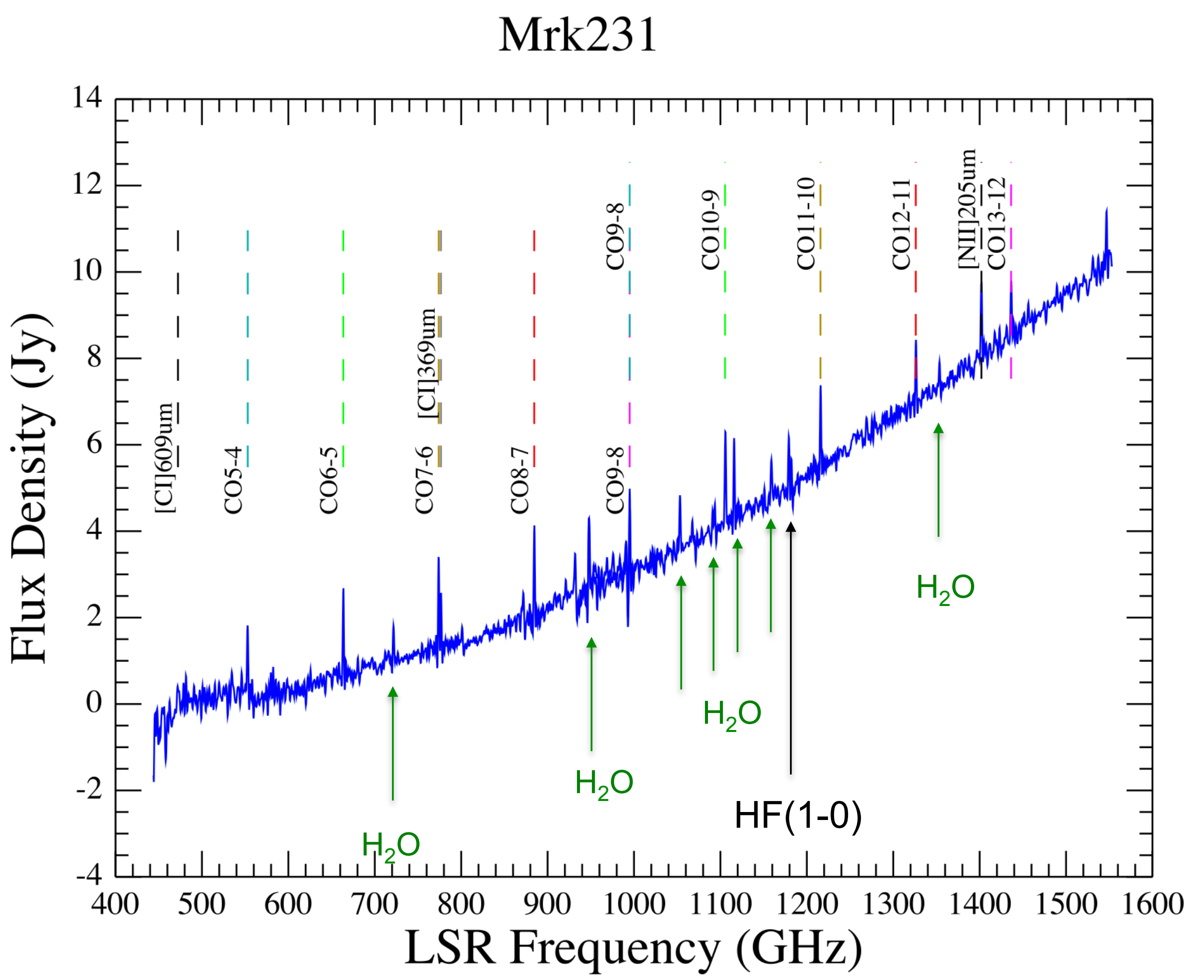
SPIRE Spectrometer

Fourier Transform Spectrometer (FTS): The entire spectral coverage of 194-671 micron is observed in one go!



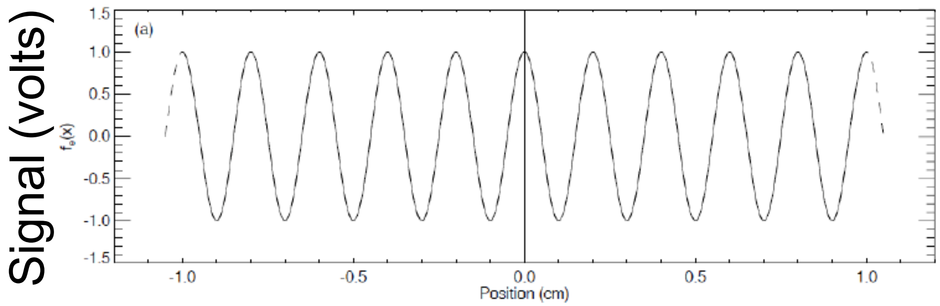
NOT USED! now at 4-5K

Probing Warm and Dense Molecular Gas



Fourier Transform: Interferogram to Spectrum

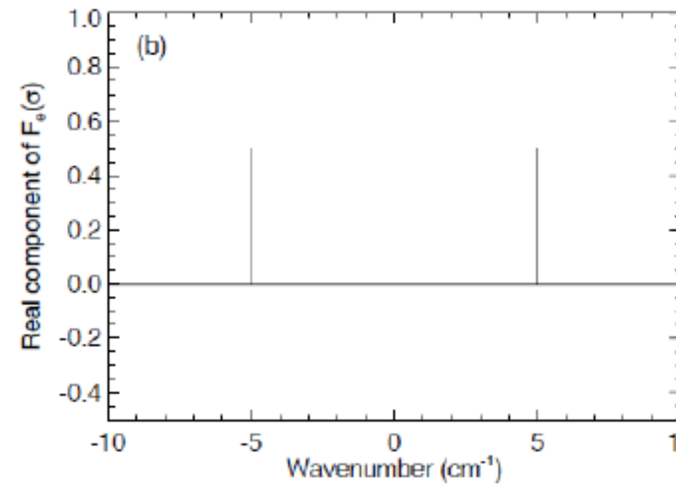
Interferogram I(x)



Optical path difference x (cm)

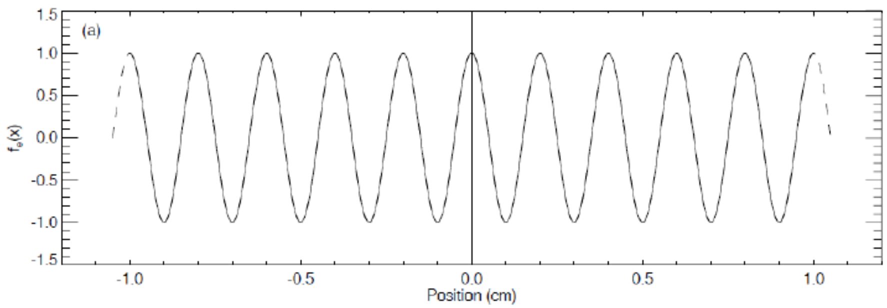
Fourier Transform

Source Spectrum B(σ)

