SPIRE Spectrometer Characterization

SPIRE Spectrometer Workshop

14 May 2007

Trevor Fulton

Contents

- Active Channels
- Spectrometer Band Edges
- Phase
- Vignetting
- Channel Fringes
- Spectral Resolution
- Modulation Efficiency
- Obliquity

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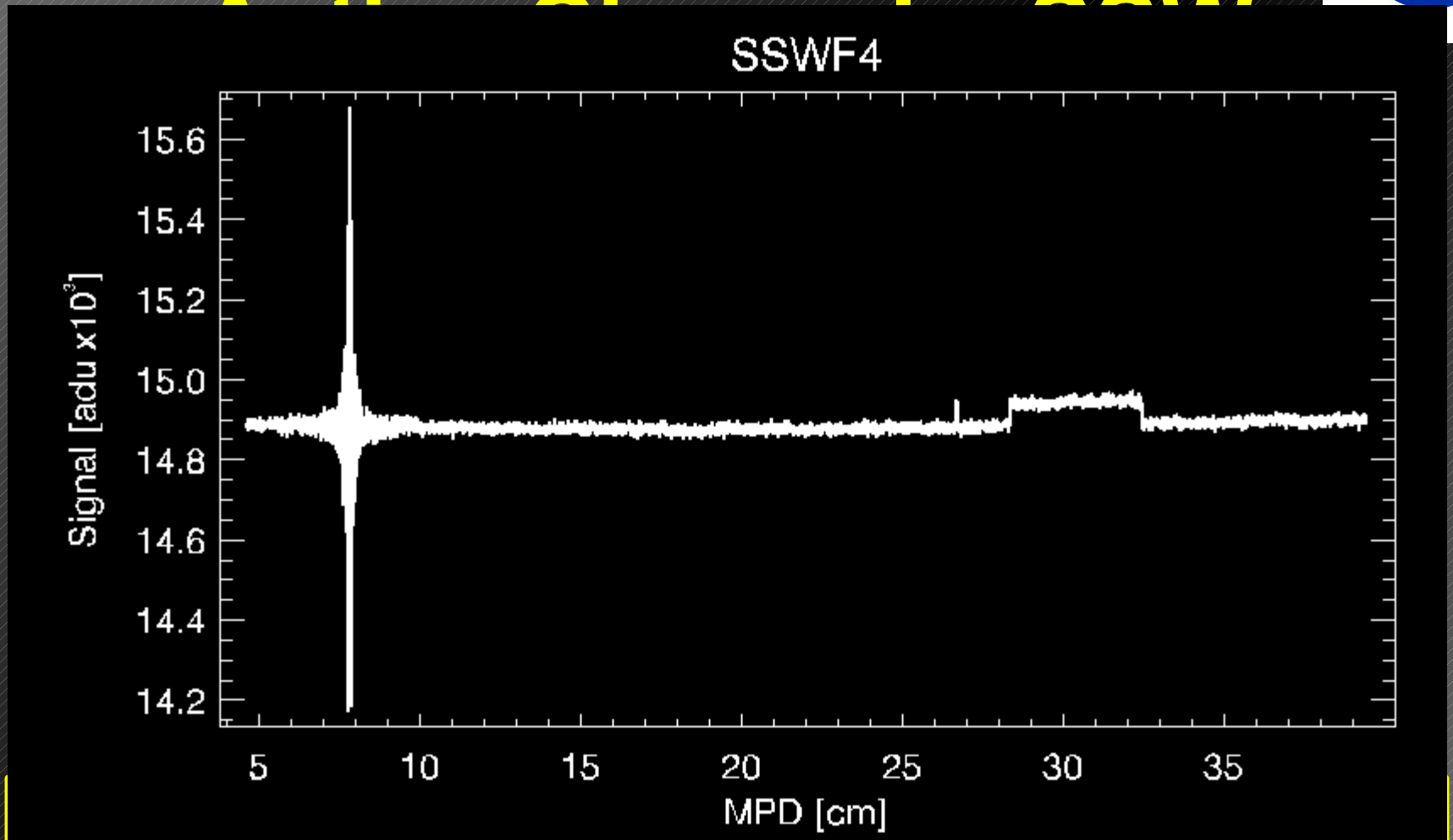
Active Channels, SLW

SLWB3 and SLWC2 not active (also SLWDP2 which is not shown here)



been updated with the status of these channels.

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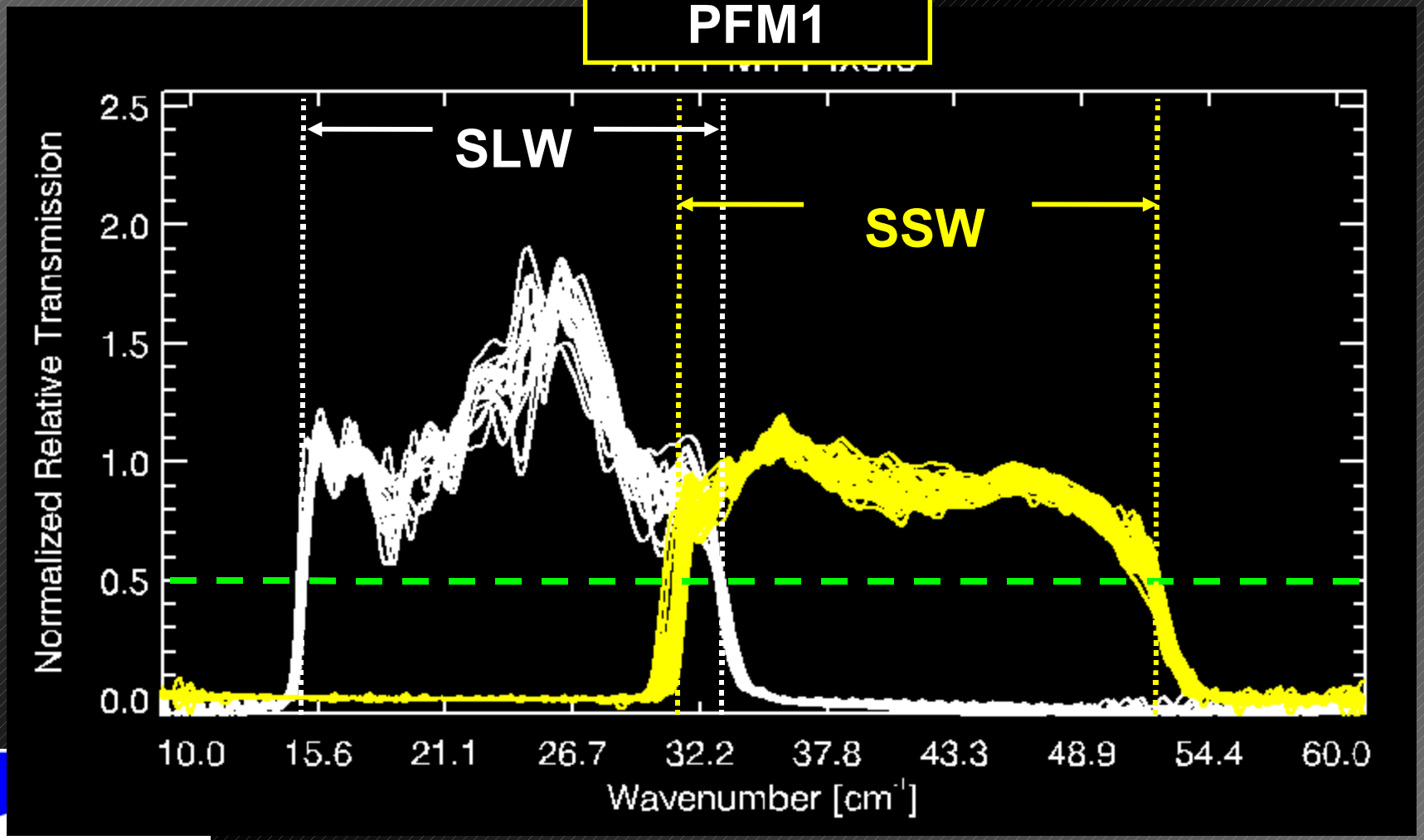
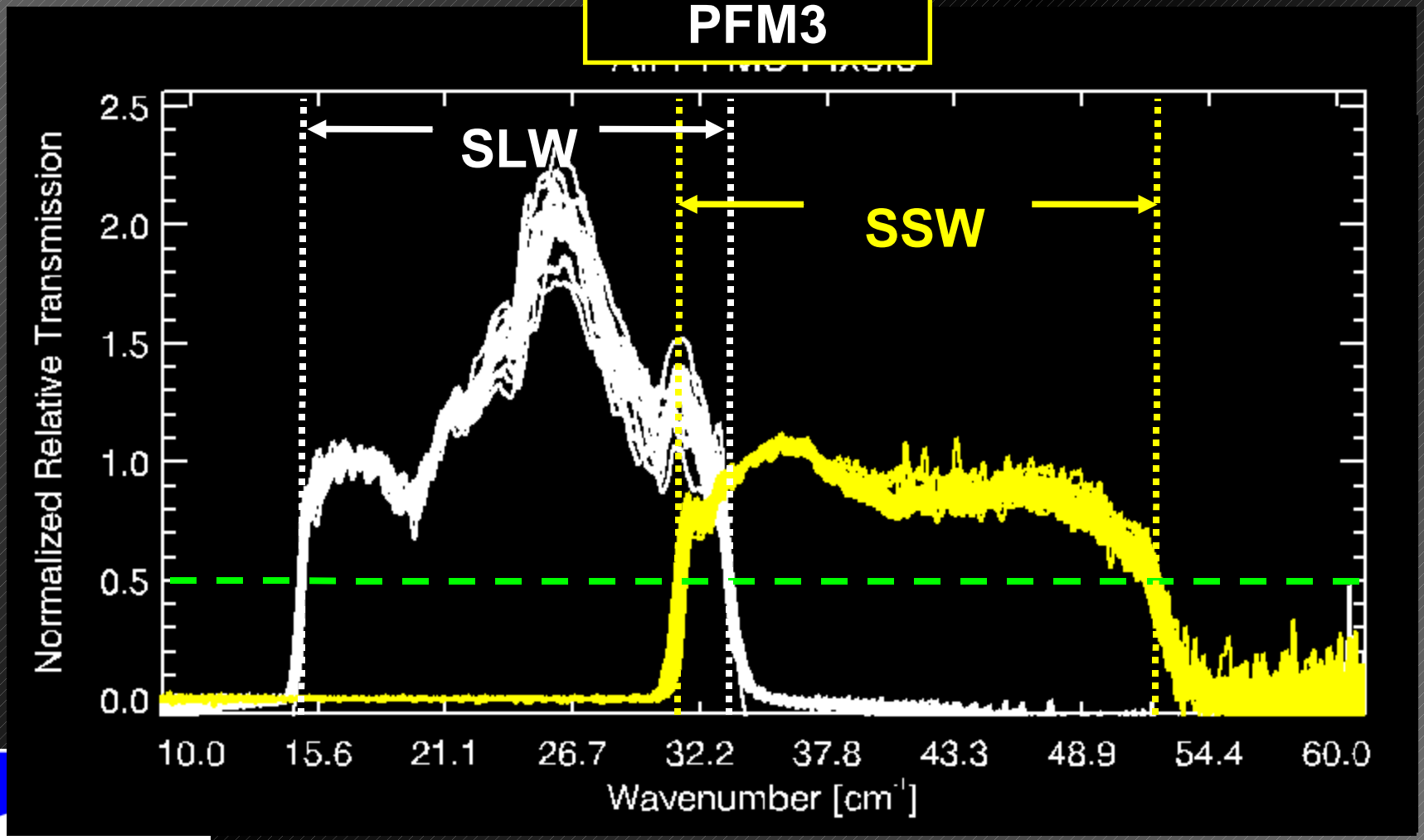
Spectrometer Bands

- Techniques similar to those in the transmission analysis were used to remove the input source from the data, leaving only the relative detector response.
- The relative detector response of each was then normalized to one in the single mode region:
  - SLW at 17cm^{-1}
  - SSW at 34.5cm^{-1}
- From these normalized response curves, the band-edges were defined as the points where the spectral response was equal to 0.5 (50%).

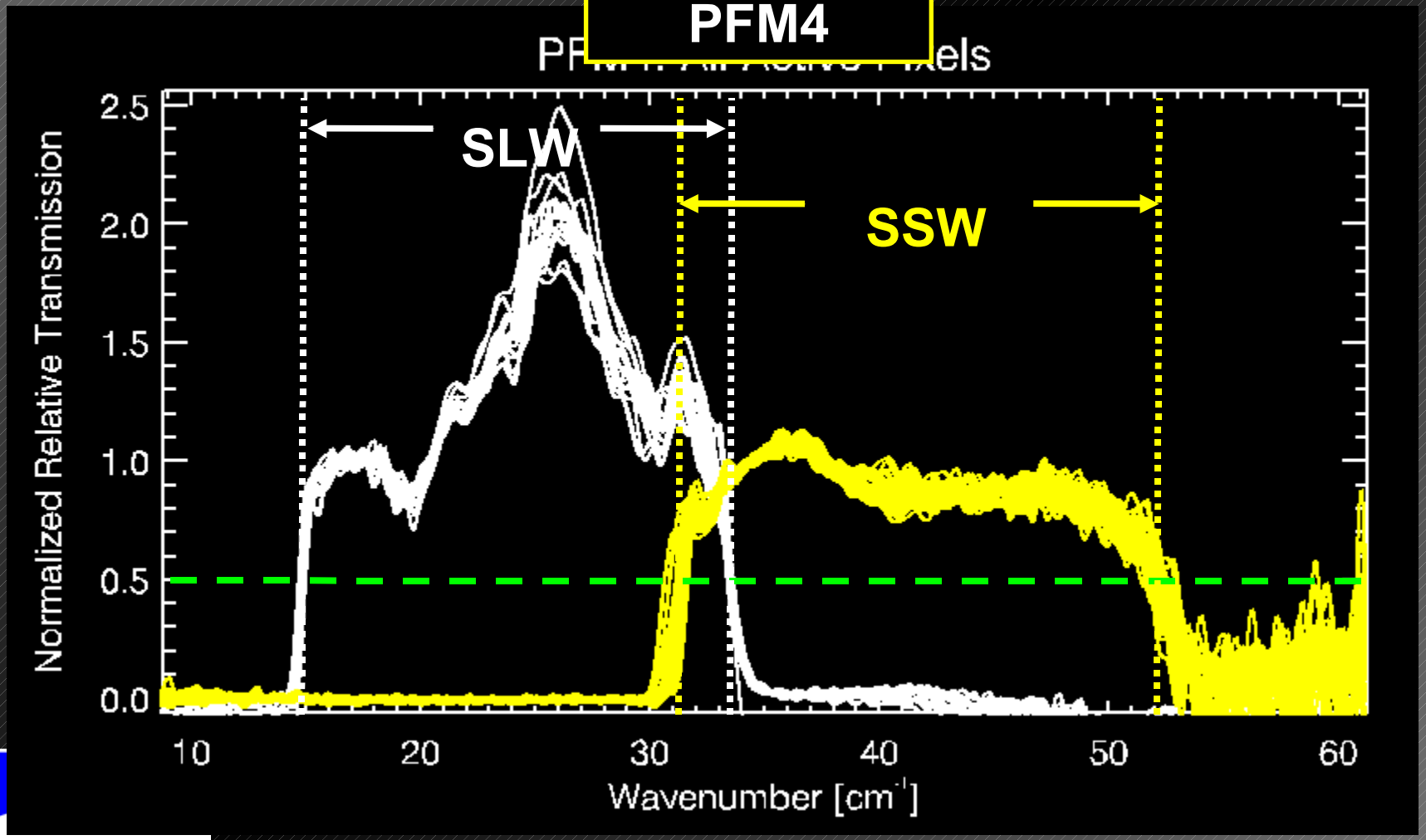
Spectrometer Bands



Spectrometer Bands



Spectrometer Bands



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Spectrometer Bands

	SLW		SSW	
	Cut on [cm^{-1}]	Cut off [cm^{-1}]	Cut on [cm^{-1}]	Cut off [cm^{-1}]
Specs	14.64 – 15.02	33.00 – 33.67	30.40 – 31.15	52.08 – 53.19
PFM1	14.905 ± .099	33.068 ± .096	31.32 ± .28	51.99 ± .24
PFM3	14.899 ± .091	33.525 ± .096	31.37 ± .17	51.98 ± .20

The individual band edges from this study will be stored in the ScalSpecBandEdge calibration product.

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Phase

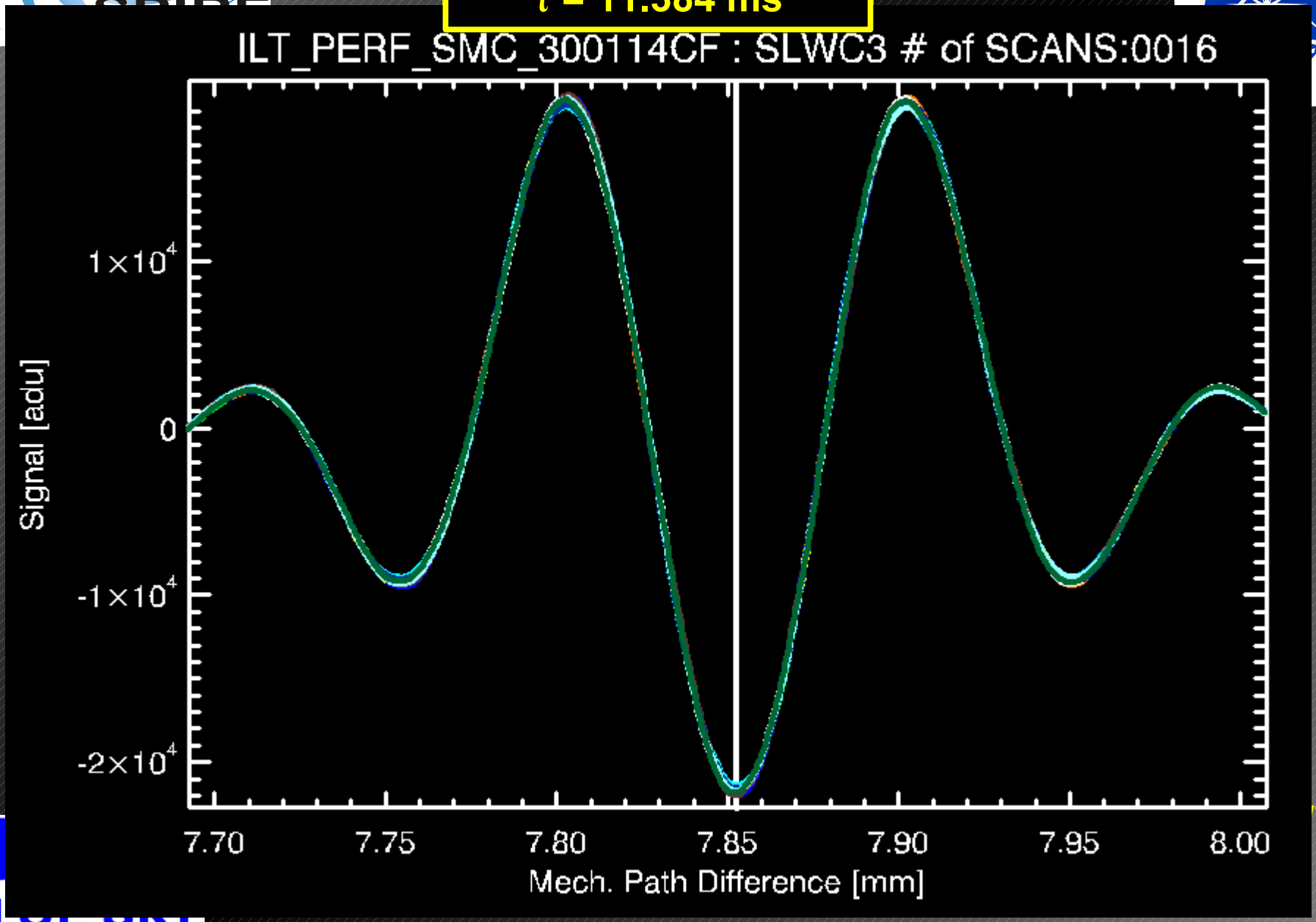
- Split the overall phase in terms of position- and time-dependent components:

$$\phi_{Total} = \phi_{position} + \phi_{time}$$

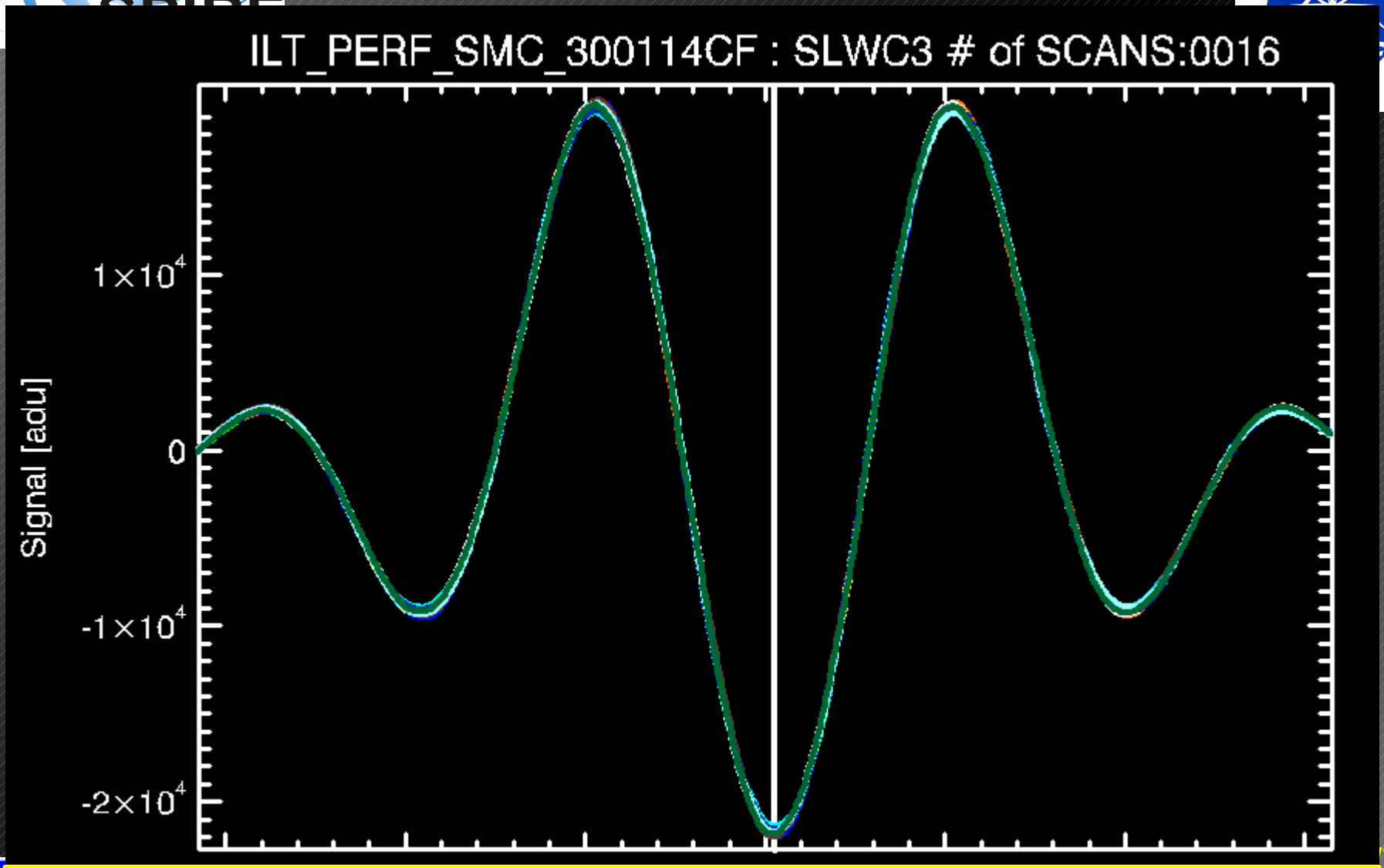
$$\phi_{Total} = \phi_{ZPD} + \phi_{Optical} + \phi_{Electronics/Thermal}$$

Electronics/Thermal Phase

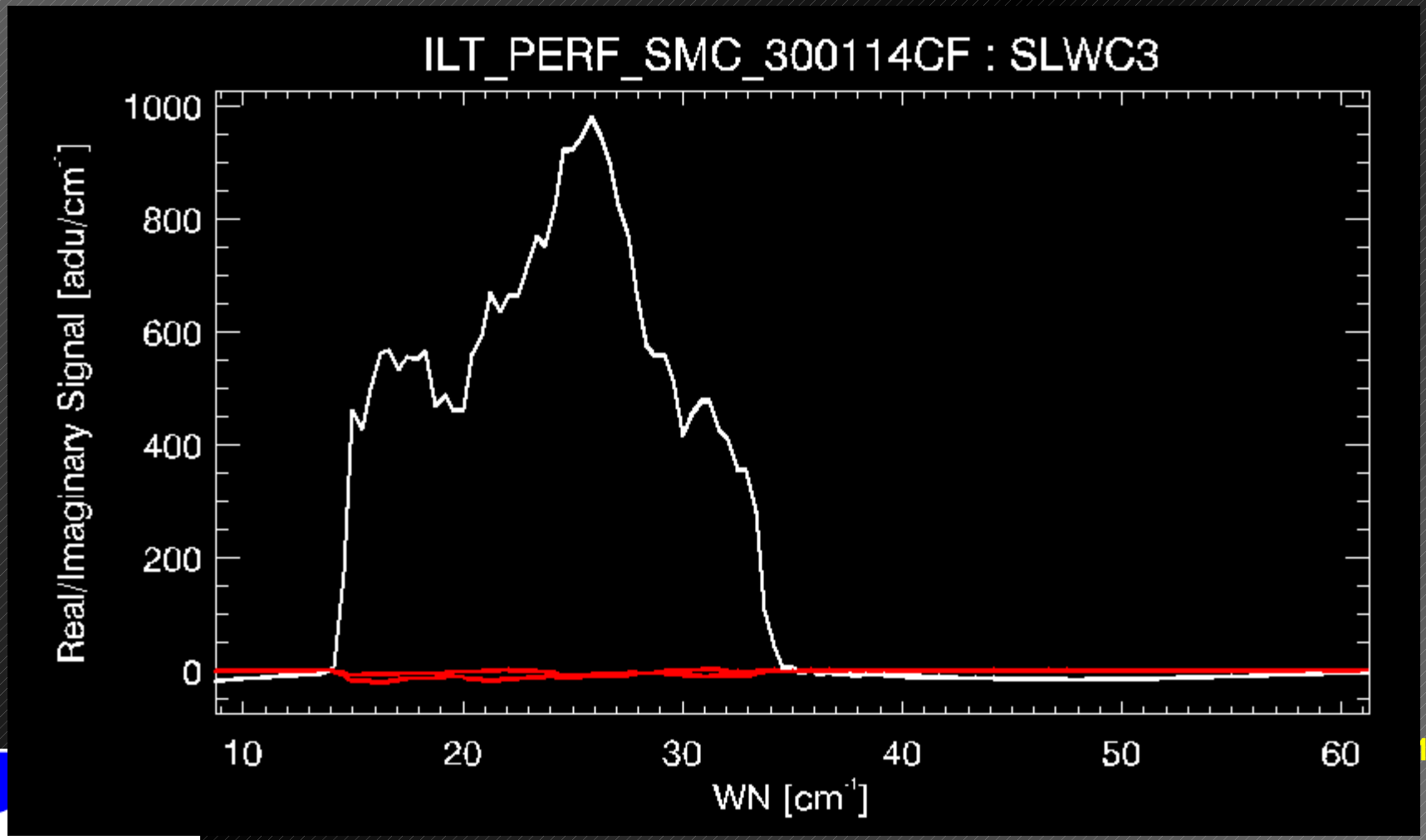
- Recall that the model of the detectors includes not just the read-out electronics but a simple RC low pass model to account for the thermal response of the bolometers.
- For this model, the response due to the read-out electronics is fixed while the thermal response is variable (τ is variable).
- A phase correction function is derived from the combined frequency response of the detector model.

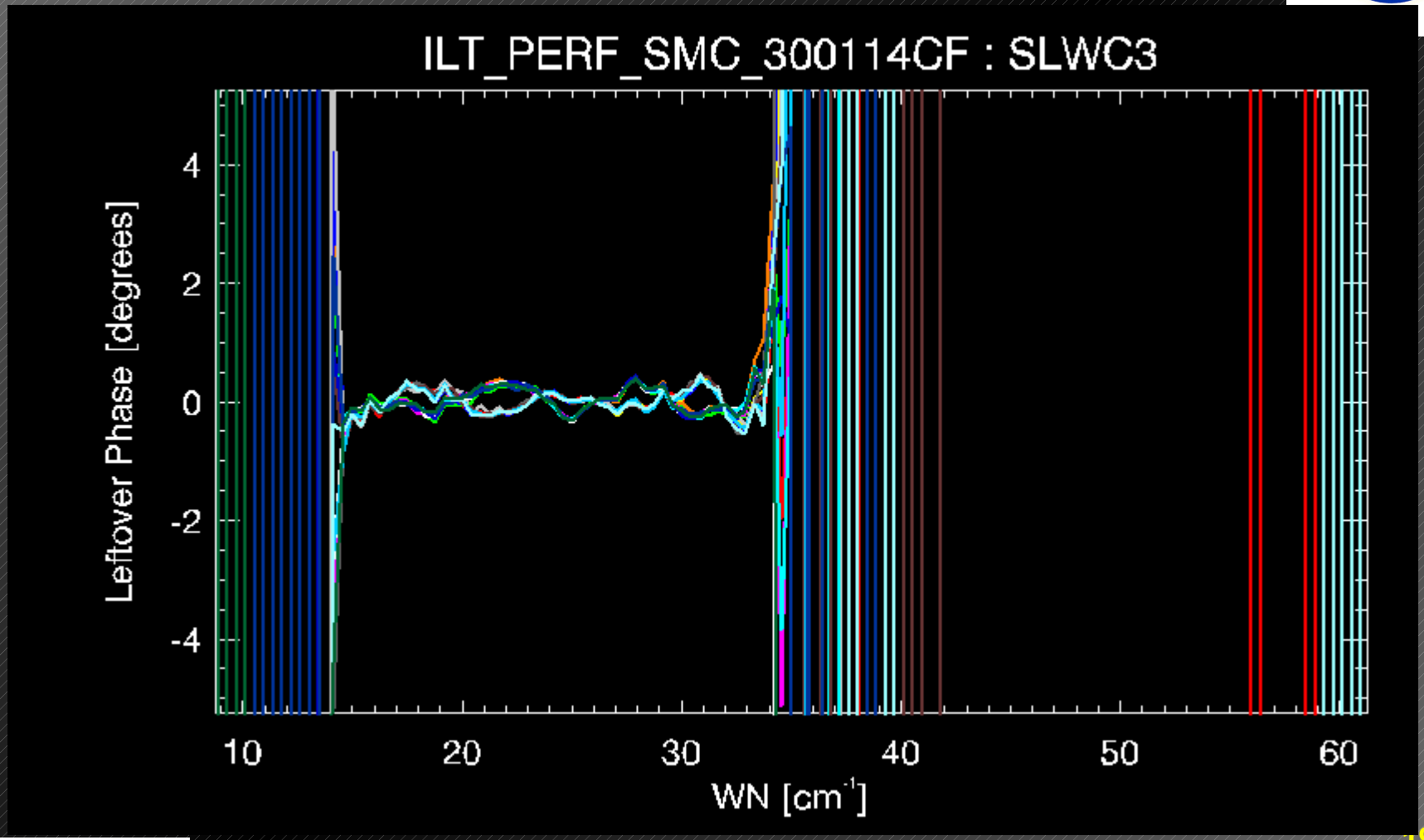


SPECTROSCOPY



This analysis derives not just the thermal time constant (and therefore the time domain phase), but the position of ZPD as well.


ILT_PERF_SMC_300114CF : SLWC3
Real/Imaginary Signal [adu/cm-1]
1000
800
600
400
200
0
10
20
30
40
50
60
WN [cm-1]


ILT_PERF_SMC_300114CF : SLWC3
Leftover Phase [degrees]
4
2
0
-2
-4
10
20
30
40
50
60
WN [cm-1]

Optical Phase

- The remaining phase term has been labelled as optical phase.
- It may be that this term is just a manifestation of the difference in the position of ZPD for the emitting elements
  ($ZPD_{Telescope} \neq ZPD_{SCAL2} \neq ZPD_{SCAL4}$)
- Proper correction for these elements may in fact remove this phase term.

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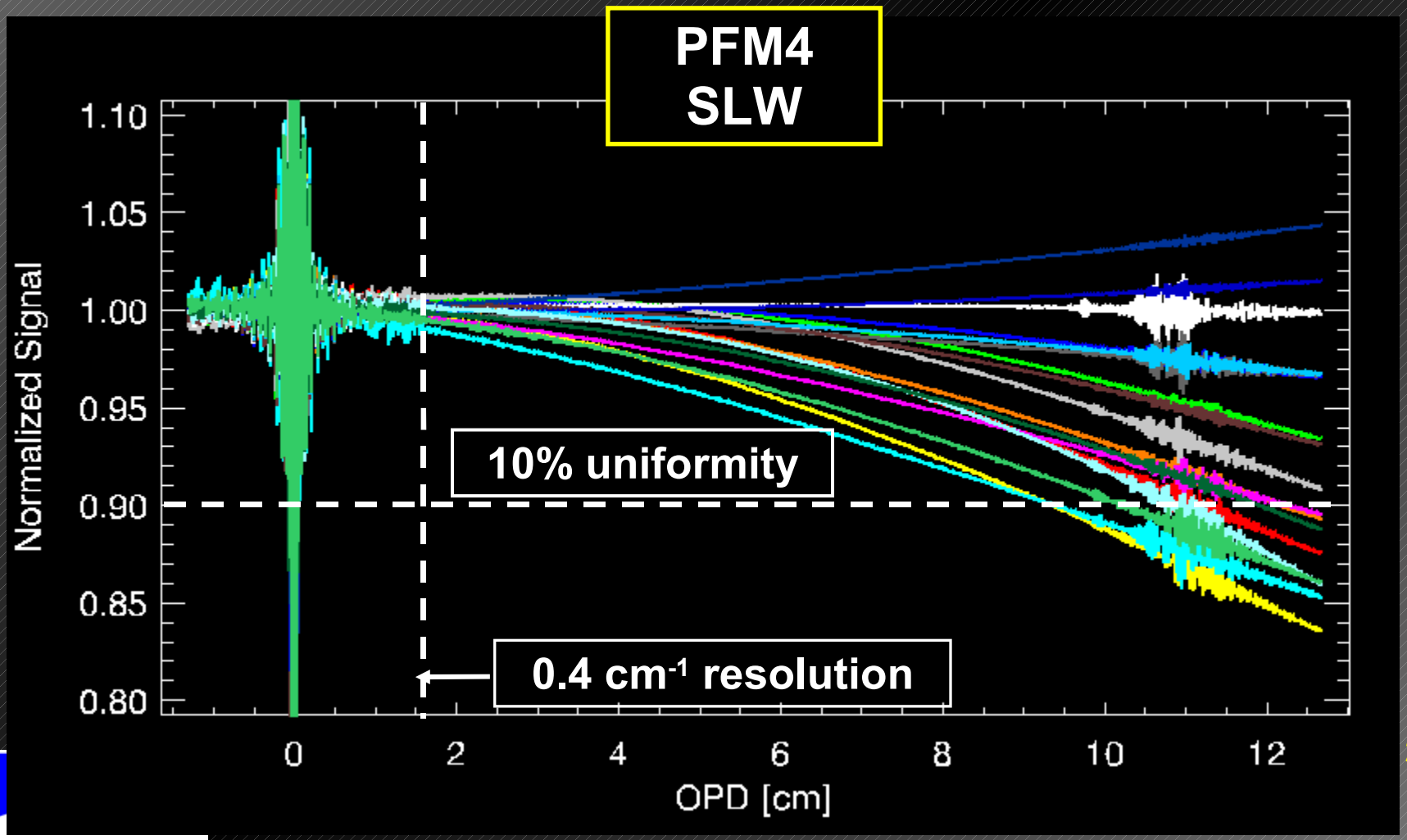
Vignetting

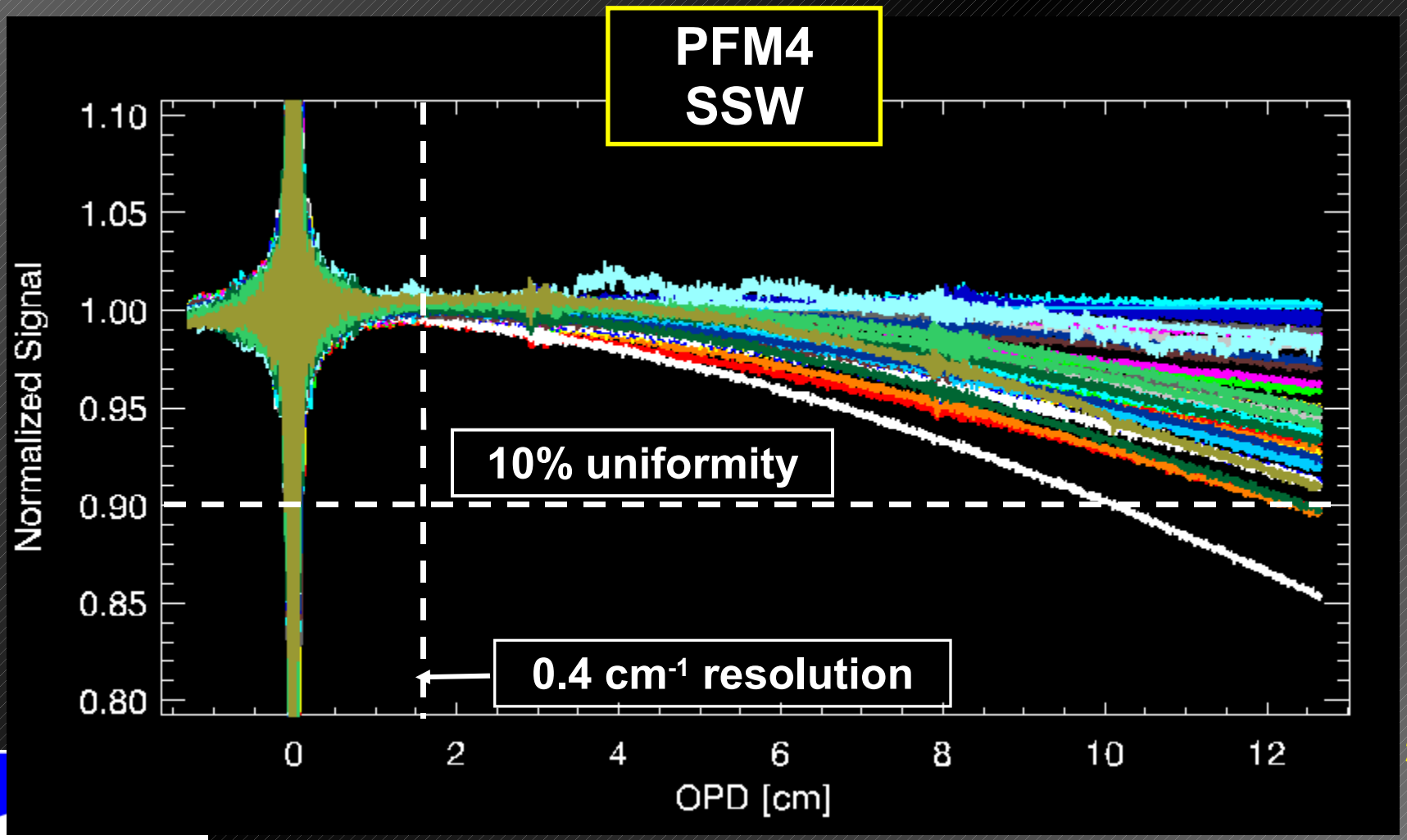
- Observed as a deviation in the baseline of the interferogram as OPD increases.
- The following slides show the vignetting for most pixels* of SLW and SSW for PFM1 and PFM3.

  (*Some of the pixels are not shown for clarity)

Vignetting


PFM4
SLW
1.10
1.05
1.00
0.95
0.90
0.85
0.80
Normalized Signal
10% uniformity
0.4 cm-1 resolution
0
2
4
6
8
10
12
OPD [cm]

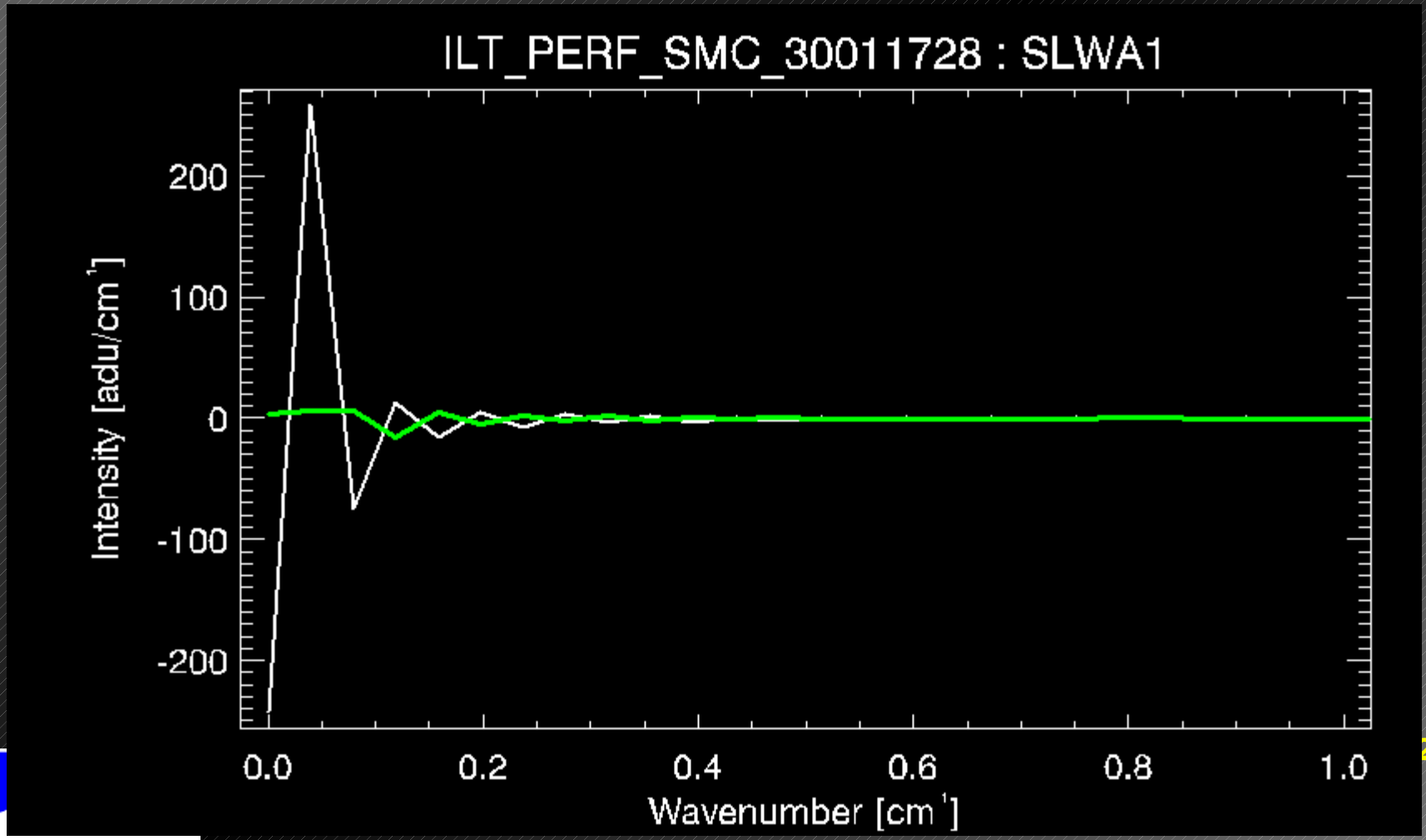
Vignetting


PFM4
SSW
1.10
1.05
1.00
0.95
0.90
0.85
0.80
Normalized Signal
10% uniformity
0.4 cm-1 resolution
0
2
4
6
8
10
12
OPD [cm]

Vignetting

- Vignetting curves observed during PFM4 are similar to those observed for PFM1 and PFM3.
- Analysis is currently being undertaken to determine the reproducibility of these curves on a channel-by-channel basis.
- If the results are promising, this effect can then be corrected for using the calibration information.

Vignetting


ILT_PERF_SMC_30011728 : SLWA1
Intensity [adu/cm^{-1}]
200
100
0
-100
-200
0.0
0.2
0.4
0.6
0.8
1.0
Wavenumber [cm^{-1}]

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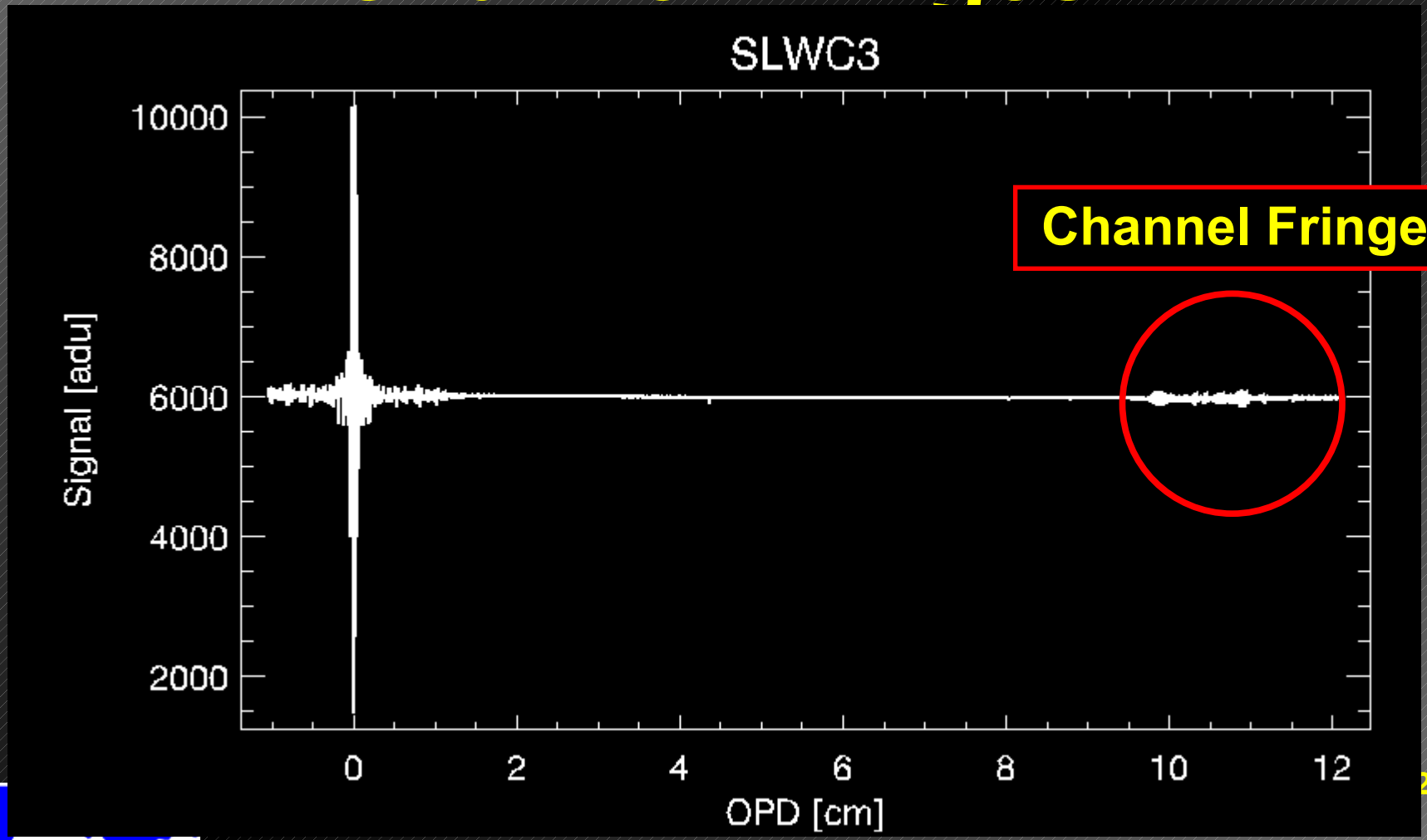
Channel Fringes



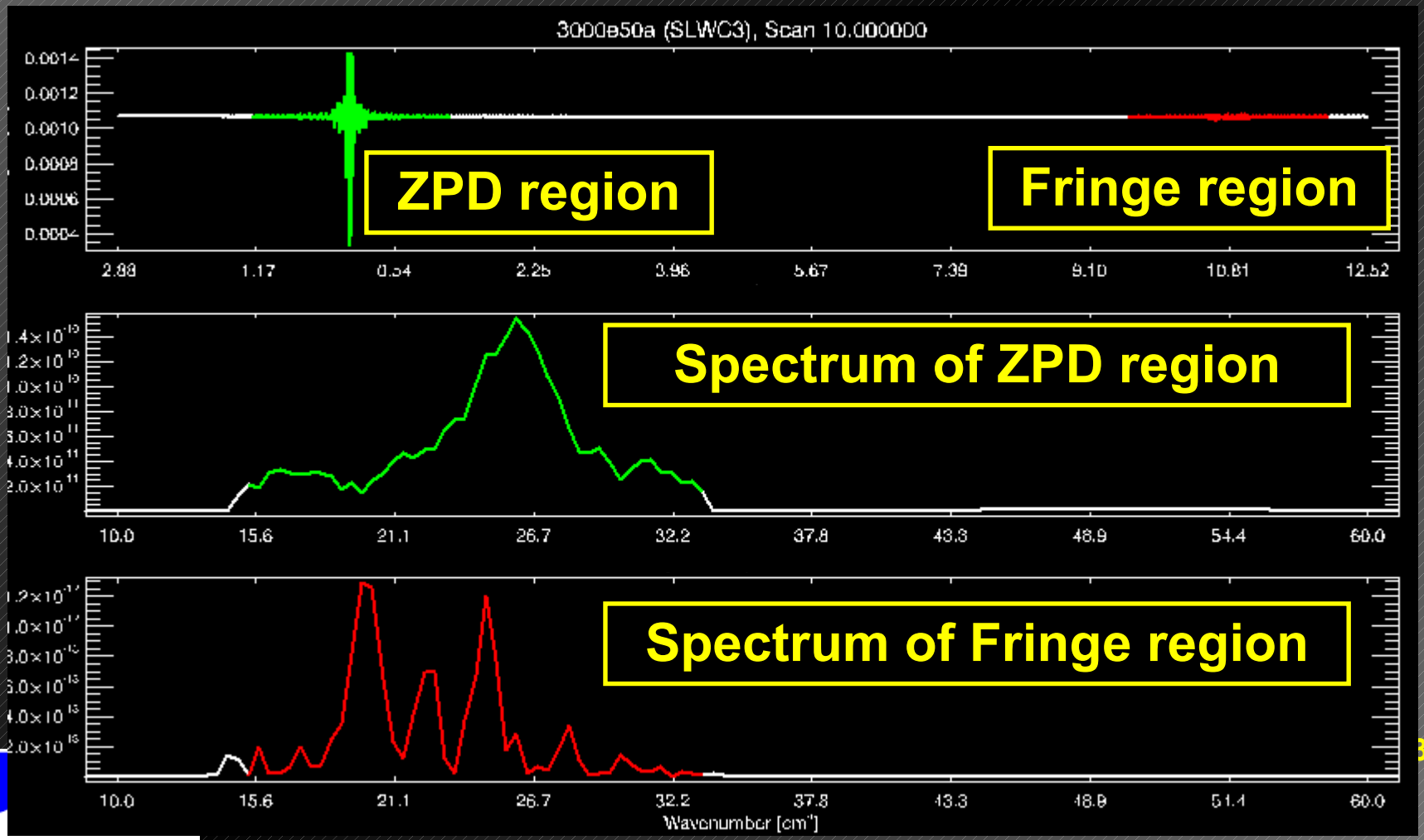
Channel Fringes

- The integrated in-band spectral power was determined for spectra derived from both the ZPD region and the fringe region.

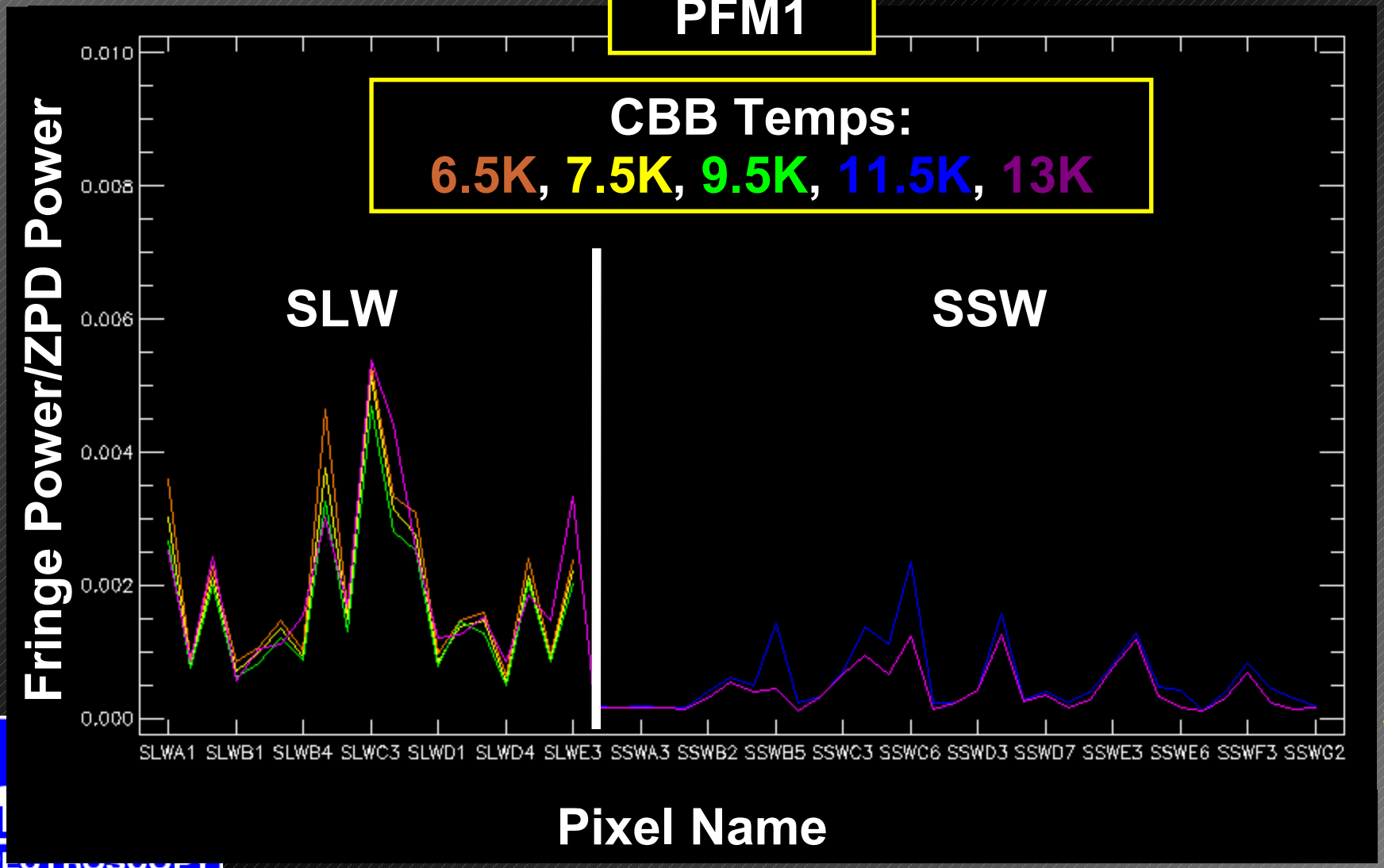
  Fringe region:

  - **SLW: 10.2 cm OPD**
  - **SSW: 7.8 cm OPD**
- The ratio of the integrated fringe power to the integrated ZPD power was used as a metric for the channel fringes and allowed a comparison to be drawn between PFM1 and PFM3.

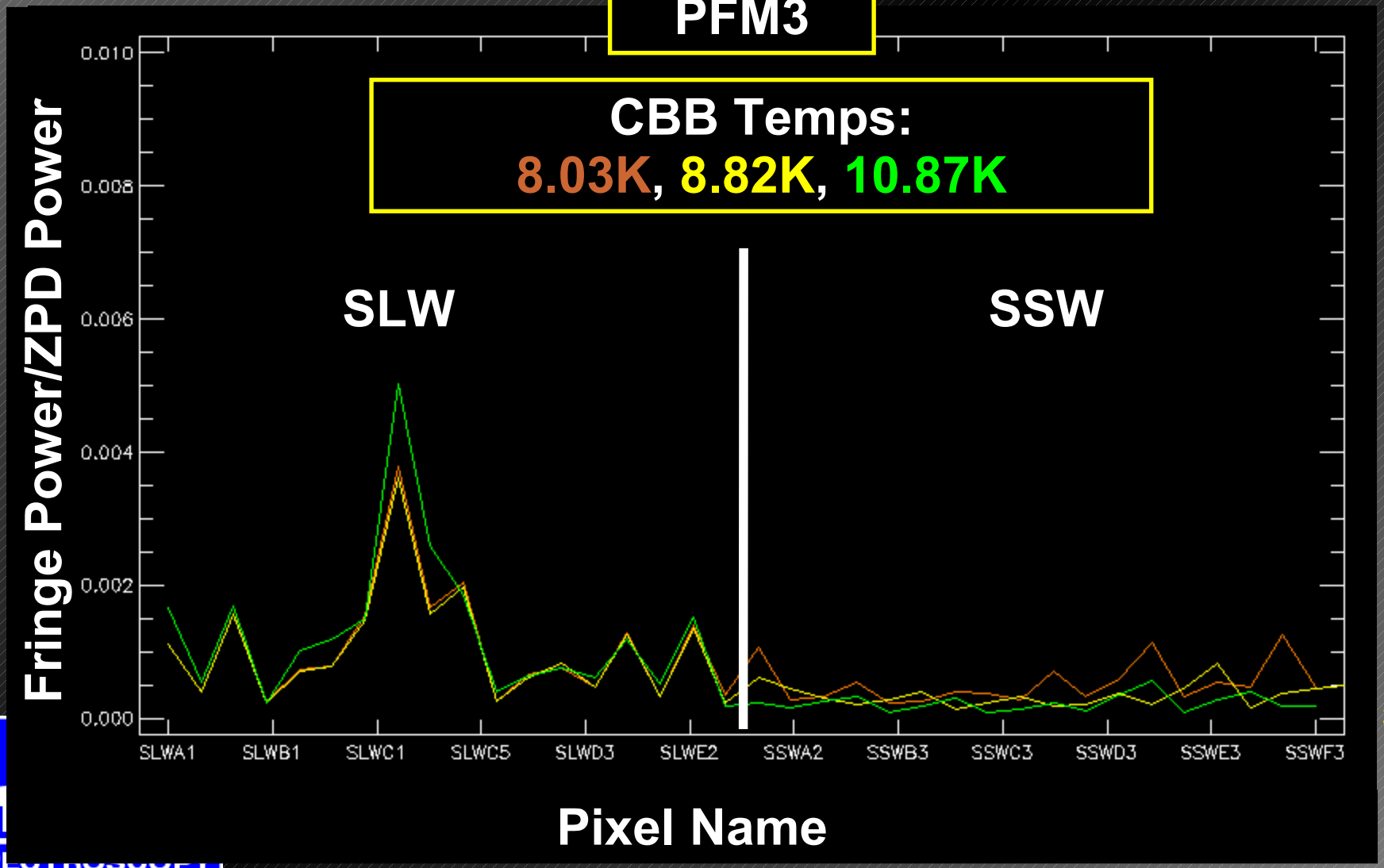
Channel Fringes



Channel Fringes



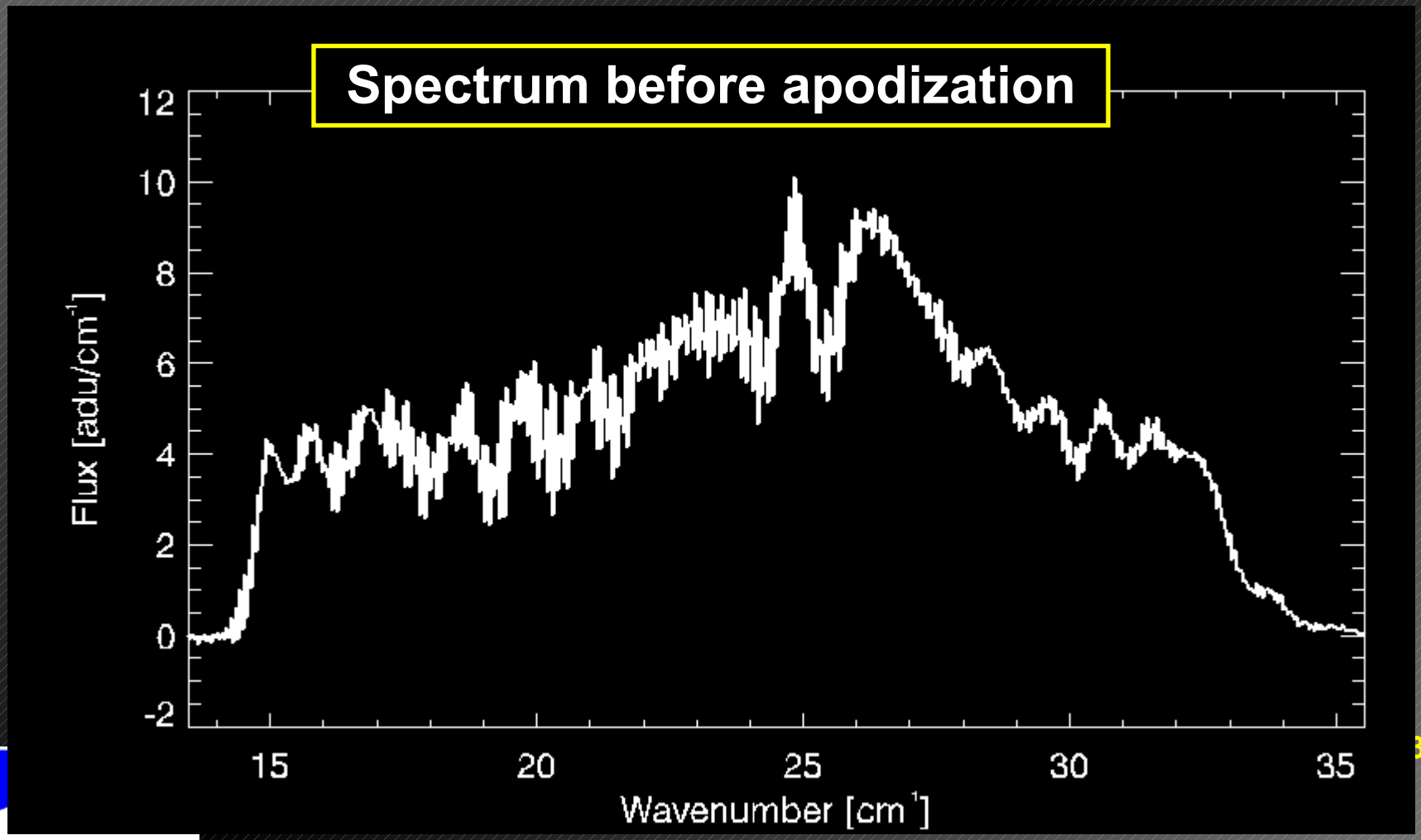
Channel Fringes



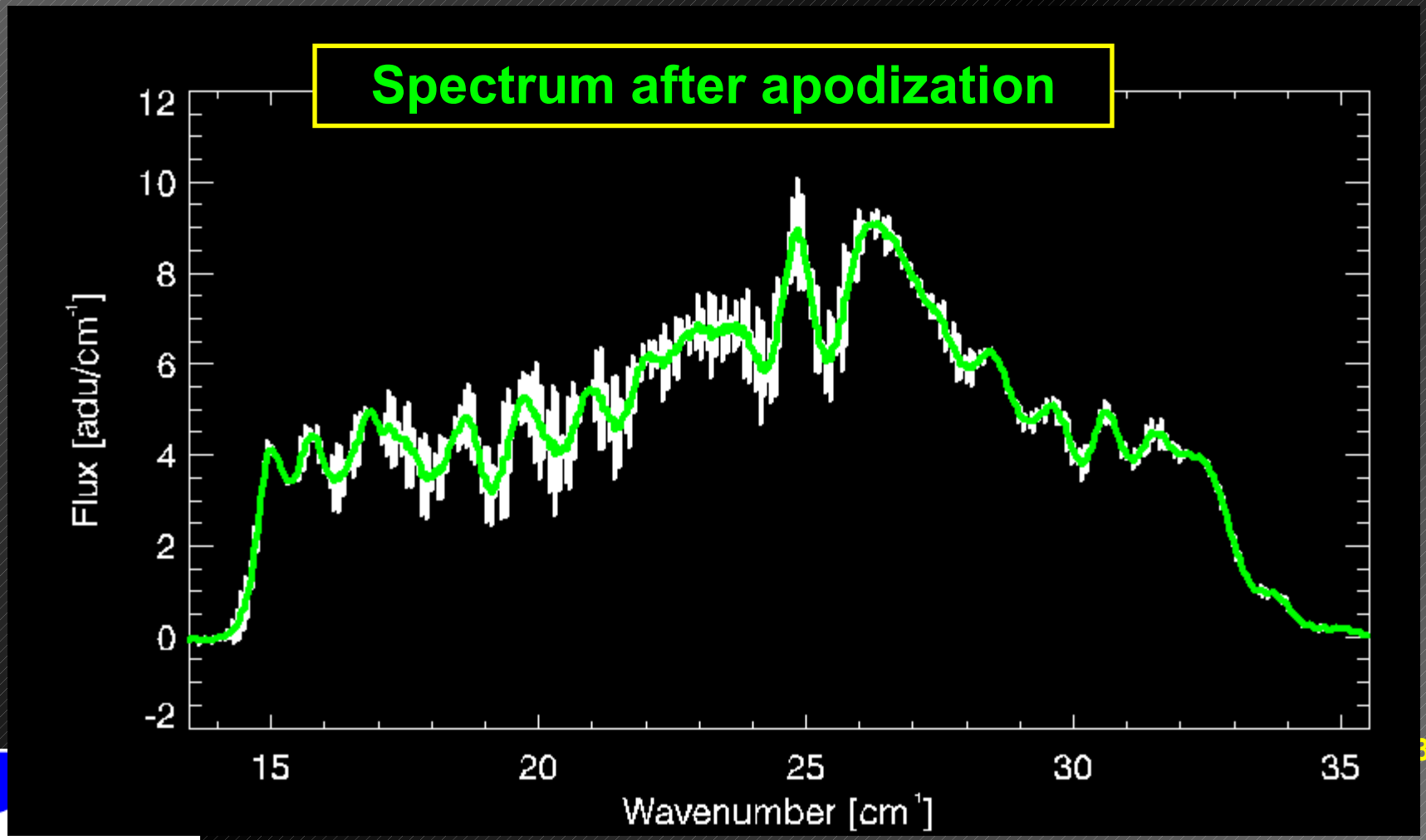
Channel Fringe Removal

- Apodization has been proposed as a method by which the channel fringe features could be removed from the measured interferograms.
- This technique involves multiplying the measured interferogram by a tapering function.
- The cost of this method is a reduction in the spectral resolution.

Channel Fringes



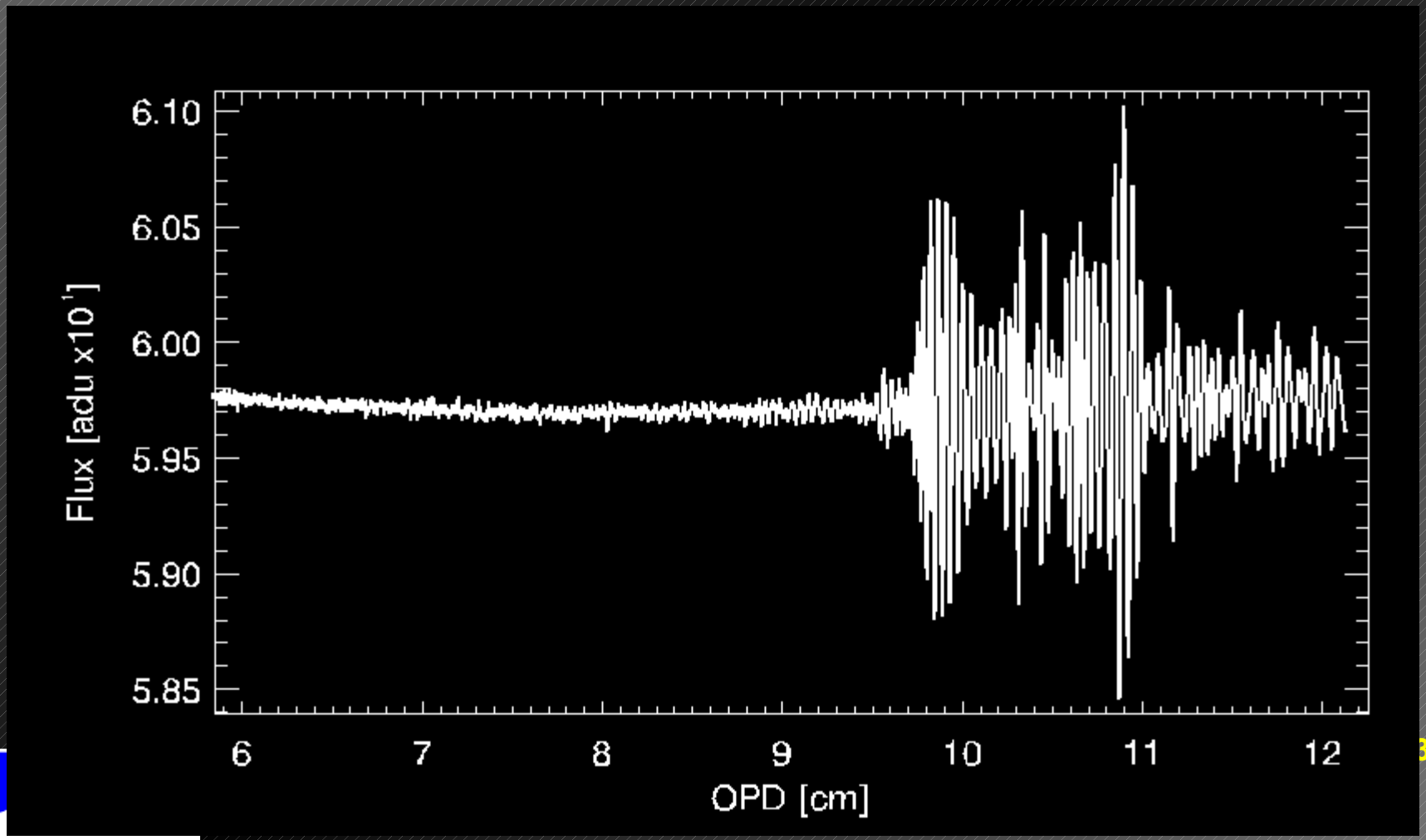
Channel Fringes



Channel Fringe Removal

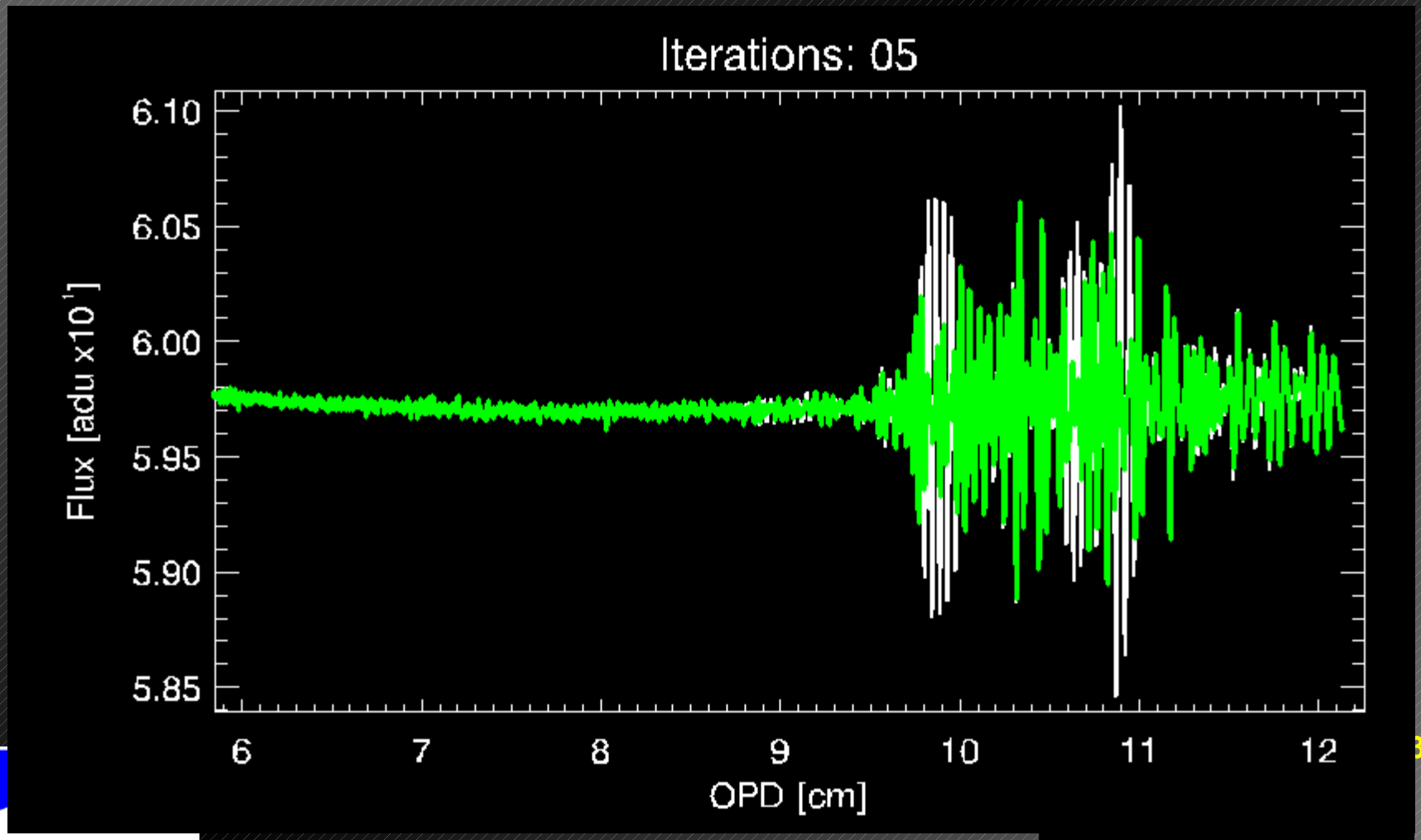
- It has been argued that the source of the channel fringes is a reflection of the incoming radiation by the field lenses situated at the front of the BDAs.
- It might therefore be expected that the fringe signal would be some form of copy of the signal in the region near ZPD.
- The current study focuses on fringe removal by subtraction of a scaled copy(ies) of the signal near ZPD.

Channel Fringes



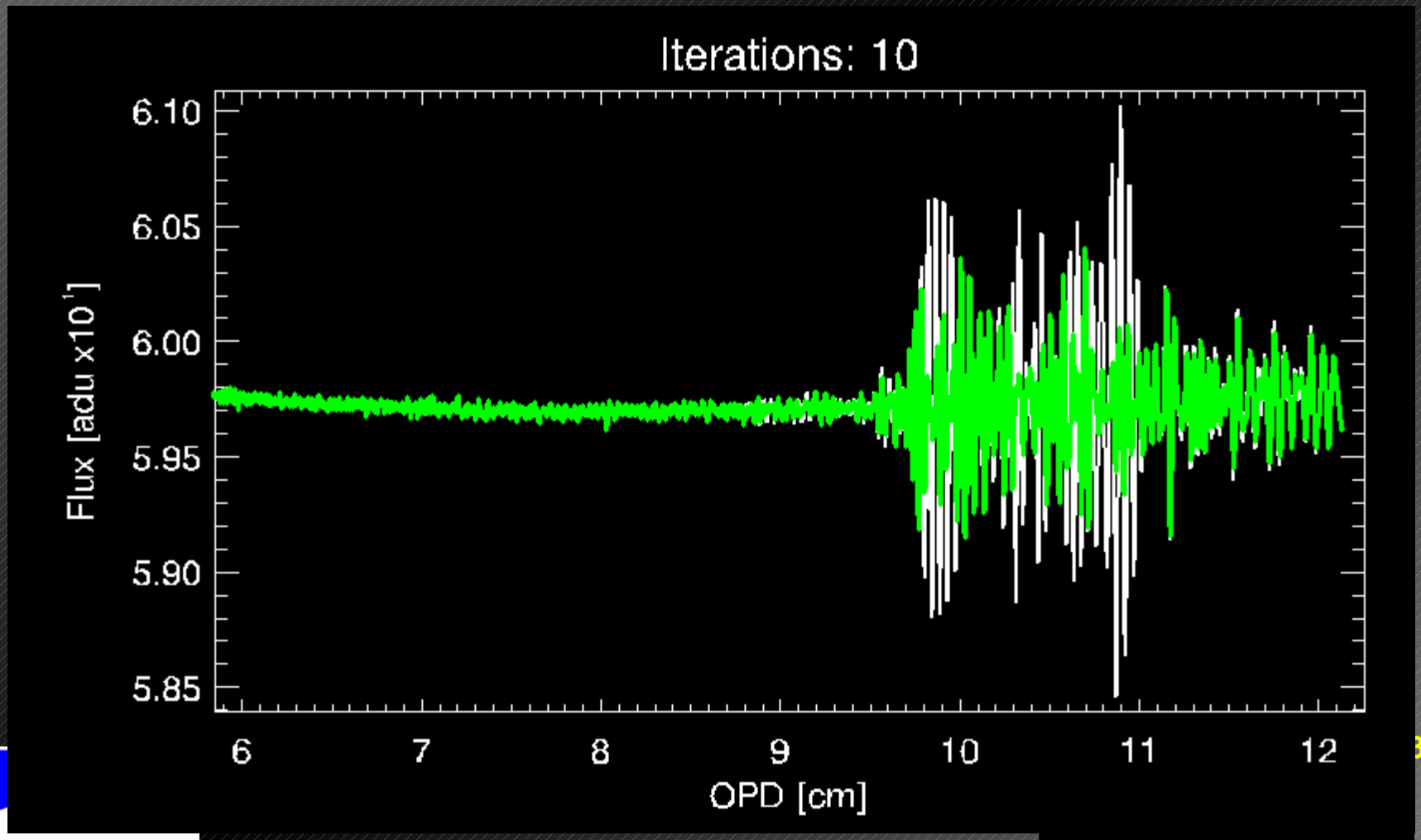
BLUE SKY SPECTROSCOPY

Channel Fringes



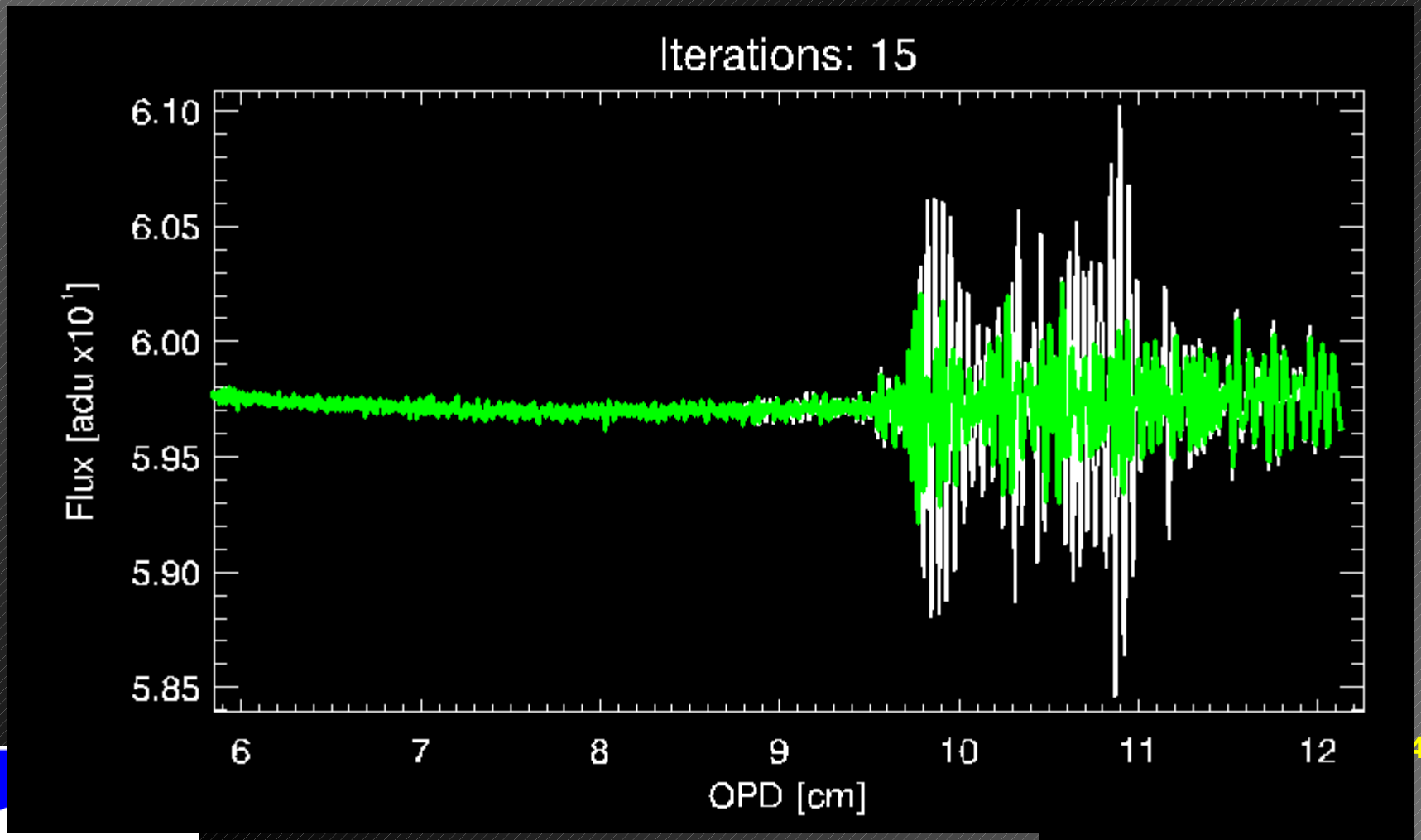
Rao, 2007

Channel Fringes



Rao, 2007

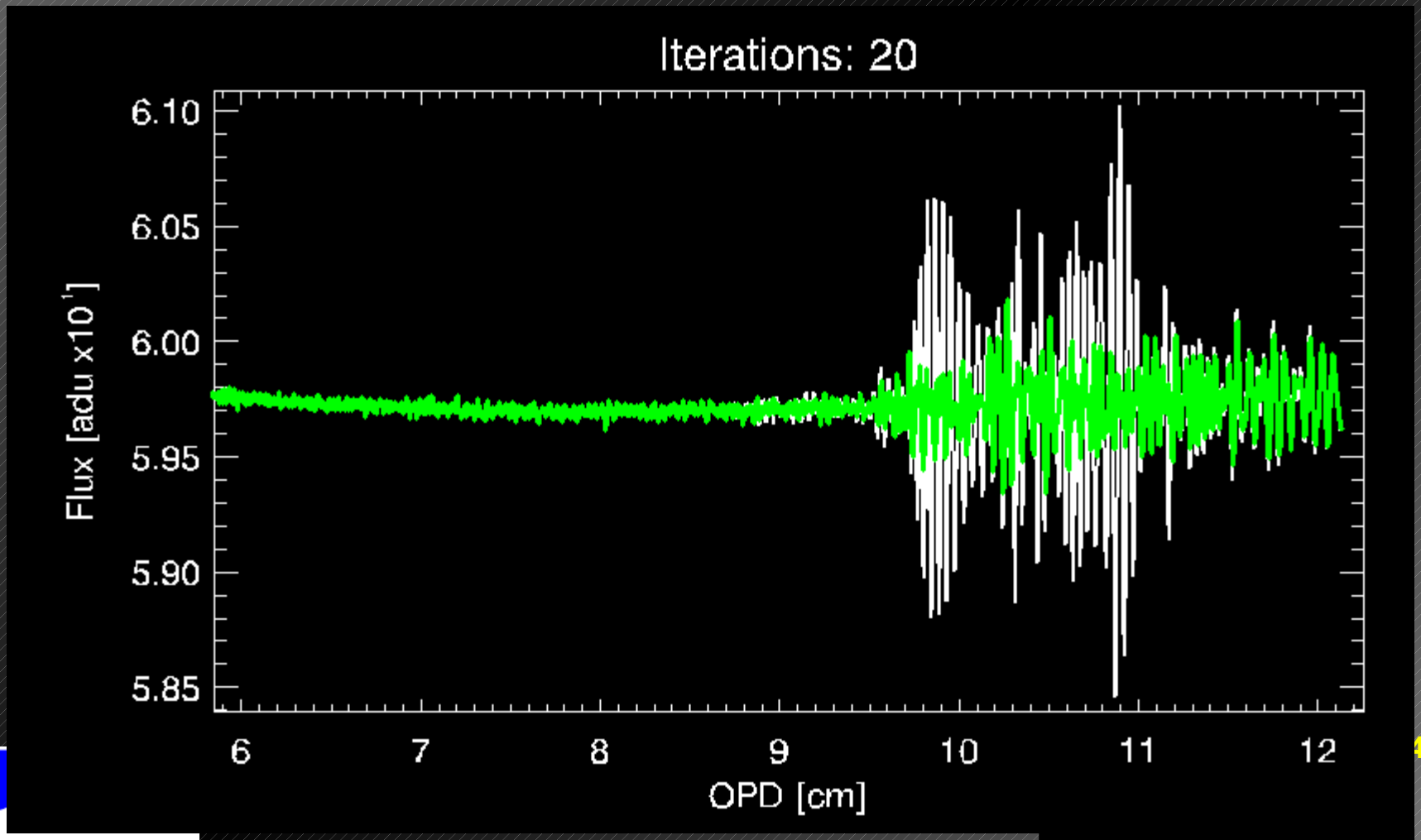
Channel Fringes



Rao, 2007

BLUE SKY SPECTROSCOPY

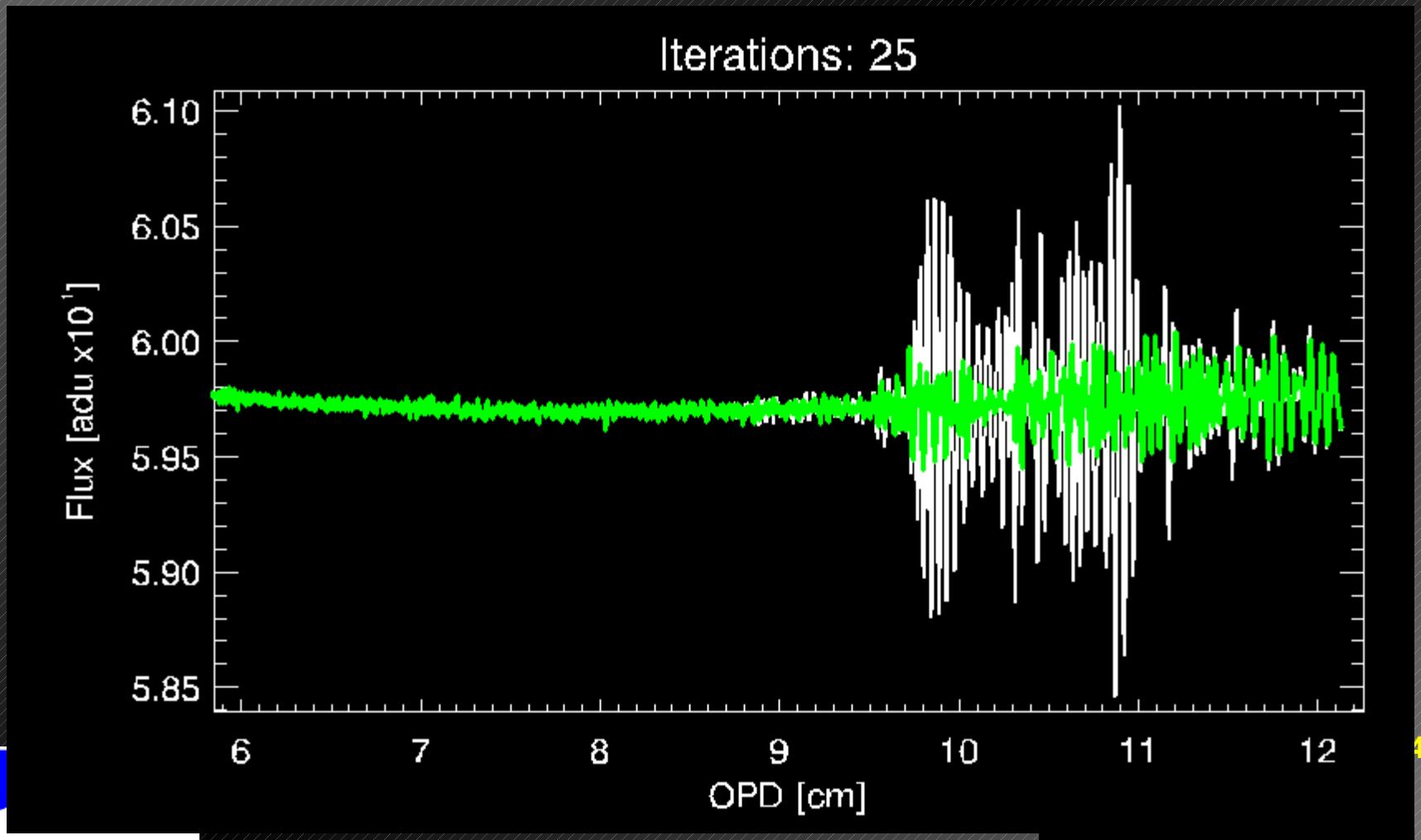
Channel Fringes



Rao, 2007

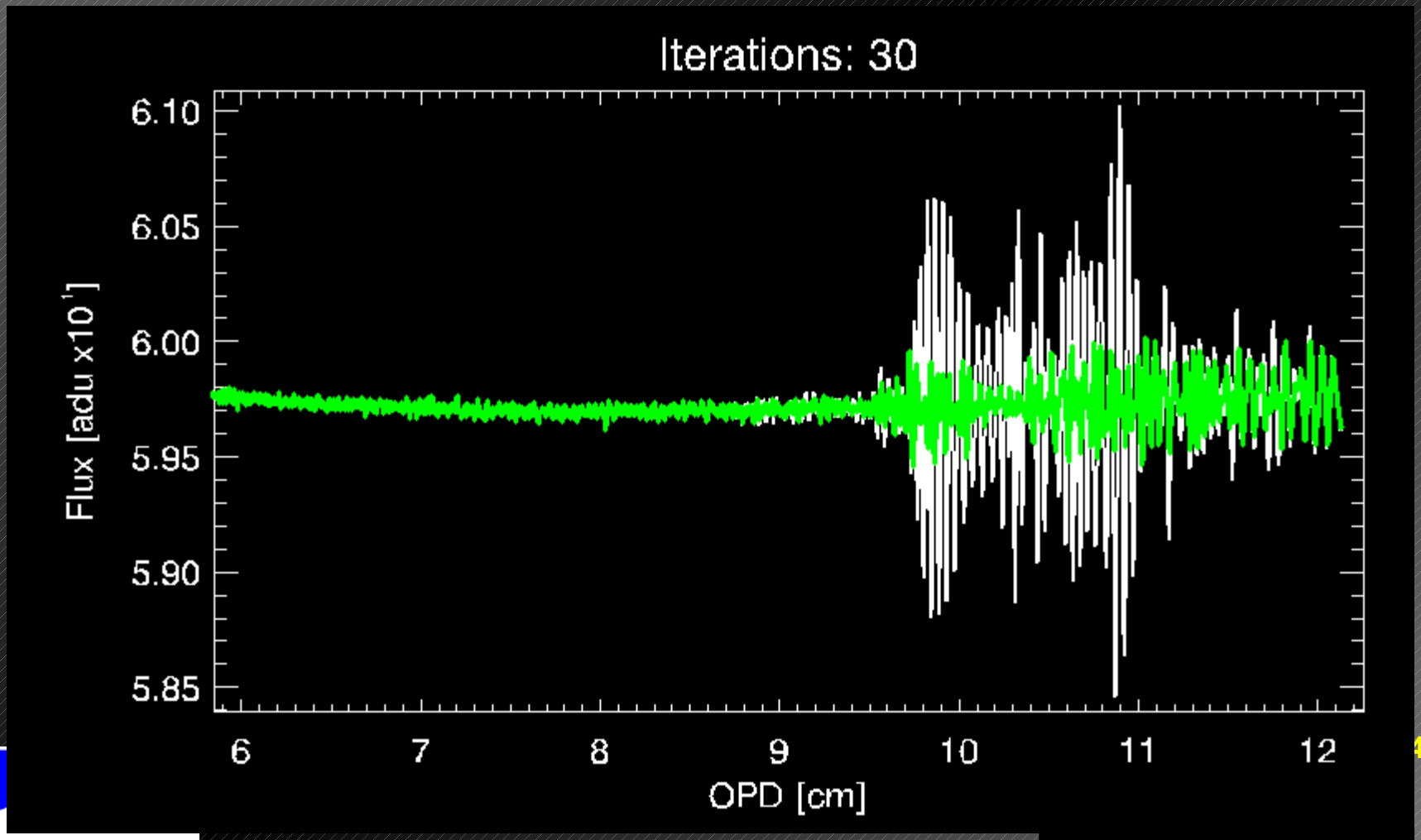
BLUE SKY SPECTROSCOPY

Channel Fringes



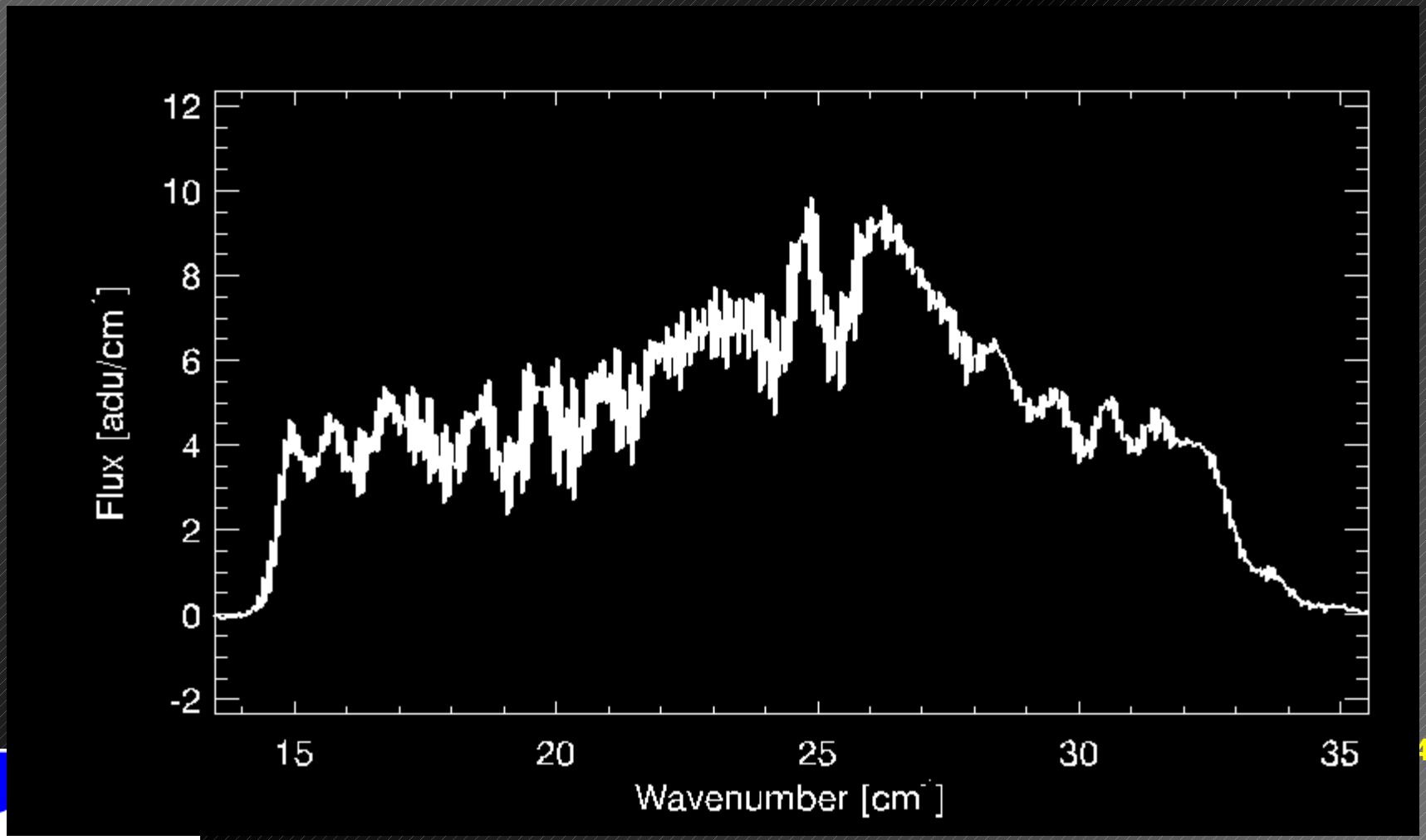
Rao, 2007

Channel Fringes



Rao, 2007

Channel Fringes



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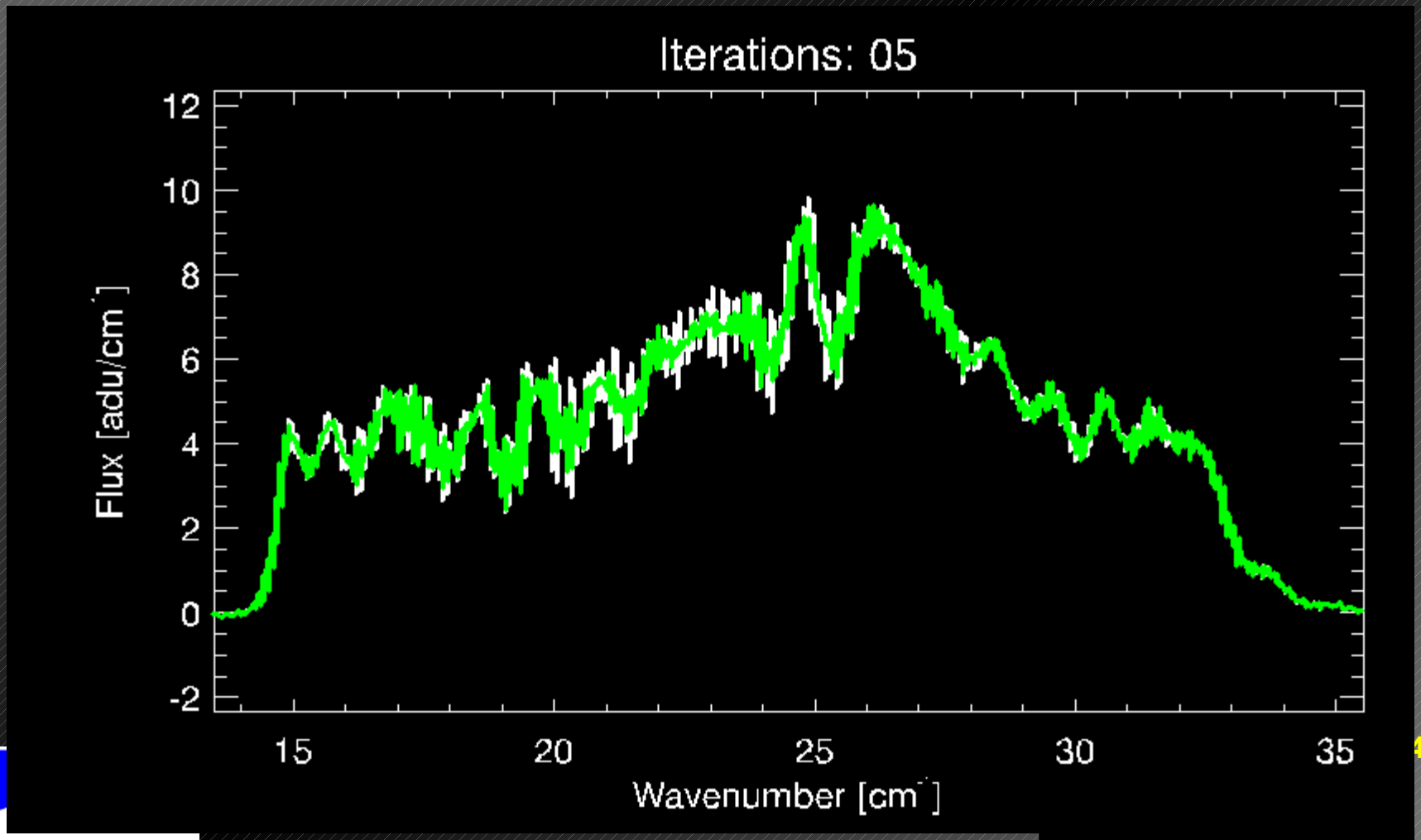
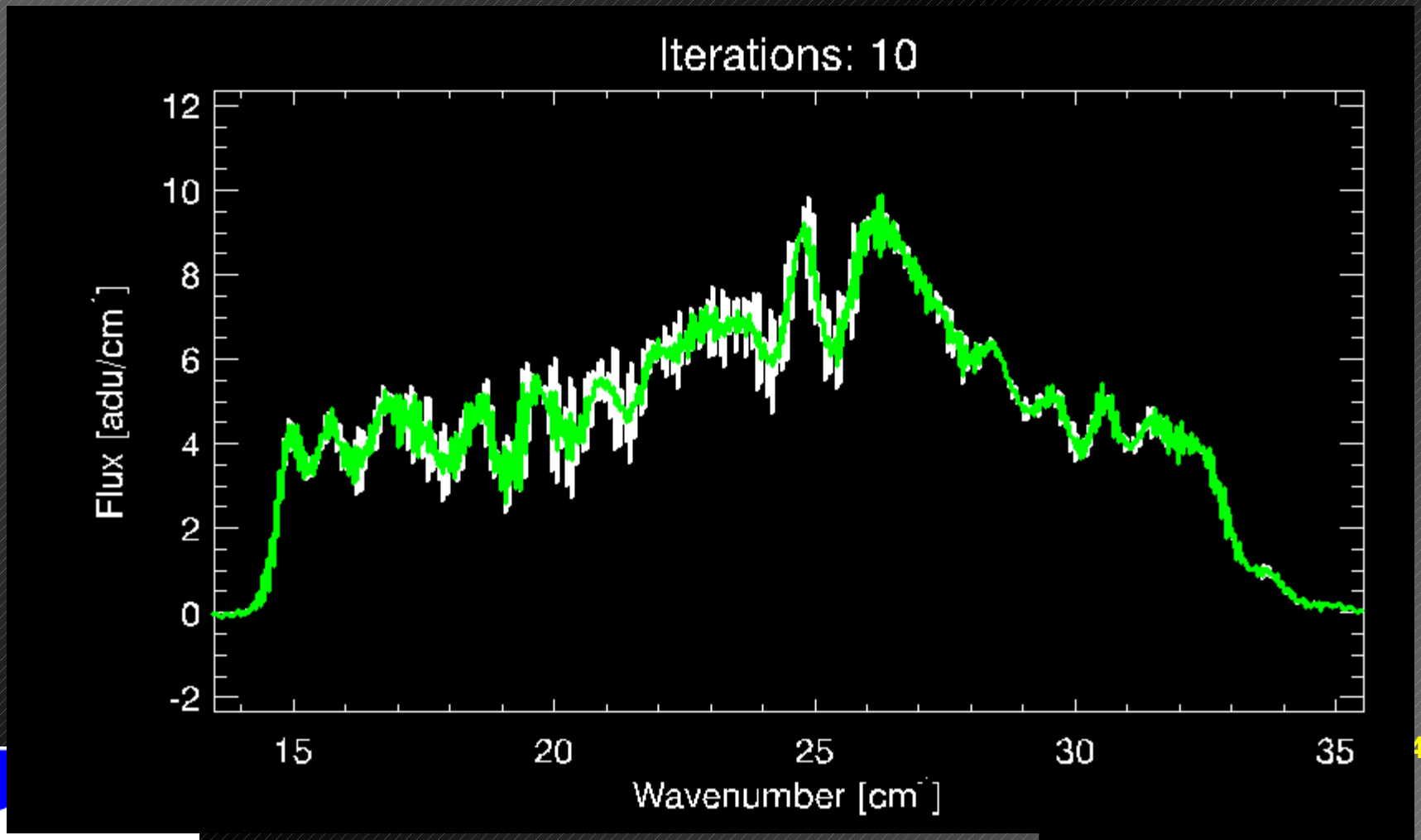
Channel Fringes



