SPIRE FTS Calibration Overview

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On behalf

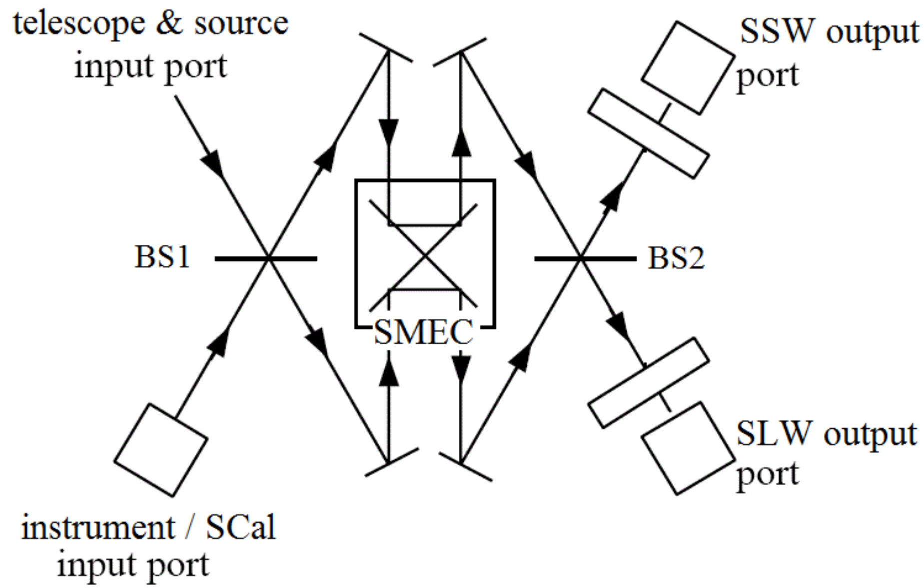
SPIRE FTS Calibration Team

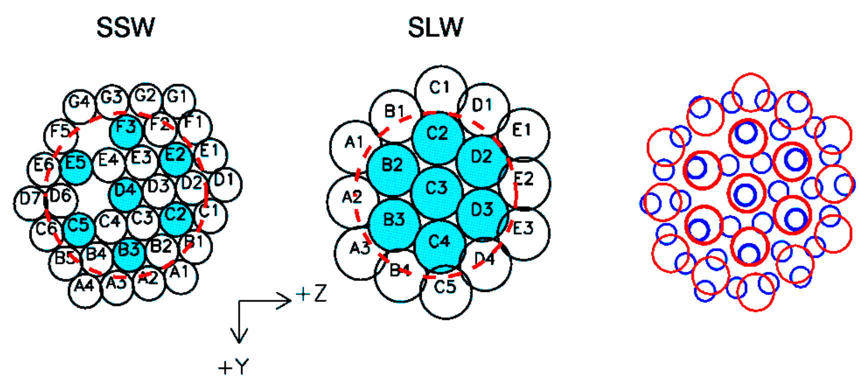
What this talk is about

- Provide context for the folks who did the real work
  - Ros Hopwood – calibration repeatability and sensitivity (next)
  - Nanyao Lu – non-linearity correction (here) and bright source correction (tomorrow)
  - Ed Polehampton – mapping and all the other detectors (tomorrow)
  - Ronin Wu – how to deal with semi extended sources (tomorrow)
  - Gibion Makiwa – beam size (poster)
  - Trevor Fulton – RSRF (poster)
  - Yvan Yaltchanov – relative pointing (poster)

SPIRE FTS Operation

- SPIRE spectrometer is a four port FTS
- Output ports split into short (SSW) and long (SLW) wavelength arrays
- Sparse sampling feedhorn +waveguide arrays
- Some pixels overlap
- Power falling on detectors comes from Sky and Instrument
- Calibration source is not used but instrument contribution needs to be removed