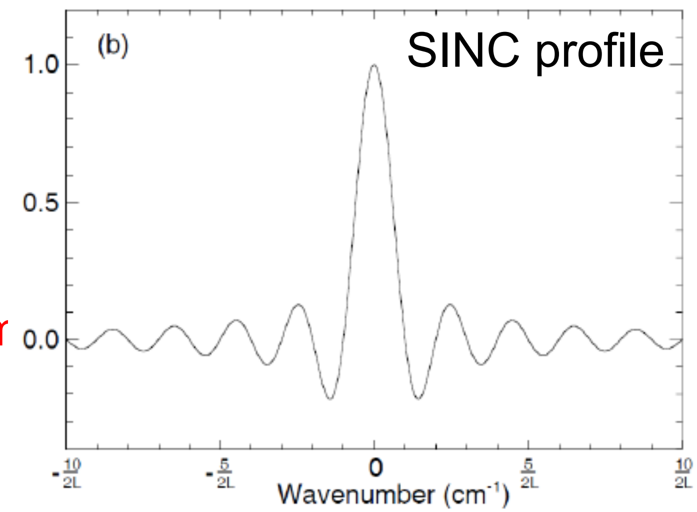


Discrete Fourier Transform: $B(\sigma) = \sum_i I(x_i) \exp(-i2\pi\sigma x_i)\, \Delta x$

Real World: Finite Interferogram



Fourier Transform



Multiplied by a top hat function

$B(\sigma) \otimes \sin(\pi\sigma/\Delta\sigma)/(\pi\sigma/\Delta\sigma)$

For unresolved lines:

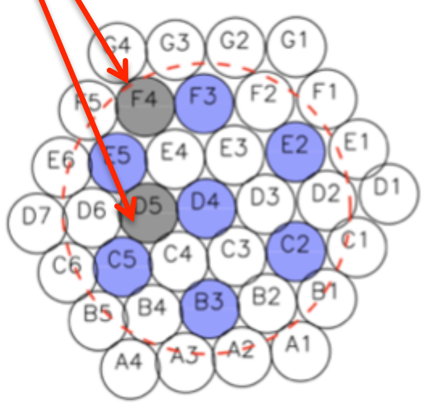
- $A \sin[\pi(\sigma-\sigma_0)/\Delta\sigma]/(\pi(\sigma-\sigma_0)/\Delta\sigma)$;
- Flux = $A\,\Delta\sigma$;
- FWHM = $1.207\,\Delta\sigma$.

($\Delta\sigma$ = spectrometer resolution element)

Two Bolometer Detector Arrays

Two dead detectors

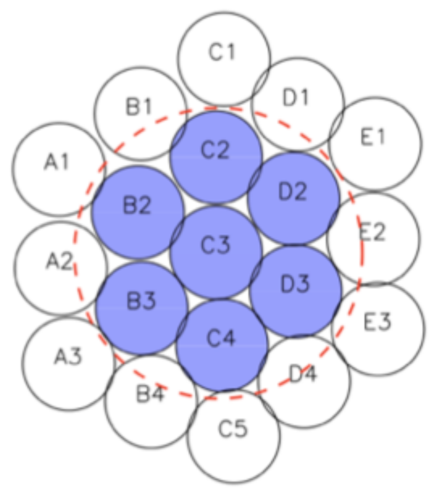
SSW



194 – 313 microns

Beam = 17”- 21”

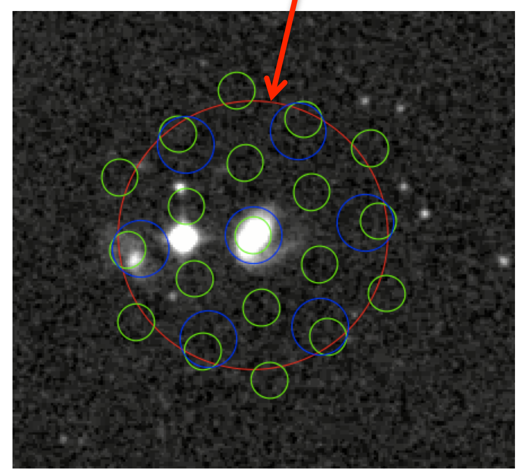
SLW



303 – 671 microns

Beam = 29”- 42”

2’ diameter



Foot print on sky

Observing Modes

Detector Setting:

- Nominal
- Bright-source

Spectral resolution:

High Resolution (HR):
- 0.0395 cm^{-1} (or 1.1854 GHz)
- R = 1290 – 370
- ΔV = 230 – 800 km/s;

Suitable for line fluxes.

Low Resoltion (LR):
- 0.83 cm^{-1} (25 GHz)
- R = 62 – 18

Suitable for continuum.

High + Low:
- High & Low scans.

Spatial sampling using an internal jiggle mirror (BSM):

Sparse
(2 beam spacing)

Intermediate
(1 beam spacing)

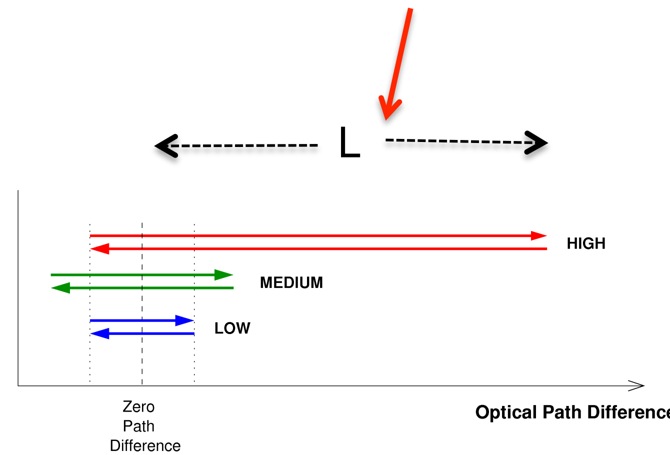
Full
(1/2 beam spacing)

Telescope pointing:

Single Pointing

Raster

FTS scanning



Spectral resolution, Δσ, depends on the maximum SMEC scan length L:

$\Delta\sigma = 1/(2L)$, where L =12.8 cm for High Res.

SPIRE FTS Observations

Each observation is divided into individual ***Building Blocks***:

- Observations of sparse sampling:

Your data is taken here!

Initialization + Move BSM | FTS scans + PCAL flash | End

- All other observations (i.e., intermediate or full spatial sampling or raster):

At each of the multiple telescope pointings (if a raster map):

Initialization + LOOP OF 1, 4 or 16 [Move BSM | FTS scans] + PCAL flash | End

Pipeline data processing just loops through individual FTS scan BB's.