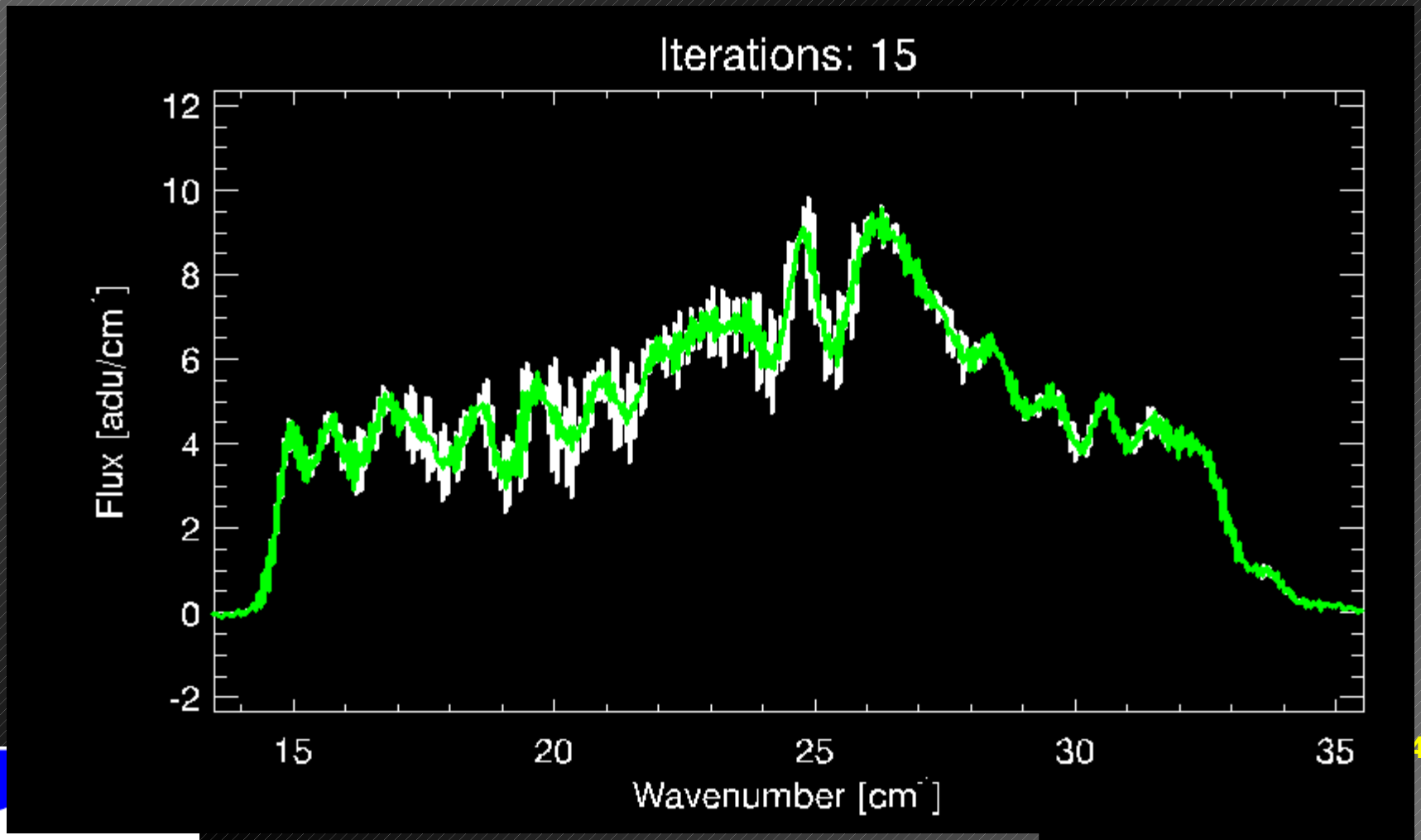
Rao, 2007

Channel Fringes



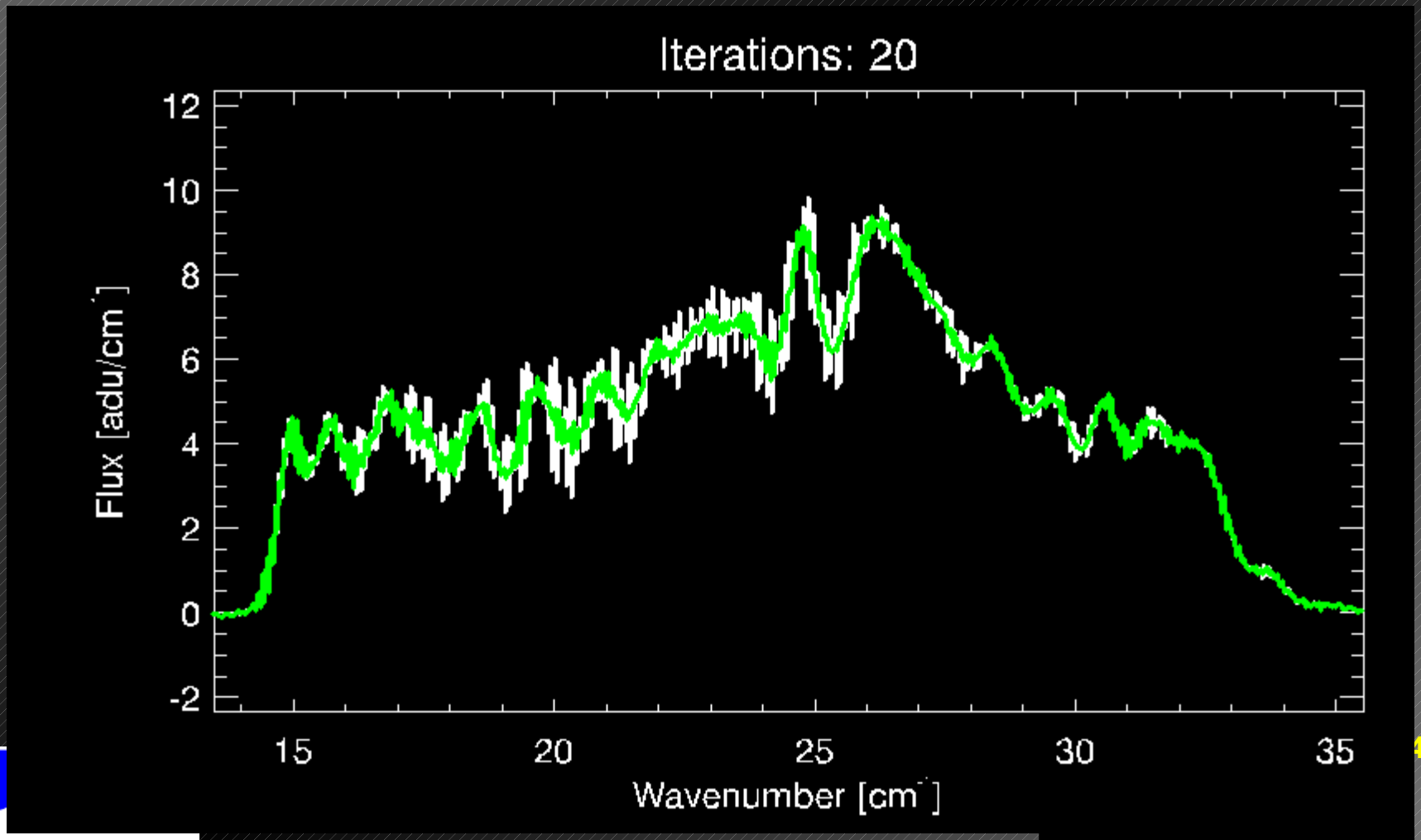
Rao, 2007

Channel Fringes



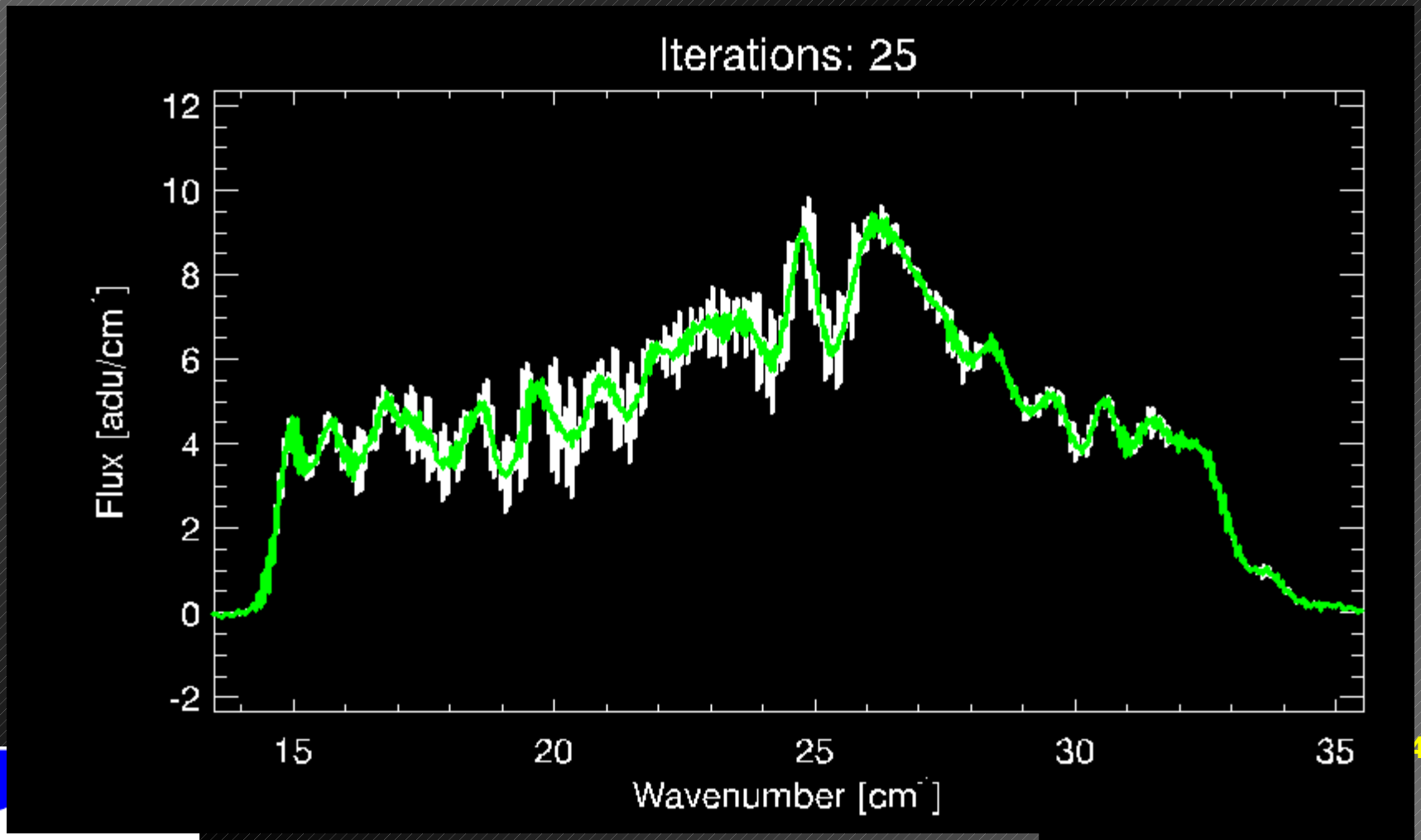
Rao, 2007

Channel Fringes



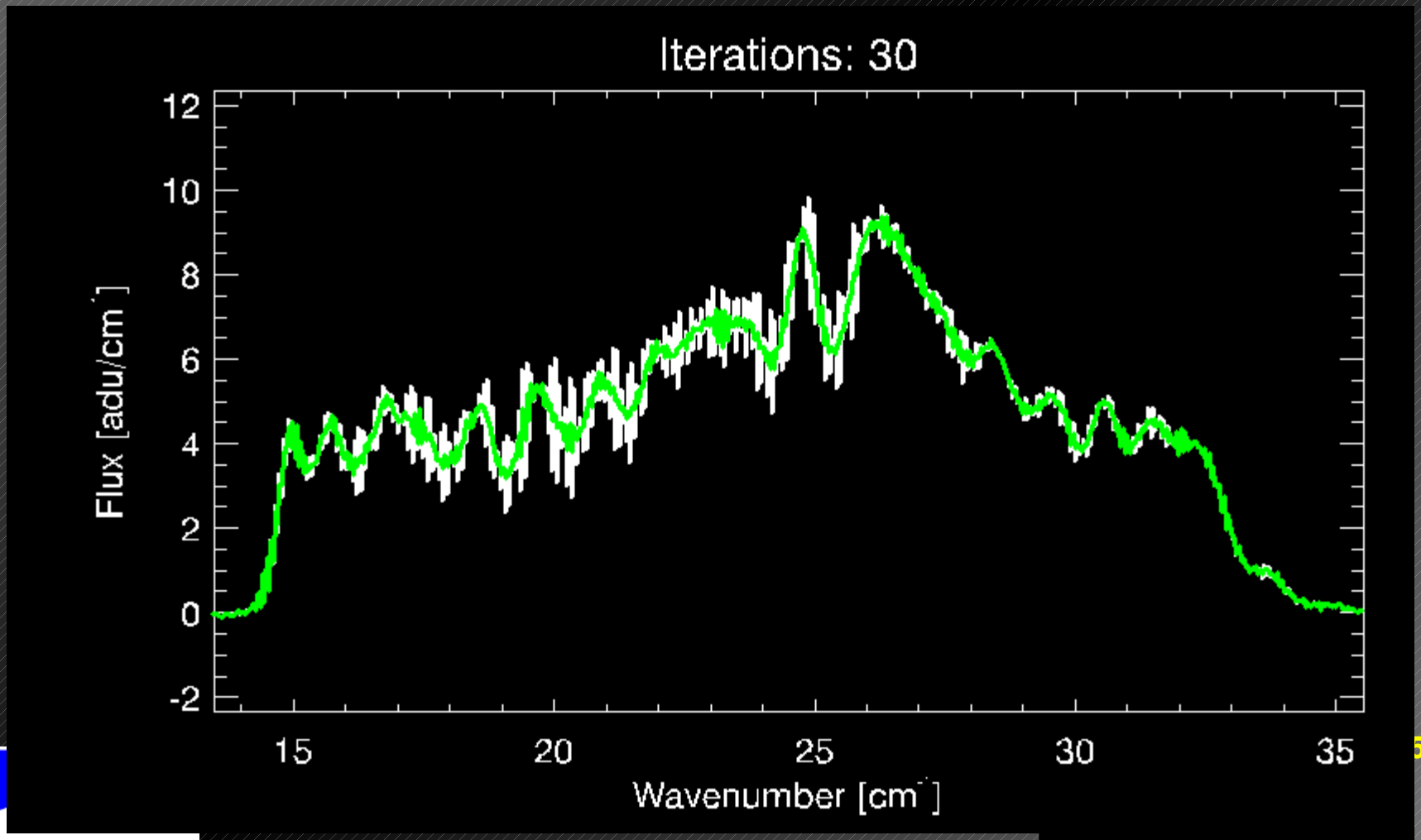
Rao, 2007

Channel Fringes



Rao, 2007

Channel Fringes



Rao, 2007

Channel Fringe Removal

- The initial results of this new fringe removal algorithm are promising.
- Further improvements in terms of the optimal number of iterations, and shifting the samples of the scaled copies are under development.

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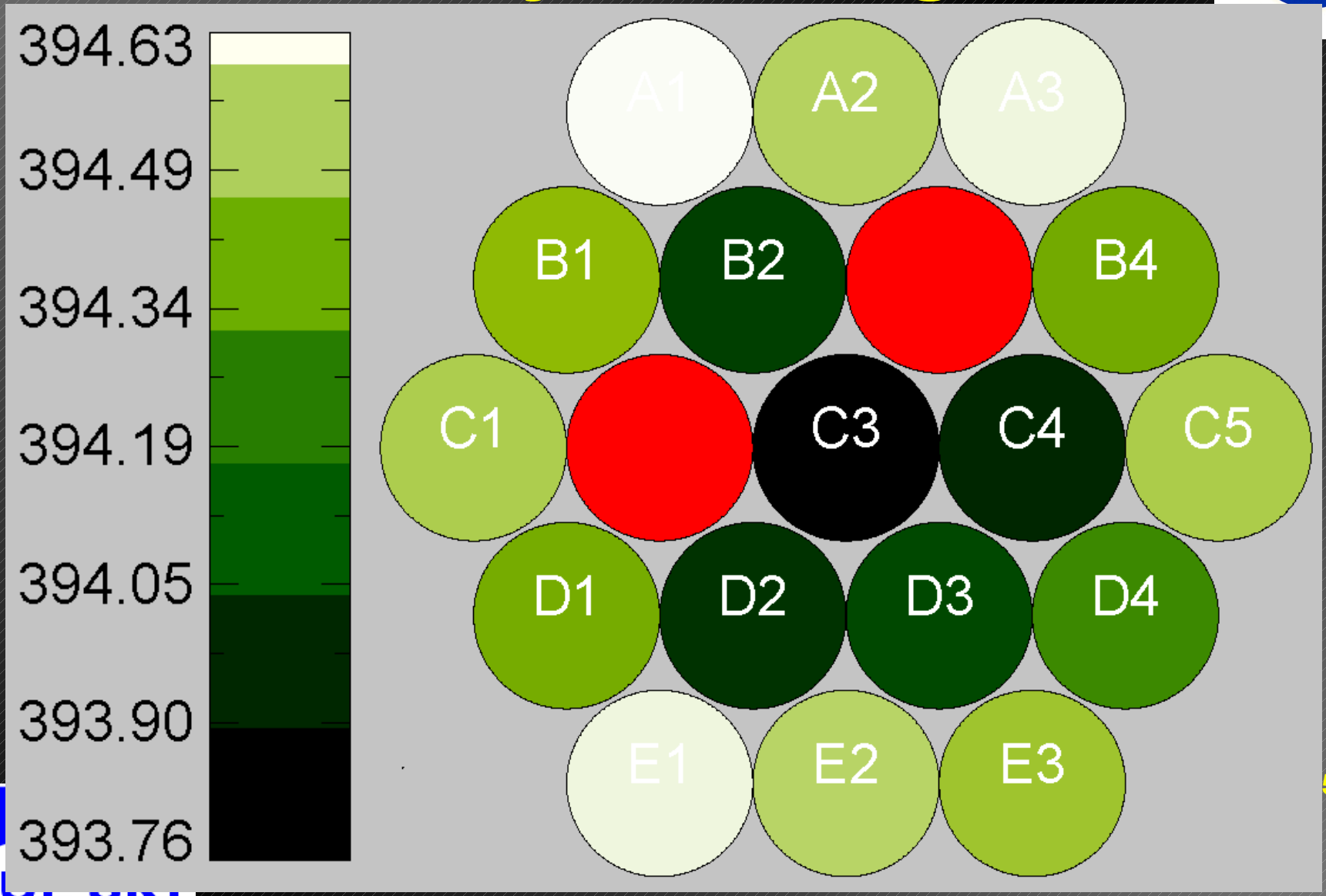
Laser Line Analysis

- An analysis of the laser line observations from PFM4 was undertaken in order to determine spectral resolutions, modulation efficiencies, and line centres.
- A fitting function was then applied to the laser spectrum or interferogram to derive the laser line parameters for each pixel for a given observation.

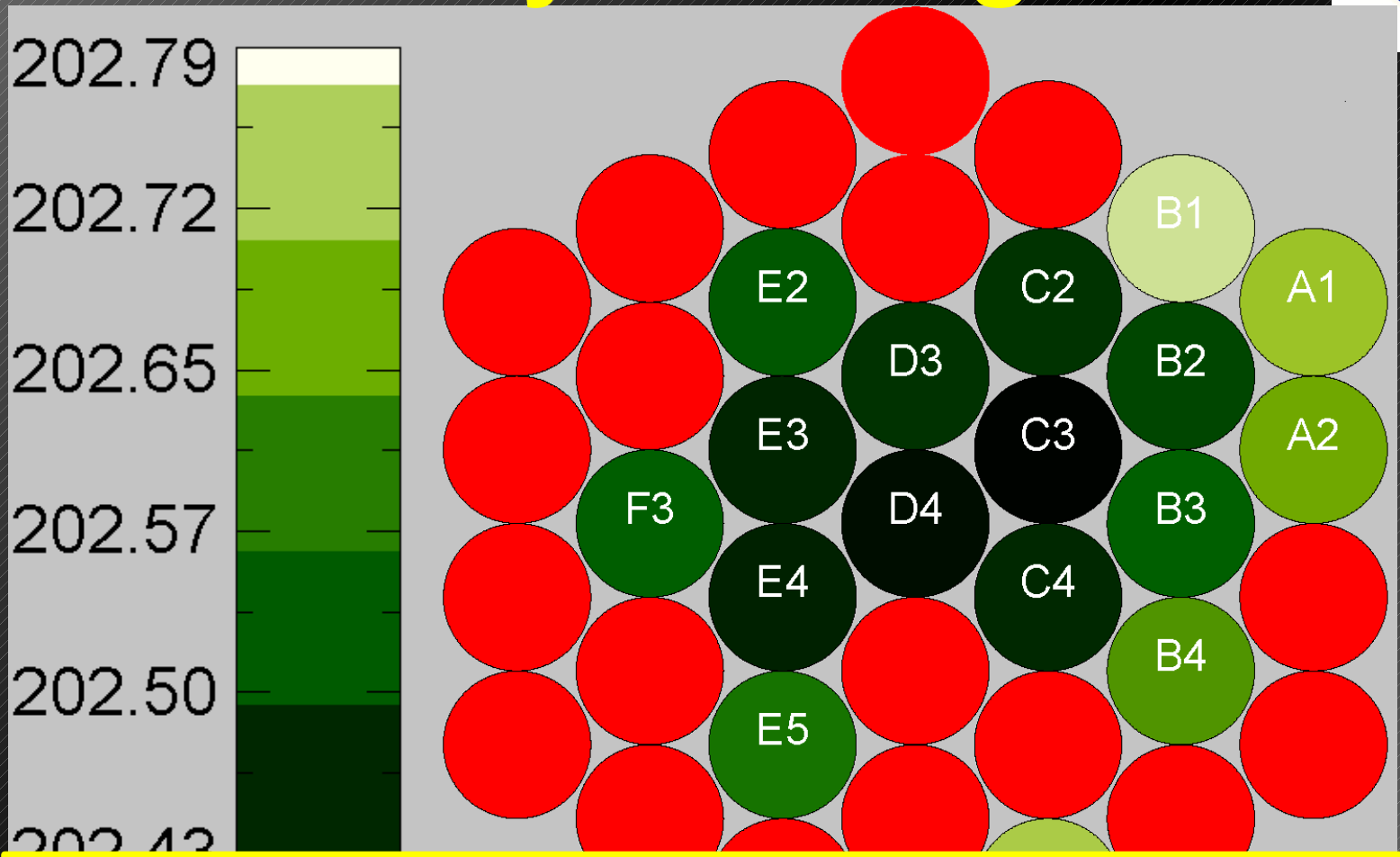
PFM4 Laser Observations

Observation	Laser Source [μm]	Target Pixel
ILT_PERF_SMC_3001178E	393.63	SLWC3
ILT_PERF_SMC_3001178C	393.63	SLWC5
ILT_PERF_SMC_30011785	393.63	SLWD2
ILT_PERF_SMC_30011787	393.63	SLWE2
ILT_PERF_SMC_30011789	393.63	SLWE2
ILT_PERF_SMC_3001177A	393.63	SLWC3
ILT_PERF_SMC_30011792	393.63	SLWC3
ILT_PERF_SMC_300117ED	202.38	SSWD4
ILT_PERF_SMC_300117EE	202.38	SSWD4

Array Coverage



Array Coverage



The pixels shown in red indicate either dead channels or channels for which the laser signal was of poor quality

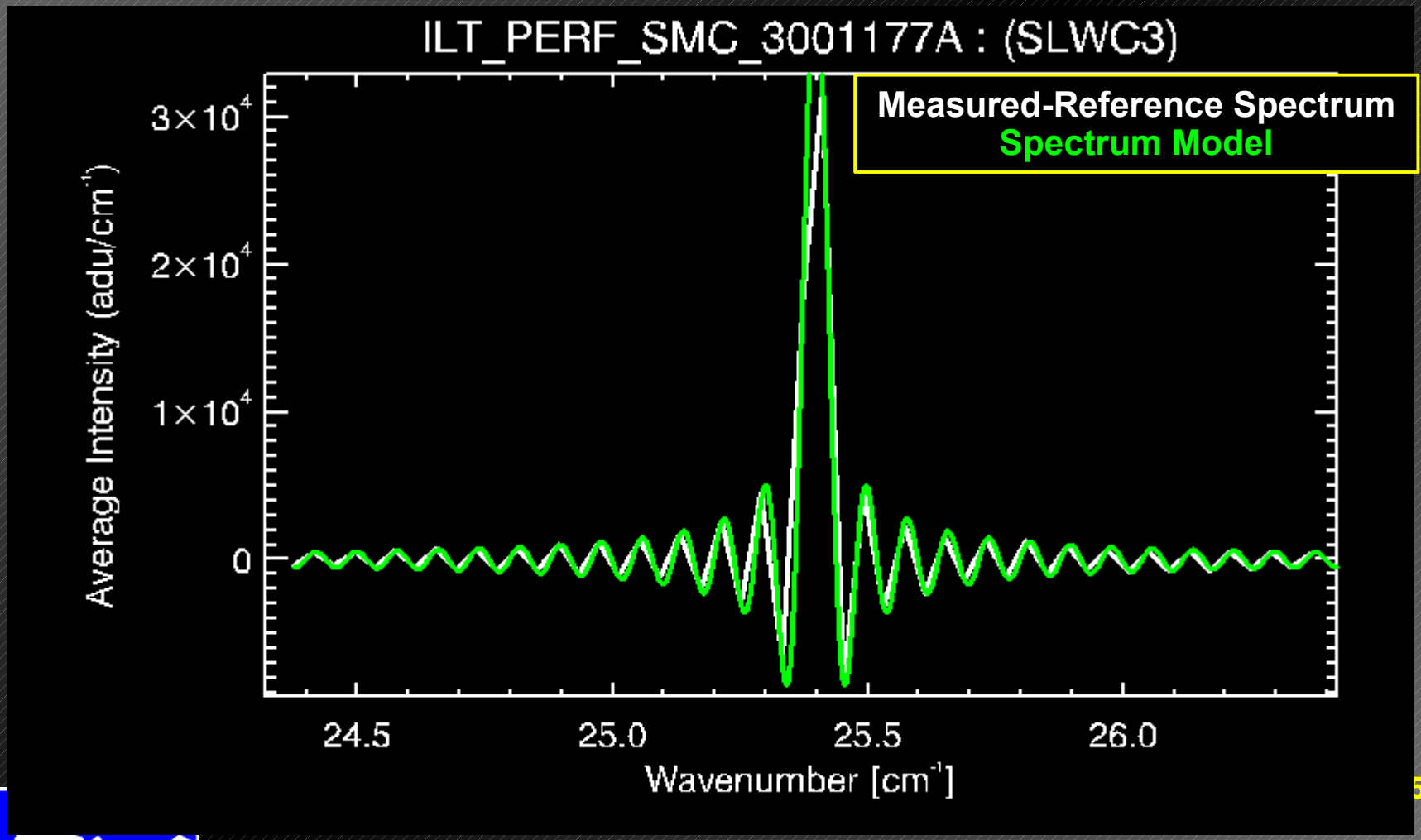
Laser Line Models

- A model of the form:

$$Spectral\ Model = A \frac{\sin\left(\frac{\sigma - \sigma_c}{\Delta\sigma}\right)}{\frac{\sigma - \sigma_c}{\Delta\sigma}}$$

was fit to each measured spectrum. From this model, the measured line centre, σ_c, and resolution, $\Delta\sigma$, were determined.

Laser Line Models



Spectral Resolution

- From the fit to the model .

Observation	Target Pixel	Line Centre [cm^{-1}]	Resolution [cm^{-1}]
ILT_PERF_SMC_3001178E	SLWC3	25.3990 ± 0.0035	0.0407 ± 0.0078
ILT_PERF_SMC_3001178C	SLWC5	25.3566 ± 0.0083	0.0404 ± 0.0096
ILT_PERF_SMC_30011785	SLWD2	25.3792 ± 0.0031	0.0407 ± 0.0044
ILT_PERF_SMC_30011787	SLWE2	25.3501 ± 0.0079	0.0416 ± 0.0016
ILT_PERF_SMC_30011789	SLWE2	25.3495 ± 0.0032	0.0438 ± 0.0027
ILT_PERF_SMC_3001177A	SLWC3	25.3975 ± 0.0011	0.0400 ± 0.0029
ILT_PERF_SMC_30011792	SLWC3	25.3969 ± 0.0015	0.0401 ± 0.0017
ILT_PERF_SMC_300117ED	SSWD4	49.4123 ± 0.0035	0.0400 ± 0.0010
ILT_PERF_SMC_300117EE	SSWD4	49.4120 ± 0.0053	0.0401 ± 0.0010

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Modulation Efficiency

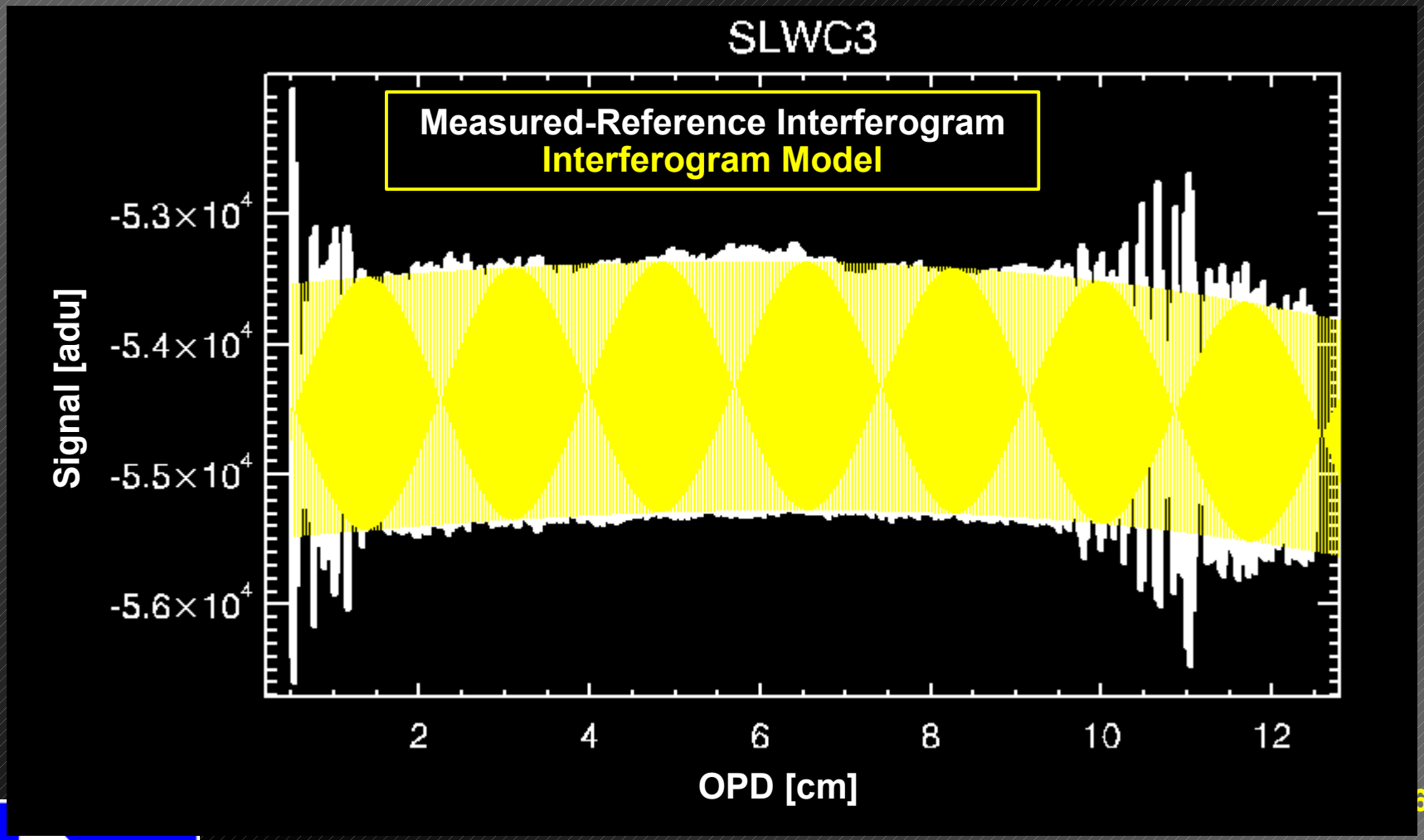
- A model of the form:

$$Interferogram\ Model = A\cos(bx)\cos(2\pi\sigma_c x + \phi)$$

was fit to the interferograms of the target pixel for each observation. The purpose of this model was to verify the fitted line centre from the spectrum model and to attempt to determine the modulation efficiency.

- **NB**: Modulation efficiency was derived for only the target pixels.

Modulation Efficiency



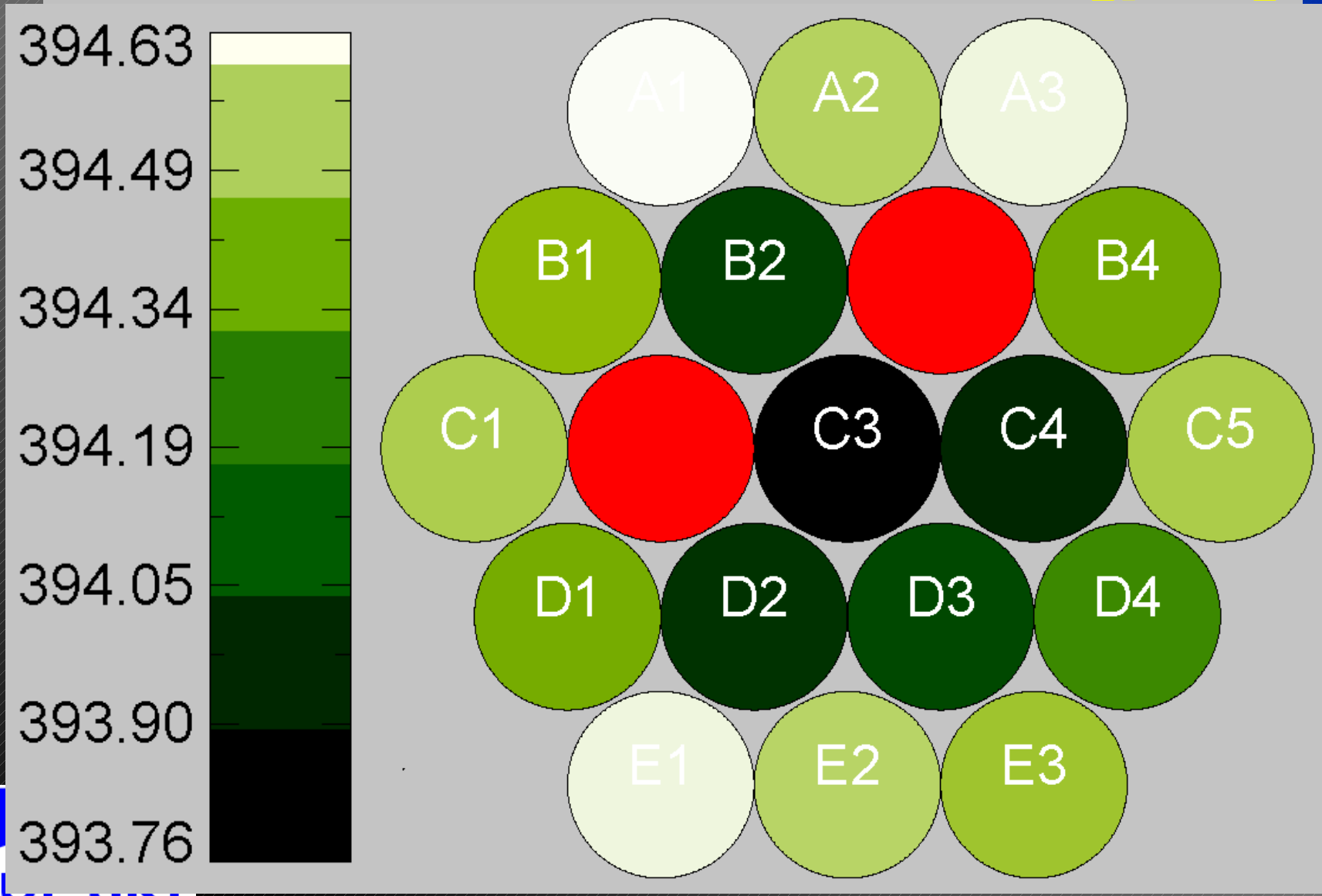
Modulation Efficiency

Observation	Target Pixel	Line Centre [cm^{-1}]	Modulation Efficiency
ILT_PERF_SMC_3001178E	SLWC3	25.3990 ± 0.0035	0.951 ± 0.029
ILT_PERF_SMC_3001178C	SLWC5	25.3566 ± 0.0083	0.842 ± 0.055
ILT_PERF_SMC_30011785	SLWD2	25.3792 ± 0.0031	0.964 ± 0.023
ILT_PERF_SMC_30011787	SLWE2	25.3501 ± 0.0079	0.833 ± 0.010
ILT_PERF_SMC_30011789	SLWE2	25.3495 ± 0.0032	0.818 ± 0.033
ILT_PERF_SMC_3001177A	SLWC3	25.3975 ± 0.0011	0.975 ± 0.019
ILT_PERF_SMC_30011792	SLWC3	25.3969 ± 0.0015	0.947 ± 0.040
ILT_PERF_SMC_300117ED	SSWD4	49.4123 ± 0.0035	0.966 ± 0.027
ILT_PERF_SMC_300117EE	SSWD4	49.4120 ± 0.0053	0.903 ± 0.071

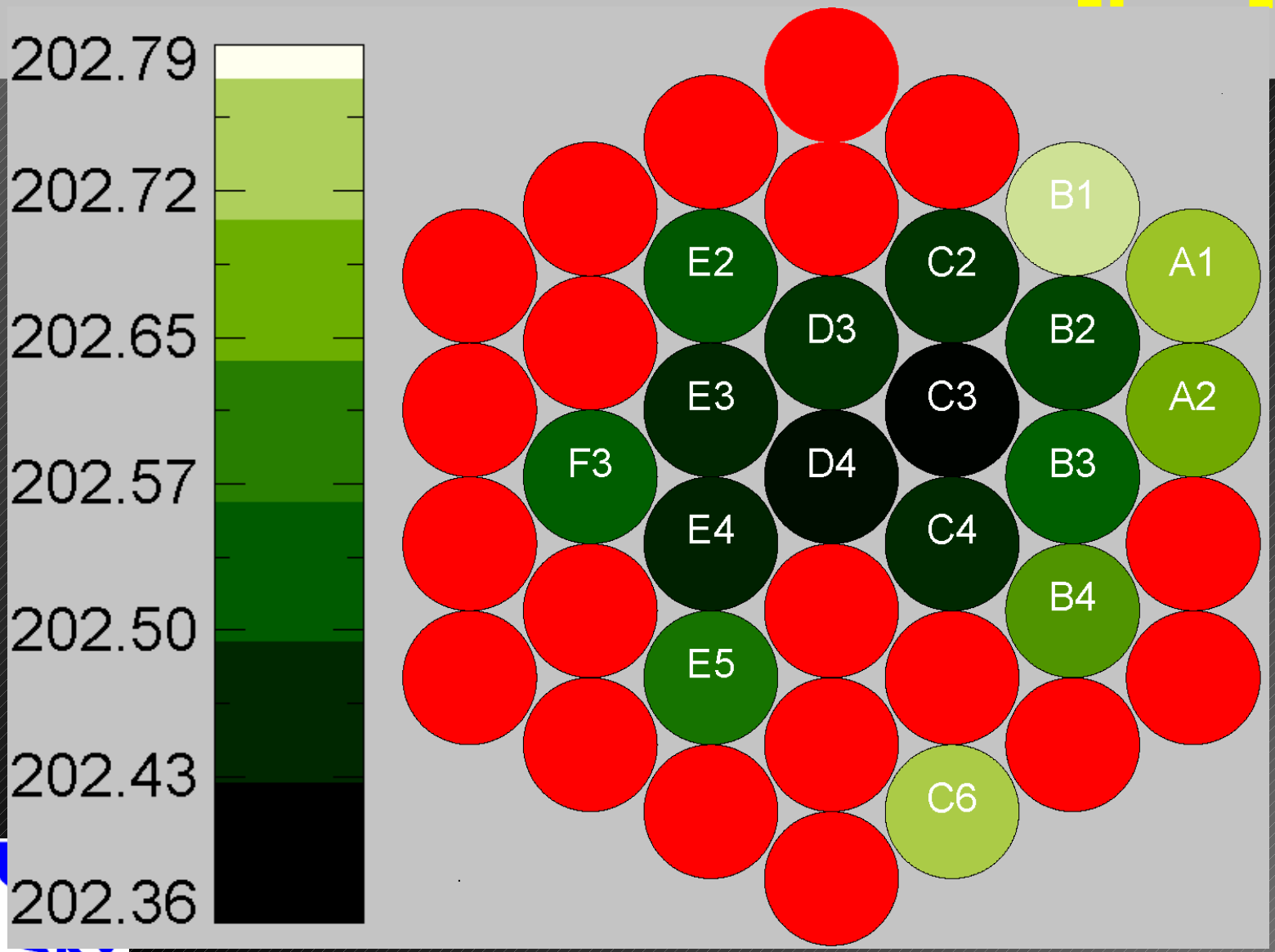
Contents

- Active Channels
- Spectrometer Band Edges
- Phase
- Vignetting
- Channel Fringes
- Spectral Resolution
- Modulation Efficiency
- Obliquity

Measured Line Centres [μm]



Measured Line Centres [µm]



Obliquity

- As can be seen from the preceding plots, the measured line centres shift in a concentric pattern.
- According to theory, the line centres should shift by the following amount:

$$\sigma_{th} = \sigma_0 \left(1 - \frac{\Omega}{4\pi} \right)$$

where σ_0 is the actual line centre, and Ω is the solid angle as seen by the detector.

Obliquity

- The solid angle, Ω, is given by:

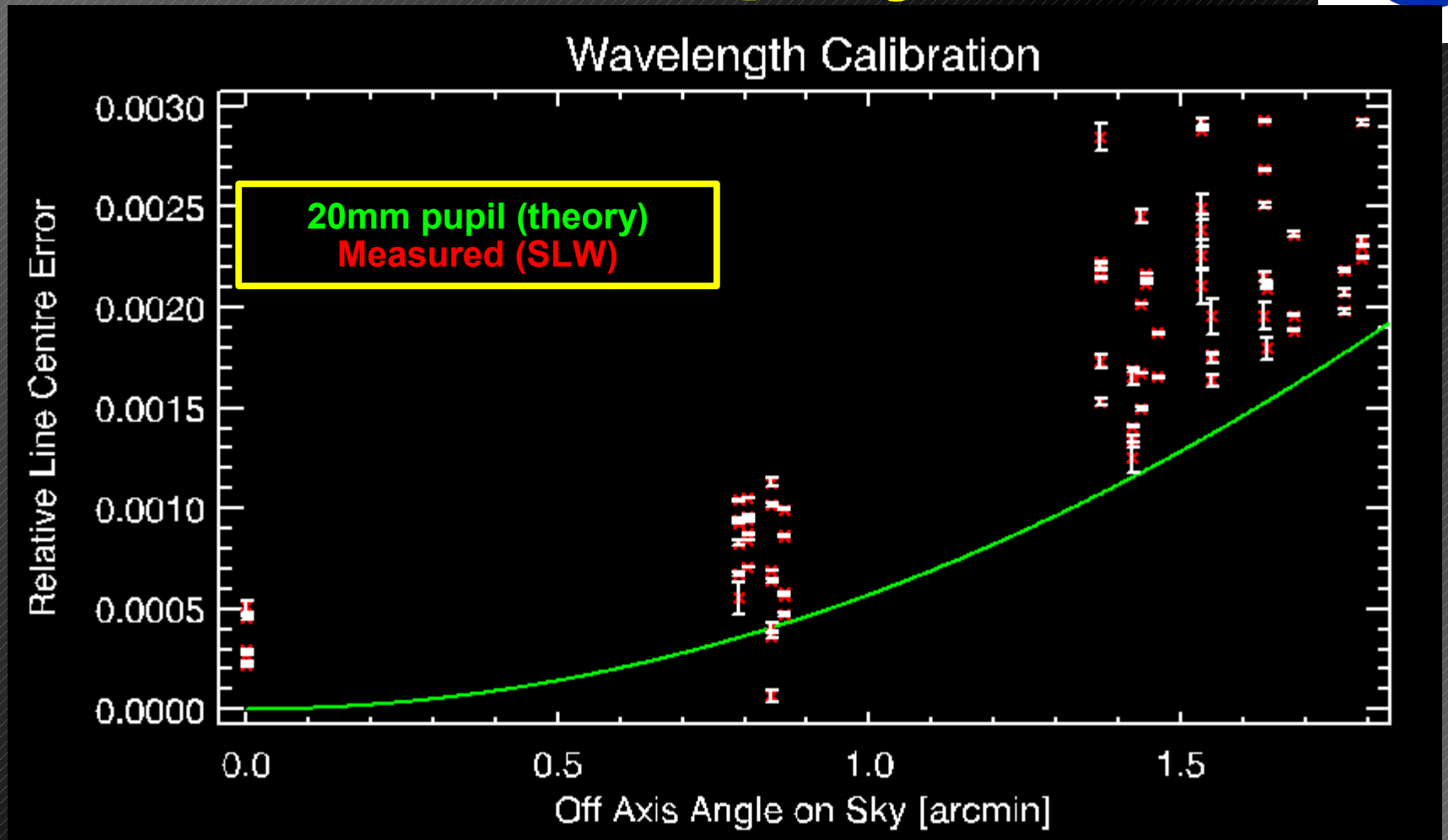
$$\Omega = \pi \beta^2$$

where β is the angular separation of a detector from the optical axis with respect to the FTS pupil. This angle is related to the angle projected onto the sky by:

$$\alpha = \frac{D_{Pupil}}{D_{Telescope}} \beta$$

- As such, knowledge of the pupil diameter, telescope diameter, and of the projected angle on the sky for each detector, the theoretical line shift can be determined.

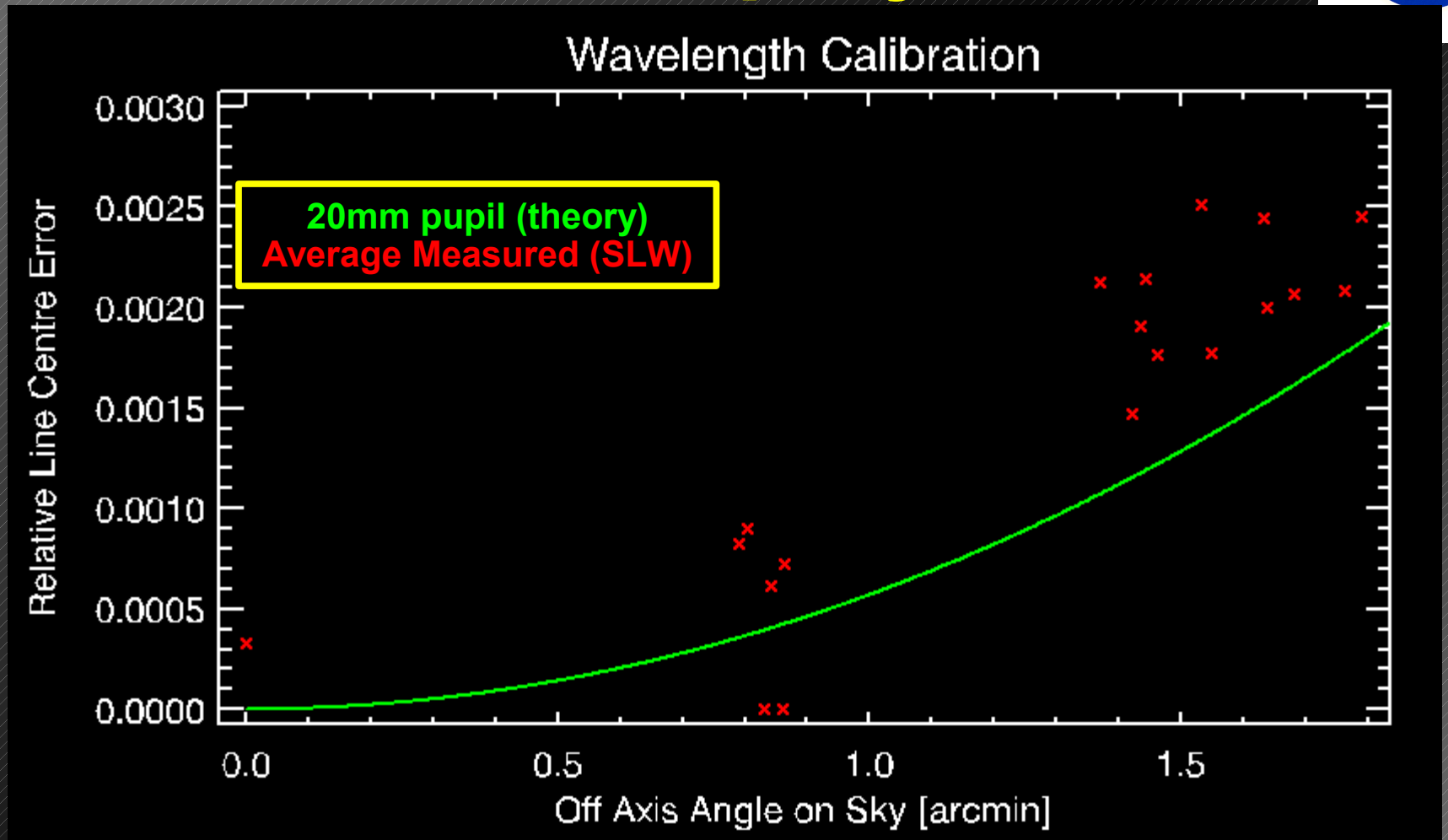
Obliquity



Rao, 2007

Off-axis angles for SLW pixels from "Optical Performances", Marc Ferlet, SPIRE Consortium Meeting, 19-20 July, 2005.

Obliquity



Rao, 2007

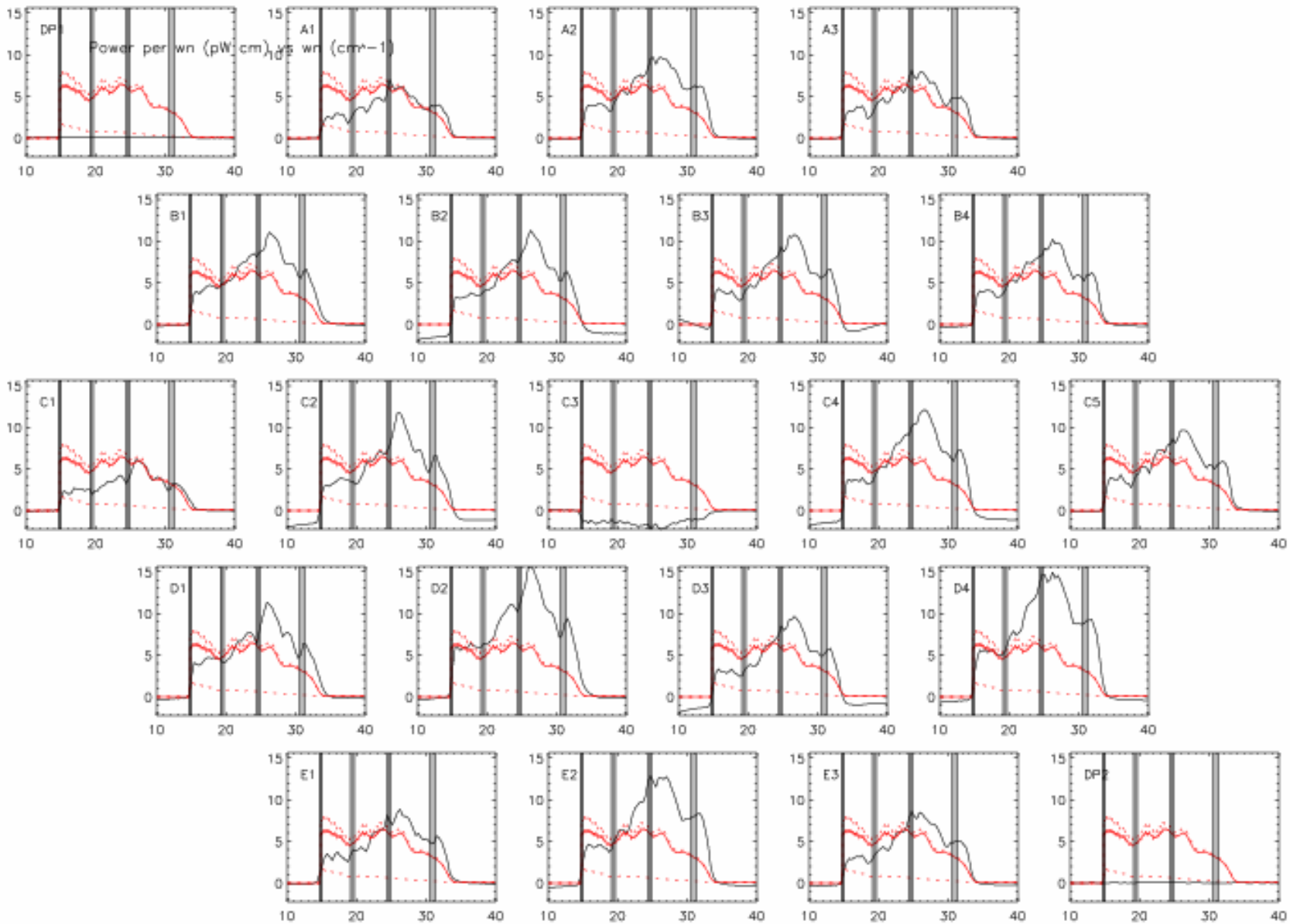
Off-axis angles for SLW pixels from "Optical Performances", Marc Ferlet, SPIRE Consortium Meeting, 19-20 July, 2005.

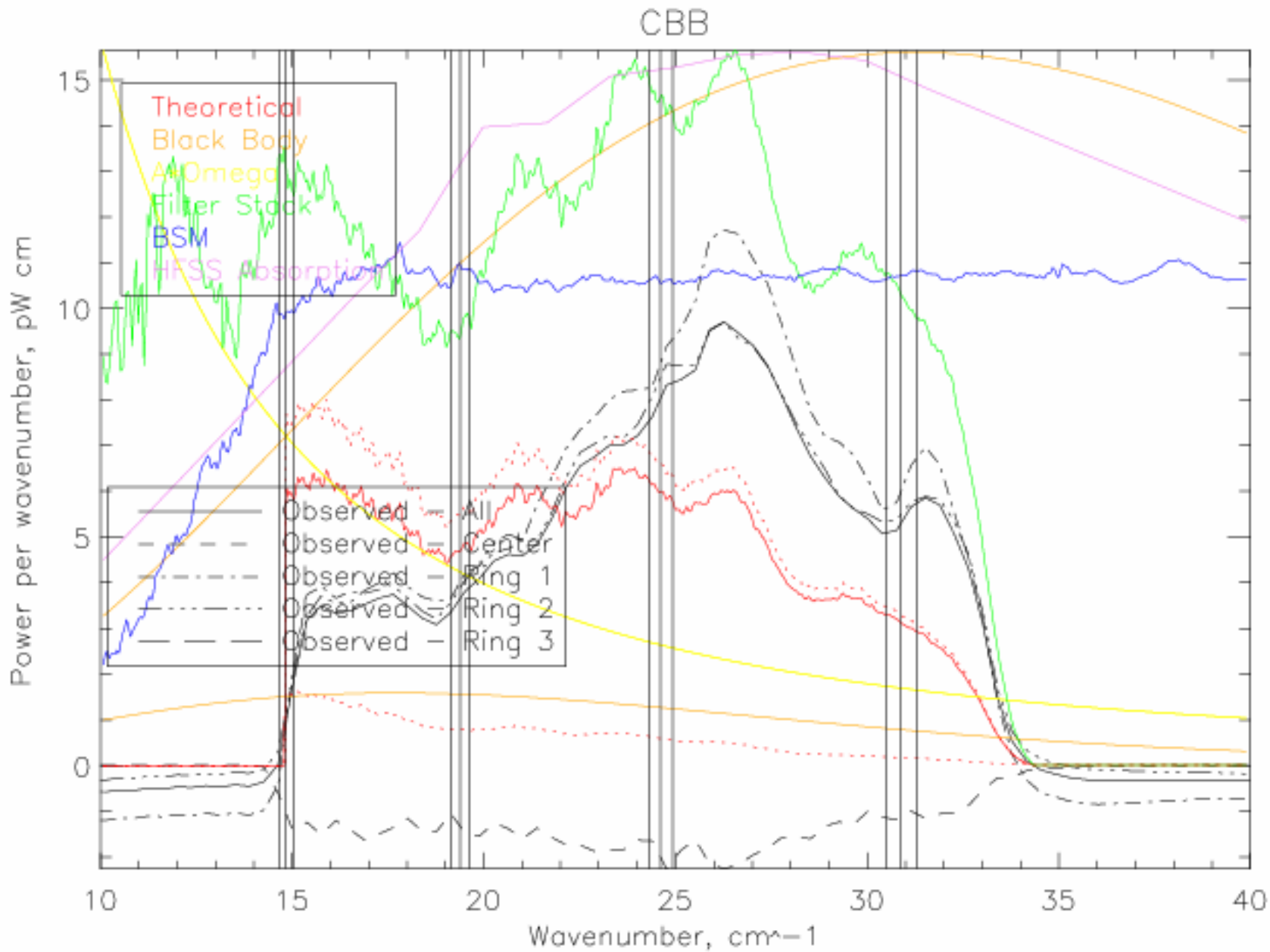
FTS Beam Map Summary

G. Laurent
U. Colorado

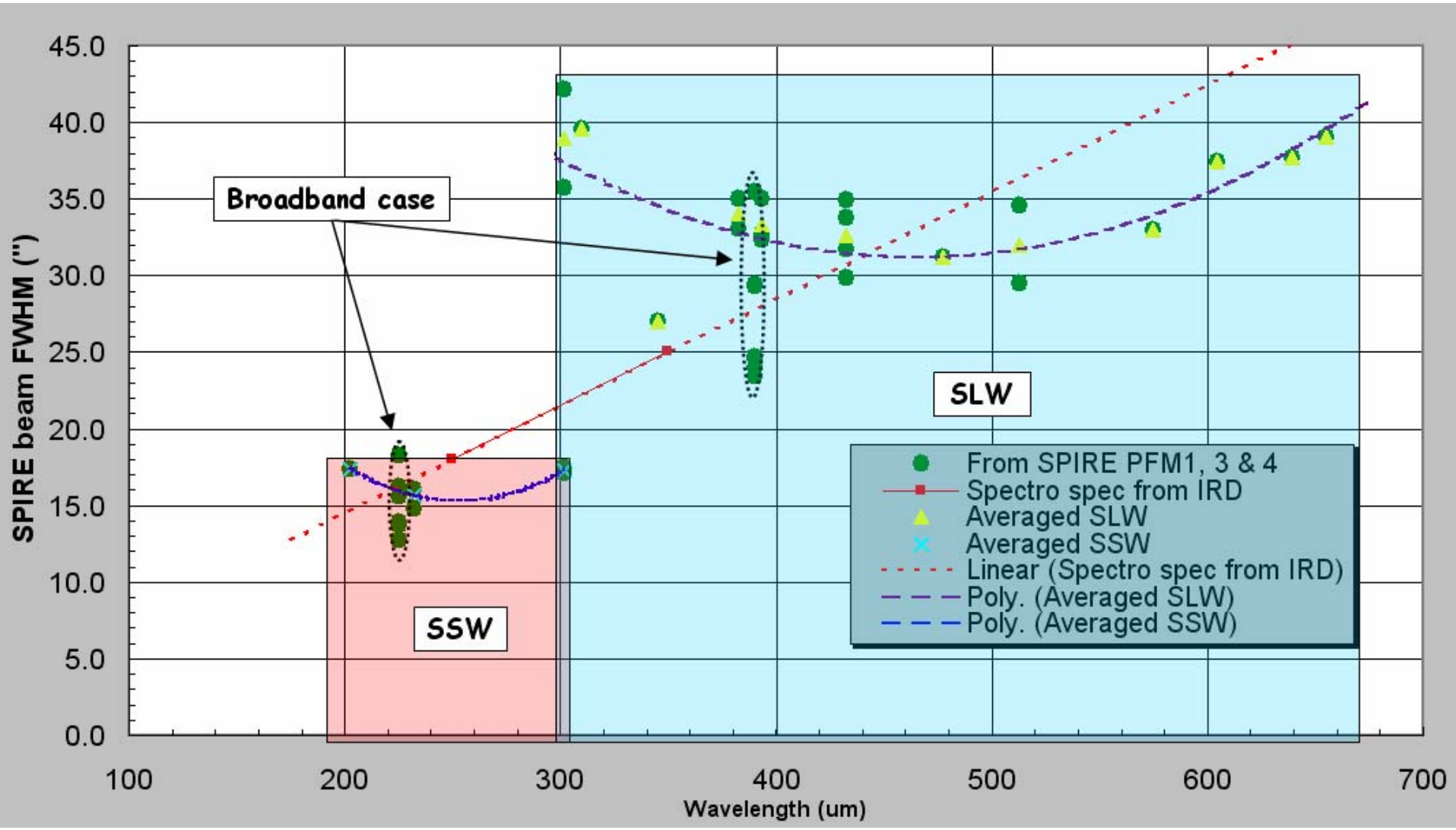
5/14/2007
ICC Meeting

Motivation

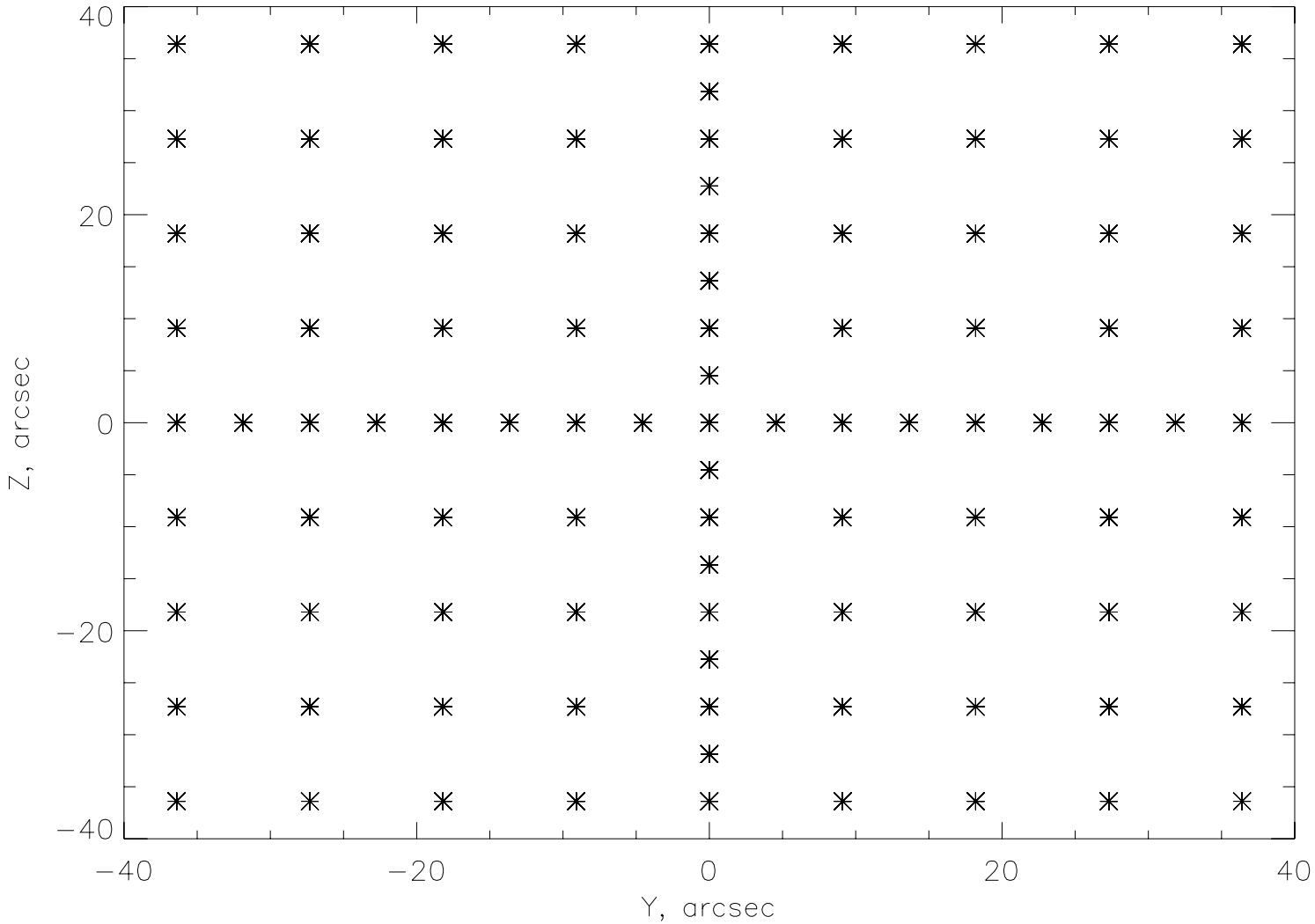

DP1
Power per wn (pW/cm)/vs wn (cm^-1)
A1
A2
A3
B1
B2
B3
B4
C1
C2
C3
C4
C5
D1
D2
D3
D4
E1
E2
E3
DP2


CBB
Theoretical
Black Body
AllOmega
Filter Stack
BSM
HFSS Absorption
Observed - All
Observed - Center
Observed - Ring 1
Observed - Ring 2
Observed - Ring 3
Power per wavenumber, pW cm
Wavenumber, cm^-1
15
10
5
0
10
15
20
25
30
35
40

Broadband / Laser

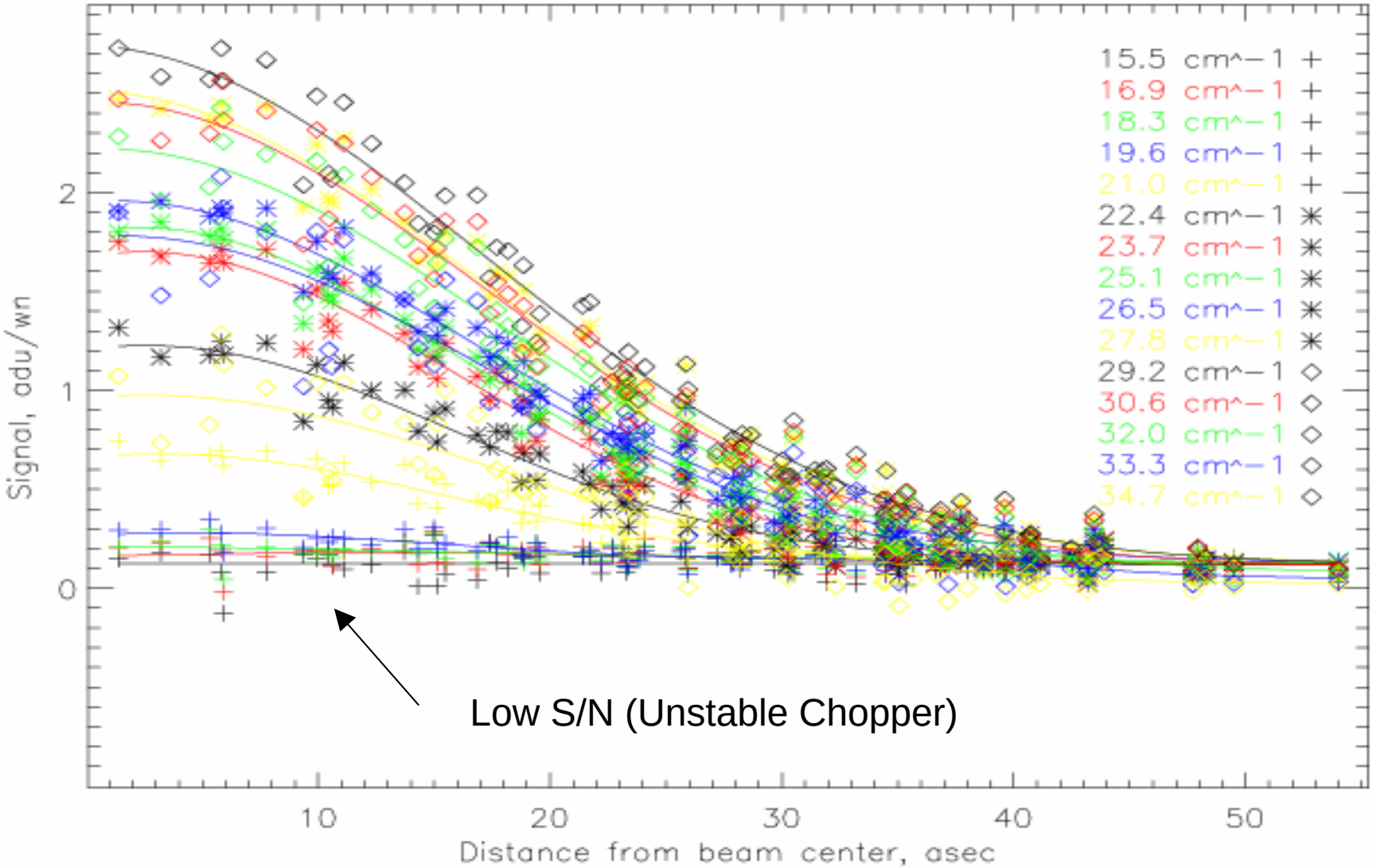


PFM4 Observations

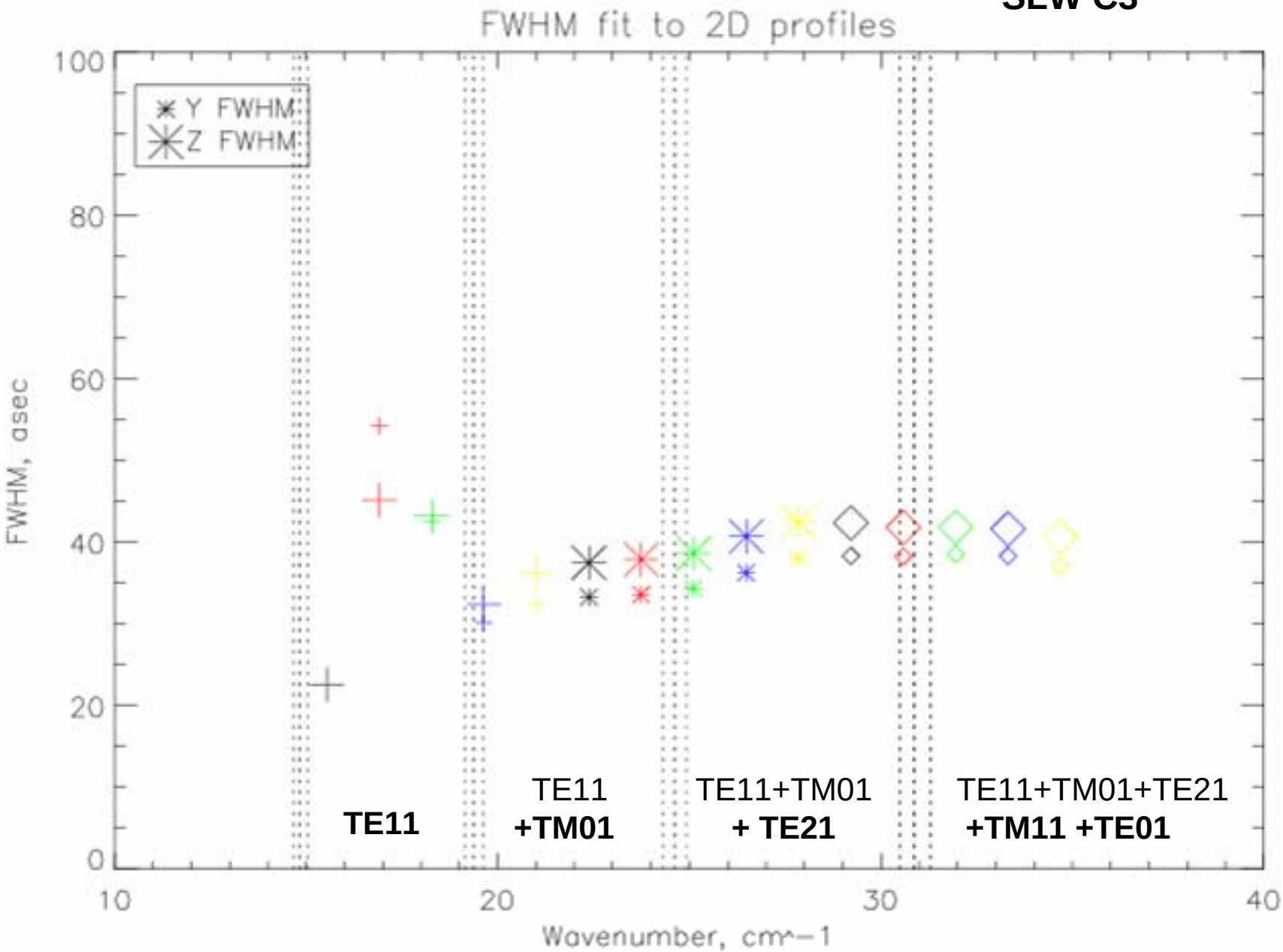


SLW C3

HBB Modulated by FTS, Chopper (17.7 Hz)

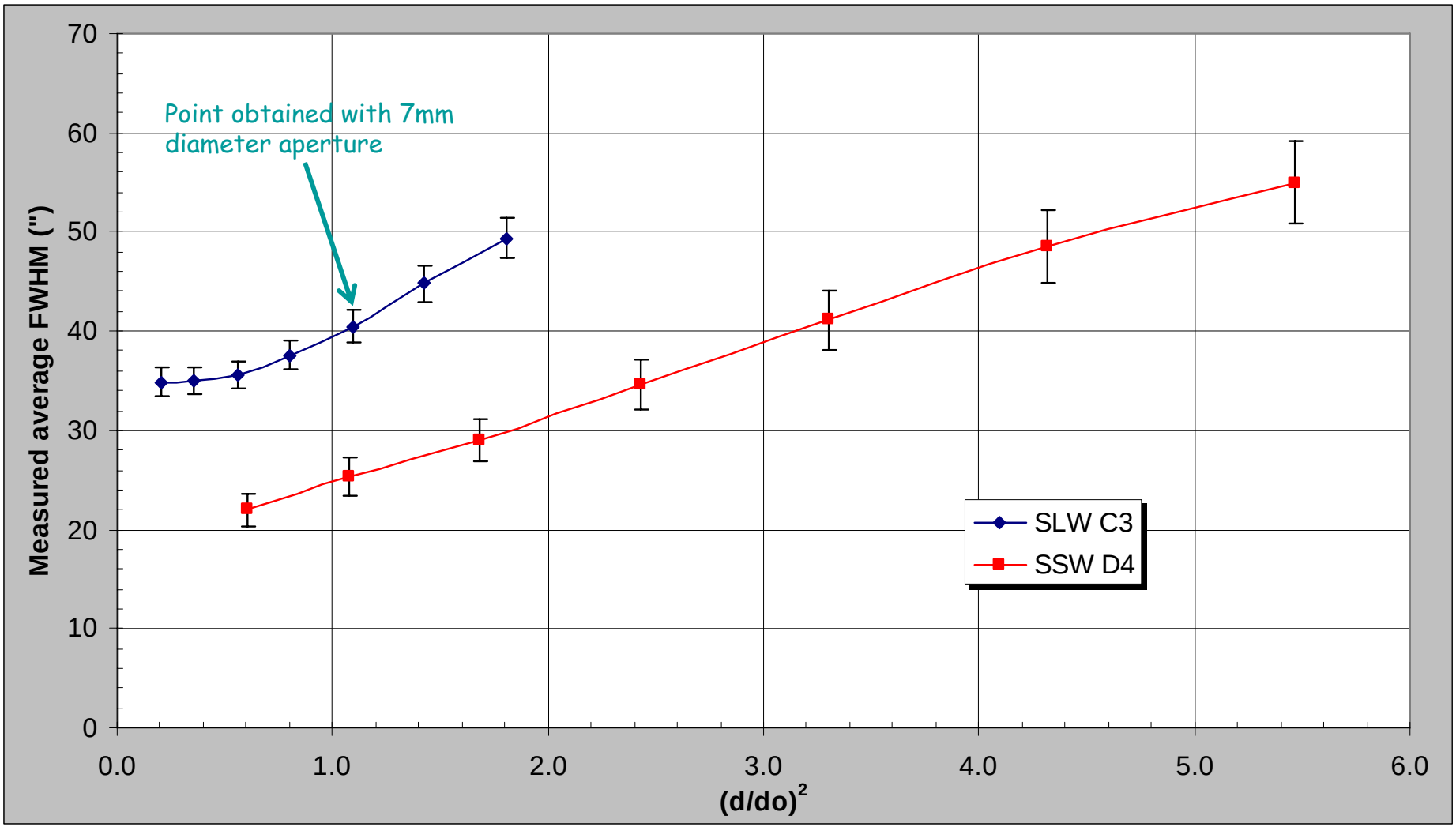


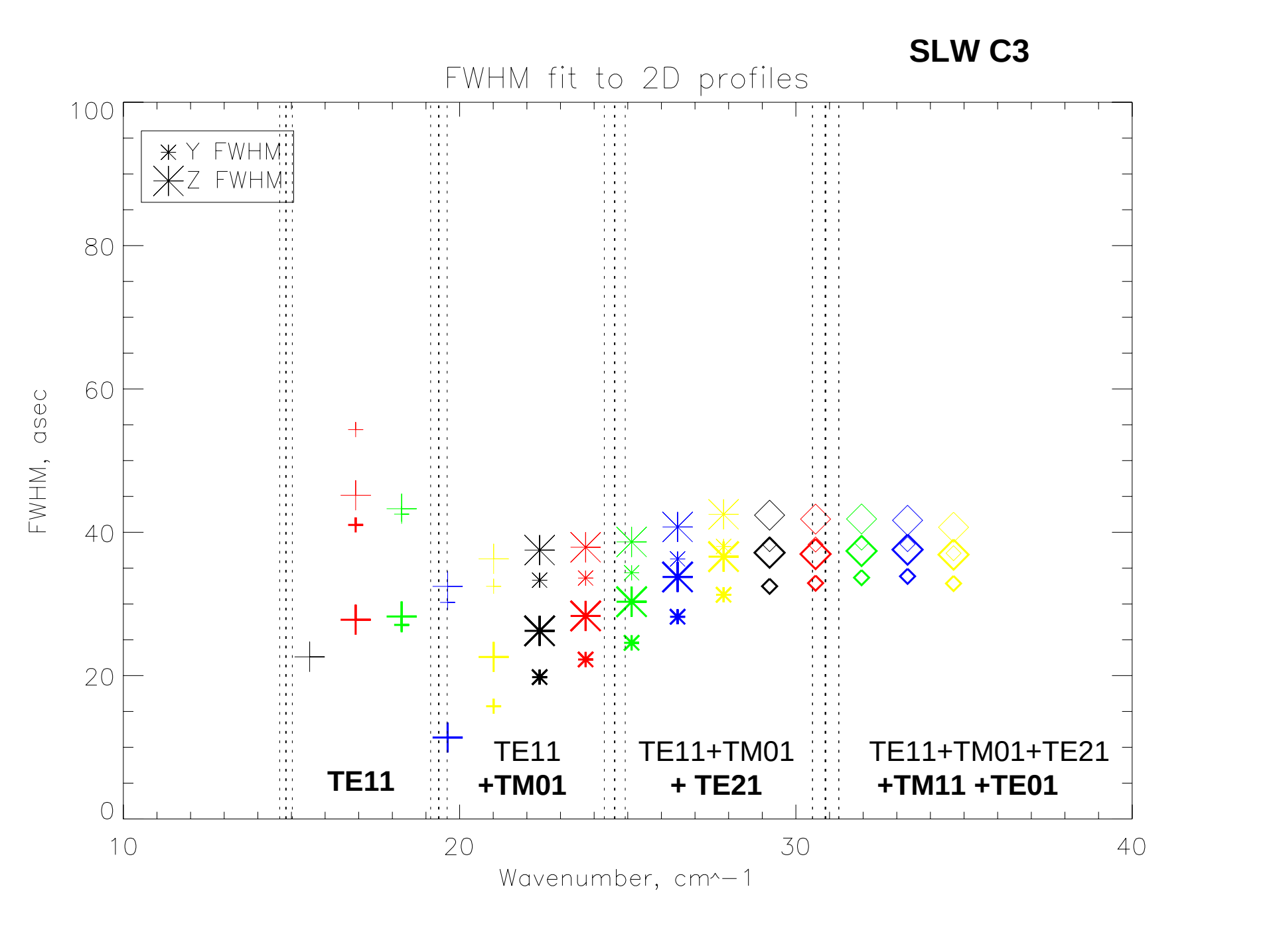
SLW C3

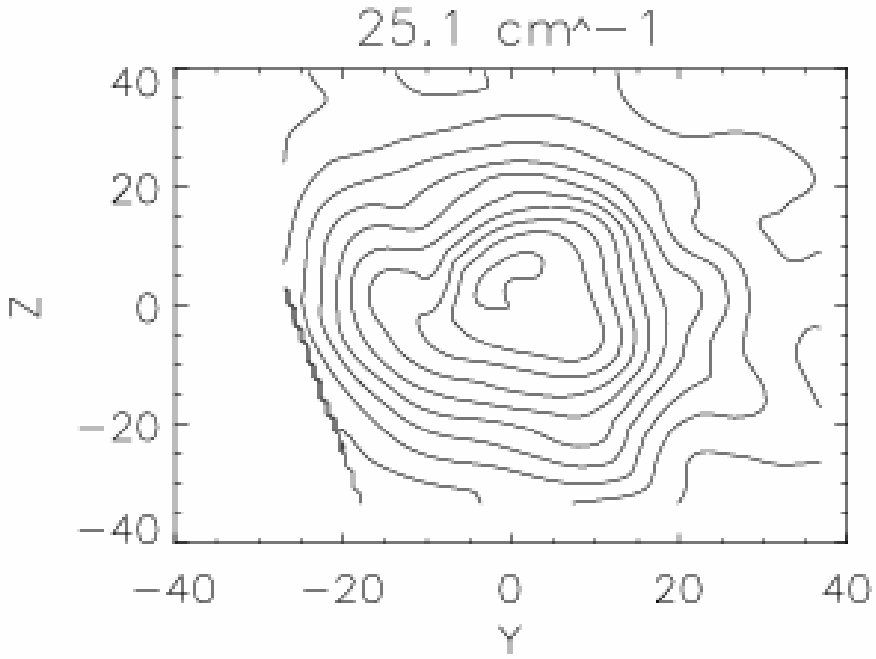

FWHM fit to 2D profiles
Y FWHM
Z FWHM
FWHM, asec
Wavenumber, cm^-1
100
80
60
40
20
0
10
20
30
40
TE11
TE11
+TM01
TE11+TM01
+ TE21
TE11+TM01+TE21
+TM11 +TE01

SPIRE PFM4: Results of source size effect test / Spectro side

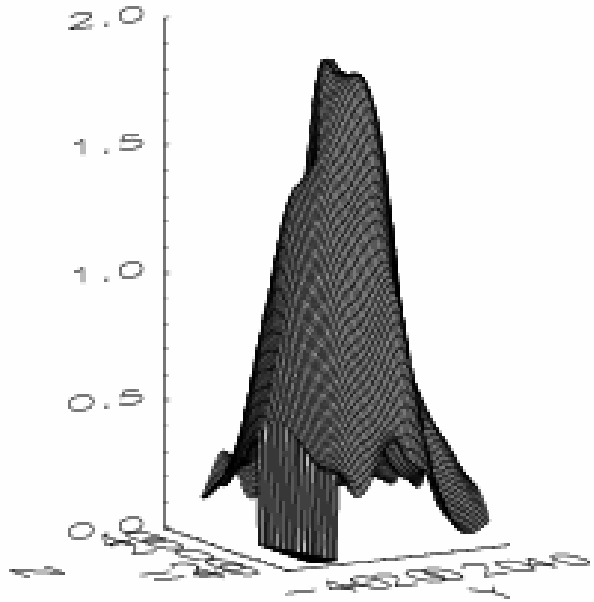
Beamsize (FWHM) vs normalised source area / HBB illumination



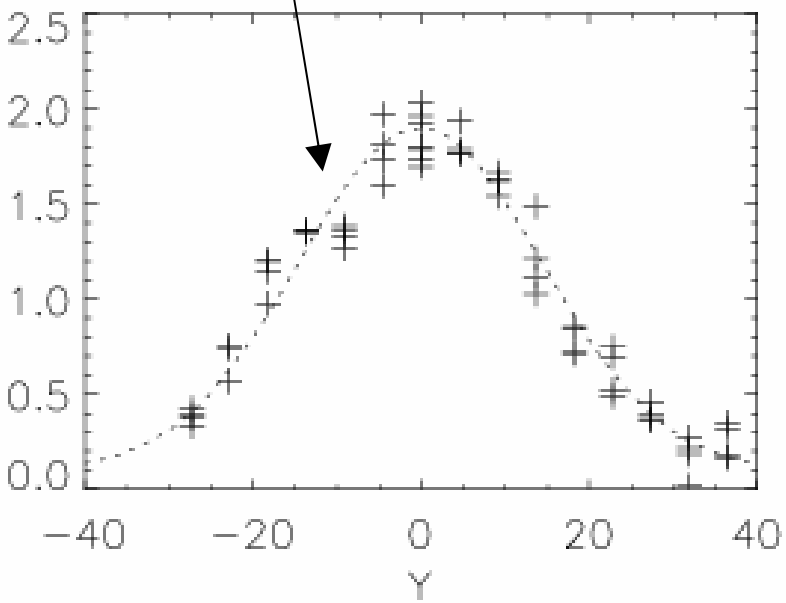

SLW C3
FWHM fit to 2D profiles
Y FWHM
Z FWHM
FWHM, asec
Wavenumber, cm^-1
100
80
60
40
20
0
10
20
30
40
TE11
TE11
+TM01
TE11+TM01
+ TE21
TE11+TM01+TE21
+TM11 +TE01