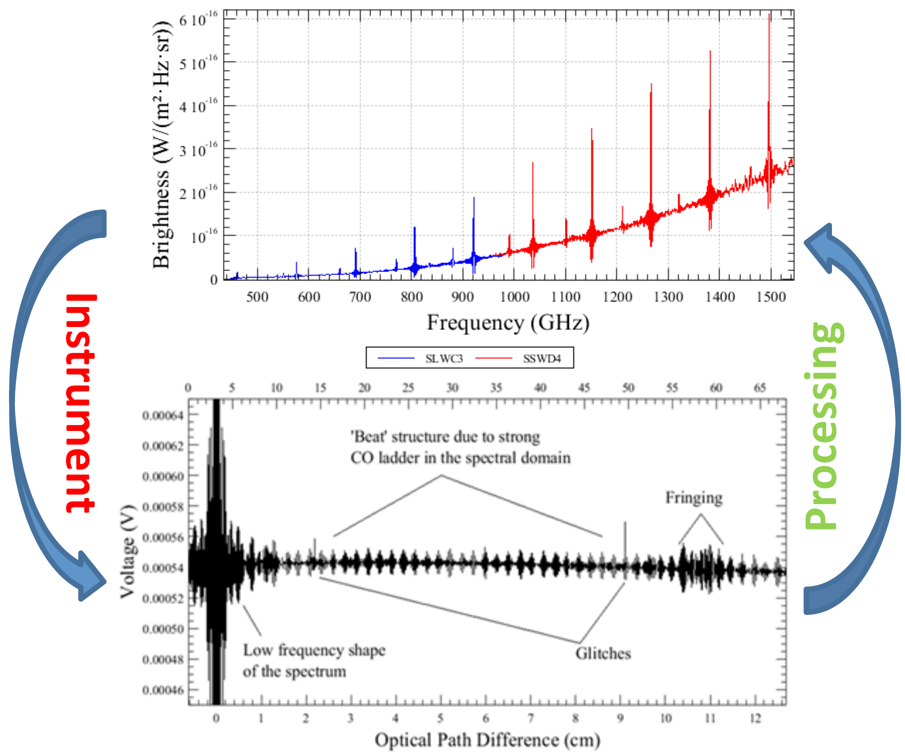




Basic Calibration Scheme - I

- Spectrometer converts input spectrum into interferogram
- Need to invert this process via FFT
- Large dynamic range in interferogram → need to linearise detector output

- Similar method to Photometer(see Bendo et al.2013)
- Linearisation is carried out by integrating over the inverse bolometer response function
- Here we use a model of the bolometers rather than empirical measurements

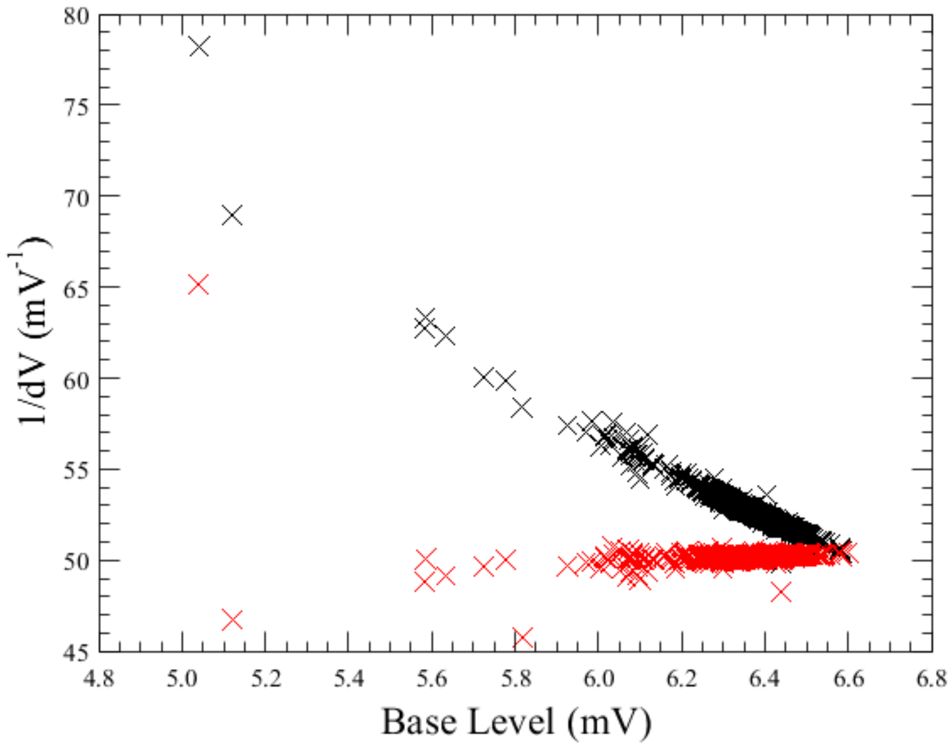


$$S = \int_{V_0}^{V_m} f(V)\,dV \qquad V' = \frac{1}{f(V_0)} \int_{V_0}^{V_m} f(V)\,dV$$

$$\frac{f(V)}{f(V_0)} = K_1 + \frac{K_2}{V - K_3} \qquad V' = K_1(V_m - V_0) + K_2 \ln\left(\frac{V_m - K_3}{V_0 - K_3}\right)$$

Basic Calibration Scheme – II Linearity Demonstration

- PCAL flashes are used for testing the calibration
- Taking flashes taken over a range of backgrounds we can test the linearity correction