The FTS Pipeline – Overall Flow Chart

SPIRE Common Pipeline

1. Modify Detector Timeline V(t)
2. Create Interferogram V(x)
3. Modify Interferogram V(x)
4. Fourier Transform V(x)->S(σ)
5. Modify Spectra S(σ)
(extended source flux cal.)
6. Create Level-2 products

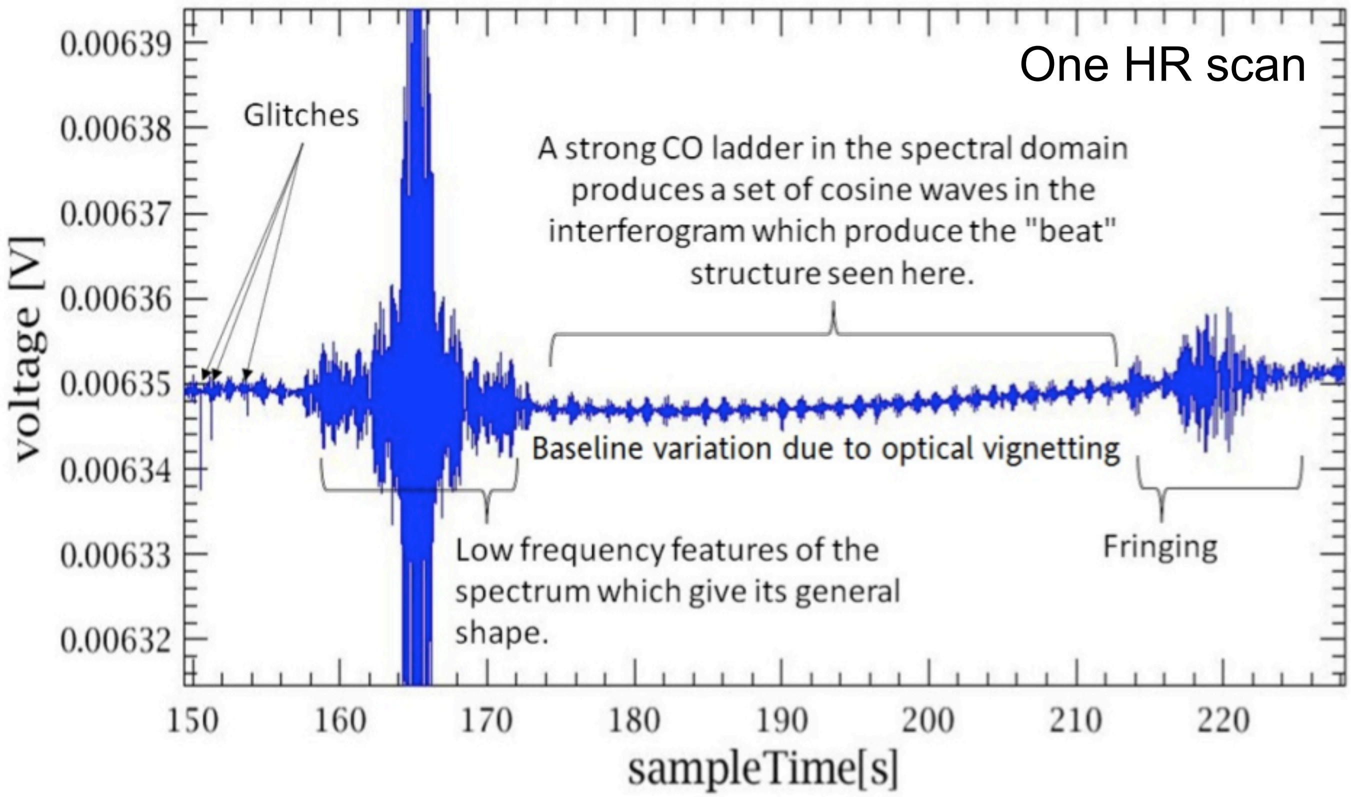
Level 0.5 products:
- detector time lines
- scan mirror time line
- house keeping time lines

Interferograms (stored in Level 1)

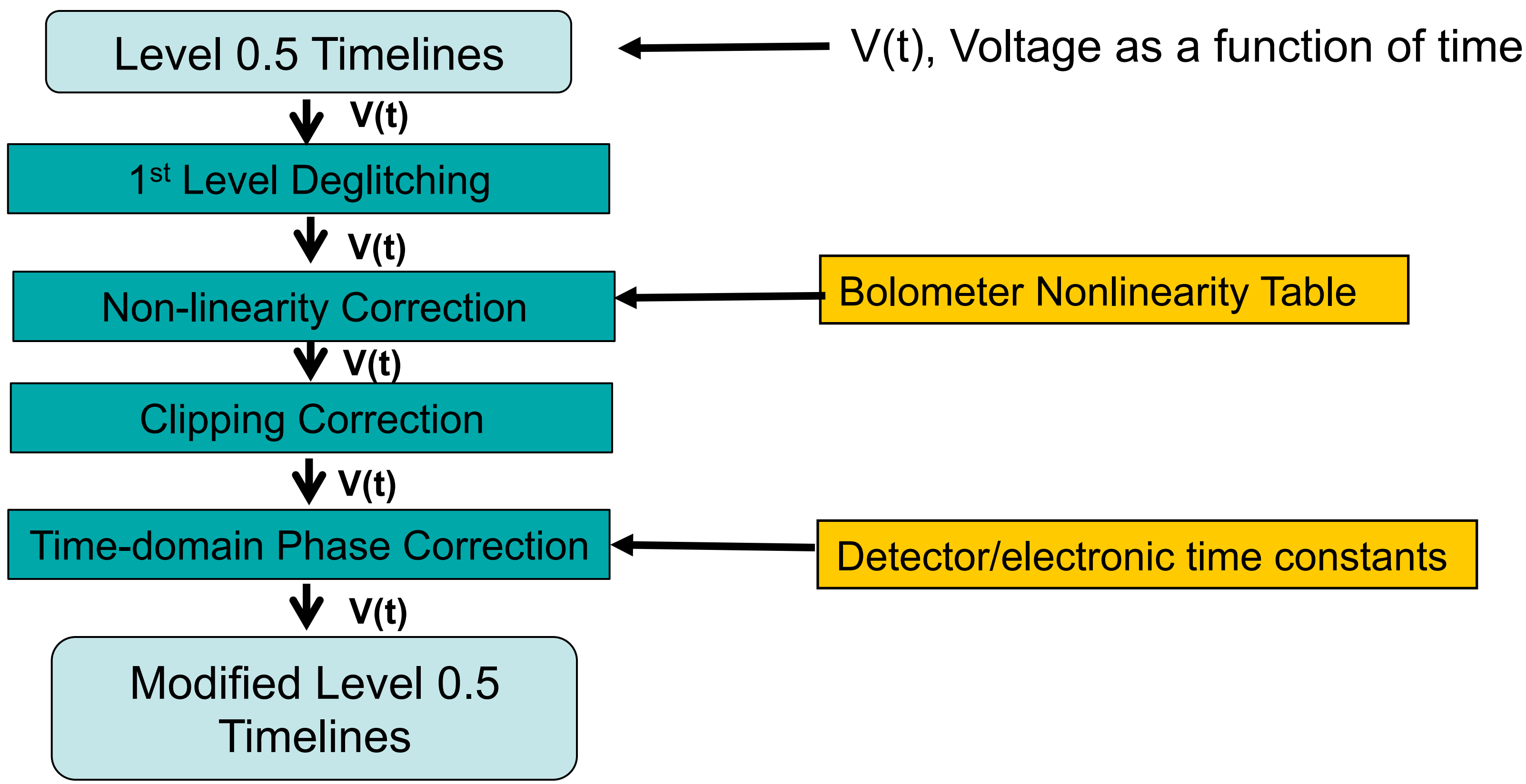
Level 1 products:
- unmodified interfergrams
- average spectrum (apodized)
- average spectrum (unapodized)

Spectral cube if a mapping obs, or a point-source spectrum for each of the unvignetted detectors.