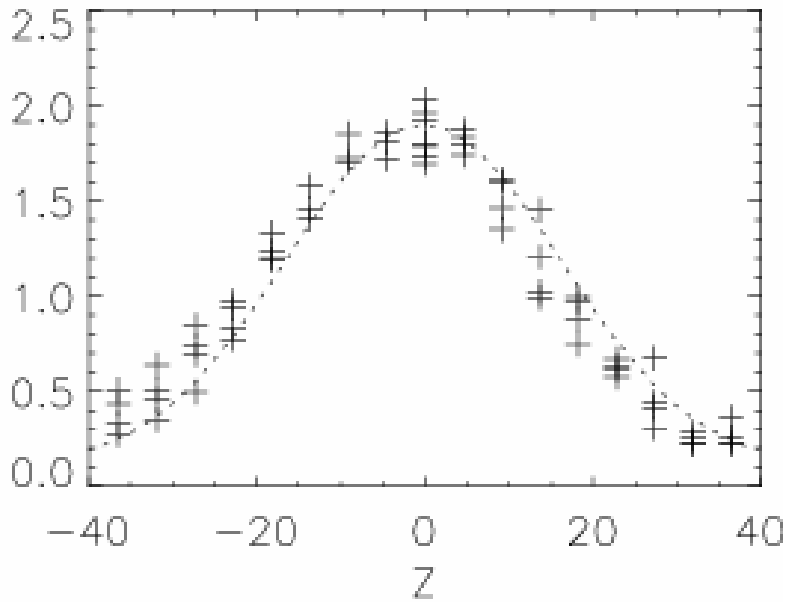


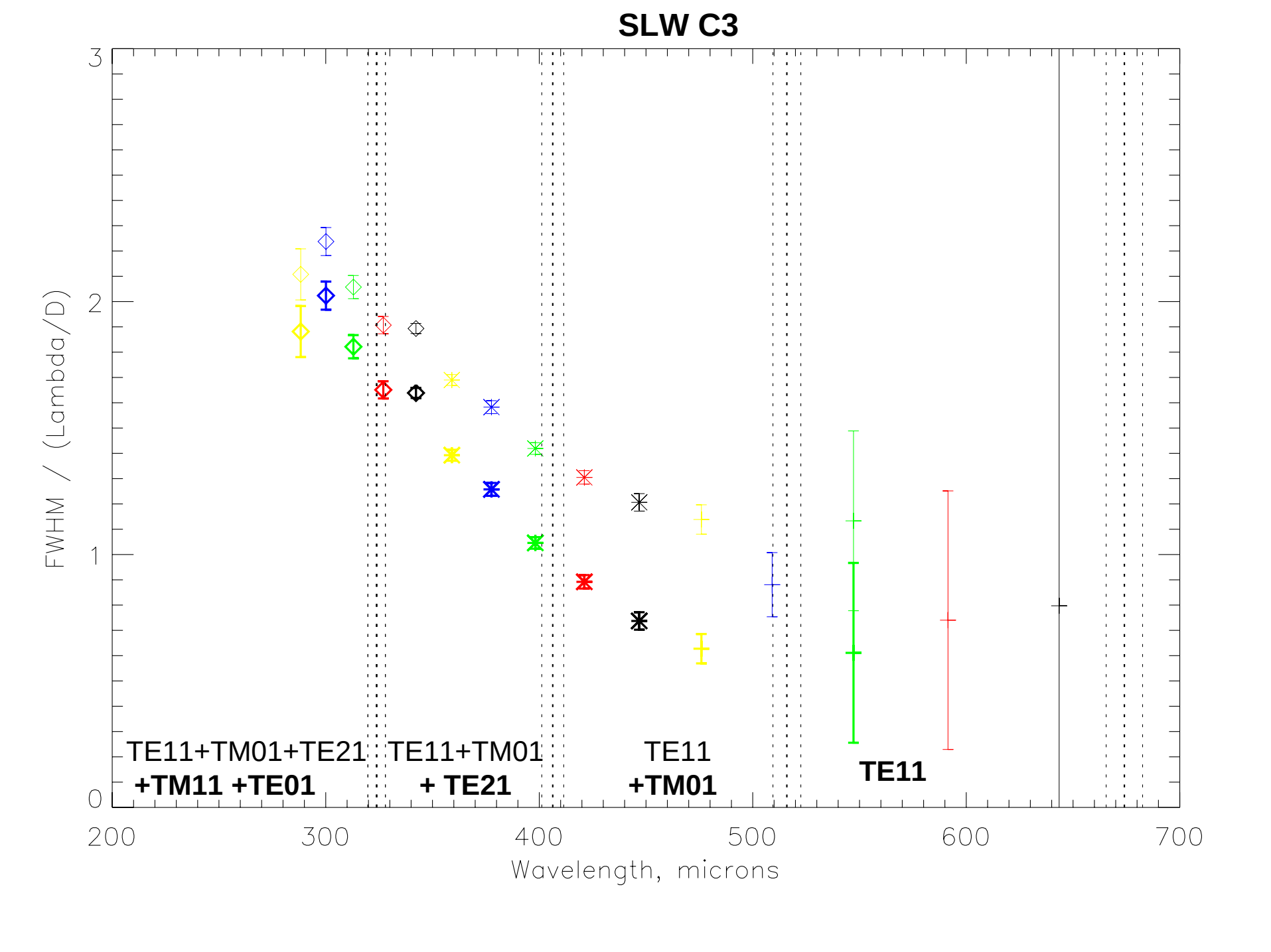
SLW C3

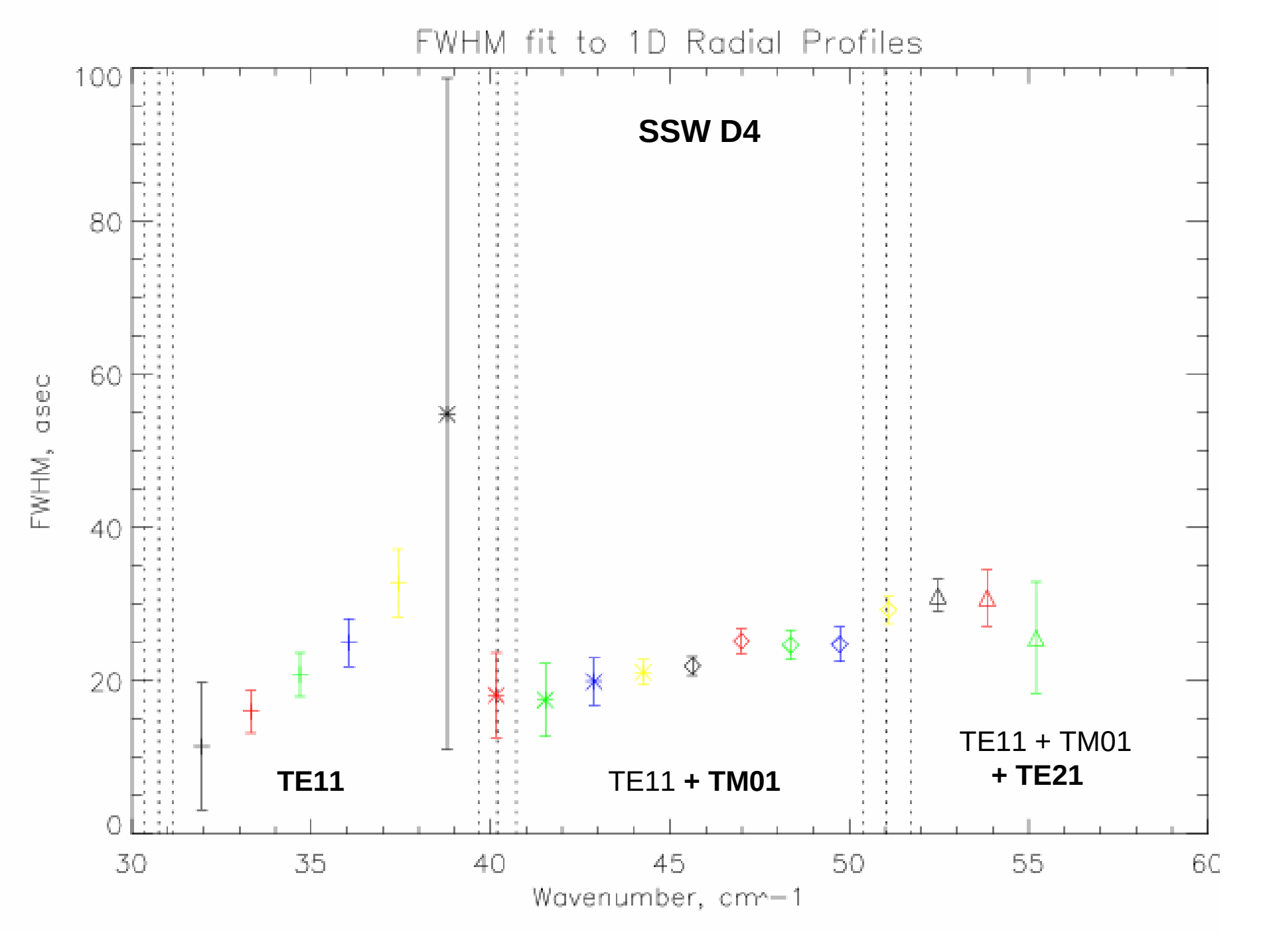


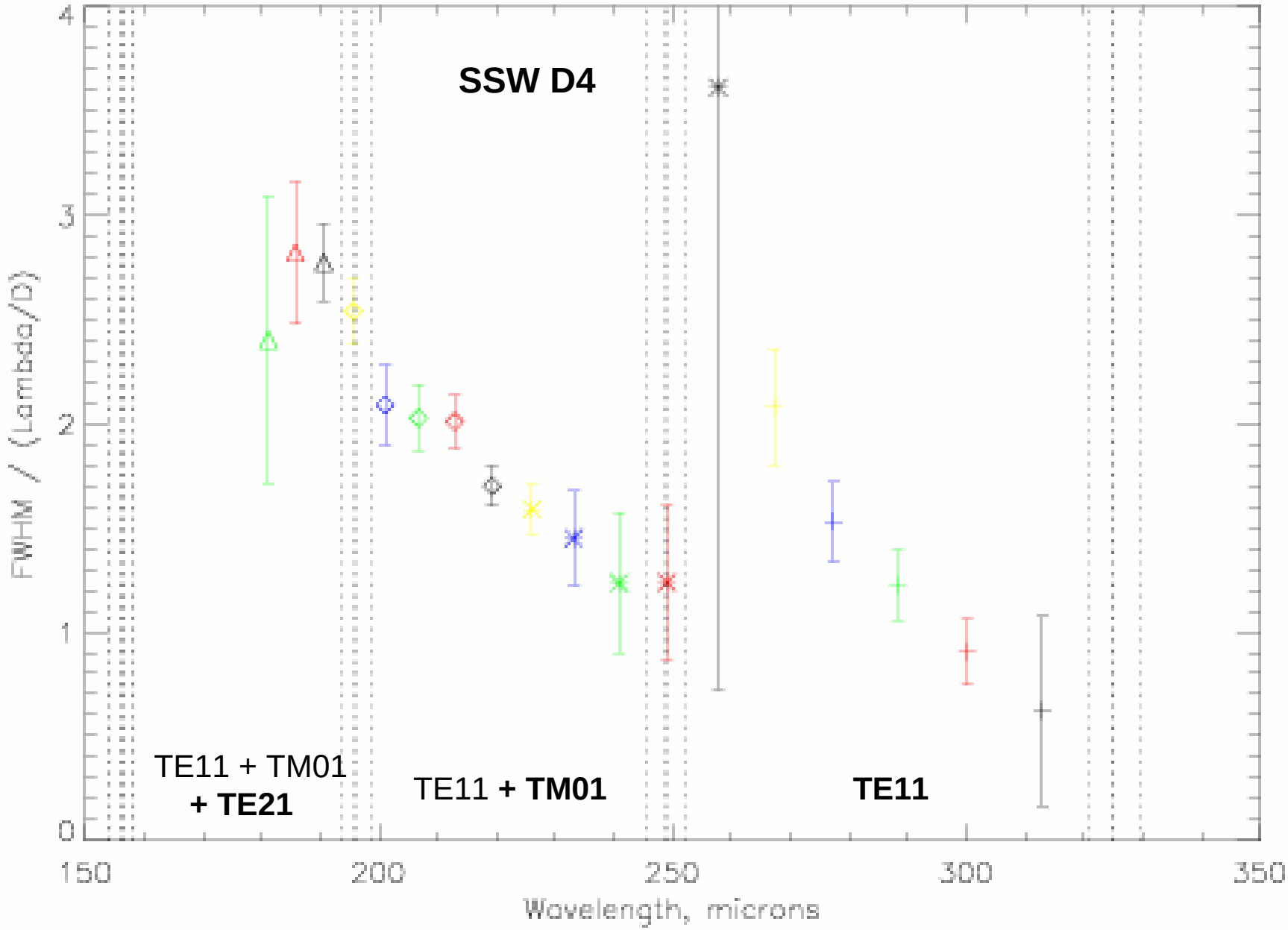
Dip in Z-slice is independent of wavenumber



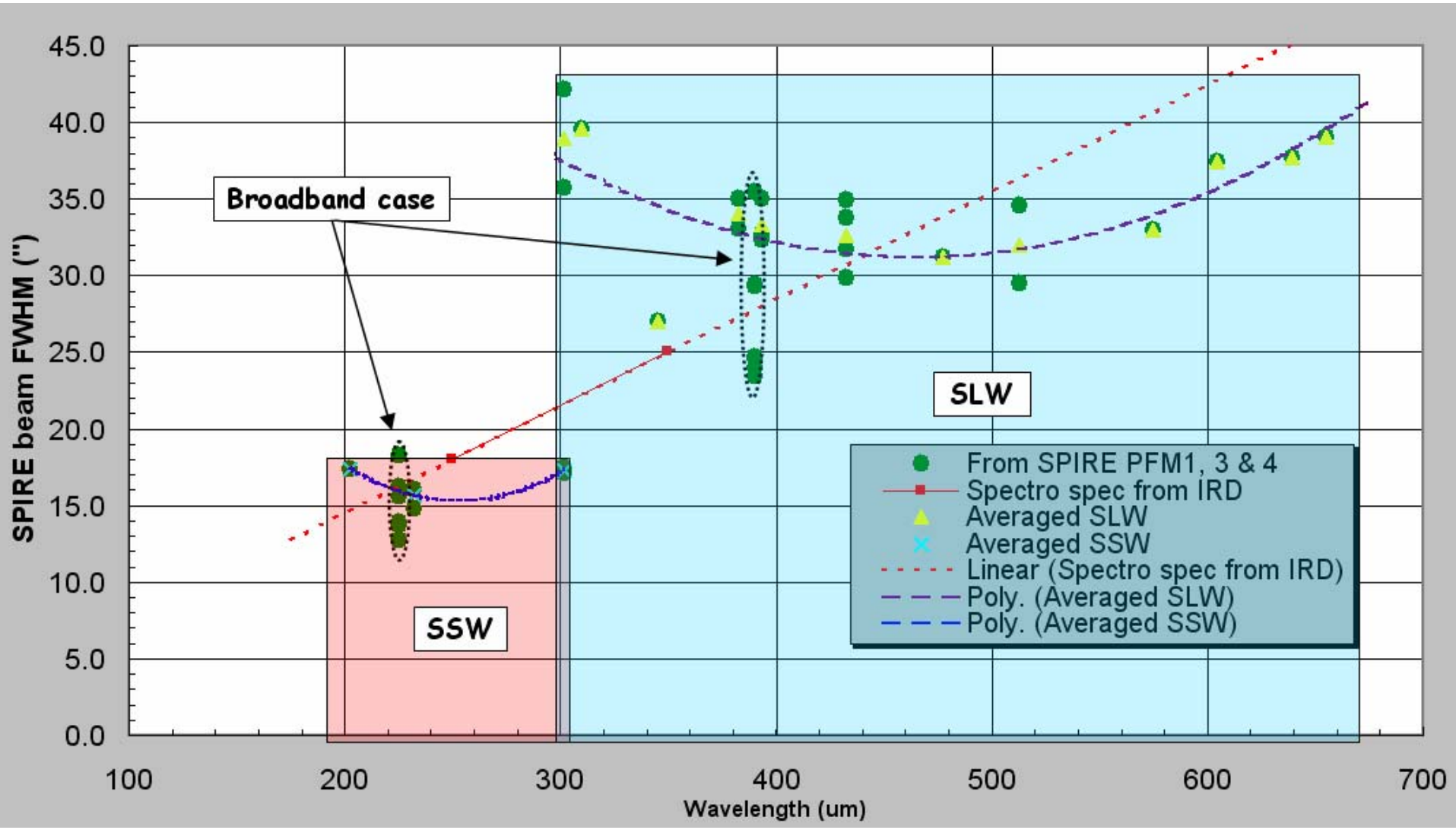



SLW C3
FWHM / (Lambda/D)
Wavelength, microns
0
1
2
3
200
300
400
500
600
700
TE11+TM01+TE21
+TM11 +TE01
TE11+TM01
+ TE21
TE11
+TM01
TE11


FWHM fit to 1D Radial Profiles
SSW D4
FWHM, asec
Wavenumber, cm^-1
TE11
TE11 + TM01
TE11 + TM01
+ TE21
0
20
40
60
80
100
30
35
40
45
50
55
60


SSW D4
FWHM / (Lambda/D)
Wavelength, microns
0
1
2
3
4
150
200
250
300
350
TE11 + TM01
+ TE21
TE11 + TM01
TE11

Comparison to M.F. Analysis



Review of Pipeline Structure

Inputs

- The flowcharts presented here are based on:
  - Matt's detector processing note
  - Calibration Products for the SPIRE Imaging Spectrometer
  - SPIRE Spectrometer Pipeline Description
  - SPIRE Fourier Transform Module Description

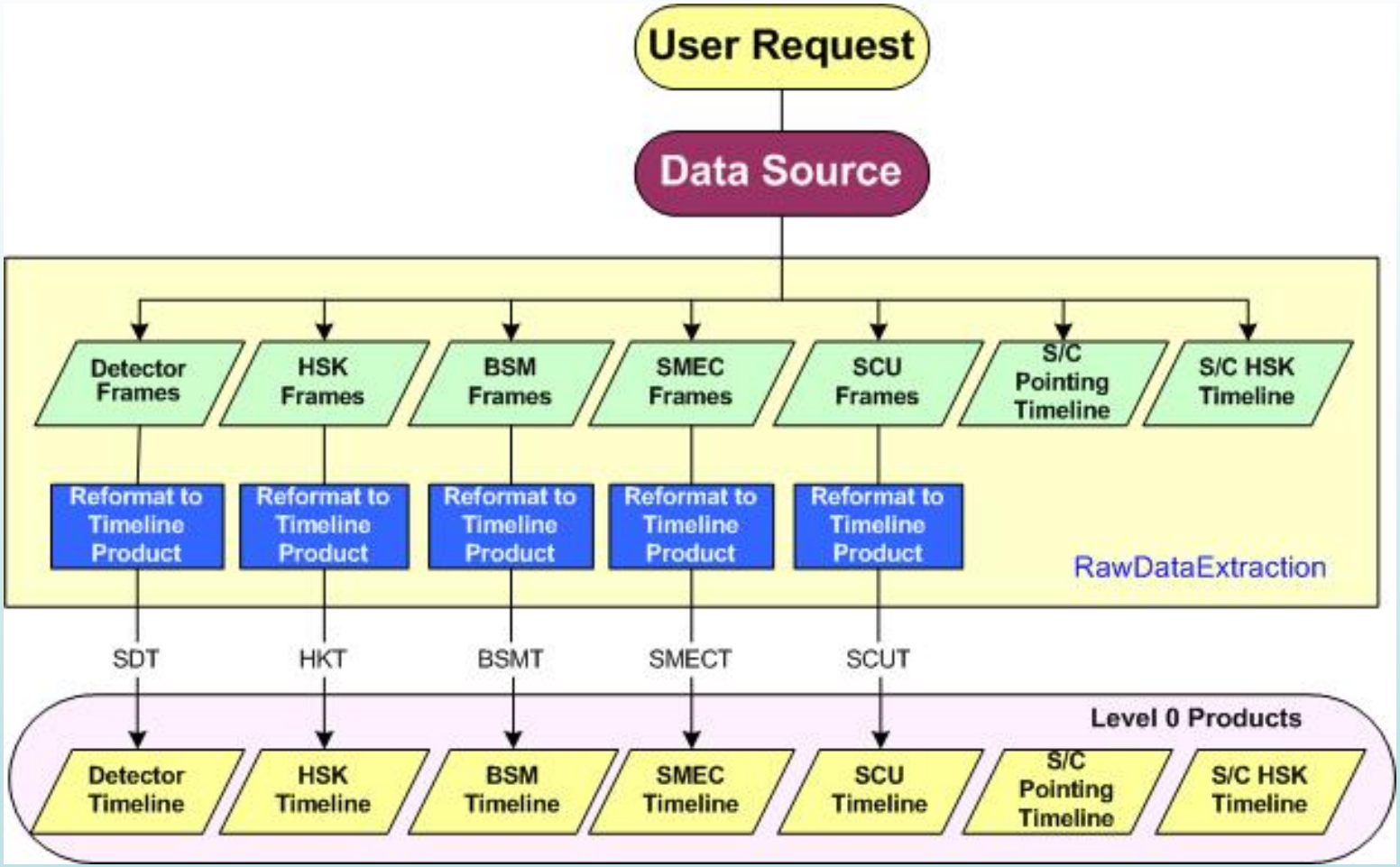
Main Changes

- RC correction now done as part of Engineering processing
- Level 0.5 products now replace SCalSpecDerPar intermediate cal file – will be persistent
- Remainder of detector processing now has two schemes
  - *full pipeline as previously defined*
  - *simple pipeline – empirical approach – full Bolometer model not applied*
- Full pipeline represented in flowchart – simple pipeline assumed to plug in to same place
- Note only simple pipeline uses PCAL – will discuss further in ICC meeting
- Electrical and optical crosstalk separated
- SCAL and Telescope Corrections now fleshed out based on Lethbridge note
- Minor changes to spectrometer processing to reflect current status

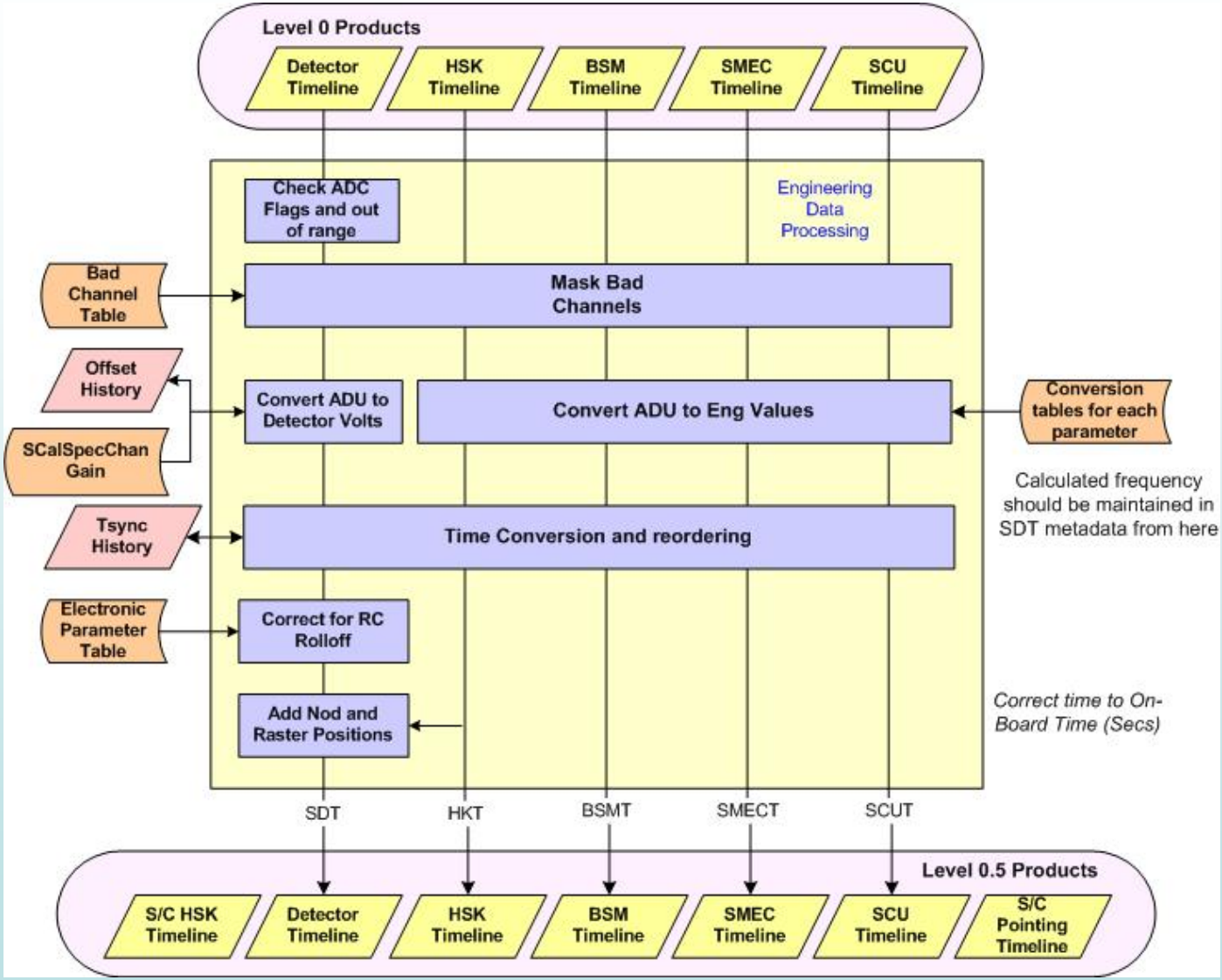
Cal Files

- All new cal files in note added
- The following cal files have been removed
  - **SCalSpecFlat** (included in optical crosstalk)
  - **SCalSpecStray** (included in optical crosstalk)
  - **SCalSpecDerPar** (changed definition slightly and status to level 0.5 product)
  - **SCalSpecScalTempHist** (dropped although we could consider reinstating this as a trend analysis product)
- The file **SCalSpecOffsetHist** is not necessarily needed for pipeline processing but will be useful as a trend analysis product so is retained.

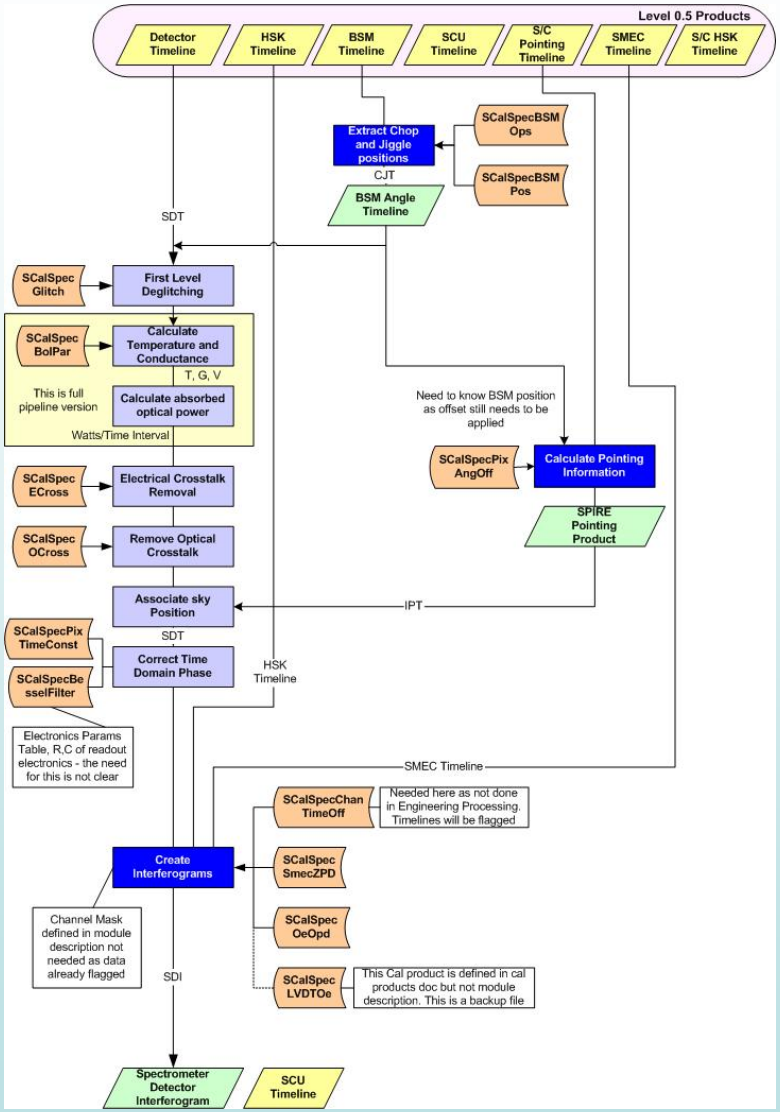
Data Extraction



Engineering Processing



Level 0.5 To Interferograms

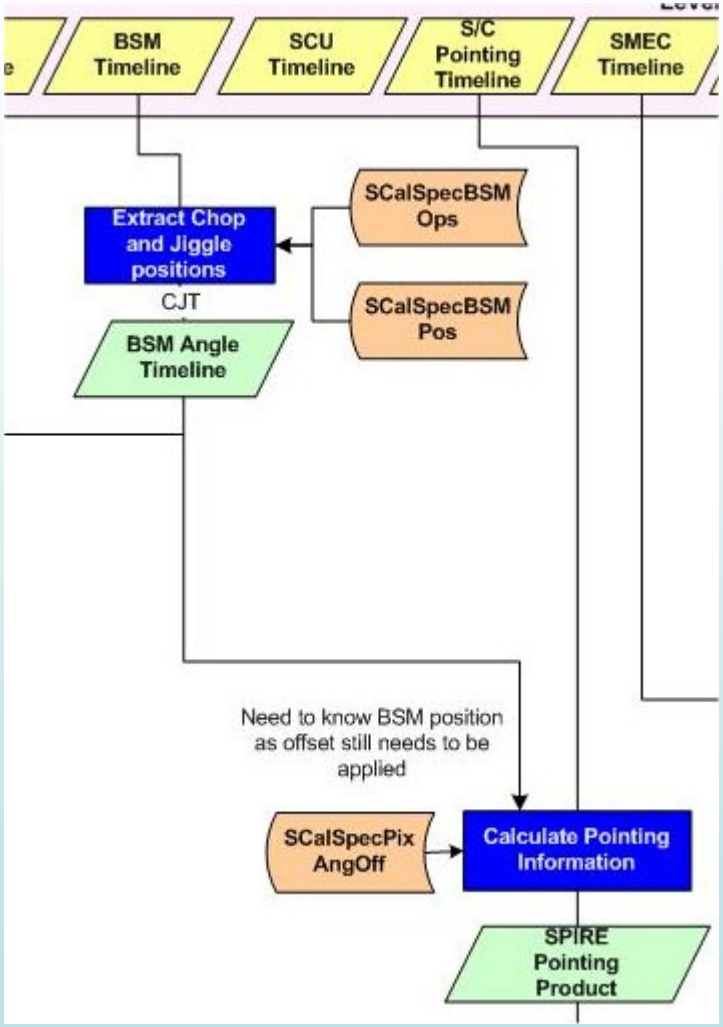


Engineering processing is common between photometer and spectrometer observations.

The spectrometer processing is then split for convenience into three stages

1. Up to formation of Interferograms
2. Up to level 1
3. Up to level 2

Pointing Information



The BSM Ops file gives all the positions the BSM should be at for each observing mode.

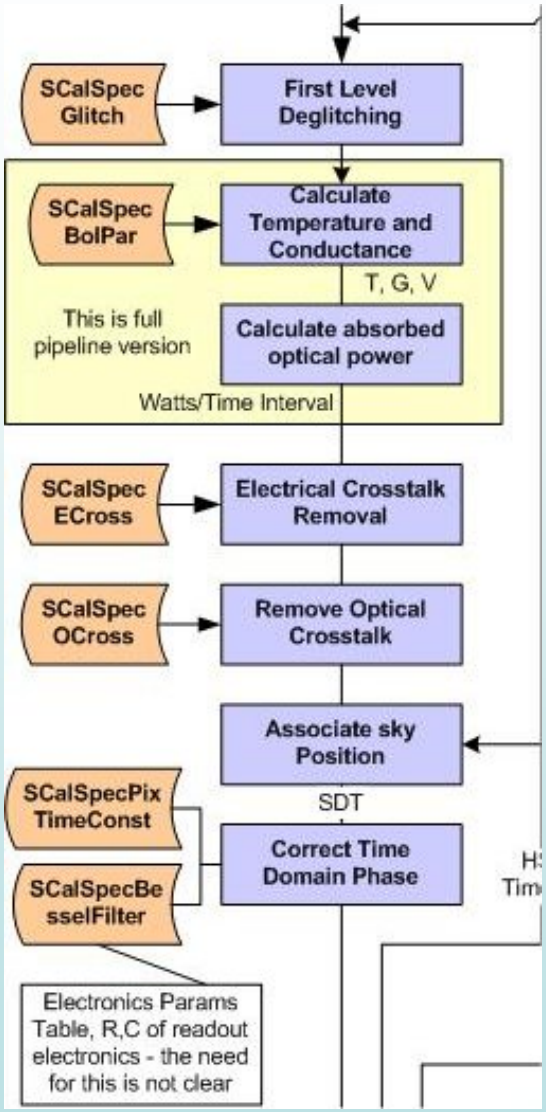
This includes all offsets for spectrometer jiggle maps.

The BSM Pos file gives an angle on the sky vs BSM encoder position

The angle timeline gives the angle on the sky from the SPIRE boresight along with ‘at position’ flags for jiggle observations

The calculate pointing module then takes the BSM position and the telescope position into account along with the angular offset of each pixel to determine where each pixel is looking at the sky

Detector Processing and Corrections



First level deglitching is intended to remove obvious outliers. It is not clear if this is feasible/necessary for spectrometer observations

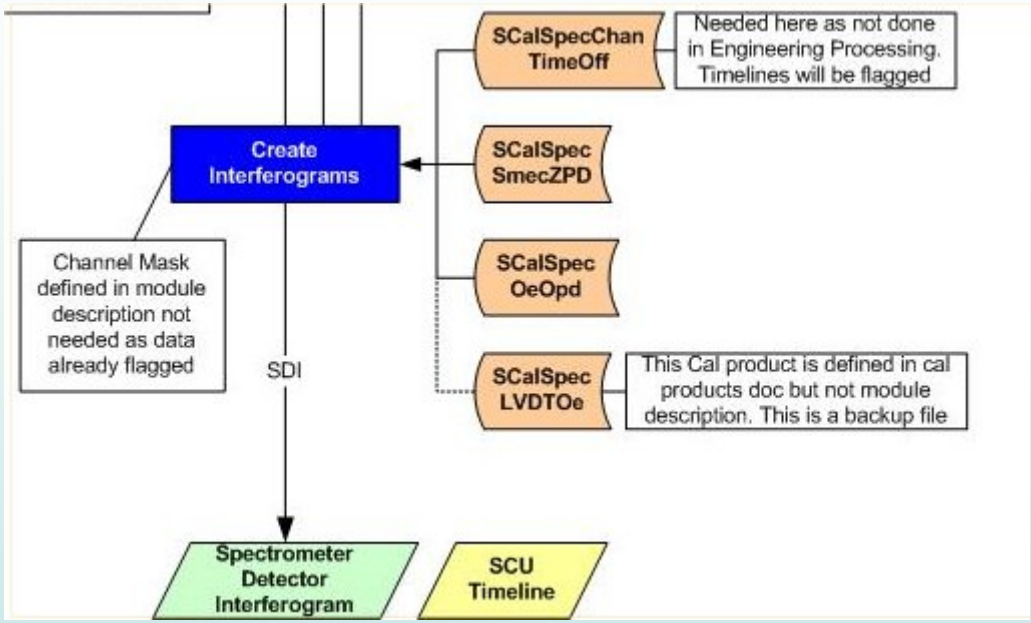
The detector processing then continues to be done in the same way as the photometer.

Using the full pipeline the combination of watts here and the processing later gives the astronomical signal. For the simple pipeline we may need a further responsivity term or the later processing using different RSRFs

Optical crosstalk removal now includes any straylight.

For the time domain correction the detector time constants are used but there is also a second file defined with the RC values is this necessary?

Generate Interferograms

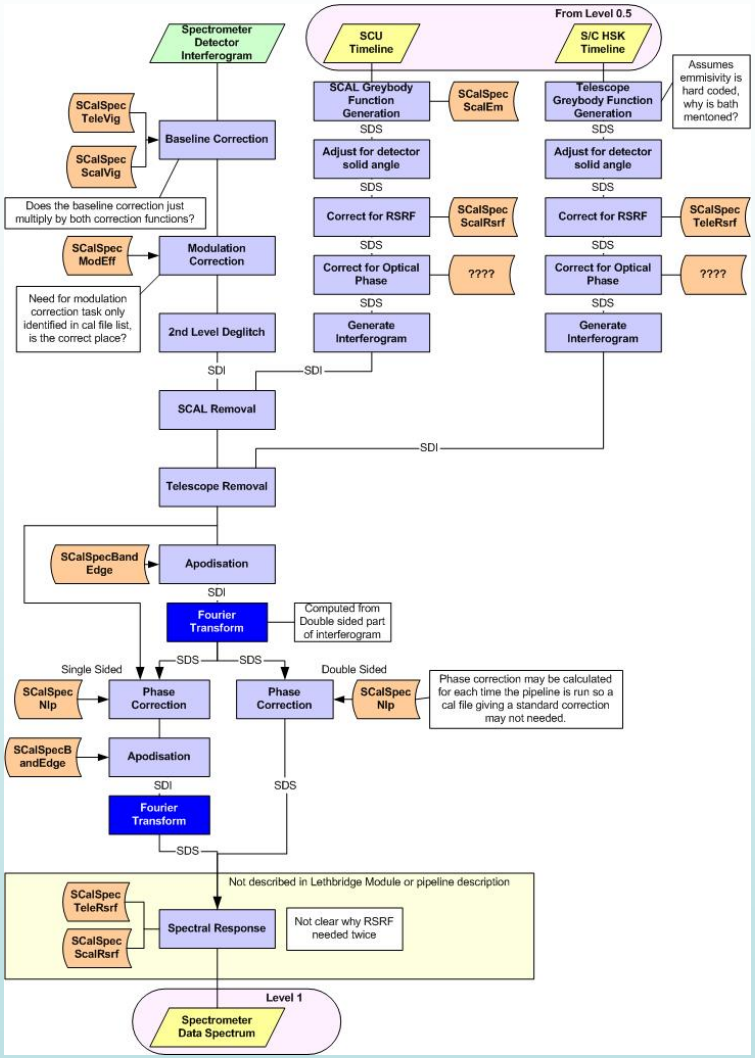


One task:

- Creates regular SMEC position timeline
- Locates individual scans
- Corrects for pixel readout delay
- Interpolates detector timelines on to SMEC position timeline

This task is also scoped to check for bad channels and not process them. These channels should already be flagged during engineering processing. **Should bad channels be rejected earlier?**

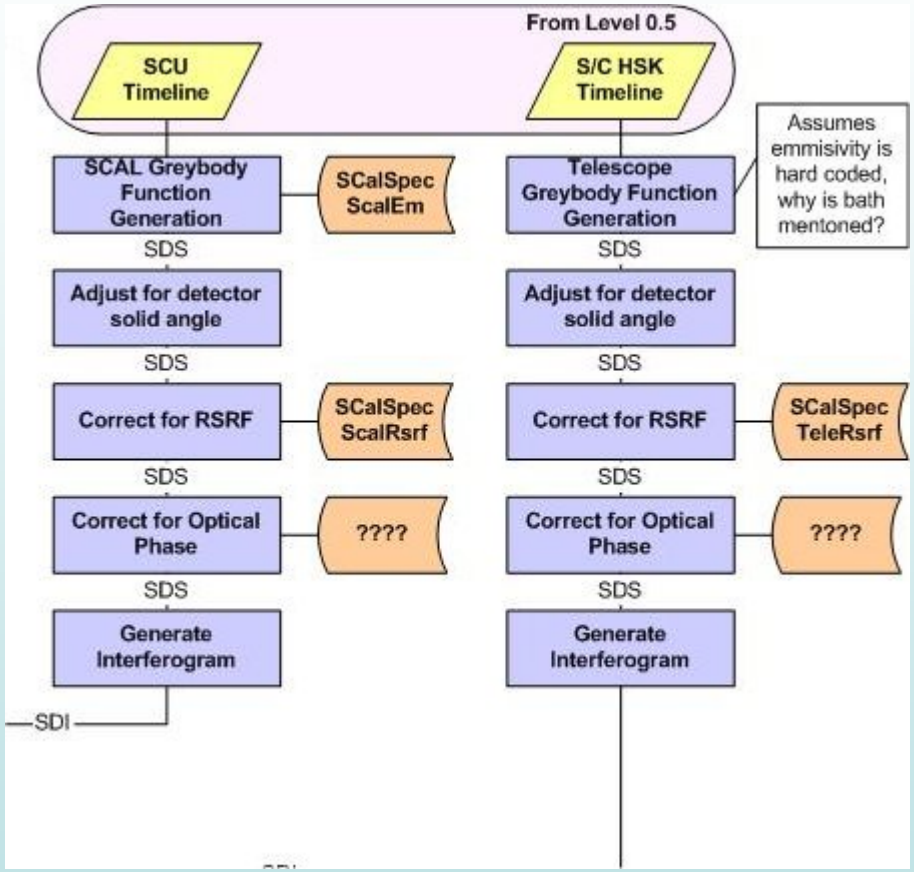
Spectrometer Processing



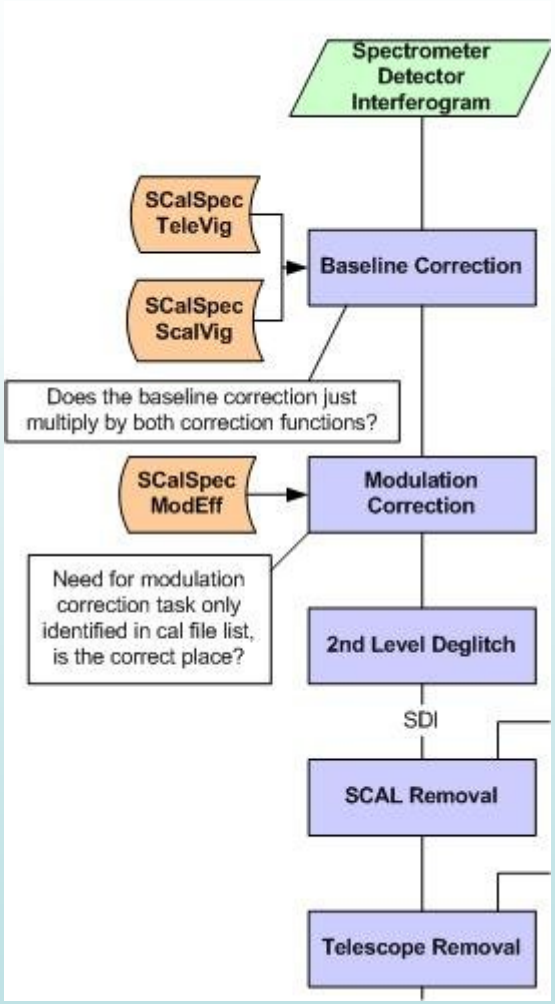
This is the data flow for spectrometer processing from interferograms to the level 1 products.

The processing essentially consists of baseline correction, correction for SCAL and telescope ports, the Fourier transform then a further spectral response correction.

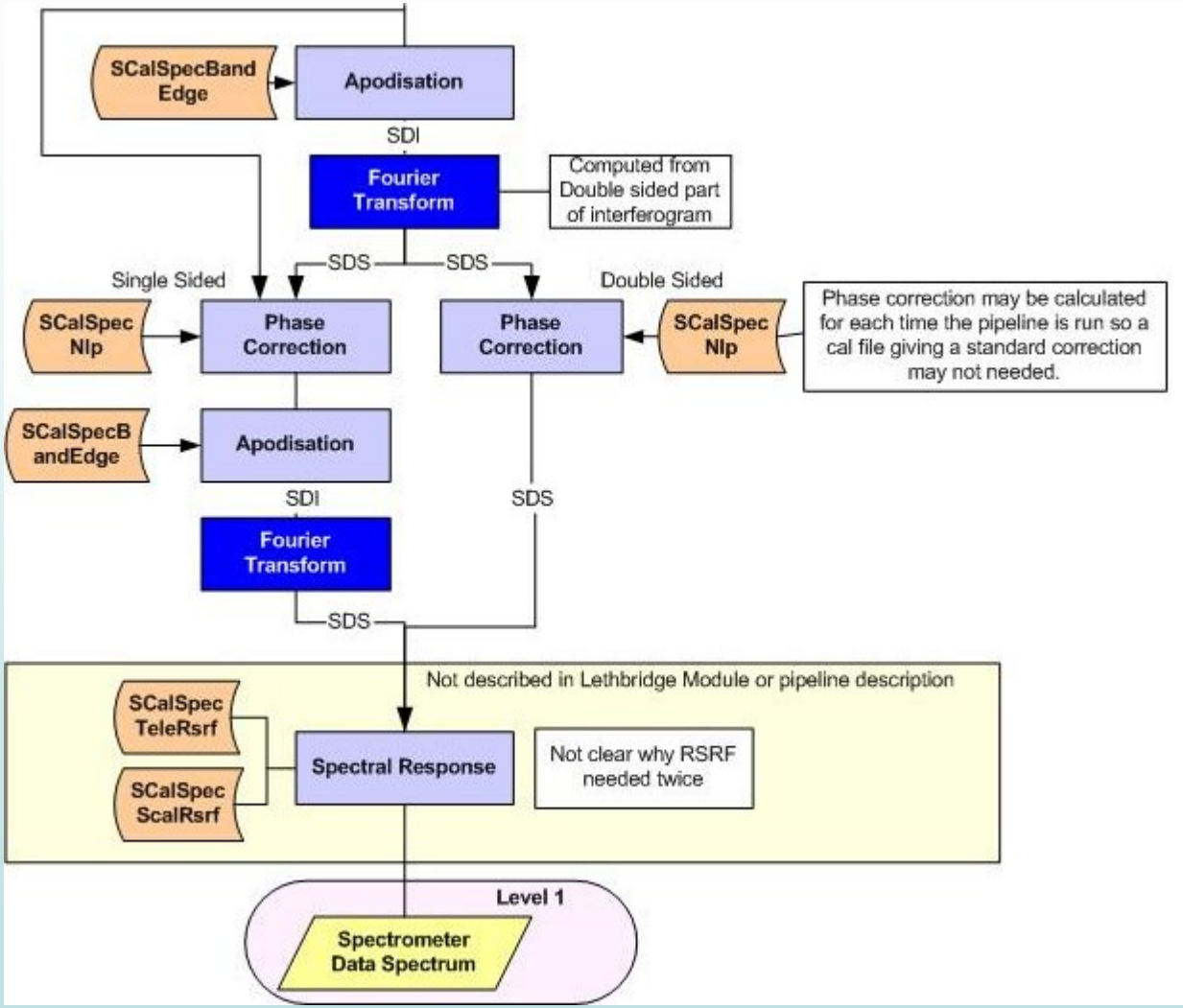
SCal and Telescope Processing



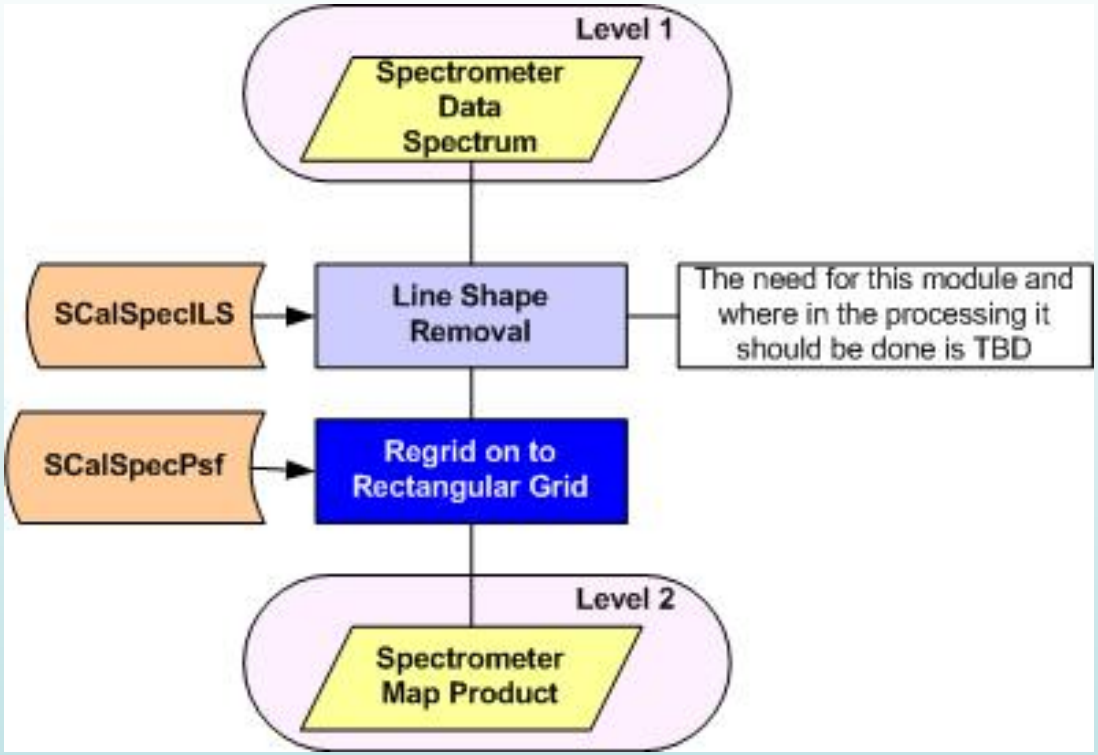
Baseline Correction



Fourier Transform



Level 2


Level 1
Spectrometer Data Spectrum
SCalSpecILS
Line Shape Removal
The need for this module and where in the processing it should be done is TBD
SCalSpecPsf
Regrid on to Rectangular Grid
Level 2
Spectrometer Map Product

SPIRE Spectrometer Data Processing Pipeline

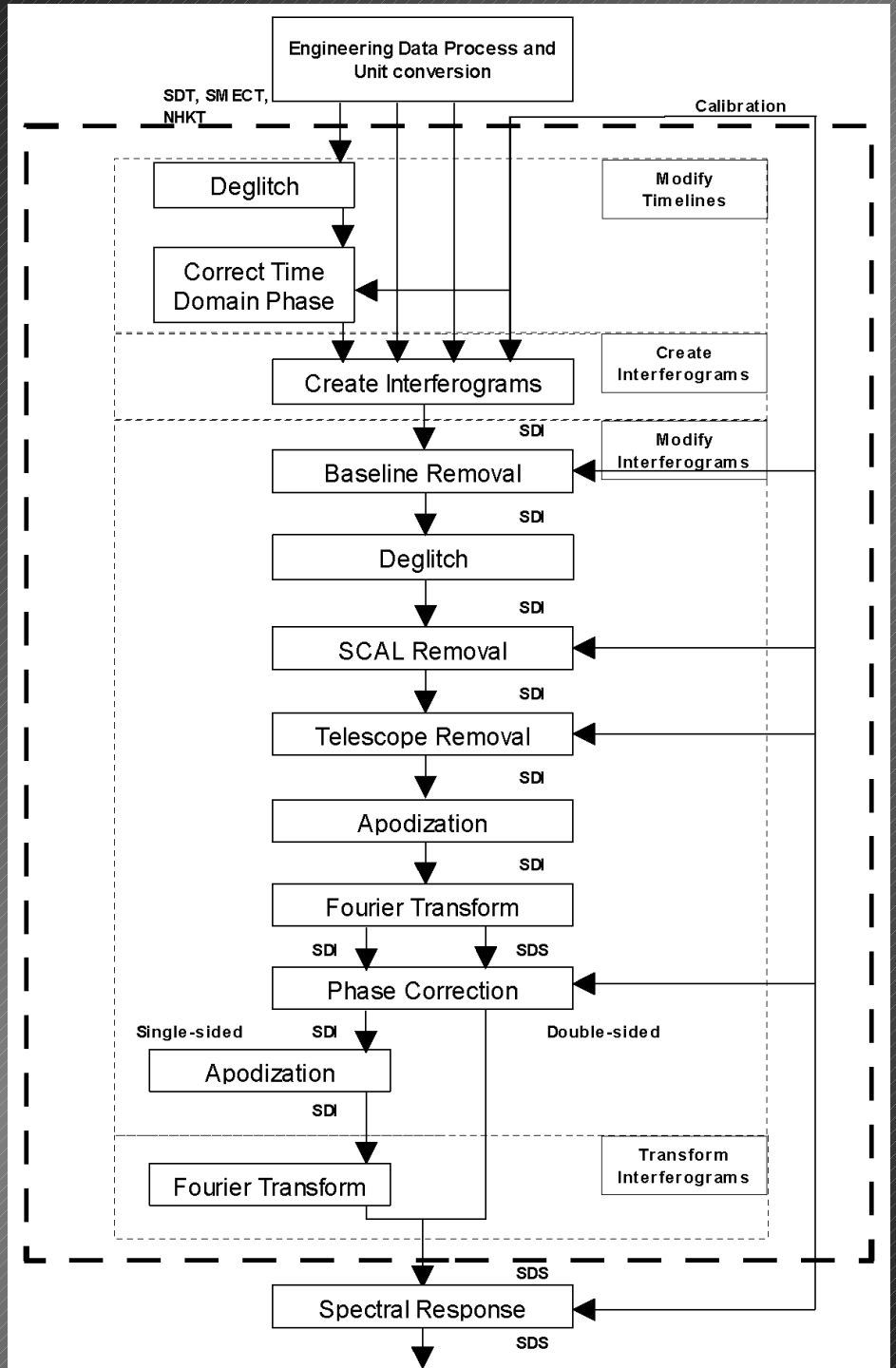
SPIRE Spectrometer Workshop

14 May 2007

Trevor Fulton

Contents

- Pipeline Module Review
  - Modify Timelines
  - Create Interferograms
  - Modify Interferograms
  - Transform Interferograms


Engineering Data Process and Unit conversion
SDT, SMECT, NHKT
Calibration
Deglitch
Modify Timelines
Correct Time Domain Phase
Create Interferograms
Create Interferograms
SDI
Modify Interferograms
Baseline Removal
SDI
Deglitch
SDI
SCAL Removal
SDI
Telescope Removal
SDI
Apodization
SDI
Fourier Transform
SDI
SDS
Phase Correction
Single-sided
SDI
Double-sided
Apodization
SDI
Transform Interferograms
Fourier Transform
SDS
Spectral Response
SDS

Pipeline Module Review

- Modify Timelines
  - Deglitching
  - Time Domain Phase Correction

Modify Timelines

- Deglitching
  - Algorithm: Implemented
  - Code: Implemented
  - Future Development:
    - Optimization (memory/speed)
    - Study how this modules could be applied to the photometer data.

Modify Timelines

- Time Domain Phase Correction
  - Algorithm: Implemented
  - Code: To be written
  - Future Development:
    - Study the effects that the source strength has on the thermal time constant.
    - Establish a set of default values.
    - Define a S/N discriminator.

Pipeline Module Review

- Create Interferograms
  - Interferogram Creation

Create Interferograms

- Create Interferograms
  - Interferogram Creation

Create Interferograms

- Interferogram Creation
  - Algorithm: Scanning Implemented, Step and Integrate to be written
  - Code: Scanning Implemented, Step and Integrate to be written
  - Future Development:
    - Implement the oversampling interpolation in Java code
    - Obliquity

Pipeline Module Review

- Modify Interferograms
  - Baseline Removal
  - Deglitching
  - SCAL Removal
  - Telescope Removal
  - Phase Correction
  - Apodization

Modify **Interferograms**

- Baseline Removal
  - Algorithm: Implemented
  - Code: Implemented
  - Future Development:
    - Change from a poly fit to a FT removal

Modify **Interferograms**

- Modulation Efficiency
  - Algorithm: Implemented
  - Code: To be written.
  - Future Development: Study this effect in more detail. Calibrate those channels fro which we have data.

Modify **Interferograms**

- Deglitching
  - Algorithm: Implemented
  - Code: Implemented
  - Future Development:
    - Compare results w/ LAM deglitching
    - Does this modules complement T-D Deglitching
    - Performance testing

Modify **Interferograms**

- SCAL Removal
  - Algorithm: Implemented
  - Code: Implemented
  - Future Development:
    - Develop the alternate method that relies on blank sky.
    - Requires many (to be quantified) PV observations of blank sky when Telescope is stable.

Modify **Interferograms**

- Telescope Removal
  - Algorithm: To be written
  - Code: To be written
  - Future Development:
    - Requires measurements of blank sky as Telescope is cooling (once every 10K change) (pointing to be specified.)

Modify **Interferograms**

- Phase Correction
  - Algorithm: Implemented
  - Code: Implemented
  - Future Development:
    -

Modify **Interferograms**

- Apodization
  - Algorithm: Implemented
  - Code: Implemented
  - Future Development:
    - Make the apodization functions widely available to Herschel

Pipeline Module Review

- Transform Interferograms
  - Fourier Transform

Transform **Interferograms**

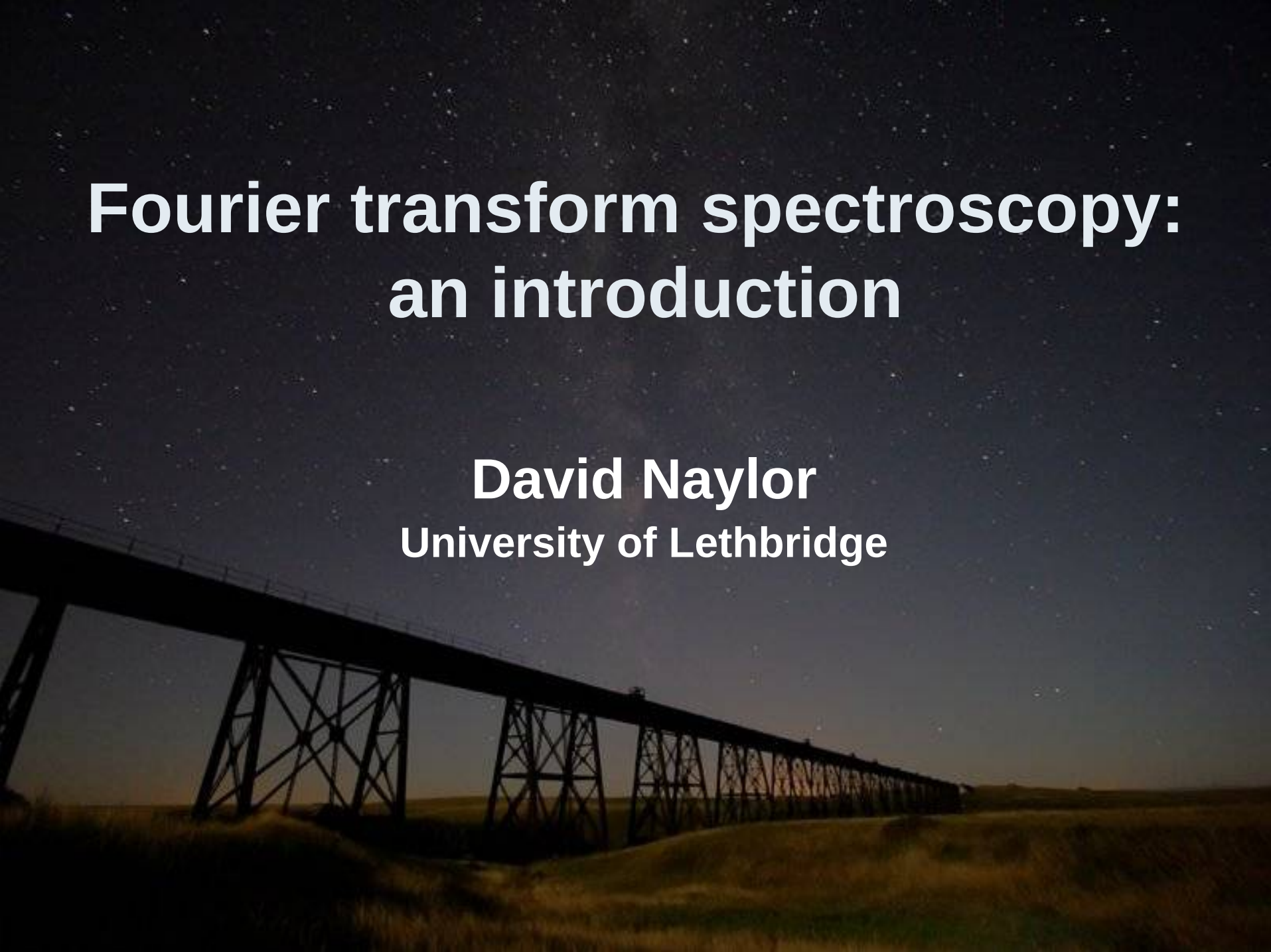
- Fourier Transform
  - Algorithm: Implemented
  - Code: Implemented
  - Future Development:
    - Make the JFFTPACK FFT widely available to Herschel

Pipeline Module Review

- Spectral Response
  - Algorithm: To be written
  - Code: To be written
  - Future Development:
    - RSRF of telescope port required.
    - Telescope defines this for extended sources. Need a calibration for point sources on-axis.
    - Should it include throughput variation?

Pipeline Module Review

- Line Shape Removal
  - Algorithm: To be Verified
  - Code: To be written
  - Future Development:
    -

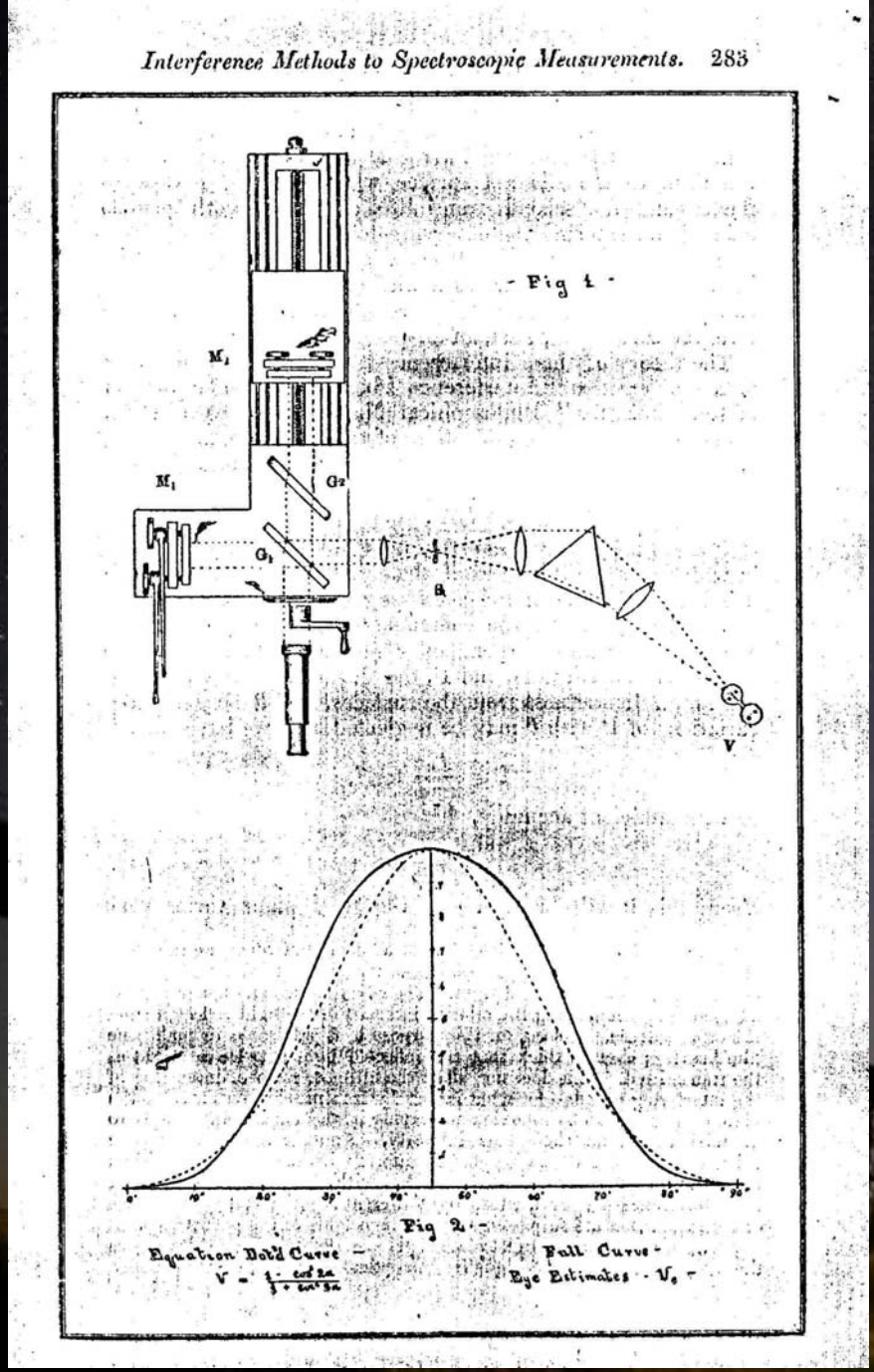


Fourier transform spectroscopy: an introduction

David Naylor
University of Lethbridge

Outline

- History
- Ideal vs real FTS
- Pros/cons
- Extension to iFTS
- Examples from toy iFTS project


Interference Methods to Spectroscopic Measurements. 285

- Fig 1 -

M1

M2

G2

G1

B

V

- Fig 2. -

Equation Dotted Curve -

Full Curve -

Eye Estimates - V_e -

Michelson's original FTS design and measurements (1892)

XLVII. *On the Interference Bands of Approximately Homogeneous Light; in a Letter to* Prof. A. MICHELSON. *By* Lord RAYLEIGH, *Sec. R.S.**

Dear Prof. MICHELSON,

WHEN we were discussing together the results of your interesting work upon high interference, you asked my opinion upon one or two questions connected therewith. I have delayed answering until I had the opportunity of seeing your paper in print (Phil. Mag. Sept. 1892), but now I may as well send you what I have to say.

First, as to the definiteness with which the character of

* Communicated by the Author.

Lord Rayleigh's response (1892)

Your results seem already to interpose serious obstacles in the way of accepting such a conclusion; and the fact that light may thus be thrown upon a much controverted question in molecular physics is only another proof of the importance of the research upon which you are engaged.

I am,

Yours very truly,

RAYLEIGH.

September 23, 1892.

Historical Background

1890 - Michelson invented the interferometer, discovered several multiplets and found the red cadmium line to be extremely narrow.

1911 - Rubens and Wood recorded the first interferogram.

1949 - Fellgett performed the first computation of Fourier transform and recognized the multiplex advantage of FTS.

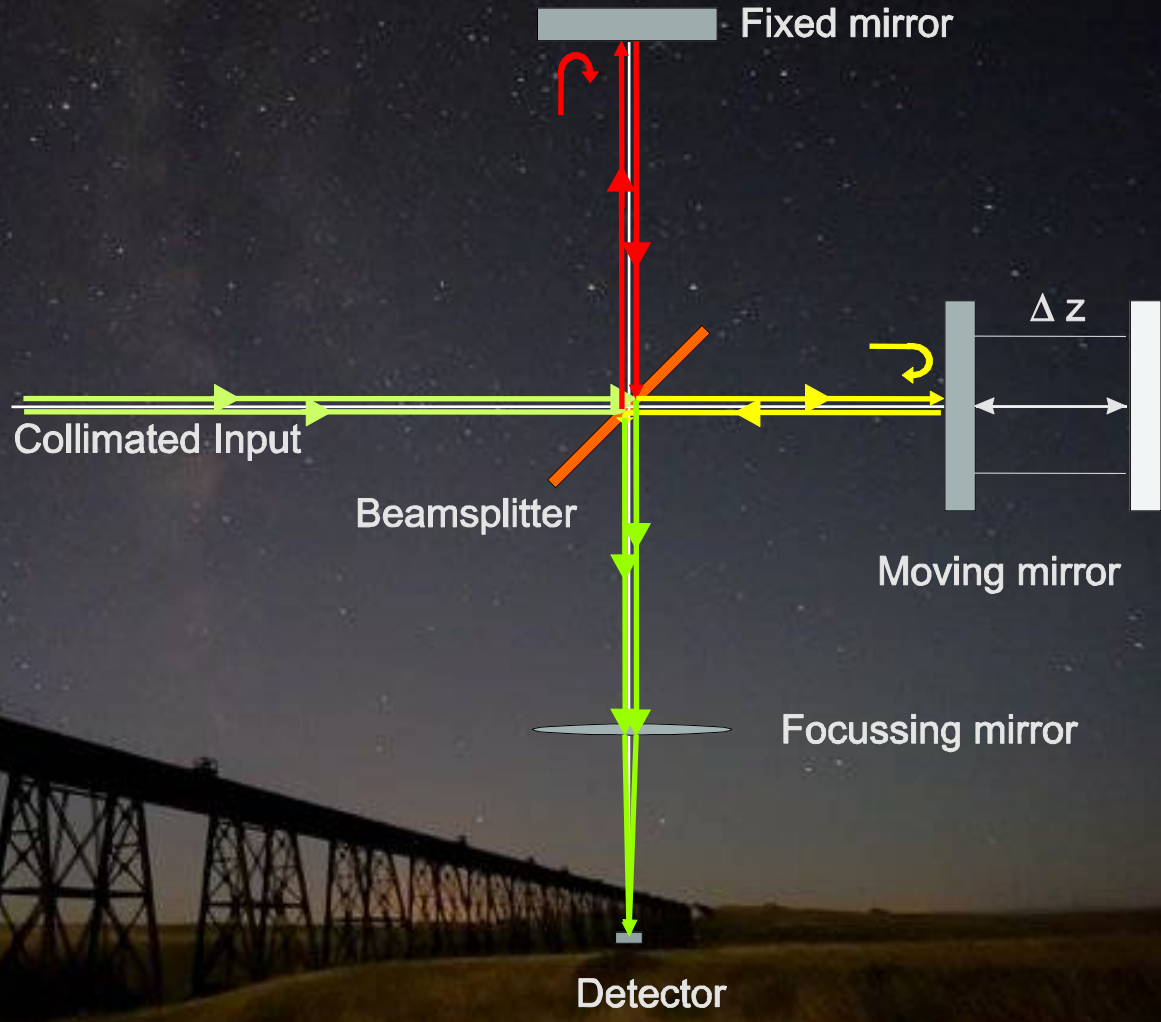
1950 - Jacquinot advantage recognized. Area x solid angle (throughput, étendue, light grasp) of an FTS much higher than dispersive spectrometers

1950 - 1965 FTS used only by those who could not obtain their measurements by conventional spectroscopic techniques (Connes, Fellgett, Gebbie, Mertz)

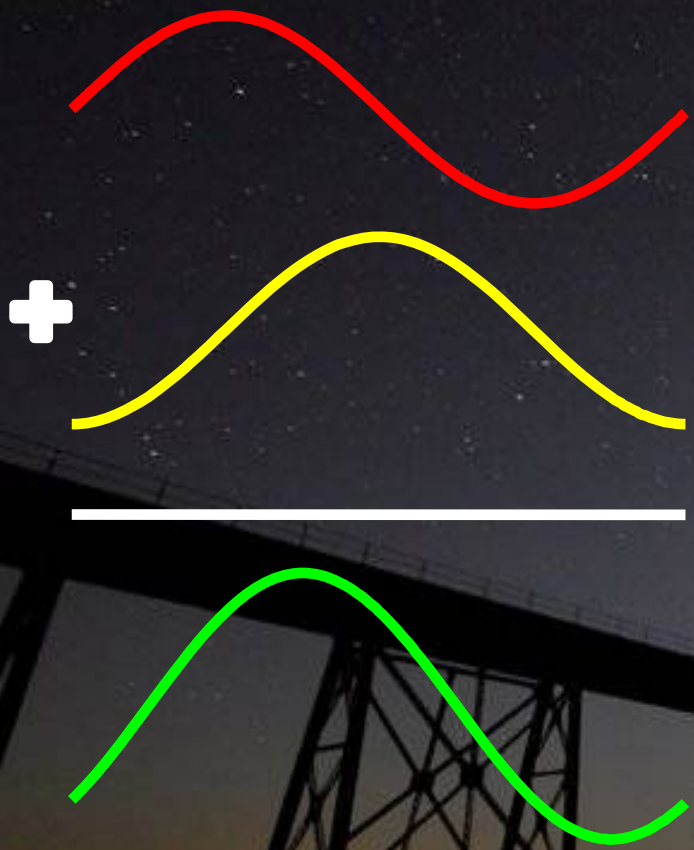
1965 - Cooley-Tukey (re) invented Fast Fourier Transform algorithm (FFT). Time to compute Fourier transform reduced from days to minutes

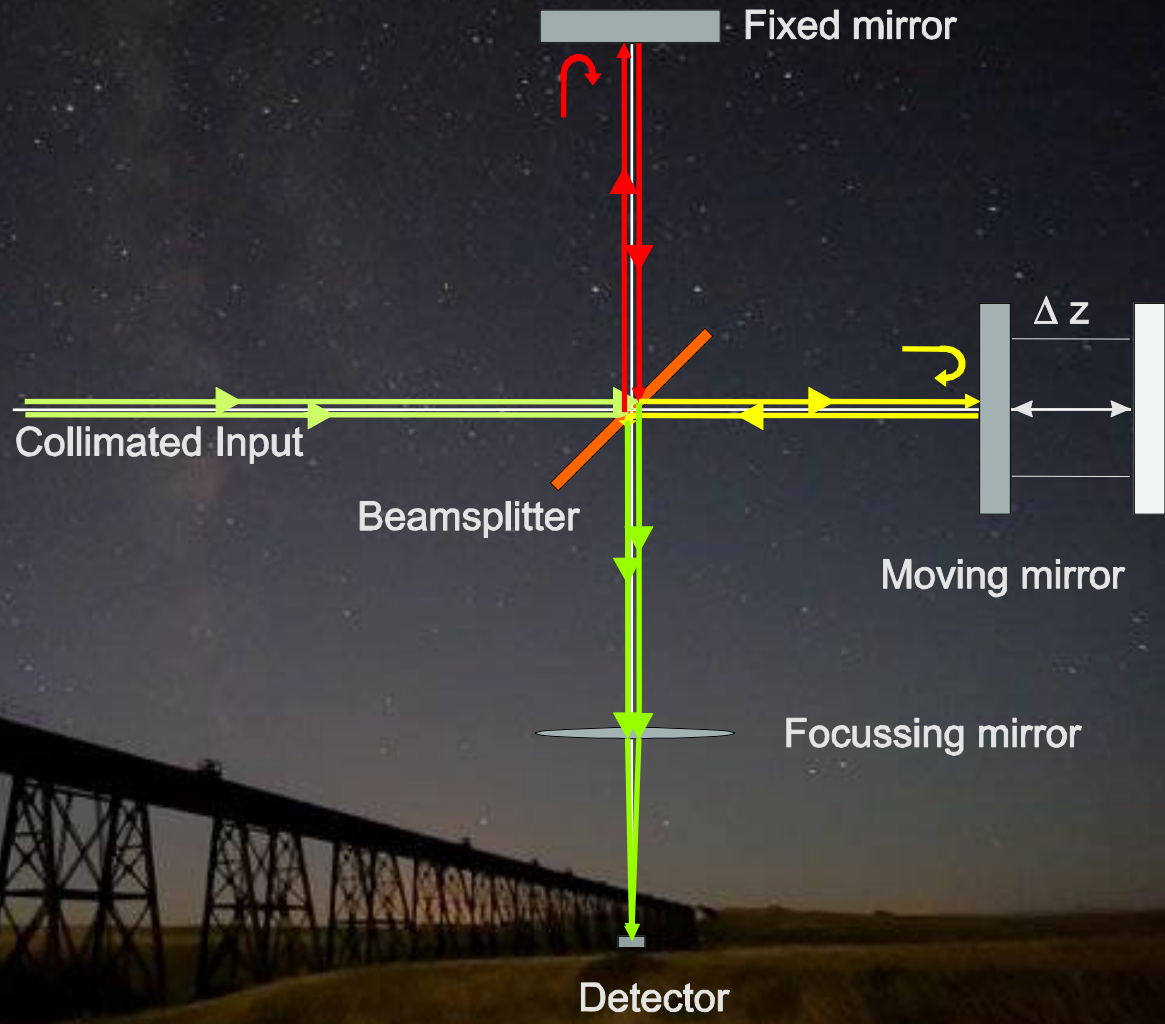
Over the last 40 years FTS have moved from the specialized domain of the physics laboratory and are now found as standard diagnostic tools in many branches of science and industry.

Michelson interferometer

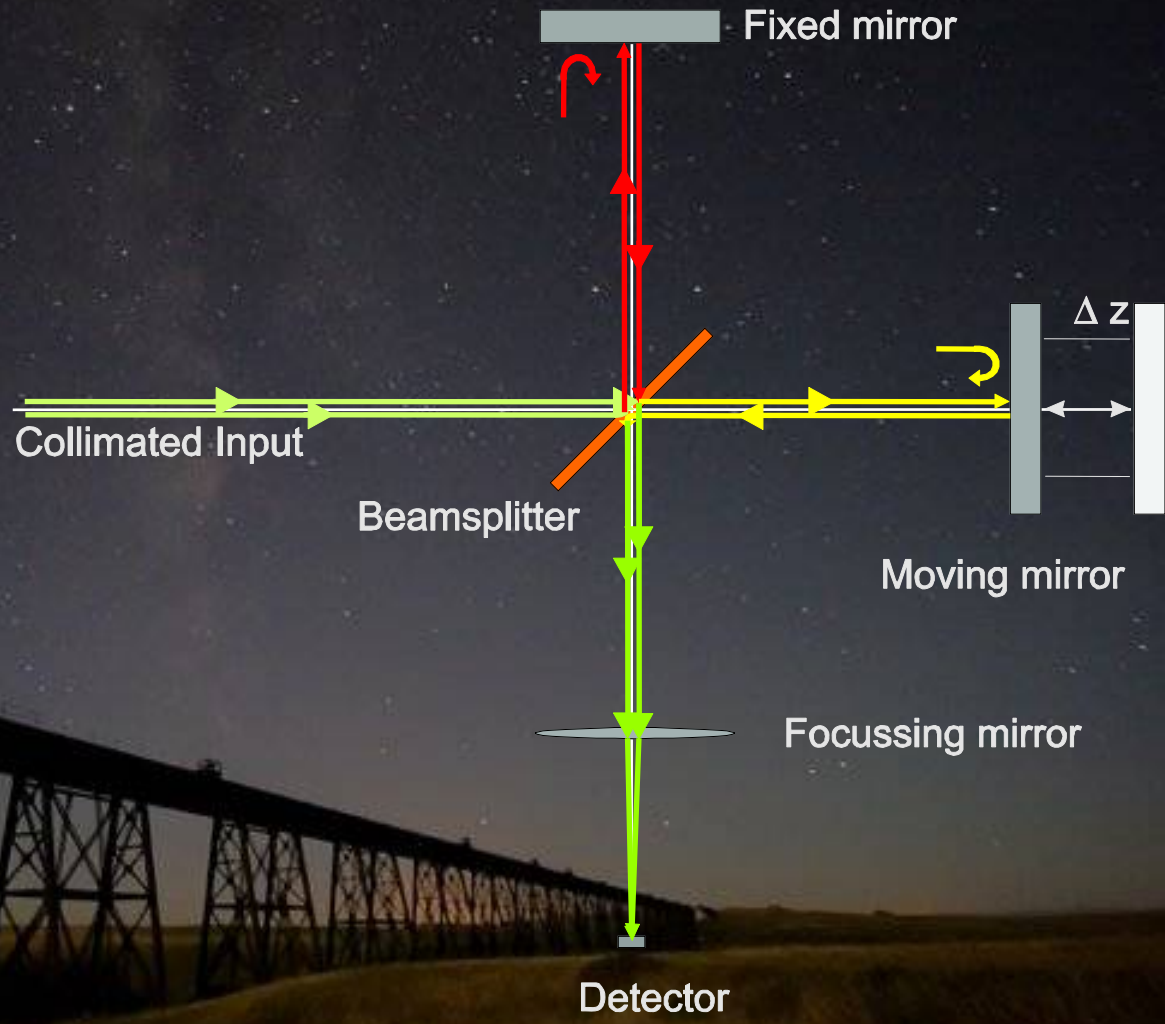


Michelson interferometer

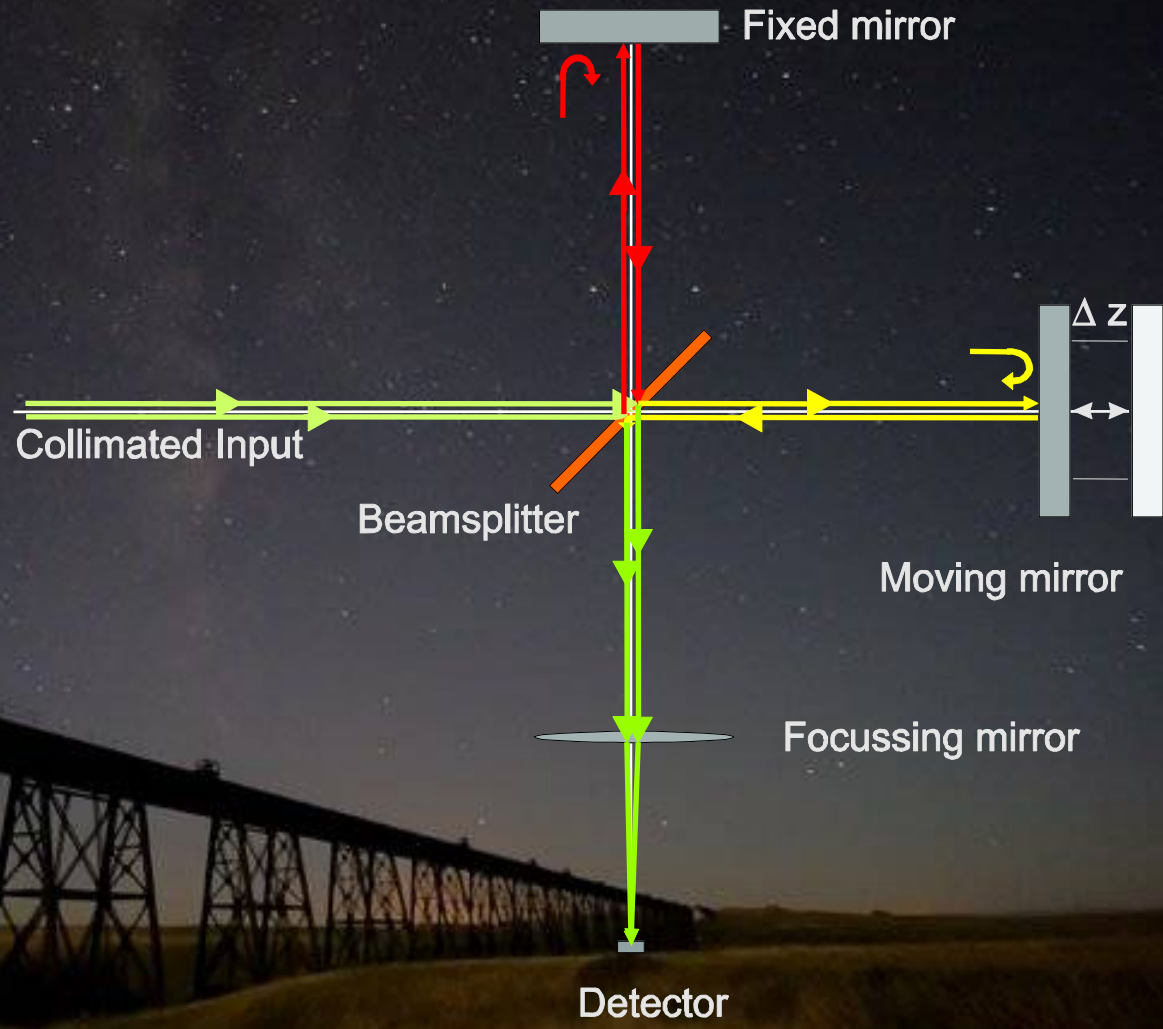




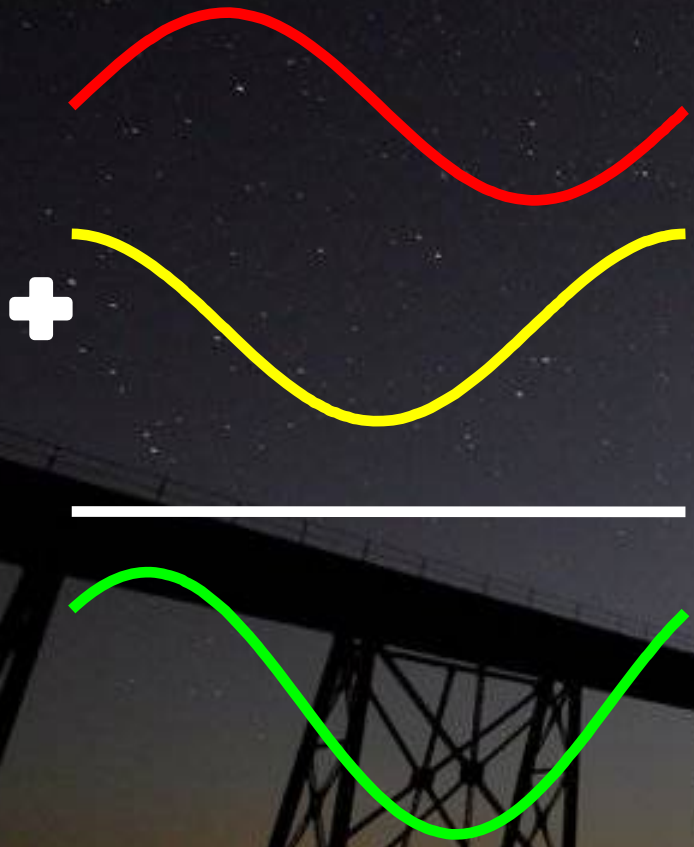
Michelson interferometer

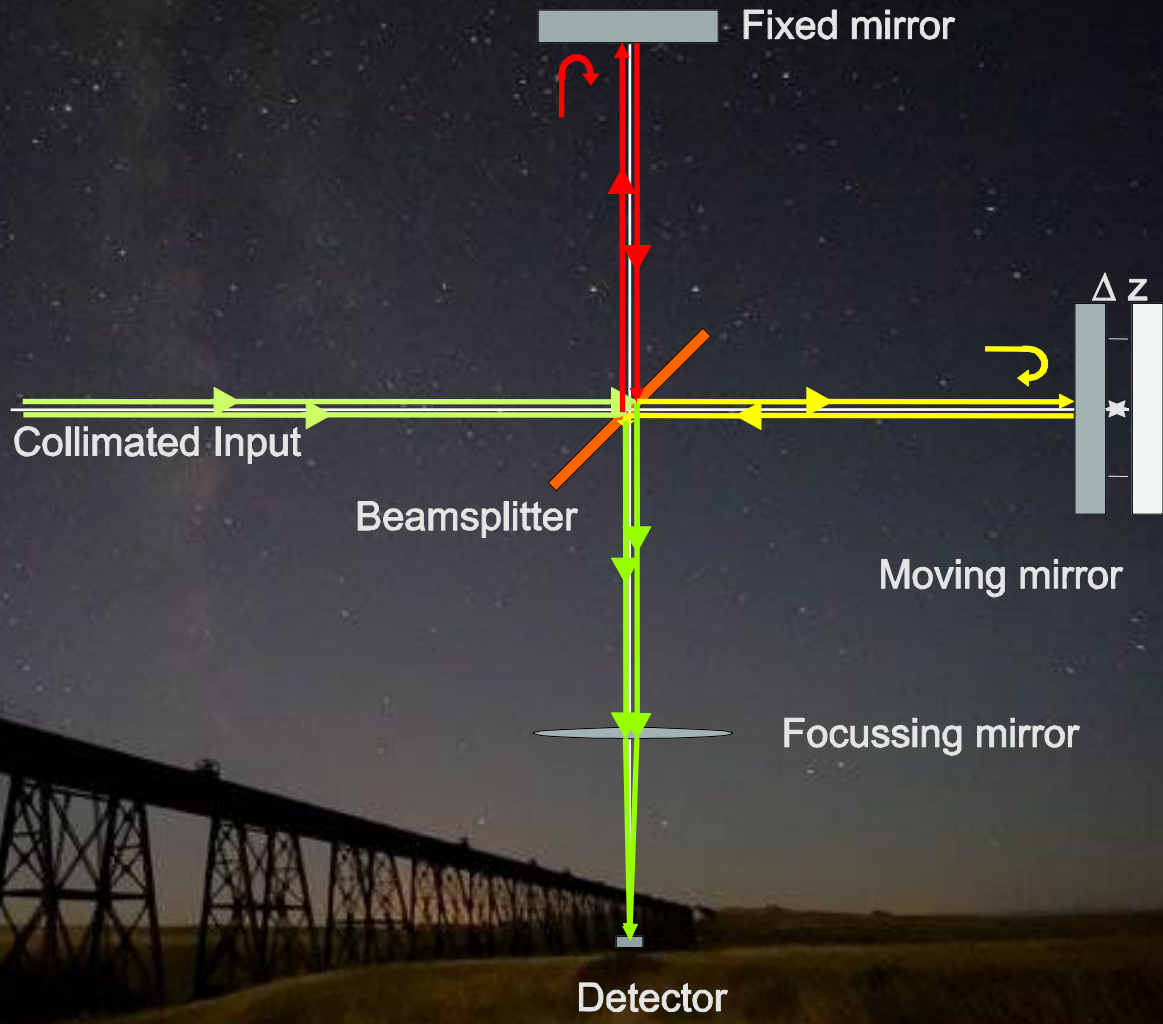


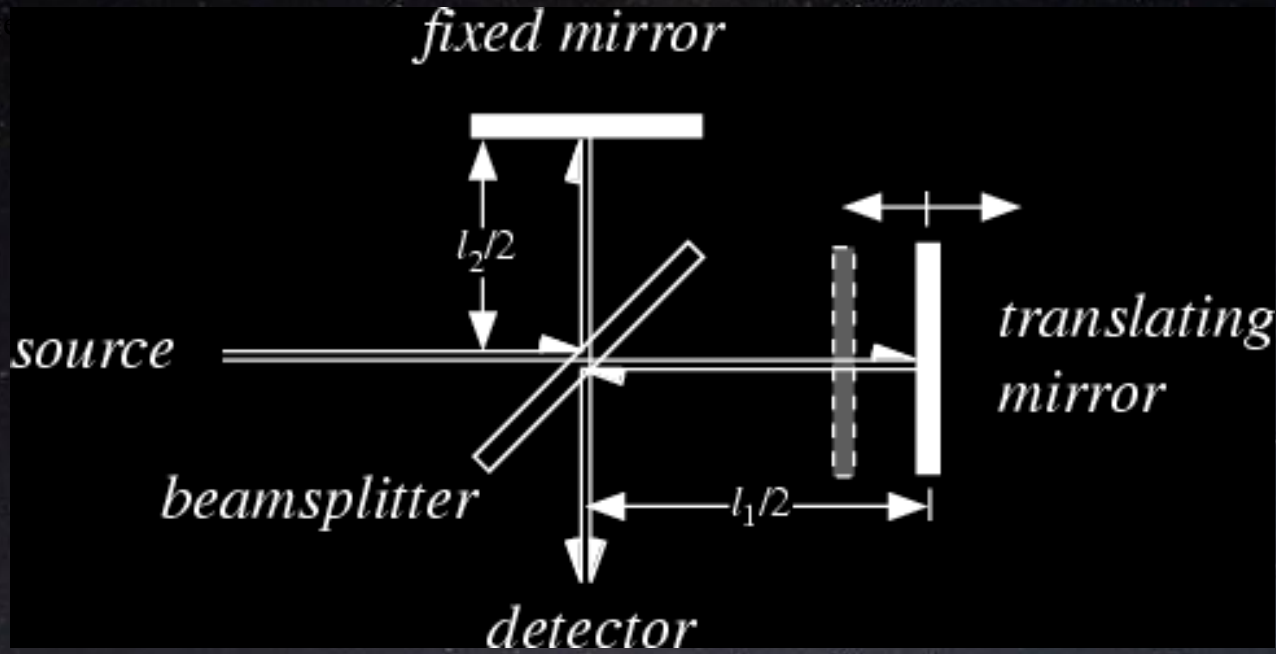
Michelson interferometer



Michelson interferometer





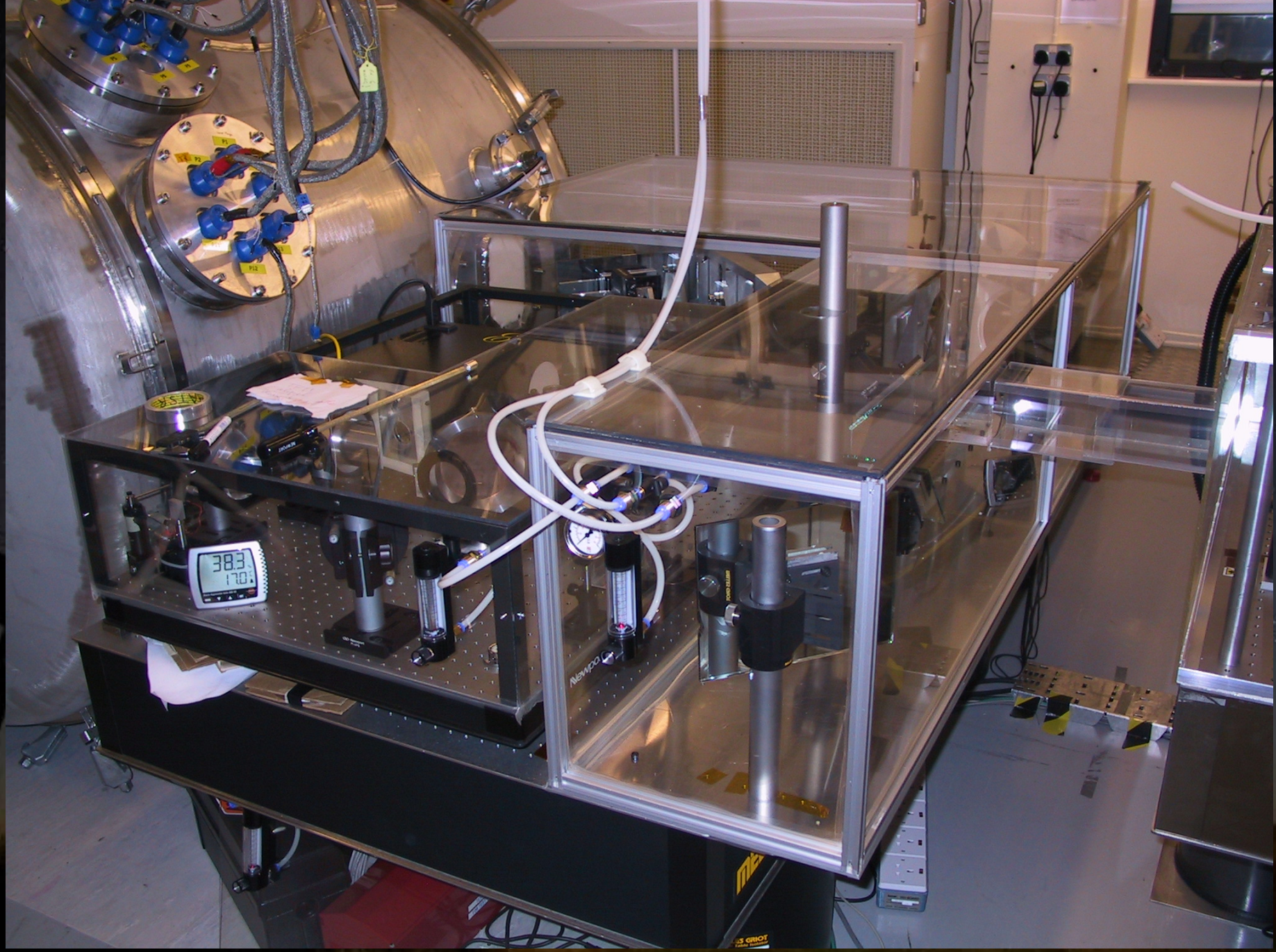


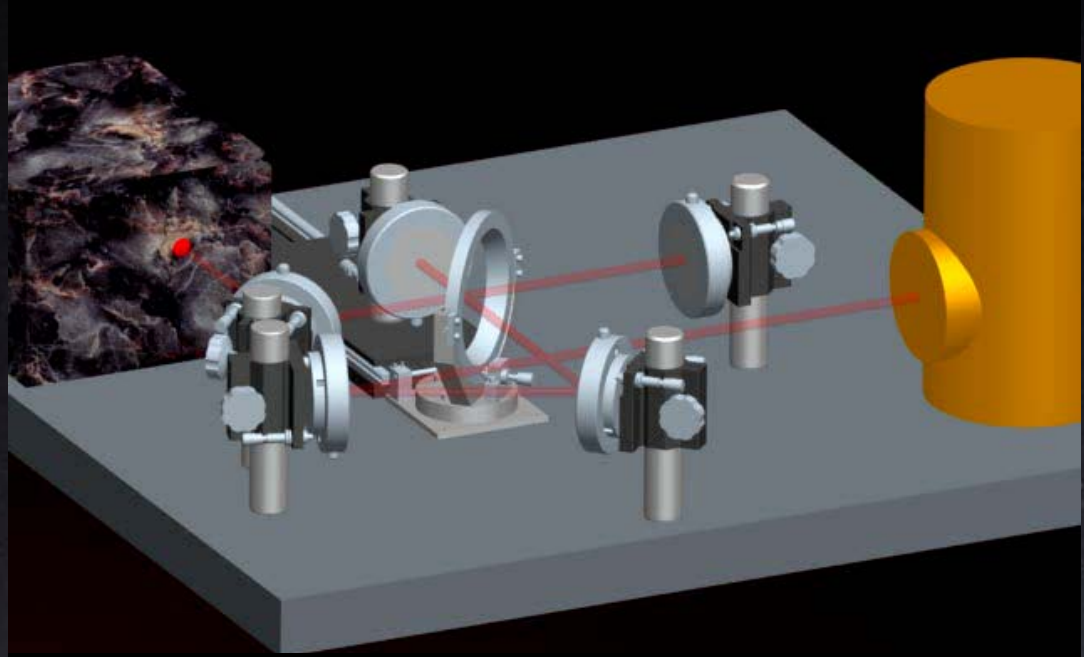
$$B(\sigma) = \int I(\delta) \cos 2\pi\sigma\delta \, d\delta$$

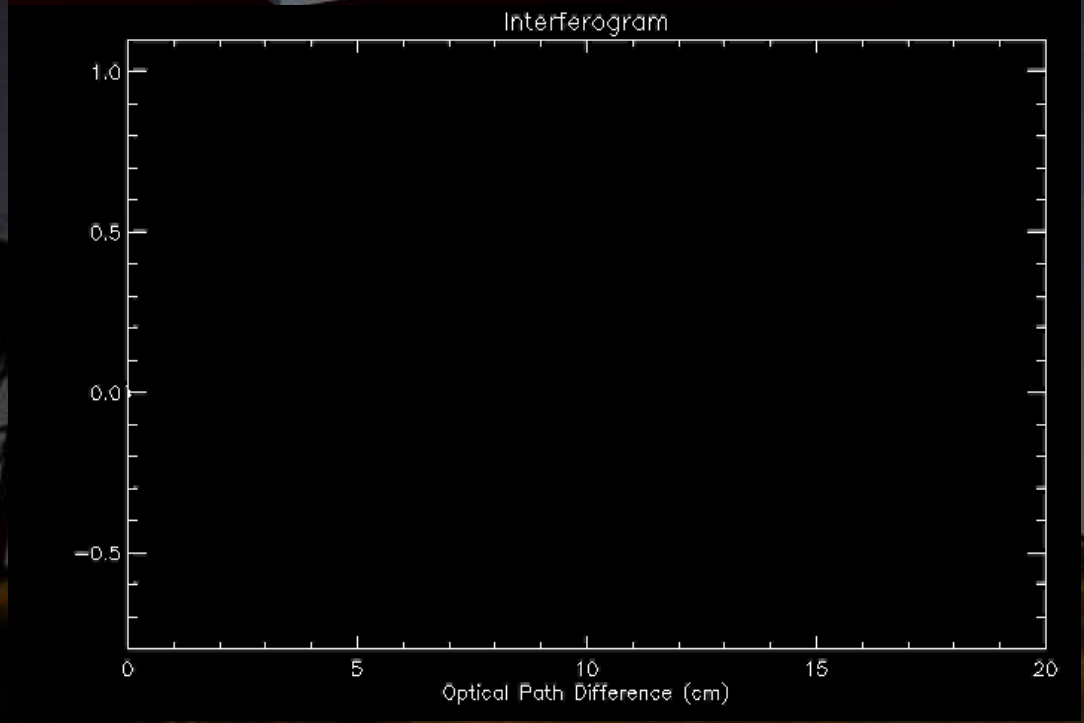
$$I'(\delta) = \int B(\sigma) \exp(i\varphi(\sigma))\exp(i2\pi\sigma\delta) \, d\sigma$$

$$\varphi_{total} = \varphi_{zpd} + \varphi_{electrical} + \varphi_{optical} + \varphi_{random}$$

Michelson interferometer


38.3
17.0




Interferogram
1.0
0.5
0.0
−0.5
0
5
10
15
20
Optical Path Difference (cm)

Advantages of Fourier spectroscopy

- Relatively simple opto-mechanical design
- High throughput (Jacquinot)
- Simultaneous measurements of all wavelengths (Felgett)
- Intrinsic Wavelength calibration (Connes)
- Best instrumental line shape function of any spectrometer

Disadvantages of Fourier spectroscopy

- Sensitivity to fluctuations in source intensity
- Multiplex disadvantage under background limited conditions
- Complex math required for analysis

Some general issues

- Dynamic Range
- Beamsplitter
- Detector feed optics
- Misaligned Mirrors
- Mirror Drive
- Channel Fringes