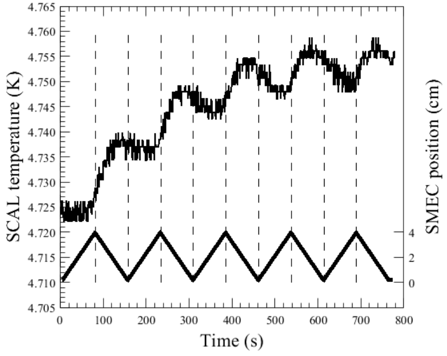
Basic Calibration Scheme – III
Conversion to flux

- The spectrum in units of "linearised voltage" density can be expressed as

$$\mathrm{FT}(V'(t)) = R^*(\nu)B_{source}(\nu) + R_{tel}(\nu)B_{tel}(\nu) + R_{inst}(\nu)B_{inst}(\nu)$$

- The object spectrum can be recovered by removing the telescope and instrument and using the "extended source" calibration
- $$I_{ext} = \frac{(V_{obs} - M_{inst}R_{inst})}{R_{tel}} - M_{tel}$$ W m^{-2} cm^{-1} sr^{-1}

- We need to have an accurate RSRF for both telescope and instrument (Fulton)
- Instrument temperature is taken from SCAL
- Telescope temperature is taken from satellite



Basic Calibration Scheme – IV Conversion to "Point Source"

- Conversion to point source

$$F_{point} = I_{ext} C_{point} \qquad C_{point} = \frac{M_{uranus}}{I_{uranus}} \quad \text{sr}$$

- This is the effective extended source or photometric beam area
- We can compare this to that measured using a point source (later)

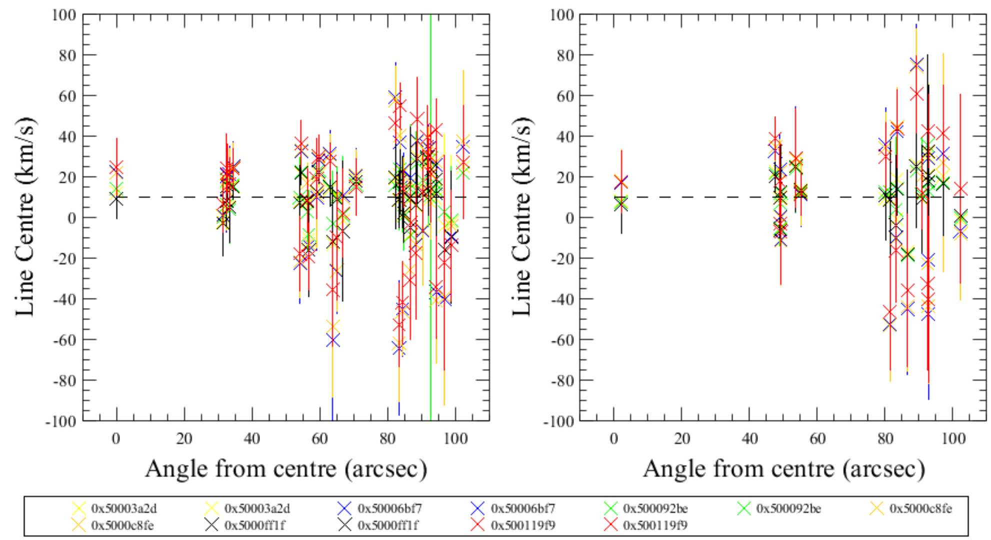
- Telescope model (Fischer et al 2009) – temporal corrections applied (Hopwood)

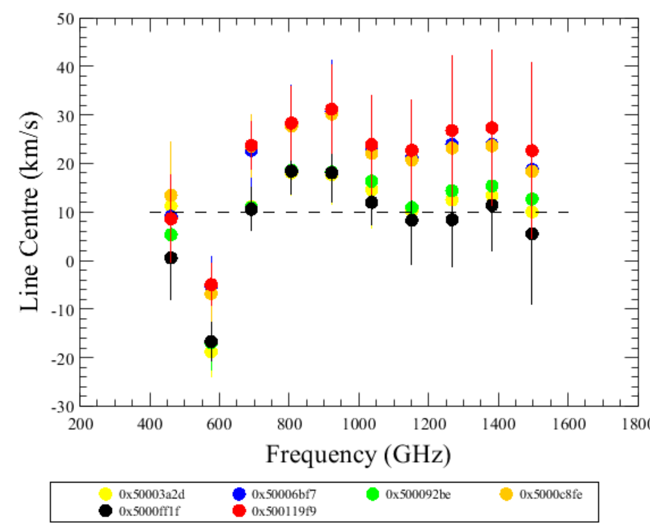
$$\varepsilon_{Tel} = 0.0336\lambda^{-0.5} + 0.273\lambda^{-1}$$

$$B_{\rm Tel} = (1 - \varepsilon_{\rm Tel})\varepsilon_{\rm Tel} B(T_{\rm M1}, \nu) + \varepsilon_{\rm Tel} B(T_{\rm M2}, \nu),$$