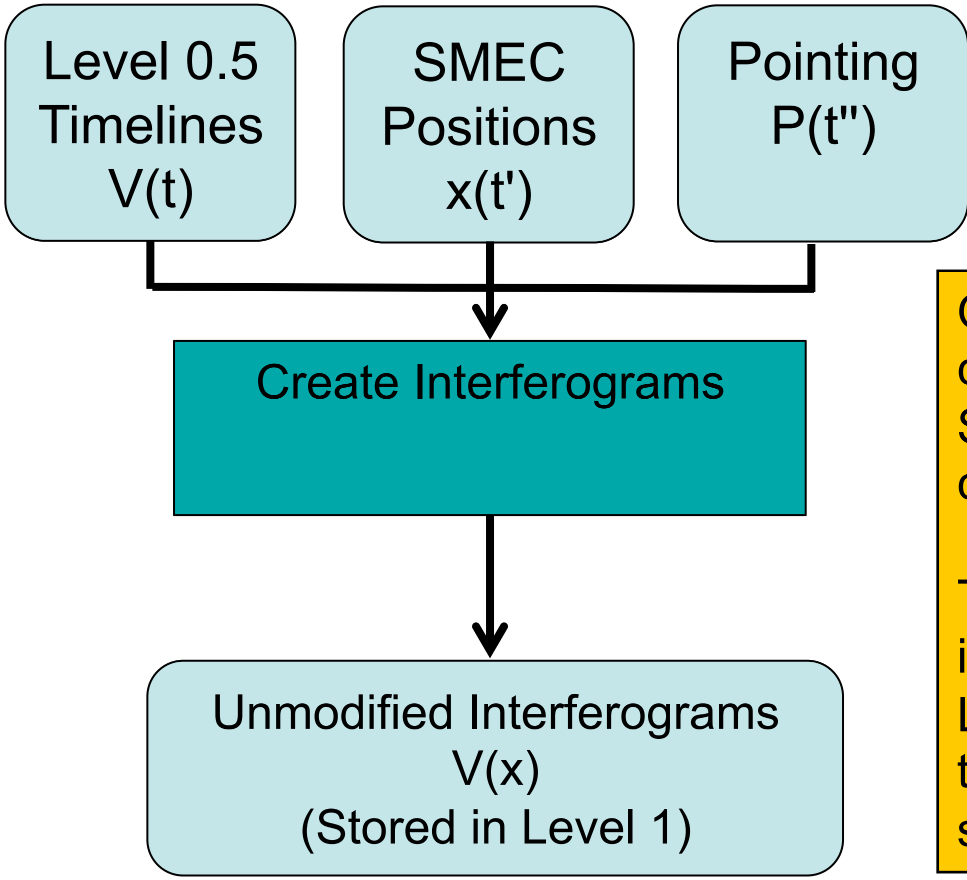
Spectrometer Detector Time Line



Pipeline Step 1: Modify Timelines



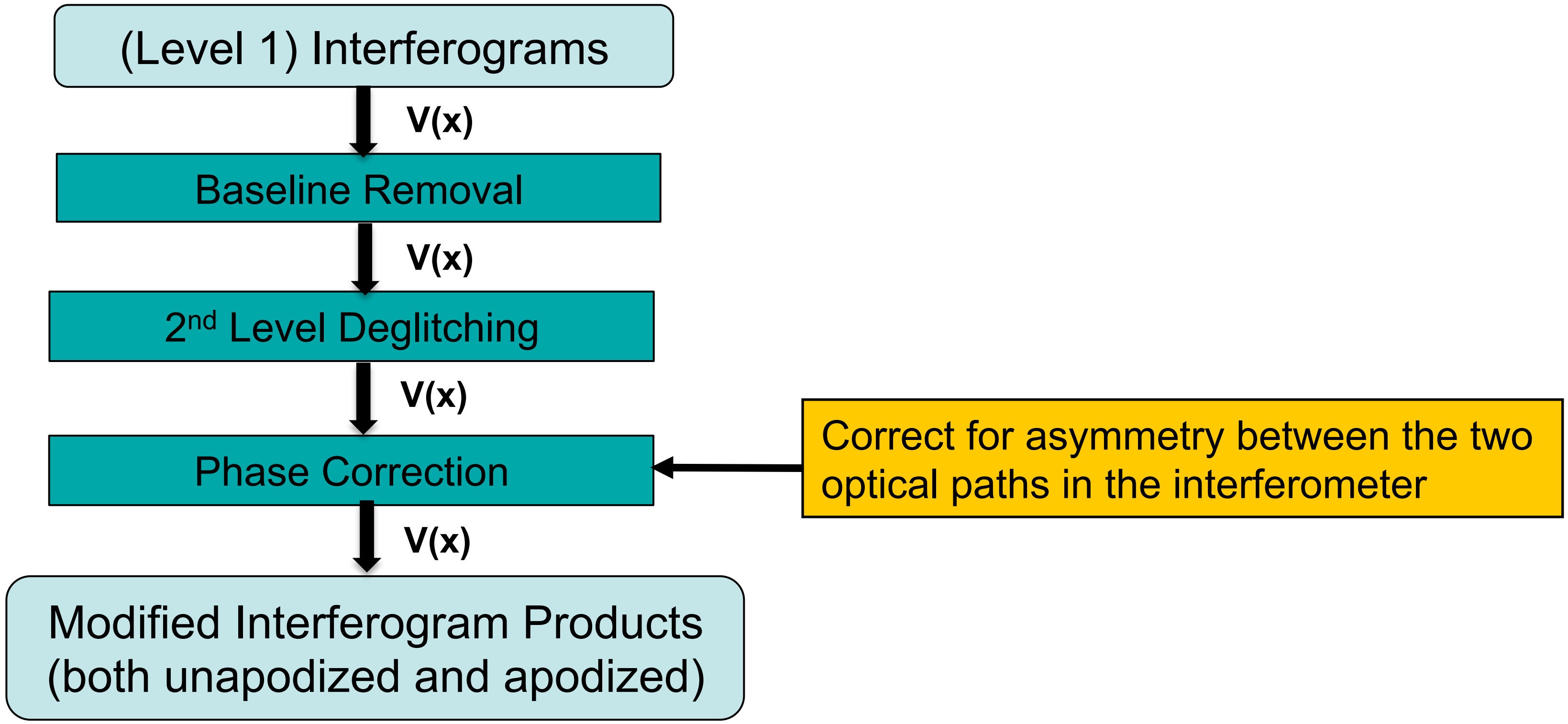
Pipeline Step 2: Create Interferograms



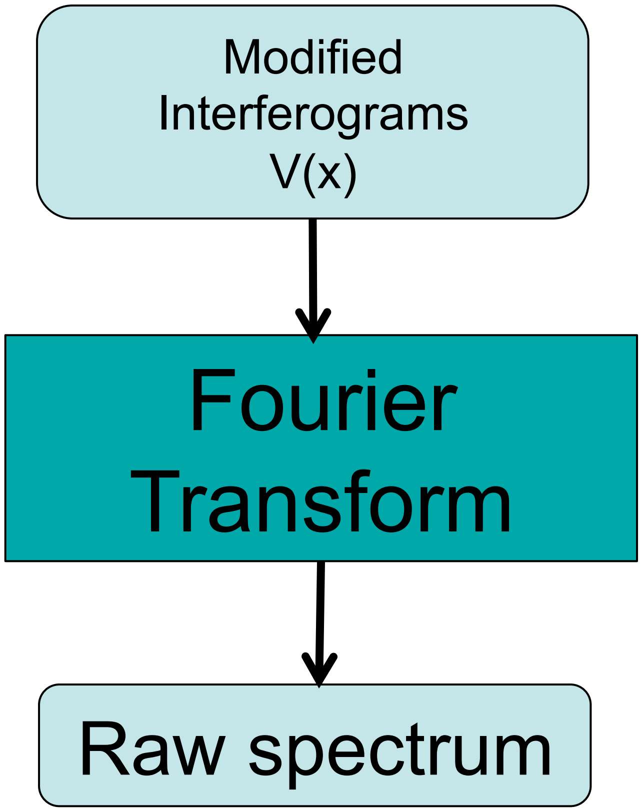
Once time domain processing is complete, the detector signals and SMEC positions can be merged to create interferograms.