Instrument Line Shape

$$B(\sigma) = 2A\int_{-L}^{L} \cos(2\pi\sigma_0 x)\exp(-i2\pi\sigma x)dx$$

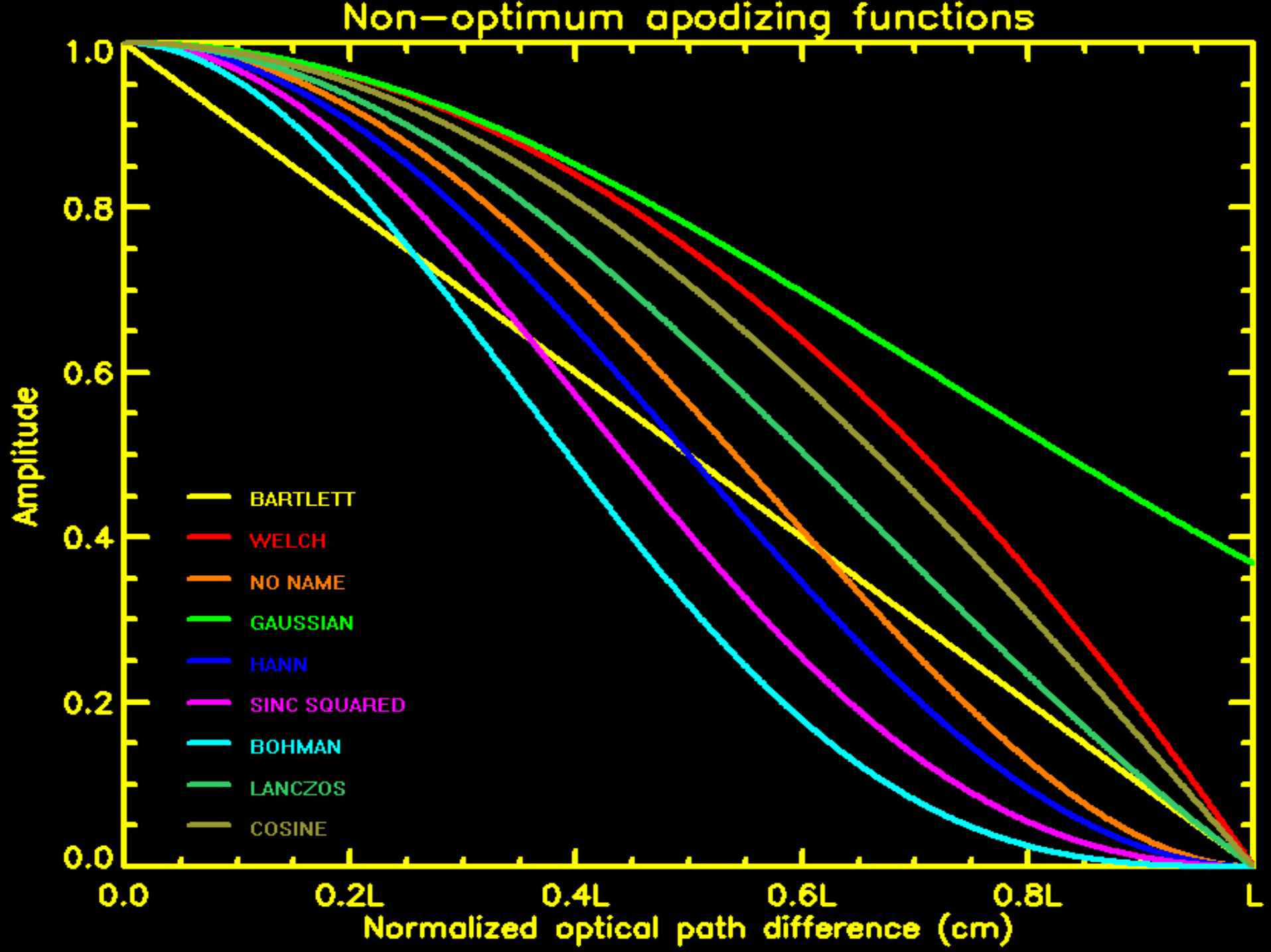
$$B(\sigma) = 2A\left[\int_0^L \cos 2\pi(\sigma_0+\sigma)x\,dx) + \int_0^L \cos 2\pi(\sigma_0-\sigma)x\,dx\right]$$

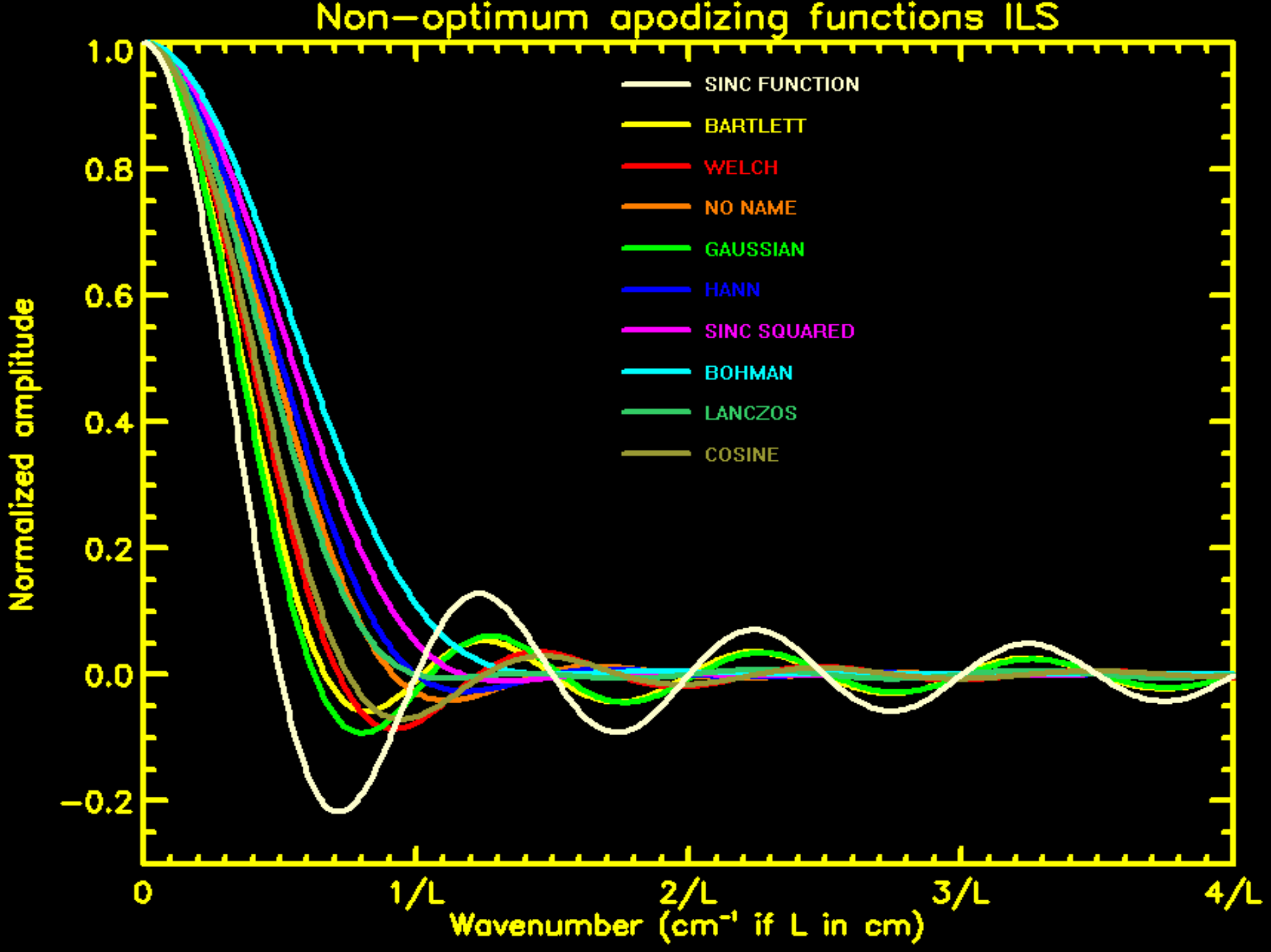
$$B(\sigma) = 2A\left[\frac{\sin[2\pi(\sigma_0+\sigma)L]}{2\pi(\sigma_0+\sigma)} + \frac{\sin[2\pi(\sigma_0-\sigma)L]}{2\pi(\sigma_0-\sigma)}\right]$$

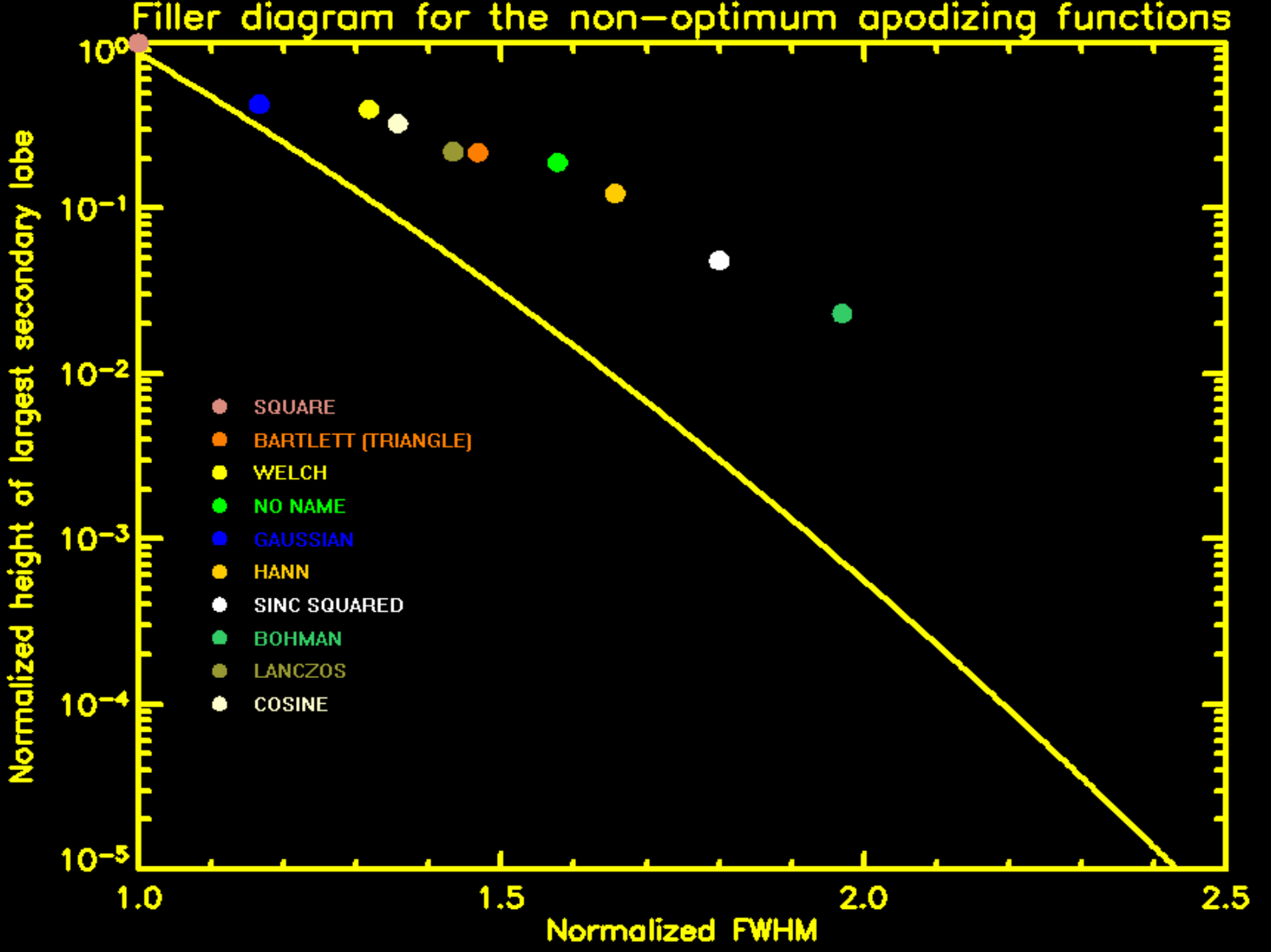
Rapidly decays

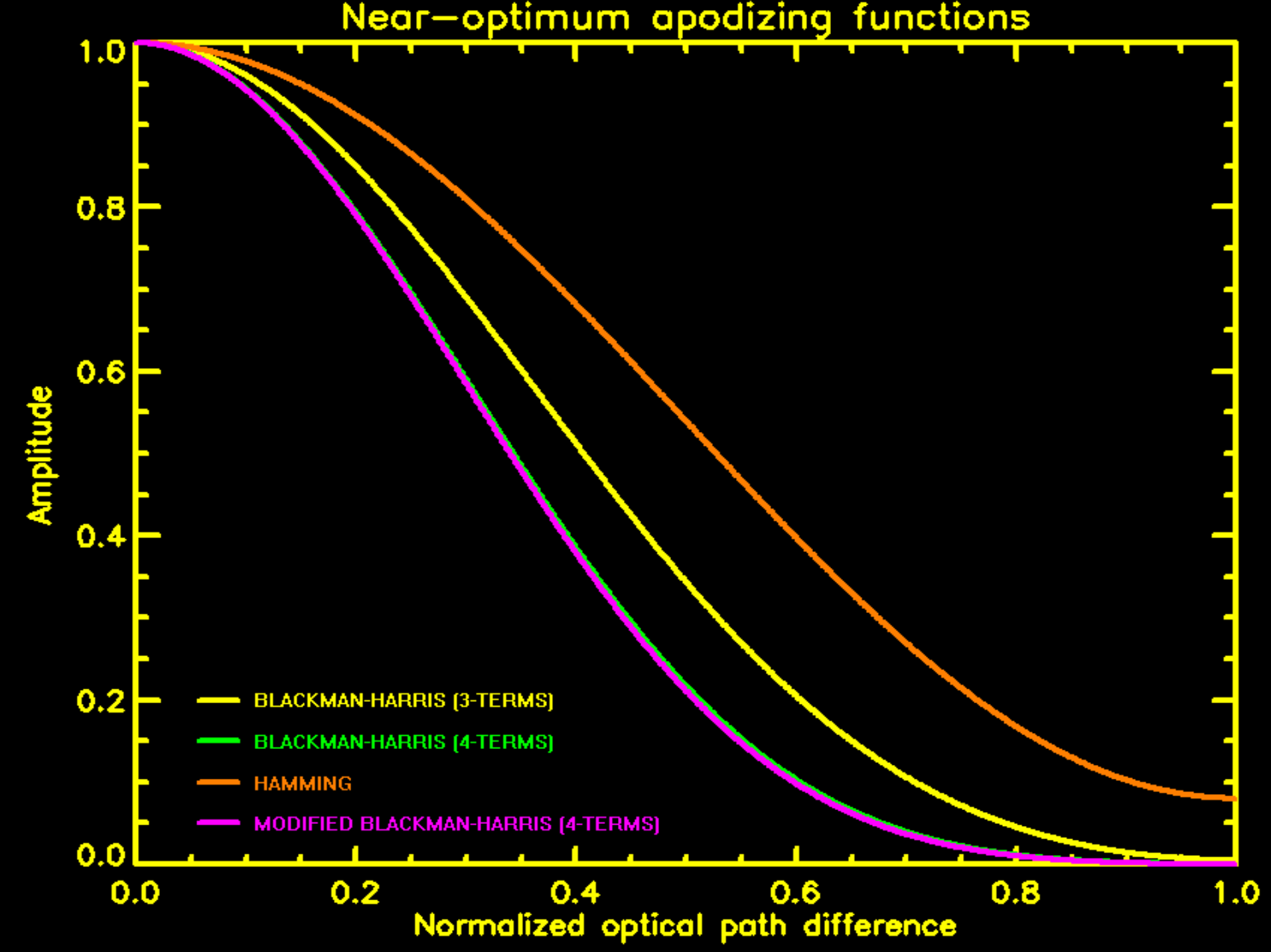
Sinc ILS

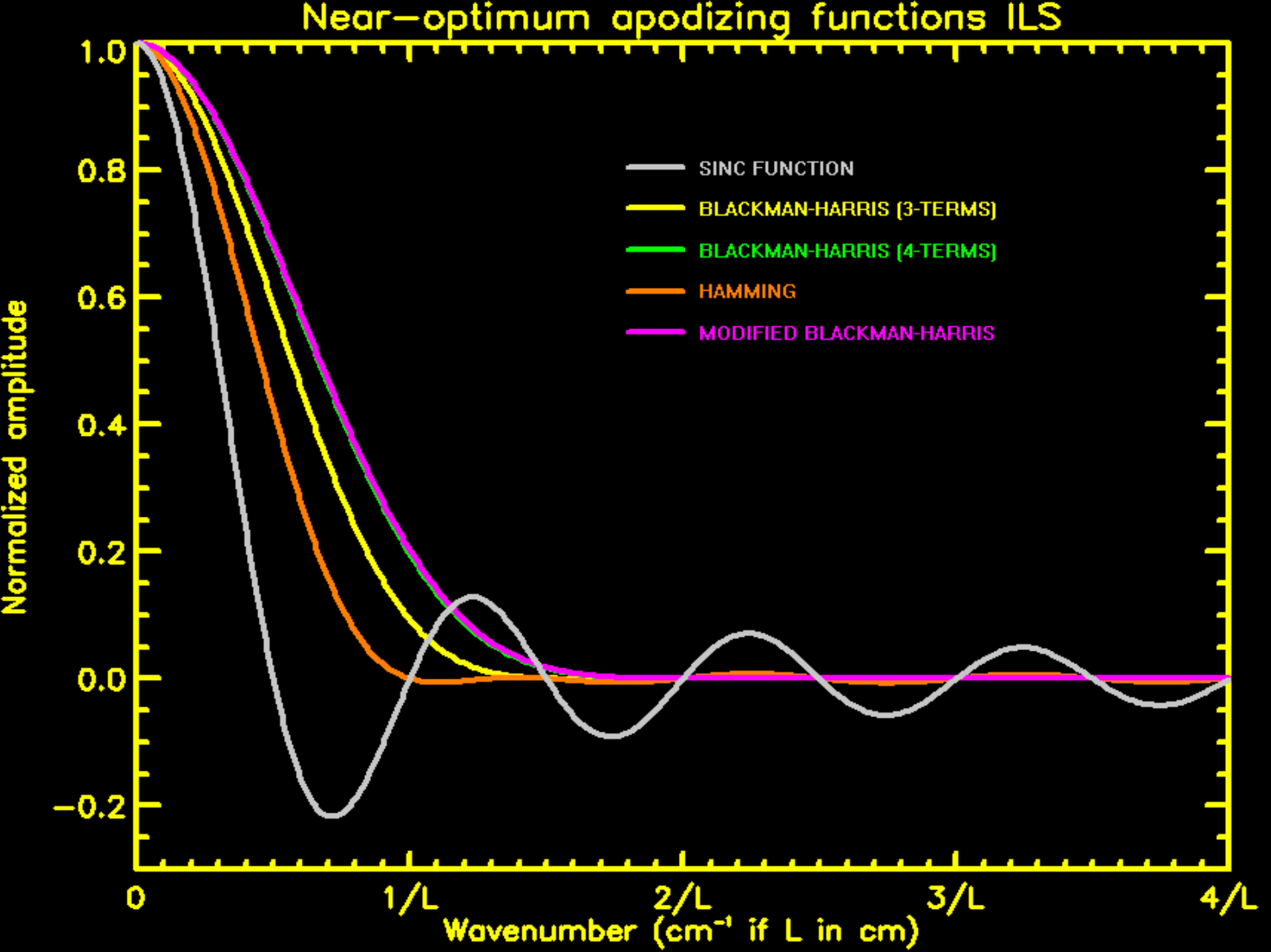
First zero of this function occurs at δσ = 1/2L
In terms of FWHM δσ = 1.207/2L

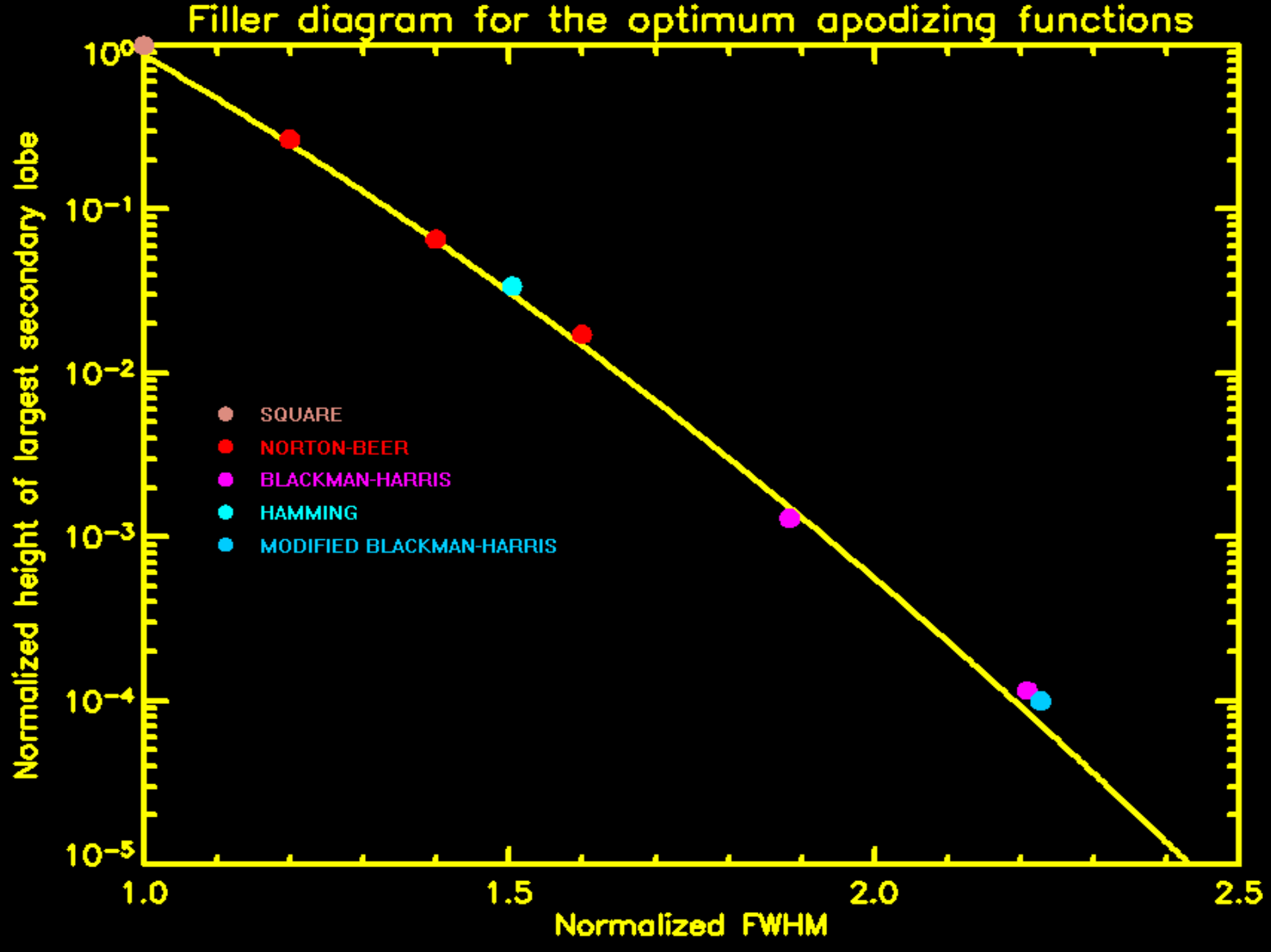

Non-optimum apodizing functions
1.0
0.8
0.6
0.4
0.2
0.0
Amplitude
BARTLETT
WELCH
NO NAME
GAUSSIAN
HANN
SINC SQUARED
BOHMAN
LANCZOS
COSINE
0.0
0.2L
0.4L
0.6L
0.8L
L
Normalized optical path difference (cm)

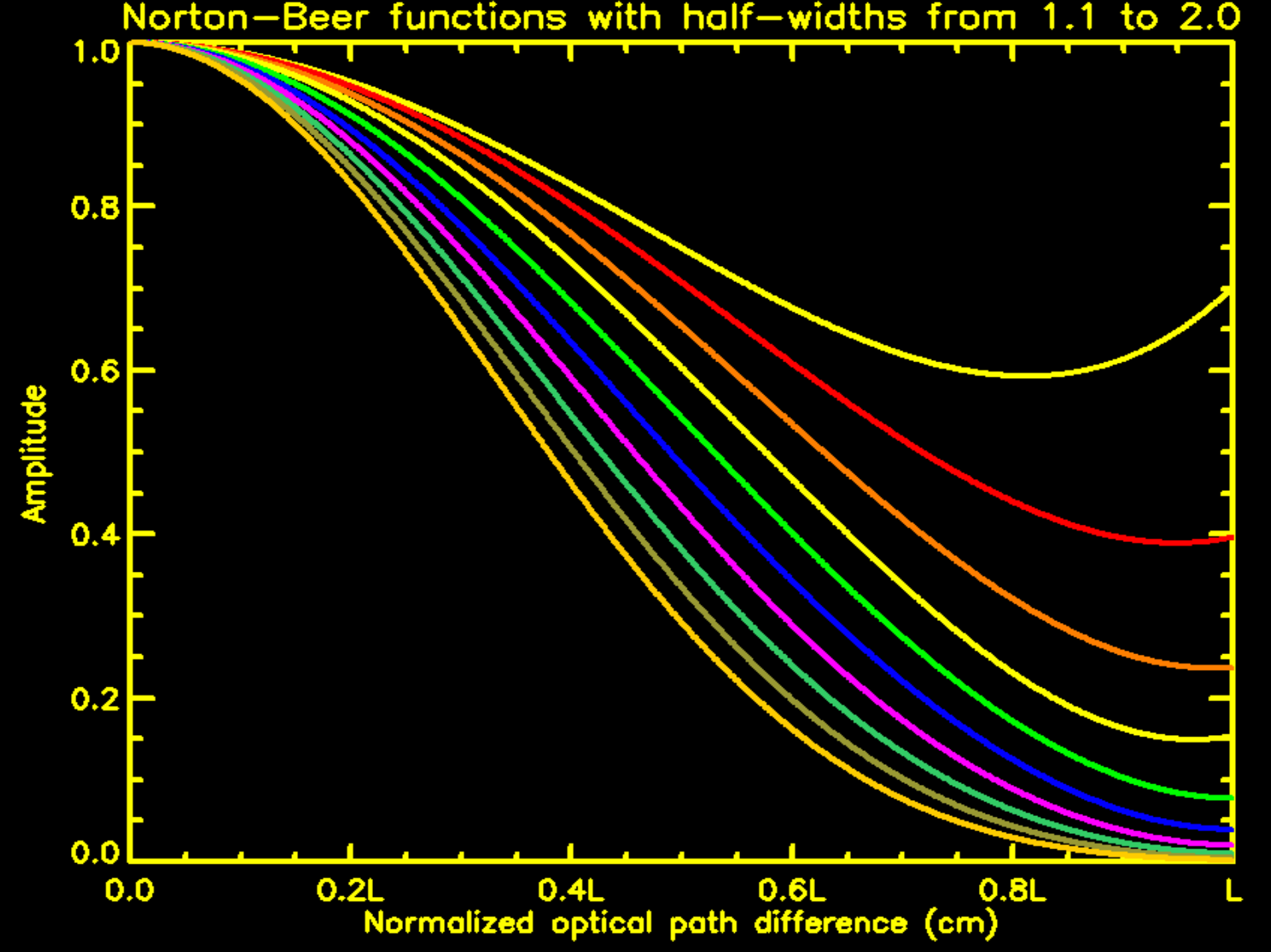

Non−optimum apodizing functions ILS
SINC FUNCTION
BARTLETT
WELCH
NO NAME
GAUSSIAN
HANN
SINC SQUARED
BOHMAN
LANCZOS
COSINE
Normalized amplitude
1.0
0.8
0.6
0.4
0.2
0.0
−0.2
0
1/L
2/L
3/L
4/L
Wavenumber (cm⁻¹ if L in cm)

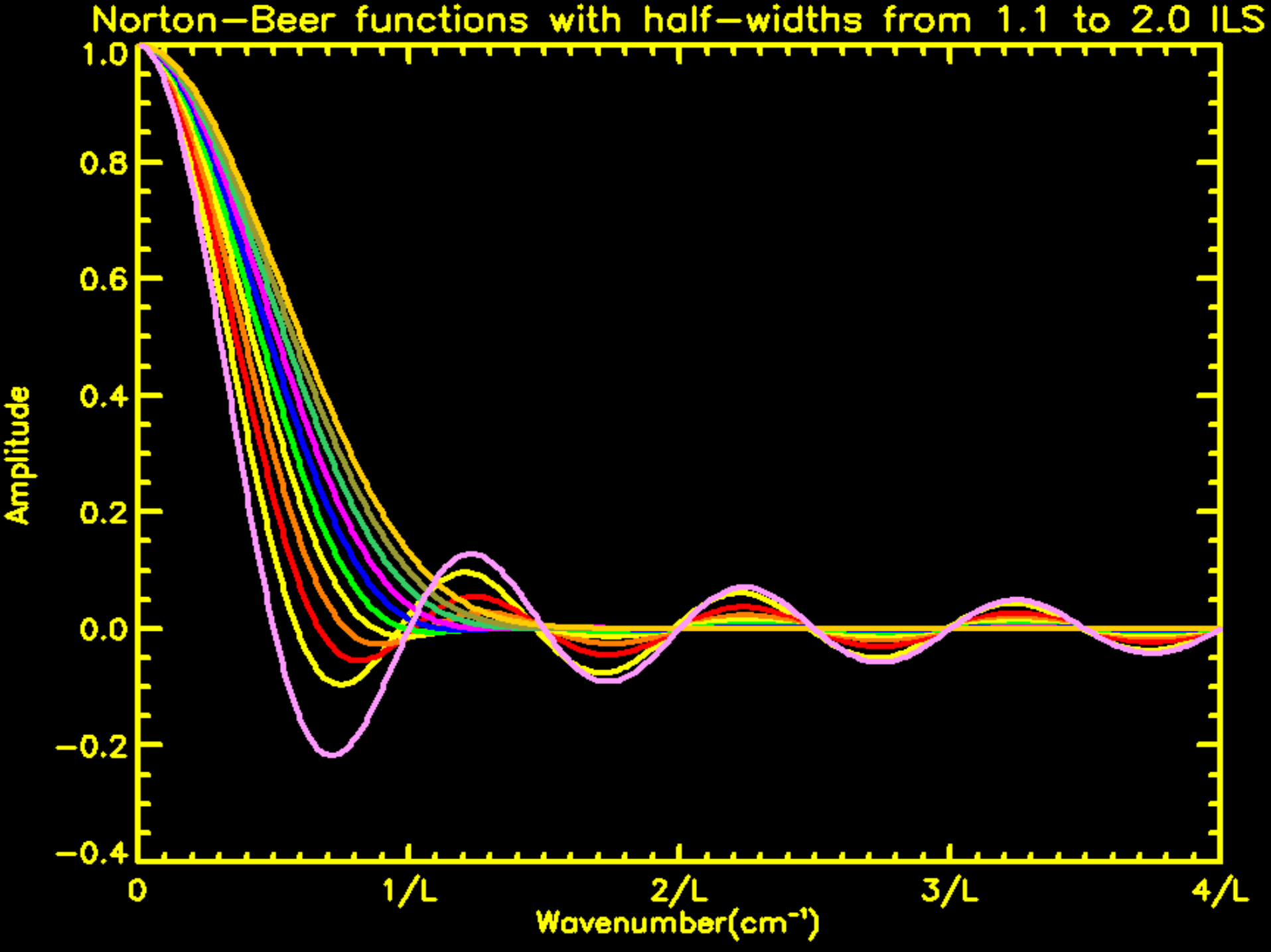

Filler diagram for the non-optimum apodizing functions
Normalized height of largest secondary lobe
Normalized FWHM
10^0
10^-1
10^-2
10^-3
10^-4
10^-5
1.0
1.5
2.0
2.5
SQUARE
BARTLETT (TRIANGLE)
WELCH
NO NAME
GAUSSIAN
HANN
SINC SQUARED
BOHMAN
LANCZOS
COSINE

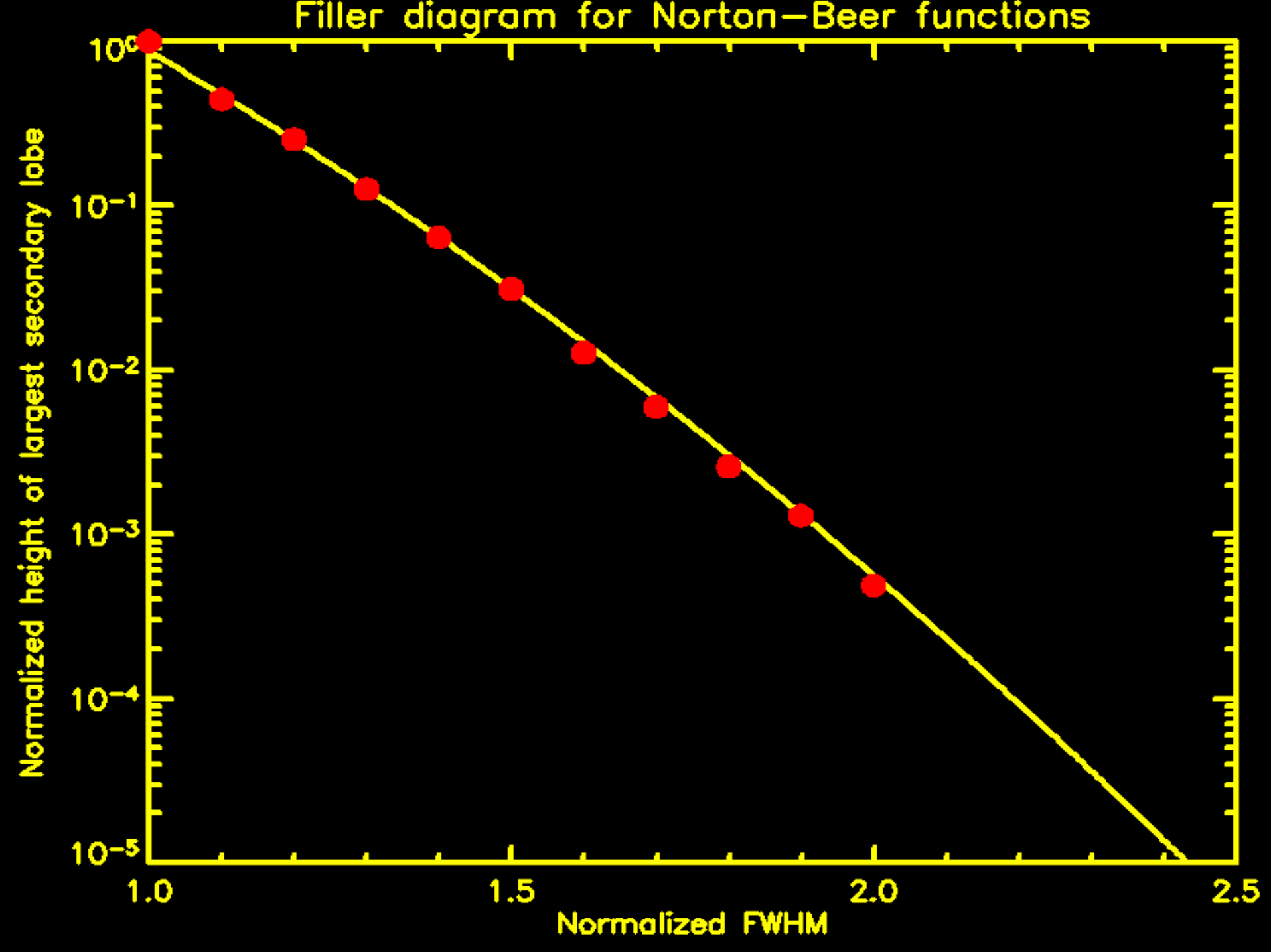

Near−optimum apodizing functions
1.0
0.8
0.6
0.4
0.2
0.0
Amplitude
BLACKMAN-HARRIS (3-TERMS)
BLACKMAN-HARRIS (4-TERMS)
HAMMING
MODIFIED BLACKMAN-HARRIS (4-TERMS)
0.0
0.2
0.4
0.6
0.8
1.0
Normalized optical path difference


Near−optimum apodizing functions ILS
SINC FUNCTION
BLACKMAN-HARRIS (3-TERMS)
BLACKMAN-HARRIS (4-TERMS)
HAMMING
MODIFIED BLACKMAN-HARRIS
Normalized amplitude
1.0
0.8
0.6
0.4
0.2
0.0
−0.2
0
1/L
2/L
3/L
4/L
Wavenumber (cm⁻¹ if L in cm)


Filler diagram for the optimum apodizing functions
Normalized height of largest secondary lobe
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
SQUARE
NORTON-BEER
BLACKMAN-HARRIS
HAMMING
MODIFIED BLACKMAN-HARRIS
1.0
1.5
2.0
2.5
Normalized FWHM


Norton–Beer functions with half–widths from 1.1 to 2.0
1.0
0.8
0.6
0.4
0.2
0.0
Amplitude
0.0
0.2L
0.4L
0.6L
0.8L
L
Normalized optical path difference (cm)


Norton–Beer functions with half–widths from 1.1 to 2.0 ILS
1.0
0.8
0.6
0.4
0.2
0.0
−0.2
−0.4
Amplitude
0
1/L
2/L
3/L
4/L
Wavenumber(cm⁻¹)


Filler diagram for Norton–Beer functions
Normalized height of largest secondary lobe
10^0
10^-1
10^-2
10^-3
10^-4
10^-5
1.0
1.5
2.0
2.5
Normalized FWHM

Phase correction

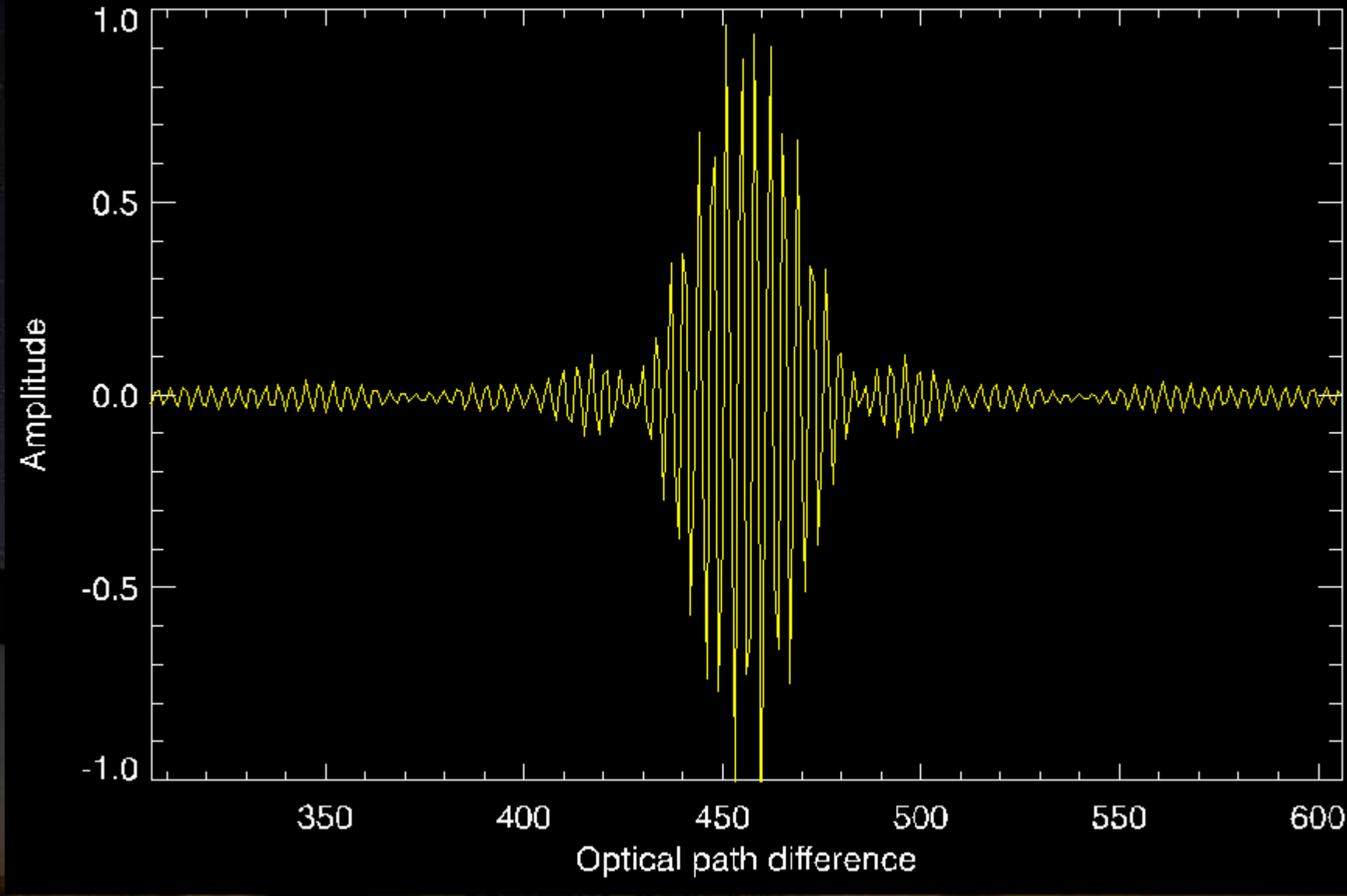
Goal: to correct for phase errors that arise from electrical, optical and sampling effects.

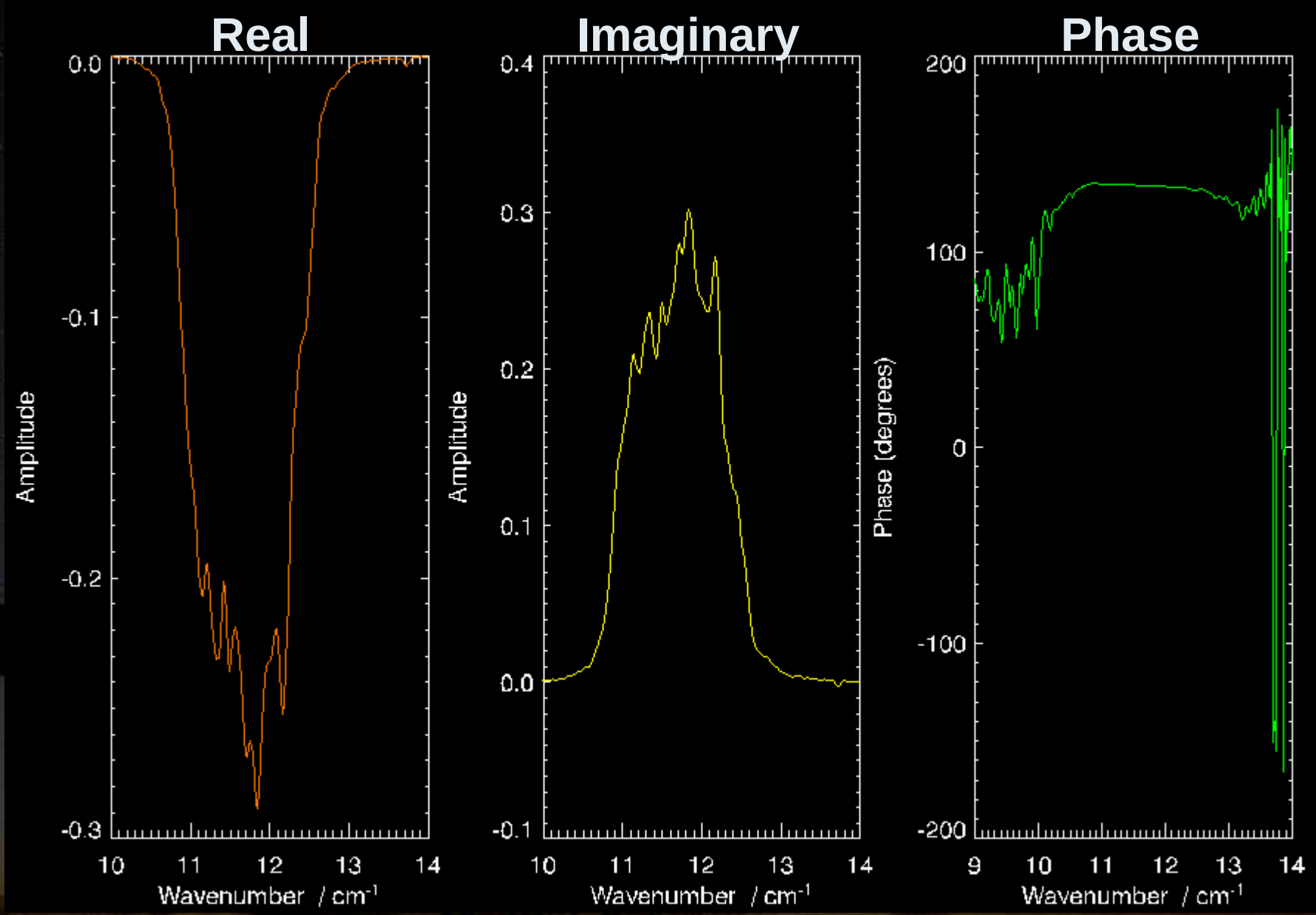
Method: convolve interferogram with phase correction function (PCF) derived from phase information extracted from a short double-sided portion of the interferogram.

$$PCF(\delta) = \int \exp(-i\varphi(\sigma))\exp(i2\pi\sigma\delta)\, d\sigma$$

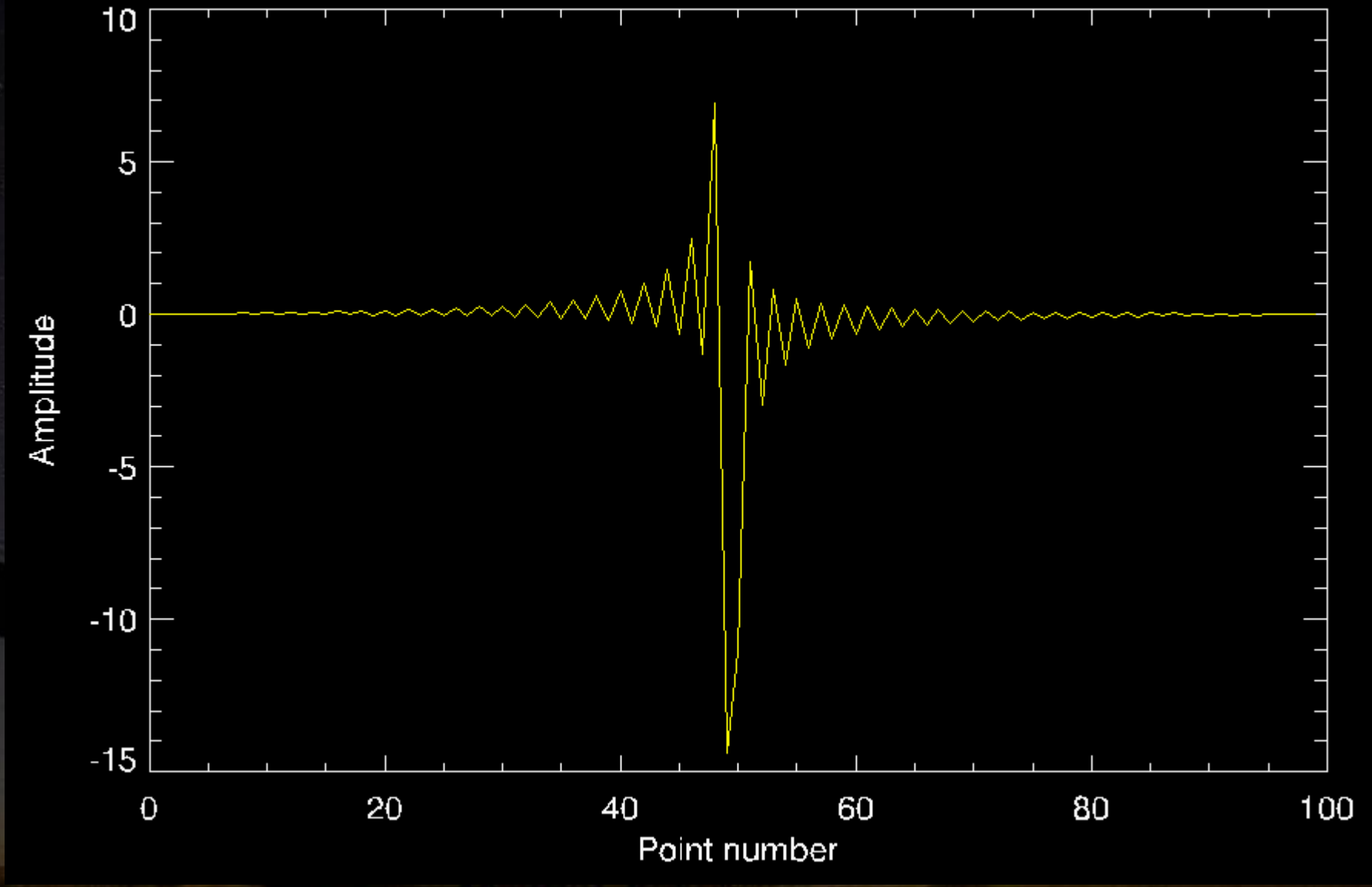
$$I_{symmetrical}(\delta) = PCF(\delta) * I(\delta)$$

Raw asymmetrical interferogram

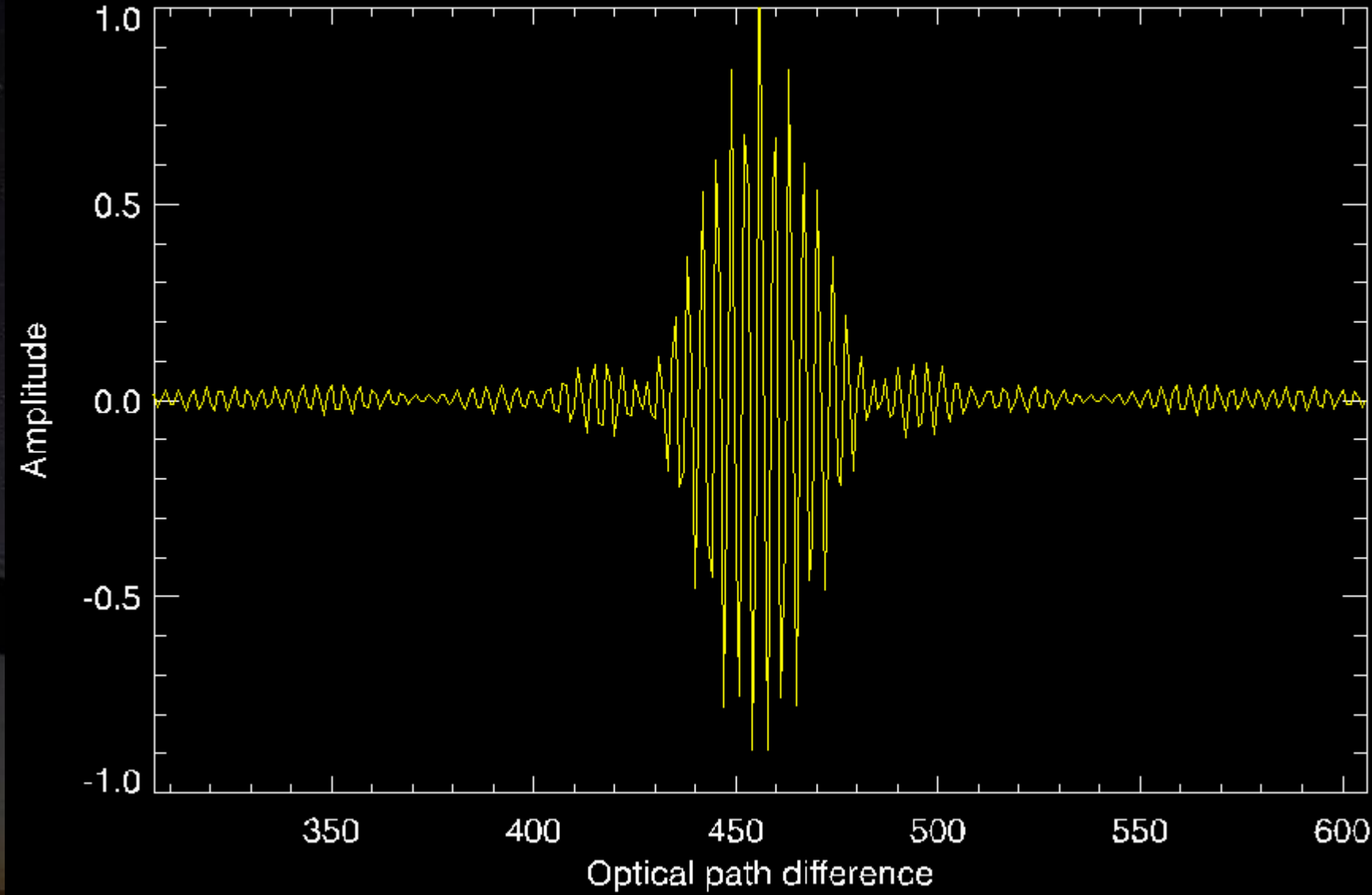


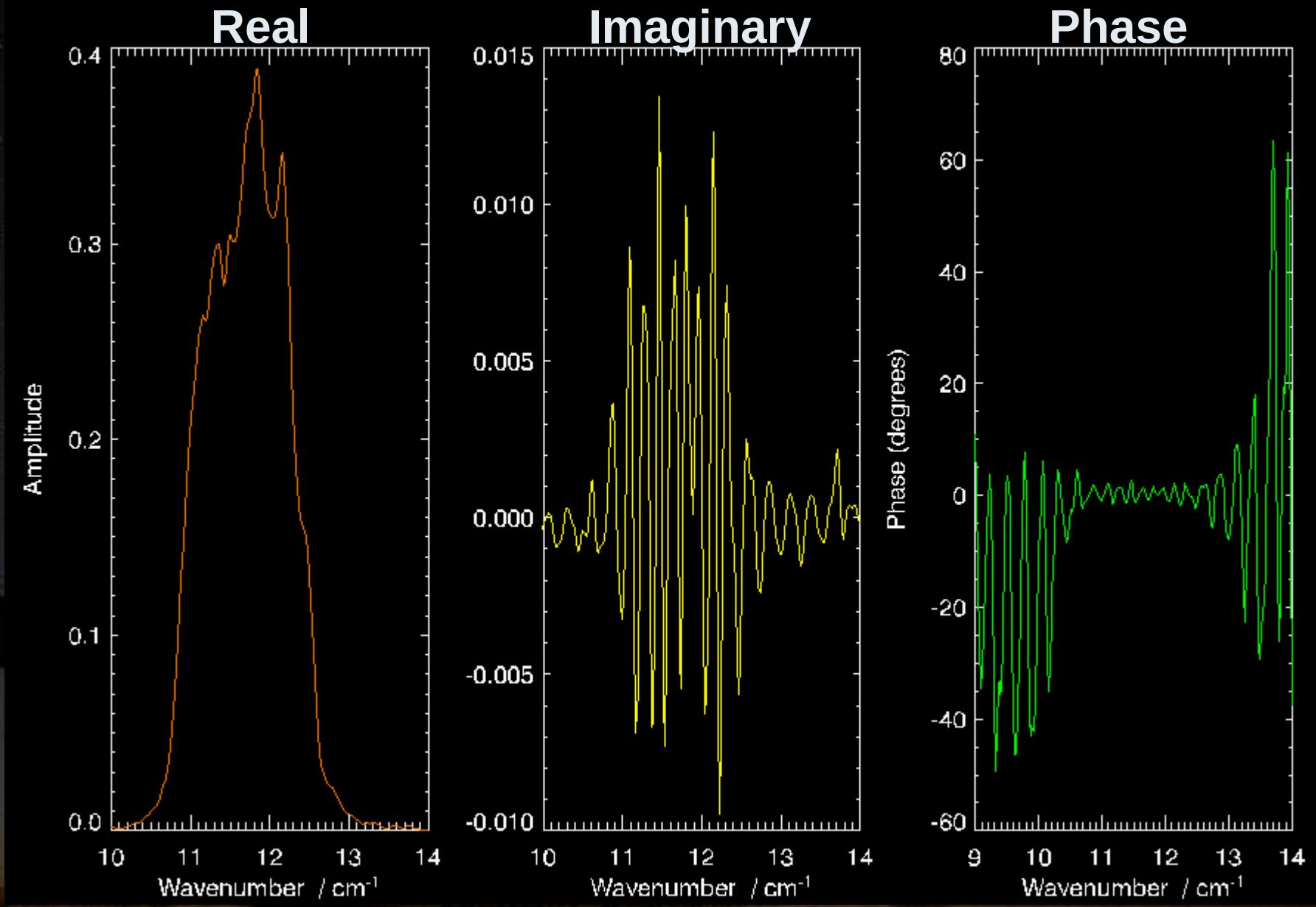

Real
Imaginary
Phase
Amplitude
Amplitude
Phase (degrees)
Wavenumber / cm-1
Wavenumber / cm-1
Wavenumber / cm-1
0.0
-0.1
-0.2
-0.3
0.4
0.3
0.2
0.1
0.0
-0.1
200
100
0
-100
-200
9
10
11
12
13
14

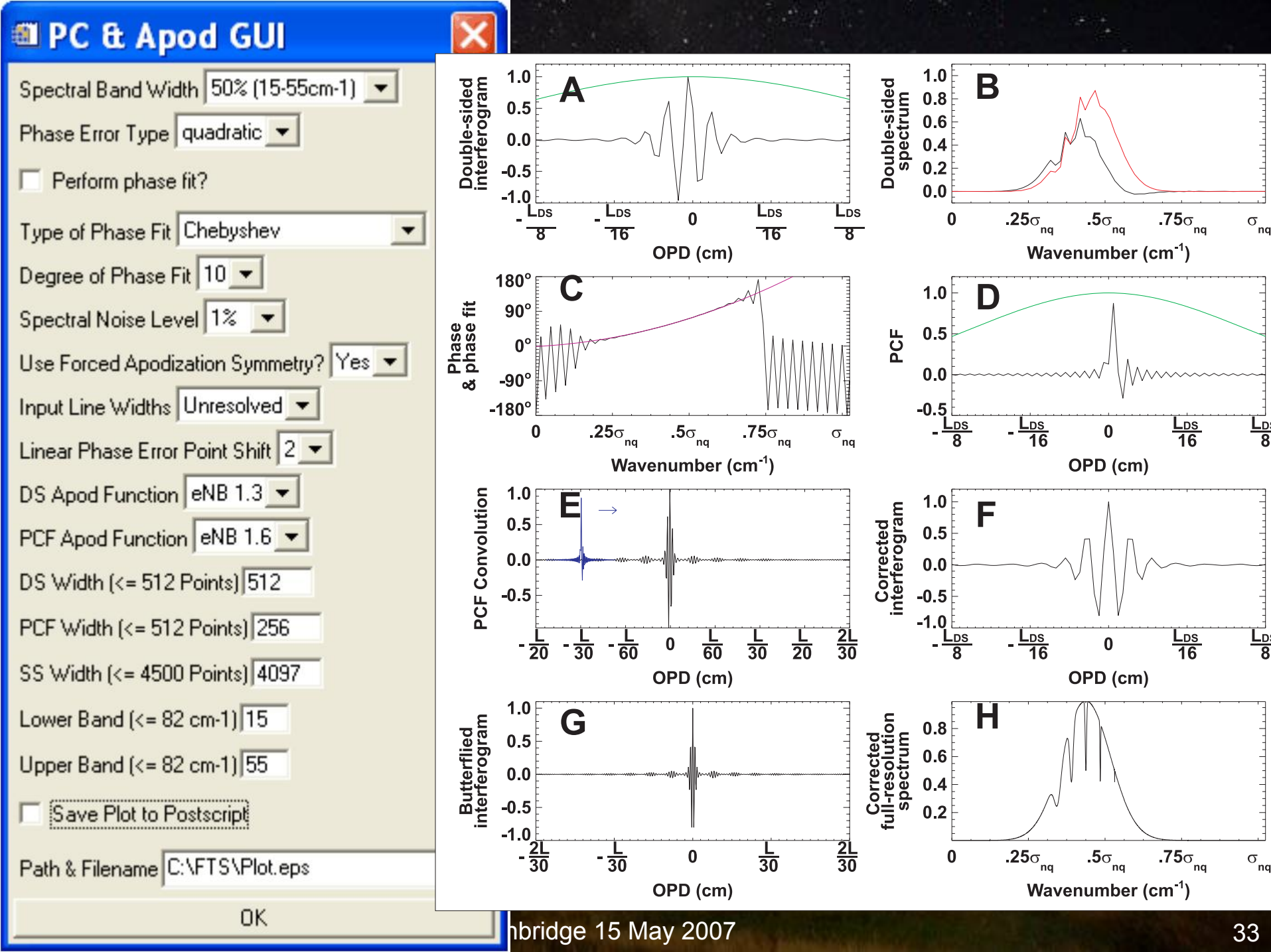
Phase correction function



Phase corrected symmetrical interferogram




Real
Imaginary
Phase
Amplitude
Phase (degrees)
Wavenumber / cm-1
Wavenumber / cm-1
Wavenumber / cm-1
0.4
0.3
0.2
0.1
0.0
0.015
0.010
0.005
0.000
-0.005
-0.010
80
60
40
20
0
-20
-40
-60
10
11
12
13
14
9


PC & Apod GUI
Spectral Band Width
50% (15-55cm-1)
Phase Error Type
quadratic
Perform phase fit?
Type of Phase Fit
Chebyshev
Degree of Phase Fit
10
Spectral Noise Level
1%
Use Forced Apodization Symmetry?
Yes
Input Line Widths
Unresolved
Linear Phase Error Point Shift
2
DS Apod Function
eNB 1.3
PCF Apod Function
eNB 1.6
DS Width (<= 512 Points)
512
PCF Width (<= 512 Points)
256
SS Width (<= 4500 Points)
4097
Lower Band (<= 82 cm-1)
15
Upper Band (<= 82 cm-1)
55
Save Plot to Postscript
Path & Filename
C:\FTS\Plot.eps
OK
A
Double-sided interferogram
OPD (cm)
B
Double-sided spectrum
Wavenumber (cm-1)
C
Phase & phase fit
Wavenumber (cm-1)
D
PCF
OPD (cm)
E
PCF Convolution
OPD (cm)
F
Corrected interferogram
OPD (cm)
G
Butterflied interferogram
OPD (cm)
H
Corrected full-resolution spectrum
Wavenumber (cm-1)
nbridge 15 May 2007
33

Generic FTS Data Processing Pipeline

Instrument Control

Interferogram Processing

Single Sided FT

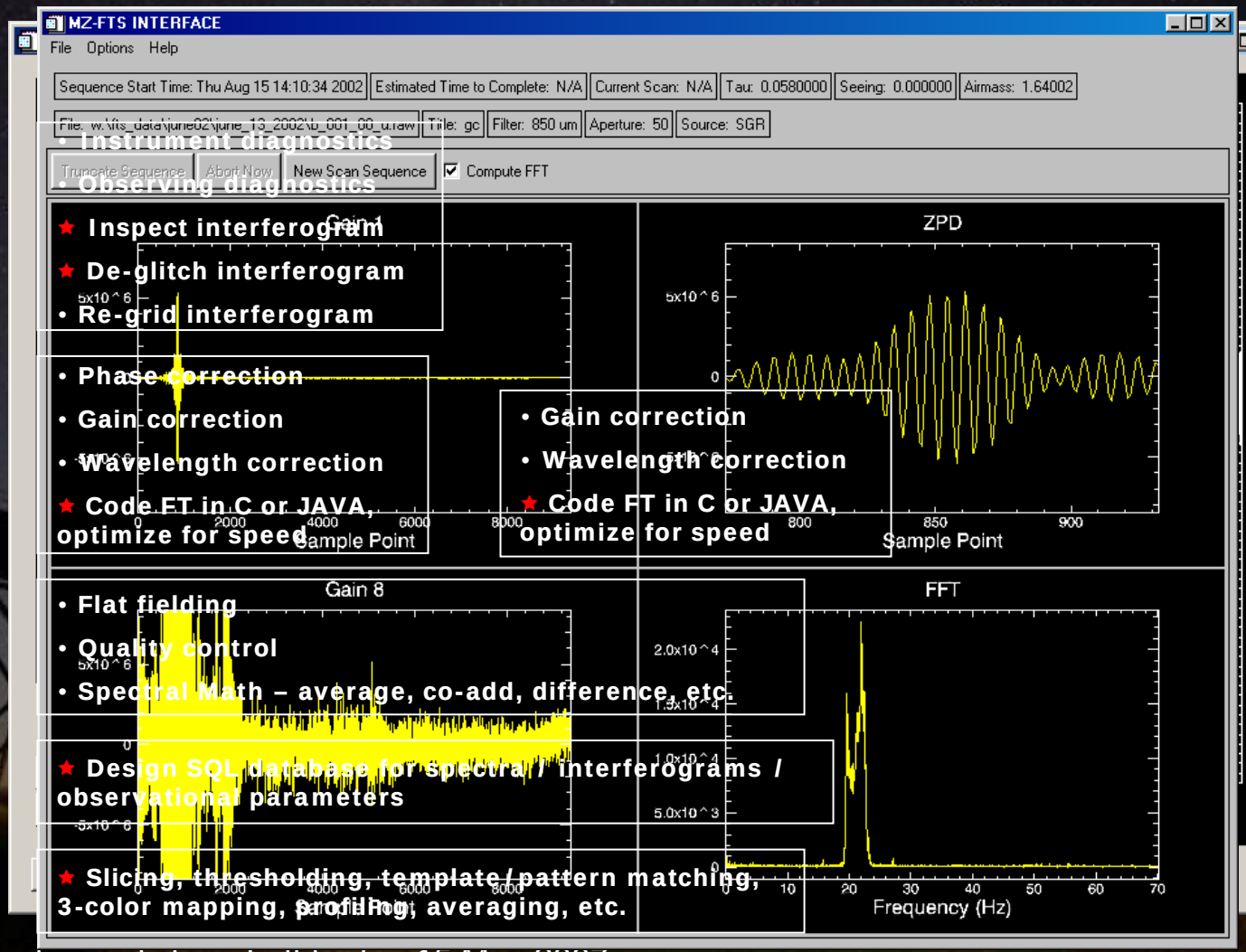
Double Sided FT

Spectral Processing

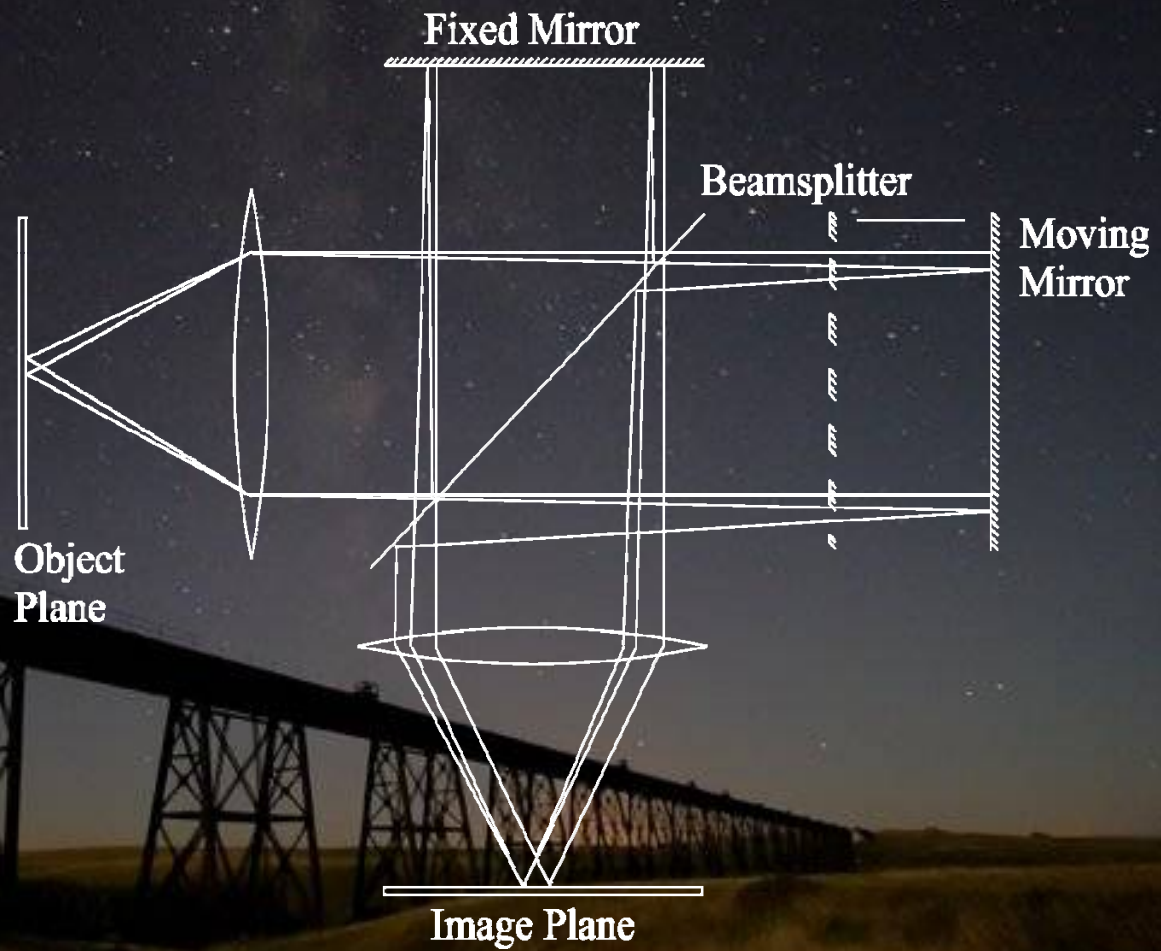
Archiving

Visualization

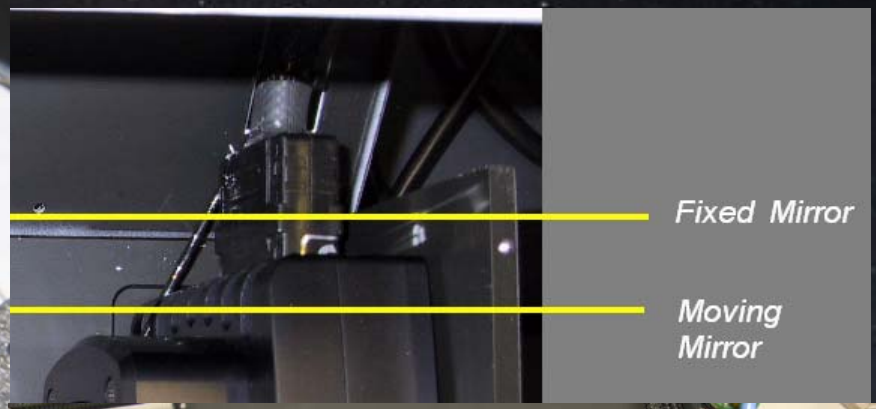
Software Components

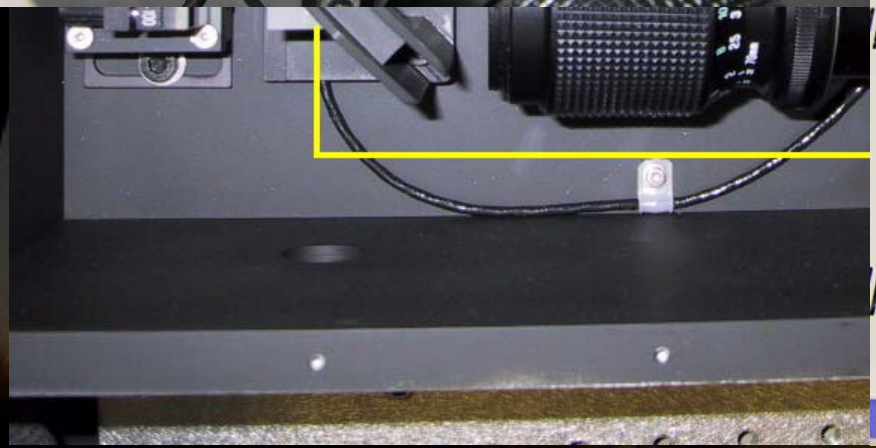


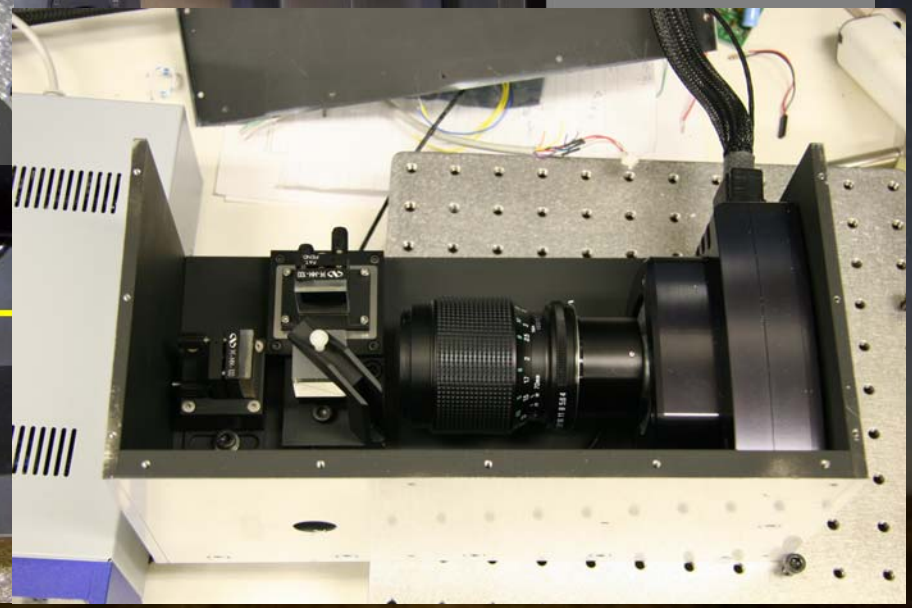
The FTS is readily adapted to imaging spectroscopy - iFTS

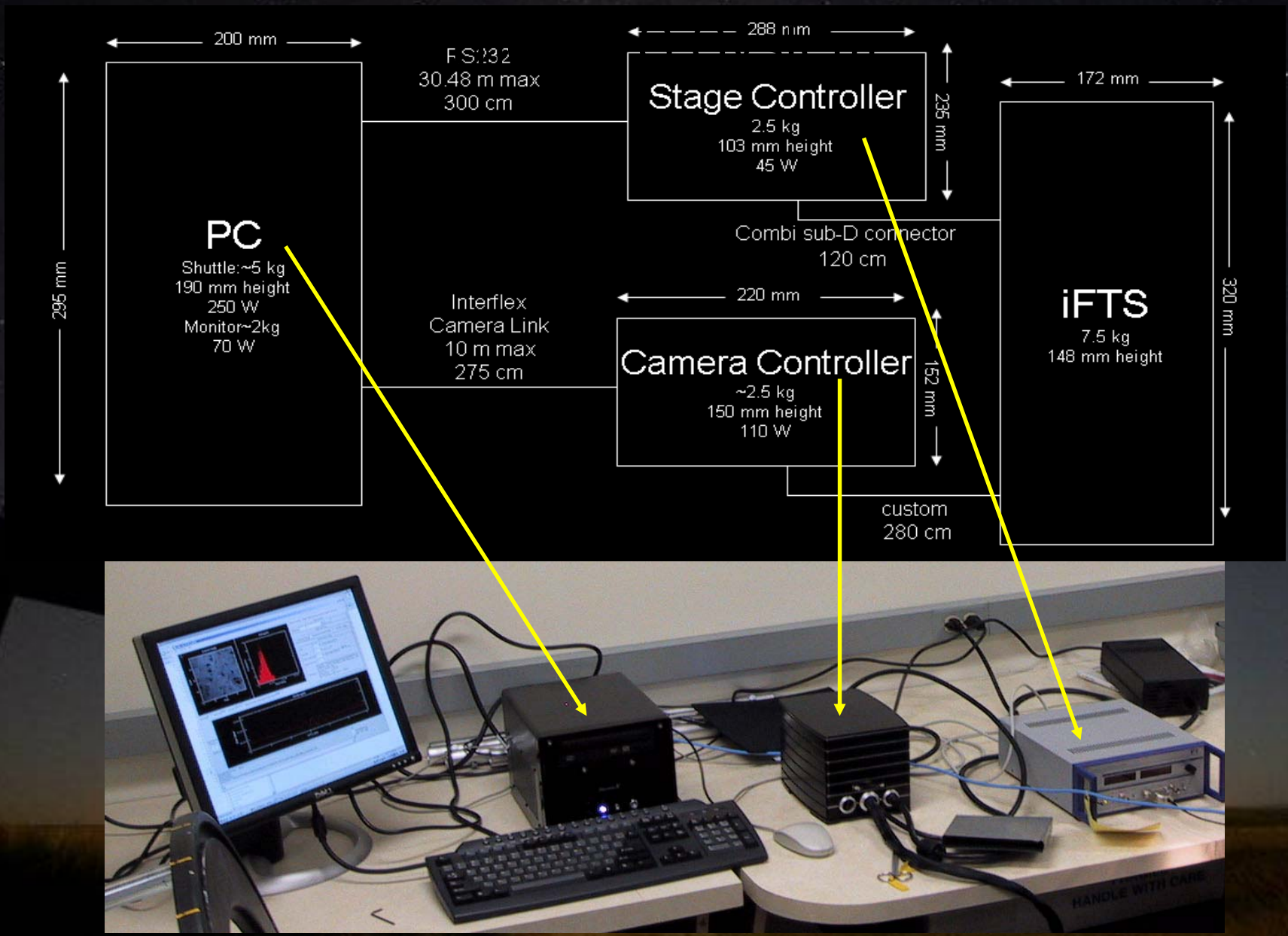


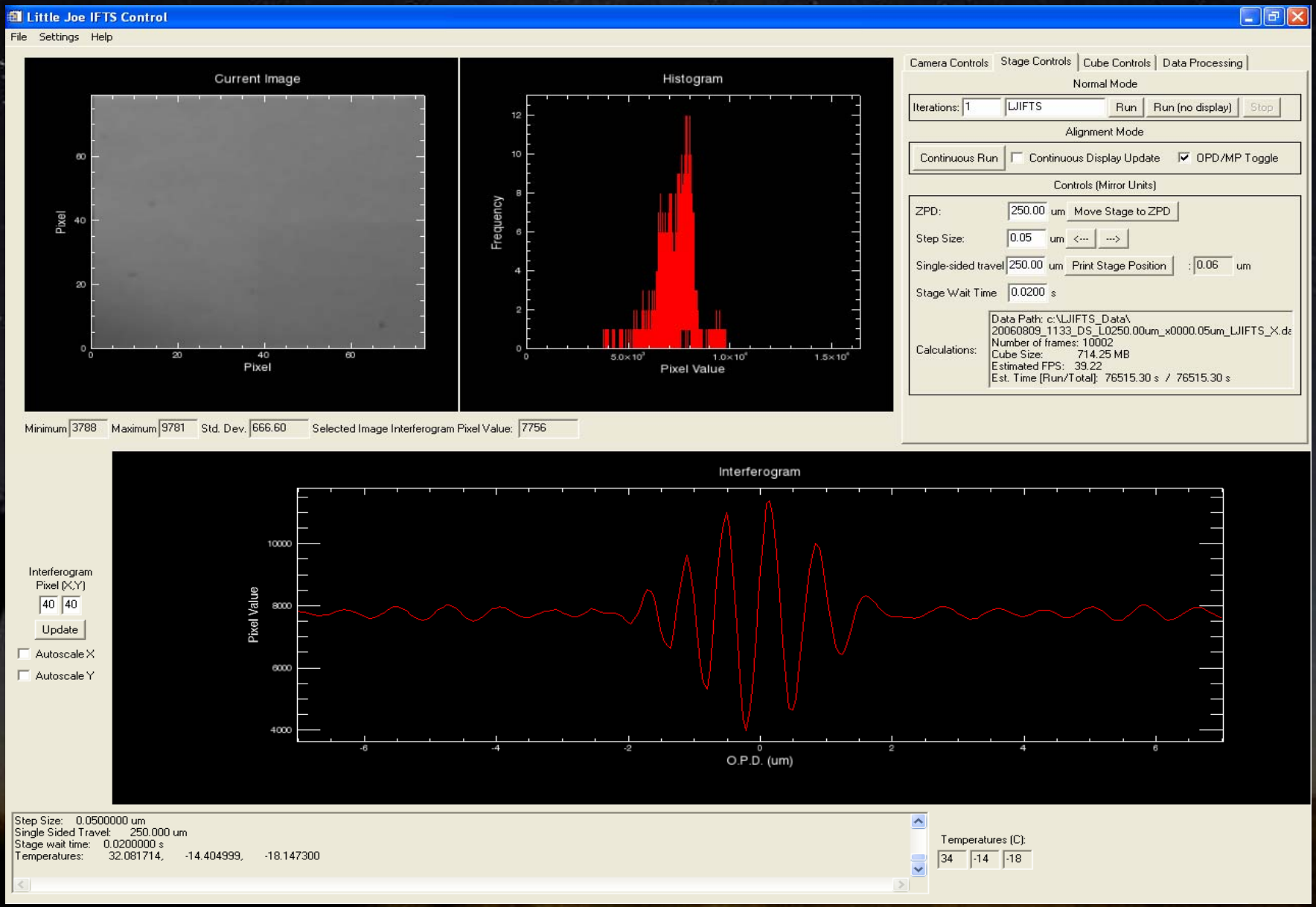
Imaging spectroscopy
A toy imaging Fourier Transform Spectrometer (iFTS)








200 mm
295 mm
PC
Shuttle:~5 kg
190 mm height
250 W
Monitor~2kg
70 W
FS:232
30.48 m max
300 cm
288 mm
Stage Controller
2.5 kg
103 mm height
45 W
235 mm
Combi sub-D connector
120 cm
172 mm
320 mm
iFTS
7.5 kg
148 mm height
Interflex
Camera Link
10 m max
275 cm
220 mm
Camera Controller
~2.5 kg
150 mm height
110 W
152 mm
custom
280 cm

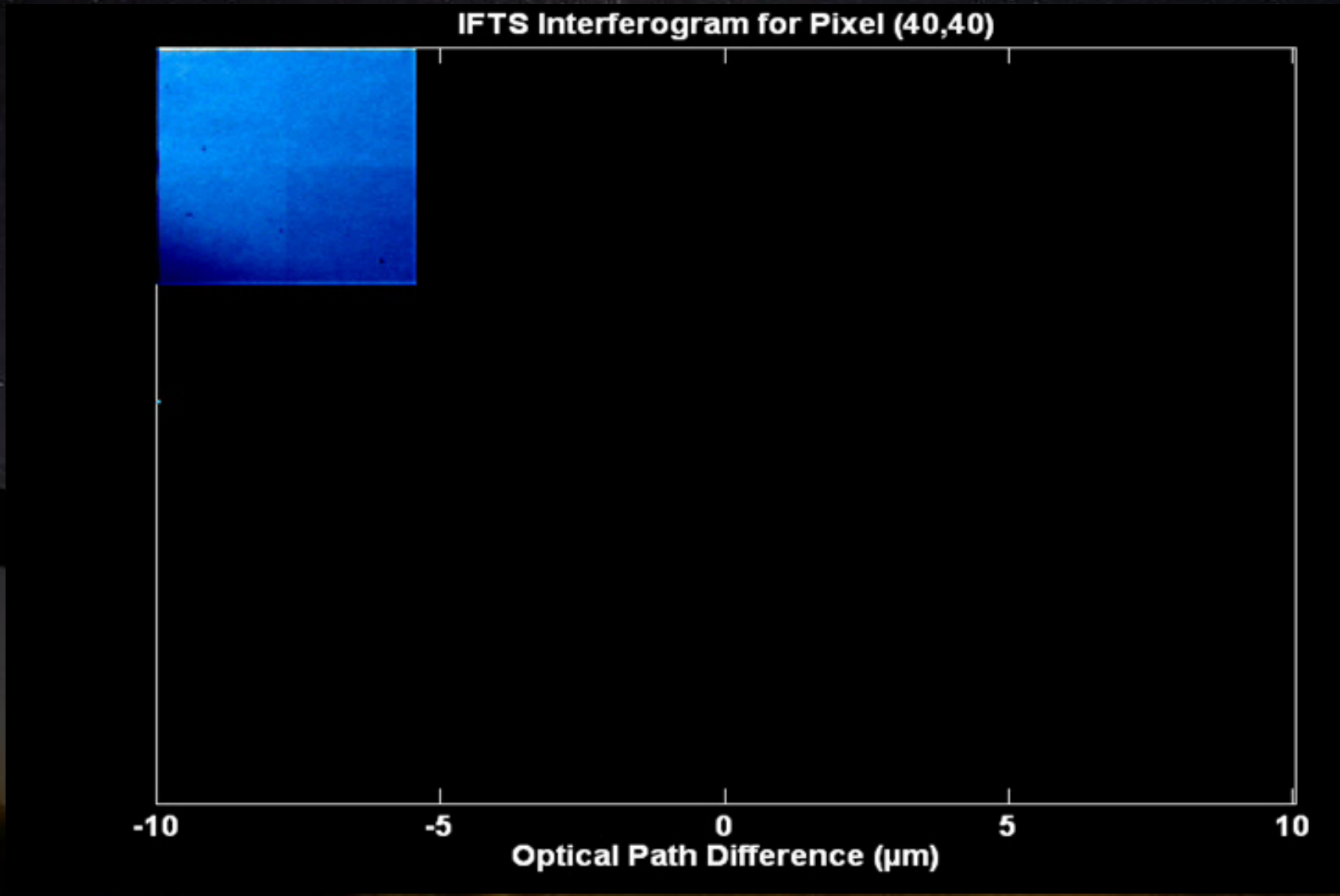

Little Joe IFTS Control
File Settings Help
Current Image
Pixel
Pixel
Histogram
Frequency
Pixel Value
Camera Controls
Stage Controls
Cube Controls
Data Processing
Normal Mode
Iterations: 1
LJIFTS
Run
Run (no display)
Stop
Alignment Mode
Continuous Run
Continuous Display Update
OPD/MP Toggle
Controls (Mirror Units)
ZPD: 250.00 um
Move Stage to ZPD
Step Size: 0.05 um
Single-sided travel 250.00 um
Print Stage Position
0.06 um
Stage Wait Time 0.0200 s
Calculations:
Data Path: c:\LJIFTS_Data\
20060809_1133_DS_L0250.00um_x0000.05um_LJIFTS_X.da
Number of frames: 10002
Cube Size: 714.25 MB
Estimated FPS: 39.22
Est. Time [Run/Total]: 76515.30 s / 76515.30 s
Minimum 3788
Maximum 9781
Std. Dev. 666.60
Selected Image Interferogram Pixel Value: 7756
Interferogram
Pixel Value
O.P.D. (um)
Interferogram Pixel (X,Y)
40 40
Update
Autoscale X
Autoscale Y
Step Size: 0.0500000 um
Single Sided Travel: 250.000 um
Stage wait time: 0.0200000 s
Temperatures: 32.081714, -14.404999, -18.147300
Temperatures (C):
34 -14 -18

Imaging spectroscopy with a Mach-Zehnder iFTS

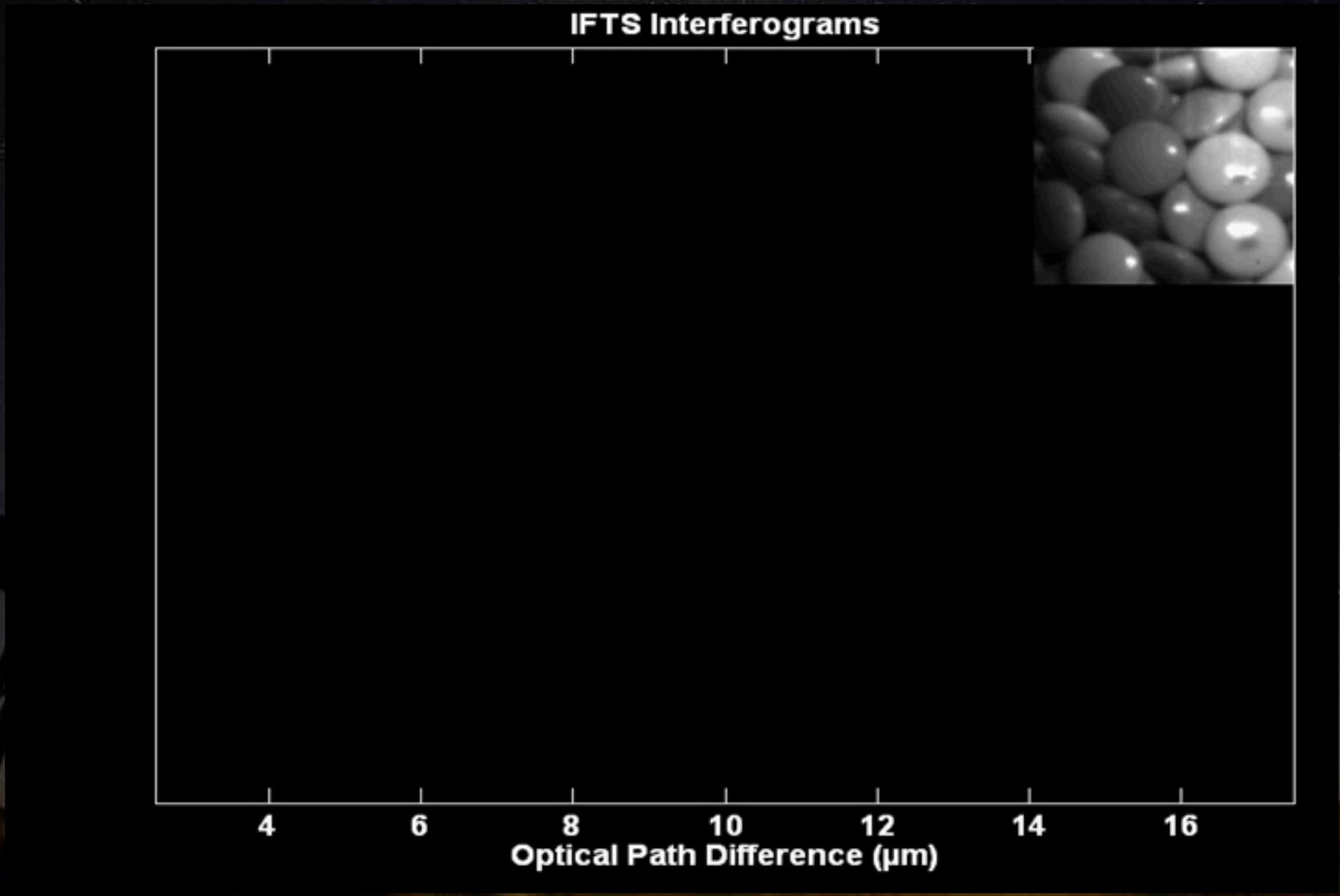
iFTS data processing pipeline modules

- **Inspect interferogram data cubes**
- **Deglitch cosmic ray events**
- **Phase correction**
- **Apodization**
- **Fourier transform time sampled interferograms**
- **Wavelength scale correction for off-axis pixels (the obliquity effect)**
- **Flat field array – adjust gain for individual pixel responsivities**
- **Calibrate spectra in Jy or W m^{-2} Hz^{-1}**
- **Inspect spectral data cubes**
- **Merge spectral data cubes from two bands**
- **Spectral processing (eg average, difference, ratio, spectral/spatial integration**

iFTS scan of a uniform white target

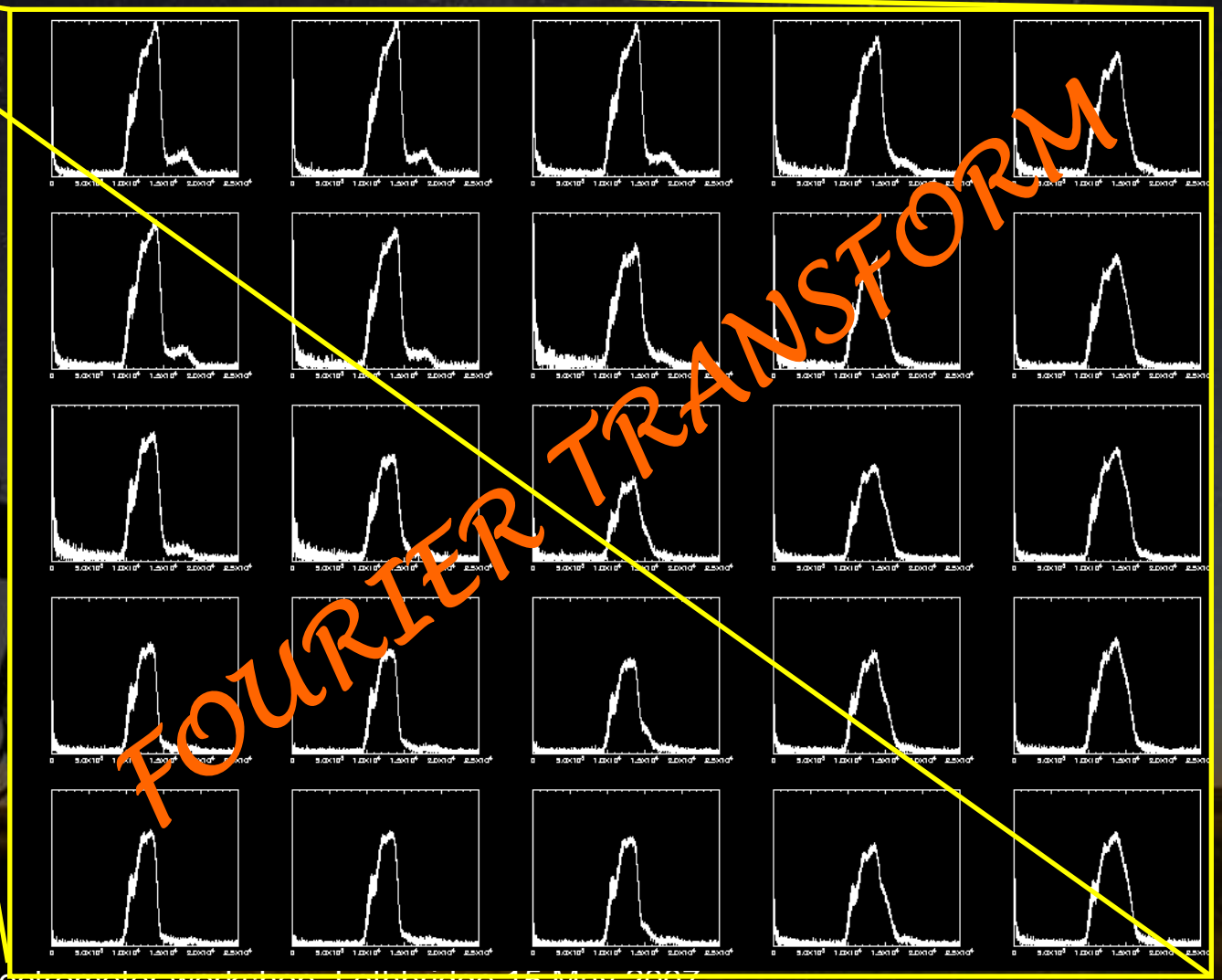


Imaging spectroscopy of something found in every well equipped physics research laboratory…..
Smarties!