Frequency Calibration

- Quick discursion
- Frequency calibration of SPIRE is excellent for central detector
- FWHM = 0.048 cm^{-1} or 1.2 GHz
- ~800 km/s at 450 GHz
- ~220 km/s at 1600 GHz
- Some variation across the array
- Line centre accuracy check based on CO in Orion < 30 km/s





Planet Model Corrections

- HIPE 9 amd 10 use Uranus model from Glenn termed "ESA4" as primary calibrator
- Now updated to ESA5 (groan)
- Need to worry about some other small corrections
  - Beam size compared to source size
  - Irrelevant for SLW ~1-2% for SSW
  - Source Omega – taken from Horizons 1 Bar radius
  - Is this the right radius?

$$K_{\mathrm{Beam}}(\theta_p, \theta_{\mathrm{Beam}}) = \frac{1 - \exp(-x)}{x}$$

$$x = 4\ln(2)\left(\frac{\theta_p}{\theta_{\mathrm{Beam}}}\right)^2$$

- Compare calibration to Neptune using Raphael ESA4

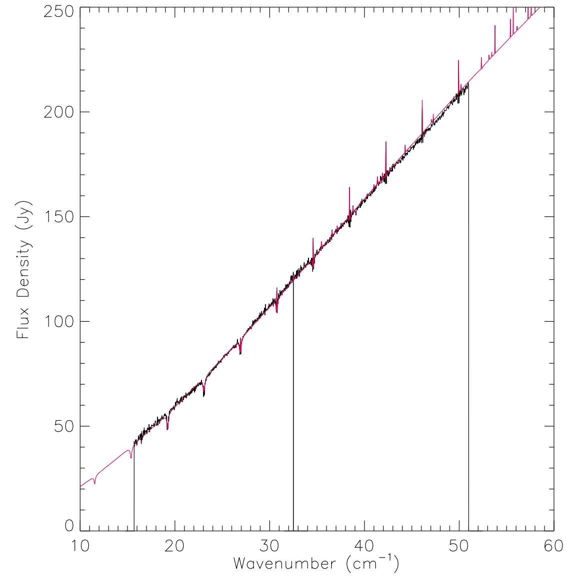
Source	OD	OBSID (hex)	Date	Time	Duration	N_{scan}	Purpose	Ω_{planet}
Uranus	383	0x50004EE0	01/06/2010	12:31:04	4445	22	Primary Cal.	2.15347E-10
Neptune	392	0x5000529D	09/06/2010	19:45:53	14130	100	Cal. Test	9.74866E-11
Neptune	742	0x5000AD87	26/05/2011	06:57:24	1060	4	Cal. Test	9.57192E-11
Cas A Centre-1	451	0x50006199	08/08/2010	09:13:18	3965	24	Extended Cal. Test	N/A

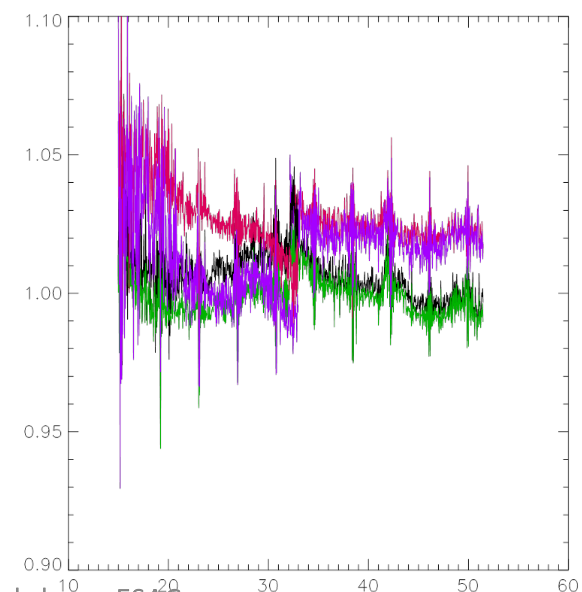
Neptune – HIPE 10 ESA4

- Upper spectrum is Neptune from OD742 processed through HIPEv10
- Uranus "ESA4" used as calibrator
- Red is Moreno "ESA4"
  - Lovely jubbly

- Lower spectrum is data/model for various observations
  - Black is OD382
  - Green is OD392
  - Red is OD1080
  - Purple is OD1125