The created "unmodified" interferograms are also stored in Level 1 in case users want to do their own interferogram-to-spectrum process.

Pipeline Step 3: Modify Interferograms

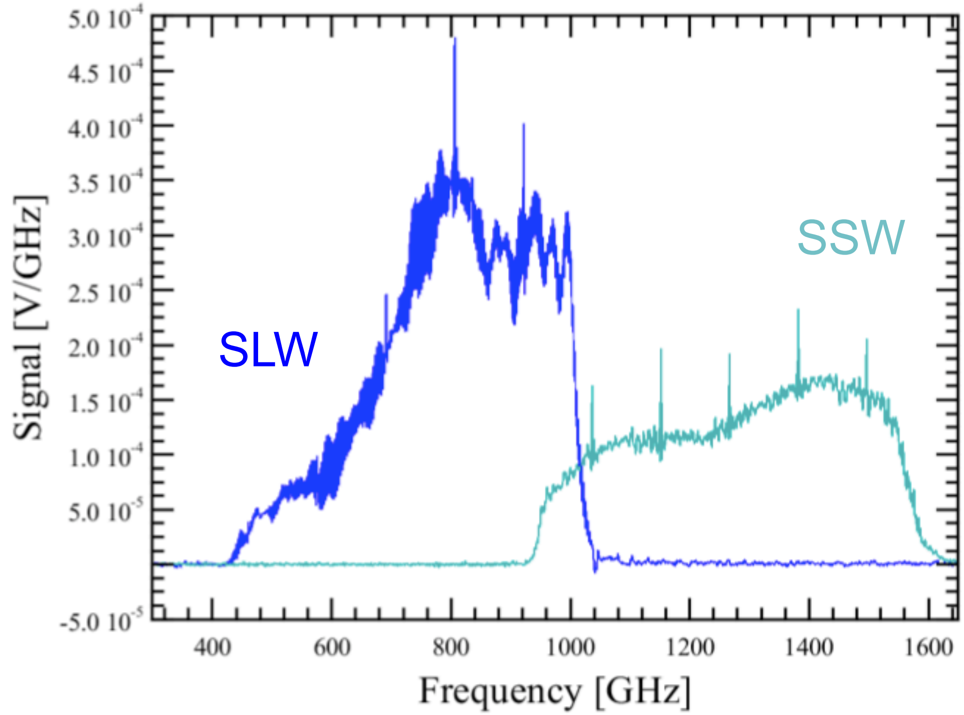


Pipeline Step 4: Fourier Transform



Apply the Fourier Transform to each interferogram to create a set of spectra for each spectrometer detector. The spectra are in units of V/GHz, not yet flux calibrated.

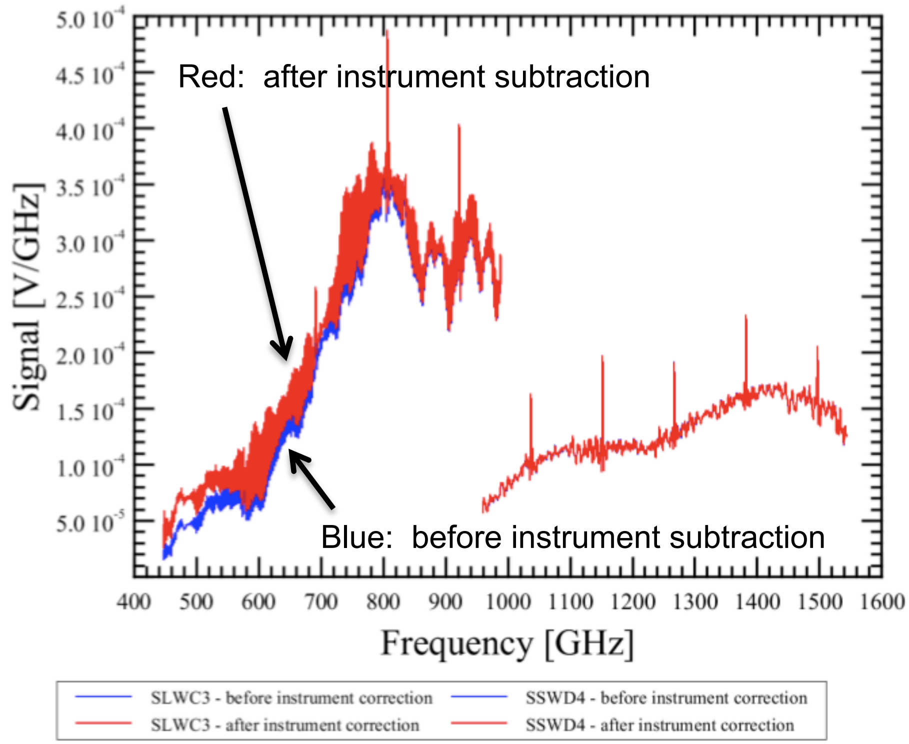
What is in the Raw Spectrum?



$$V_{Measured}(\sigma) = V_{Source}(\sigma) + V_{Telescope}(\sigma) + V_{Instrument}(\sigma)$$