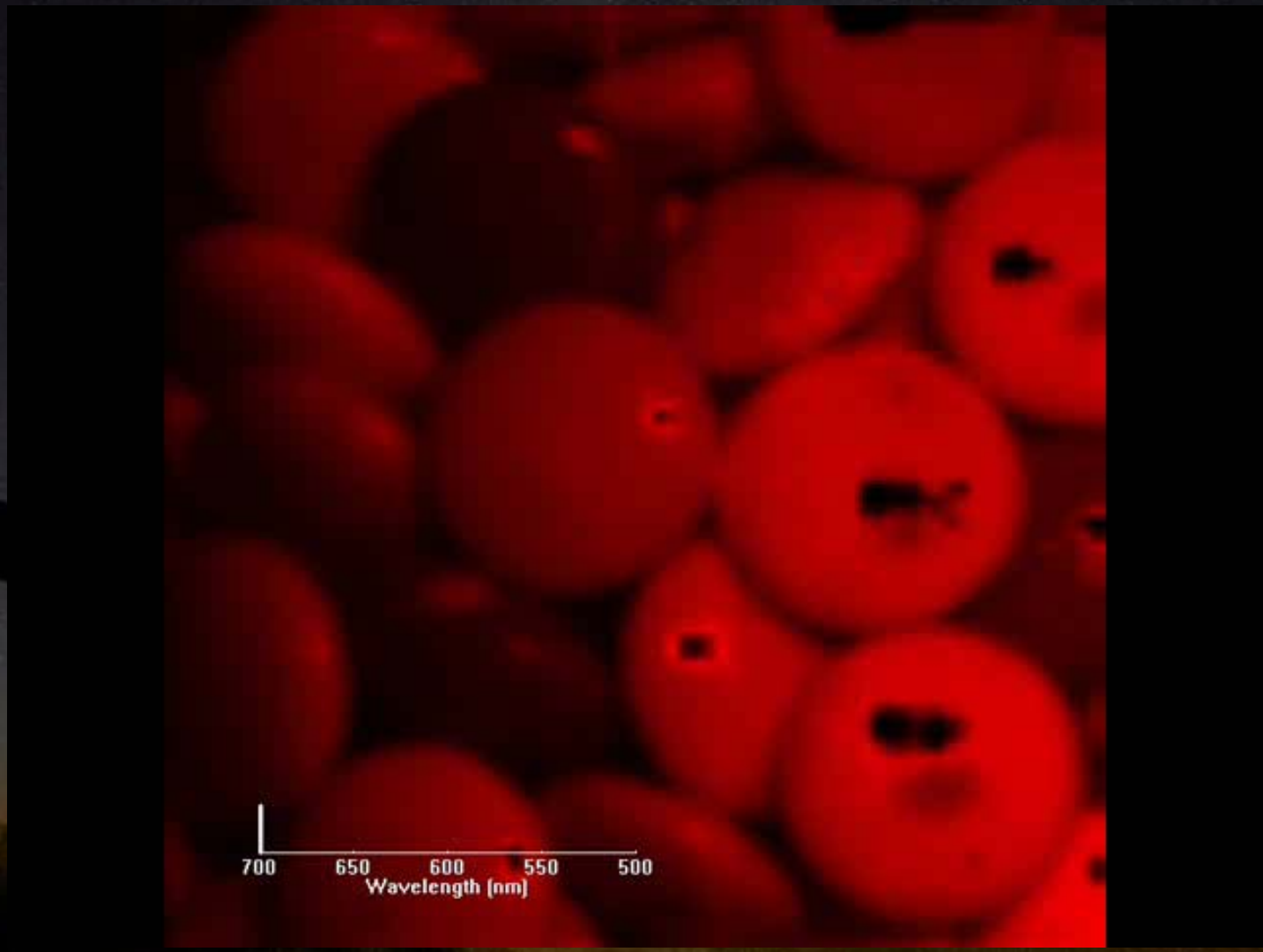

IFTS Interferograms
4
6
8
10
12
14
16
Optical Path Difference (μm)

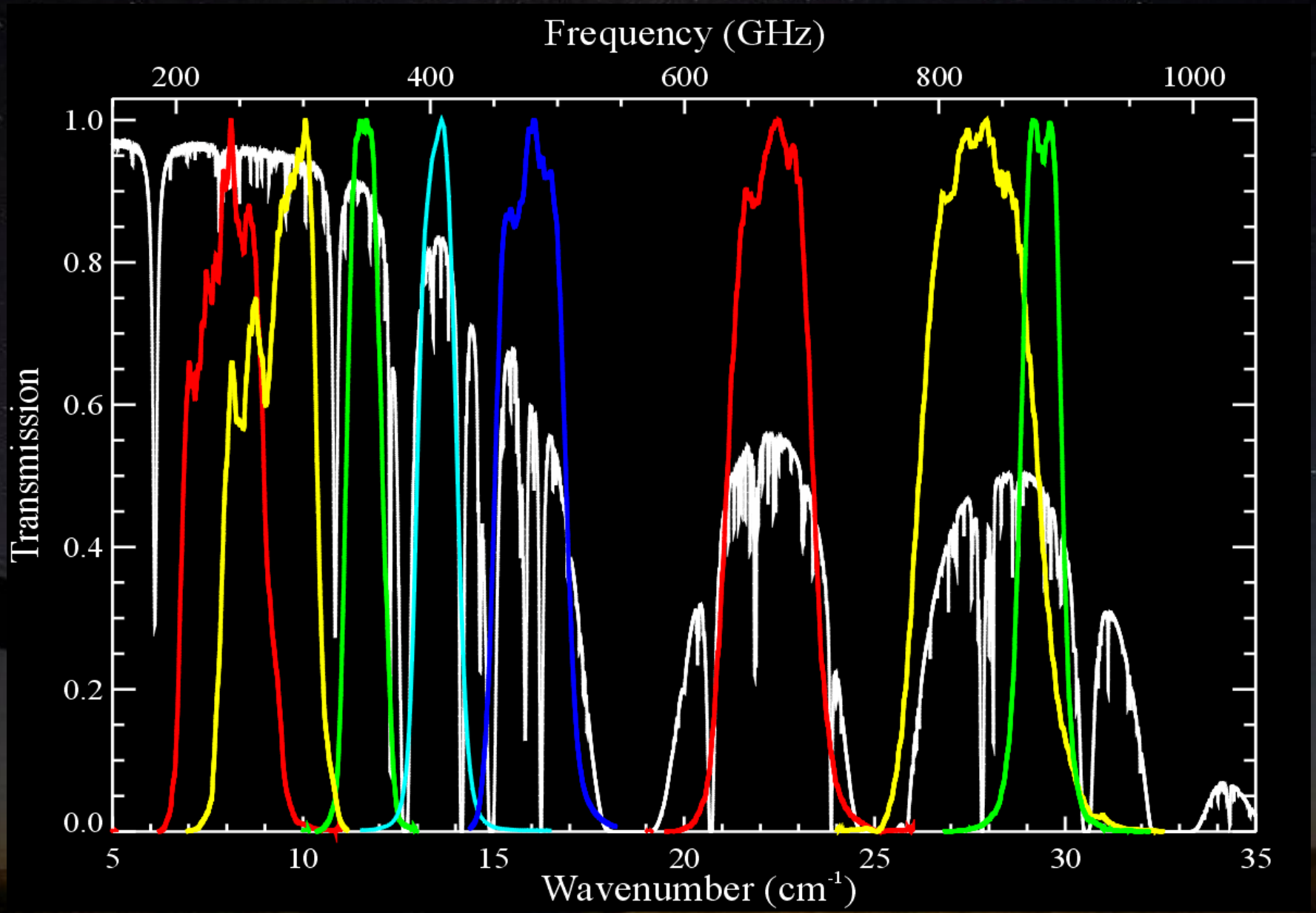
Now we have complete spectral information for… each pixel

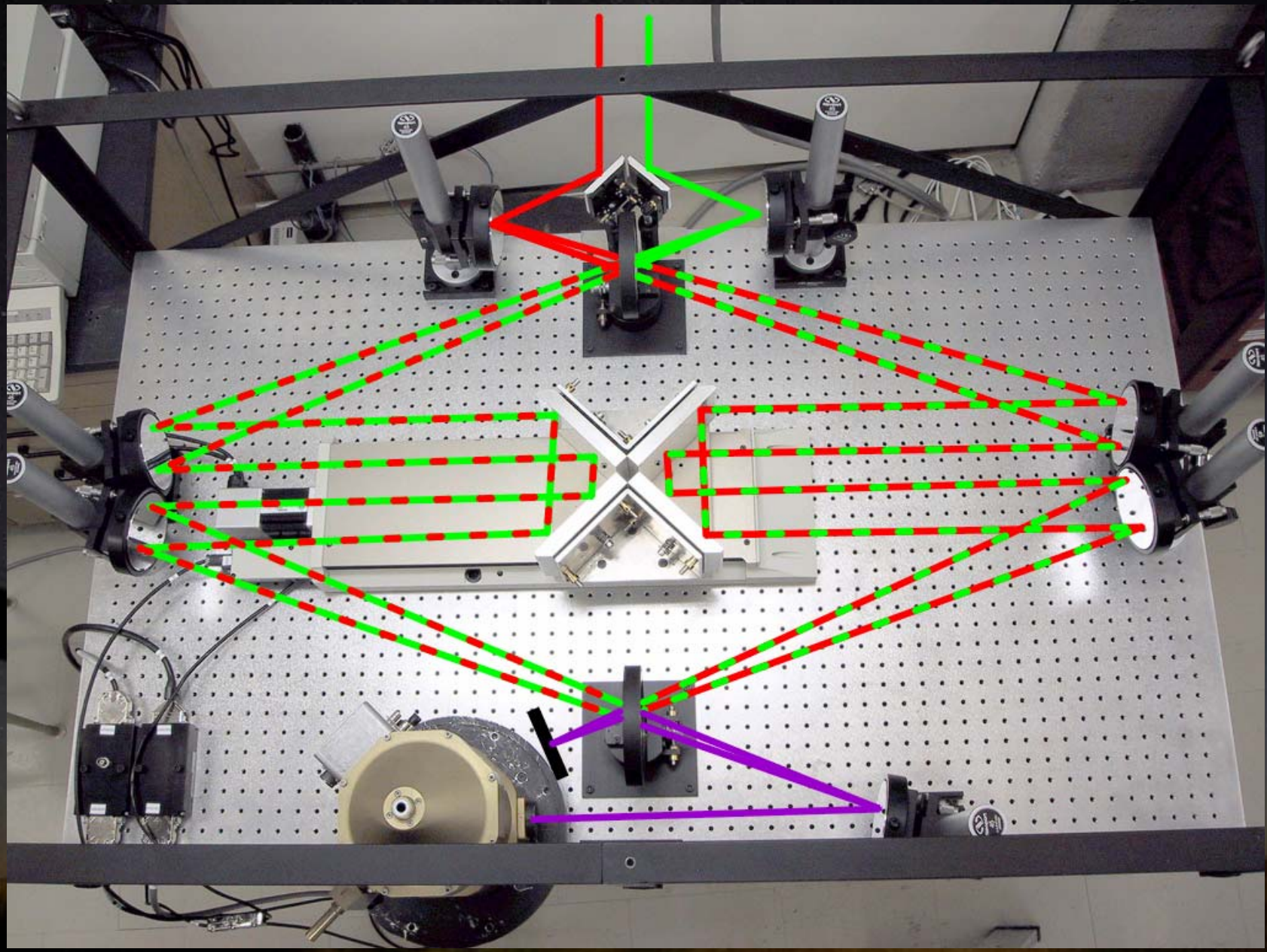
FTS + Array Detector ⇒ *Hyper*spectral Imaging

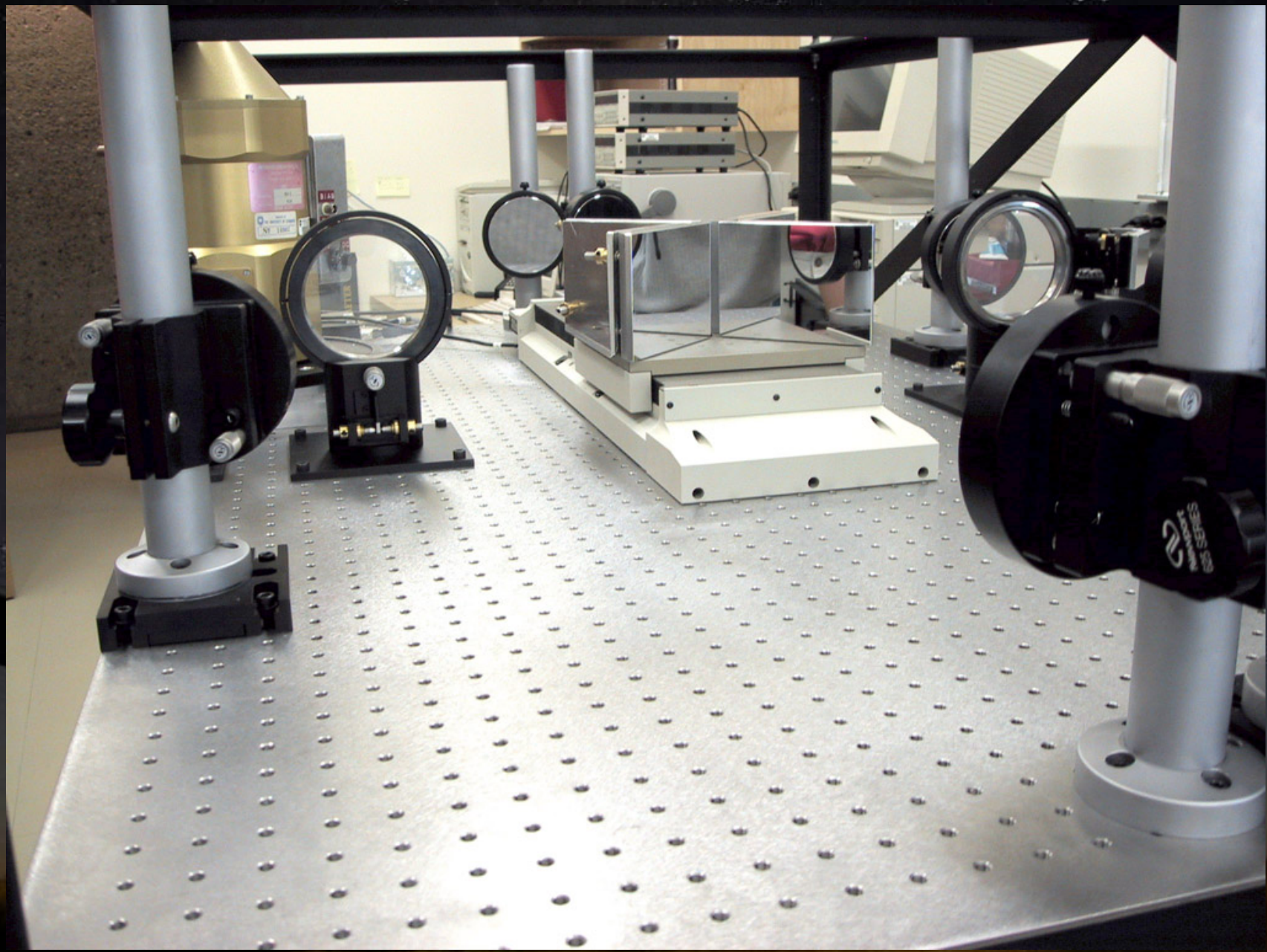


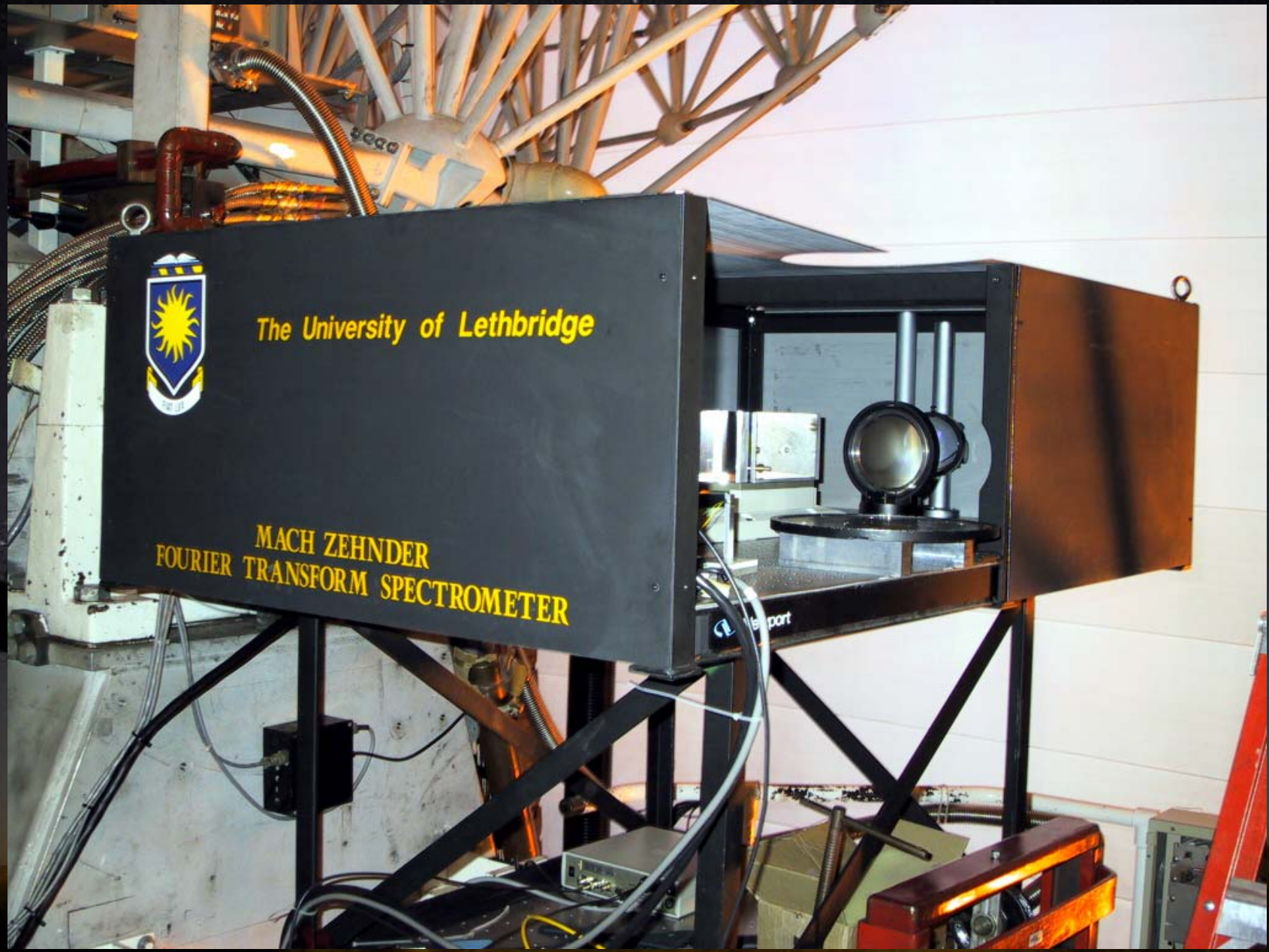
Or if we prefer we can fly through the spectral hypercube viewing a spatial image as a function of wavelength…

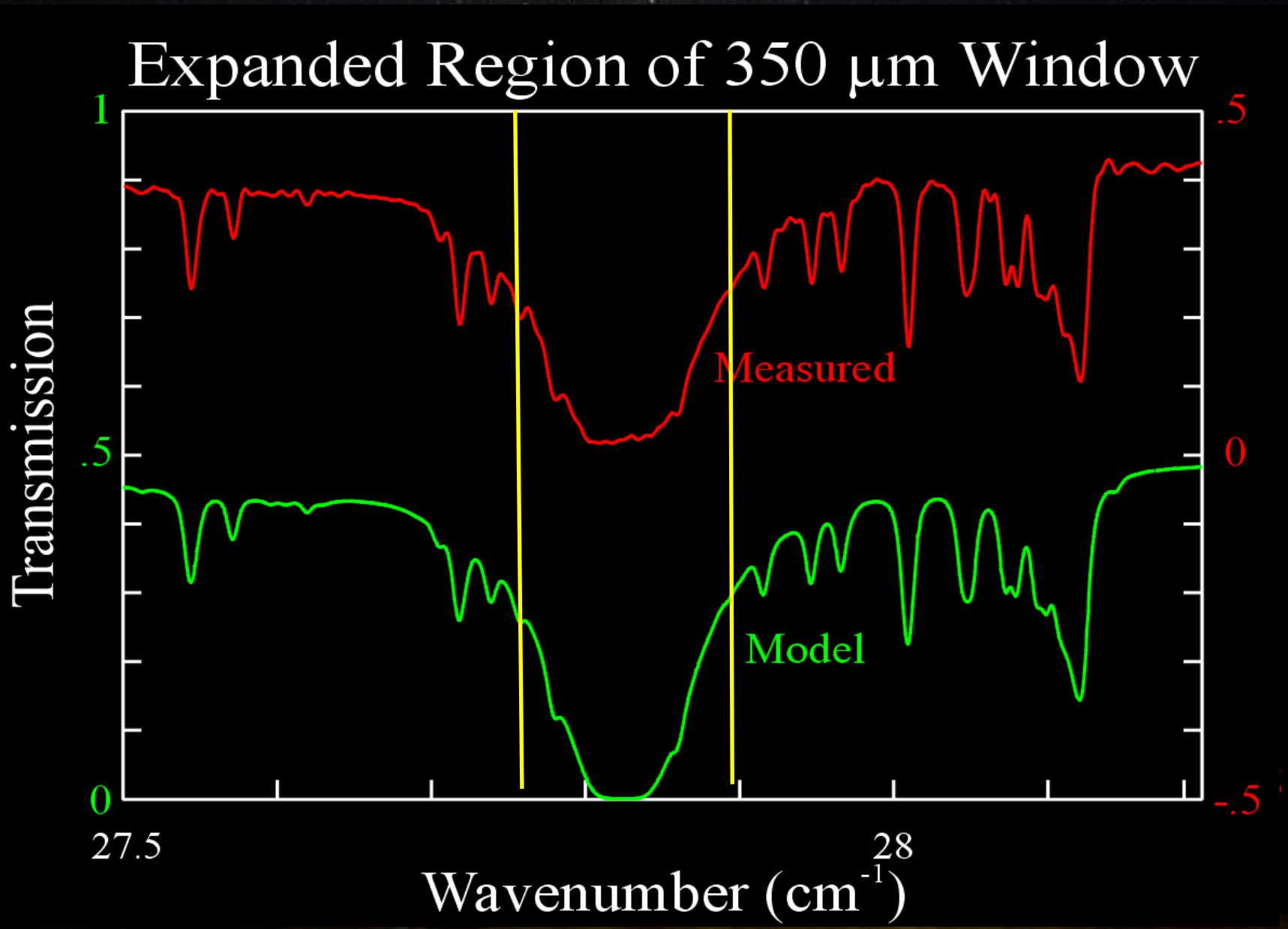



Frequency (GHz)
200
400
600
800
1000
1.0
0.8
0.6
0.4
0.2
0.0
Transmission
5
10
15
20
25
30
35
Wavenumber (cm-1)

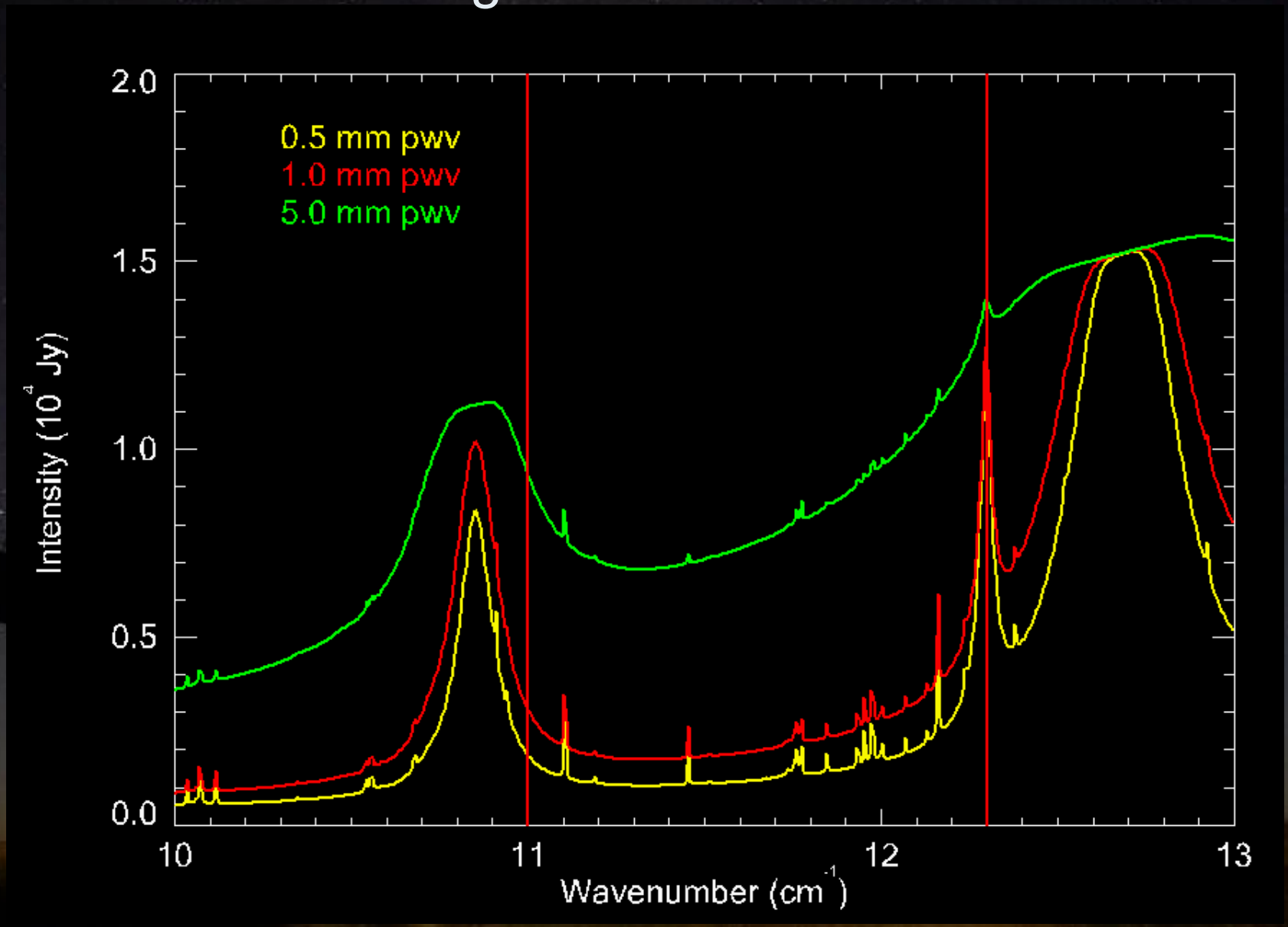


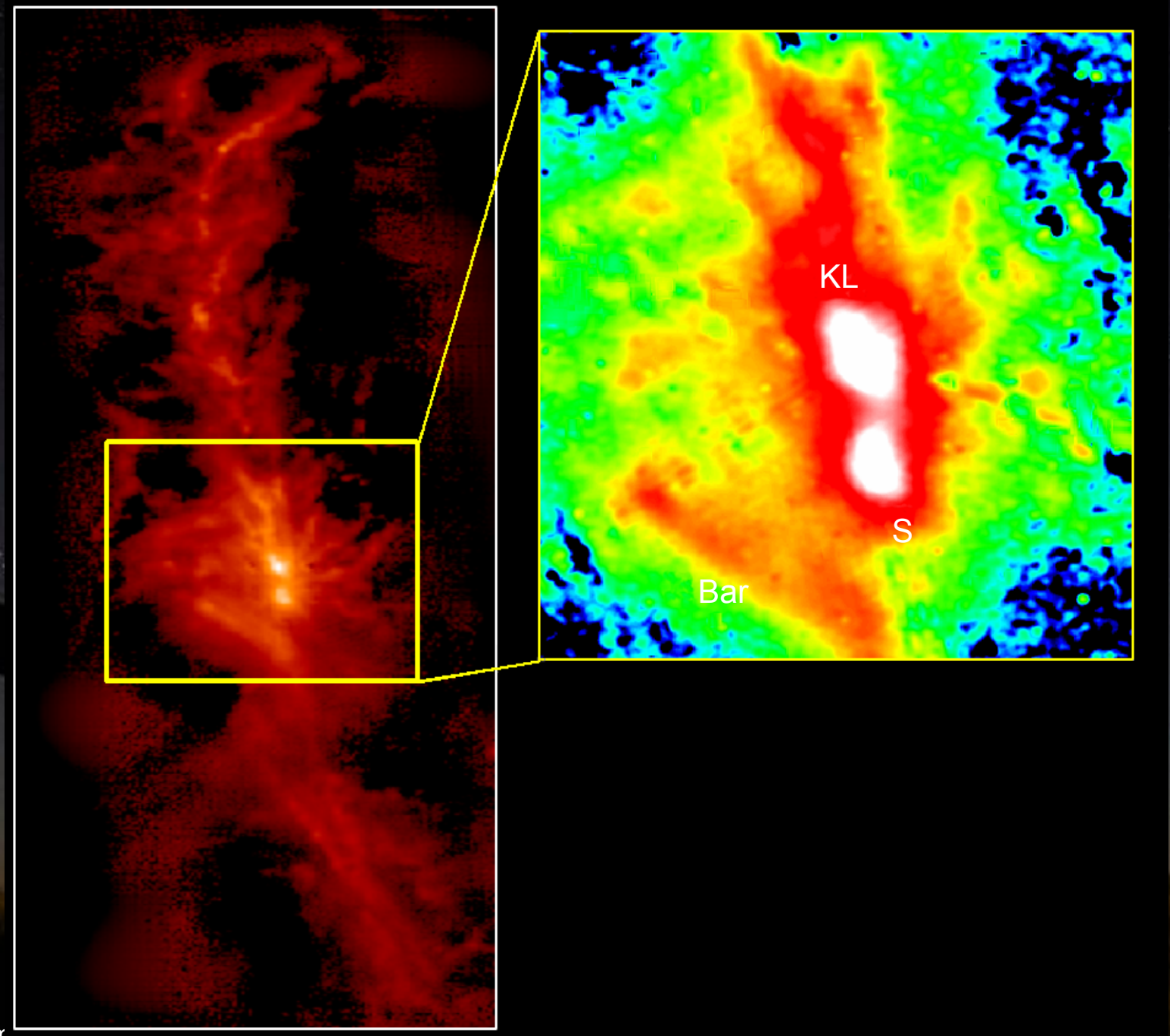


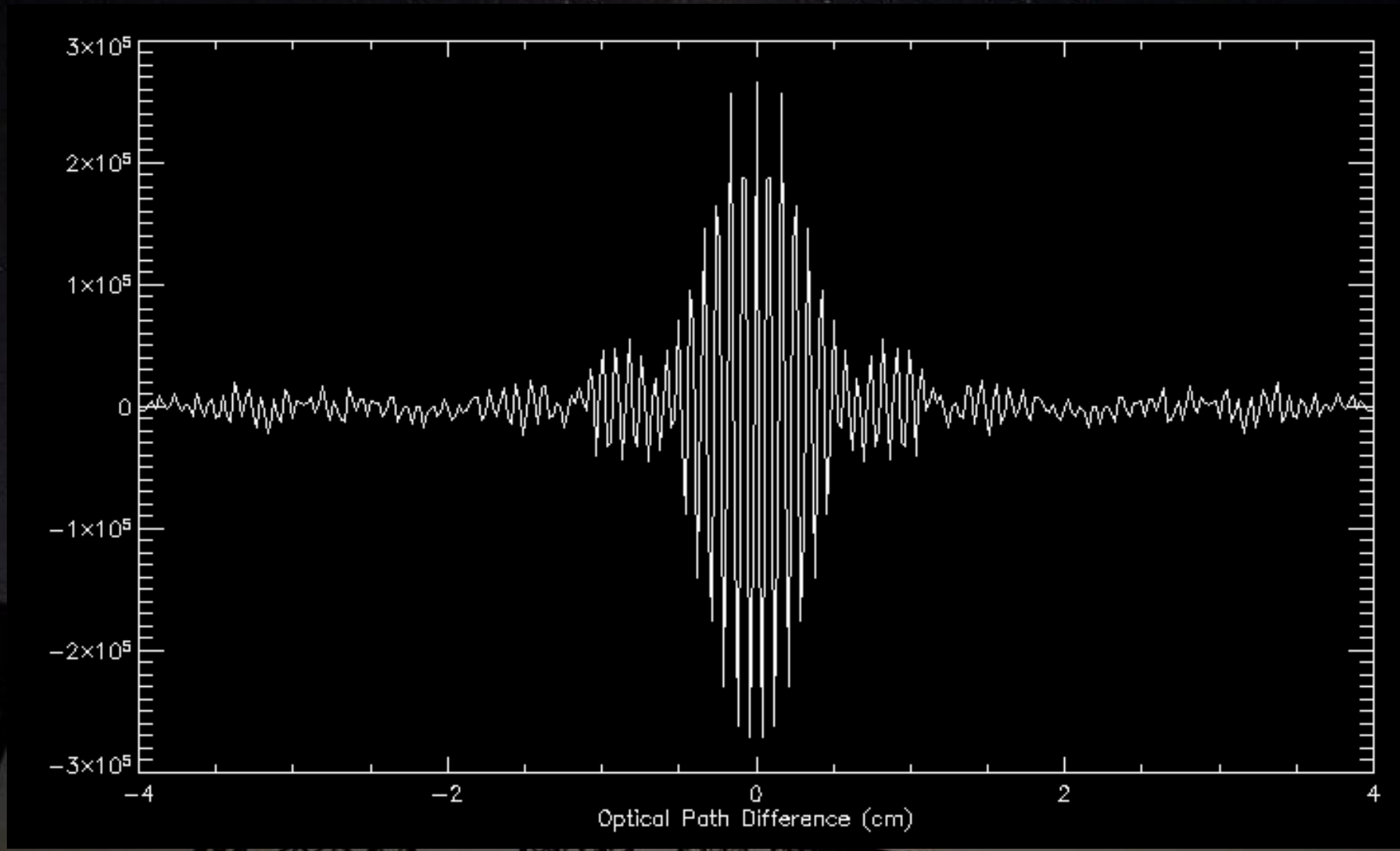

The University of Lethbridge
MACH ZEHNDER
FOURIER TRANSFORM SPECTROMETER

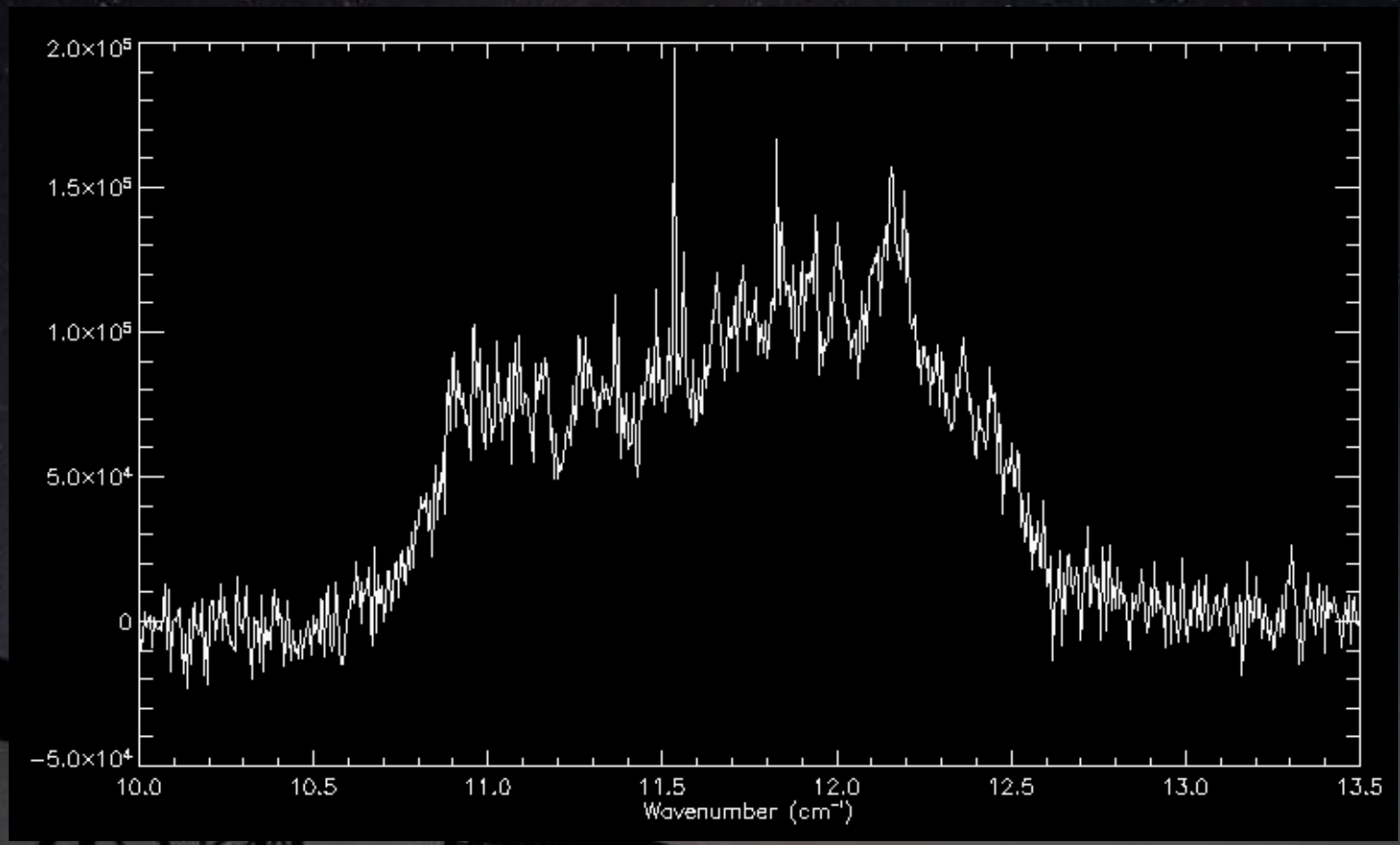

Expanded Region of 350 μm Window
Transmission
1
.5
0
.5
0
-.5
Measured
Model
27.5
28
Wavenumber (cm-1)

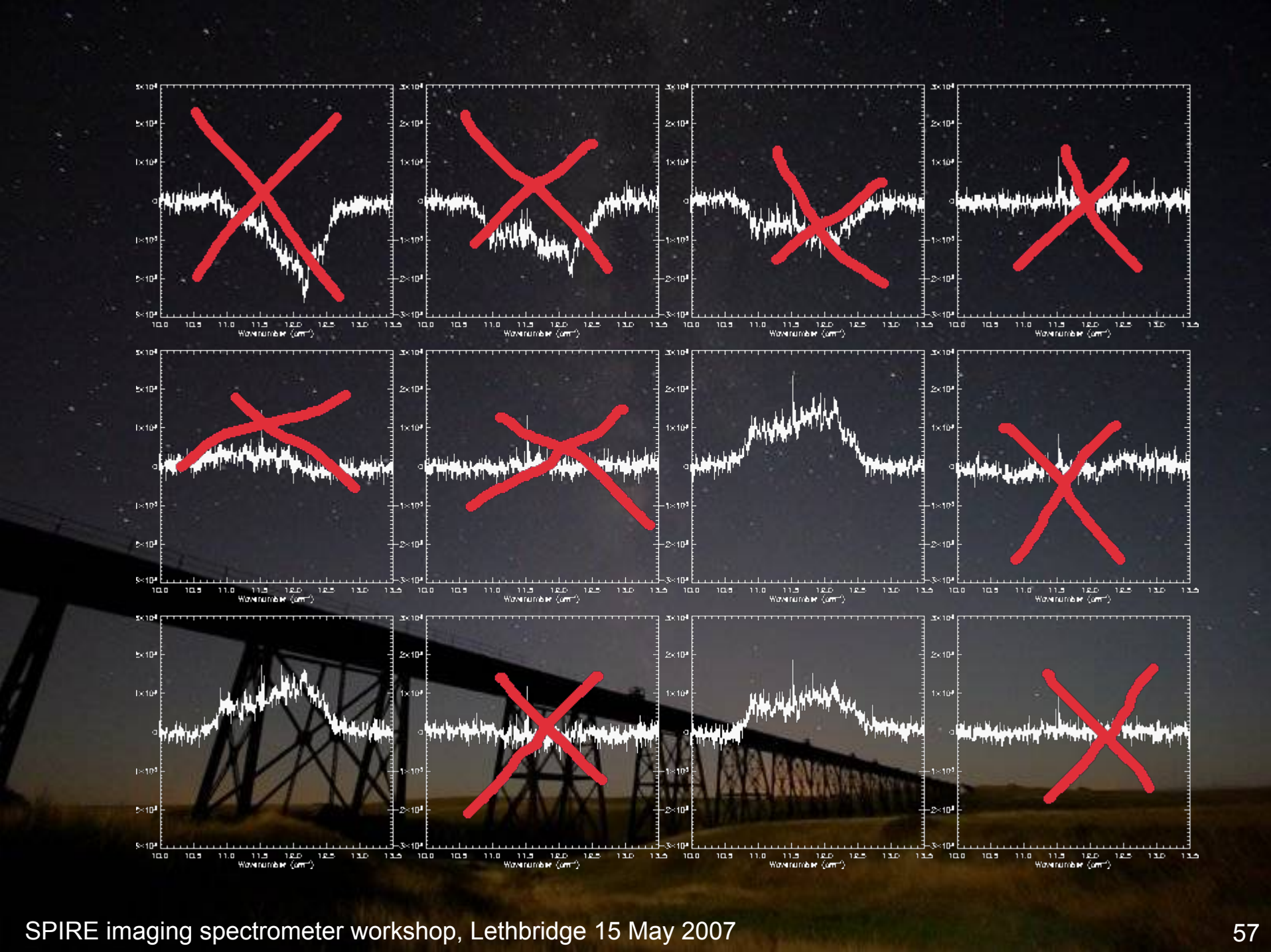
The challenge…



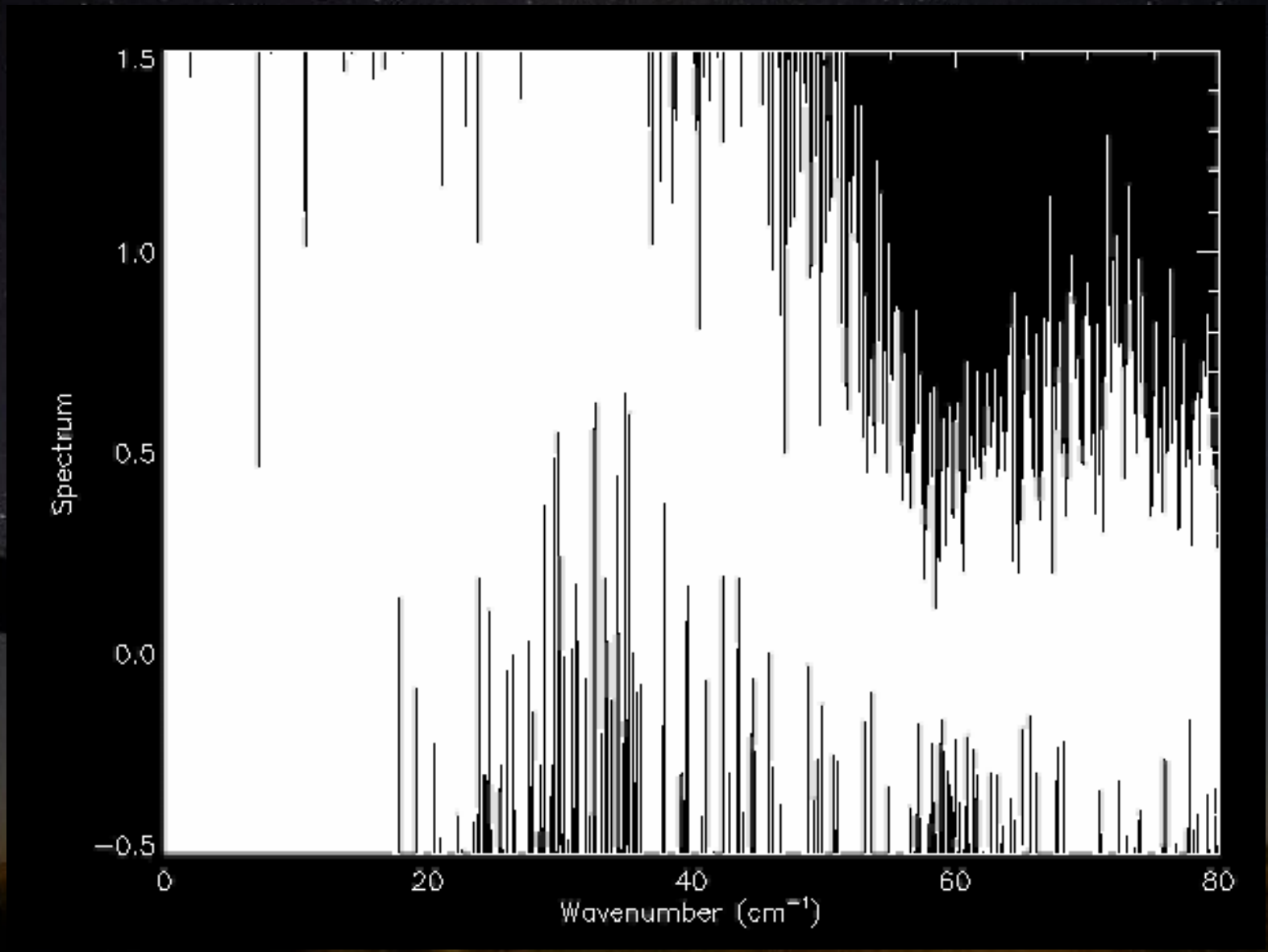

KL
S
Bar

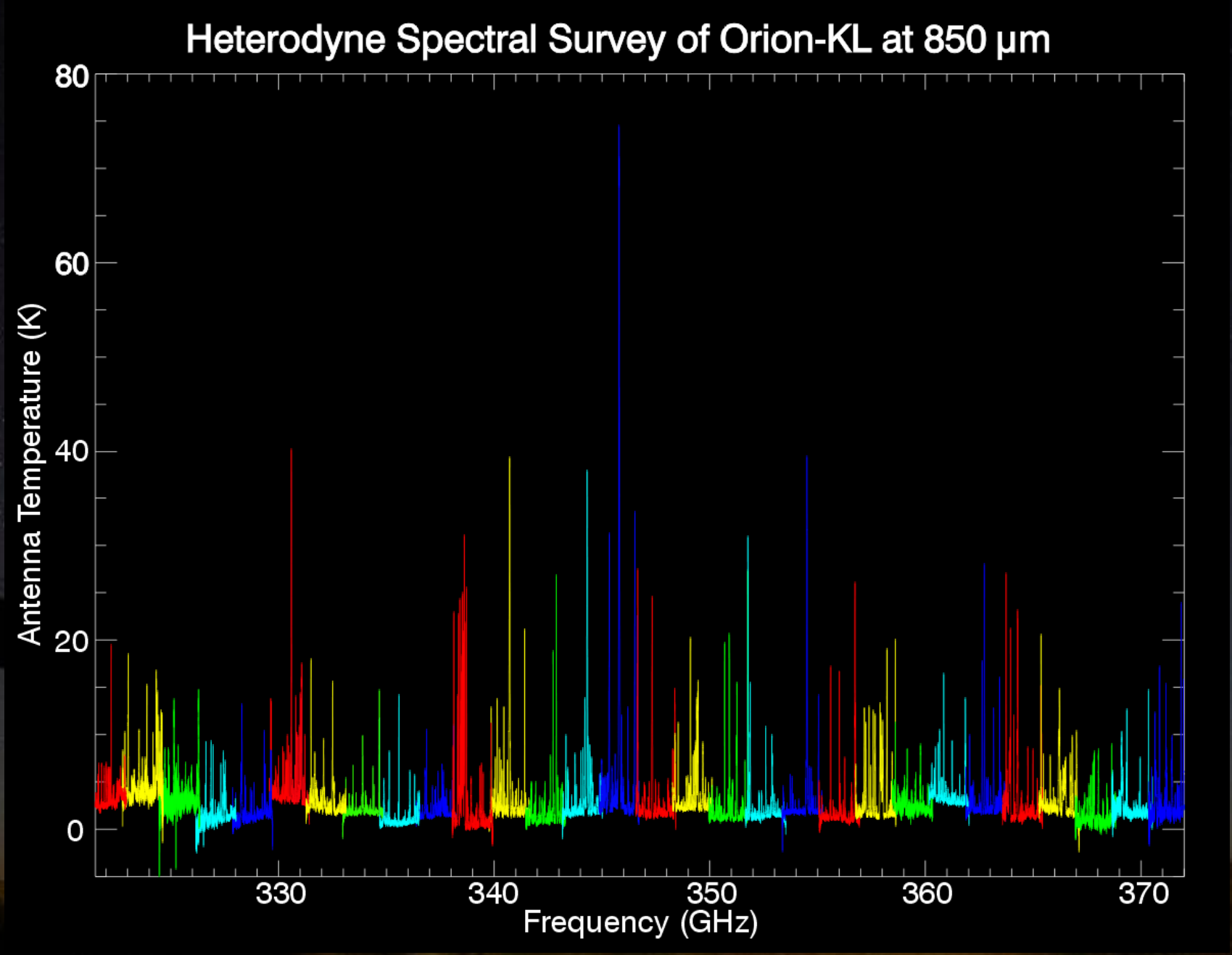

3×10⁵
2×10⁵
1×10⁵
0
−1×10⁵
−2×10⁵
−3×10⁵
−4
−2
0
2
4
Optical Path Difference (cm)

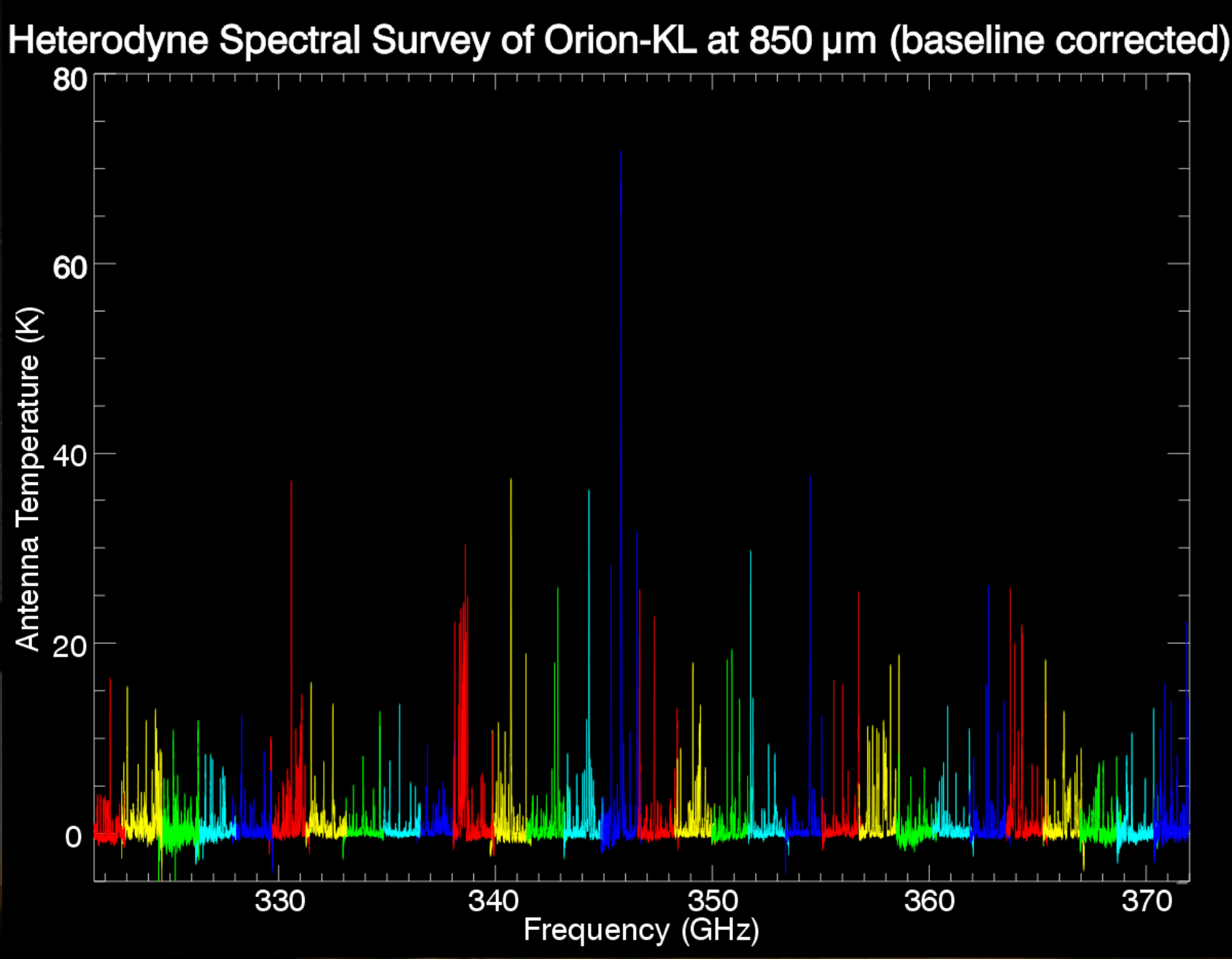

2.0×10⁵
1.5×10⁵
1.0×10⁵
5.0×10⁴
0
−5.0×10⁴
10.0
10.5
11.0
11.5
12.0
12.5
13.0
13.5
Wavenumber (cm⁻¹)

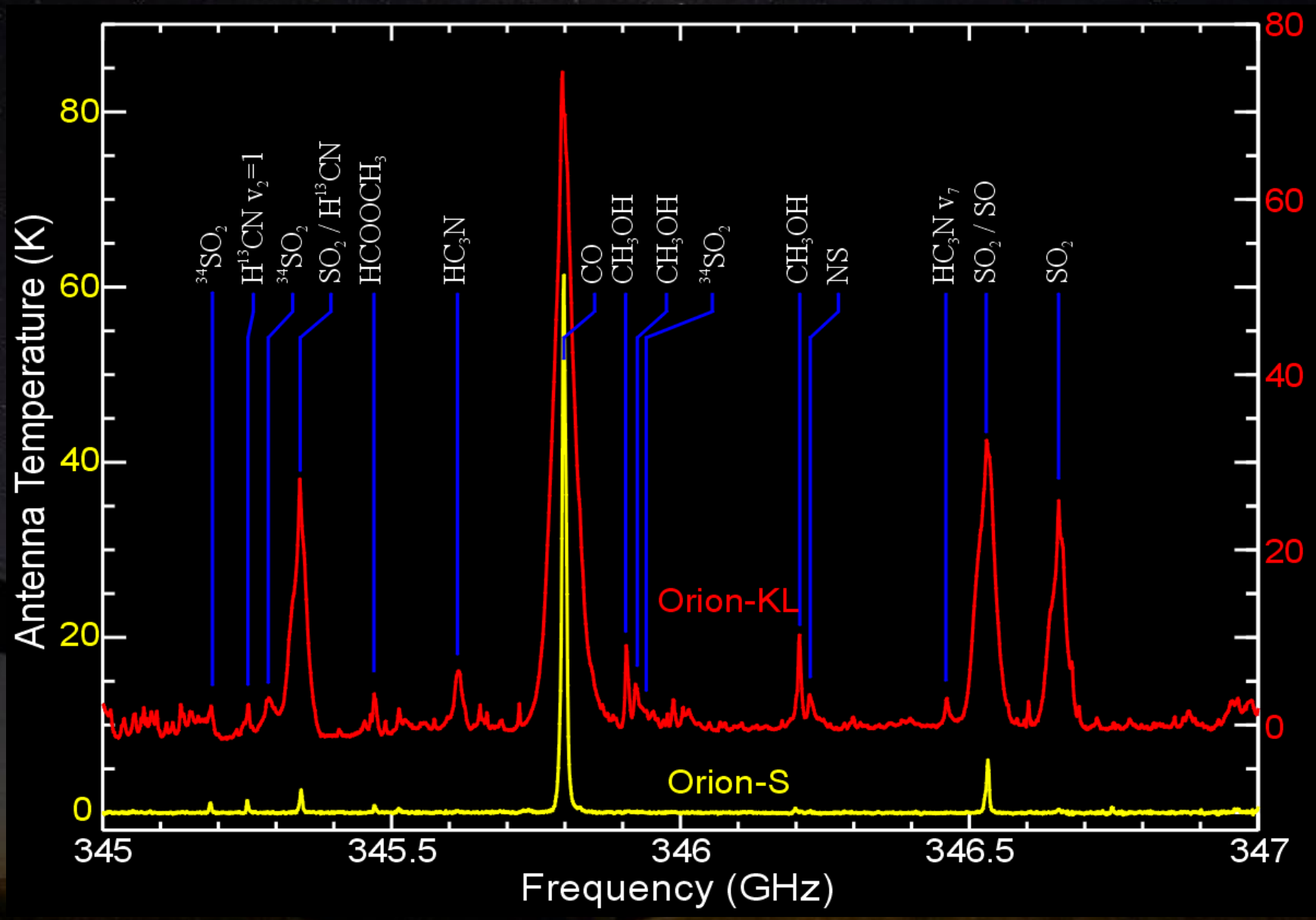


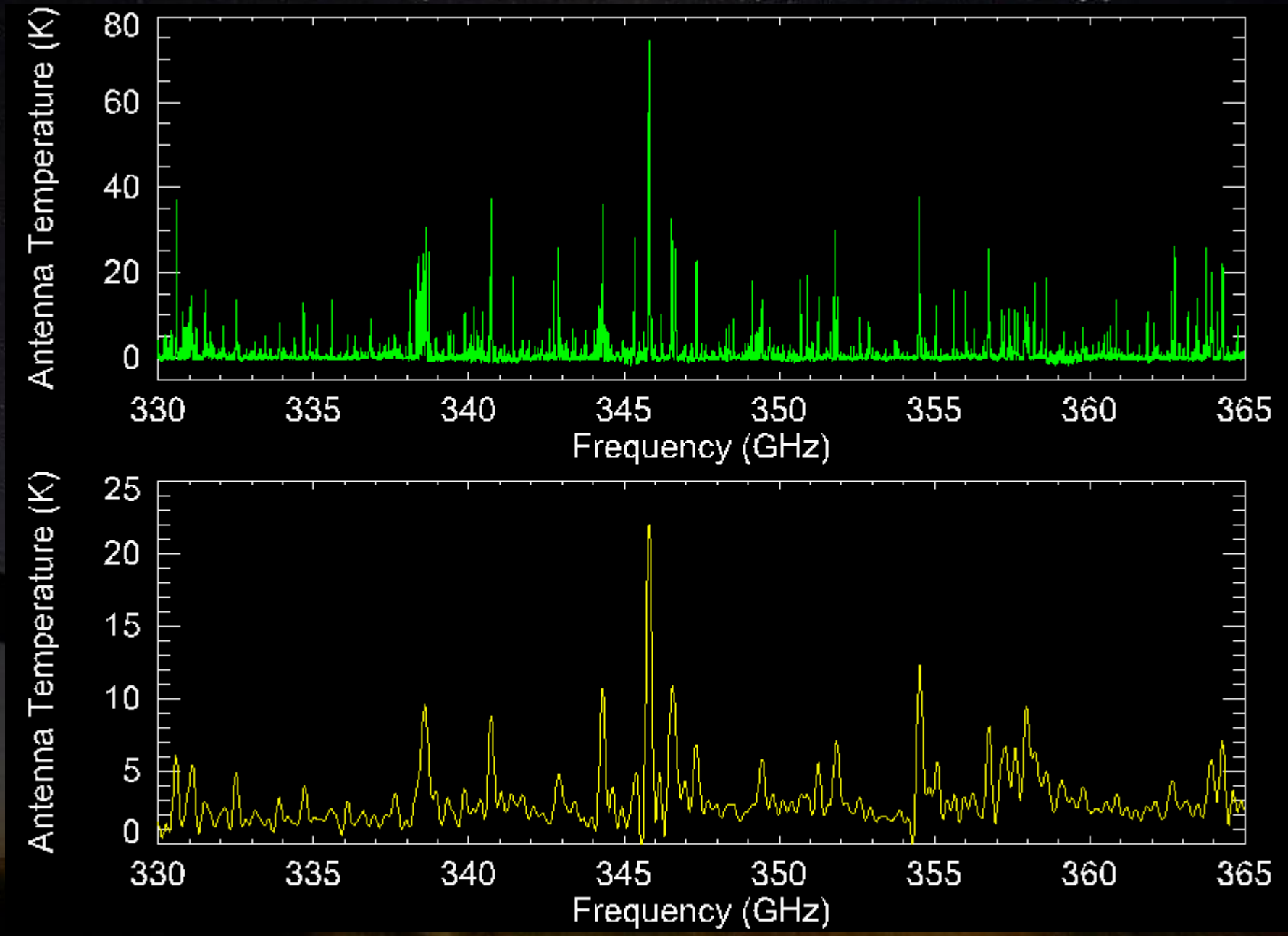
Poor S/N is not always a showstopper…

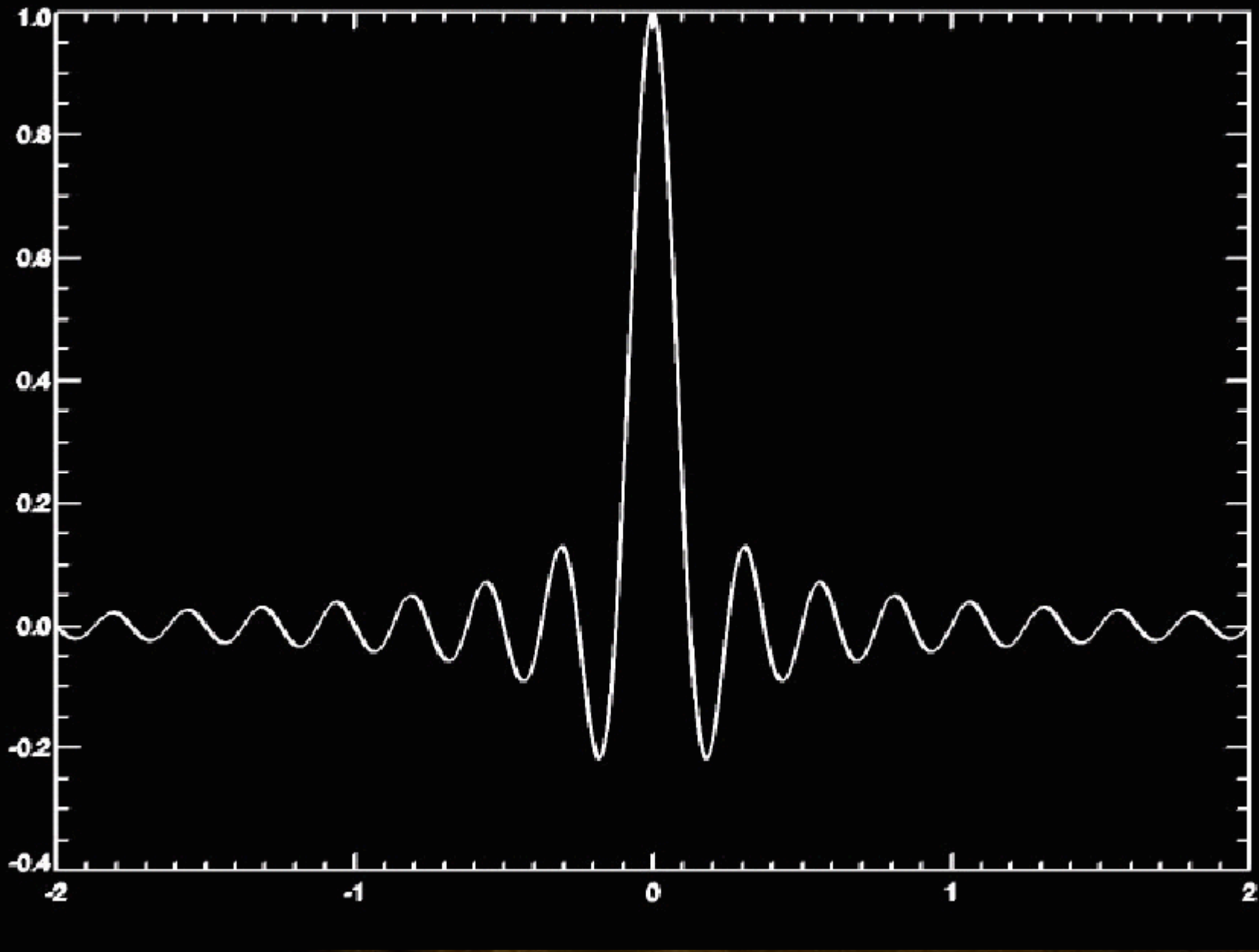


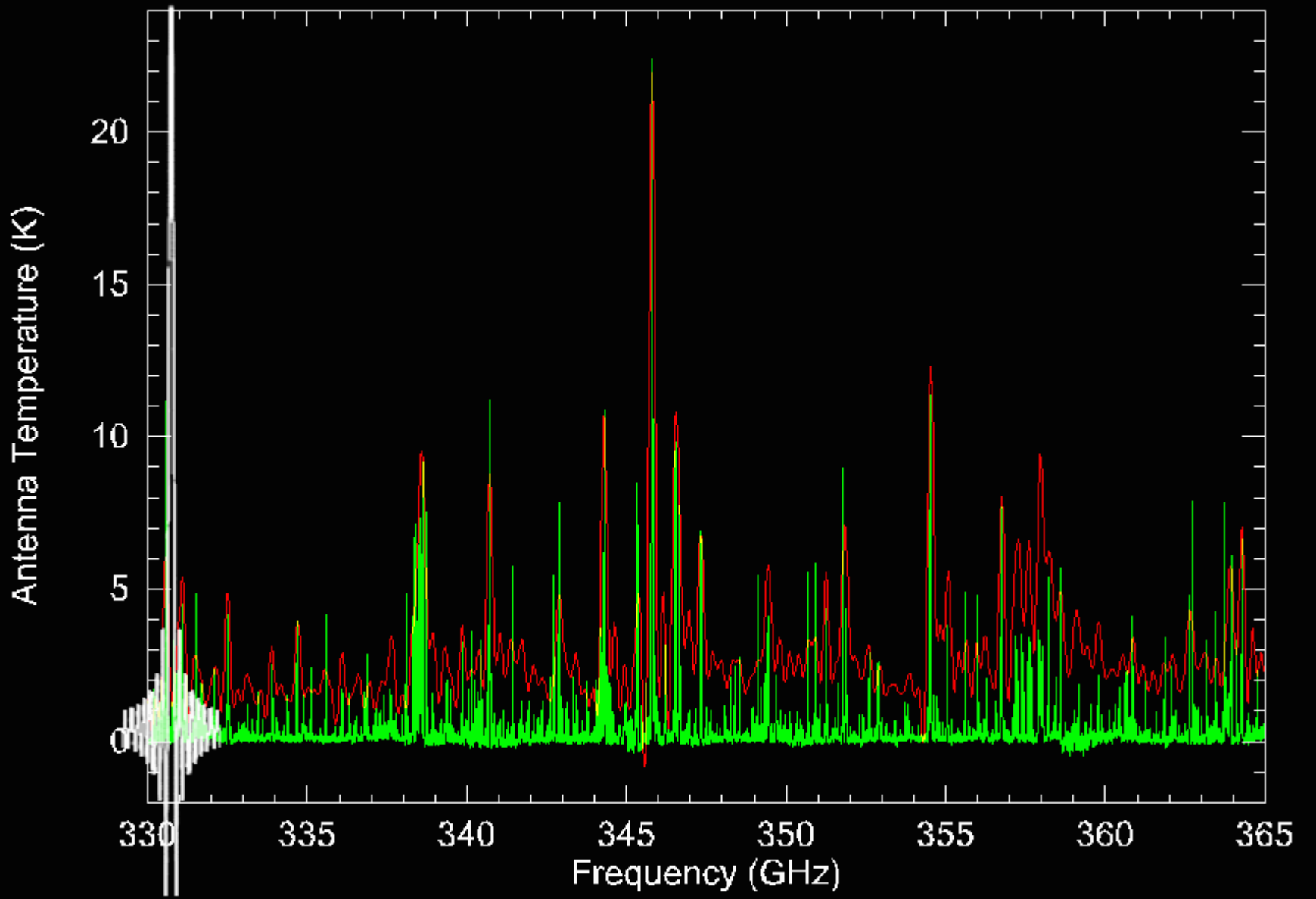

Heterodyne Spectral Survey of Orion-KL at 850 µm
Antenna Temperature (K)
0
20
40
60
80
330
340
350
360
370
Frequency (GHz)

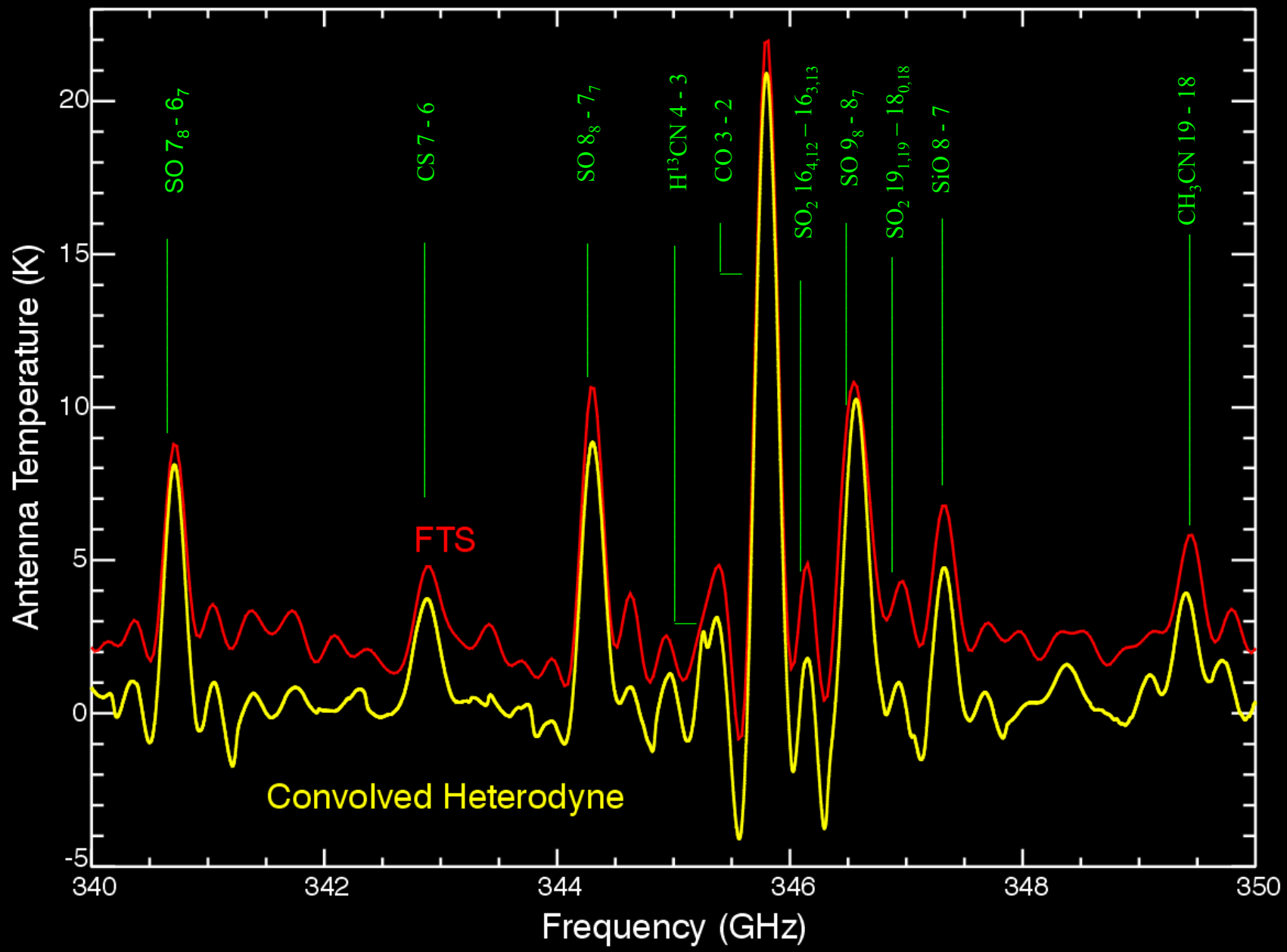

Heterodyne Spectral Survey of Orion-KL at 850 µm (baseline corrected)
Antenna Temperature (K)
80
60
40
20
0
330
340
350
360
370
Frequency (GHz)


Antenna Temperature (K)
Frequency (GHz)
345
345.5
346
346.5
347
0
20
40
60
80
$^{34}SO_2$
$H^{13}CN\ v_2=1$
$^{34}SO_2$
SO_2 / $H^{13}CN$
$HCOOCH_3$
HC_3N
CO
CH_3OH
CH_3OH
$^{34}SO_2$
CH_3OH
NS
$HC_3N\ v_7$
SO_2 / SO
SO_2
Orion-KL
Orion-S


Antenna Temperature (K)
80
60
40
20
0
330
335
340
345
350
355
360
365
Frequency (GHz)
Antenna Temperature (K)
25
20
15
10
5
0
330
335
340
345
350
355
360
365
Frequency (GHz)


1.0
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
-2
-1
0
1
2


Antenna Temperature (K)
20
15
10
5
0
330
335
340
345
350
355
360
365
Frequency (GHz)


SO 7_8 - 6_7
CS 7 - 6
SO 8_8 - 7_7
$H^{13}CN$ 4 - 3
CO 3 - 2
SO_2 $16_{4,12}$ – $16_{3,13}$
SO 9_8 - 8_7
SO_2 $19_{1,19}$ – $18_{0,18}$
SiO 8 - 7
CH_3CN 19 - 18
FTS
Convolved Heterodyne
Antenna Temperature (K)
Frequency (GHz)
20
15
10
5
0
-5
340
342
344
346
348
350

Questions?

SPIRE imaging FTS overview

Jean-Paul Baluteau (LAM)

objectives and drivers

2 main goals for SPIRE:

- **statistics & physics of galaxies and structure formation at high redshift**
- **study of the early stages of star formation**

➔ **capabilities to carry out large-area deep photometric imaging surveys at far-IR & submillimetre wavelengths**

➔ **spectroscopic capabilities as follow up of these systematic survey observations**

→ **low-resolution spectroscopic mode to obtain detailed SEDs of selected objects**

→ **high-resolution spectroscopic mode to measure key spectral lines**

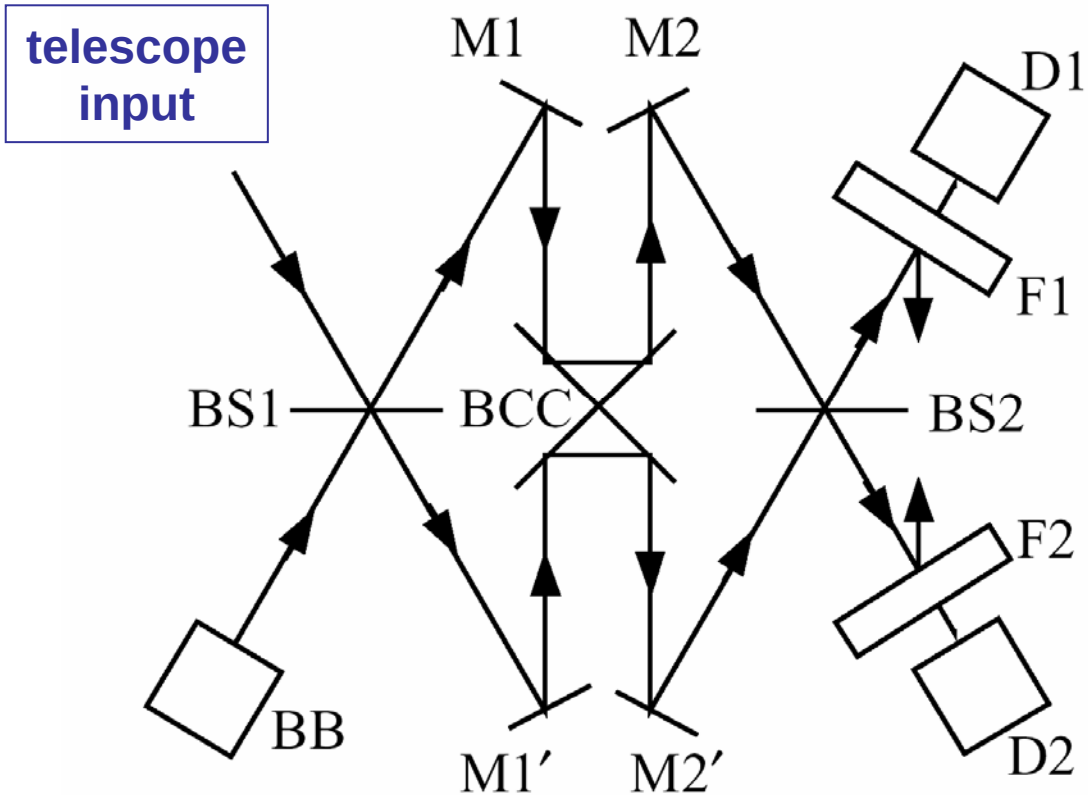
spectroscopy: requirements and constraints

- **requirement to have 2D imaging spectroscopy**
- **need for wide spectral coverage (goal: 200 - 650 μm)**
- **ability to have variable spectral resolving power**
- **requirement to have diffraction limited spatial resolution**
- **desirability of having a large instantaneous field of view**
- **necessity of having both maximum sensitivity & rapid coverage of the available spectral range**

- **radiation background due to the 80K 4% emissive telescope**
  - **photon noise limited NEP & detector operated at 300 mK**
- **difficulty in predicting and controlling straylight environment**

➔ **selection of an FTS type spectrometer**

optical design



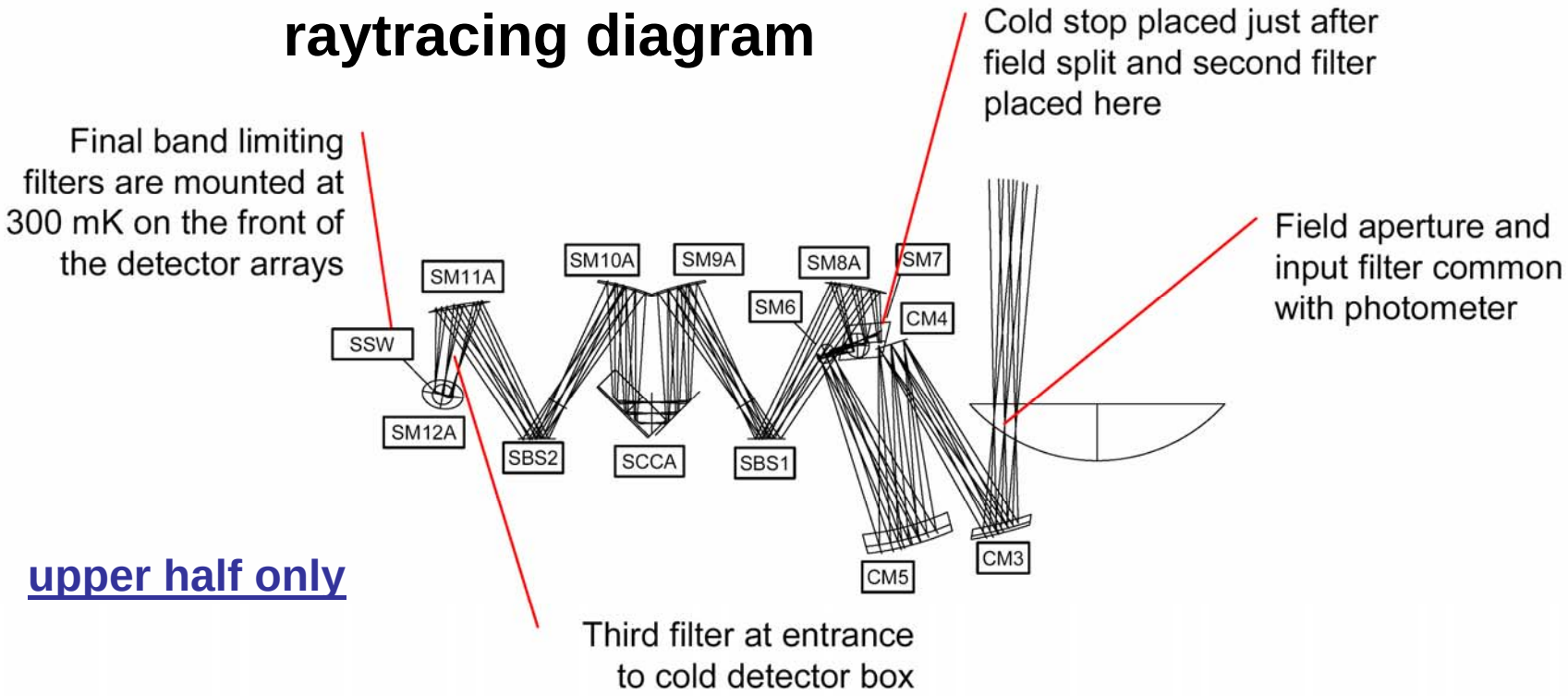
Mach-Zehnder type design

broad band intensity beam splitters (200 - 700 μm) developped at Cardiff

two input ports and two output ports available

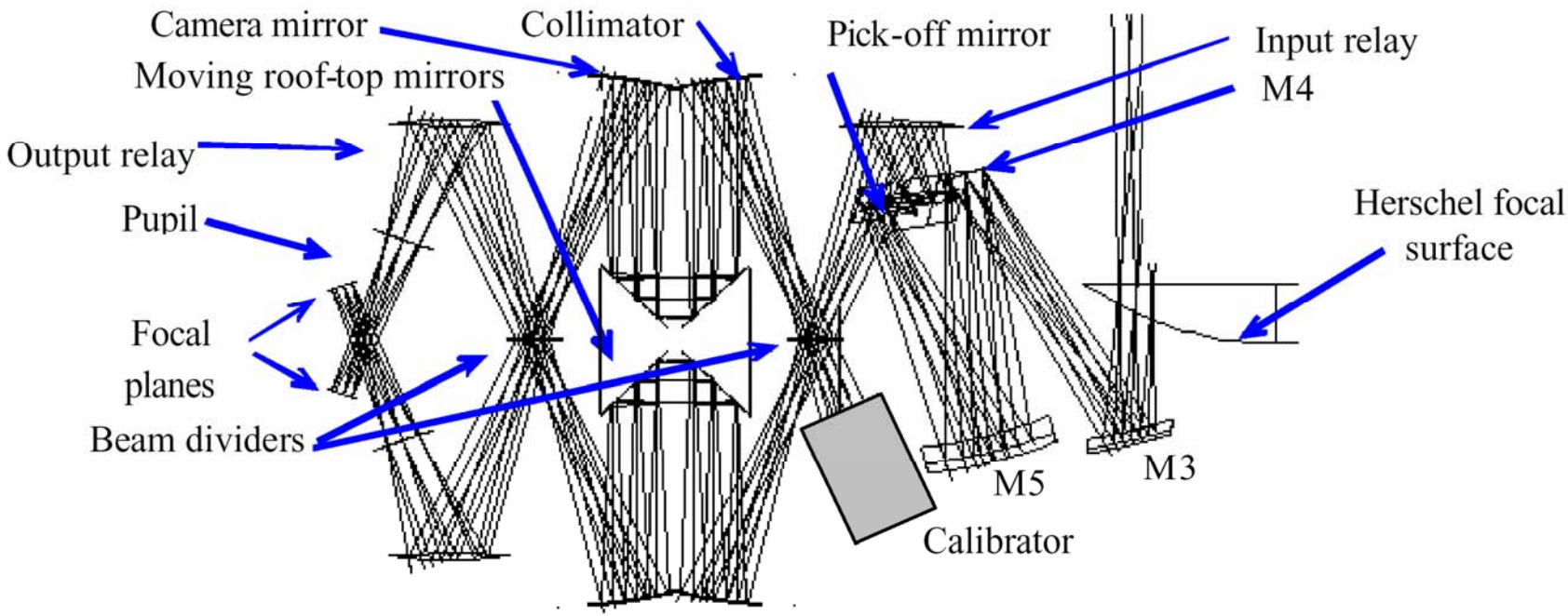
no sensitivity to polarisation of incident radiation

raytracing diagram

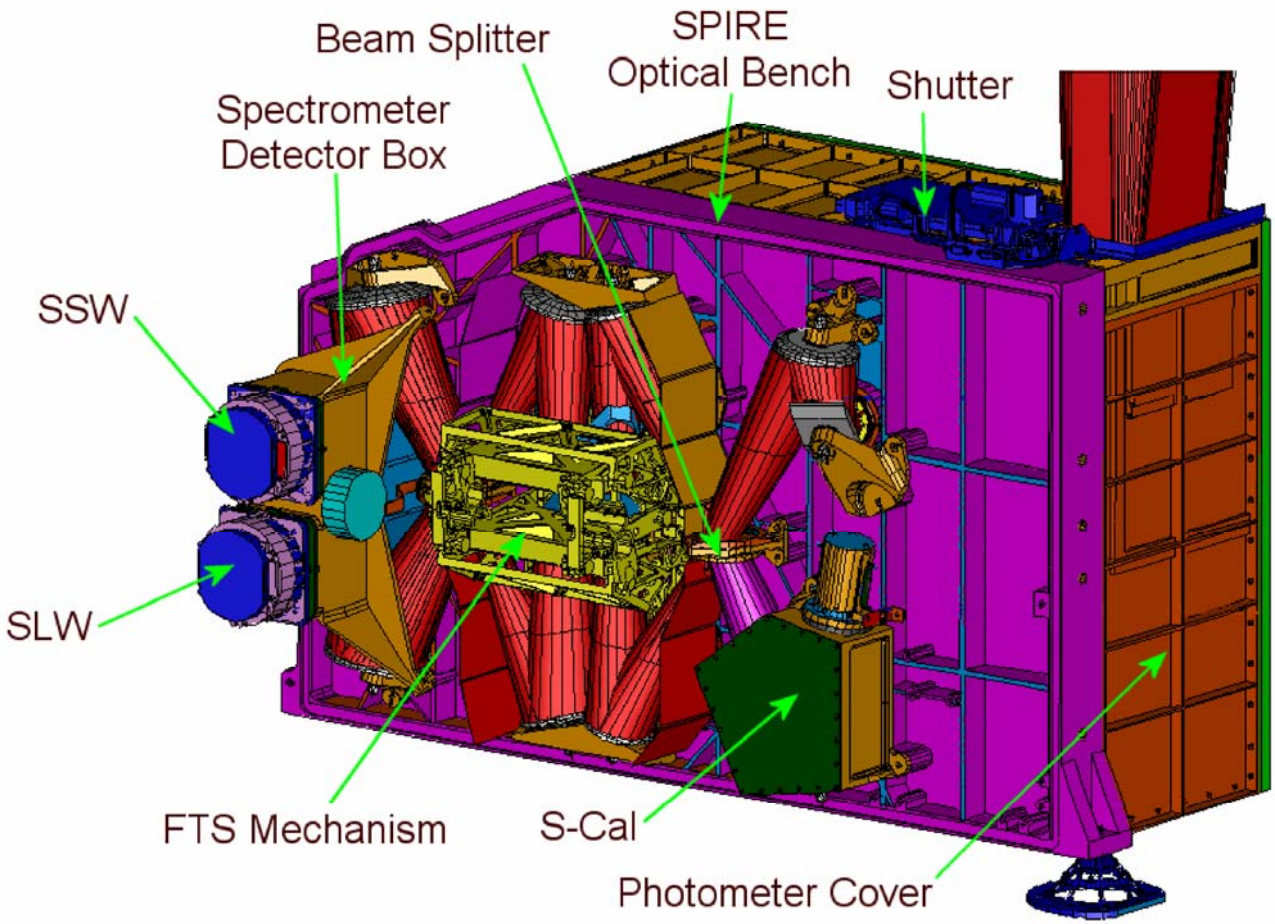


- **all powered mirrors & mechanism mounted from an optical bench at 4K**
- **final fold mirror & detector assemblies mounted from a thermally isolated box at 1.7K**
- **a pupil "cold" (4K) stop is placed between M6 & M7**
- **design (feedhorns & waveguides) improved to control the multimode performance & long wavelength efficiency**

full optical diagram

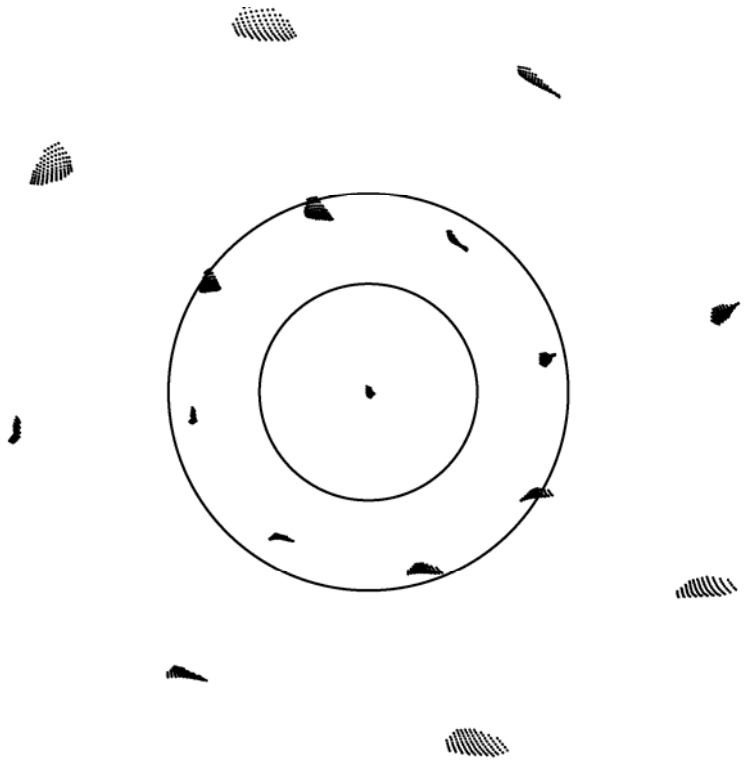


general view of accommodation



spectrometer image quality

- astigmatism close to zero
  at FOV centre
- good balance of aberrations
  over rest of FOV
- worse wavefront error ~ 6.6μm
- theoretical Strehl ratio
  better than 0.97
  anywhere in the FOV at 250μm

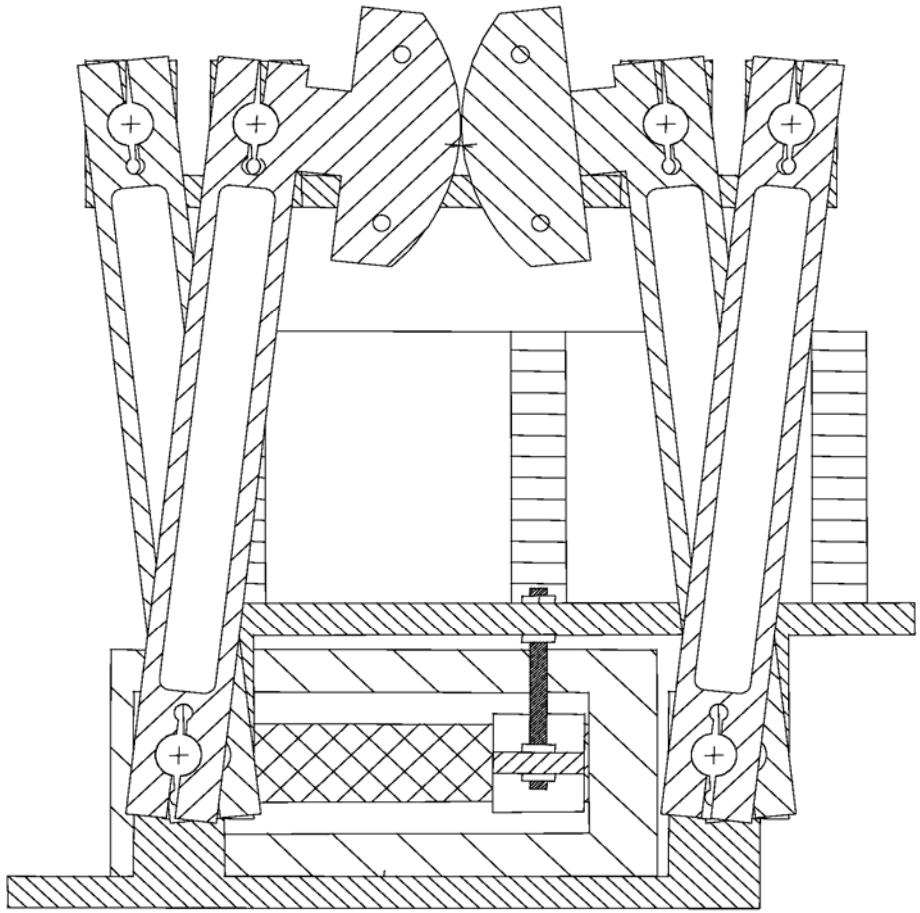


geometric spot diagrams

rooftop mirrors mechanism

based on a prototype carriage built at GSFC:

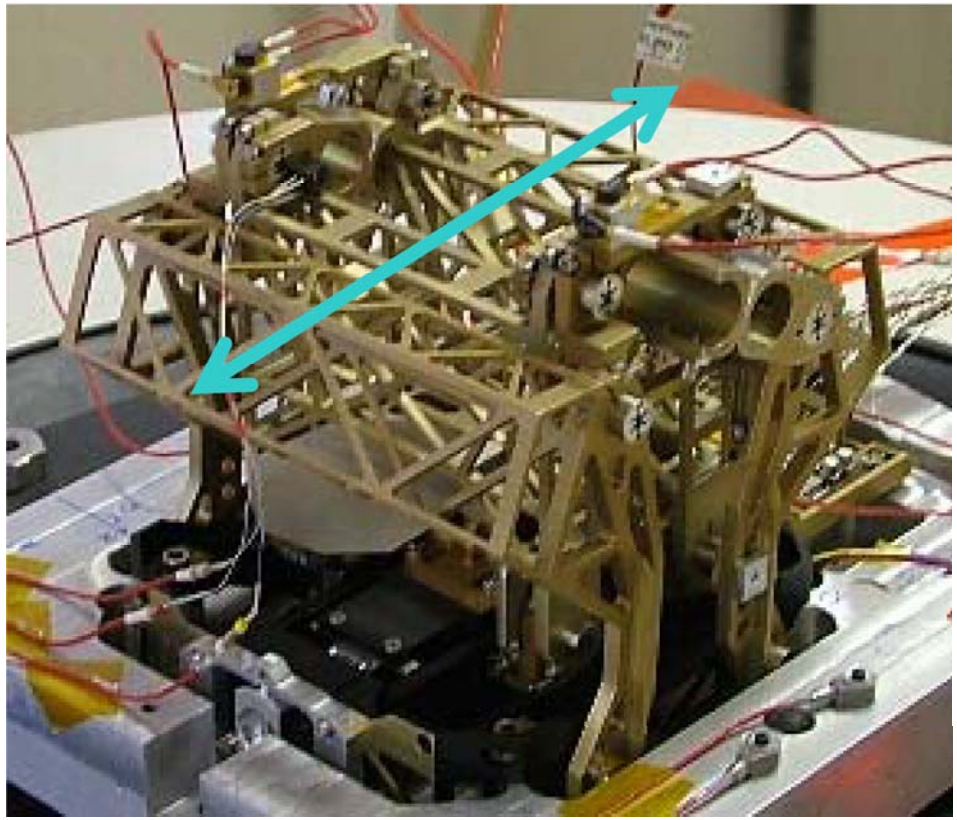
- ➔ **double parallelogram system**
- ➔ **with a frictionless gear to ensure that the two parallelogram structures move together**
- ➔ **use of roof tops as baseline means that performances are sensitive to tilt errors in the mirror movement (however requirements on mirror tilt not so severe)**



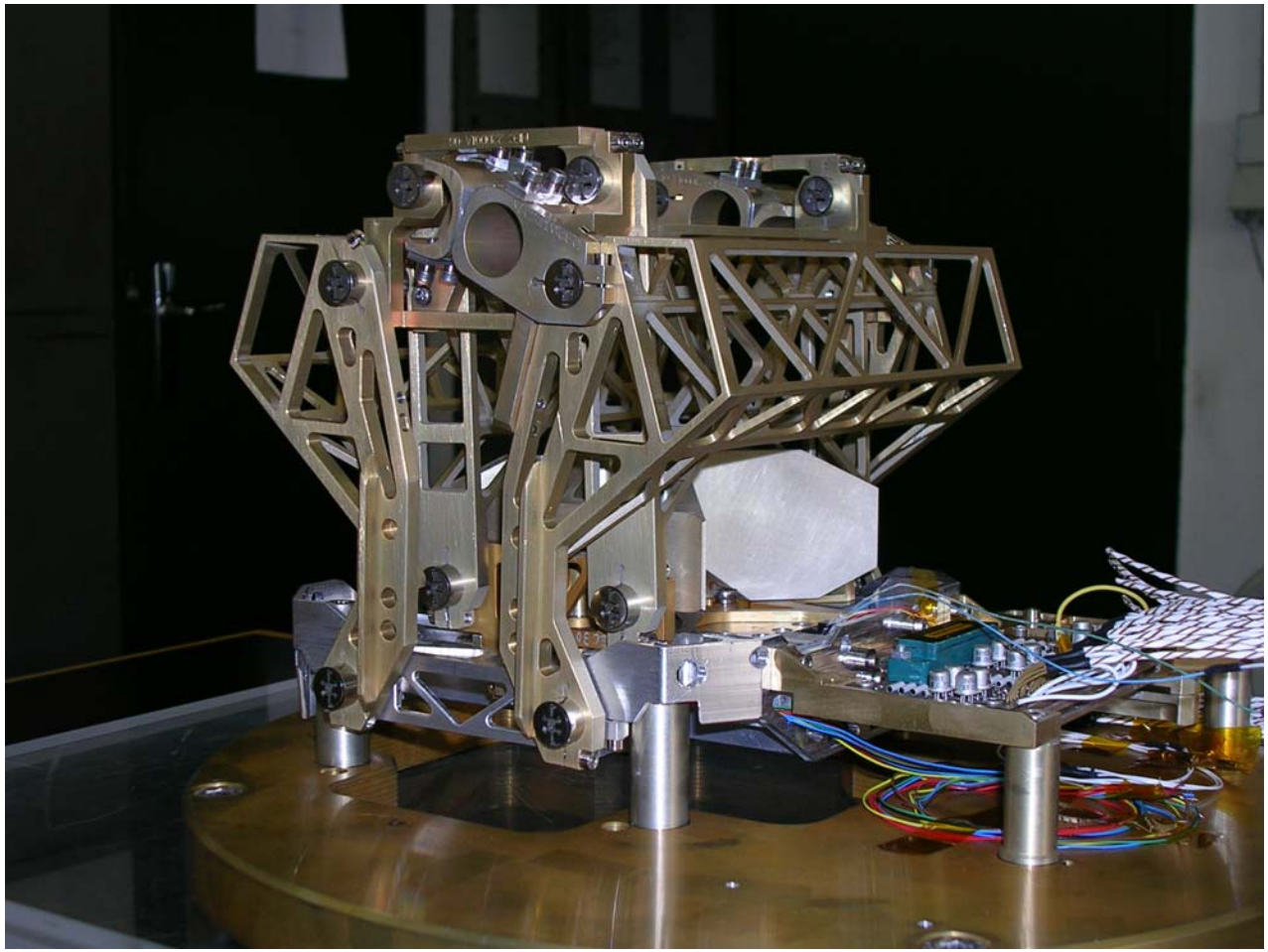
drawing of the link mechanism

SMECm requirements

- **total movement:**
  - **-3.2 to 32 mm wrt ZPD to ensure best spectral resolution of 0.04 cm-1**
- **nominal mode:**
  - **rapid scanning**
  - **nominal speed 0.5mm/s**
  - **signal frequency range from 3 to 10 Hz**
- **mirror velocity stability**
  - **less than 10µm/s (0.03 - 25 Hz)**
- **position measurement**
  - **accuracy: 0.1 µm**
- **x**



SMECm FM at LAM before delivery



position measurement systems

- **Heidenhain (Moiré fringe sensing system) optical encoder**
  - **basic grating step size = 2 μm**
  - **modified for space & cryogenic operations**
  - **3 separate detectors providing signals approximately 120°- phase shifted with respect to each other**
  - **accuracy better than 10 nm achieved in cryogenic operations**
  - **but gives only a relative position (mechanical *reference*)**
  - **presently no loss of counts in ground conditions**

- **LVDT device**
  - **able to provide an absolute position around ZPD**
  - **accuracy of about 0.1 μm over +/- 3.2 mm around ZPD**
  - **provides a back-up solution in case of optical encoder failure**

SMECm drive electronics

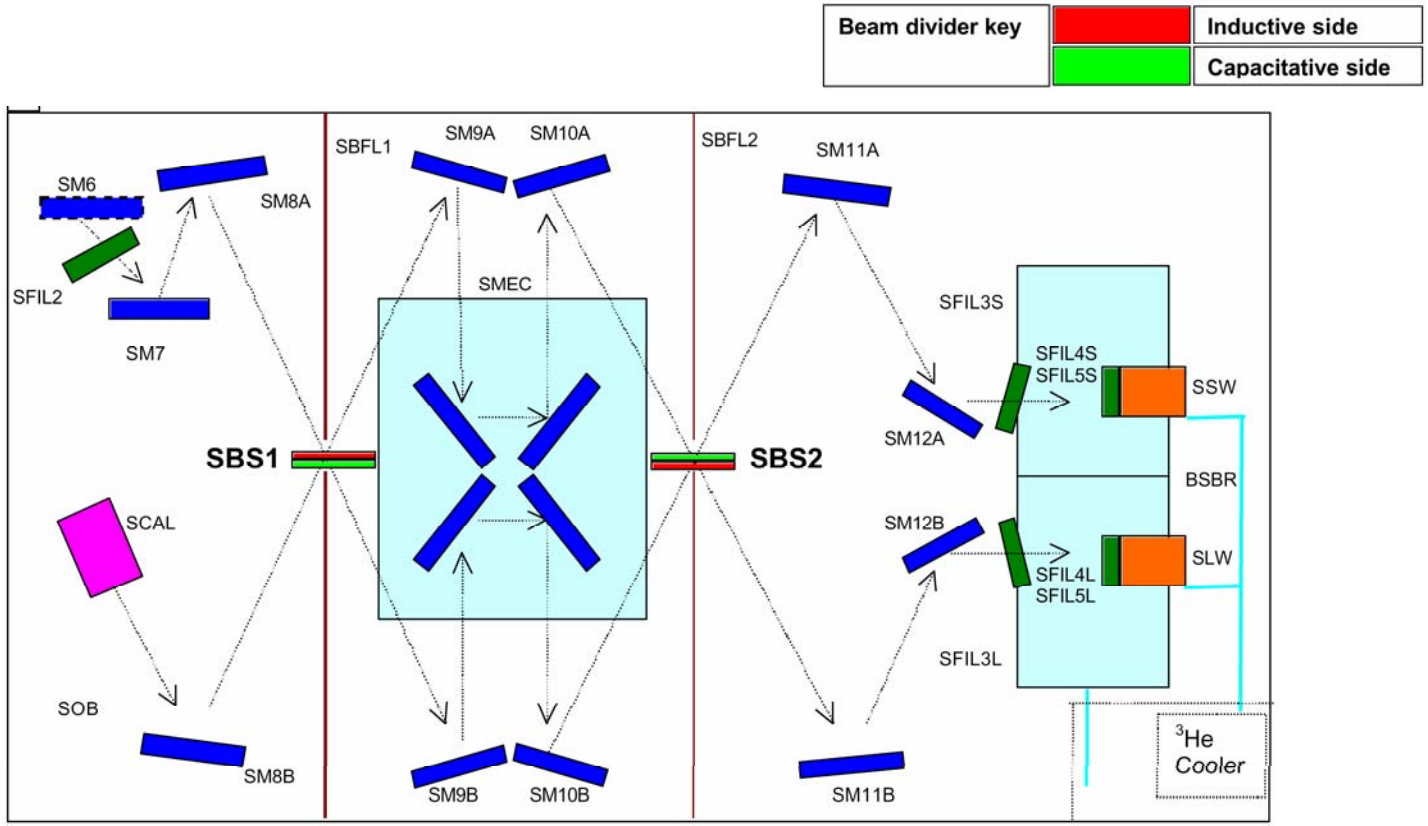
- **control of movement carried out using a DSP21020 chip**
- **DSP software based on a master scheduler (time sharing)**
- **tasks to be performed are called on by a software interrupt generated by the inner DSP timer**
- **algorithms based on trajectory generators & digital PID controllers**
- **use filtering for notching of mechanical modes**
- **the position (determined by counting encoder step pulses from the reference position) is used in the feedback loop to the drive current of the actuator to control the mirrors speed**
- **control PID parameters held in memory but can be modified by means of commands sent to the spacecraft**
- **telemetry rate able to get SMEC timeline sampling at 240 Hz (detector timeline sampling at 80 Hz)**