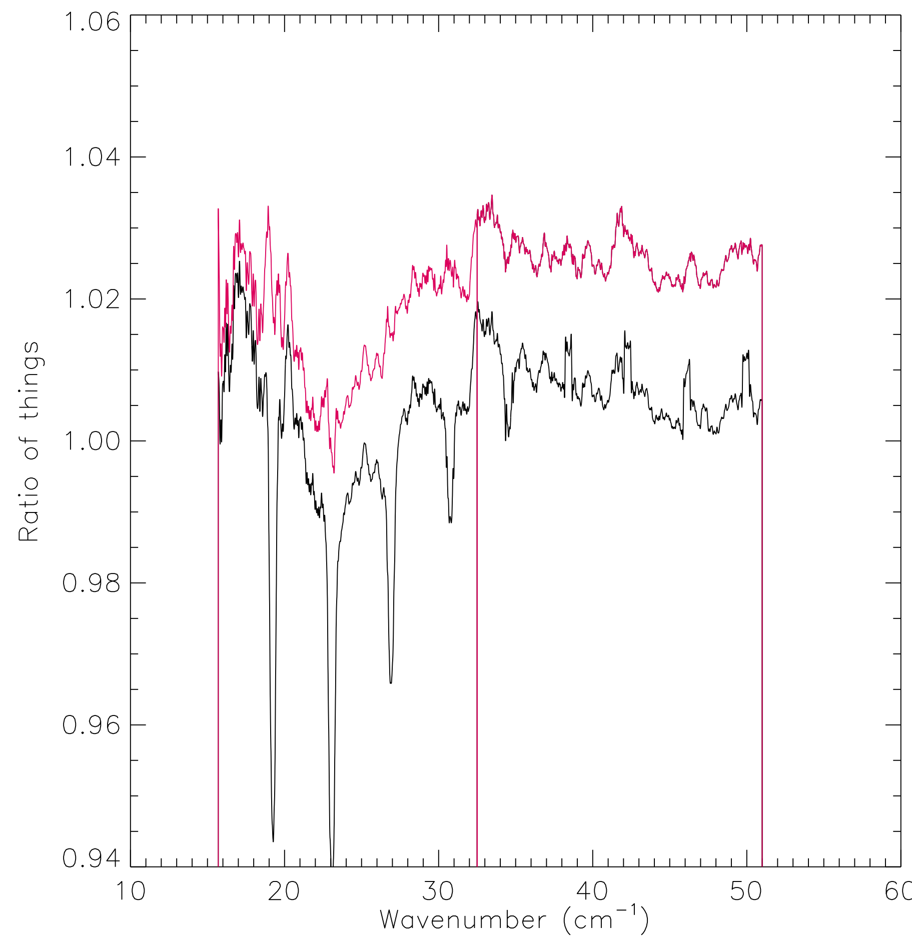
- Some of the apparent errors in the line strengths are associated with the sinc function of the ILS.
- Some may be due to spectral misalignment of the model and observed spectra.





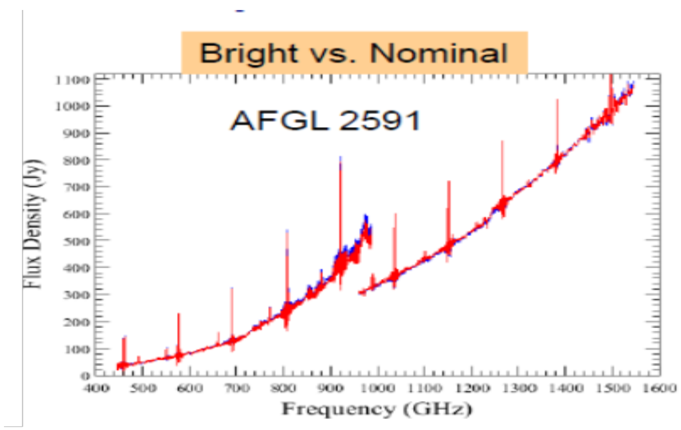
Neptune models compared Uranus ESA5

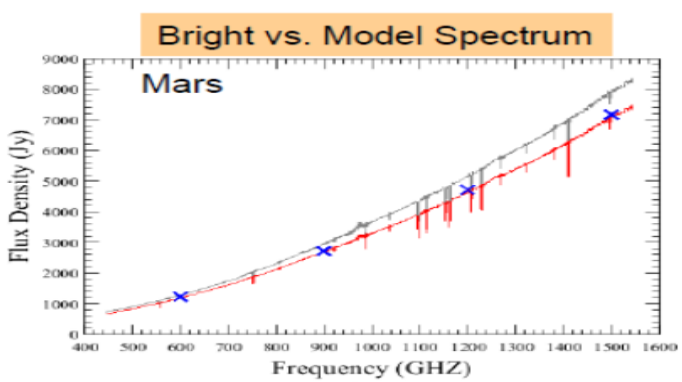
- I was happy ☺ until……
- **ESA5**
- Here I plot ratio of ratios
- $\{N_{meas}/ U_{meas}\}/\{N_{mRM}/U_{mESA5}\}$ – red
- $\{N_{meas}/ U_{meas}\}/\{N_{mGO}/U_{mESA5}\}$ – black
- U_{mESA5} warmer than U_{mESA4}
- N_{mRM} ESA4 looks a little chilly
- Boohoo ☹