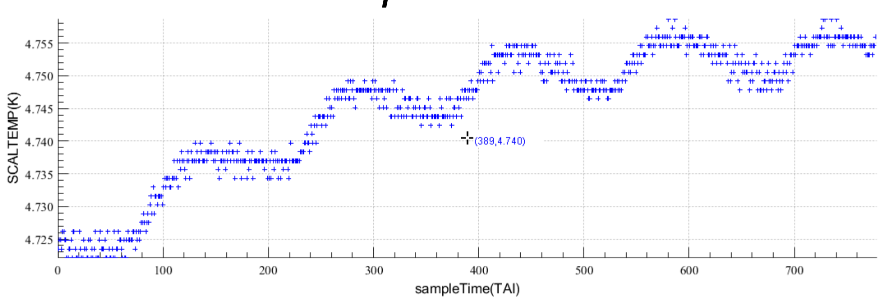
@80K @4-5K

Instrument Background Emission



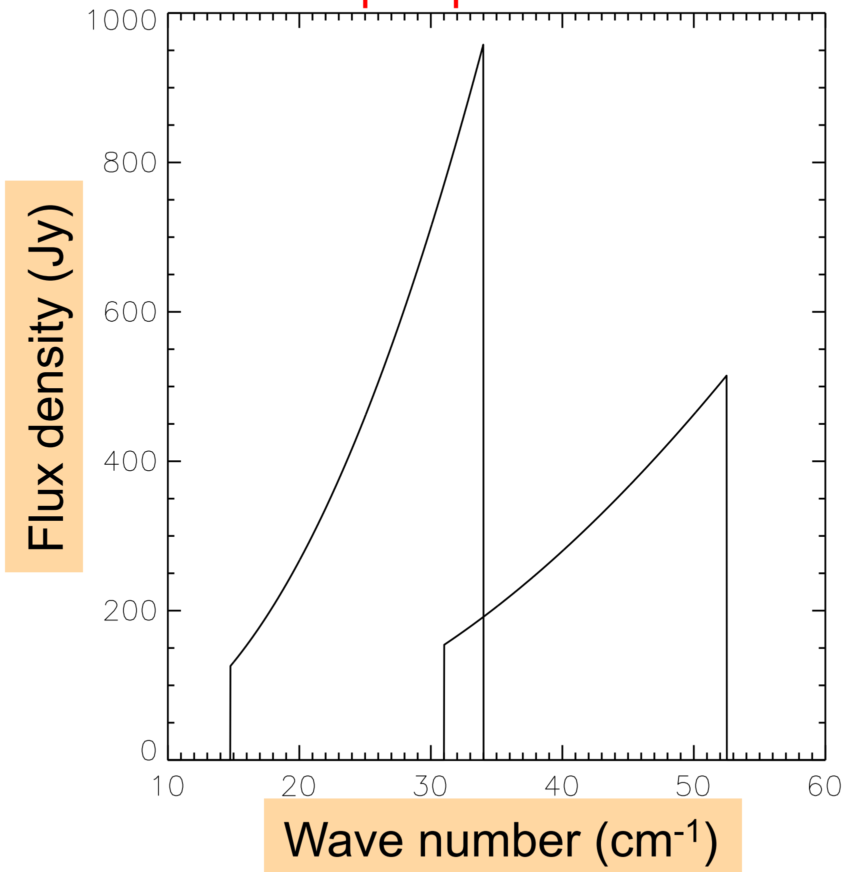
At about 4-5K, instrument emission is only significant at the long wavelength end of SLW.

Instrument temperature varies with time:



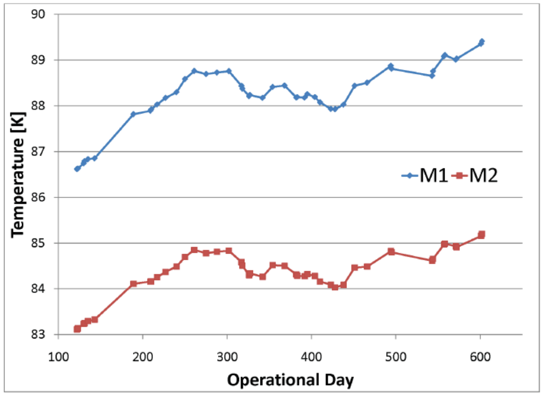
Telescope Background Emission

Sketch of the telescope spectrum as if it is a point source

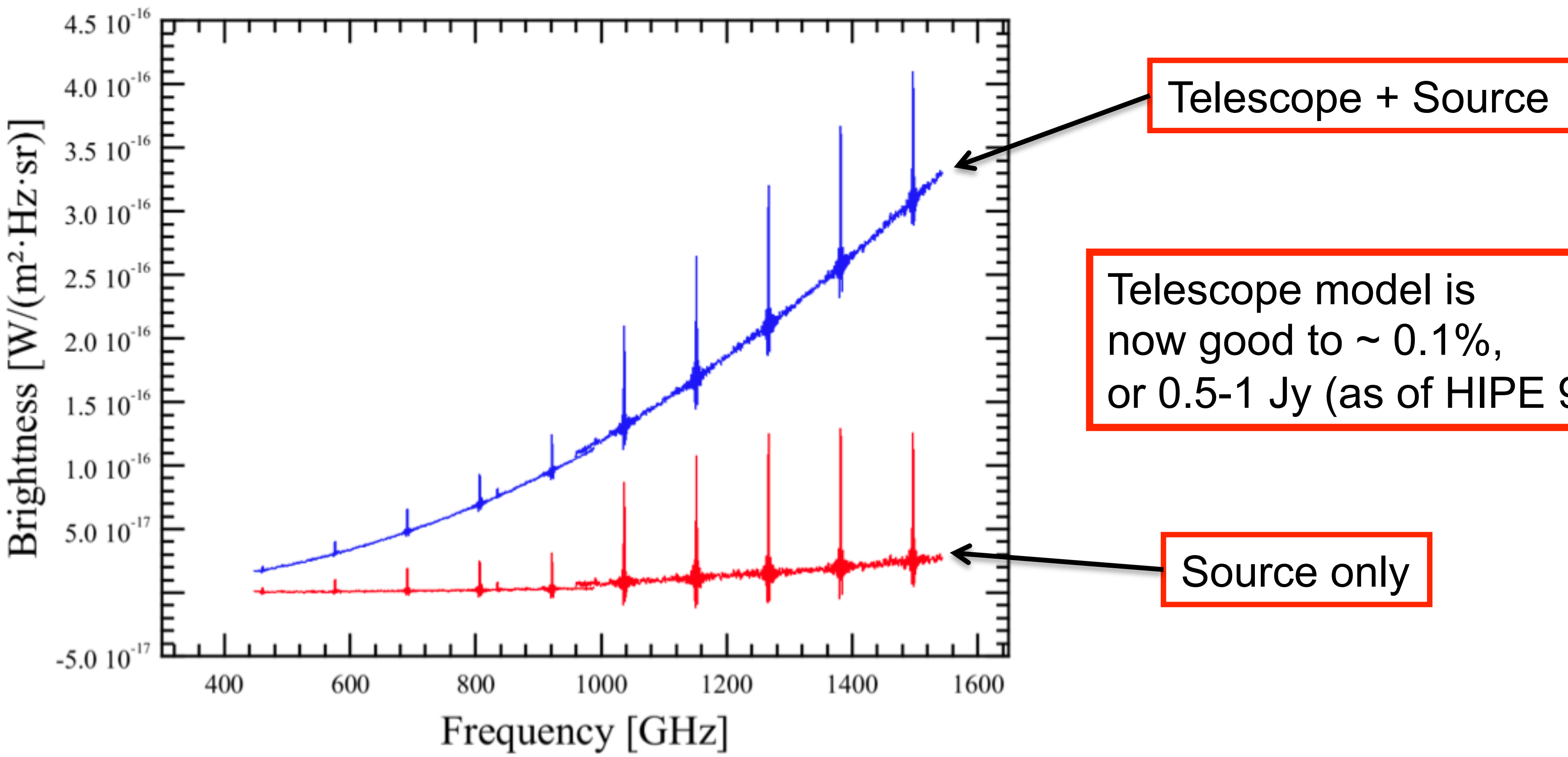


Your observations are most likely dominated by the telescope emission!