FTS filtering strategy

- **optical filtering: to insure following functions**
  - **definition of spectral passbands**
  - **minimisation of thermal loading by rejecting short wavelengths thermal energy**
  - **minimisation of straylight getting to detectors**
  - **maximisation of in-band spectral transmission**

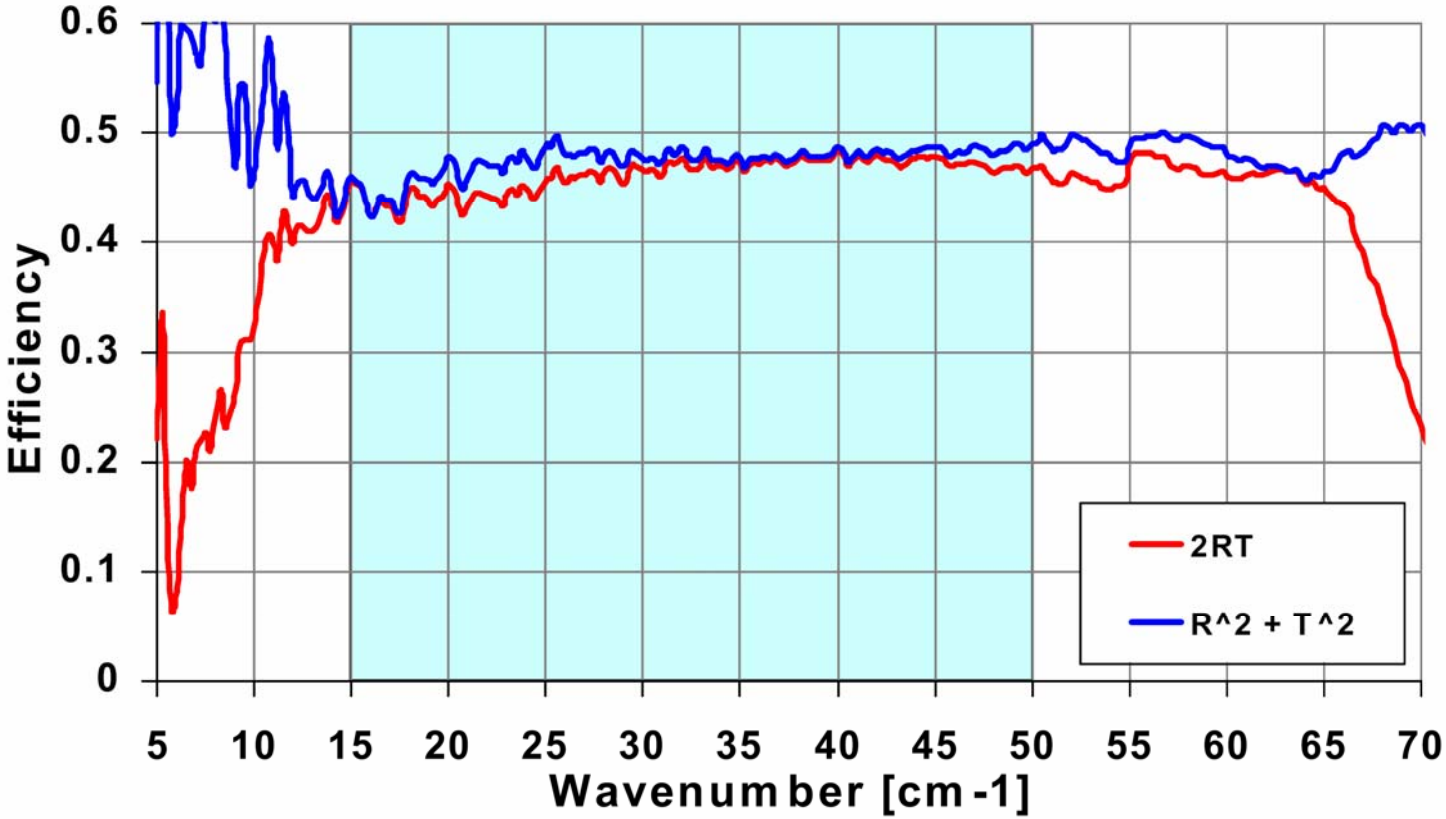
- **detector & electronical filtering:**
  - **detectors acting as low-pass RC type filter**
  - **electronical filtering to remove high frequencies (greater than 25 Hz; four poles Bessel)**
  - **this filtering introduces delay in detector data timeline stream and causes a phase dependent on frequency/wavelength**
  - **DC signal not rejected ➔ need for "offset" selection to get in the right part of ADC**

FTS optical filtering scheme



nomenclature of FTS mirrors, filters, beam splitters & dichroics (from P. Hargrave)

measured efficiency of FTS beam splitters



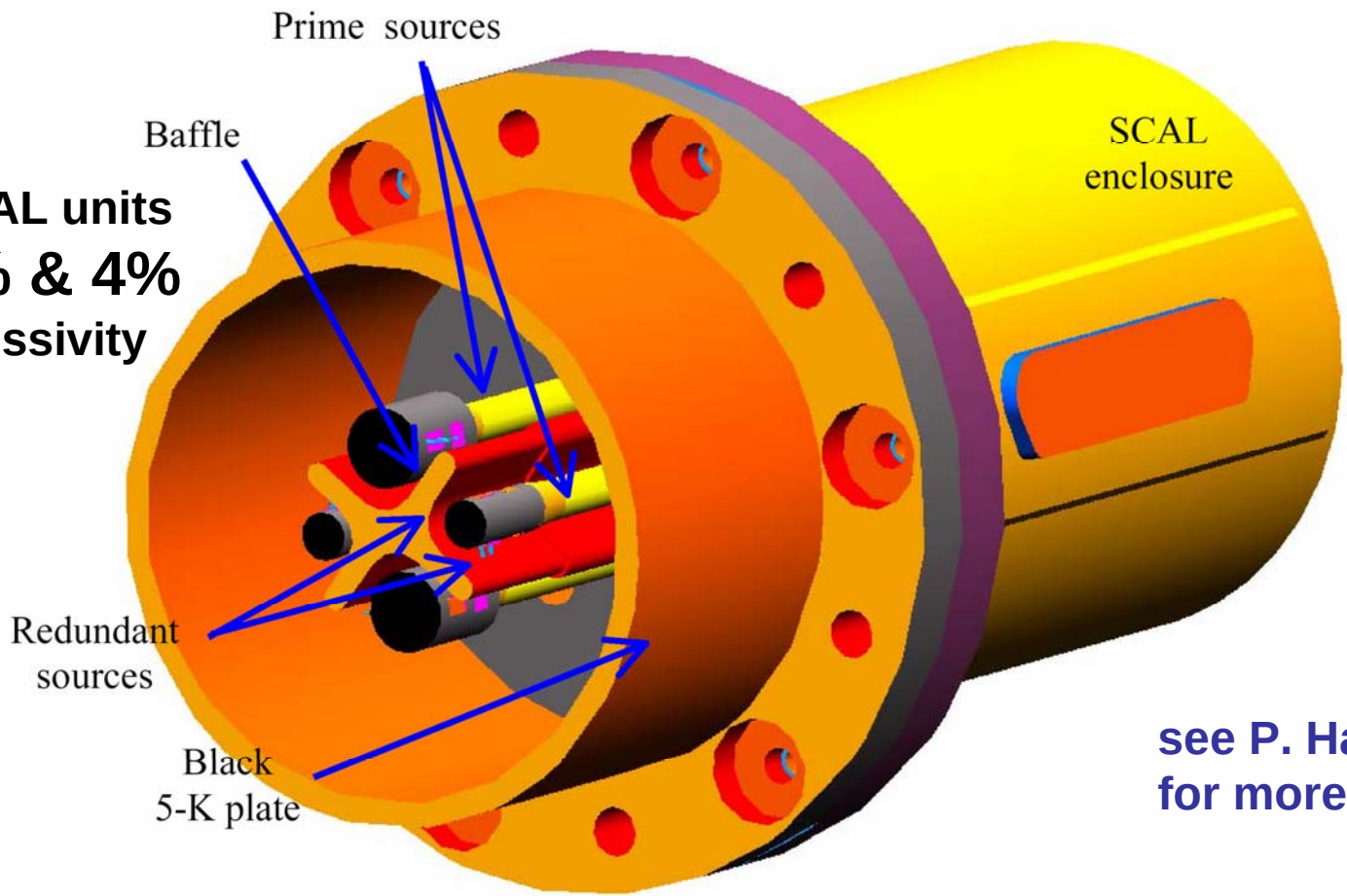
beam dividers designed to have 50% transmissivity (T) & reflectivity (R) over full FTS spectral range

SCAL calibration system

- **the second input port is used to provide a calibration source**
- **first function: to provide a direct photometric calibration for astronomical signals**
  - **compared to an accurately calibrated source during ground testing**
  - **the calibration signal can be present during the entire in-orbit operations (changes in FTS performance can be readily removed from the data during ground processing)**
- **second function: to "null" the continuum radiation from the warm telescope**
  - **allows to reduce the dynamical range of the signals close to ZPD (where electronics digitisation noise may be a problem)**
  - **allows also to reduce the "position" noise in the interferogram (directly related to position uncertainty through the slope of the modulated signal)**
  - **in case of strict "nulling" power onto detectors is twice more**

design of SCAL unit

SCAL units
2% & 4%
emissivity



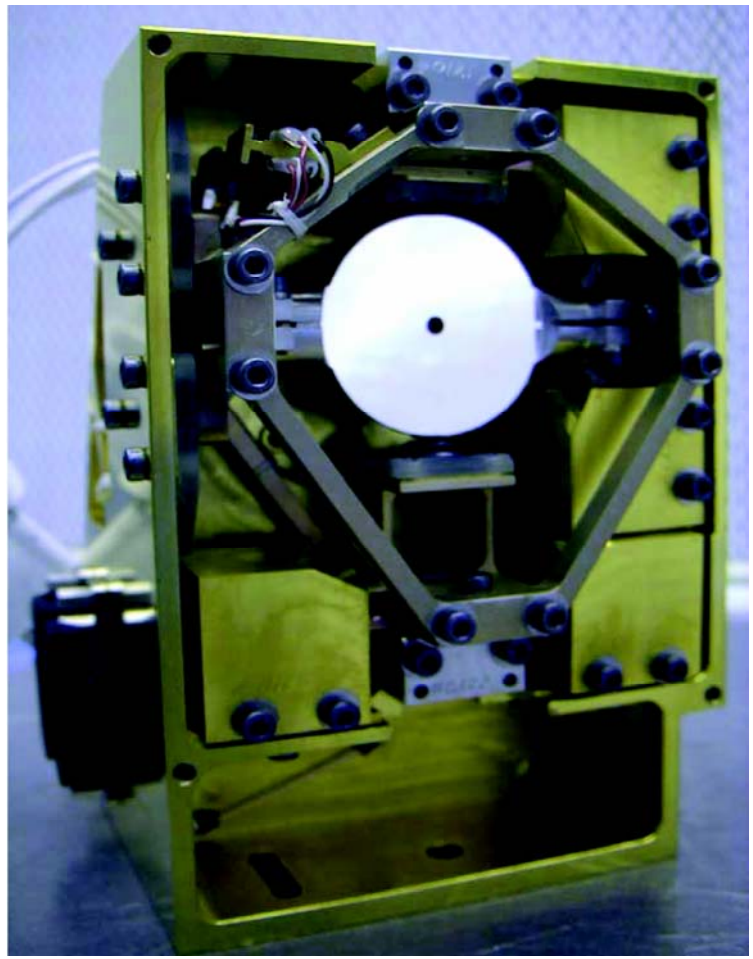
see P. Hargrave for more details

four small black plates thermally isolated from the SPIRE structure
two units can be operated (temperature controlled) simultaneously

BSM (beam steering mirror)

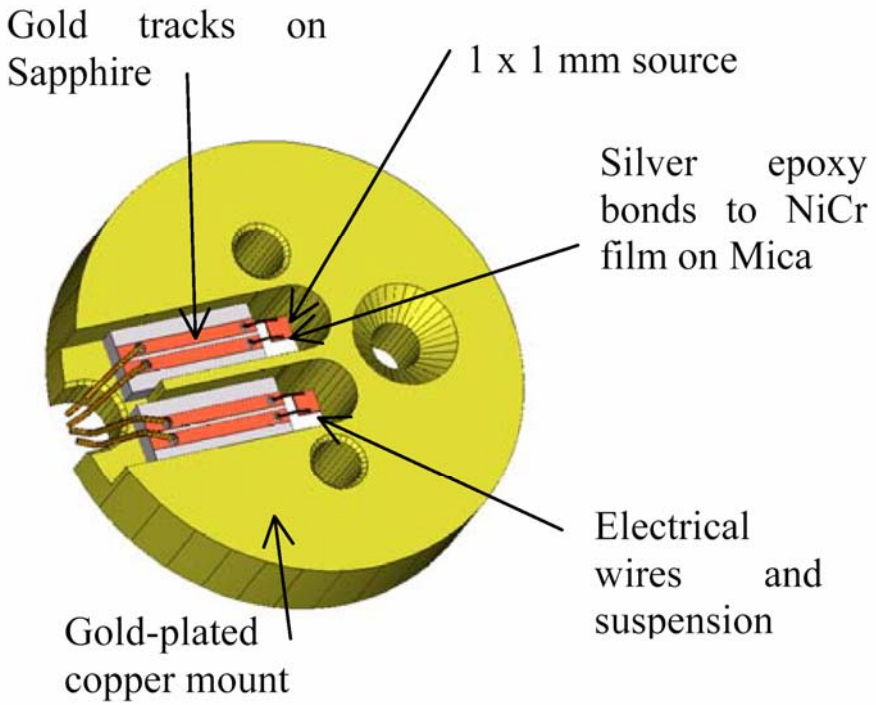
- **used to provide the necessary pointing changes for fully- or intermediate- sampled spectral mapping**

- **in the FTS step & integrate mode:**
  - **scan mirror placed at a set of positions to form a scan**
  - **SCAL units are off**
  - **BSM used for chopping between two sky positions**
  - **telescope background removed**
  - **only backup mode**



ATC BSM FM unit

PCAL



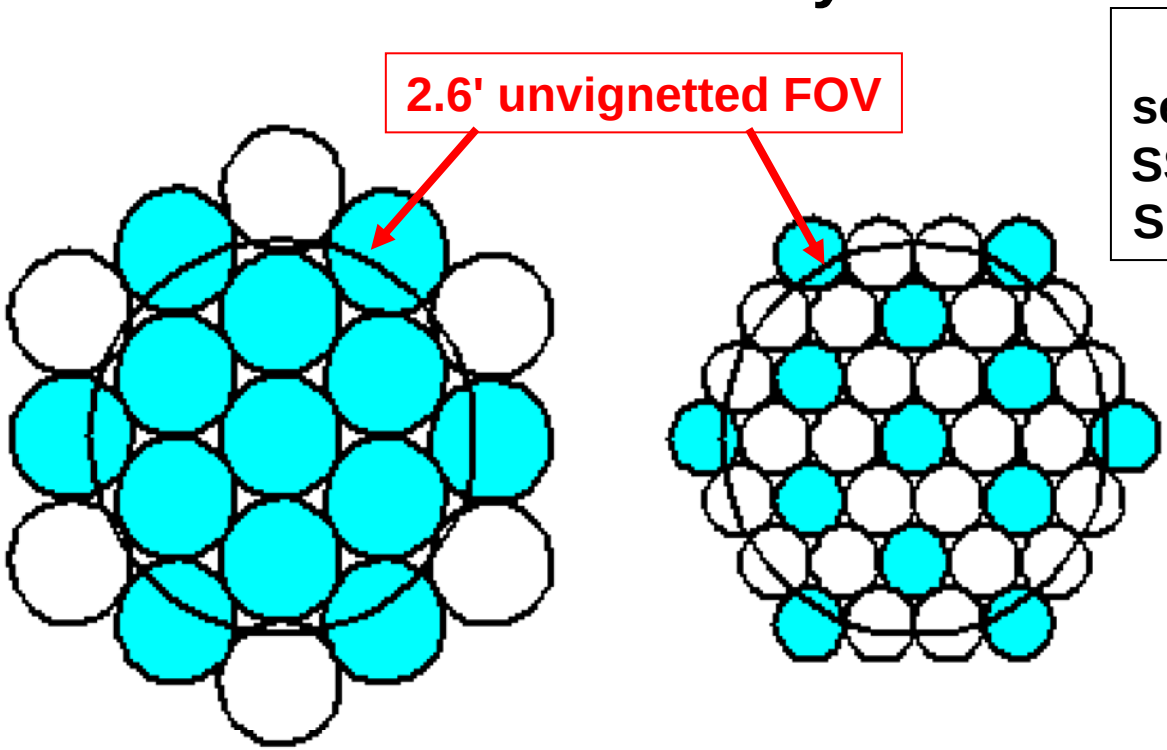
see P. Hargrave for more details

schematic diagram of PCAL design

purpose: to provide a repeatable signal for monitoring of detector health & responsivity during ground testing & in-flight operation (as for the photometer)

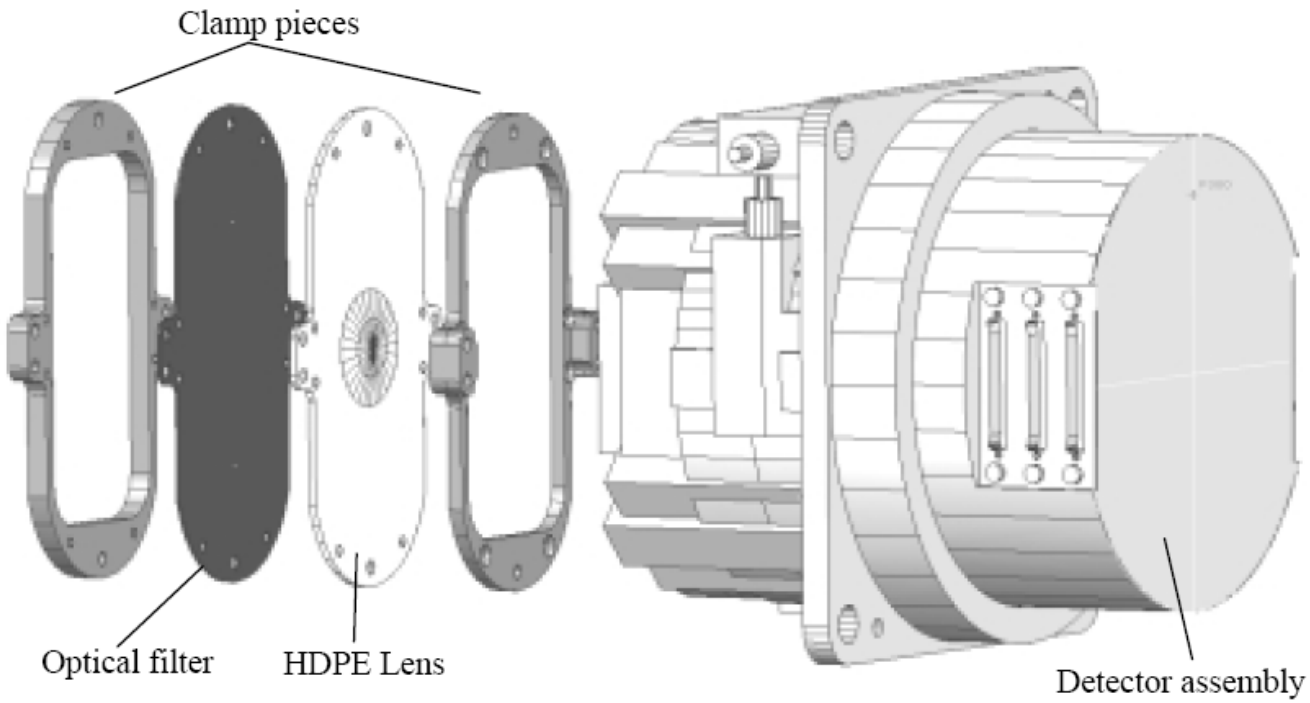
PCAL viewed by FTS arrays through BSM hole

FTS detector arrays



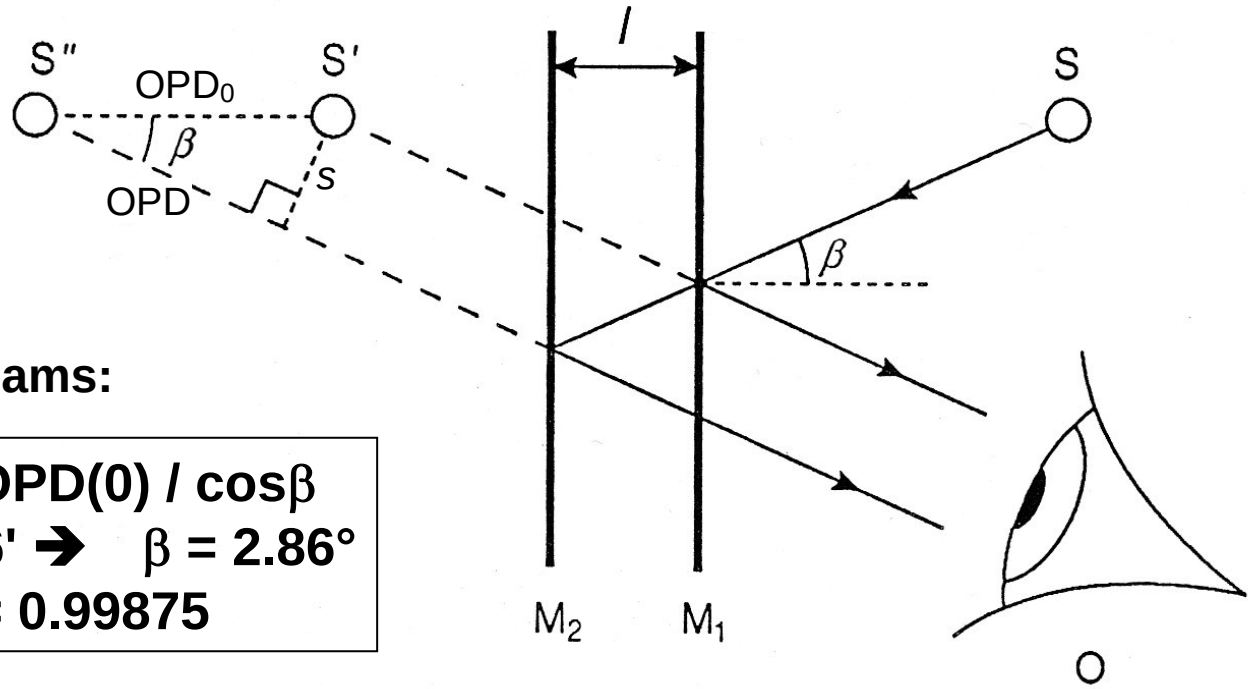
array modules (from JPL) similar to those used for the photometer
feedhorn & detector cavity designs carefully optimized to provide good sensitivity across the whole wavelength range

addition of new lenses in BDAs



<u>now each array has a lens incorporated in its 0.3K filter stack:</u>
as detectors use feedhorns they need to be on a flat focal plane
so lenses are implemented to correct for non-telecentric FTS optics
and to provide more uniform fringe contrast & efficiency across the field
but co-alignement of some pixels in the two bands affected

some iFTS optical aspects to know



for off-axis beams:

OPD(β) = OPD(0) / cosβ
for FOV =2.6' ➔ β = 2.86°
cosβ = 0.99875

so the variation of OPD across the focal plane is:

$$\Delta OPD = OPD_0(1-\cos\beta) \approx OPD_0\beta^2/2$$

the maximum OPD required to obtain a resolving power R is:

$$R = 2OPD_{\max}/\lambda$$

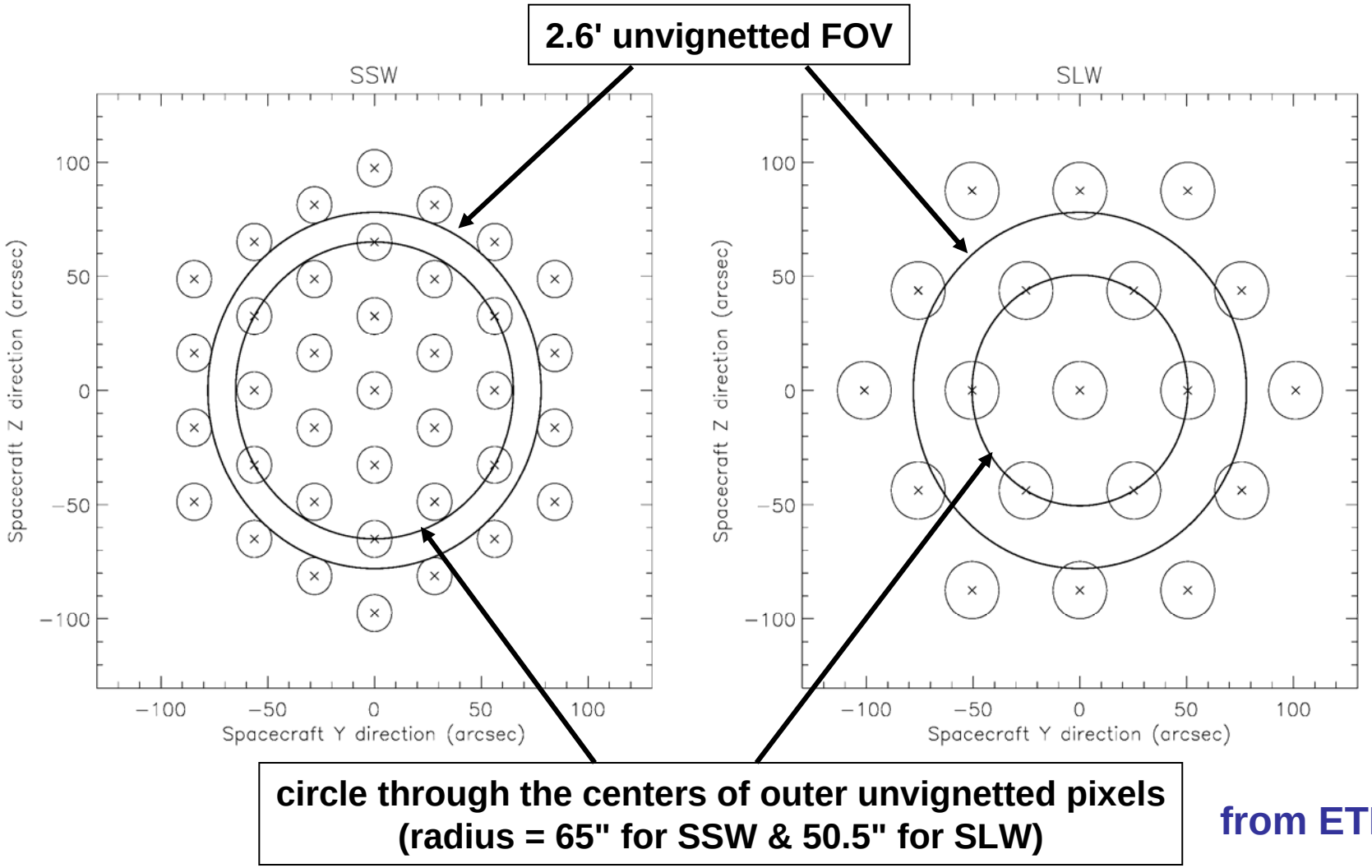
for SPIRE FTS: OPD = 4 x MPD

some more useful things to know for iFTS future scientific users

my personal views about
some capabilities of the iFTS

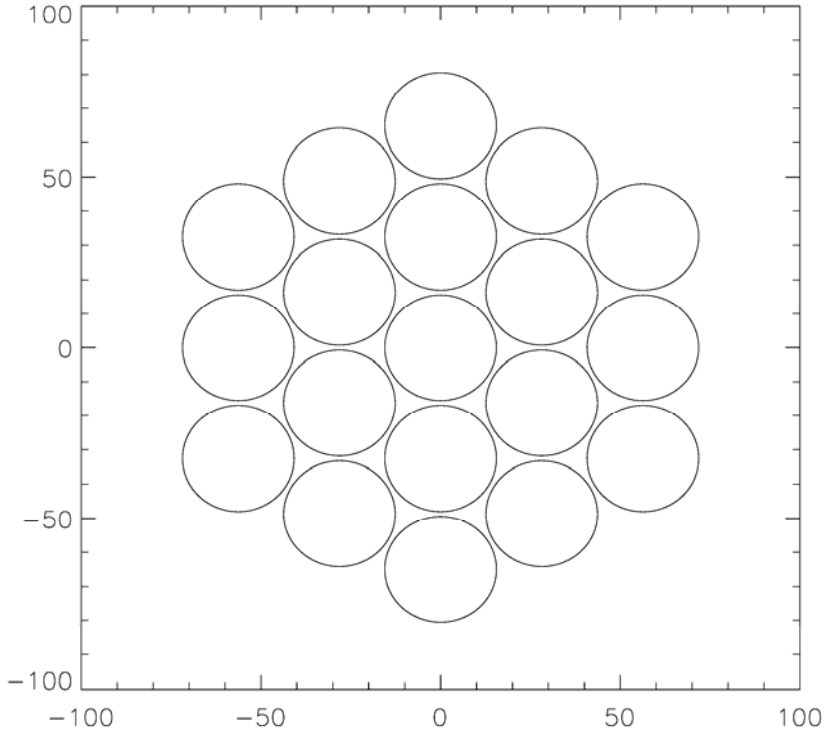
- **imaging (intermediate sampling)**
- **resolving power (simulation of M82 spectrum)**

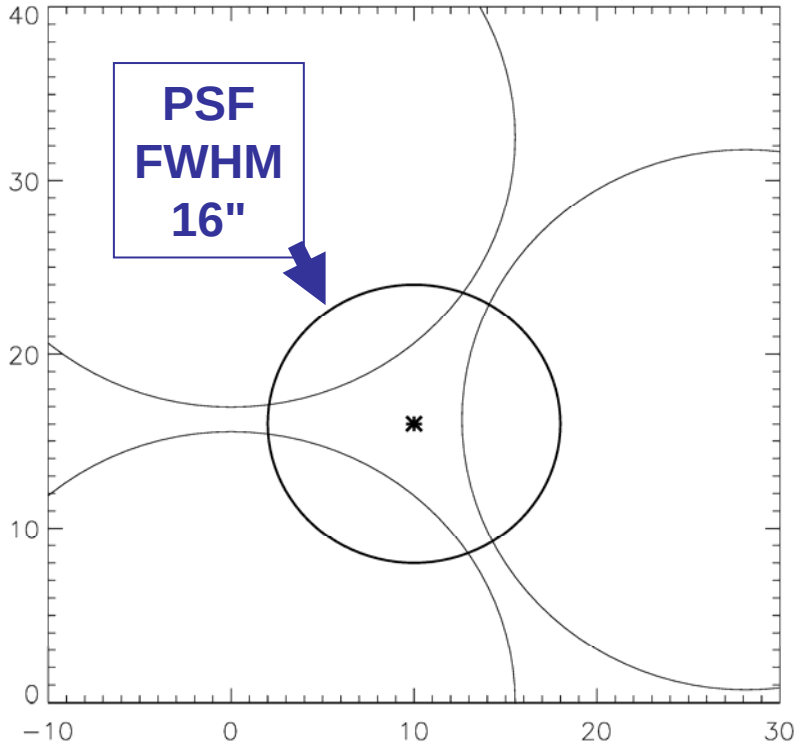
iFTS: SLW & SSW arrays



from ETP

iFTS SSW array: sparse sampling

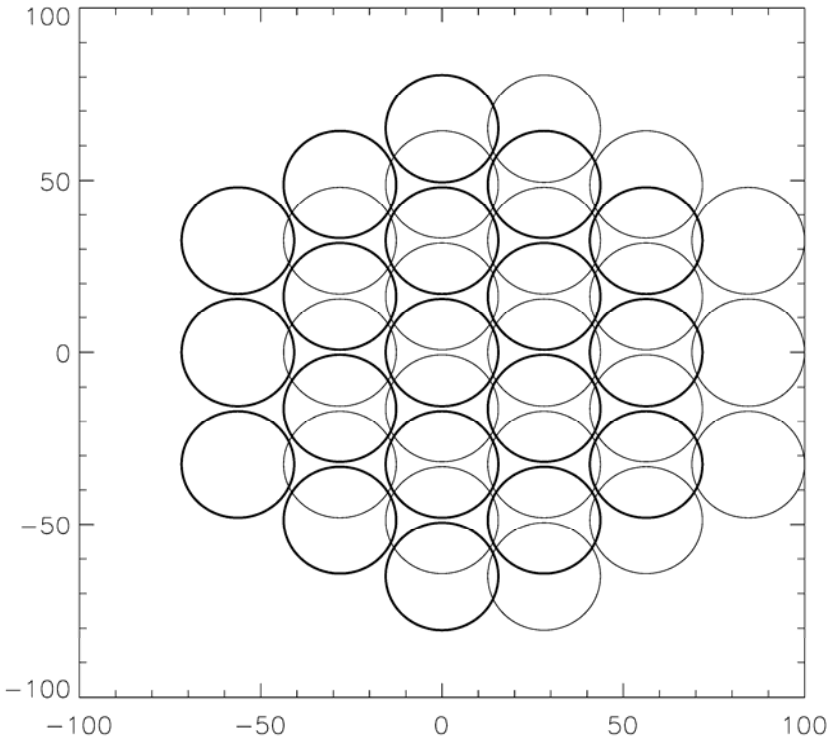


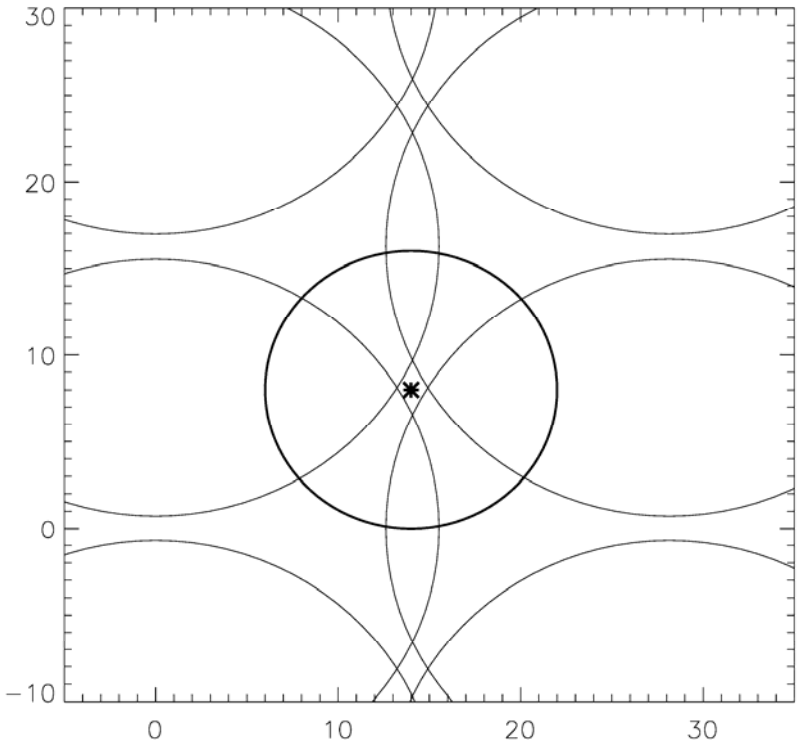


all unvignetted pixels of the SSW array the most critical in terms of spatial resolution

zoom near the centre
size of the pixel FOV ~ 31"
pixel separation ~ 32.5"

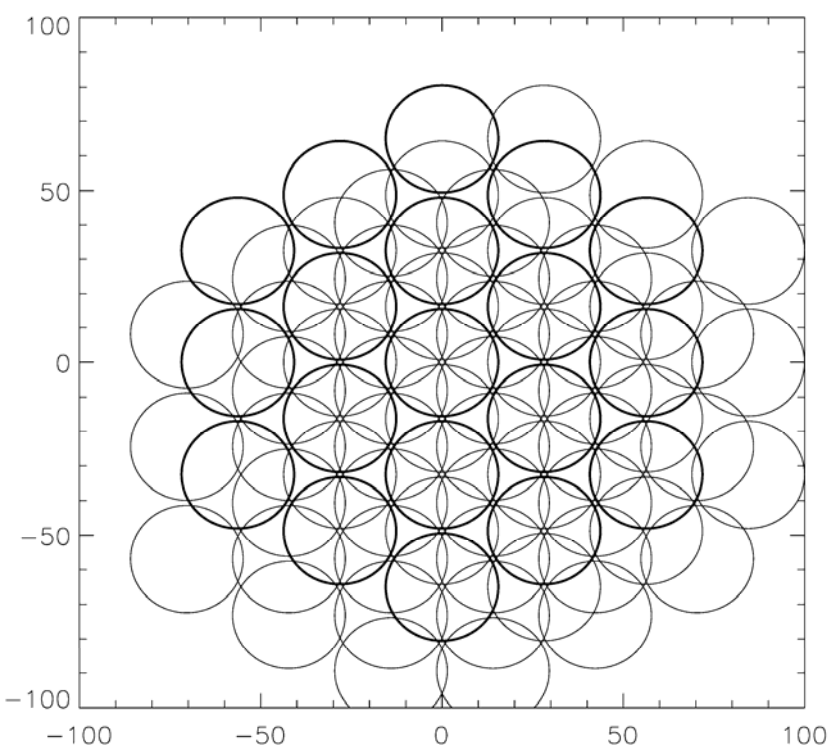
iFTS SSW array: sparse sampling (2 pointings)

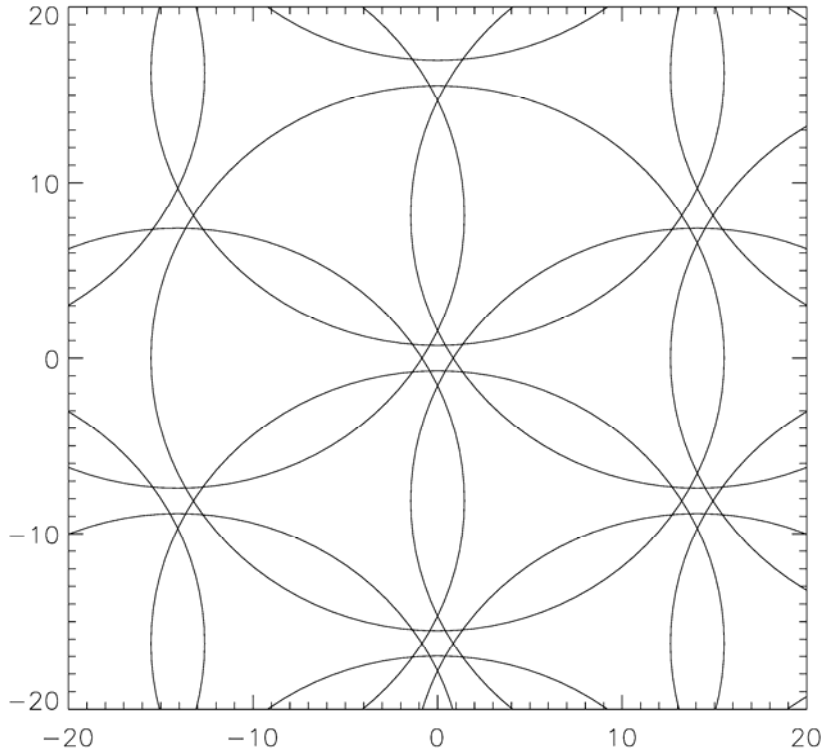




again some loss of sky flux but now marginal loss
! NOT IN CURRENT AOTs !

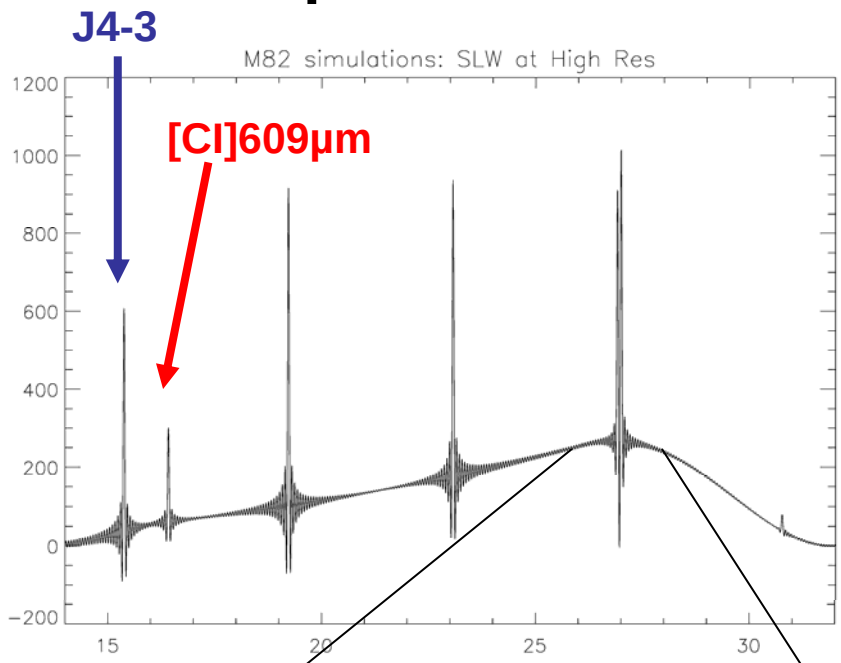
iFTS SSW array: intermediate sampling (4 pointings)

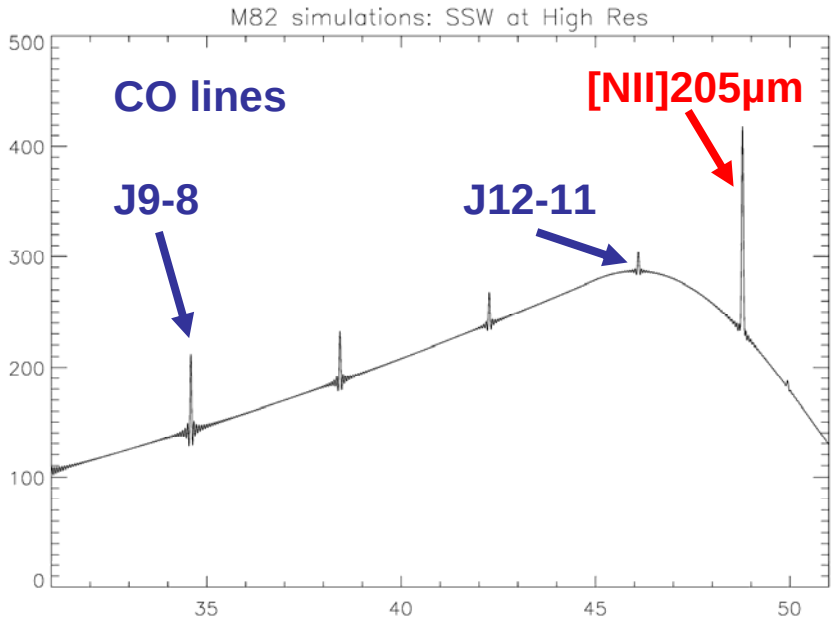


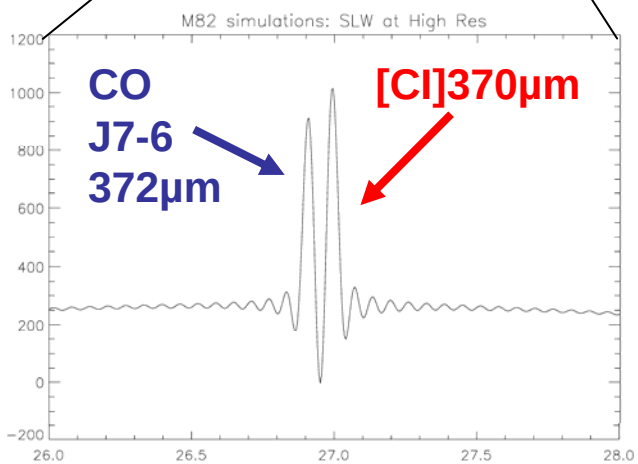


intermediate sampling AOT: no loss of power from sky sources
source modelling possible at this stage with current knowledge of PSF
remind: iFTS image quality not as good as photometer

spectral simulations: M82 at High Res

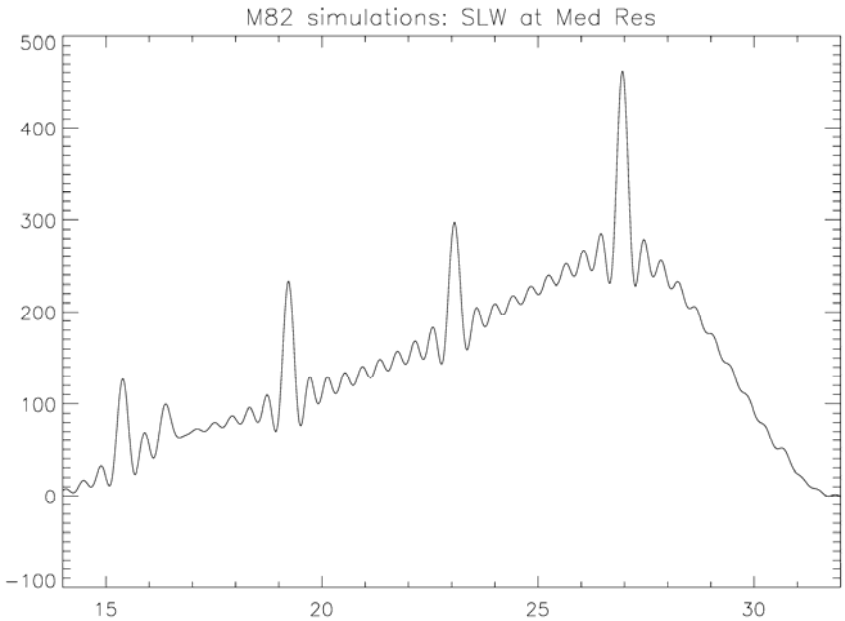


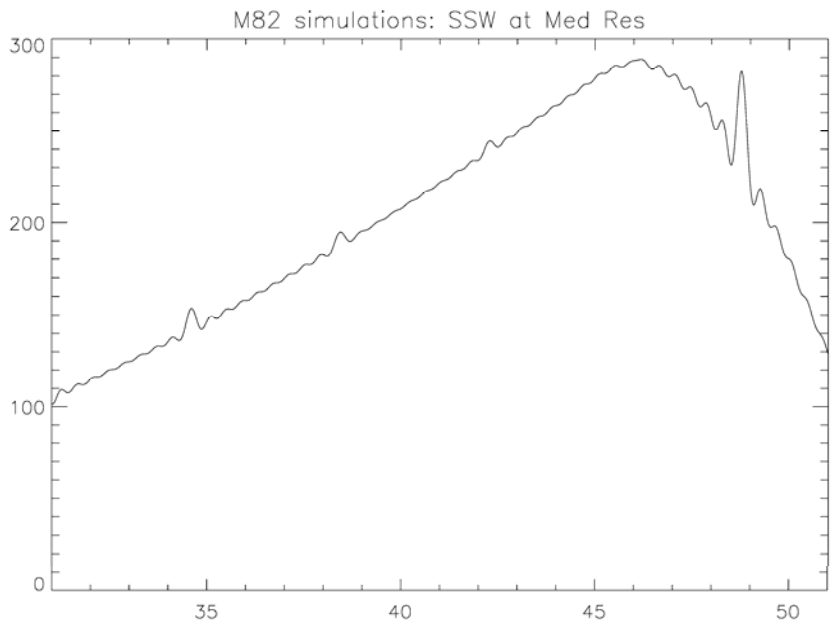




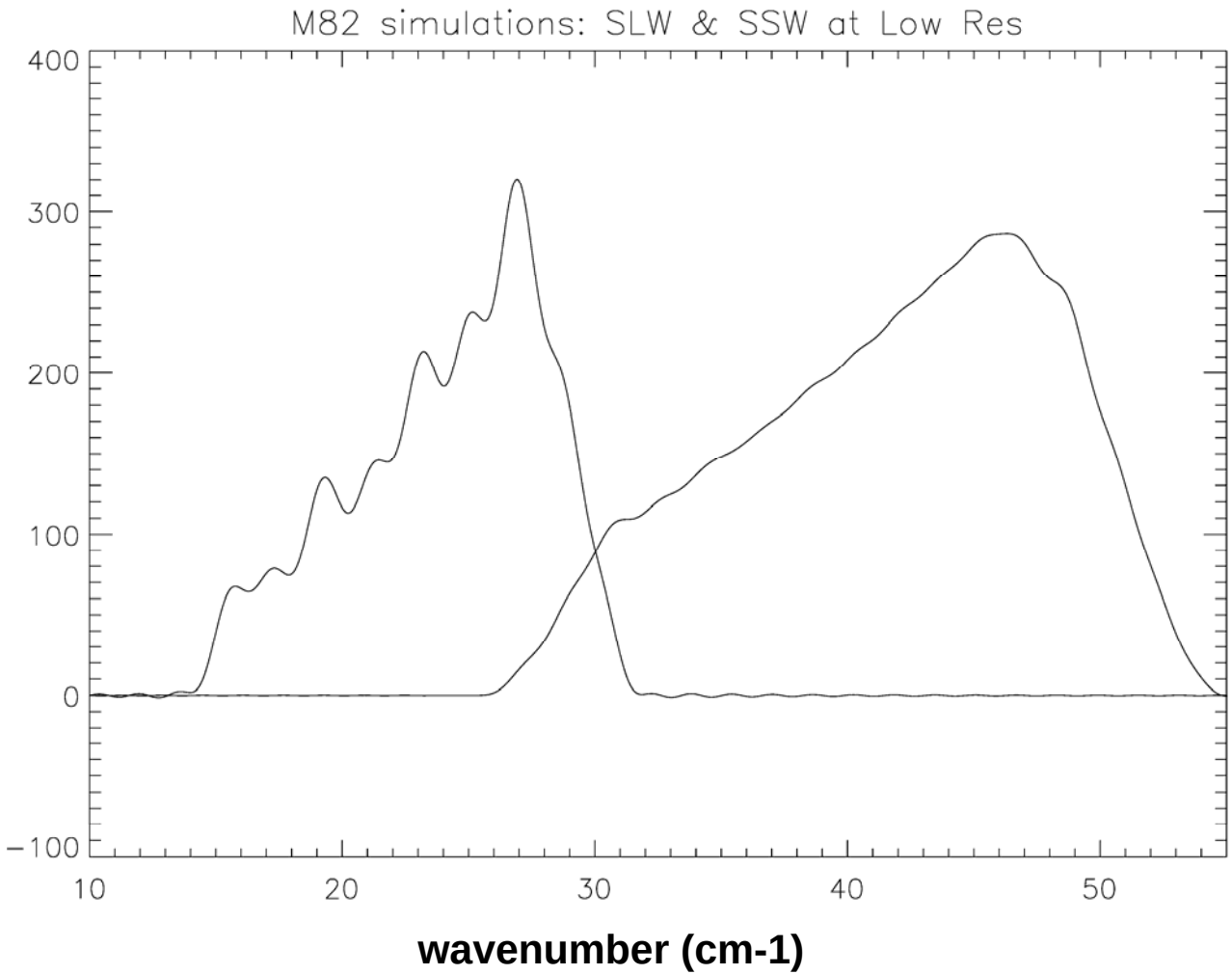
use of litterature observational data for continuum & some lines + extrapolation for missing data

spectral simulations: M82 at Med Res





spectral simulations: M82 at Low Res



a few words about calibration: ground testing

- **flux density: extended sources only**
  - **main input beam:**
    use of cold blackbody (measurements at different temperatures)
  - **SCAL input beam:**
    compare results from CBB & SCAL units
  - ➔ **unexpected measured difference in transmission for the 2 input beams**

- **line resolution:**
  - **use of (unresolved) laser (photomixer) lines**
  - **both point-like and extended sources**
  - ➔ **derived spectral line shape very close to theoretical line profile**

a few words about calibration: in-flight operations

- **flux density:**
  - **extended emission:**

    in the main beam make use of the telescope emission during cool down (~ 50 days in early PVP) towards a blank sky position

    still use of SCAL units for the other input beam
  - **point-like sources:**

    need calibration astronomical sources

- **line resolution:**
  - **check the resolution profile on some bright lines from either extended emission (galactic plane?) or point-like astronomical sources**

the end: still some matters of concern (for me)

- **presently generally good understanding of the overall system**
- **need for more detailled analysis of all PFMs data**

  but still persisting problems:
- **interferogram "truncation"**

  again some "truncated" interferograms in PFM5 measurements
- **"echos" in High Res spectra**

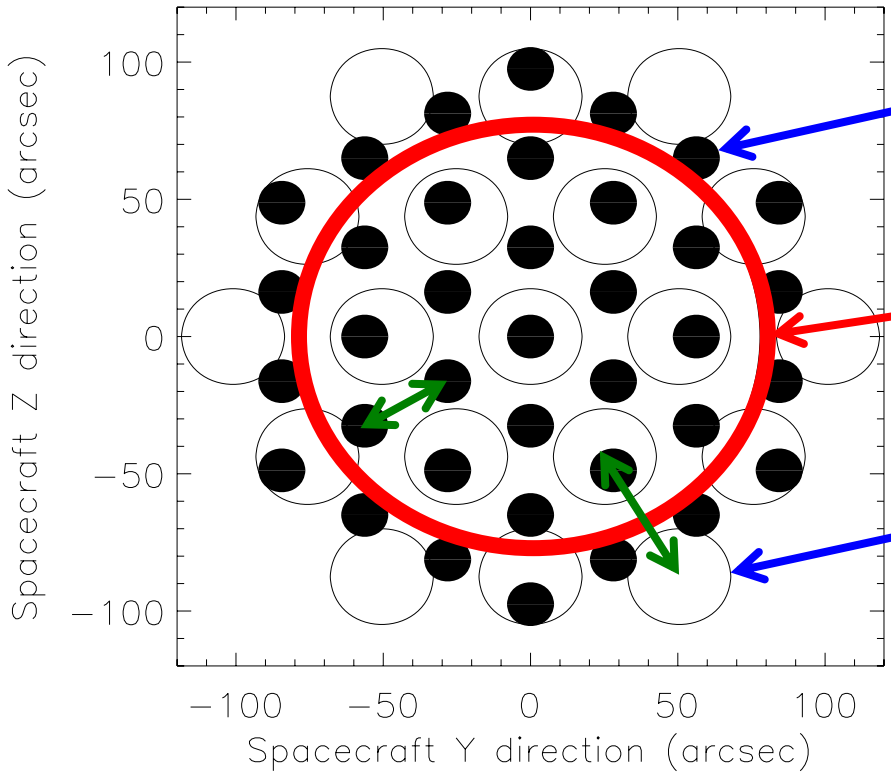
  not clear how to deal with these "echos" without degrading more or less severely the spectral resolution
- **μvibration in-flight environment ?**

  during ground testing mechanism jitter noise well below photon noise level ➔ what about in flight ?

SPIRE FTS Observing Modes

Edward Polehampton

Reminder of pixel layout



SSW pixels
***FWHM* = 16” – 18”**

2.6’ unvignetted beam footprint

SLW pixels
***FWHM* = 31” – 40”**

Centre to centre spacing:

SSW = 32.5”, SLW = 50.5” → **co-alignment not exact**

Observing Choices

Source size

Single point
(1 FOV with diameter of 2')

Raster
(many FOVs)

Spatial sampling

Sparse
2 beam spacing

Intermediate
1 beam spacing

Full
½ beam spacing
(Nyquist)

Spectral resolution

(unapodised)

High 0.04 cm^{-1}
(1.2 GHz)

Medium 0.25 cm^{-1}
(7.5 GHz)

Low 1.0 cm^{-1}
(30 GHz)

(constant in frequency)

HSpot

Source size

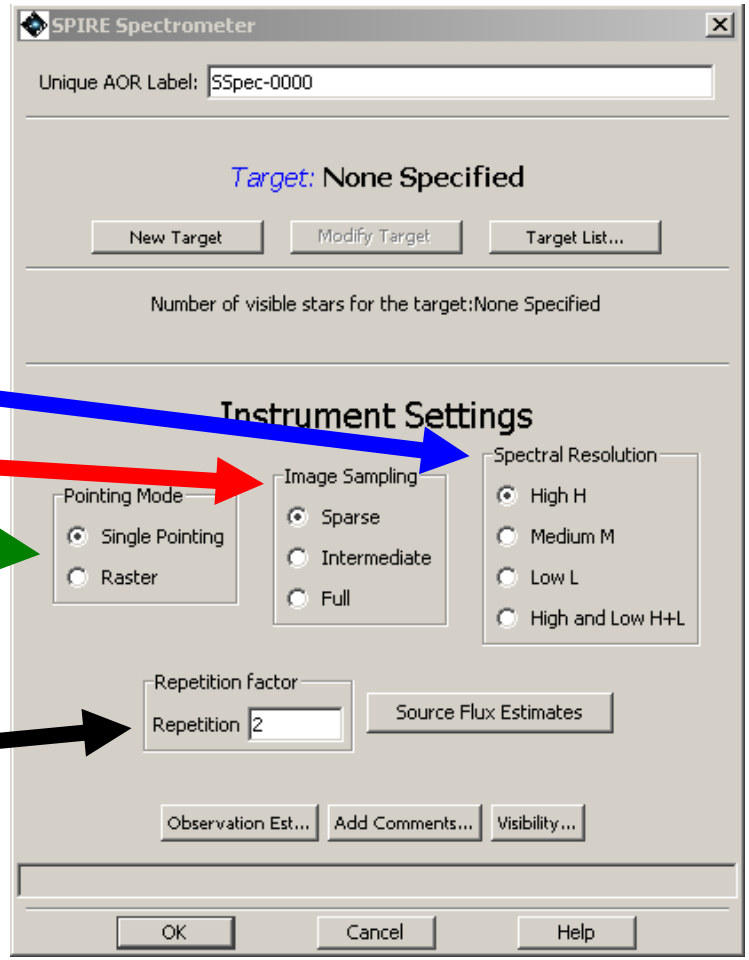
1 FOV
Raster

Spatial sampling

2 beam
1 beam
½ beam

Spectral resolution

High
Medium
Low



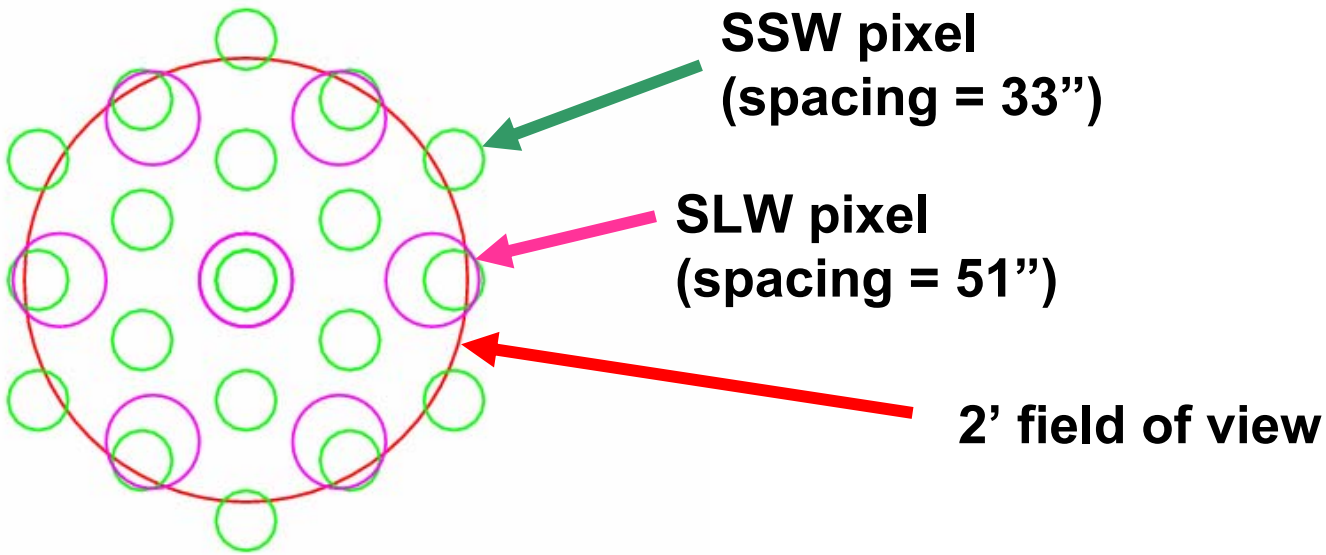
Number of repeated Spectrometer mechanism scan pairs (minimum 2)

ie. this sets the integration time per point

Map size: Single FOV

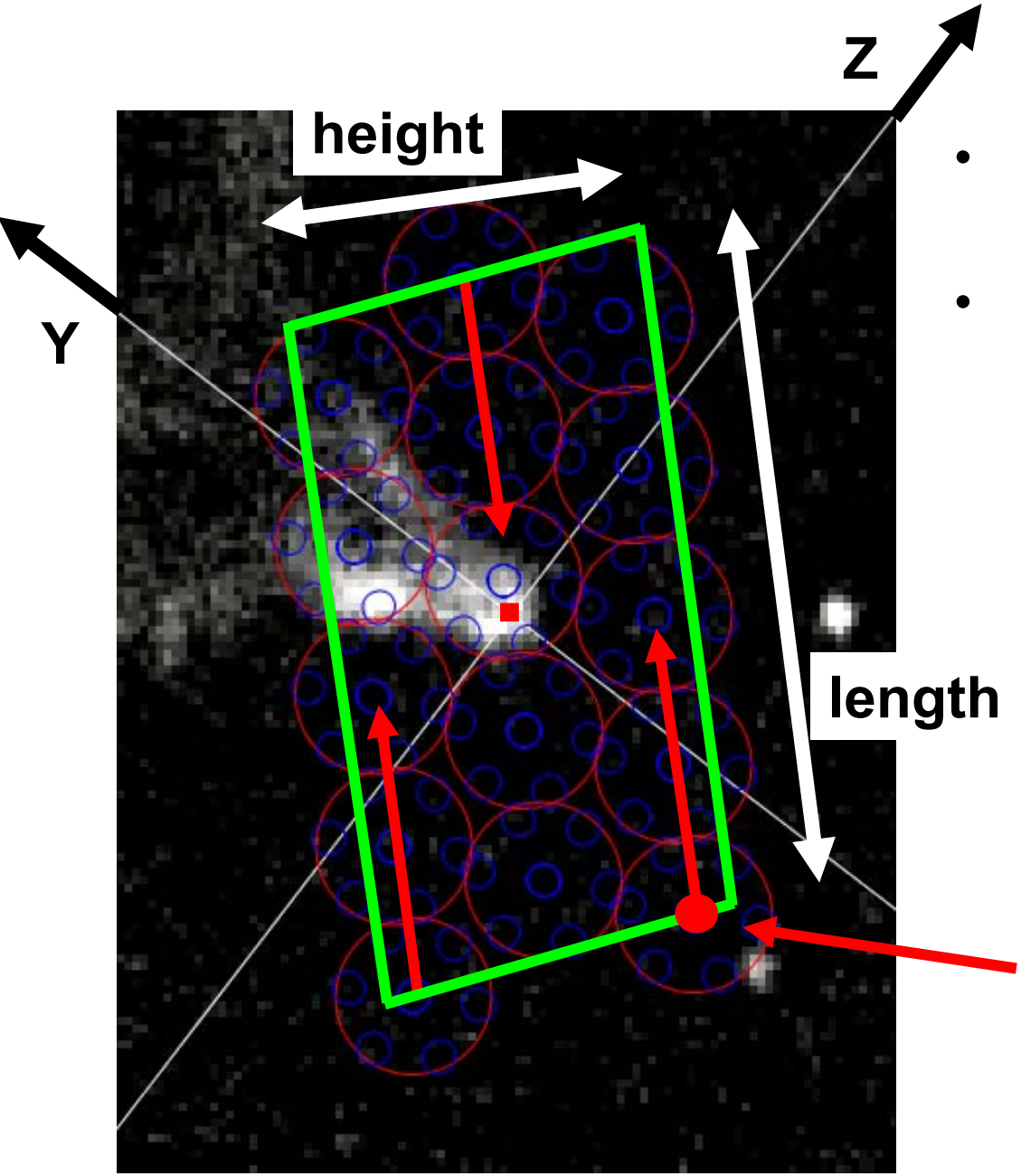
- Always get data from whole array
- HSpot shows location of array pixels for sparse mode

view in HSpot (sparse sampling):

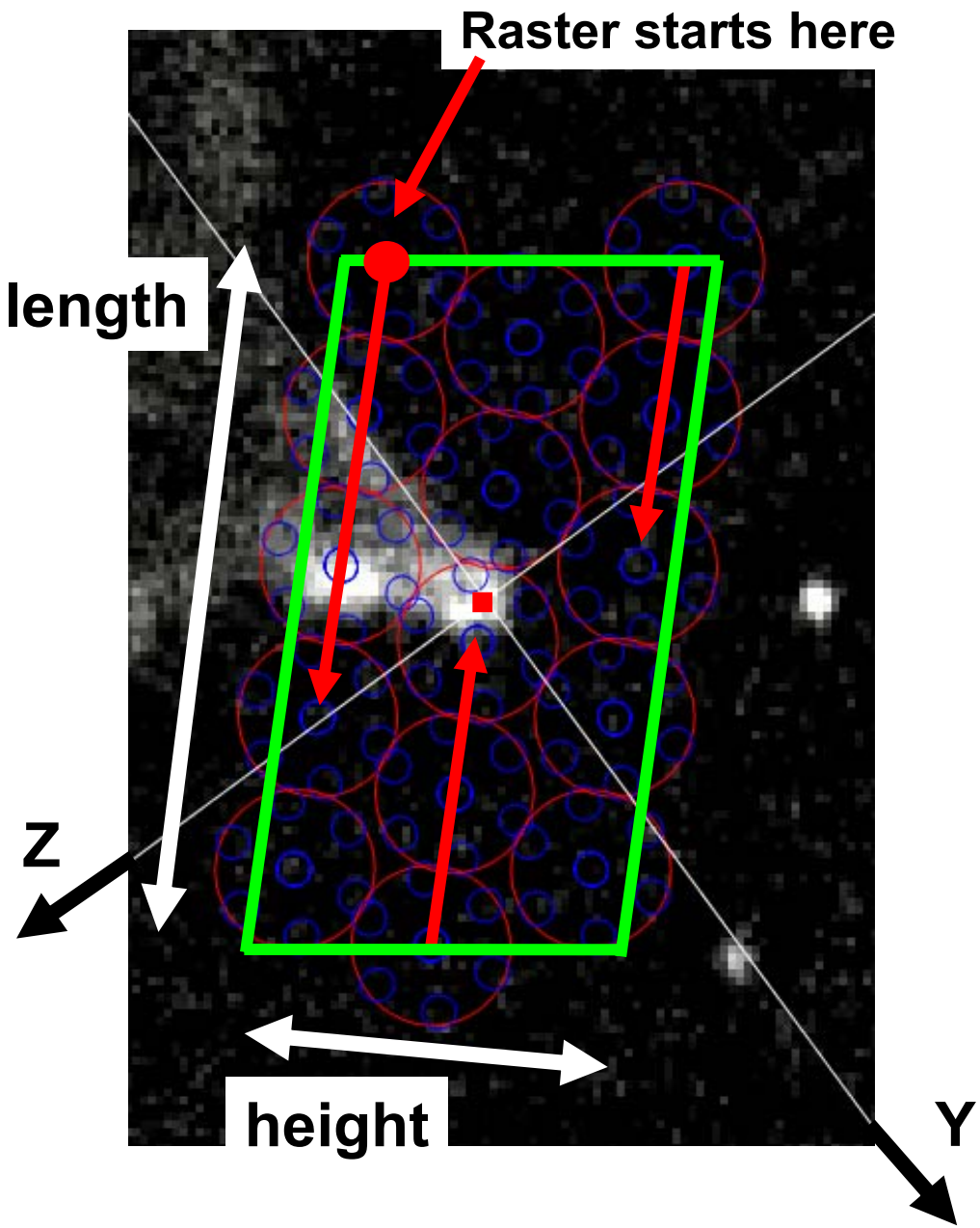


Map size: raster

- Raster map is made up from a combination of individual fields of view
- Raster direction is fixed to spacecraft axes not to sky coordinates → *check visualisation!*
- Coverage is a parallelogram on sky
- Split into separate observations to make more complicated shapes



- **Raster is performed in <u>spacecraft coordinates</u>**
- **Therefore orientation on the sky changes depending on source position & visibility constraints**



- **Raster is performed in <u>spacecraft coordinates</u>**
- **Therefore orientation on the sky changes depending on source position & visibility constraints**

Spatial sampling

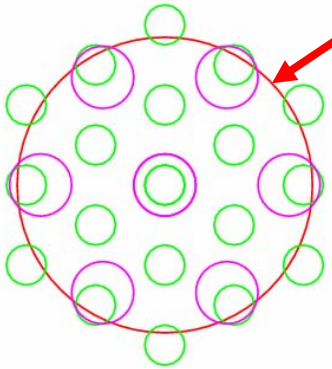
2’ field of view

SPARSE

~2 beam spacing

SSW: 33”

SLW: 51”

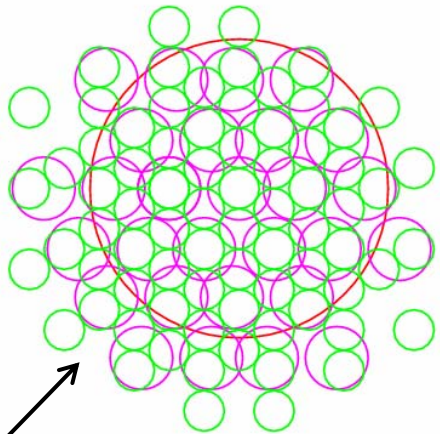


INTERMEDIATE

~1 beam spacing

SSW: 16”

SLW: 25”

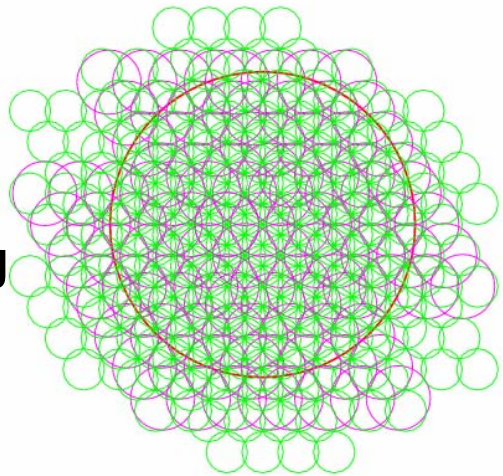


FULL

~½ beam spacing

SSW: 8”

SLW: 12”



Coverage extends out of FOV slightly

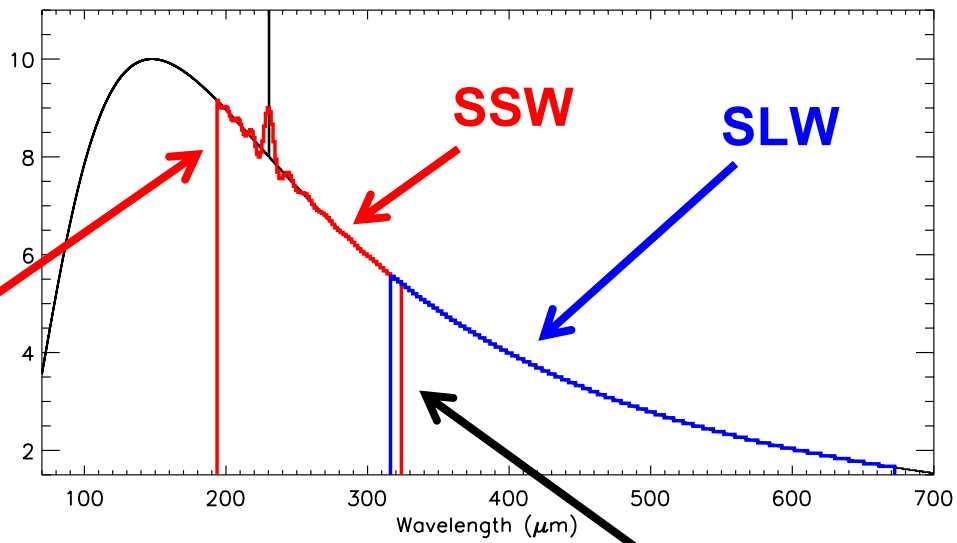
Advantages of each mode?

- **Full**:
  - mapping extended structures
  - achieves maximum spatial sampling of details
  - long time → single FOV / bright sources
- **Intermediate**:
  - shorter time – larger maps
- **Sparse**:
  - point sources
  - where detailed structure not needed – comparison of spectrum at individual points

Spectral resolution

LOW $\Delta\sigma = 1.0$ cm^{-1} (30 GHz); $R = 52 - 15$

- **Continuum measurements**
- **36 independent samples across the whole range**



resolution
1.0 cm^{-1}

overlap between bands
(0.8 cm^{-1})

MEDIUM $\Delta\sigma = 0.25\ cm^{-1}$ (7.5 GHz); ***R=200 – 60***

HIGH $\Delta\sigma = 0.04\ cm^{-1}$ (1.2 GHz); ***R=1290 – 370***

- Line spectroscopy
- Measurement of total integrated line fluxes

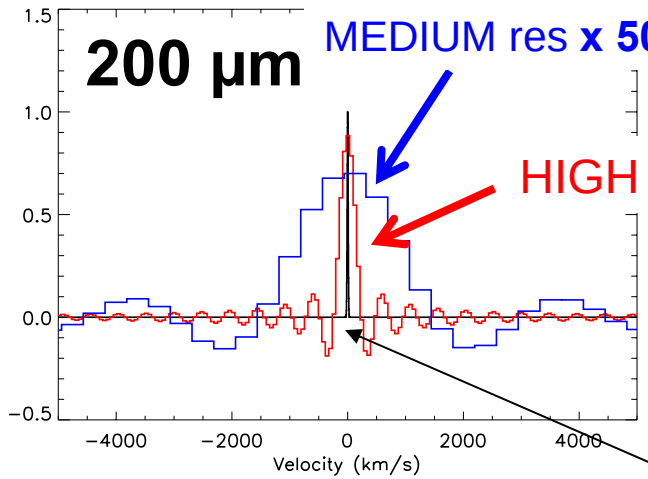
  (line widths 280 – 840 km/s in HIGH resolution mode)

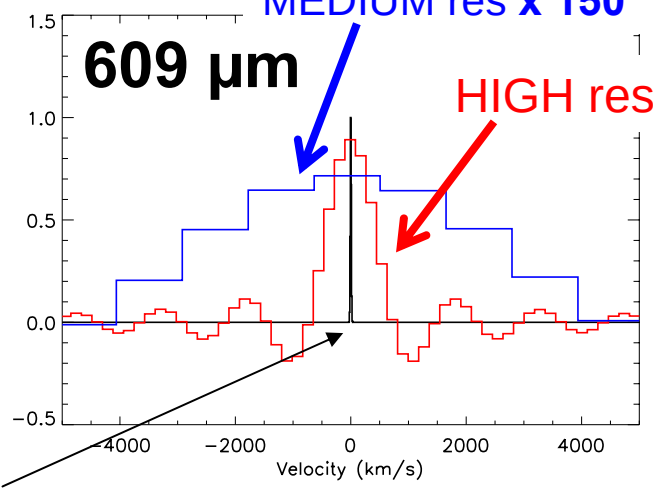
HIGH + LOW

- **Line spectroscopy with high S/N continuum measurement**

  (number of HIGH and LOW resolution scans are set independently)

Spectral resolution in HIGH & MEDIUM modes





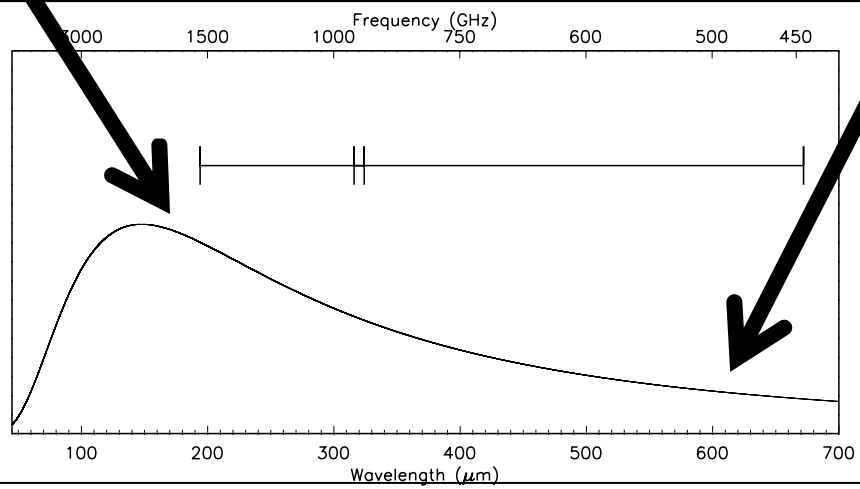
20 km/s line

200 µm

(1499 GHz)

280 km/s (HIGH)

1810 km/s (MED)



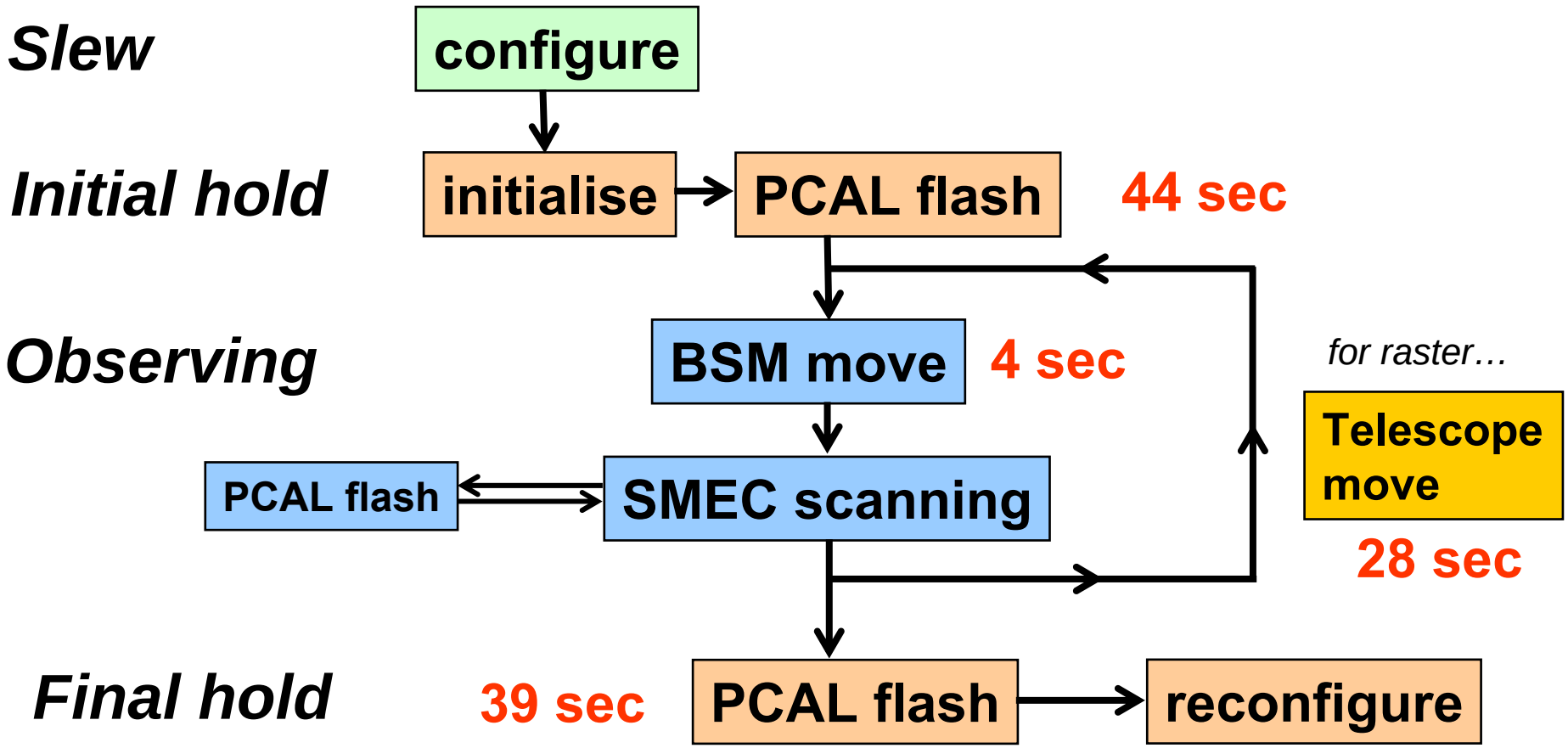
609 µm

(492 GHz)

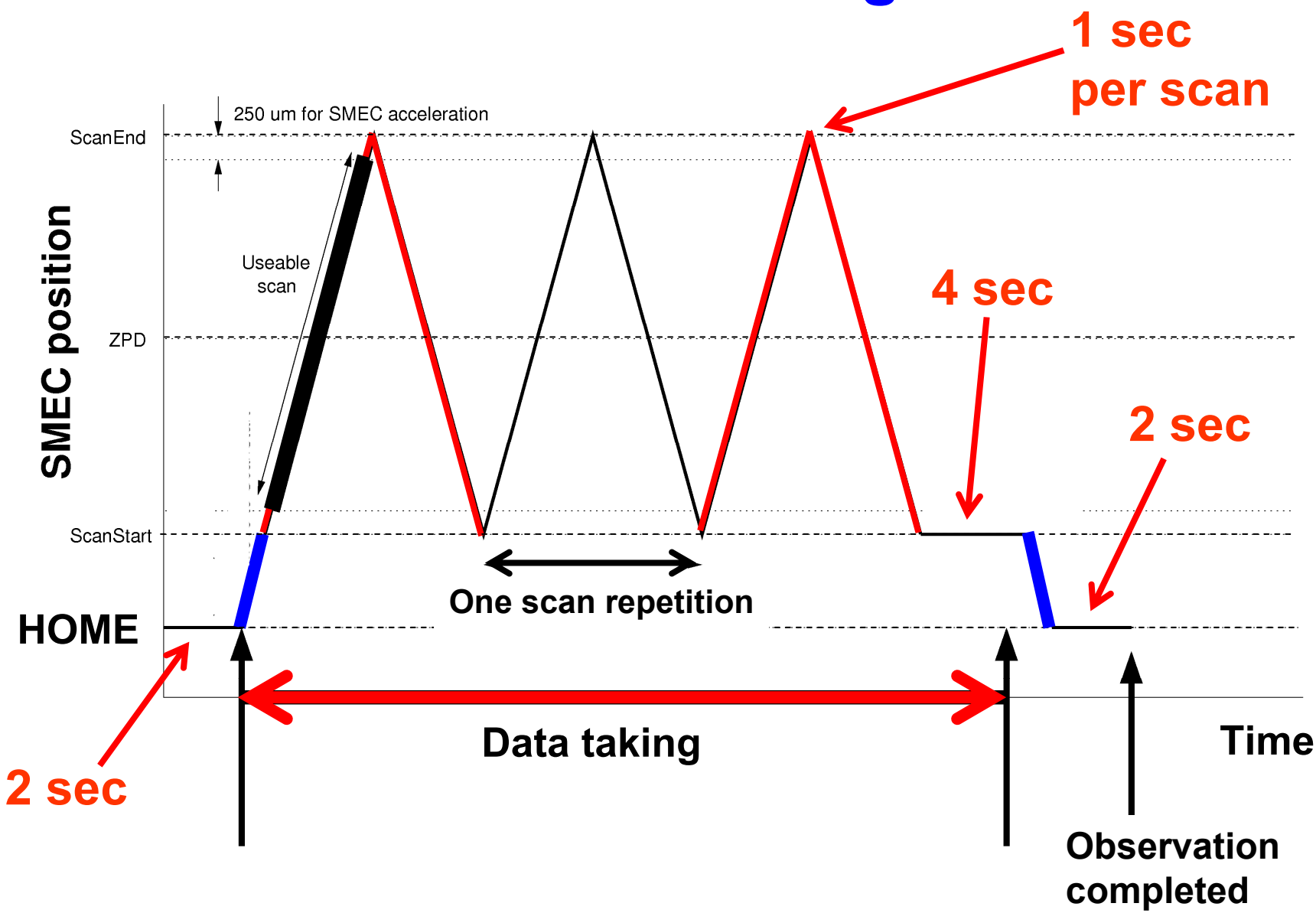
850 km/s (HIGH)

5510 km/s (MED)

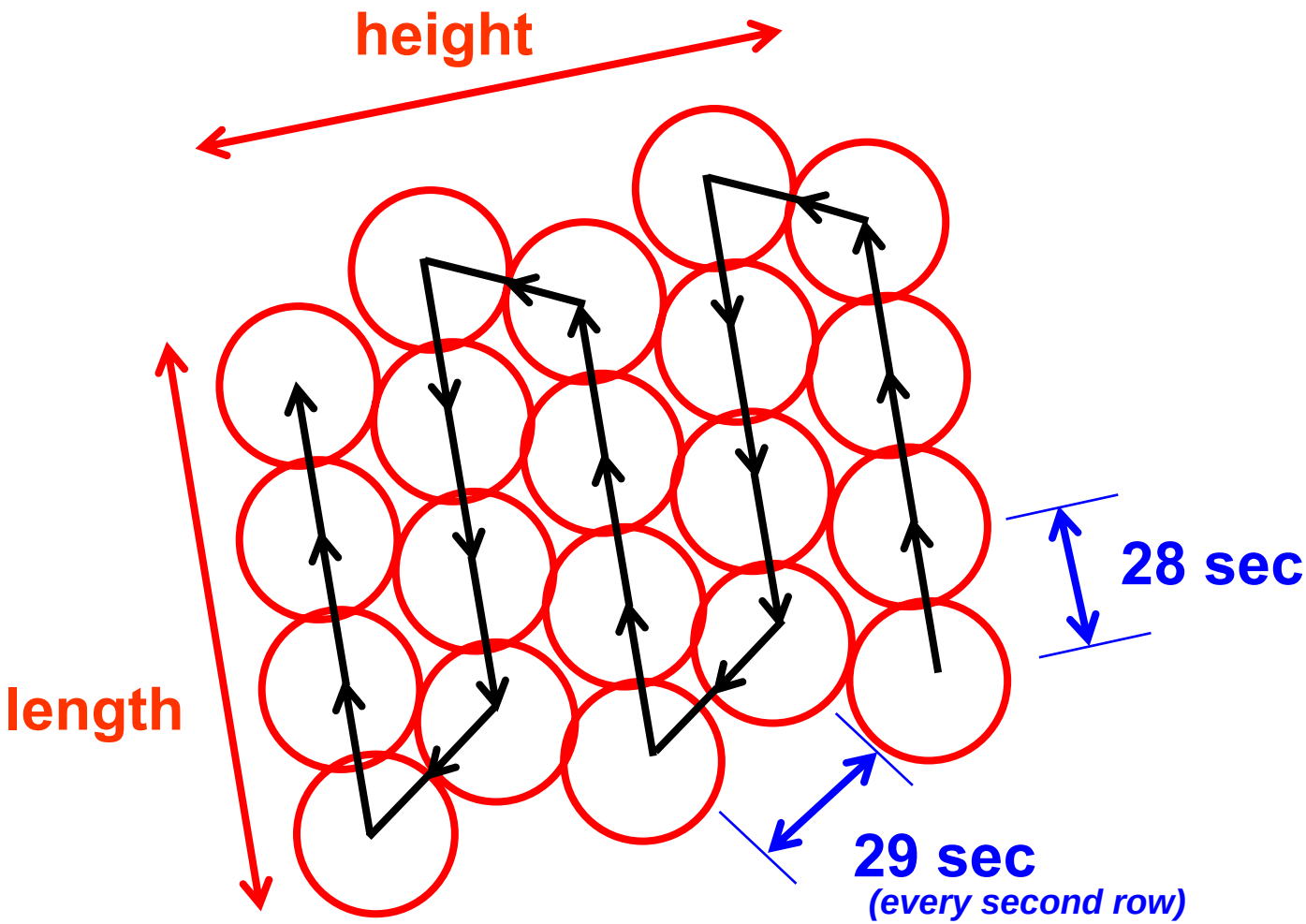
Overheads and timing



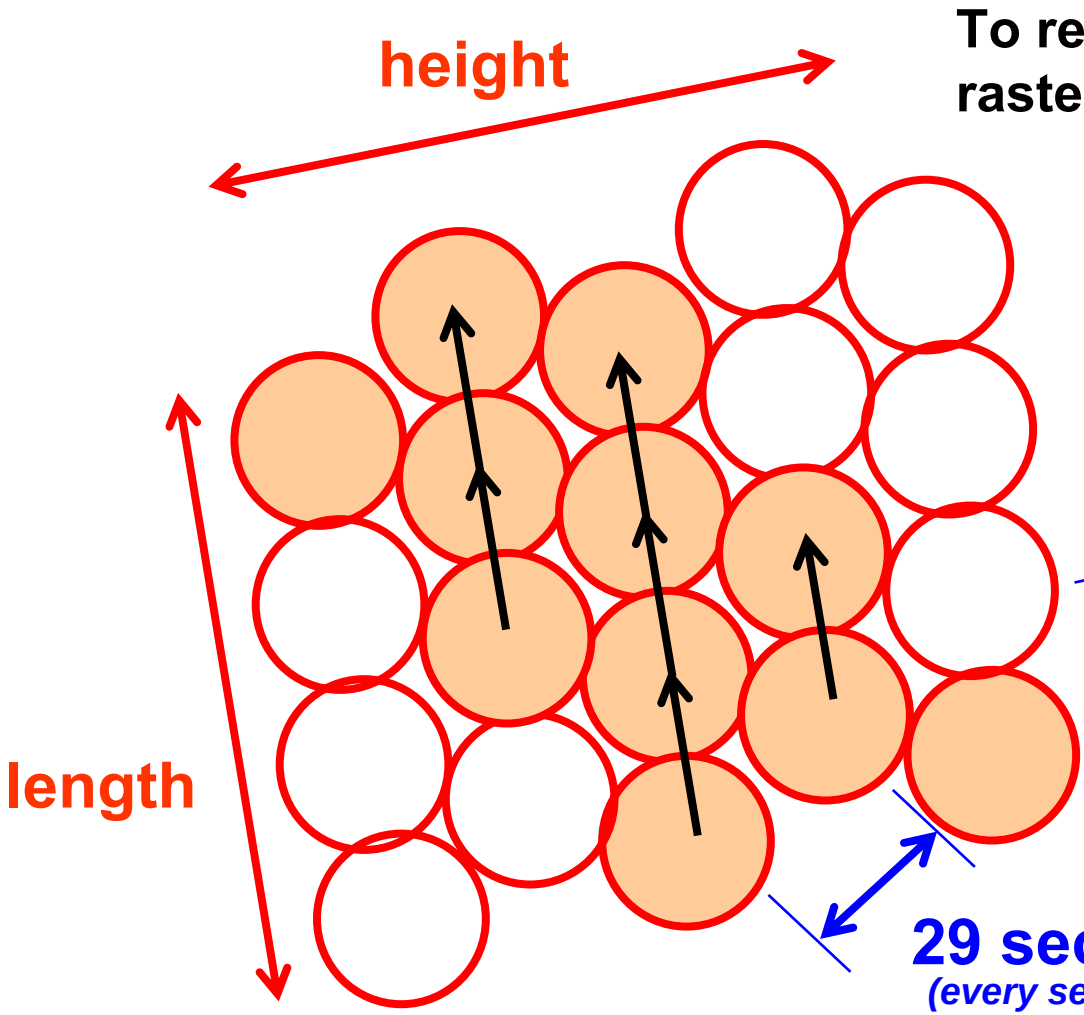
SMEC scanning



Raster overheads



Raster: custom areas



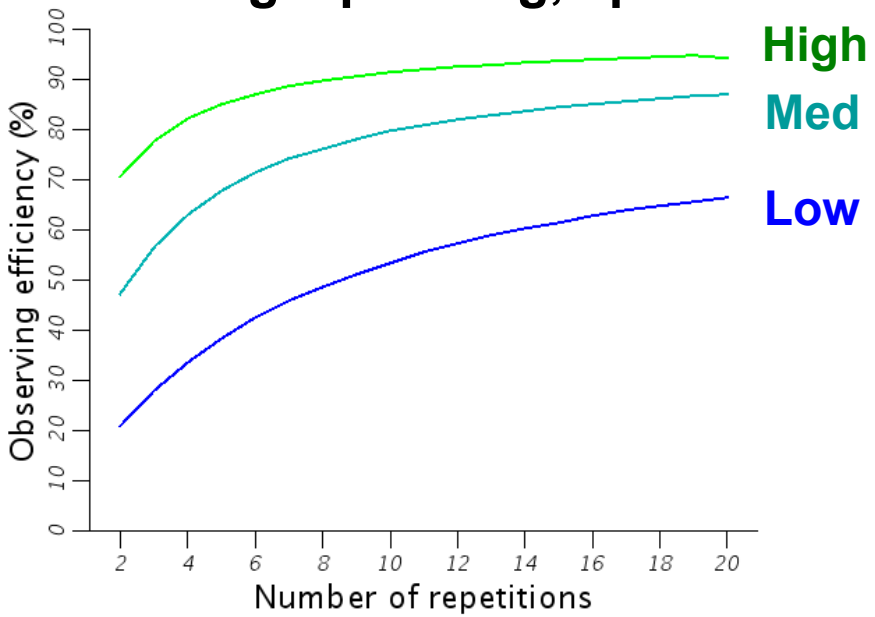
To reduce overheads, split raster into individual lines

These AORs can be concatenated but as the source position is different all get charged the 180 sec slew tax

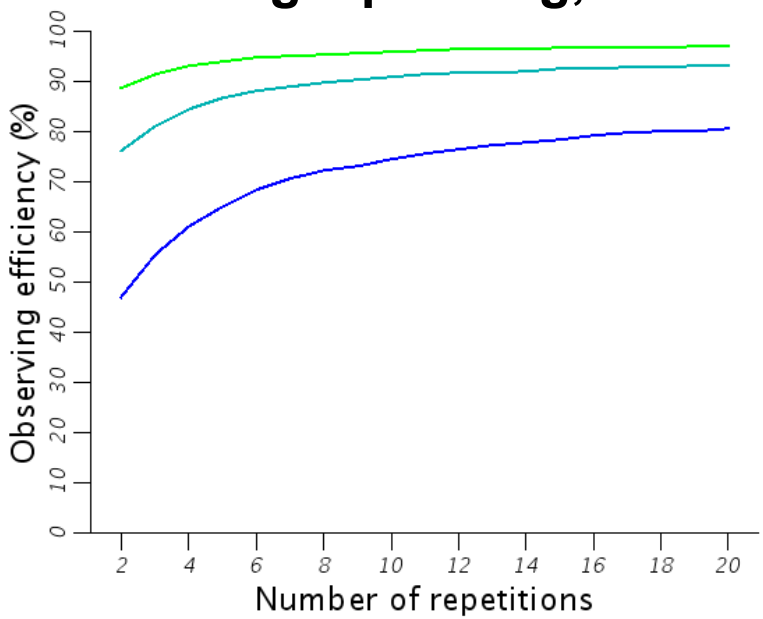
Observing efficiency

The observing efficiency depends on the spectral resolution (length of SMEC scan), the number of repetitions, and number of jiggle/raster points

Single pointing, sparse



Single pointing, full



*Efficiency calculated **excluding 180 sec slew tax** and using AOT parameters from HSpot Phase 2*

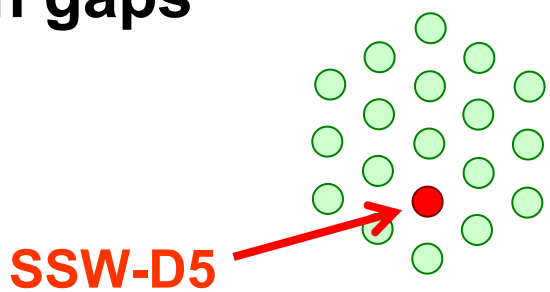
Likely updates before launch…

Efficiency likely to be increased further by reorganising the AOT to minimise the number of times SMEC travels from HOME to ScanStart

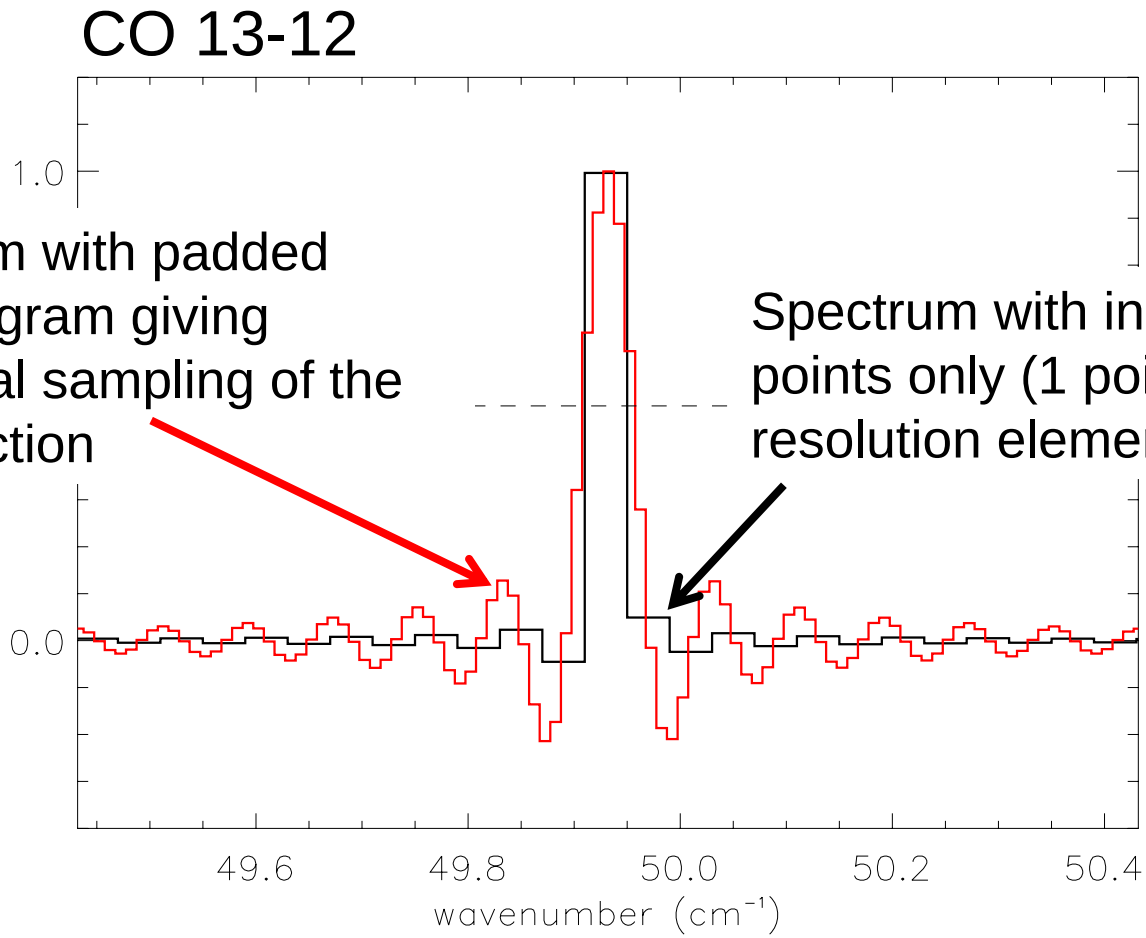
BUT….

what happens if we have dead pixel(s)?