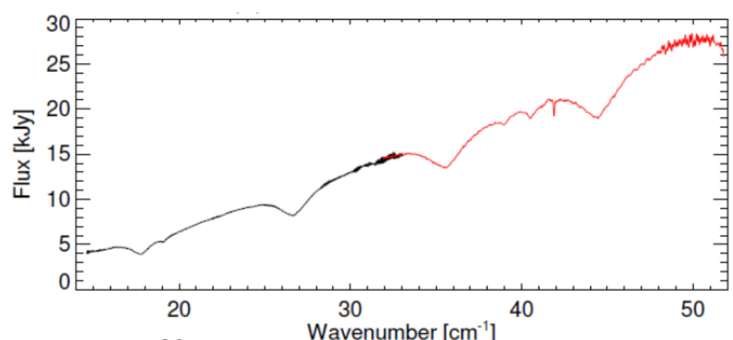
Bright Source Mode

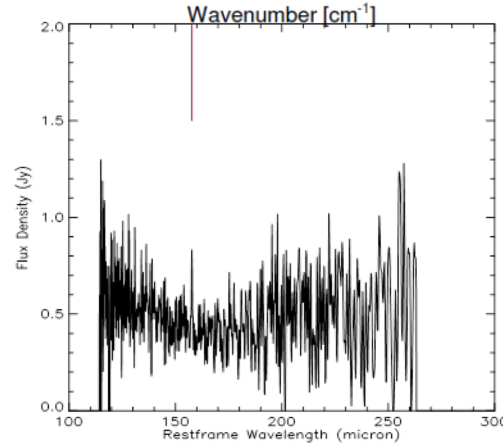
- Put the bias to maximum and dephase the bolometer bias
- Allows observation of very bright sources without saturating amplifiers
- Requires special processing
- Hipe 11 will have new version of BS linearity correction





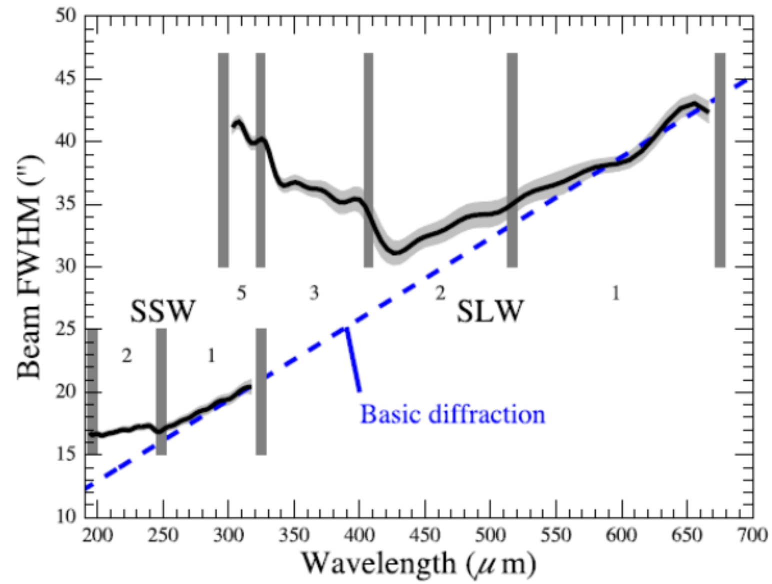
SPIRE FTS has huge dynamic range





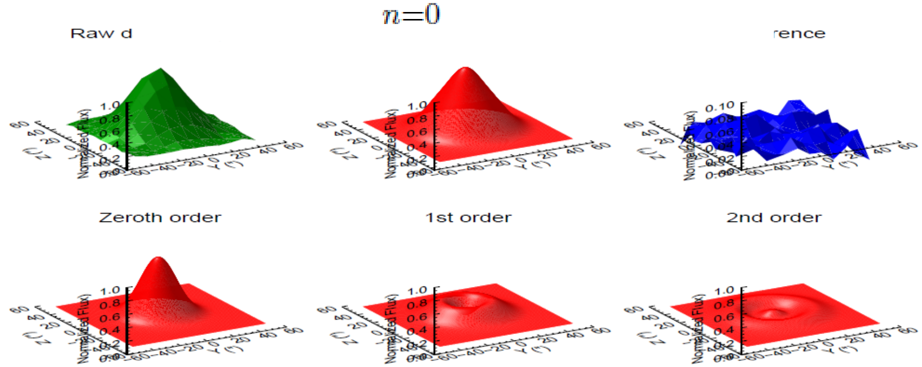
Beam Size - I Oddities

- The SPIRE FTS beam is "funny"
- Multimoded waveguides means the beam shape has "jumps"
- Can represent this as a linear decomposition of Hermite-Gauss polynomial functions
- This is a convenient mathematical form (Makiwa)