Telescope temperatures vary with time:



Telescope Background Emission: A Typical Case



Telescope model is now good to ~ 0.1%, or 0.5-1 Jy (as of HIPE 9)

Flux calibration Scheme

Level-1 spectrum

Brightness in W/m²/Hz/sr
assumes extended emission

$$I = \frac{1}{R_{tel}}[S - R_{inst}M_{inst}] - M_{tel}$$

Telescope RSRF
Raw spectrum
Instrument model and RSRF important for SLW (T ~ 4-5 K)
Telescope model

Level-2 spectrum

Flux Density in Jy
assumes point-like emission

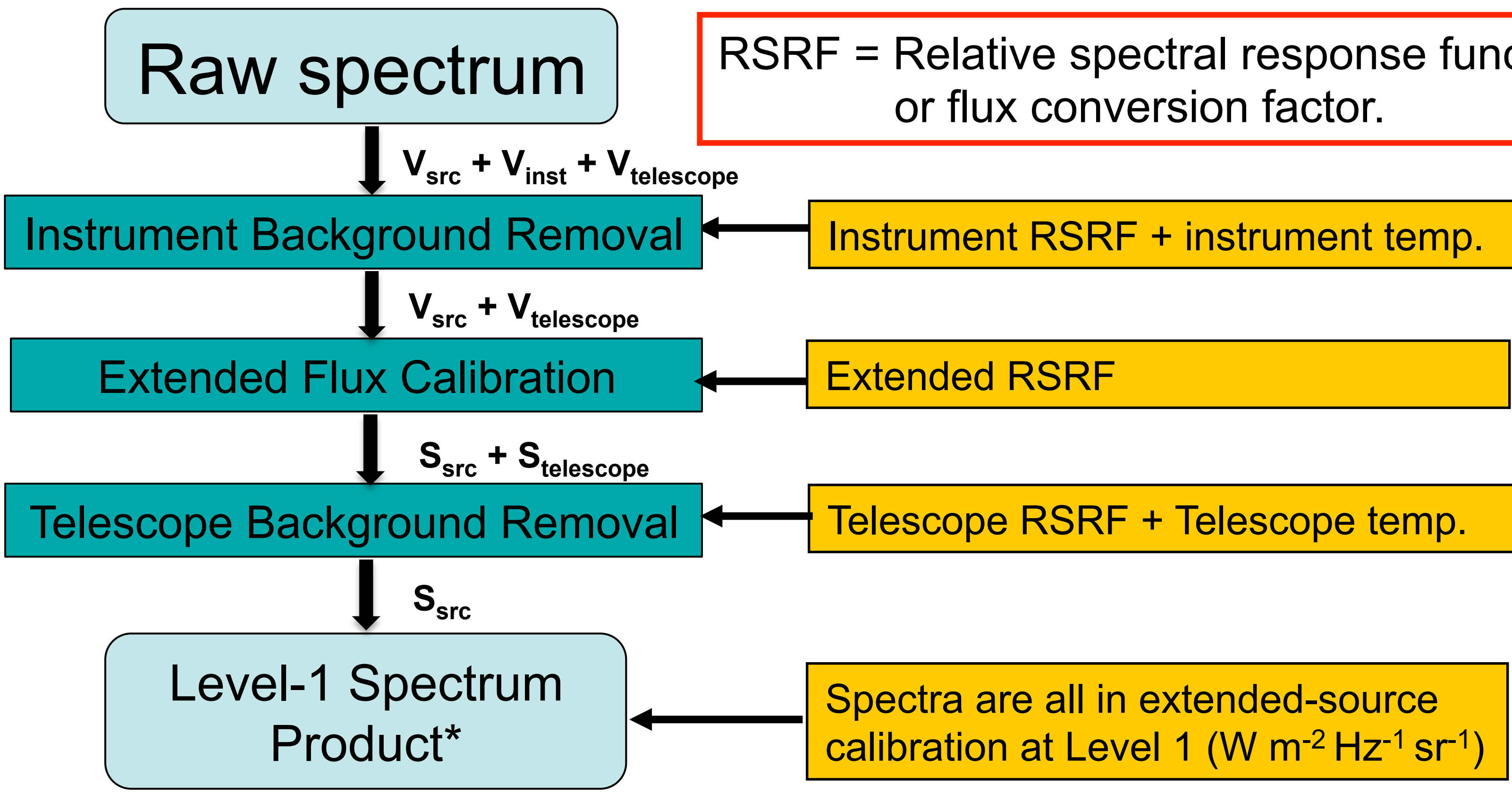
$$f = C_{point}\, I$$

Point source conversion factor (= R_{tel}/R_{point})

RSRFs are empirically derived by observing a source with a known spectrum and dividing by a model:

R_{tel}: *Dark Sky (= the telescope)*
R_{point}: *Uranus*

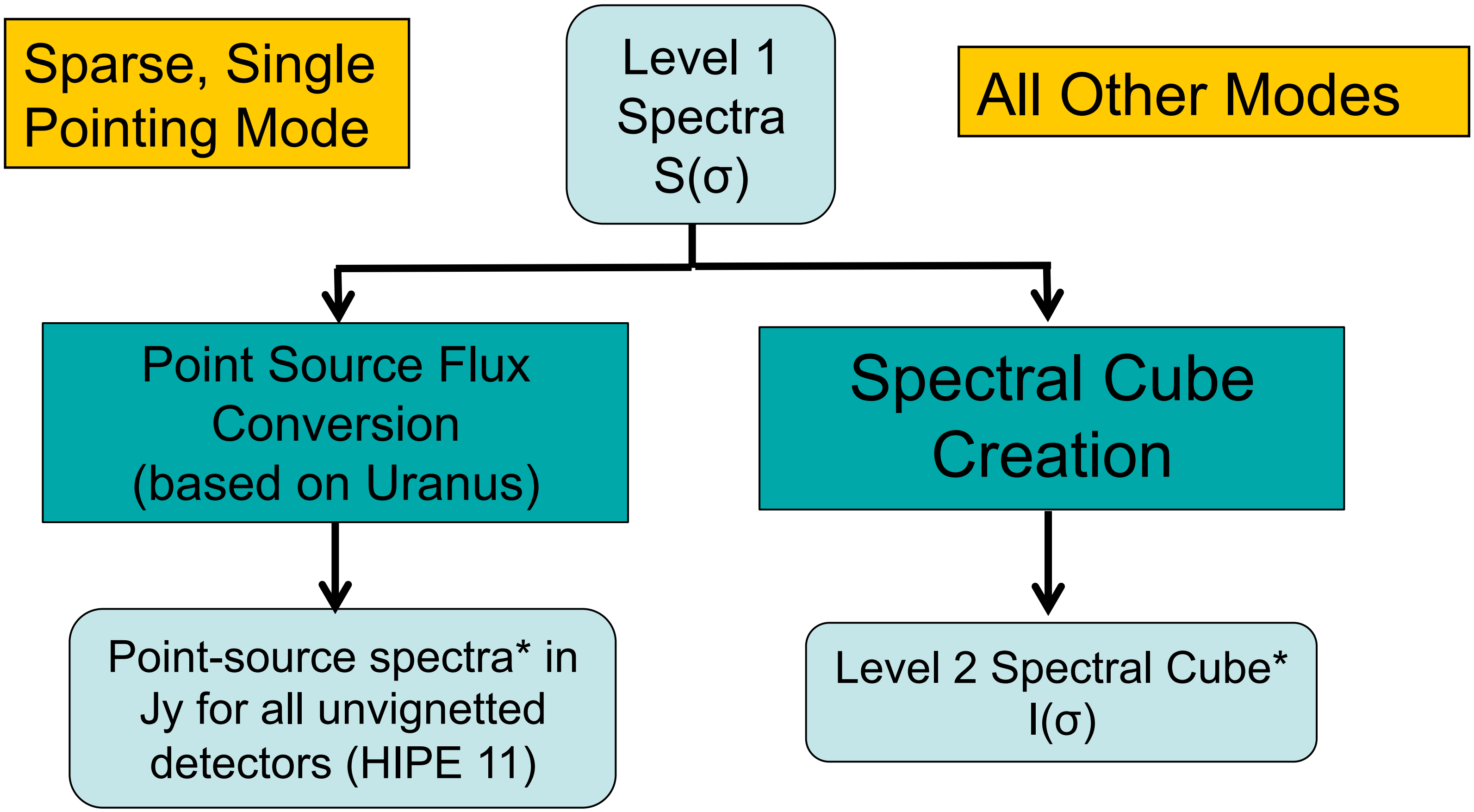
Pipeline Step 5: Modify Spectra



RSRF = Relative spectral response function, or flux conversion factor.