- **Only one certain dead pixel right now: SSW-D5**
- **Will know for sure after IST cool down in September**
- **Then optimise AOT to cope with gaps**



Final Spectra



Spectroscopy with Herschel

Edward Polehampton

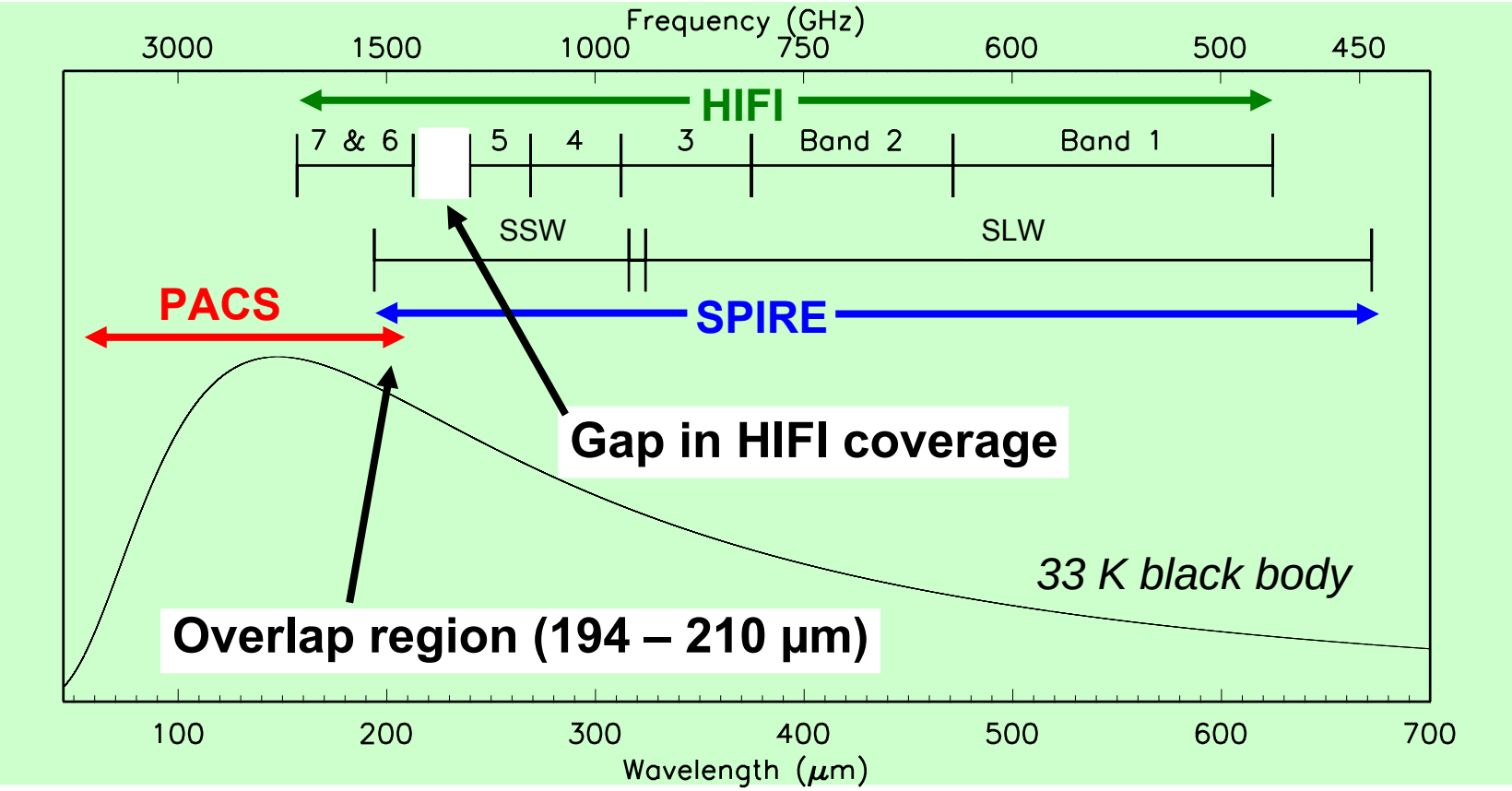
Spectroscopy on Herschel

Instantaneous bandwidth

PACS
Grating + photoconductor
0.15 – 1.8 μm
R = 940 – 5500

HIFI
Heterodyne
2.4/4.0 GHz
R up to 10^7

SPIRE
FTS + Bolometer
Entire range
R = 15 – 1300



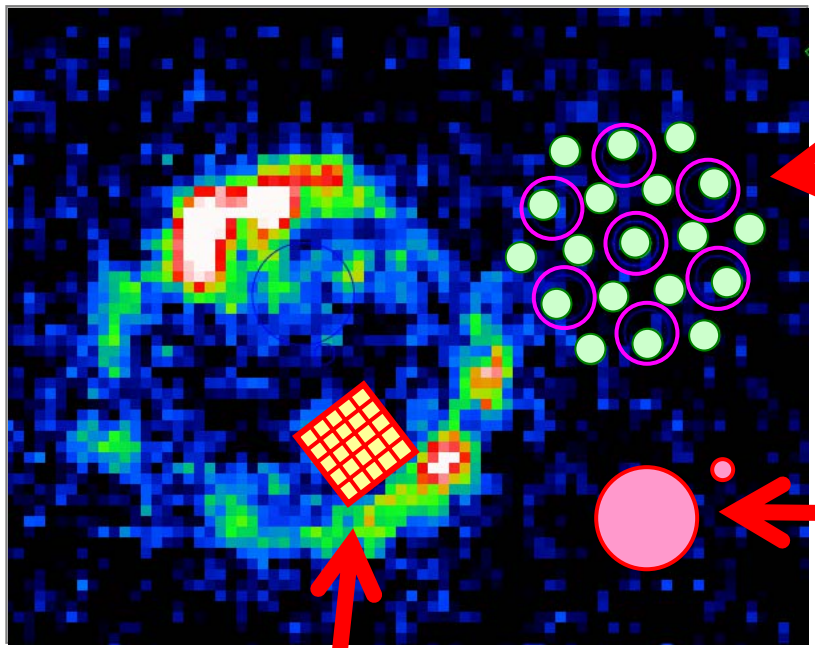
The three instruments

- **PACS**: high sensitivity, good spatial resolution (9.4” pixel) – small maps for specific λ-ranges

  (+ full range scans possible)
- **HIFI**: high spectral resolution for specific lines in narrow λ-range

  (+ wide spectral surveys)
- **SPIRE**: simultaneous wide λ coverage, large area at medium spectral resolution

Footprints on the sky



SPIRE: ~2’ FOV
Unfilled field of view
16–18” & 31–40”

HIFI: Beam size 12” – 45”
Single pixel

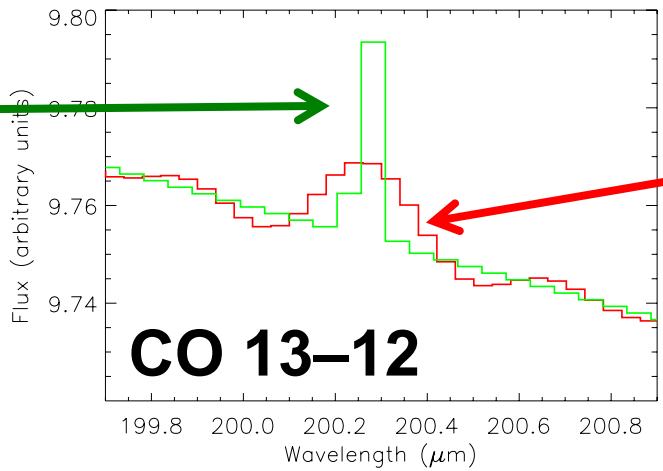
PACS: 5×5 pixels = 47”×47”
Integral field spectroscopy

Overlap regions

- Overlap region 194 – 210 μm
- Sensitivity at 200 μm, 1σ in 1 hour:

	Cont. (Jy)	Line (W/m^2)	Res.
SPIRE	0.49	0.6×10^{-17}	280 km/s
PACS	0.15	0.1×10^{-17}	160 km/s
HIFI	36	0.2×10^{-17}	1 km/s

PACS
with 2 points per res. element (SED mode)



SPIRE
with 4 points per res. element

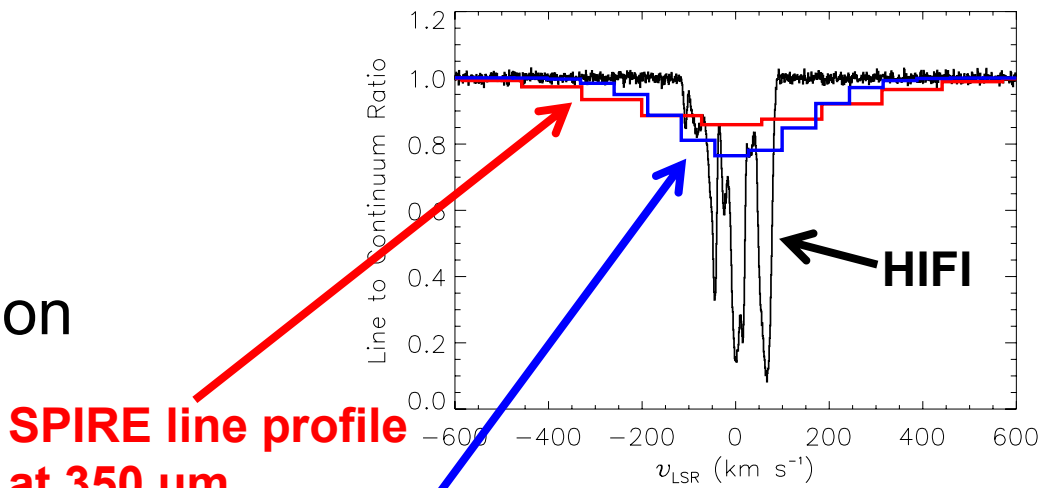
How to use the 3 instruments together

- PACS SED mode + SPIRE gives full spectrum from 55 – 670 μm
- HIFI – good for detailed study of specific lines. Mapping using OTF
- HIFI continuum sensitivity bad: need SED from SPIRE
- PACS to pick out FIR lines

HIFI - SPIRE

HIFI and SPIRE cover very similar λ-ranges

- SPIRE:
  - Total flux for many lines – excitation studies
  - Continuum
- HIFI:
  - Line shapes
  - Kinematics
  - Outflows
  - Absorption/emission



Why use SPIRE for line spectroscopy?

- In HIGH resolution mode (min length 266 sec), *RMS* in line flux is **~2.2 x 10^{-17} W/m^2**
- What does this integrated flux mean in terms of *RMS* in brightness temperature units?
    - ***Depends on intrinsic line width***

Wavelength	**535 μm**	**200 μm**
Frequency	**560 GHz**	**1499 GHz**
T_{rms} (20 km/s line)	**0.13 K**	**0.03 K**
T_{rms} (5 km/s line)	0.51 K	0.14 K

intrinsic line width

Why use SPIRE for line spectroscopy?

Wavelength	535 μm	200 μm
Frequency	560 GHz	1499 GHz
T_{rms} (20 km/s line)	0.13 K	0.03 K
T_{rms} (5 km/s line)	0.51 K	0.14 K

intrinsic line width

CONCLUSION

SPIRE is useful for *integrated flux* measurements of *BROAD lines*, particularly at high frequencies

Additional advantages:

- *always observes full spectral range simultaneously*
- *always get a sparse map of the source*

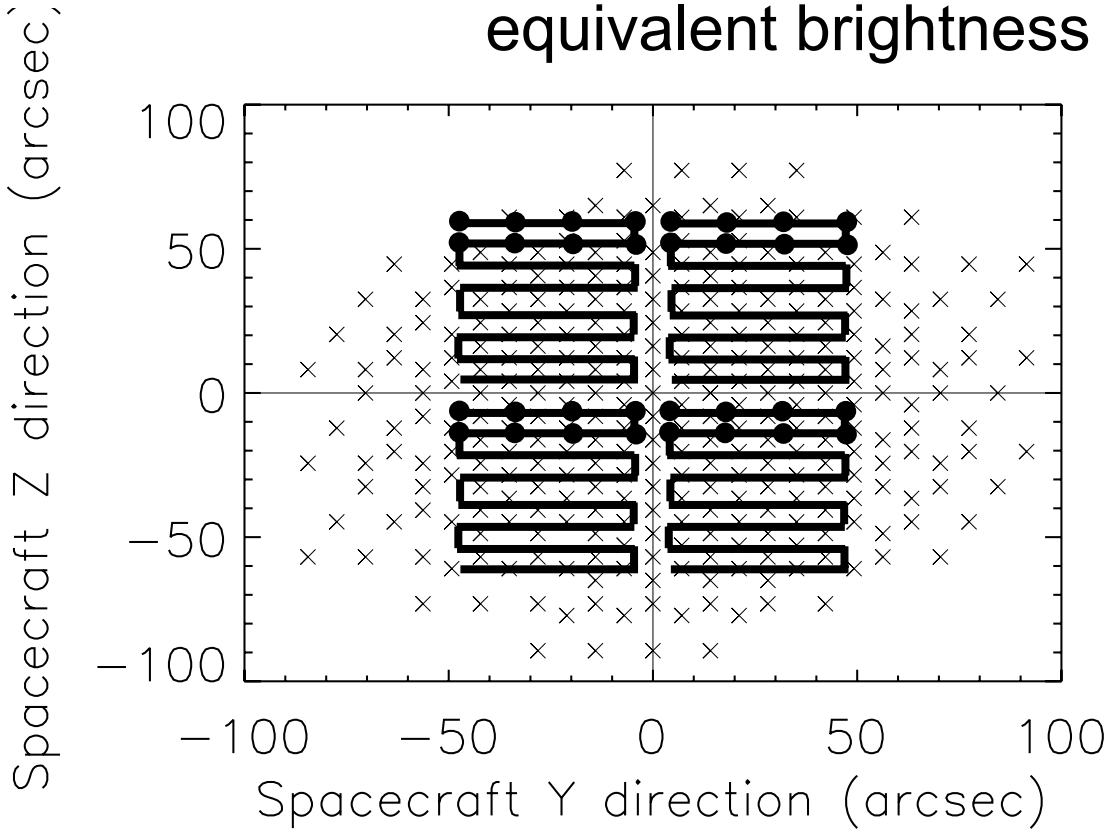
Disadvantage:

- *no line profile information*

Compare a single SPIRE 2' FOV

High res, fully sampled → point spacing = **8"**
Total time = **5035 s (1.4 hrs)** Sensitivity = **2.5×10^{-17} Wm^{-2}**

Observe CO J=13-12 at **200 μm** with HIFI
equivalent brightness temp RMS = **0.03 K**



HIFI on-the-fly with frequency switching
Assuming 20 km/s line
6.5 km/s channel width

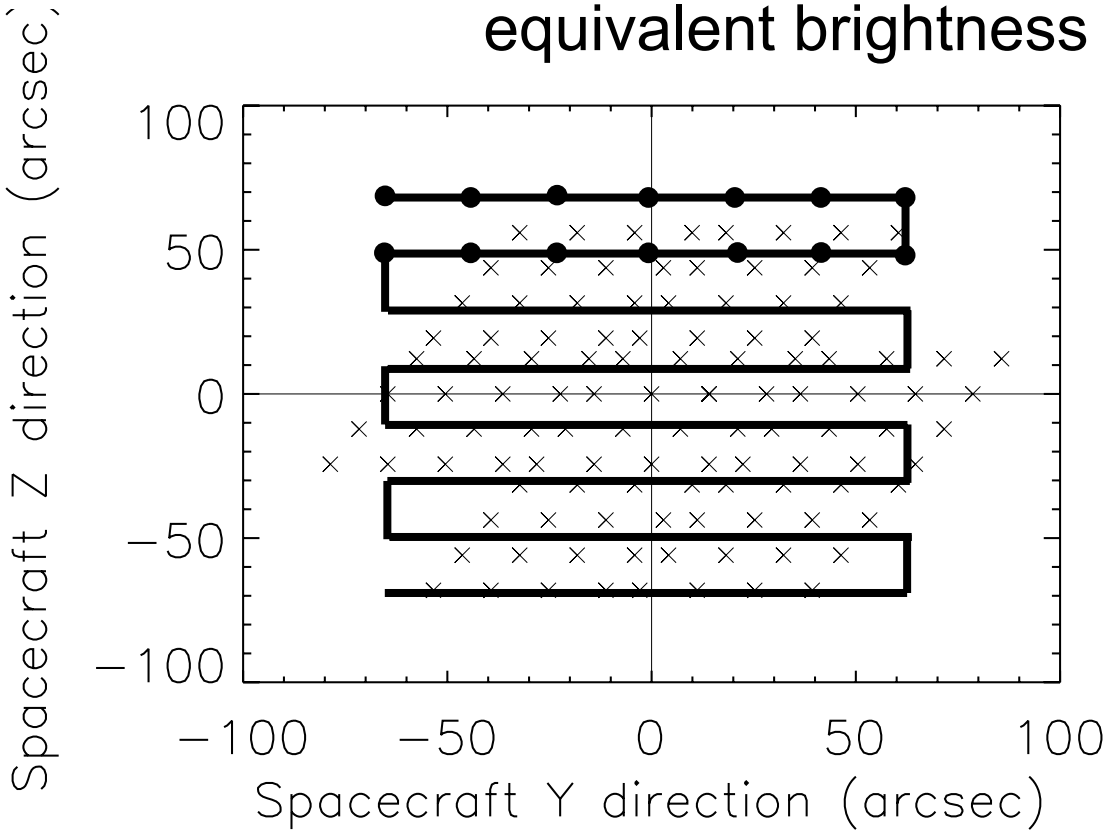
→ *requires 2 coverages with 4 small maps*

Total time = 366832 s
= *101.9 hrs !!*

Compare a single SPIRE 2' FOV

High res, fully sampled → point spacing = **12.6"**
Total time = **5035 s (1.4 hrs)** Sensitivity = **2.5×10^{-17} Wm^{-2}**

Observe CO J=5-4 at **520 μm** with HIFI
equivalent brightness temp RMS = **0.13 K**



HIFI on-the-fly with frequency switching
Assuming 20 km/s line
6.5 km/s channel width

→ *1 coverage gives much lower noise level (0.017 K)*

Total time = 2092 s
= *0.58 hrs*

Why use SPIRE for line spectroscopy?

Wavelength	535 μm	200 μm
Frequency	560 GHz	1499 GHz
T_{rms} (20 km/s line)	0.13 K	0.03 K
T_{rms} (5 km/s line)	0.51 K	0.14 K

intrinsic line width

CONCLUSION

SPIRE is useful for *integrated flux* measurements of *BROAD lines*, particularly at high frequencies

Additional advantages:

- *always observes full spectral range simultaneously*
- *always get a sparse map of the source*

Disadvantage:

- *no line profile information*

What have people proposed to do?

- **HIFI GT spectral scans**: bright sources over full HIFI range + full PACS scans.
  - Unlikely to have for many sources as so time consuming. These are bright – too bright for SPIRE FTS
- Otherwise HIFI observations generally of specific targeted lines, small maps
  - e.g. selected water lines to show excitation in small maps
- PACS lines to complement HIFI
  - e.g. higher excitation water lines

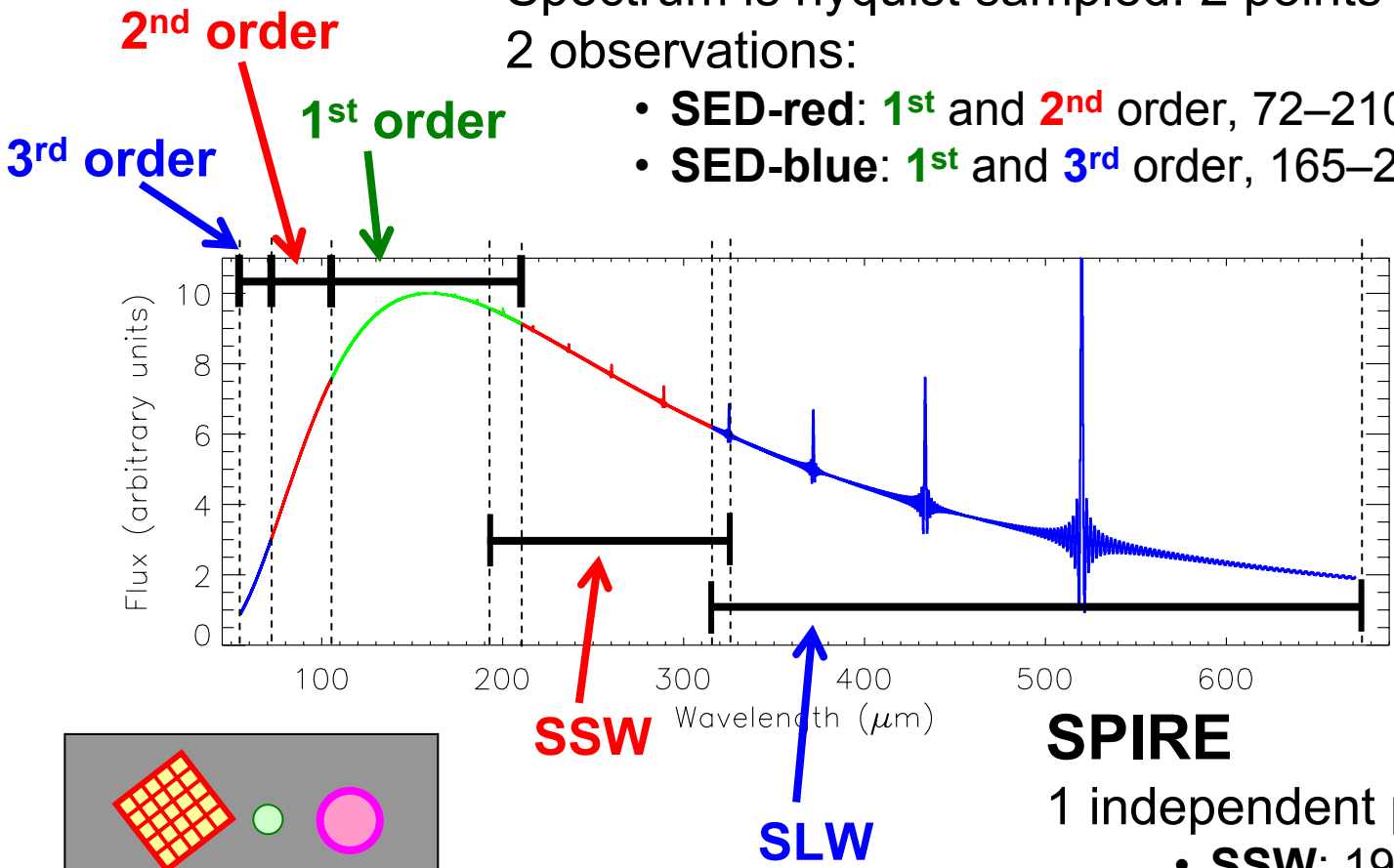
PACS - SPIRE

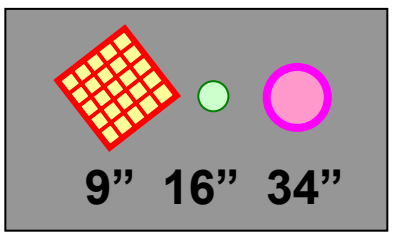
PACS SED mode – min execution time 30+15 min

Spectrum is nyquist sampled: 2 points per FWHM

2 observations:

- **SED-red**: 1st and 2nd order, 72–210 μm
- **SED-blue**: 1st and 3rd order, 165–210 μm & 55–72 μm





SPIRE

1 independent point per Δσ

- **SSW**: 194–324 μm
- **SLW**: 316–672 μm

SPIRE Guaranteed Time

- **SAG 2** *nearby galaxies*: intermediate or sparse sampling with SPIRE, individual lines with PACS
- **SAG 4** *ISM*: individual pointings with intermediate or full sampling using H+L mode
- **SAG 5** *Solar system*:
  - Mars: PACS full range, HIFI broad ranges
  - Outer planets: HIFI specific lines – PACS + SPIRE full range
  - Comets: selected lines + SPIRE high res. for “discovery” mode
- **SAG 6** *Stellar evolution*: Large low res raster maps, PACS + SPIRE full range

FTS Sensitivity Model

Matt Griffin

Sensitivity Models Updated Early 2007

Revised SPIRE Sensitivity Models

Matt Griffin

SPIRE-QMW-NOT-000642
Draft (16 January 2007)

To be tidied up and issued for SVR-3

Sensitivity Models Updated Early 2007

- **Need for update and revision**
  - Improved knowledge of flight subsystem performance (especially filters and bolometers)
  - ILT results
  - Improved telescope emissivity and stray light predictions
  - Imminent release of Key Programmes AO
  - Some corrections needed to the FTS model

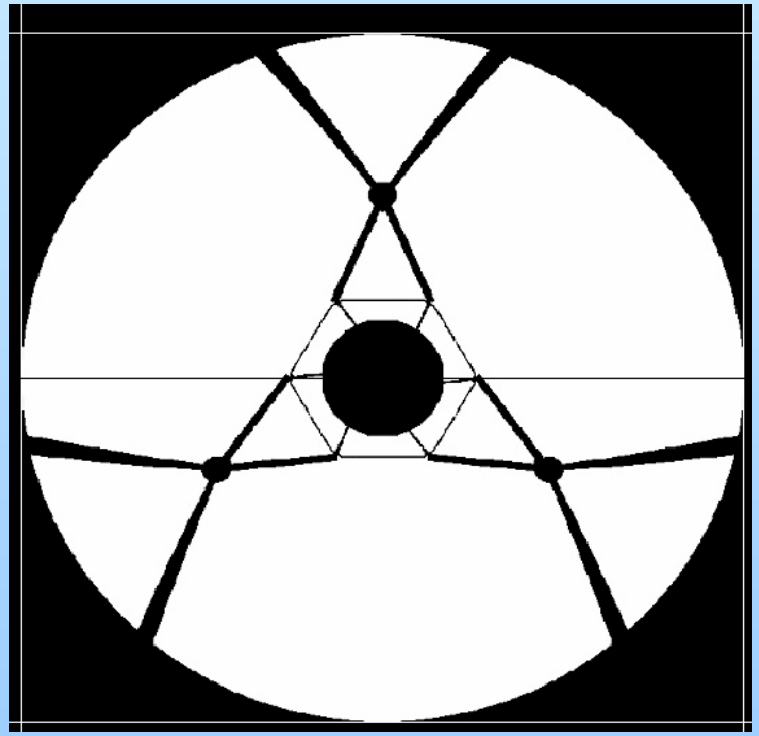
- **Update plan discussed and agreed at SVR-2**
  1. Eliminate all internal margin/pessimism factors from within the model
     - Calculate based on best knowledge
     - Apply global margin factors at the end
  2. Adopt the new lower emissivity telescope with reasonable allowance for stray light

Other Changes

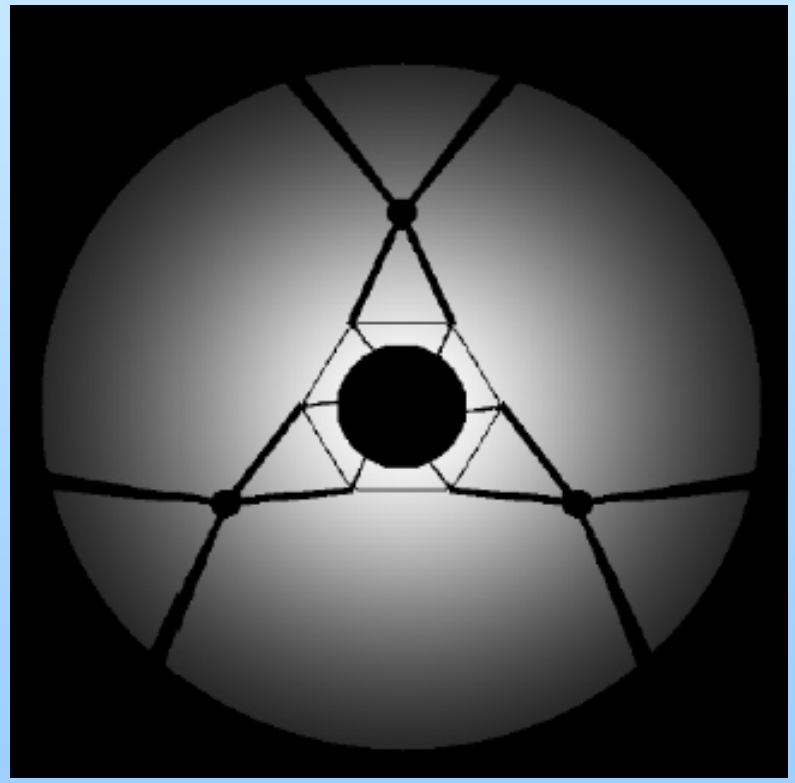
- As-measured values
  - Filter profiles
  - Median detector properties
  - Bolometer base temperature (now assuming 310 mK)
  - Electronics noise
- Deletion of all telescope overheads (now to be done in HSPOT)
- Deletion/elimination of all internal pessimism factors
  - Makes a big difference for the FTS
- Higher assmed SPIRE mirror reflectivity (now assuming 0.995)
  - Also a big difference for FTS
- Photometer scan-map: introduction of effects of nominal 1/*f* noise level
- FTS: changes to throughput ($A\Omega$) modelling

Telescope

- Used diameter = 3.29 m
- Obscuration loss factor = 0.87
- Temperature = 80 K



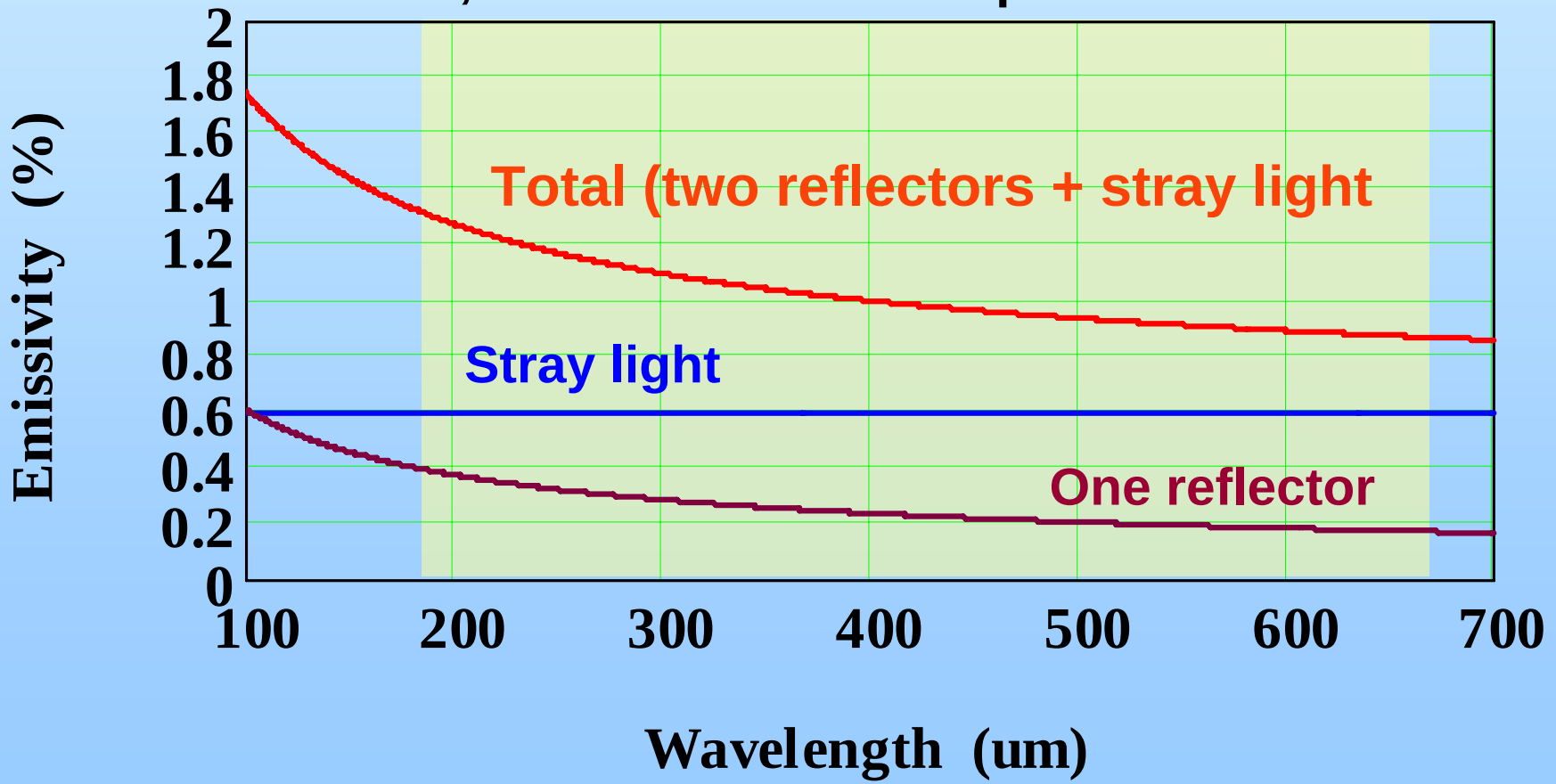
Shadowing pattern



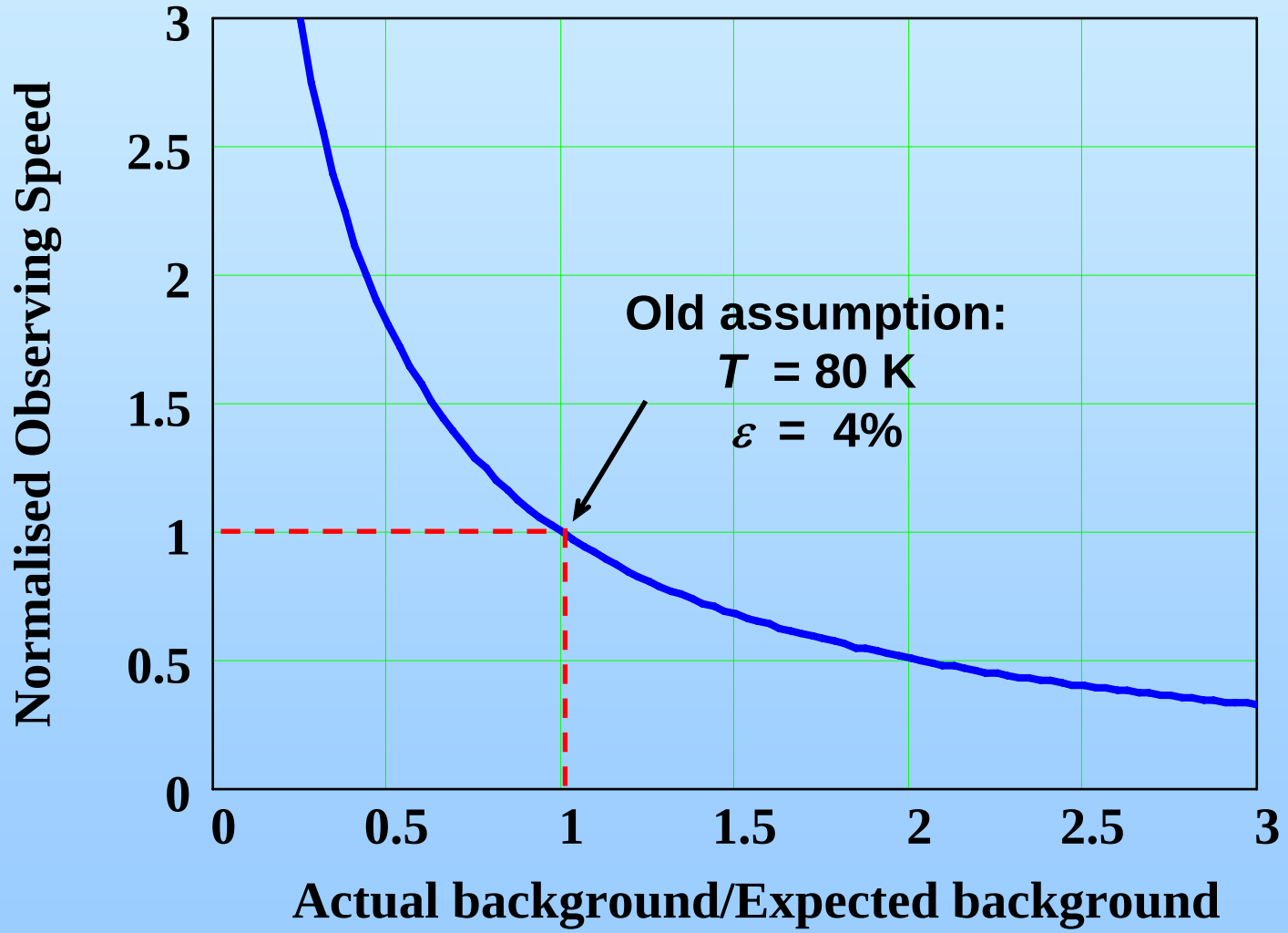
With 8-dB edge taper

Telescope Emissivity and Stray Light Model

- Two reflectors with Fischer et al. emissivity
- Stray light component equivalent to10% of a 70-K; 3% emissive telescope



Observing Speed vs. Telescope Background Power (360 μm)



Background Power and NEP

$$Q_{\mathrm{k}} = \eta_{\mathrm{S}}\,\eta_{feed} \int_{Band} \varepsilon_{\mathrm{k}}(\nu)\, td_{\mathrm{k}}(\nu)\, A\Omega(\nu)\, B(\nu, T_{\mathrm{k}})\, \mathrm{d}\nu$$

Spillover efficiency (~ 0.75)

Feed efficiency (~ 0.7)

Emissivity

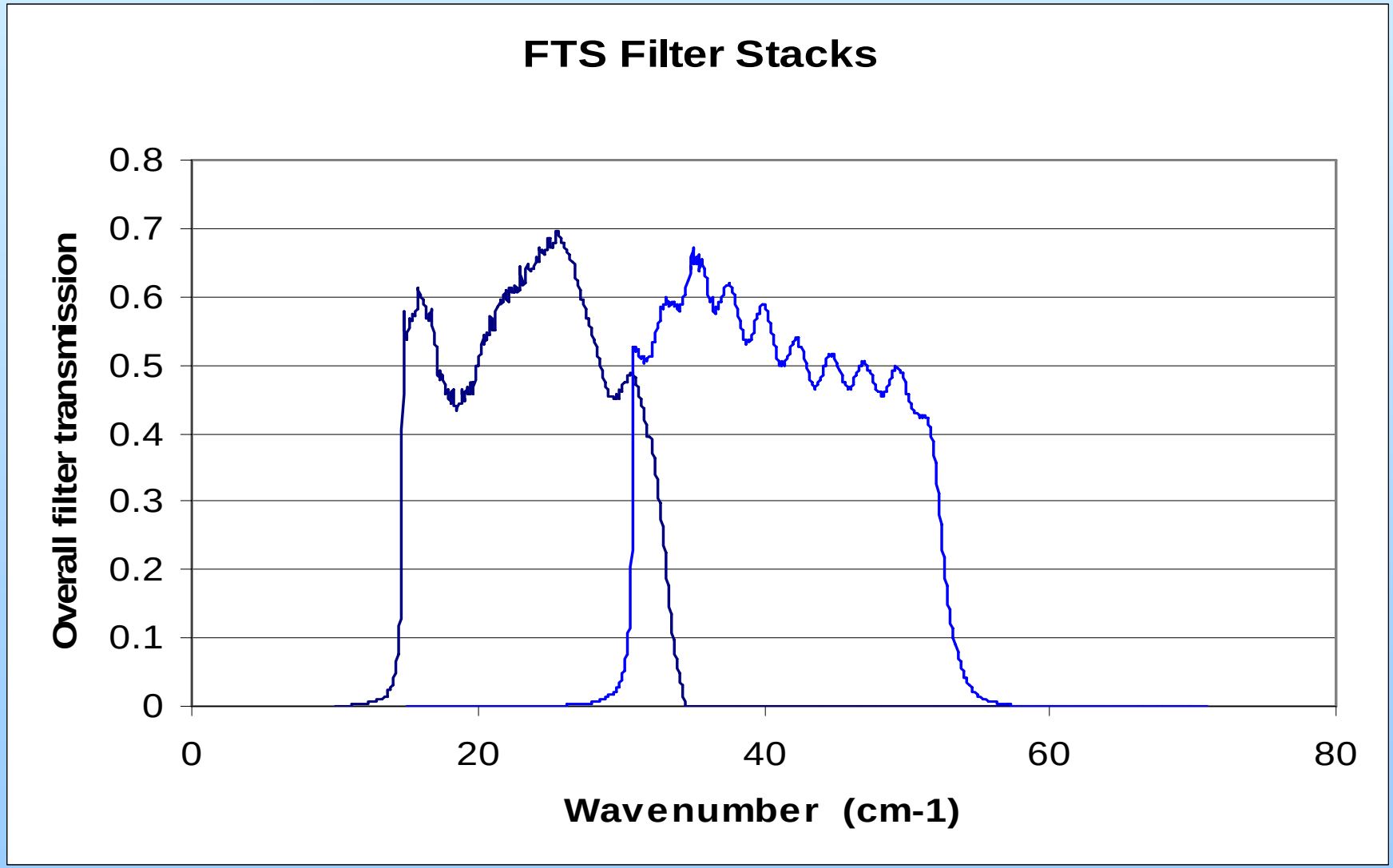
Transmission to detector

Throughput

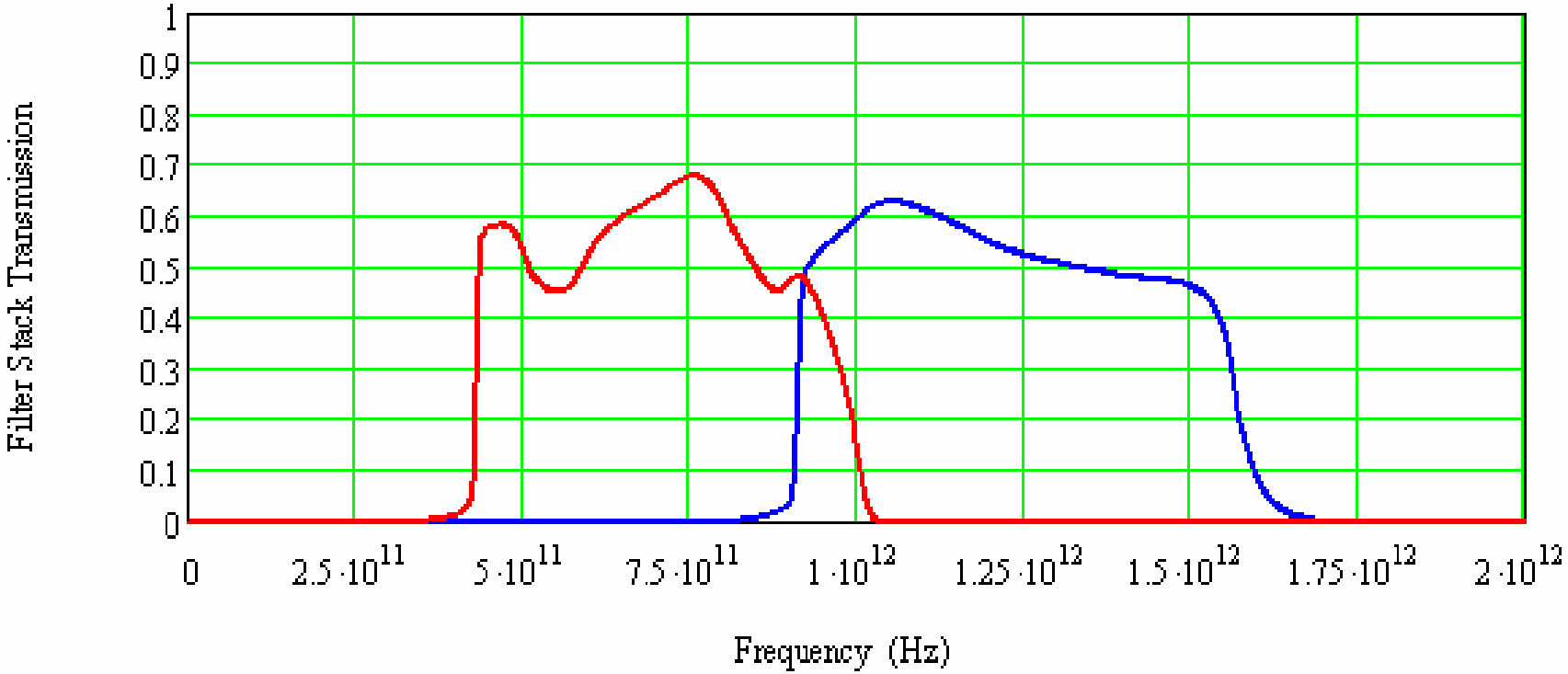
$$NEP_{ph}^{\ 2} \approx \left(2Q_{\mathrm{tot}} h \nu_{\mathrm{o}}\right)^{1/2}$$

$$NEP_{tot}^{\ 2} = NEP_{det}^{\ 2} + NEP_{ph}^{\ 2}$$

FTS Filter Bands



FTS Filter Bands



Operational wavelength ranges (μm)

	As measured	Old model nominal values
SSW	194 – 324	190 - 325
SLW	316 – 672	300 - 670

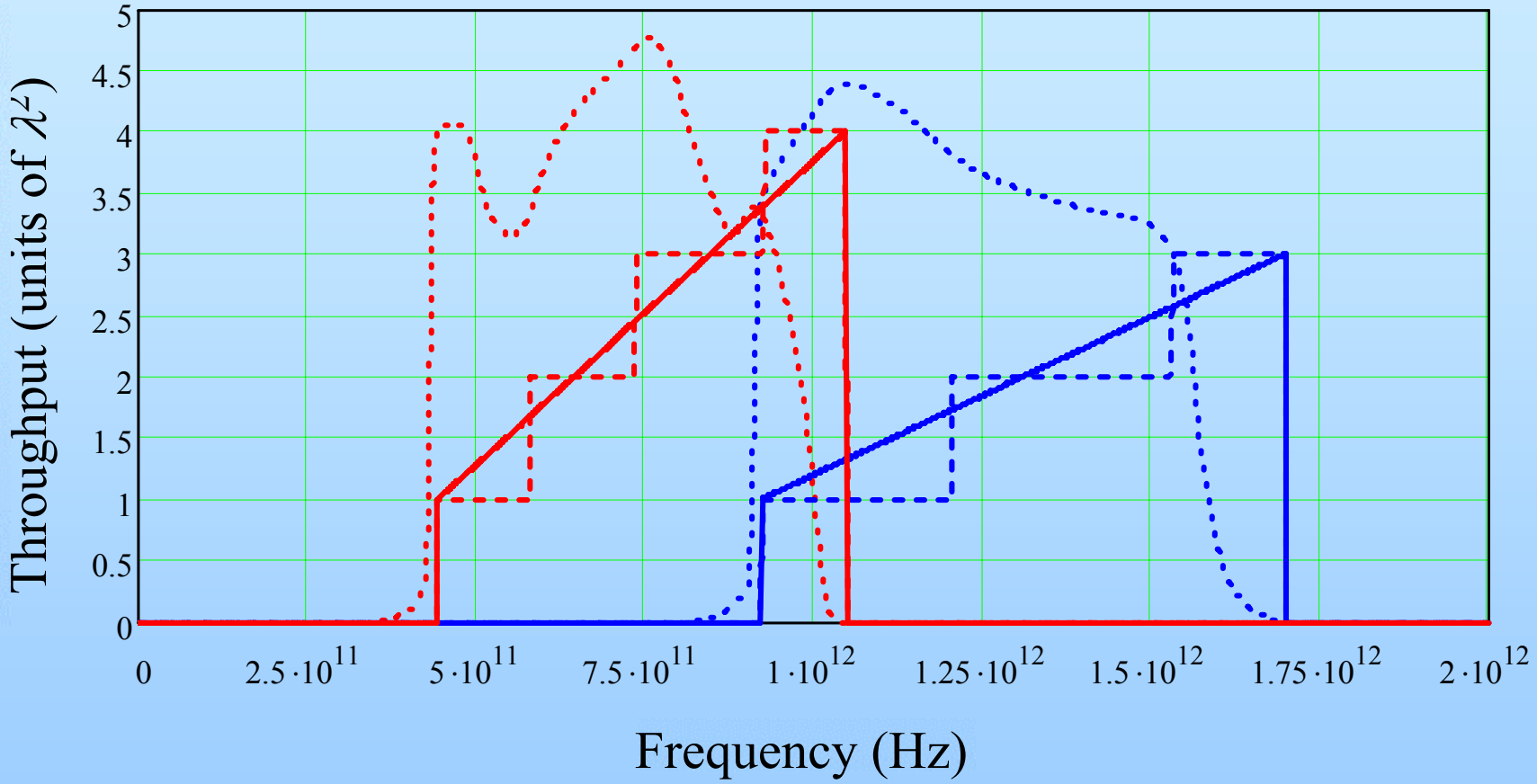
Crossover wavelength ~ 320 μm

Waveguide Modes

$$\lambda_c = \frac{2\pi r_o}{\chi_{mode}}$$

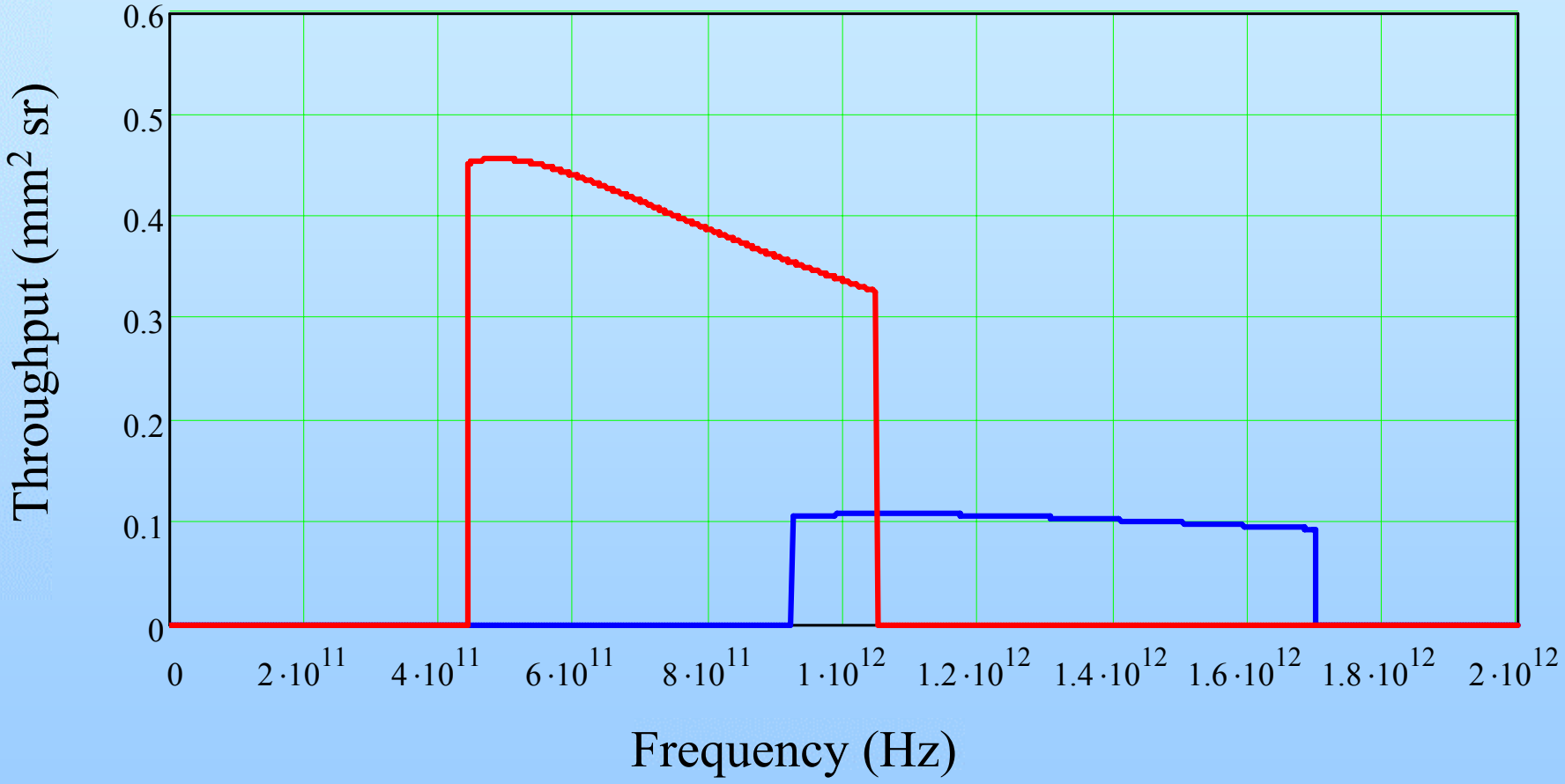
Mode	TE11	TM01	TE21	TM01/ TM11	TE31
χ_{mode}	1.841	2.405	3.054	3.832	4.201
SSW λ_c (μm)	324	248	195	156	142
SLW λ_c (μm)	671	513	404	322	294

Mode propagation



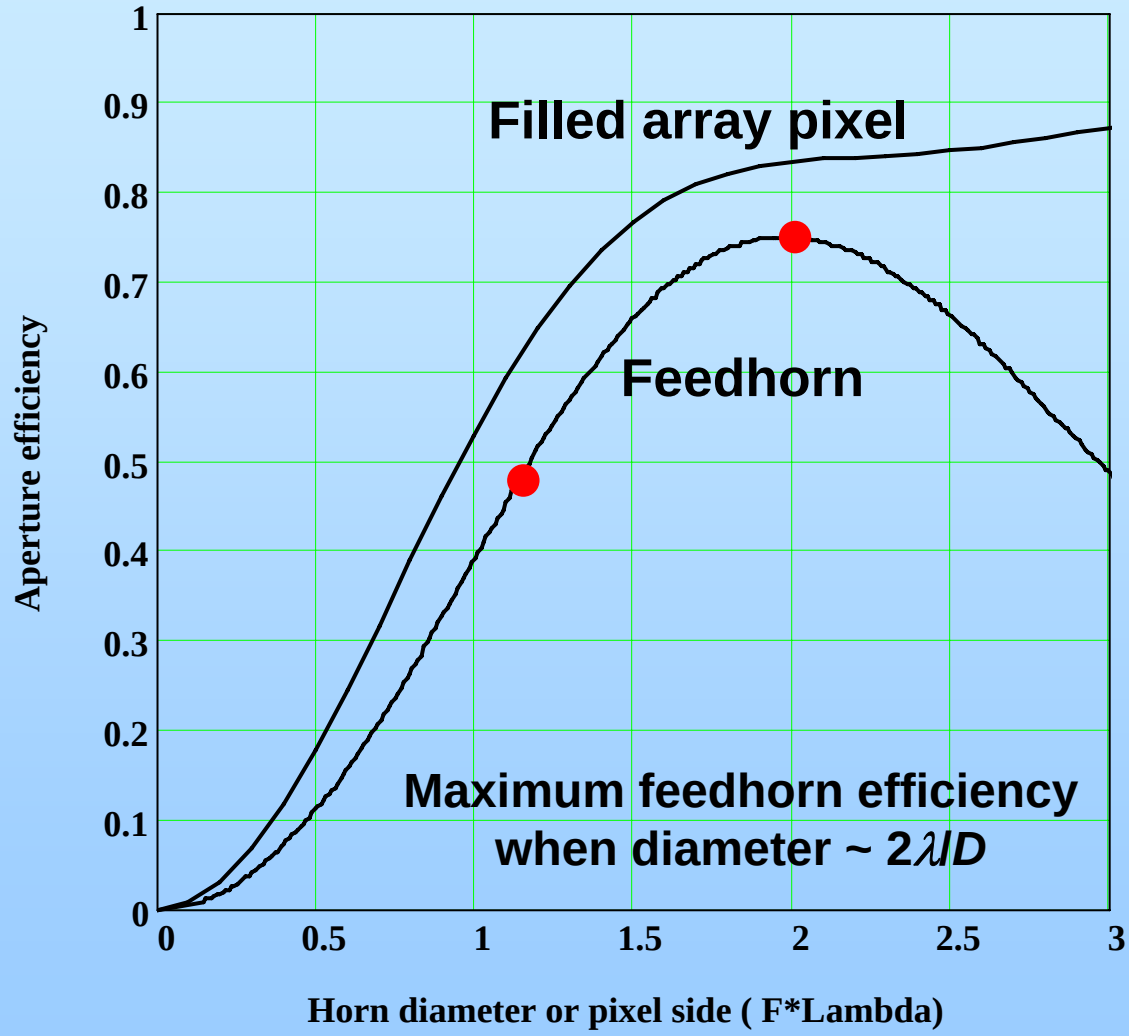
Throughput = (Filter profile)(Mode profile)(λ^2)

Adopted Throughput Variation

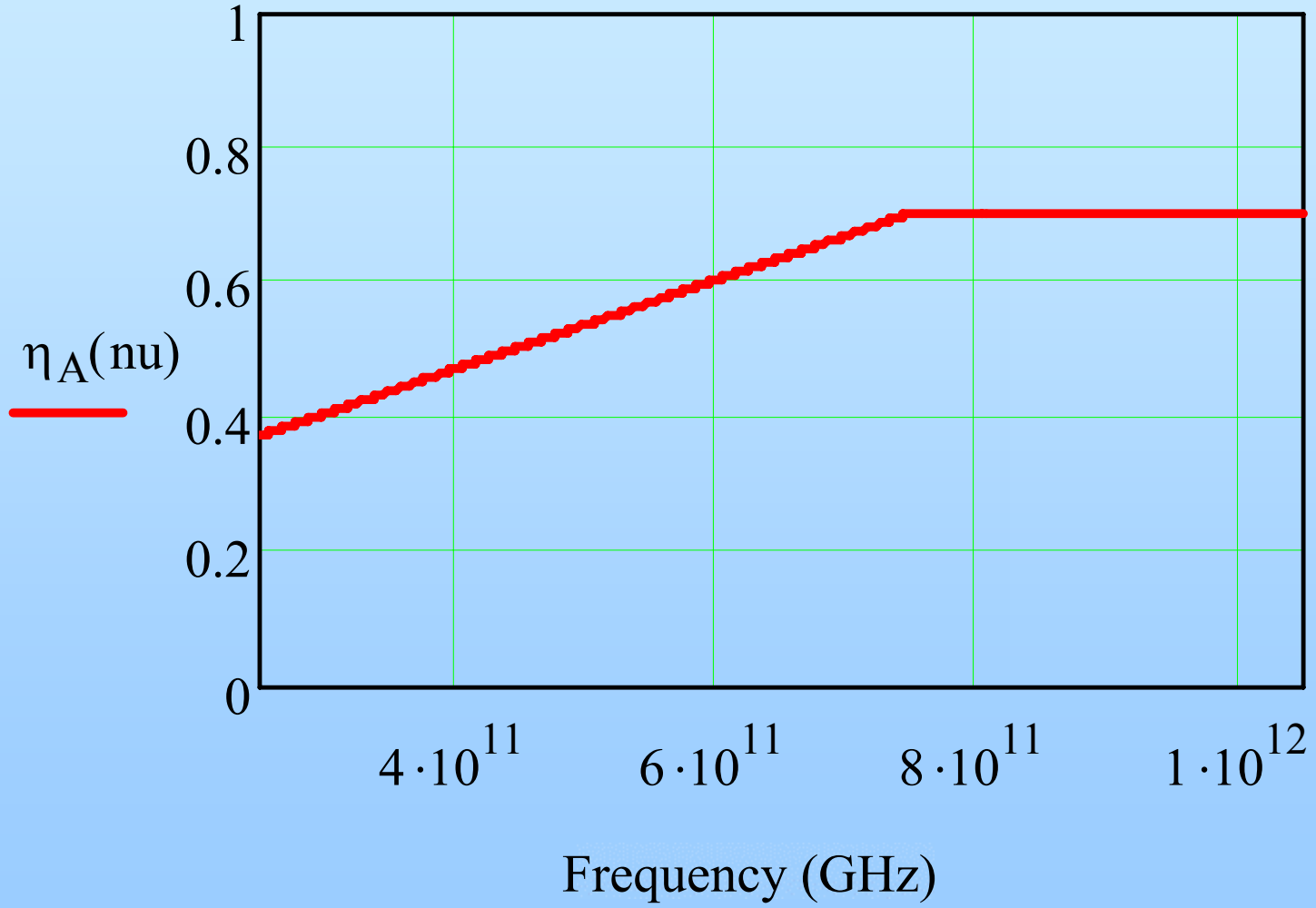


Feedhorn Aperture Efficiency

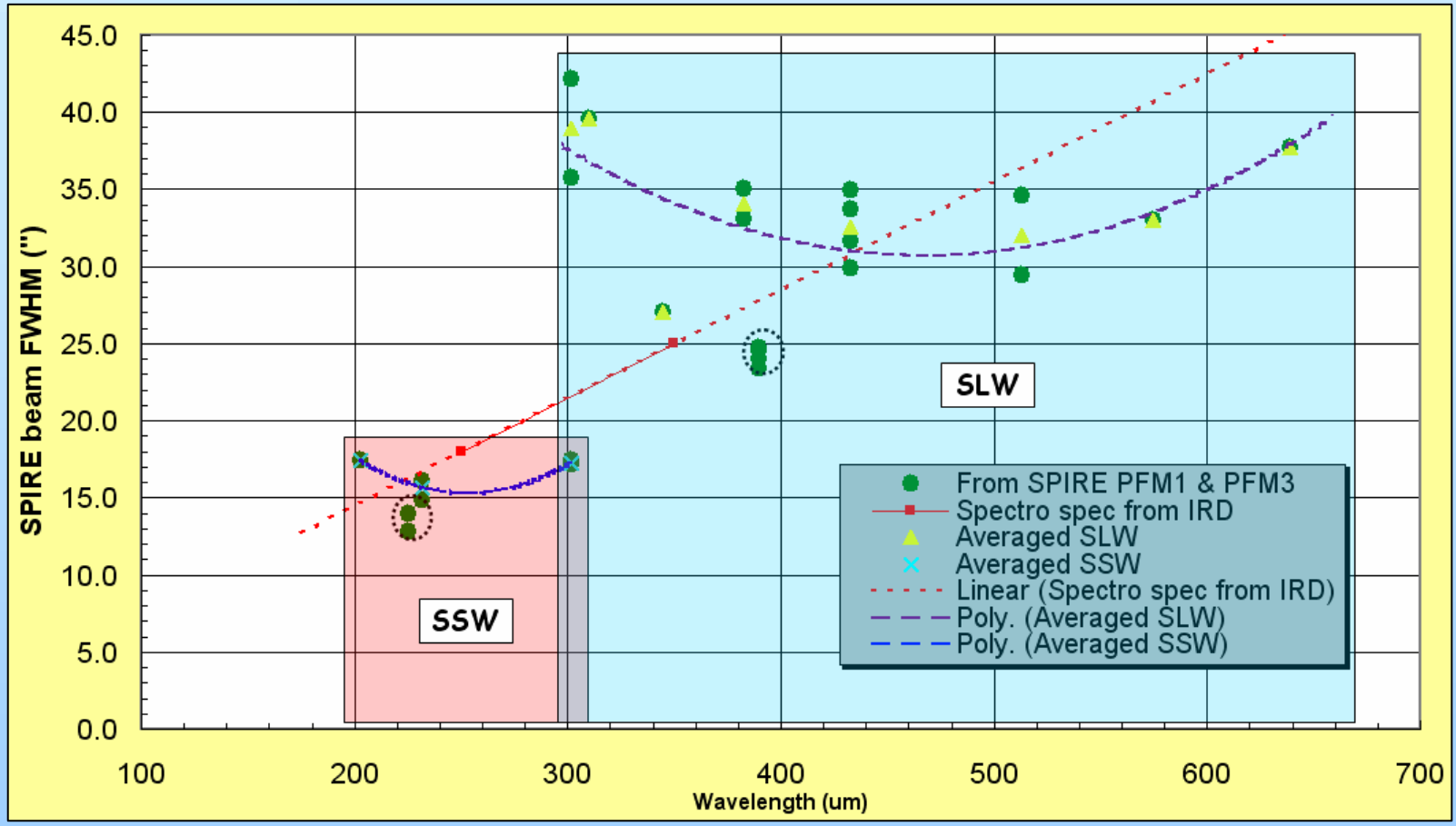
SLW horn is 2*Fλ* at 390 μm but only 1.2*Fλ* at 670 μm



Aperture Efficiency Variation (SLW)



Beam Profiles



SSW: Wavelength-independent value of 16”

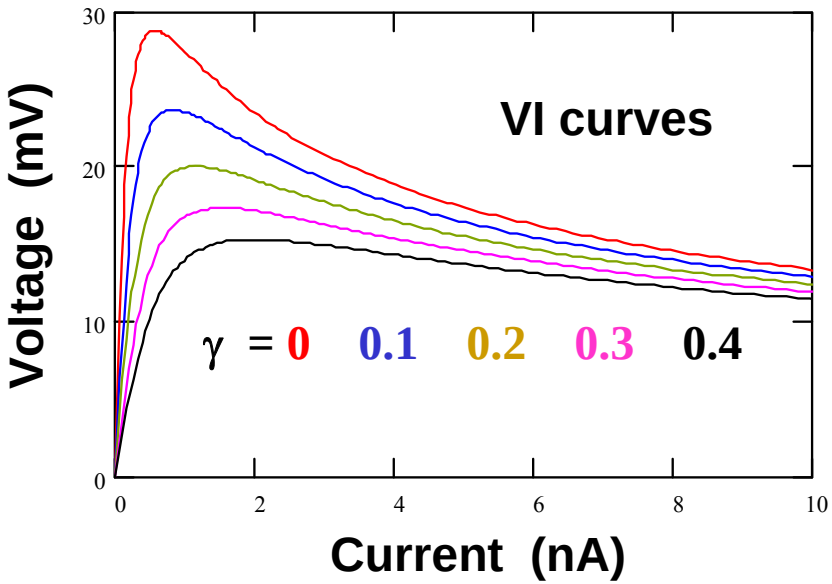
SLW: FWHM = 32” - 40” from the centre to the band edges.
35” is adopted for the whole band

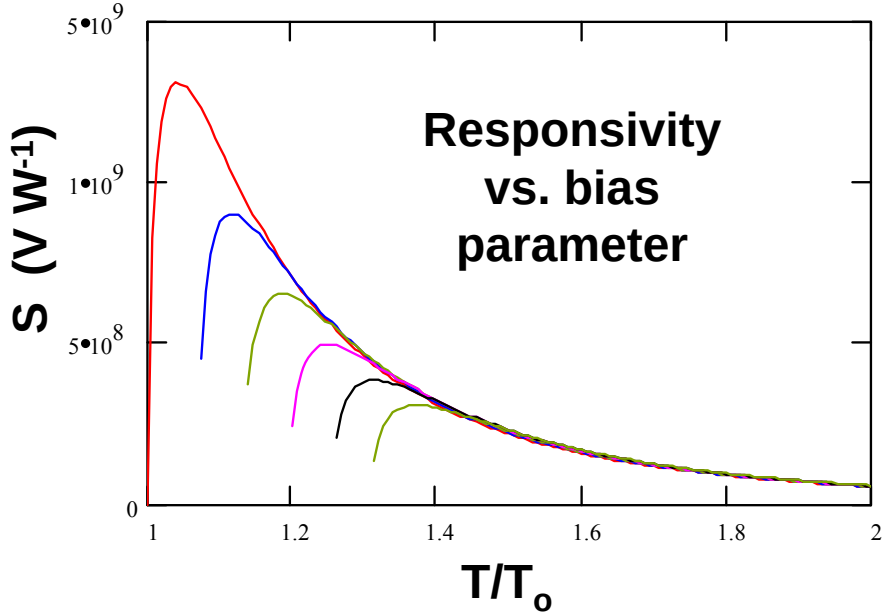
Detector Parameters

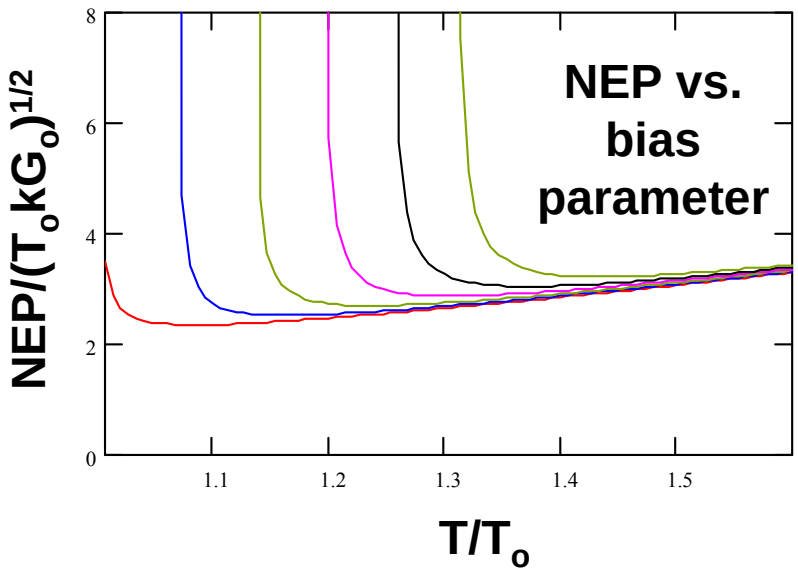
Currently using median values for the two arrays

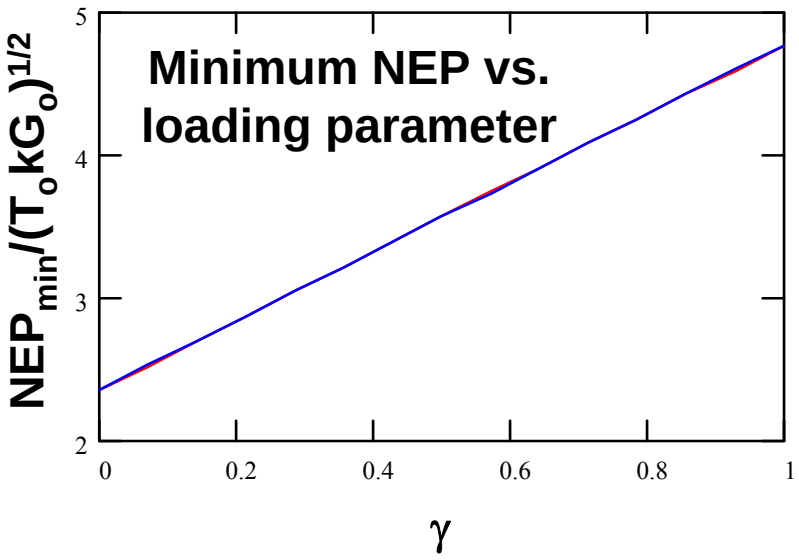
	Units	Description	SSW	SLW
R_o	Ω	Resistance parameter	79.3	92.2
T_g	K	Band-gap temperature	42.1	41.0
R_L	MΩ	Load resistance	19.2	23.2
G_o	pW K^{-1}	Static thermal conductance at 0.3 K	194	163
C_o	pJ K^{-1}	Heat capacity at 0.3 K	1.02	1.0
n		*R-T* index	0.5	0.5
β		Thermal conductivity power-law index	1.30	1.23
ρ		Heat capacity power-law index	1	1

Bolometer Model









Background Power, NEP, and NEFD

	SSW	SLW
Absorbed power (pW)	4.1	4.9
Photon noise NEP (W $Hz^{-1/2}$ x 10^{-17})	8.8	7.2
Overall NEP (W $Hz^{-1/2}$ x 10^{-17})	12	10

$$NEFD_{basic}(\nu,\Delta\nu) = \frac{\left(2^{1/2}\right)NEP_{tot}}{\eta_A(\nu)\,\eta_{feed}\,\eta_{cosq}\,A_{tel}\,t_{sky}\,\Delta\nu} \quad \text{Jy Hz}^{-2}$$

Aperture efficiency

FTS modulation efficiency

Telescope area

Transmission from sky to det.

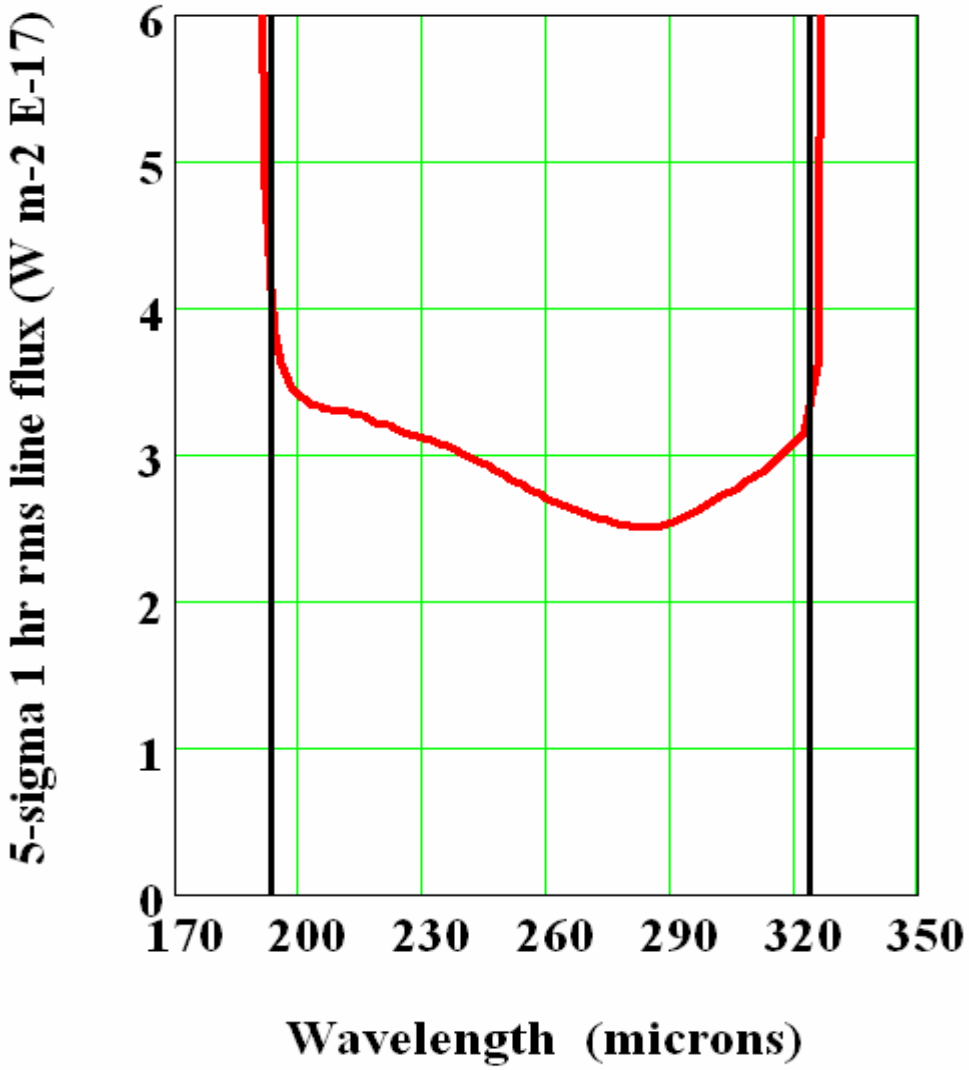
Bandwidth

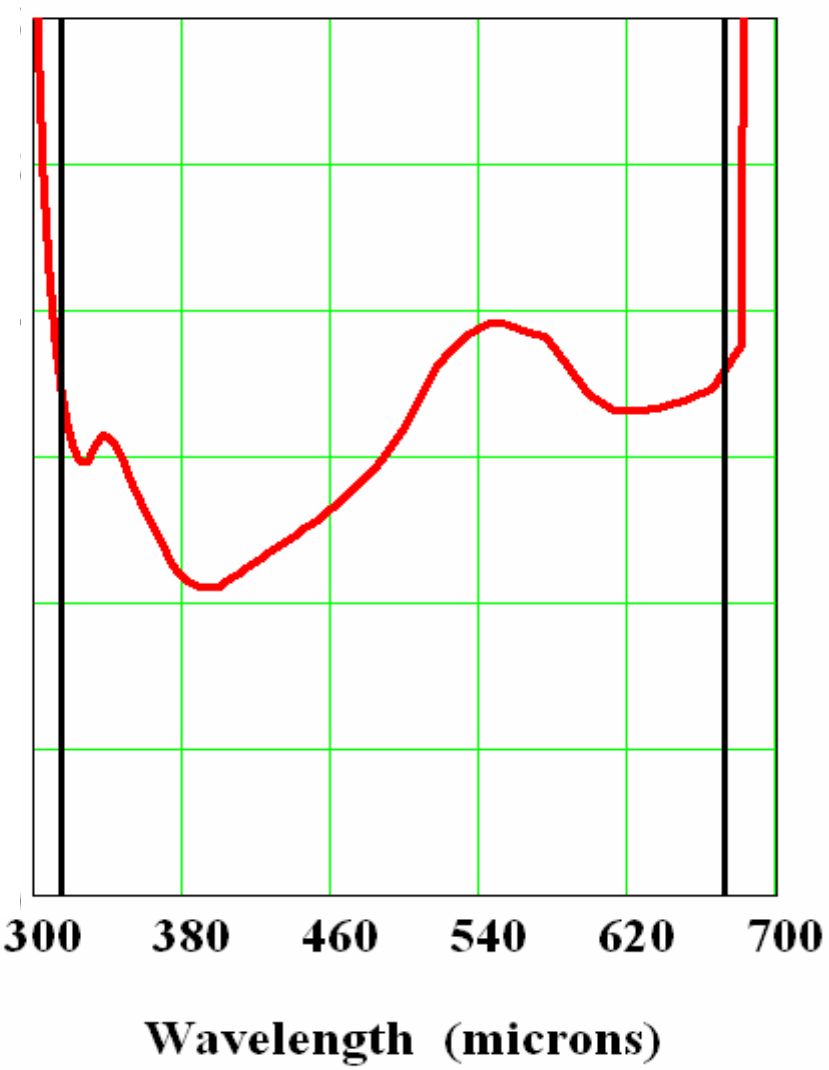
Limiting Flux Density and Line Flux

$$\Delta S_{5\sigma_1\mathrm{hr_pt}}(\nu) = \frac{5\,NEFD_basic(\nu,\Delta\nu)}{2^{0.5}} \frac{1000}{(3600)^{0.5}} \quad \text{mJy}$$

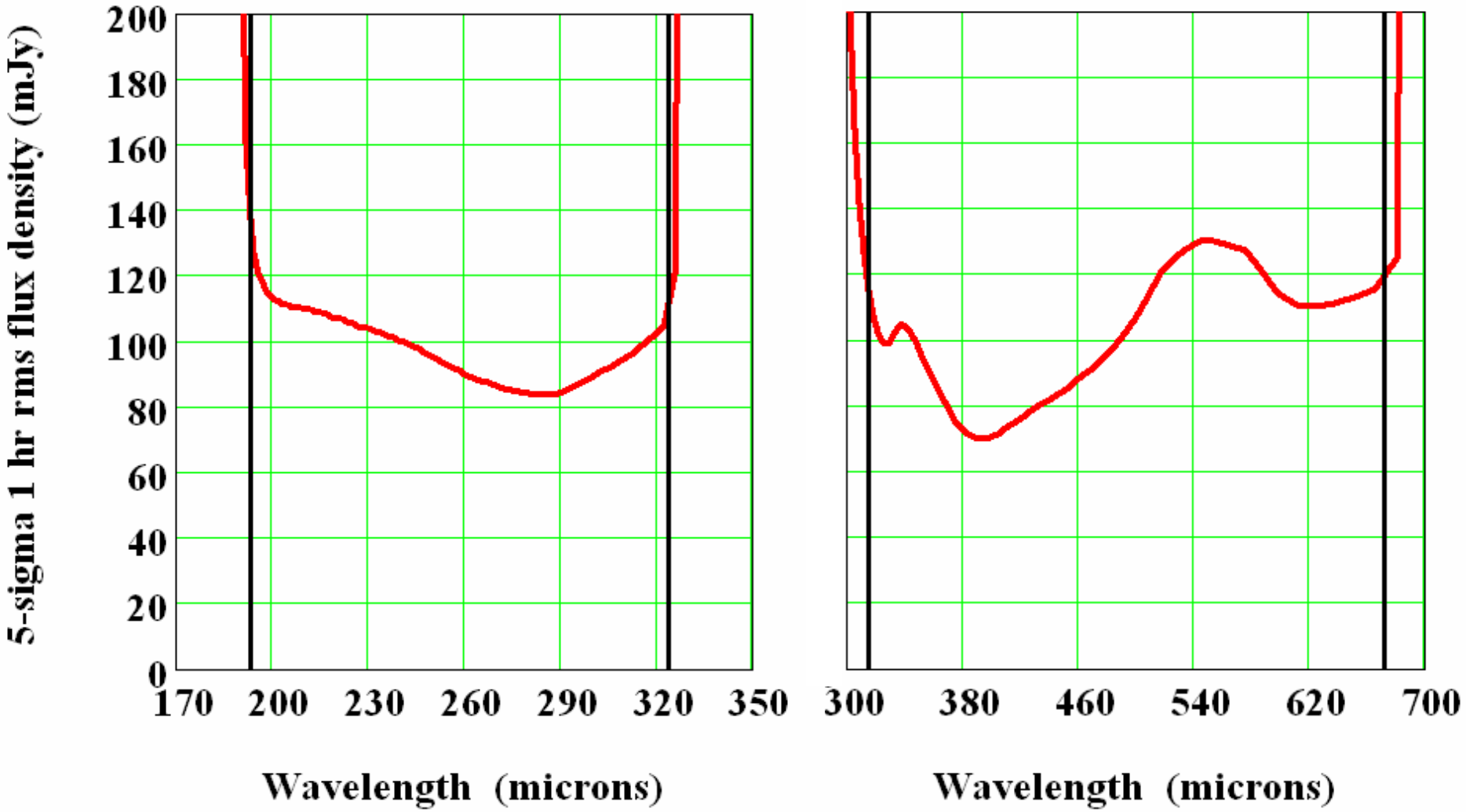
$$\Delta F_{5\sigma_1\mathrm{hr_pt}}(\nu) = \left[\Delta S_{5\sigma_1\mathrm{hr_pt}}(\nu)\right]\Delta\nu\left[\frac{10^{-26}}{1000}\right] \quad \text{W m}^{-2}$$

FTS Line Spectroscopy
(W m^{-2} x 10^{-17} 5-σ 1 hr)





FTS Low-Res. Spectrophotometery ($\Delta\sigma$ = 1 cm^{-1} ; mJy 5-σ 1 hr)



Some Comments on Sensitivities

- **Assumption: point source on-axis**
  - **Same applies to pipeline**
- **Many assumptions about instrument performance and telescope effective emissivity**
  - **Large uncertainties**
  - **Could be better or worse by nominal factor of 2**
  - **Scientific merit of proposals should not rely on achieving the nominal sensitivities**

Next Upgrade

- Band profile variations and operational wavelength ranges
  - Decide on nominal detector sets for point source observations and adopt appropriate values for those particular channels
  - Simple characterisation of variation across the arrays

- Beam profile vs. wavelength
  - Keep simple approach for now

- Further comparison of sensitivity predicted by model and by Jean-Paul's analysis of ILT data

iFTS
transmission & SNR

Jean-Paul Baluteau (LAM)

input beams transmission

- **the overall response of the detector chain (adu-V-pW) is not (presently) known so a direct estimate of the overall FTS transmission is not yet possible**
- **only a comparison of the actual measurements to simulations of incident radiation (from CBB and SCALs) through the FTS can be achieved**
- ***transmissions* here are defined as the measurements over simulations ratios**
- **presently simulations include all known (measured) transmissions of optical elements (filters, beam splitters, …)**
- **so *transmission* should be the actual one within a multiplicative factor for elements not included in simulations**
- **and deviation from a constant value would mean that some unknown elements have a wavelength dependent transmission/efficiency**

extraction of the "transmission" in each input port

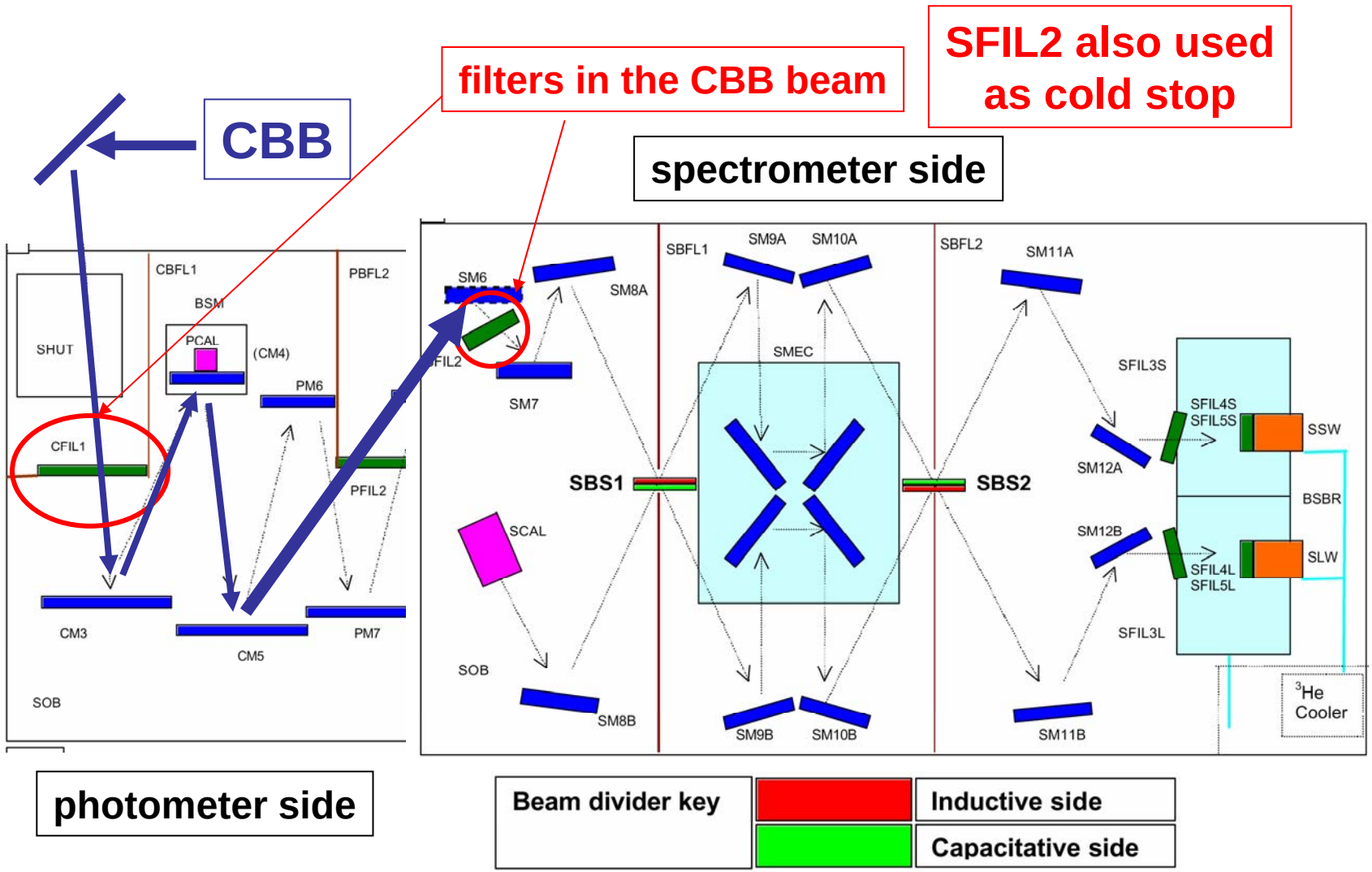
- **simulated spectrum from each input port is product of:**
  - **Planck function (at an assumed CBB or SCAL temperature)**
  - **assumed (CBB or SCAL) emissivity**
  - **assumed transmission (here only filters & beamsplitters)**
  - **assumed constant throughput over each band**

    (here 0.12 & 0.48 mm^2.sr for SSW & SLW)
- **"transmission" is obtained from the difference between two measured/simulated spectra:**
  - **only one parameter (the CBB or SCAL temperature) is changed**
  - **all other conditions/settings are the same**
  - **"transmission" = (measured difference spectrum) divided by (simulated difference spectrum)**

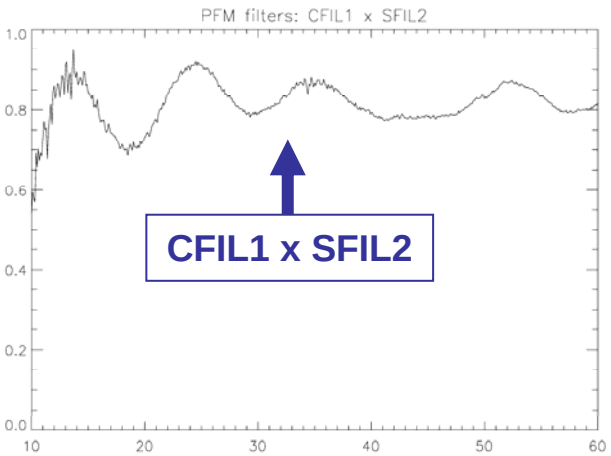
  ➔ **it should be a constant if the assumed parameters variation with wavenumber is well representative of the actual one**

  ➔ **it should equal to the detector conversion factor if all parameters are correctly assumed**

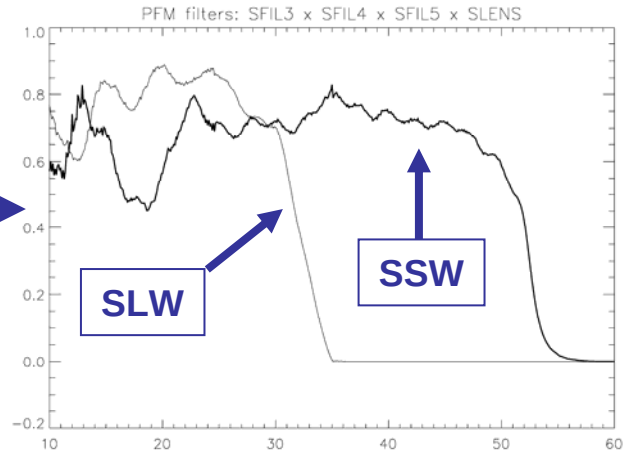
PFMs cold tests optical configuration on CBB

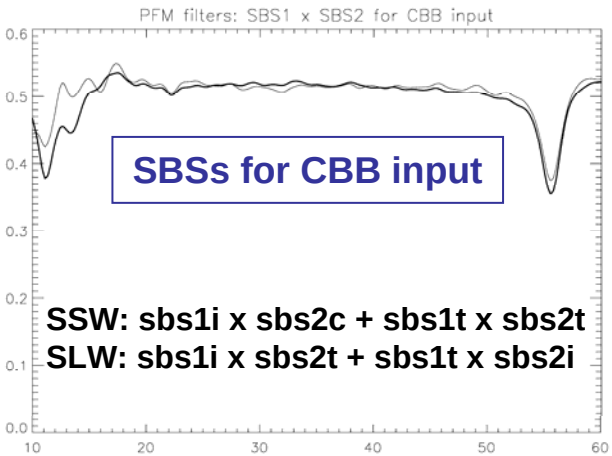


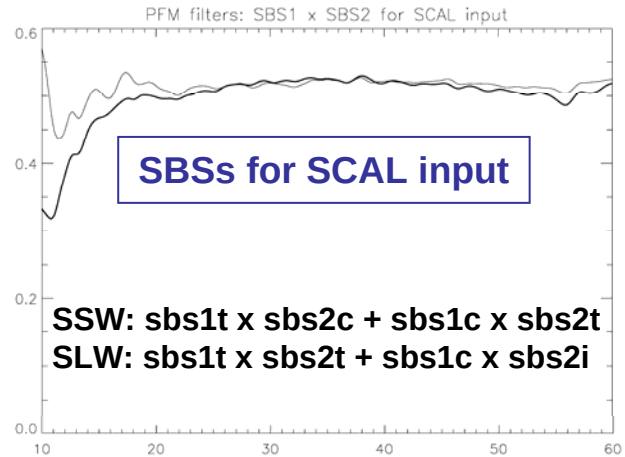
filters & beamsplitters transmission



SFIL3 x SFIL4 x SFIL5 x SLENS

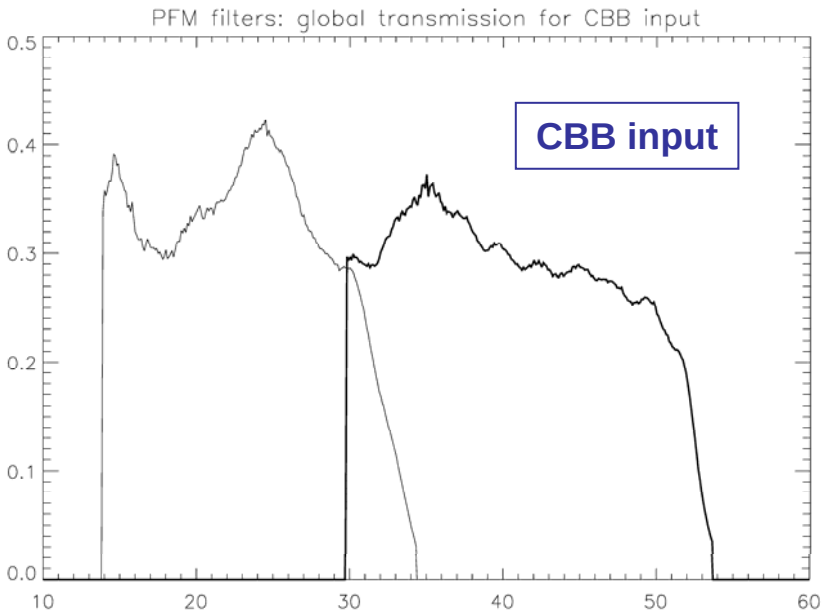


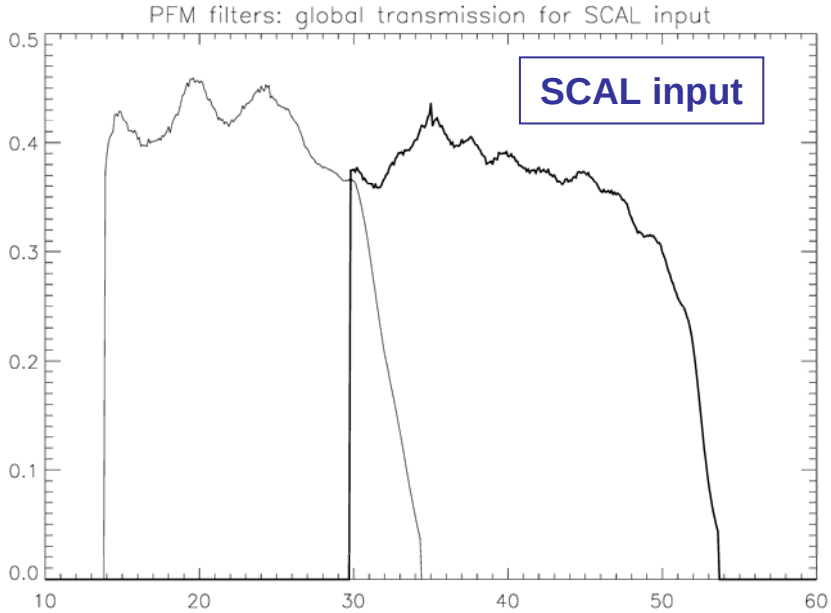




plots of transmissions vs wavenumber
from Pete data (june '06)

transmission for the two input ports





plots of transmissions vs wavenumber

(from previously shown filters & beamsplitters data only)

➔ **note that some additional components in the CBB input beam have to be included in the simulations**