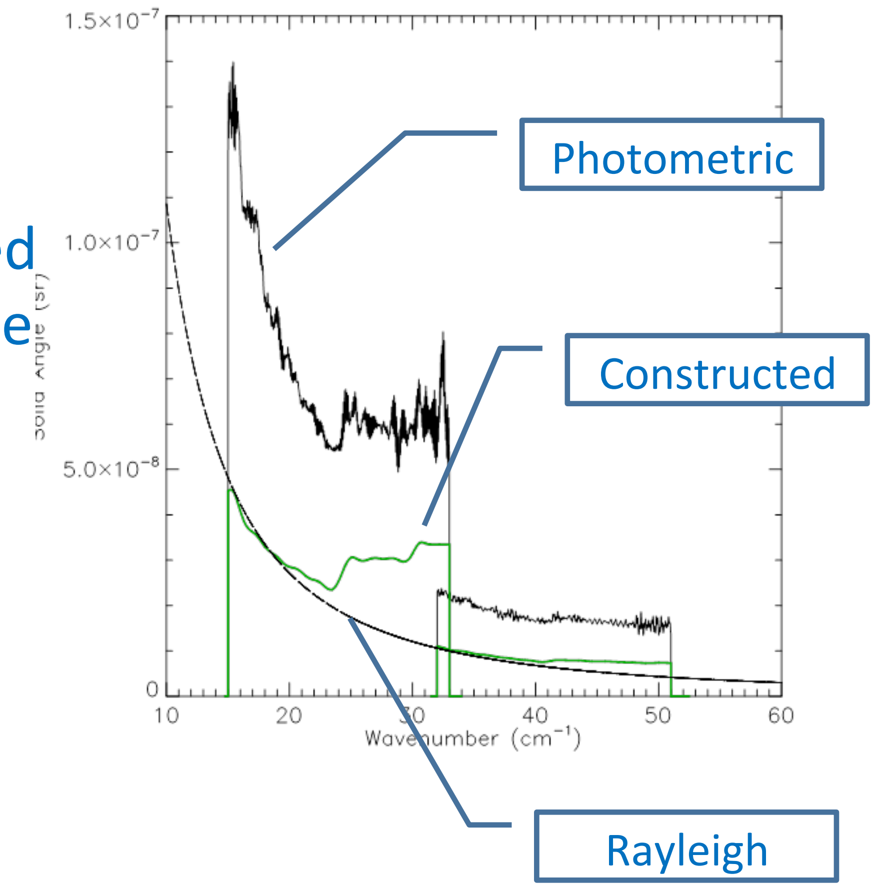
$$\varphi_n(r,\lambda) = \left(\frac{2}{\pi}\right)^{1/4} \cdot \frac{1}{\sqrt{w_0(\lambda)}} \cdot \frac{1}{\sqrt{2^n \cdot n!}} \cdot H_n\left(\sqrt{2}\frac{r}{w_0(\lambda)}\right) e^{-r^2/w_0^2(\lambda)}$$

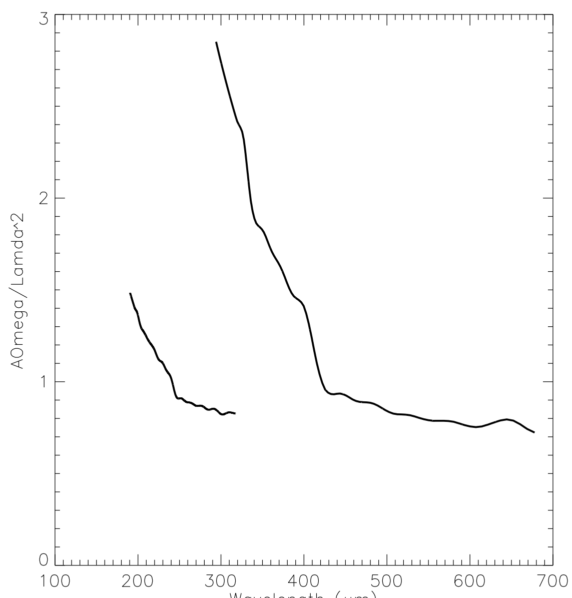
$$S(x,y,\lambda) = \sum_{n=0}^{\infty} c_n(\lambda) |\varphi_n(x,y,\lambda)|^2$$