* Both unapodized and apodized spectra [using the default apodization func. NB(1.5)]

Pipeline Step 6: Create Level-2 Products



* Both unapodized and apodized data [using the default apodization func. NB(1.5)]

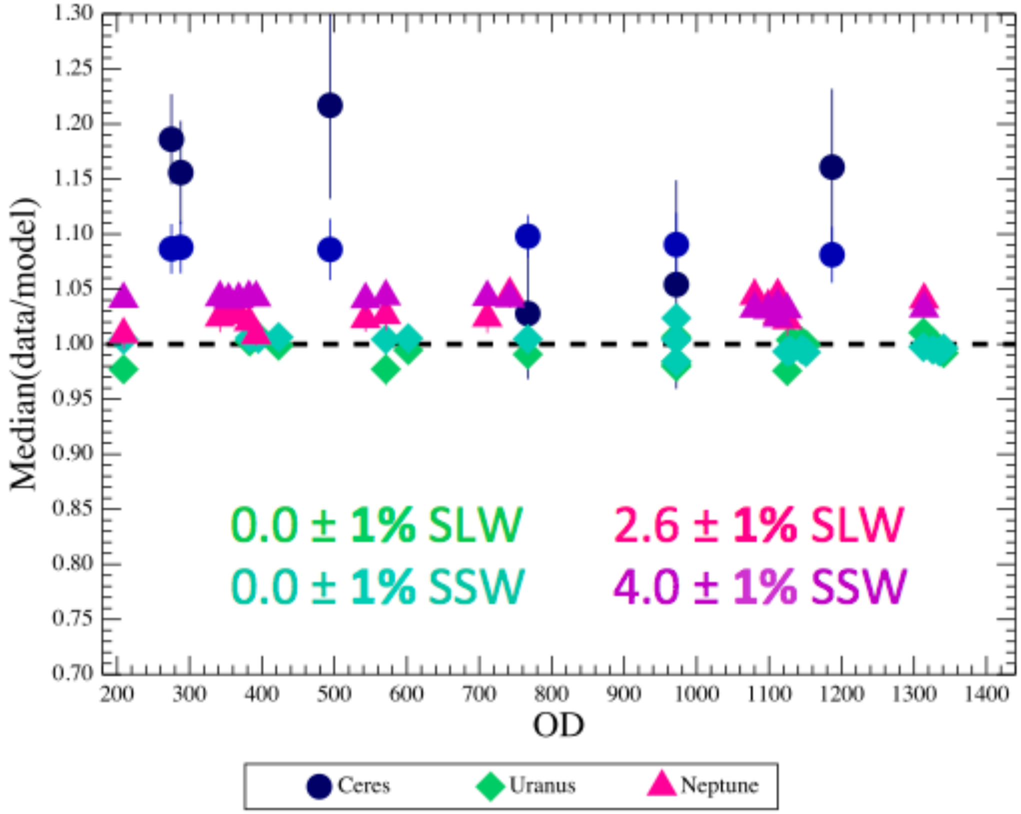
Calibration Accuracy

- Flux accuracy for point source on the central detectors
  - 1% absolute flux accuracy w.r.t. Uranus (after pointing correction).
  - 3-4% accuracy of the Uranus model.
  - Pointing-related errors (e.g., 3% in SSW for 2” pointing offset)

  Total error: ~ 6%.

  (Note: Additive continuum offset uncertainty: ~0.4 Jy, affecting faint sources; 2% additional error for observations in the bright-source mode.)
- Flux accuracy for maps:
  - Additional uncertainty from variations among detectors and less accurate calibration of outer detectors.
  - Overall repeatability is seen to be ~7%.
- Wavelength calibeartion:
  - 5 - 7 km/s for line velocity.

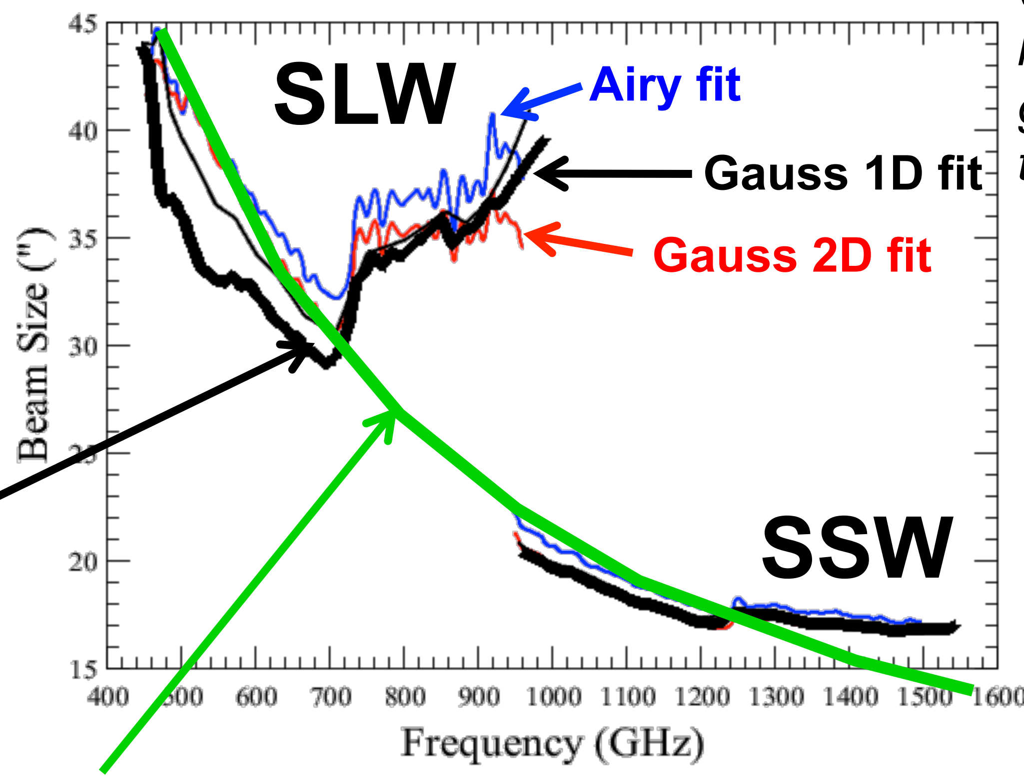
Flux Calibration



Note: Model fluxes are much more accurate for planets than for asteriods

Beam Profile

***Gauss 1D** (thick black line) are the only values given to users in the cal tree*



Sharp changes in size where **feedhorn modes** cut in

HIFI beam size

You are good if you have a point source or truly extended source. Tricky if you are in between.

Extended vs. Point Source Flux Calibration