Beam Size - II
Groping for an explanation

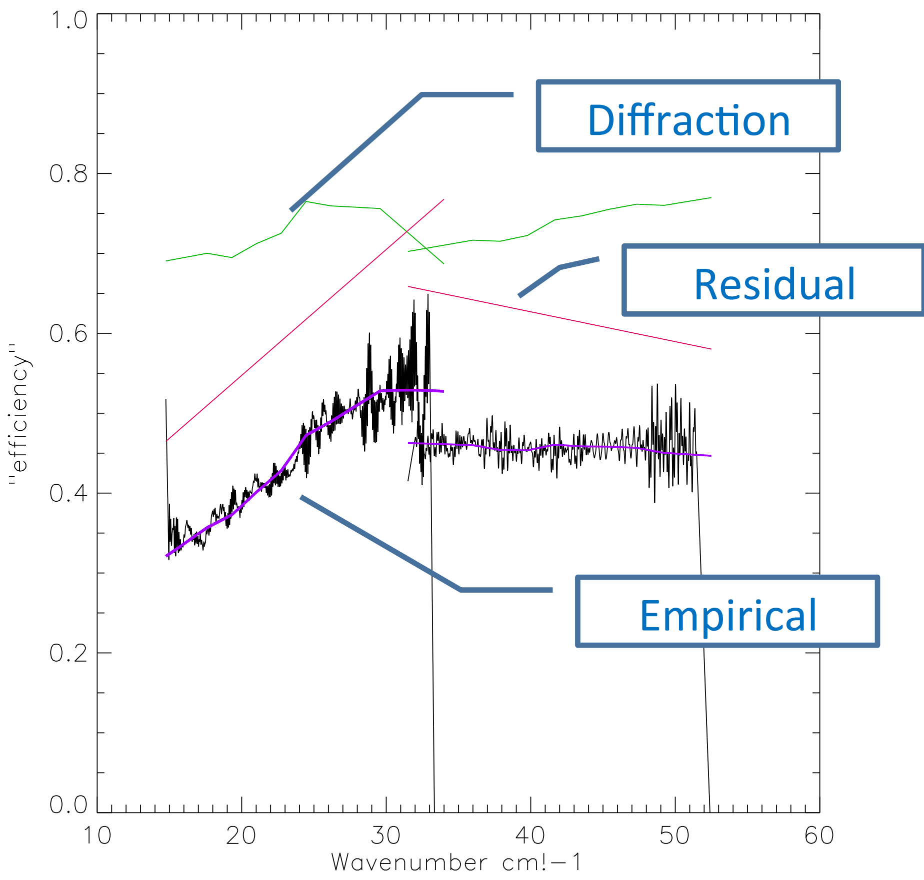
- Can compare the “constructed” beam to the “photometric” beam
- Can also compare the measured AΩ to the expected single mode λ^2





Beam Size – III
More groping in the dark

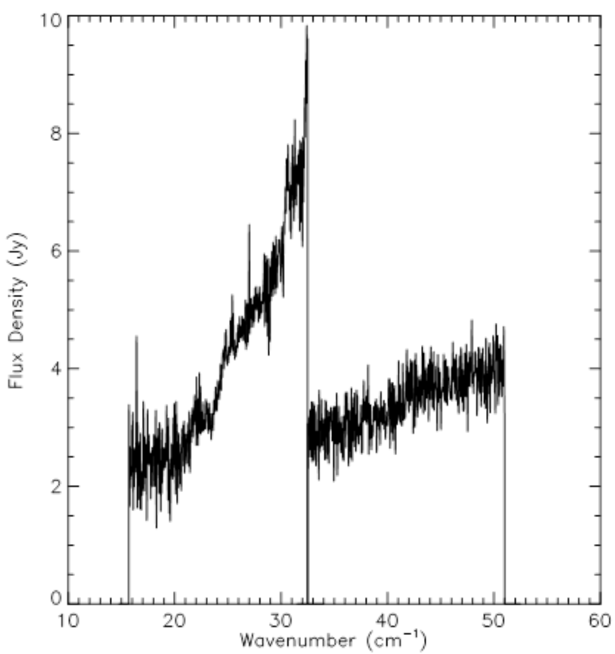
- Using a simple FT model can numerically simulate diffraction loss
- Residual between this and measured Ω_c / Ω_{phot} is then a measure of the (in)efficiency of the fully populated “modal” beam and the “single mode” beam
- SLW looks reasonable
- SSW doesn’t!



Proof it works

- Irrespective of the source of "efficiency" curve – it does work in converting from point to fully extended calibration
- Here an example of a fully extended source (in direction of Cas A)

"Point Source" Calibrated



Summary

- SPIRE spectro-photometery is absolutely calibrated to <2% assuming independently derived Uranus and Neptune models
  - Only true if Source ~> Telescope
  - Only true if point or fully extended source
  - Only true for nominal bias mode
  - Only true for on axis detector
- Have observed source fluxes from few 100 mJy to tens of kJy – accuracy at each end to be confirmed
- Frequency calibration is <30 km/s on central detector – somewhat worse on outer detectors
- We almost nearly sort of understand the beam shape
- See following detailed papers to prove these statements wrong!