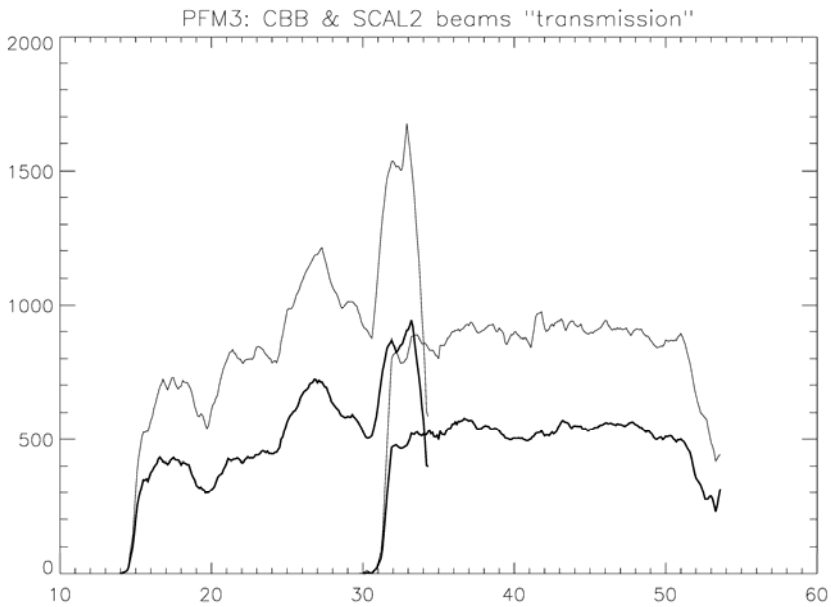
"improved" spectral simulations

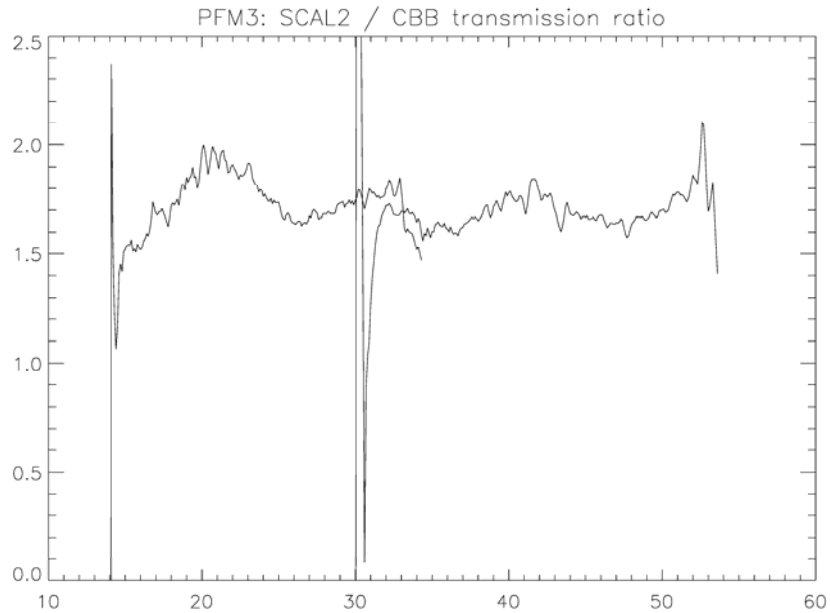
➔ **add contribution by components in the CBB beam (not present in the SCAL beam) as seen in the FTS optical configuration (p. 4)**

- **supplementary transmission efficiency:**
  - **6 additional mirrors (99% each ➔ 94%)**
  - **loss due to the hole in the BSM (95%)**
  - **expected cold stop (at SFIL2 location) efficiency (75%)**
  - **<u>all assumed to be constant over wavenumber</u>**
- **supplementary emission:**
  - **what is absorbed/lost (transmission losses by CFIL1, SFIL2, mirrors , BSM hole & cold stop) should be (re-)emitted at the FPU internal temperature (assumed here to be about 4.6K):**

    assume emissivity = loss of transmission
  - **as this emission is expected to keep the same in the two measurements it should have no impact on the derived "transmission"**

CBB & SCAL2 beams transmission: results from PFM3





PFM3 results: plots of transmission vs wavenumbers
left: SCAL2 beam "transmission" (thin line)
& CBB beam "transmission" (thick line)
right: SCAL2 over CBB beam transmission ratio

➔ **SLWC3 & SSWD3 only processed here**

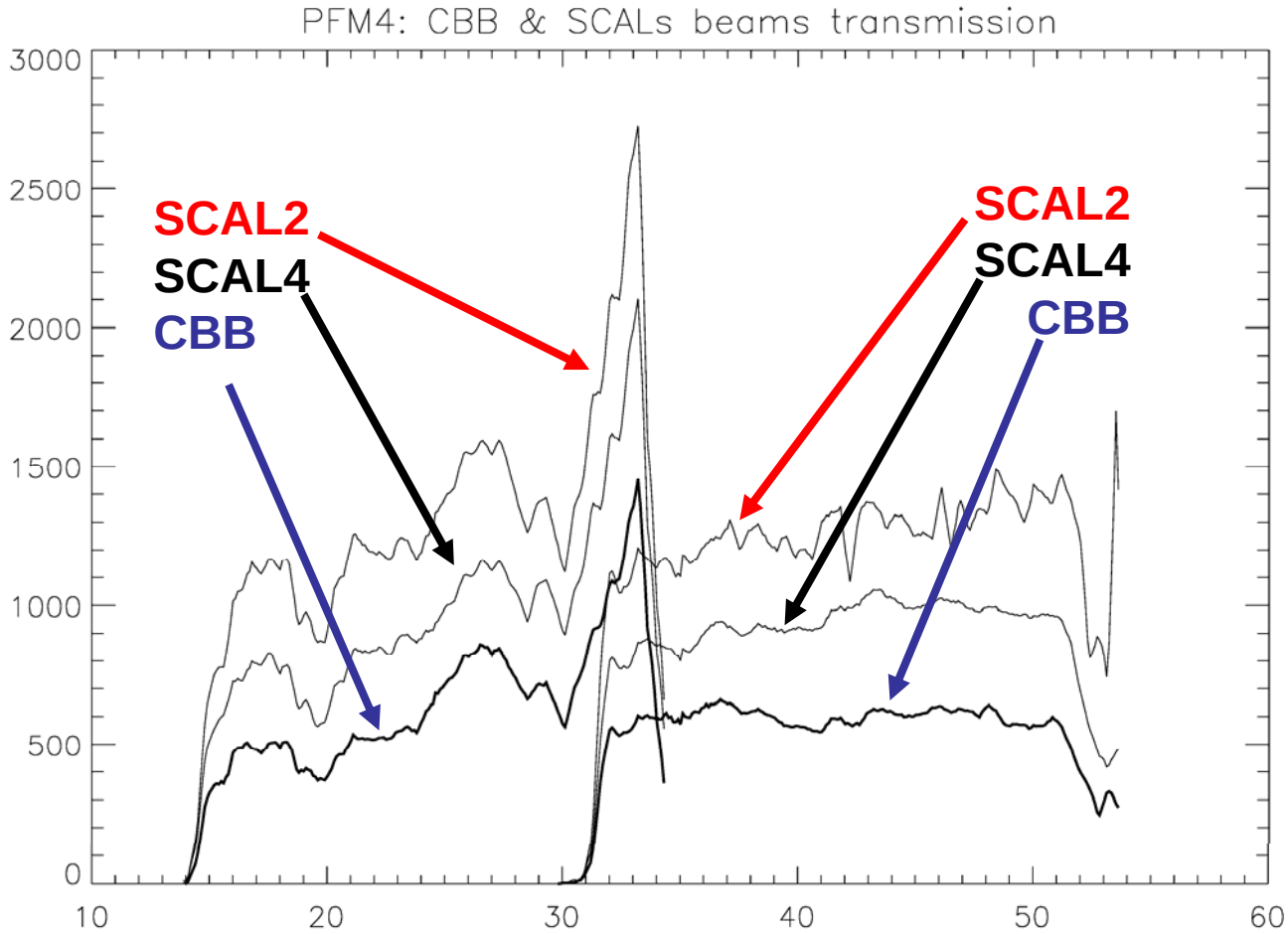
PFM4 measurements used here

- **PFM4A:**
  - **Nov. 13th: 11F1 & 1200 CBB @ 7.2K & 8.2K**
  - **Nov. 14th: 121B & 1221 SCAL4 @ 9.4K & 17.5K**
  - **Nov. 17th: 12FA CBB & SCALs "off"**
  - **Nov. 20th: 139C SCAL2 @ 8.98K**

- **PFM4B:**
  - **Nov. 21st: 13B4/13BB/13BE SCAL4 @ 9K/15K/20K**
  - **Nov. 27th: 14CA & 14CF CBB @ 6.7K & 9.0K**
    14D7/14DD/14E3 SCAL2 @ 9.2K/14.2K/20.2K
    14EC SCAL4 @ 20.2K
  - **Dec. 6th: 1720/1724/1728/172B CBB @ 7.2K/7.7K/8.2K/8.7K**
    1760 SCAL2 @ 25.9K

all measurements with same detector bias except 12FA

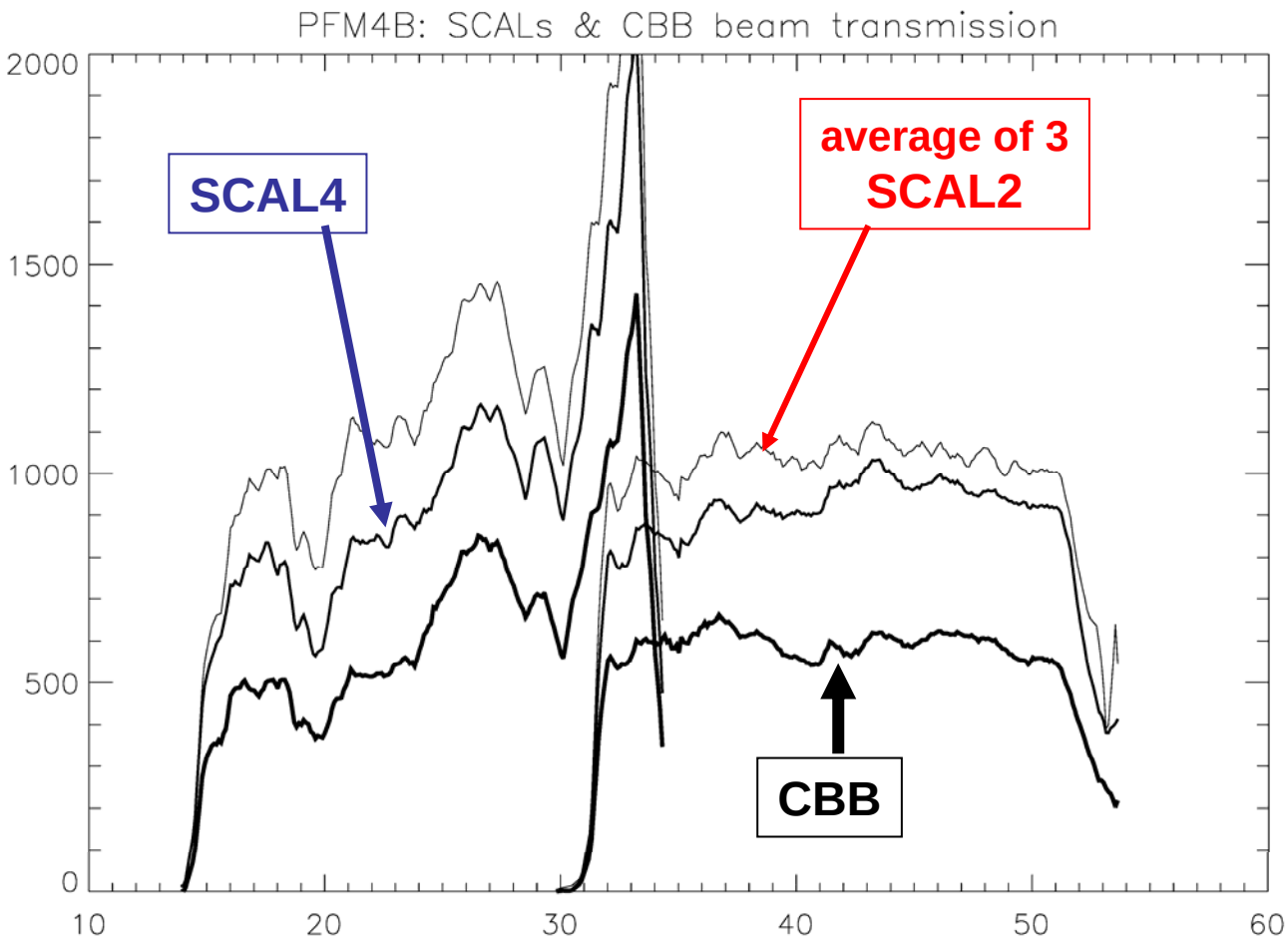
CBB & SCALs transmission: results from PFM4A



plots of transmission vs wavenumbers
only SLWC3 & SSWD3 processed here

! SCAL2 ! measurements with # bias

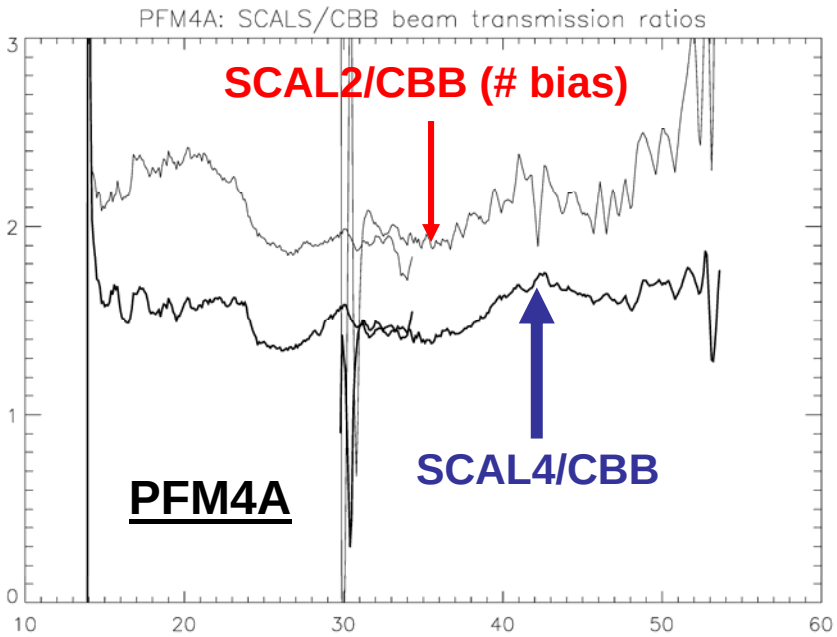
CBB & SCALs transmission: results from PFM4B

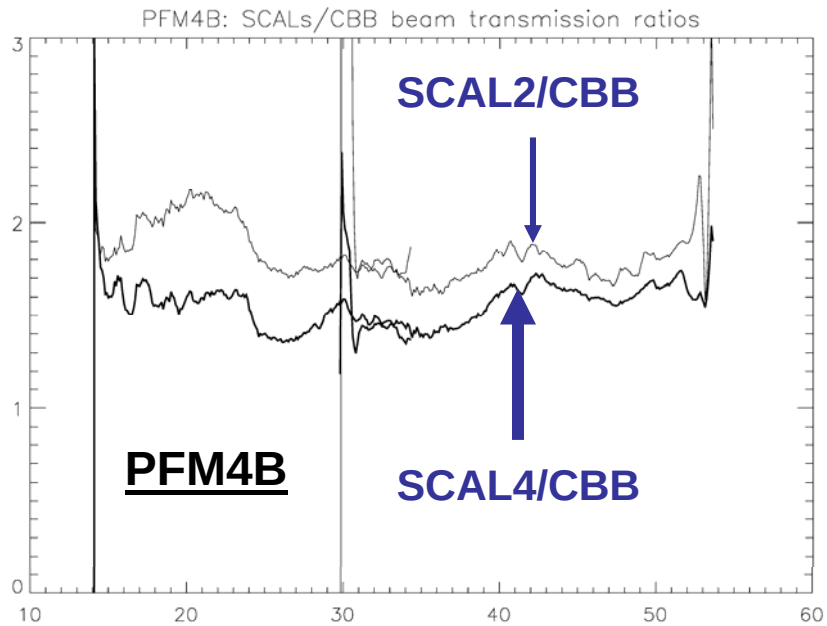


plots of beam transmission vs wavenumbers

again only SLWC3 & SSWD3 here

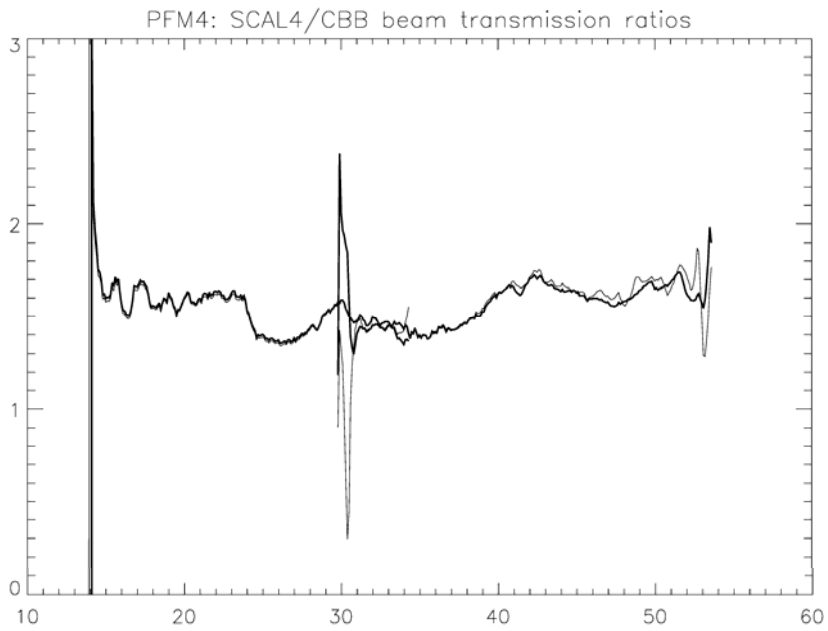
SCALs/CBB beam transmission ratios from PFM4

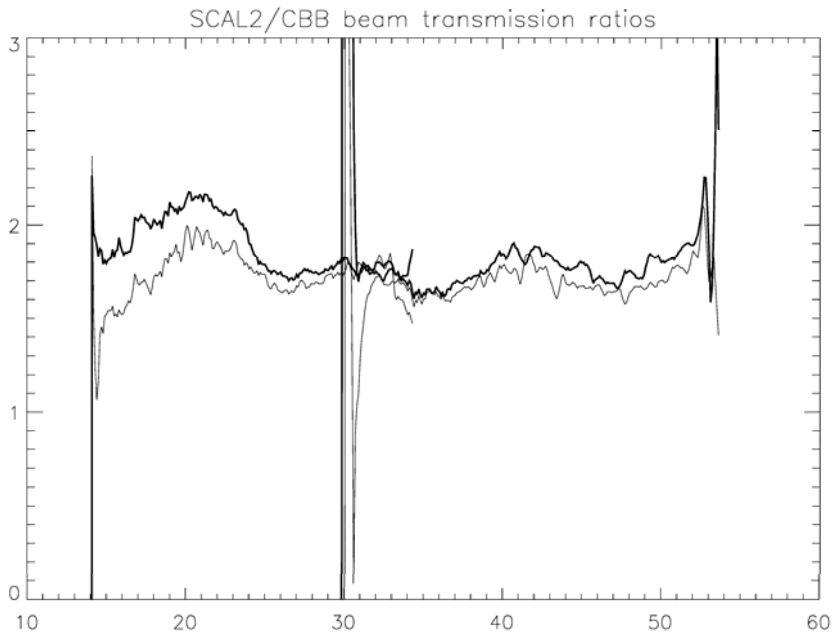




plots of SCALs/CBB beam transmission ratios vs wavenumber

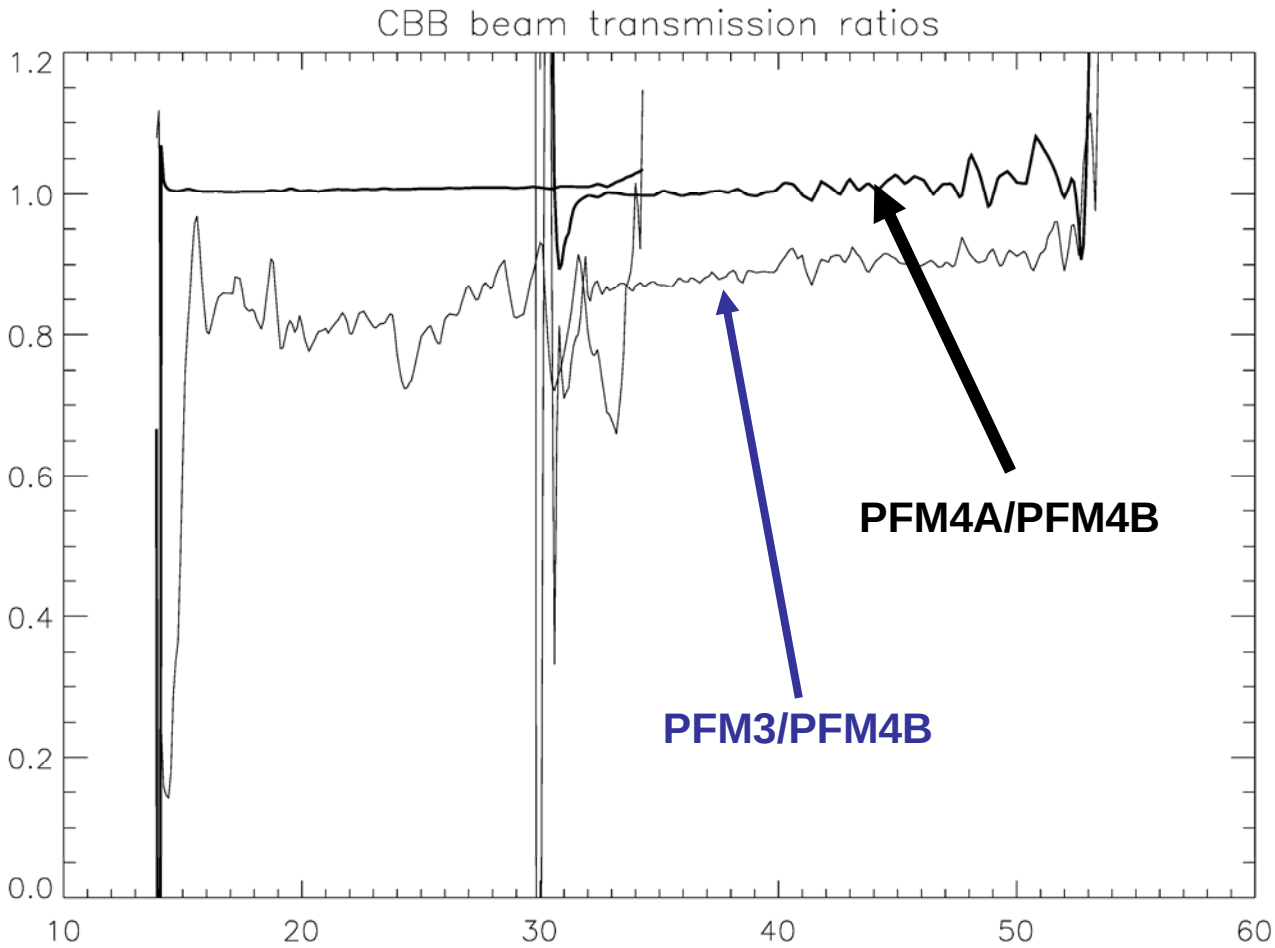
SCALs/CBB beam transmission ratios in PFM3 & PFM4





plots of SCALs/CBB transmission ratios vs wavenumber
left: SCAL4/CBB from PFM4A & PFM4B (thick line)
right: SCAL2/CBB from PFM3 & PFM4B (thick line)

CBB beam transmission in PFM3 & PFM4



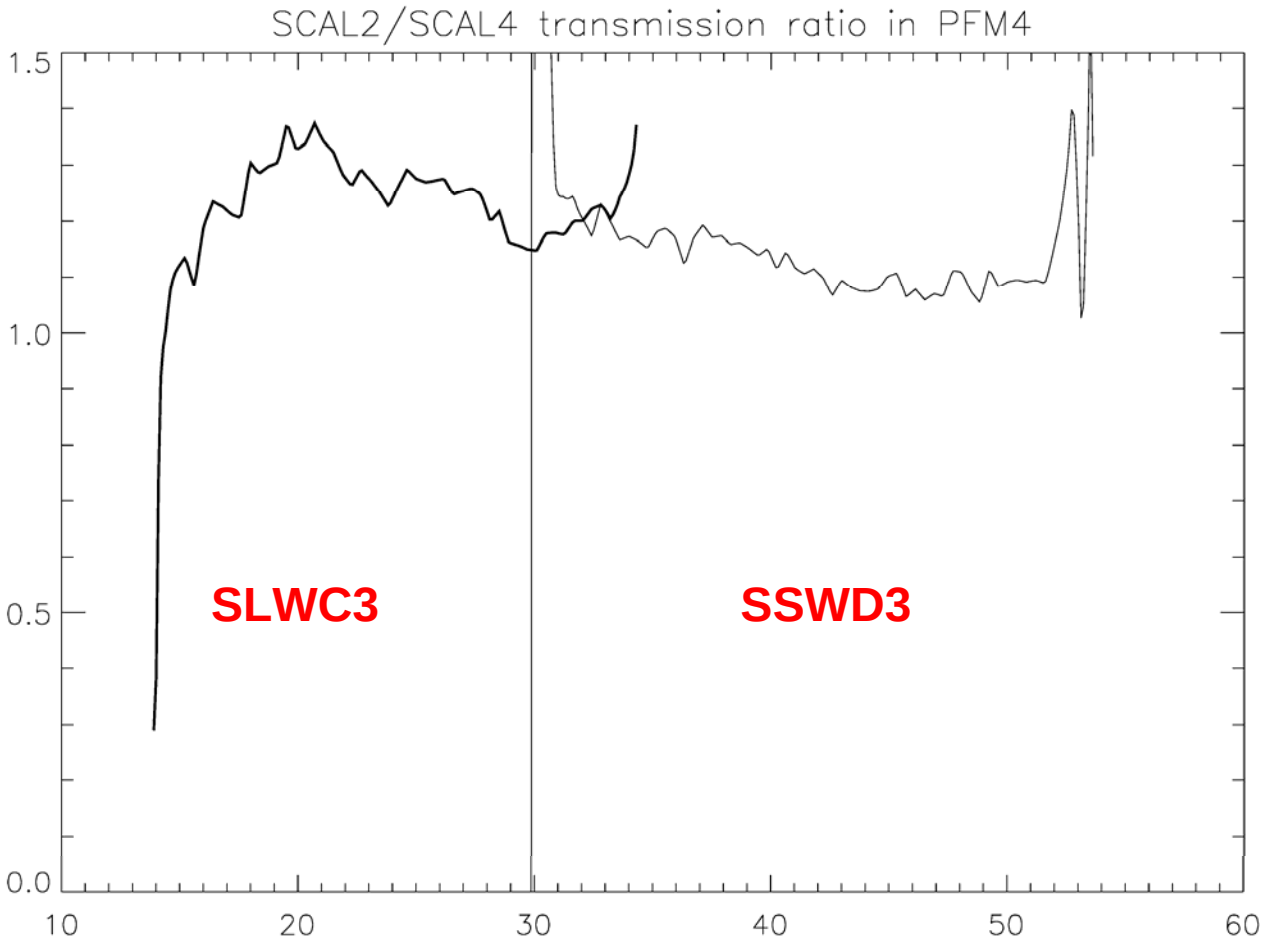
plots of CBB transmission ratios vs wavenumber
PFM3/PFM4B & PFM4A/PFM4B (thick line)

first conclusions

- **CBB beam "transmission" ratios:**
  - **PFM4A/PFM4B close to 1 ➔ good results reproducibility**
  - **PFM3/PFM4B about 0.85 ➔ modifications done ?**
    - **better polishing of rooftop in PFM4**
    - **better positioning of flip mirror for PFM4**
    - **other changes ???**
- **SCAL/CBB beam "transmission" ratio:**
  - **good reproducibility of results for SCAL4/CBB in PFM4 tests**
  - **apparent change of SCAL2/CBB from PFM3 to PFM4**
    - **about 5% for SSW but up to 15% at long wavelengths in SLW**
  - **SCAL2/CBB & SCAL4/CBB still greater than 1**
    - **would imply more "absorption" in the CBB beam (other factor 0.75?)**
  - **different behavior of SCAL2 & SCAL4 (see next page)**
    - **potential causes ???**

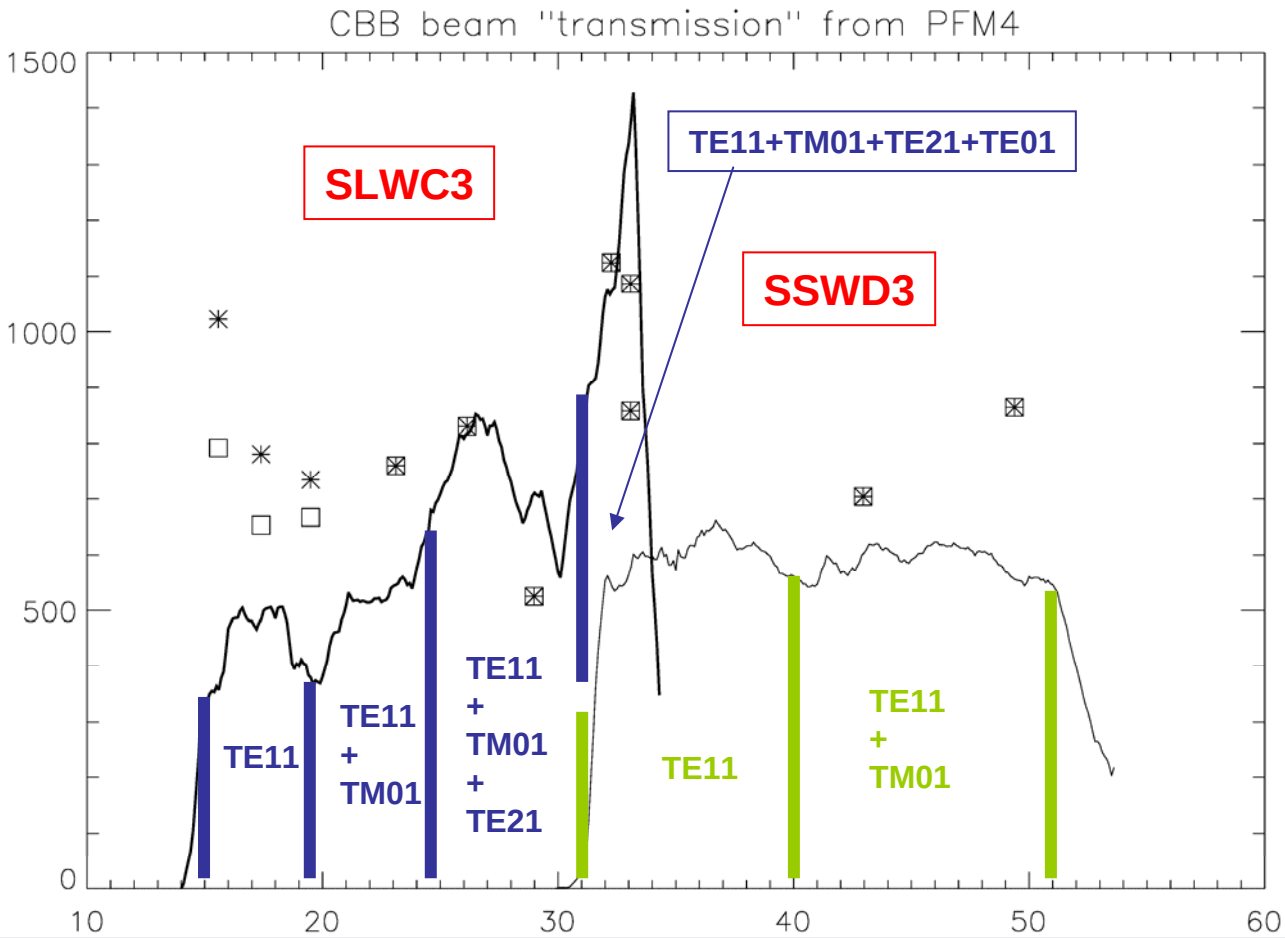
➔ for better understanding need to process other pixels than SSWD3 & SLWC3 done here

SCAL2/SCAL4 beam "transmission" ratio in PFM4



plot of SCAL2/SCAL4 transmission ratio vs wavenumber

CBB beam "transmission"

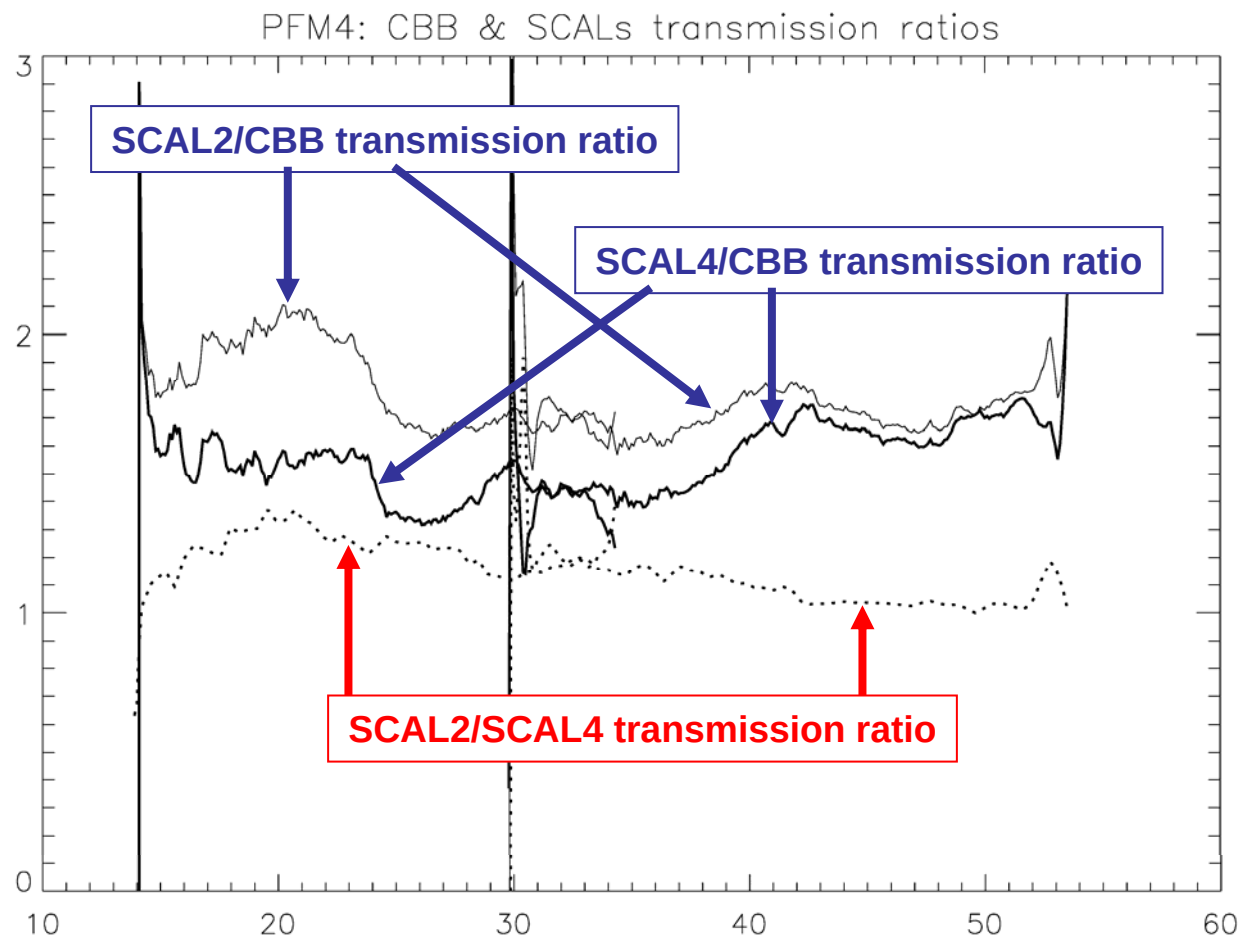


plot of CBB beam transmission vs wavenumber
FOV PFM3 measurements from Marc (Dec. '06):
stars = normalized at 26cm-1 & squares = with spillover efficiency from Matt

second conclusions

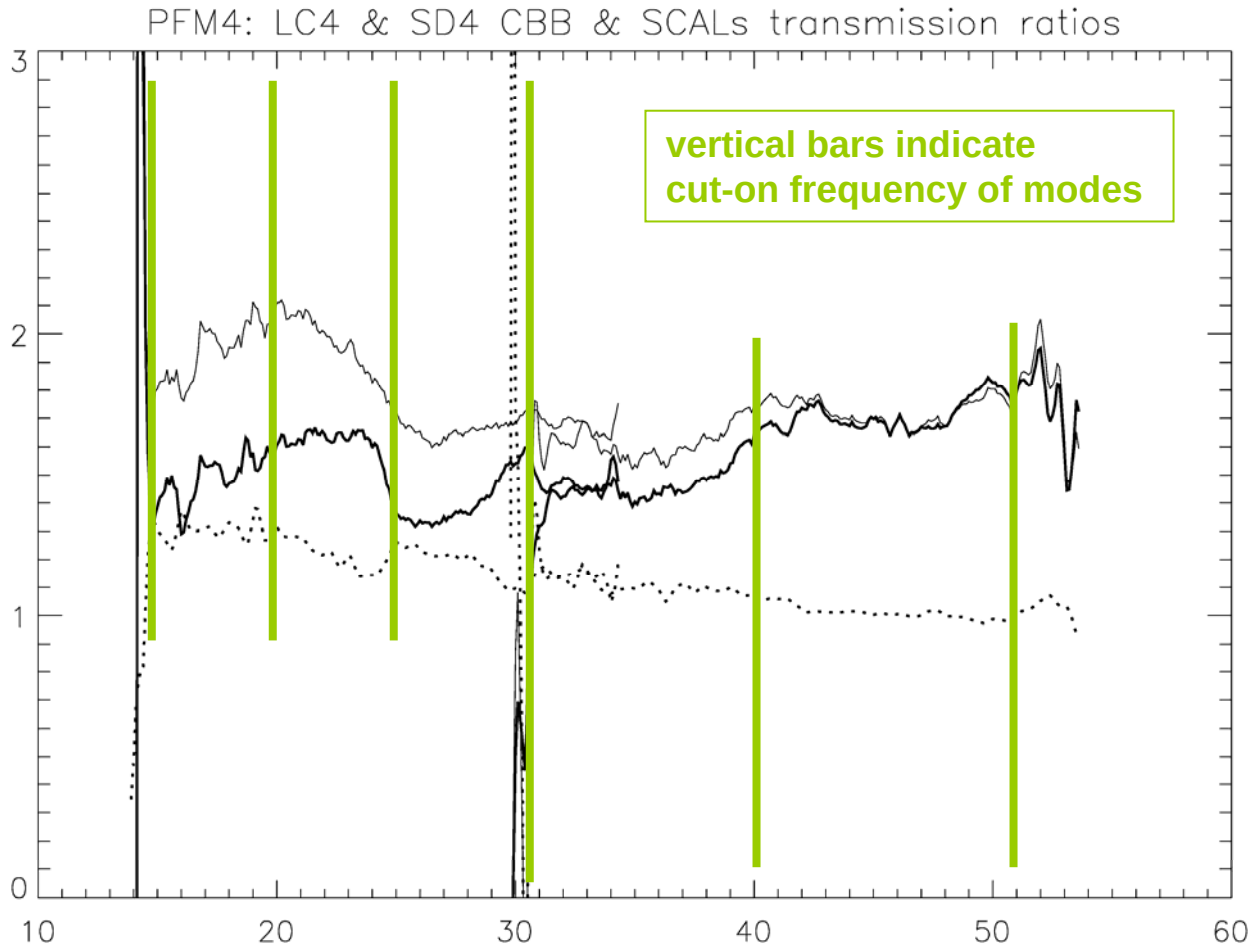
- **SSW band:**
  - **measured "transmission" looks flatter than measured FOV variation over band (the fact that the spectral measurements are fainter than the FOV expectations may imply that the overall gain for SSWD3 is lower than the one for SLWC3: TBC)**
- **SLW band:**
  - **strong enhancement at short wavelengths apparently correlated with FOV variation**
  - **introduction of spillover efficiency at long wavelengths looks insufficient to explain the rapid decrease in transmission**
- **waveguide response:**
  - **apparently quite good correlation of "transmission" with occurence of expected modes**

PFM4 SLWC3 & SSWD3 results



plot of CBB & SCALs transmission ratios vs wavenumber

PFM4 SLWC4 & SSWD4 results



plot of CBB & SCALs transmission ratios vs wavenumber (same labelling as previous figure)

transmission conclusions

- **very similar results obtained from the two couples (SLWC3+SSWD3 & SLWC4+SSWD4)**

  ➔ should apply for all the "unvignetted" field pixels

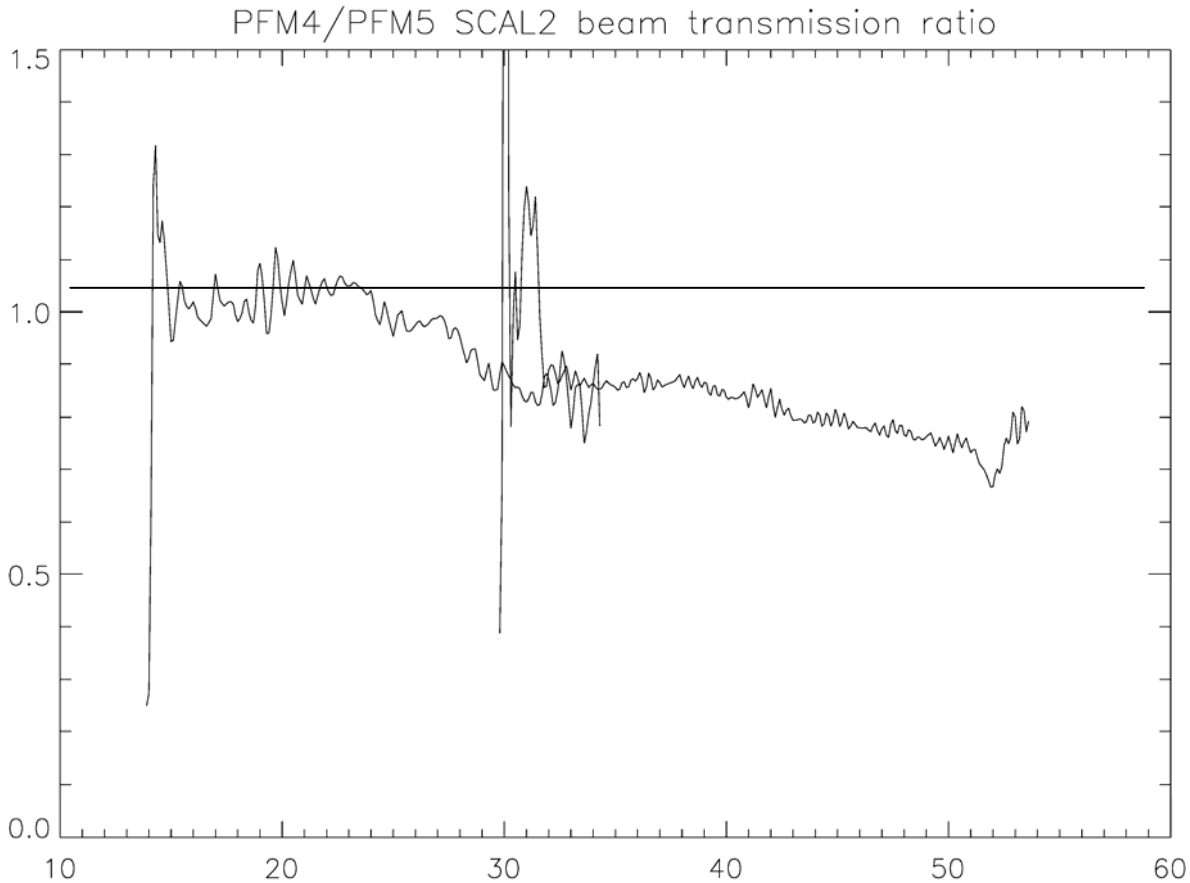
- **SCAL2/SCAL4 transmission ratio:**
  - **we note a smooth (quite linear) efficiency increase of SCAL2 compared to SCAL4 from unity to about 1.3 for increasing wavelengths ➔ explanation ???**
- **SCALs/CBB transmission ratios:**
  - **"absolute" SCALs/CBB transmission ratio depending on assumptions made for simulations (uncorrect assumptions ?)**
  - **no clear indication of change in the transmission ratio variation with wavelength where we expect cut-on frequencies of new modes (except maybe around 25 cm^{-1}; cut-on for TE21)**
  - **<u>the smooth features observed are real ones (noise is much lower)</u> and could be due to uncorrect transmission for filters (or beamsplitters) as used in the simulations or to unknown wavelength dependent transmission/efficiency of components not included in simulations**

what about *transmission* in PFM5 ?

- **no more CBB**
- **SCAL2 beam *transmission*** ➔ **see next page**
- **SCAL4 beam *transmission***

  SCAL4 @ 27K measurements exhibit "truncated" interferograms, so no useful data (for this purpose)
- **conclusions:**
  - **note that for PFM5 the "redundant" SCALs units were used**
  - **it seems that the SCAL beam "transmission" depends on the actual location of the SCAL unit inside the beam (see also p. 20)**
  - **is this fact the correct explanation for some change in the derived beam transmission ?**

PFM4/PFM5 SCAL2 beam *transmission* ratio



plot of transmission ratio vs wavenumber
explanation for the slow decrease above 25 cm-1 ???

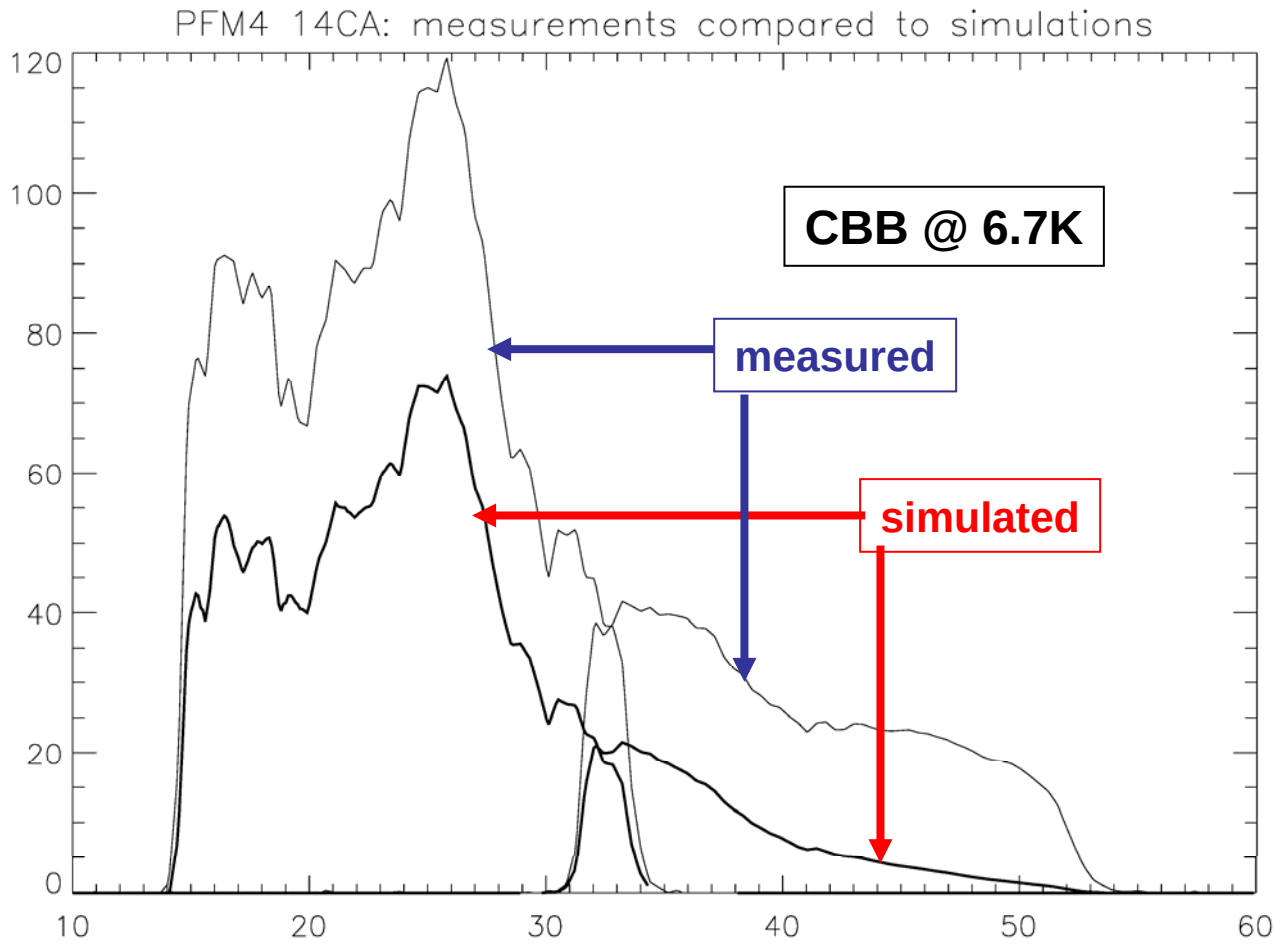
how to simulate measured spectra?

- **make use for each input beam of the measured/simulated ratio as "calibration" factor:**
  - **this factor should remove any departure of the assumed simulation parameters from the "true" ones**
  - **now the ratio (measured) over (simulated) is strictly 1 for the difference spectra seen before, and *should be 1 for any measured spectrum***
- **assumptions:** **(essentially the same as before)**
  - **emissivities: 100% for CBB, 2% for SCAL2 & 4% for SCAL4**
  - **derived transmission for SCAL4 beam used for both SCAL2 & SCAL4**
  - **resulting spectrum is the difference between the CBB and the SCAL inputs (no phase correction applied here)**

➔ **simulation of PFM4 14CA: CBB & SCALs off**

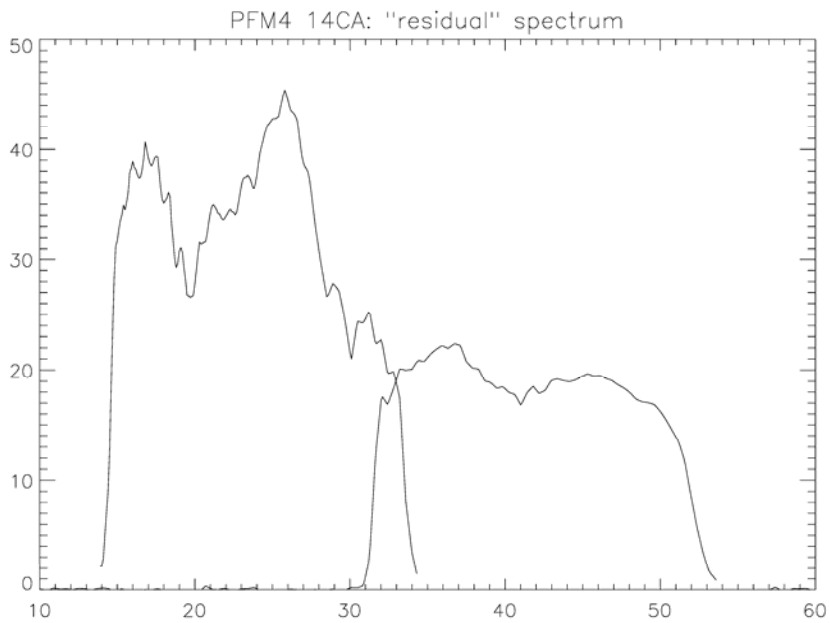
(*i.e. PFM4 measurement with the lowest background*)

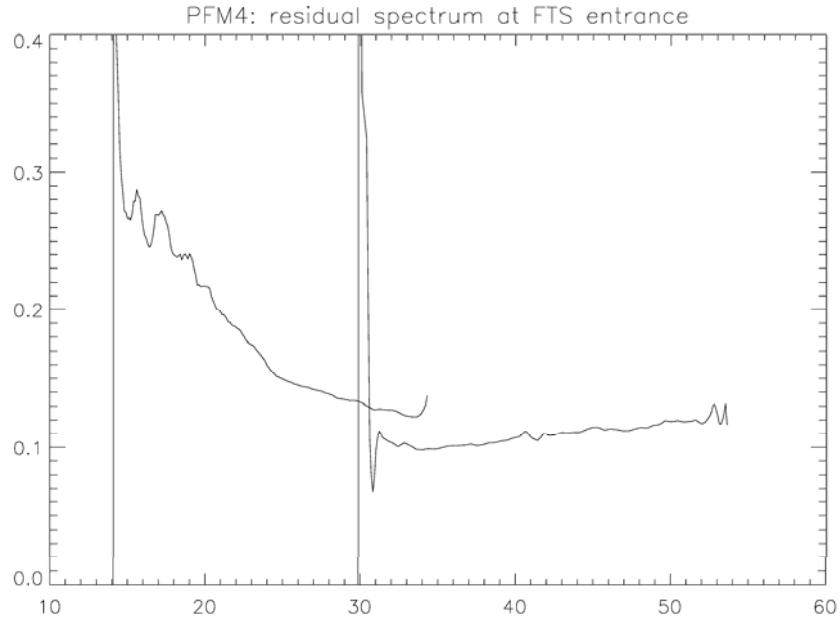
PFM4 14CA: measurements compared to simulations



measured & simulated spectral density vs wavenumber
➔ excess emission measured

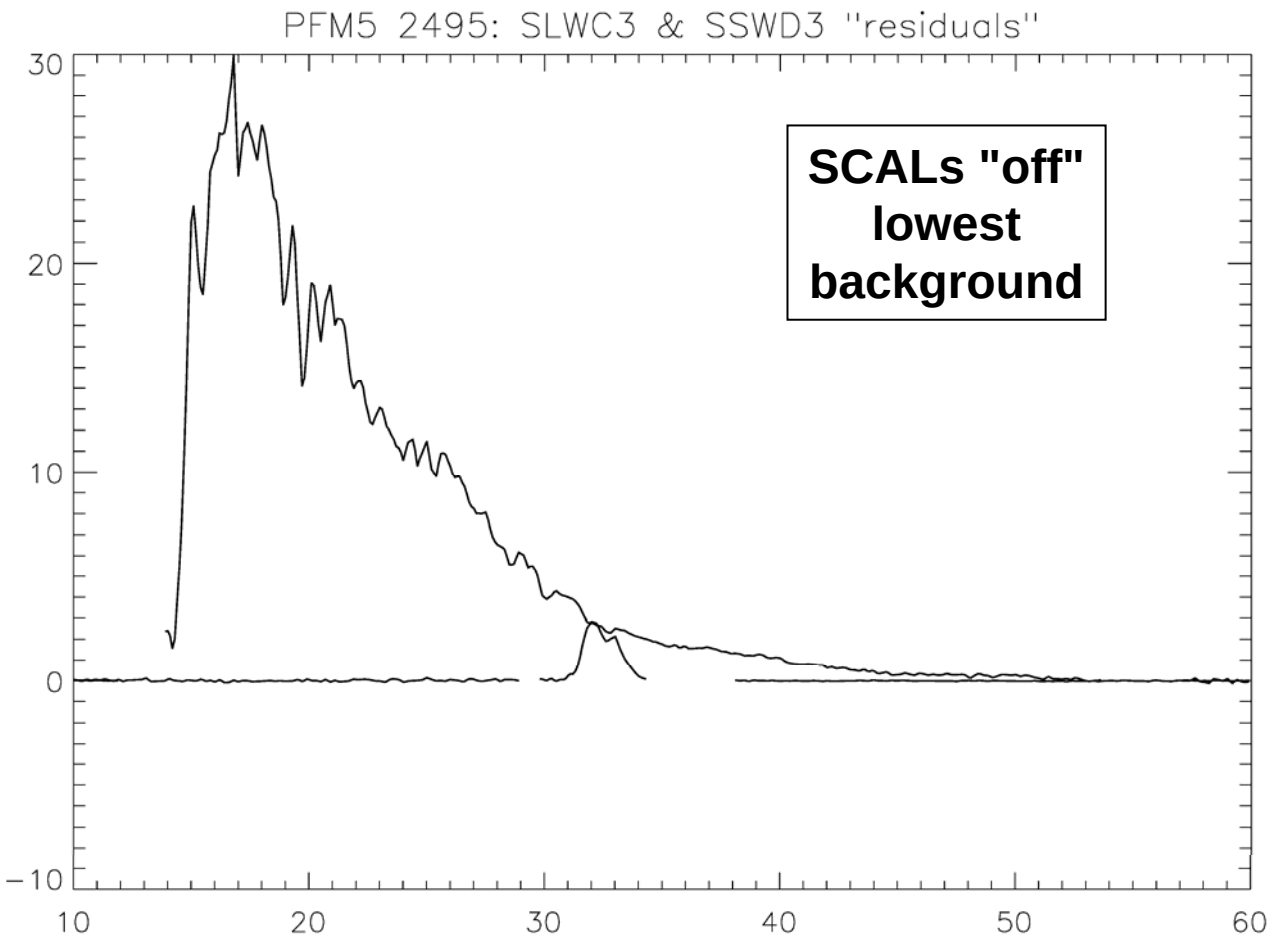
PFM4 14CA: excess measured emission





excess measured (residual) emission spectral density vs wavenumber
left: as effectively measured by detectors (coding unit)
right: residual emission at the FTS entrance (pW/cm^{-1})
➔ either "straylight" emission
or combination of warm (~25K) + cold emission components

PFM5 2495: excess measured emission



excess measured (residual) emission spectral density vs wavenumber

simulations conclusions

- **simulations provide quite good results**
  - **demonstrated for very low signals/backgrounds**
  - **good matching for high signals**
- **warm (straylight or thermal) radiation component seen in PFM4**
  - **no more seen in PFM5**
  - **imply some radiation leaking from outside the SPIRE enclosure**
- **cold radiation component seen in PFM4**
  - **still present in PFM5 but implies that in PFM4 the major part of this radiation is coming from outside the SPIRE enclosure**
  - **the remaining part (seen in PFM5) has certainly an origin within SPIRE box ➔ to be investigated more**
- **simulation improvements**
  - **solve conflict between transmission from CBB & SCAL input beams**
  - **explore field of assumptions to better understand the "residual"**

measured noise performances

noise estimates in measured spectra:

- **spectral noise at each wavenumber is derived from deviation of individual spectra from the average spectrum**
- **a mean rms noise value is derived over each spectral bands**
  SLW 450-670um, SLW 315-450um & SSW 200-315um
- **together with the mean signal to noise achieved in one spectrum over each spectral bands**
- **results for the set of MR scans recorded in Nov. 27th:**
  each run is composed of 16 double-sided scans
  table (next page) gives for each sub- band the measured:
  mean spectral density/mean rms noise/mean SNR
  (in measured spectra units)
  results only for SLWC3 & SSWD3
  nota: no "phase correction" achieved in the data reduction

noise results in SLWC3 & SSWD3 measured spectra

new values after error correction

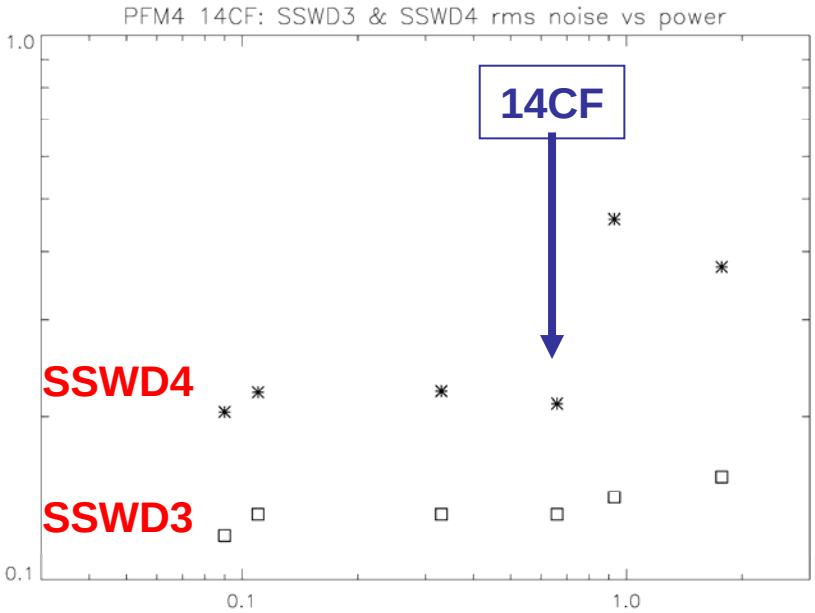
run	SLW 450-670um	SLW 315-450um	SSW 200-315um
14CA	81.6/0.175/466	83.8/0.186/451	7.15/0.121/59
14CF	211/0.441/478	272/0.453/600	24.4/0.132/185
14D7	65.7/0.336/196	66.7/0.266/251	5.47/0.132/41
14DD	28.9/0.151/191	16.1/0.159/101	5.60/0.132/42
14E3	30.7/0.323/95	101/0.345/293	36.4/0.142/256
14EC	85.3/0.522/163	229/0.621/369	76.0/0.155/490

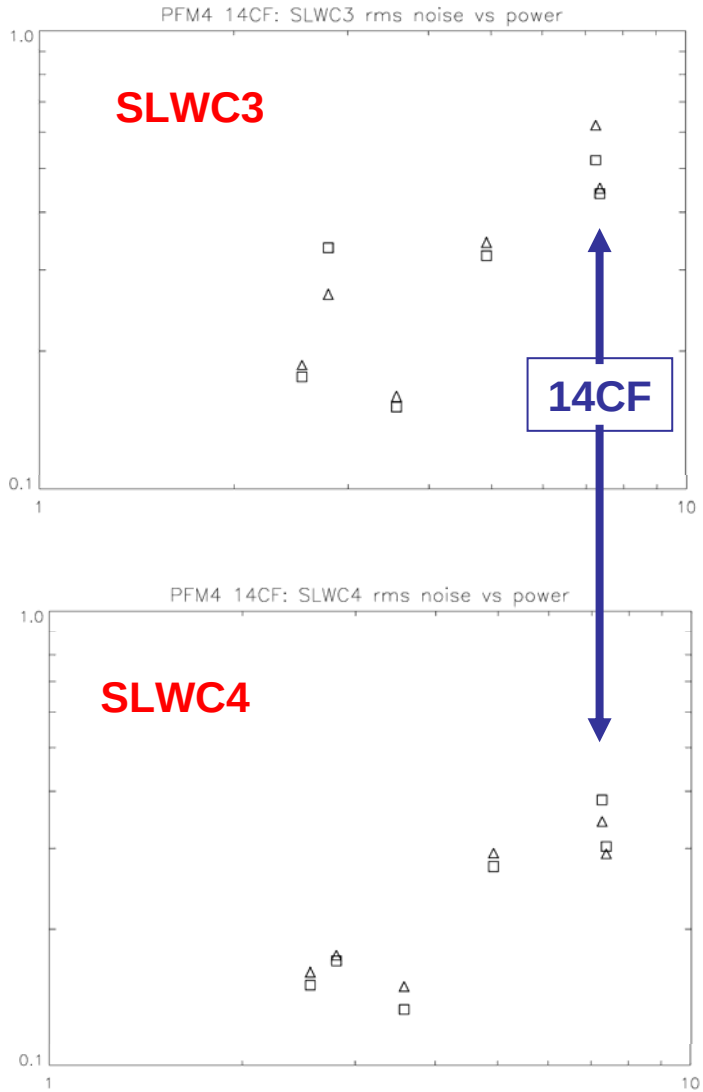
➔ plot of these results vs power falling on the detector next page

this power (in pW) is calculated in my simulations: it may be not representative of the reality as the effective overall FTS transmission is not known, but relative values should be considered correct

together with results for SLWC4 & SSWD4

measured noise vs power on detector





plots of rms noise vs power received by detector

nota: in the <u>right plots</u>, squares & triangles are for the long wavelength and short wavelength parts of the SLW band respectively

in-flight FTS performances

- **make use of measured noise in PFM4 14CF run**
  - **no phase correction (my data reduction)**
  - **after "phase correction" and "optimization" (newly processed data by UoL, see Trevor for more details)**
  - **derive mean SNR in the 3 bands for both results:**

		my values / UoL values	
SLW			
LC3	**450-670µm**	**σ ~ 0.441/0.295**	**<SNR> ~ 478/764**
	315-450µm	**σ ~ 0.453/0.491**	**<SNR> ~ 600/581**
LC4	**450-670µm**	**σ ~ 0.303/0.152**	**<SNR> ~ 649/1390**
	315-450µm	**σ ~ 0.292/0.170**	**<SNR> ~ 890/1658**
SSW			
SD3	**200-315µm**	**σ ~ 0.132/0.136**	**<SNR> ~ 185/192**
SD4	**200-315µm**	**σ ~ 0.211/0.214**	**<SNR> ~ 111/119**

FTS performances derived from simulated spectrum

- derive mean spectral density (pW/cm^{-1}) in the 3 bands
- use telescope area = 7.4 m^2 ➔ pW/m^2.cm^{-1}
- use 1 cm^{-1} = 3 10^{10} Hz ➔ pW/m^2.Hz
- convert in Jy [1 pW/cm^{-1} ➔ 450 Jy]
- noise from 1 MR scan (1 σ in 13 s) to 5 σ in 1 hour: gain = 3.33
- noise from MR to LR scans: gain = 2.5
- noise increase due to photon noise in band: loss = 1.414

  detector power increase from 14CF to in-flight conditions (Ttel = 90K, εtel = 1%): 2.3 for SLW & 13.7 for SSW

- results (5σ, 1hr, LR spectra): model predictions
  - 450-670µm LC3: 290 mJy/ 190 mJy 30 - 40 mJy
    LC4: 220 mJy/ 105 mJy
  - 315-450µm LC3: 140 mJy/ 150 mJy 25 - 35 mJy
    LC4: 100 mJy/ 55mJy
  - 200-315µm SD3: 66 mJy/ 64 mJy 30 - 40 mJy
    SD4: 110 mJy/ 103 mJy

in-flight noise performances: conclusions

- **investigate some more noise aspects deeper**
  - ➔ **still to be done**
- **improve simulations for a better understanding of the FTS as a whole system**
  - ➔ **again a lot to be done**
- **performances derived from PFMs measurements**
  - ➔ **to be performed for all pixels**
- **relatively good agreement with "sensitivity model" predictions**
  - ➔ **presently measurements look a bit more pessimistic**

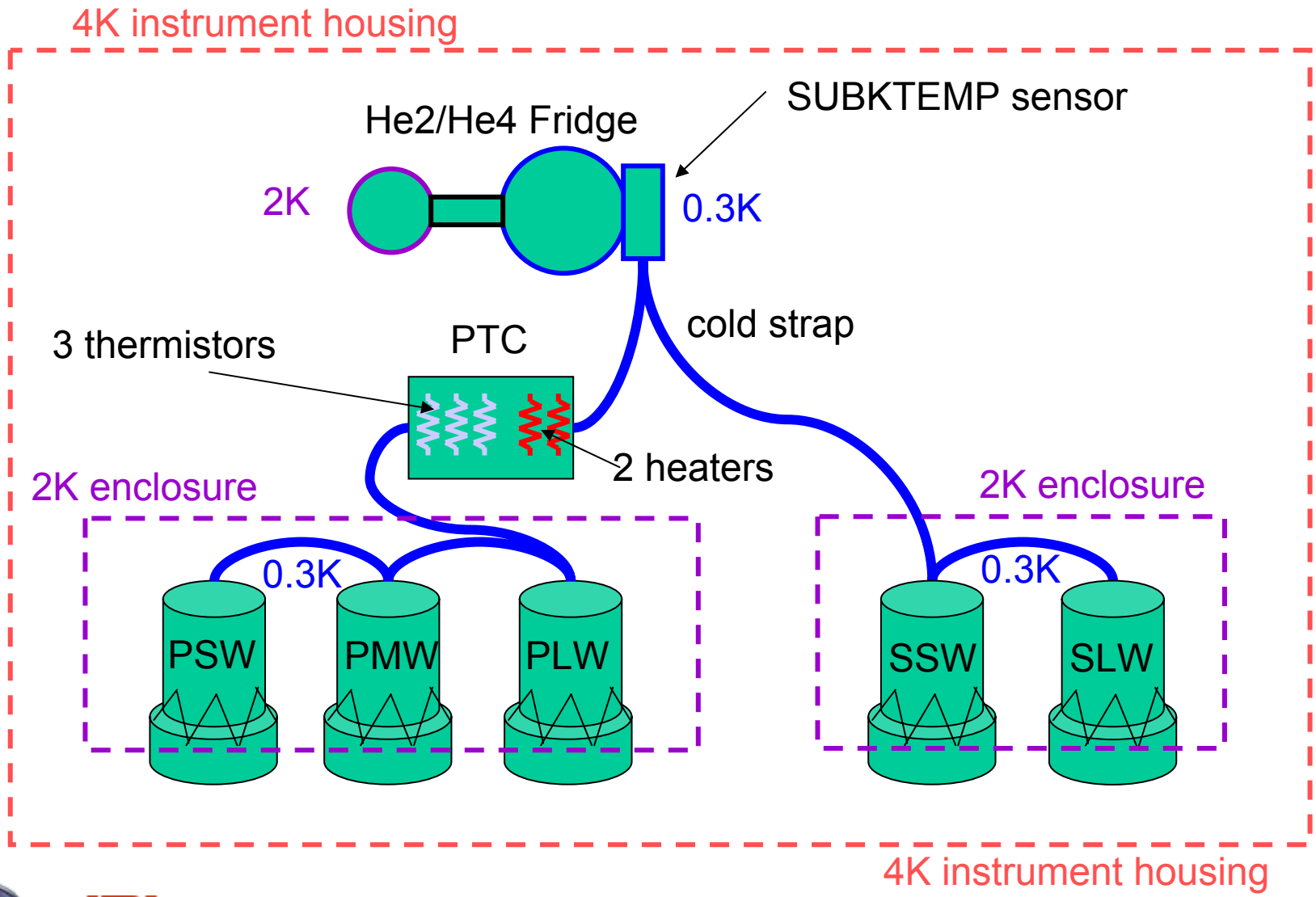
Bolometers in SPIRE*

Bernhard Schulz (NHSC/IPAC)

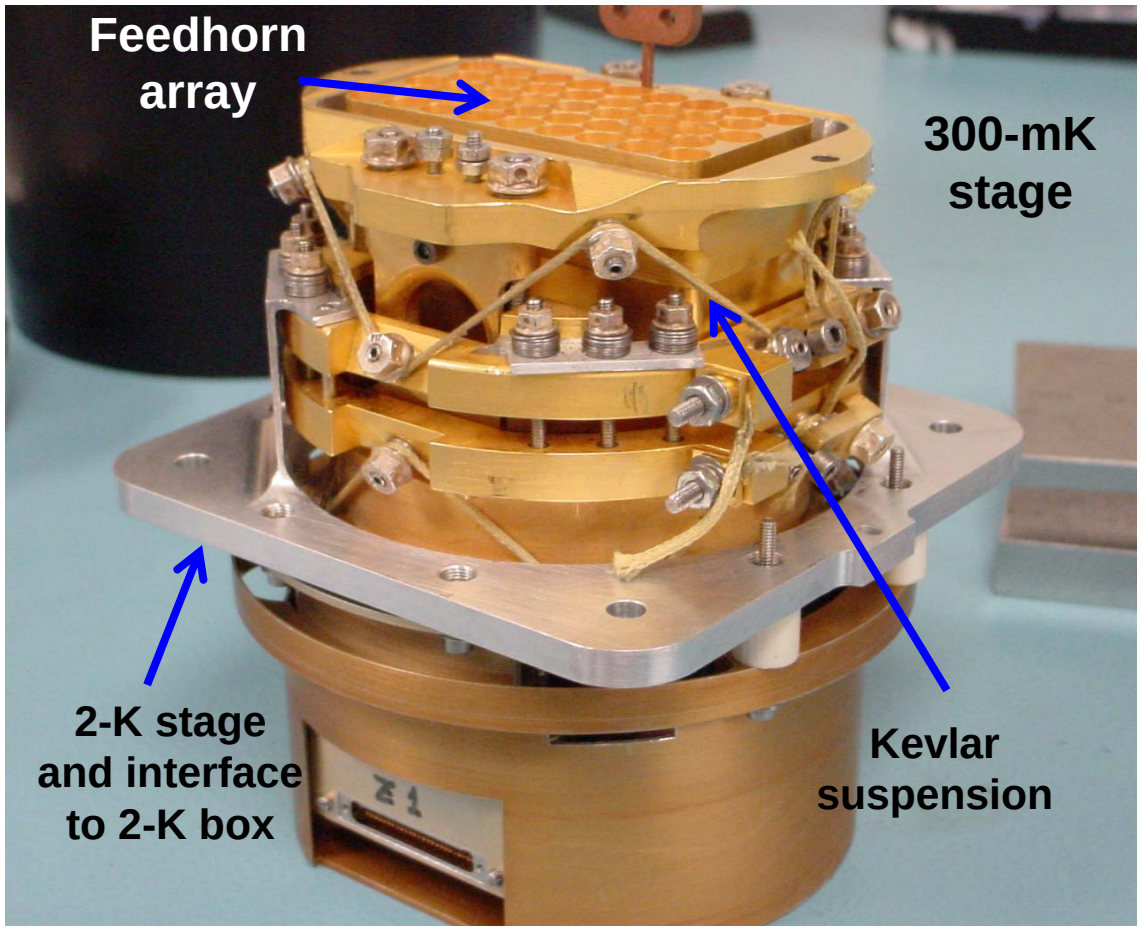
** stealing all the knowledge from*
Jamie Bock, Hien Nguyen, Matt Griffin and many others

15 May 2007

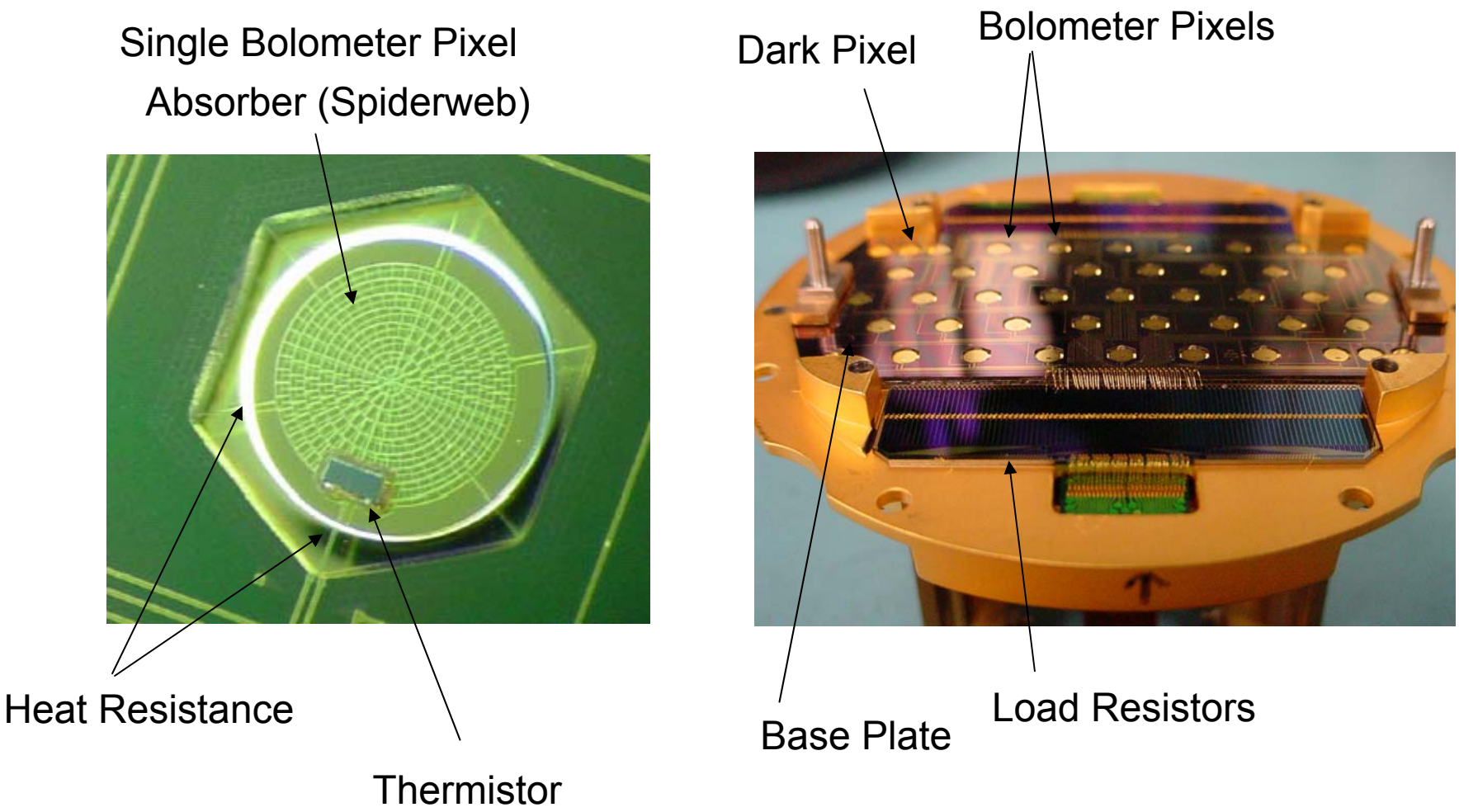
SPIRE Thermal System



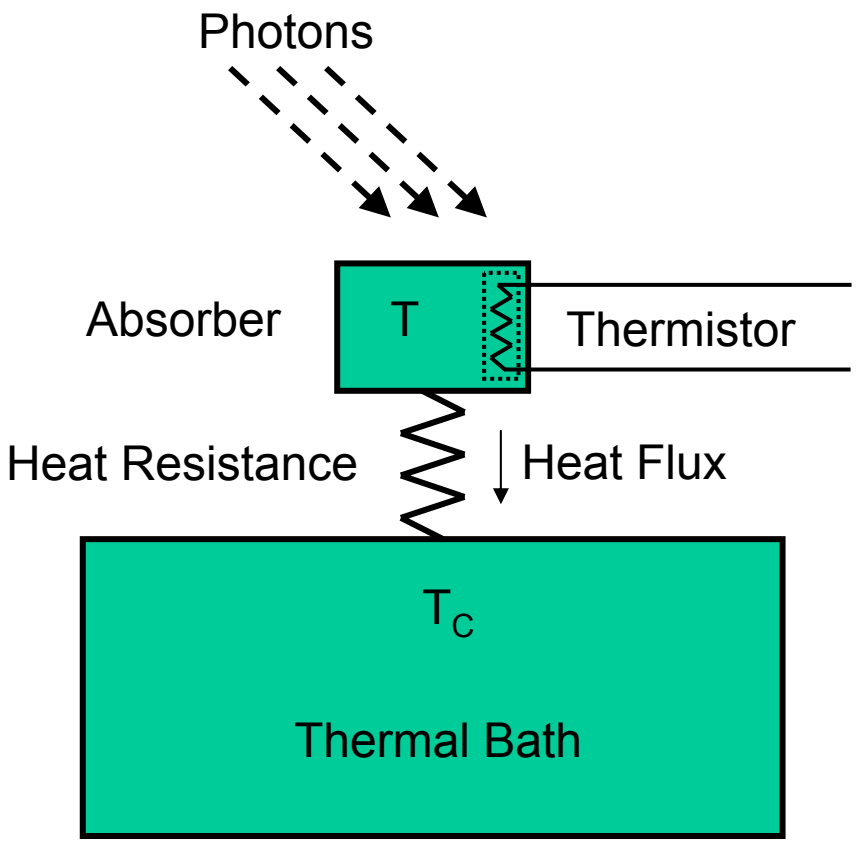
Bolometer Detector Array (BDA)



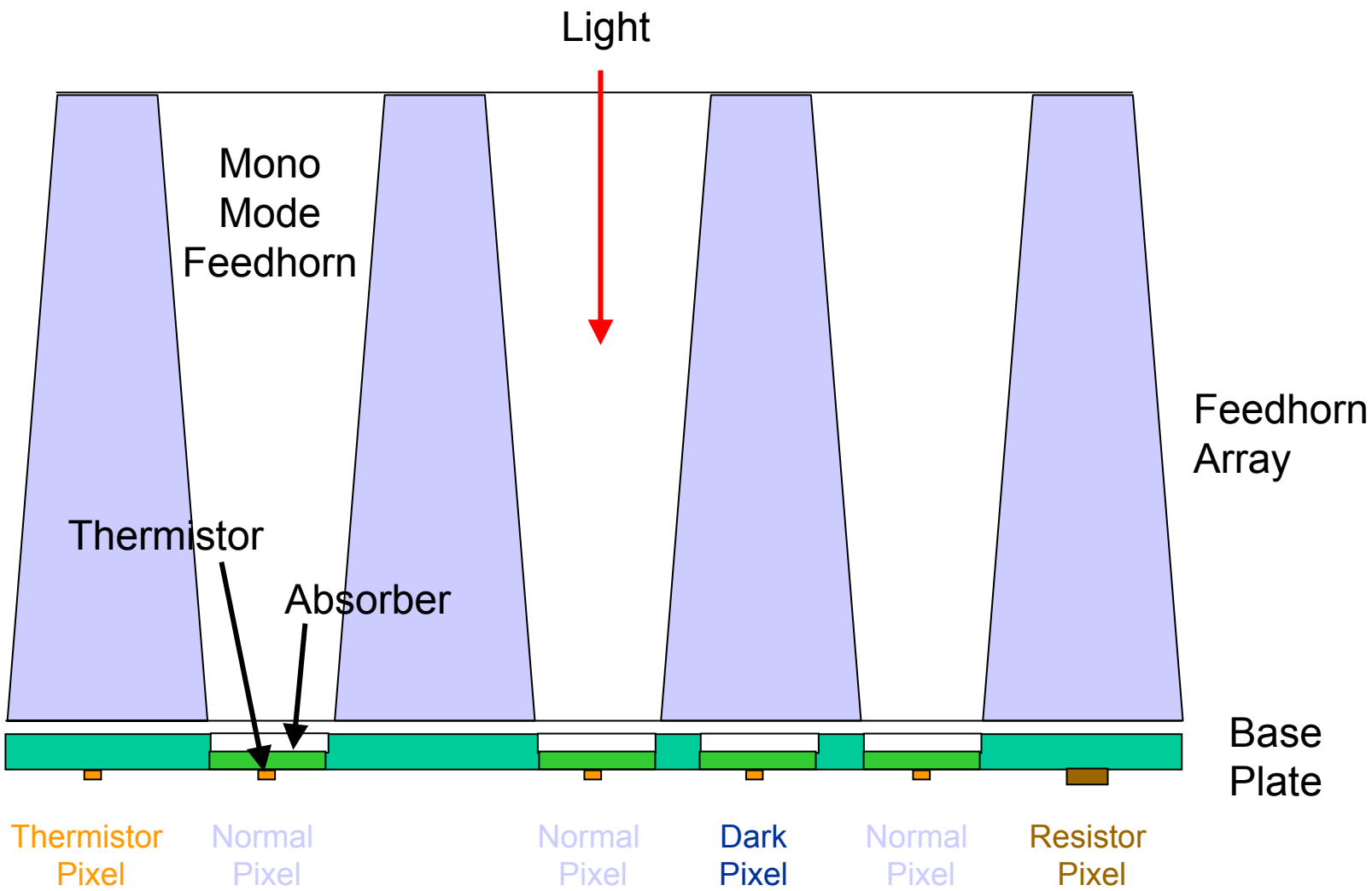
Components in the BDA



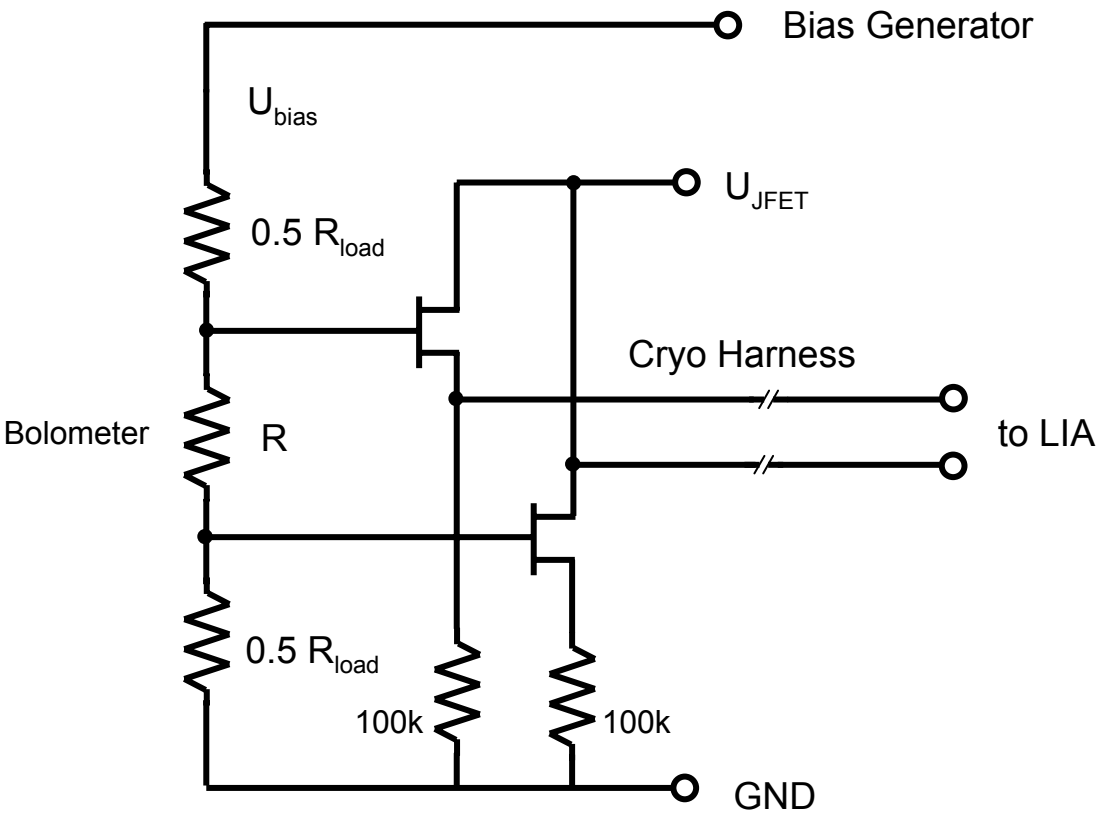
Physical Model



Pixel Variety



Electronic Front End



$$\frac{R}{U} = \frac{R_{load}}{U_{bias} - U}$$

$$R(U) := U \cdot \frac{R_{load}}{(U_{bias} - U)}$$

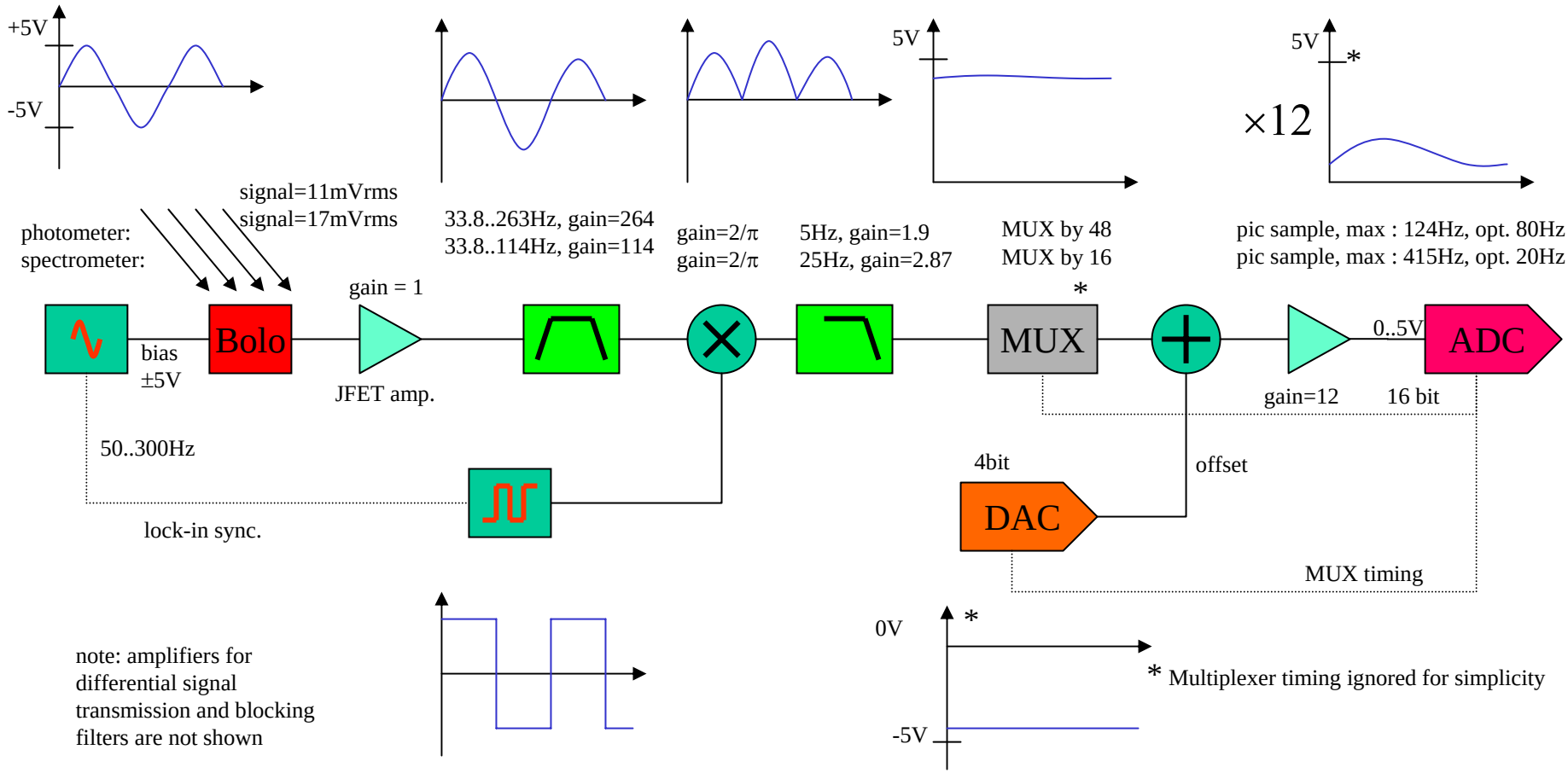
$$I(U) := \frac{(U_{bias} - U)}{R_{load}}$$

$$P_e = R \cdot I^2$$

$$P_e(U) := (U_{bias} - U) \cdot \frac{U}{R_{load}}$$

SPIRE Signal Chain

simplified schematic



note: amplifiers for differential signal transmission and blocking filters are not shown

compiled by B. Schulz (IPAC)
based on SPIRE DCU Design Document
SAp-SPIRE-FP0063-02, 04/03/02

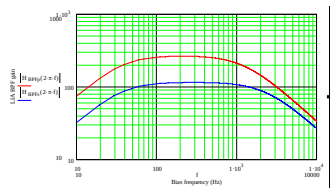
AC Bias Effects

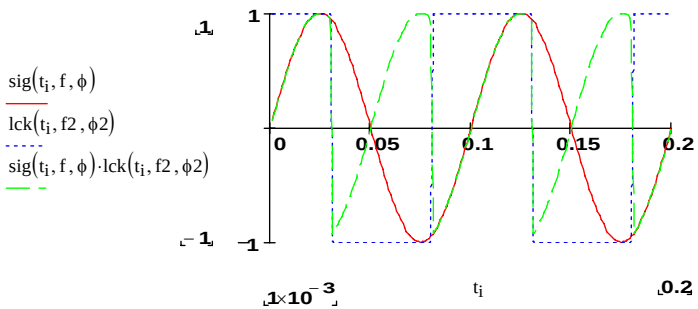
- RC roll-off between bolometer and JFET due to parasitic C
- Bias frequency dependence of LIA bandpass
- Signal loss due to phase shift between bias sine wave and rectangular wave to LIA

$$H_H(\omega) = \frac{1}{1 + j\omega\tau_H} \qquad j = \sqrt{-1} \qquad \tau_H = \left[\frac{R_L R_d}{R_L + R_d}\right] C_H$$

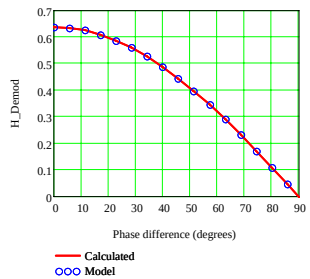
$$|H_H(\omega)| = \frac{1}{\left[1 + (\omega\tau_H)^2\right]^{1/2}}$$

$$H_{BPF}(\omega) = H_o\left[\frac{j\omega\tau_B}{1 + j\omega\tau_B + (j\omega)^2 \tau'_B \tau_B}\right]$$





$$H_{Demod}(\phi) = \left[\frac{2}{\pi}\right]\cos(\phi)$$



Thermometry Basics

$$\frac{R}{U} = \frac{R_{load}}{U_{bias} - U}$$

$$R = U \cdot \frac{R_{load}}{\left(U_{bias} - U\right)}$$

$$P_e = R \cdot I^2$$

$$P_e = \left(U_{bias} - U\right) \cdot \frac{U}{R_{load}}$$

$R_{load} := 20 \cdot M\Omega$ load resistance

$R_0 := 180 \cdot \Omega$

$\Delta := 41.8 \cdot K$

$G_0 := 66 \cdot \frac{pW}{K}$

$\beta := 1.5$

bolometer parameters (examples)

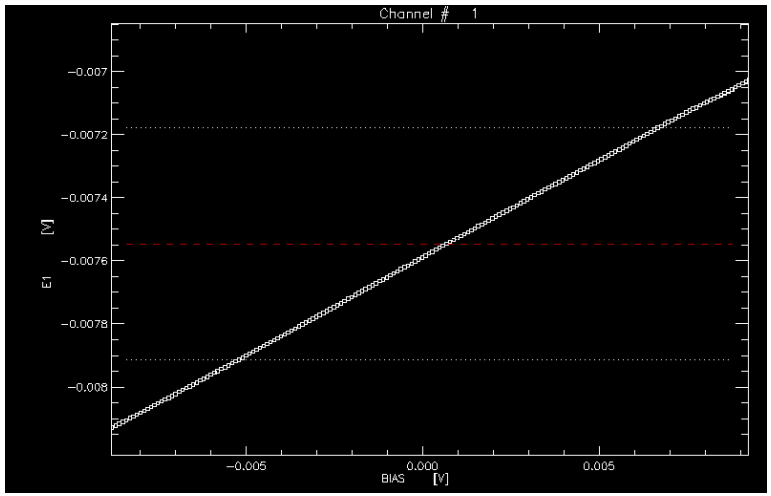
Bolometer Thermometry Ro, Δ

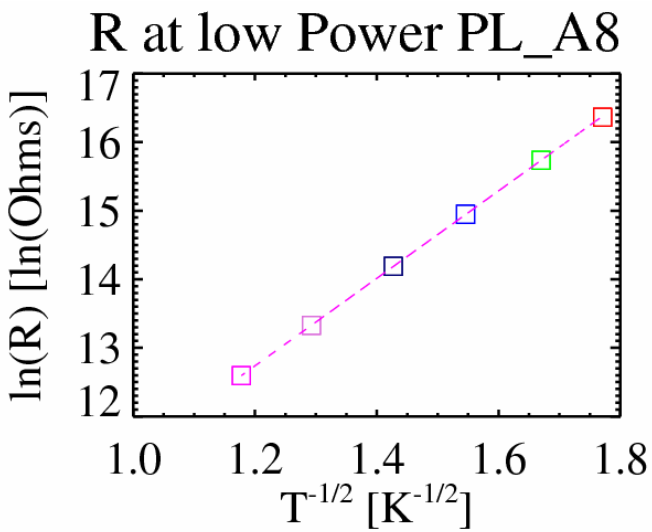
$$R = R_0 \cdot e^{\sqrt{\frac{\Delta}{T}}}$$

$$T = \frac{\Delta}{\ln\left(\frac{R}{R_0}\right)^2}$$

$$T = \frac{\Delta}{\ln\left[U \cdot \frac{R_{load}}{\left(U_{bias} - U\right)} \cdot \frac{1}{R_0}\right]^2}$$

Thermometry: R_0, Δ





- Calibrate thermistor with dark load curves at several known bath temperatures
- Need only small bit around zero bias so that $P_{el} \approx 0$
- Determine bolometer resistance at zero bias from slope to avoid electr. offsets
- Determine first two parameters R_0 and Δ from line fit to ln(R) and $T^{-1/2}$

Heat Conductance: G_0, β

For those who want to know

$$G = G_0 \cdot \left(\frac{T}{T_0}\right)^{\beta} \qquad dP = G(T) \cdot dT$$

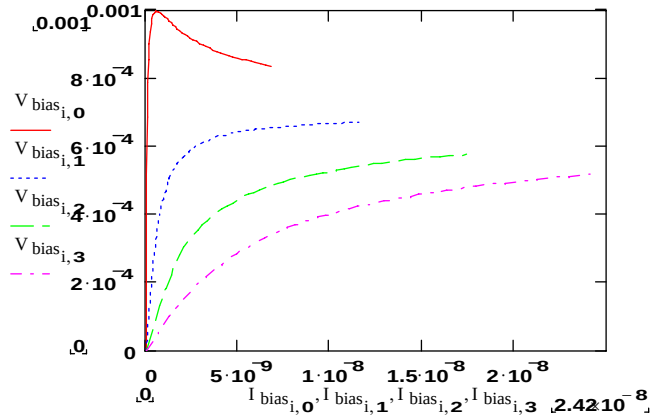
$$P = \int_{T_c}^{T} G(T)\, dT$$

$$P = \int_{T_c}^{T} G_0 \cdot \left(\frac{T}{T_0}\right)^{\beta} dT$$

$$P = \left(\frac{T}{T_0}\right)^{(\beta+1)} \cdot \frac{T_0}{(\beta+1)} \cdot G_0 - \left(\frac{T_c}{T_0}\right)^{(\beta+1)} \cdot \frac{T_0}{(\beta+1)} \cdot G_0$$

$Q = P - P_{el}$ Optical Power

$$Q = \frac{T_0 \cdot G_0}{\beta + 1} \cdot \left[\left(\frac{T}{T_0}\right)^{\beta+1} - \left(\frac{T_c}{T_0}\right)^{\beta+1} \right] - P_{el}$$

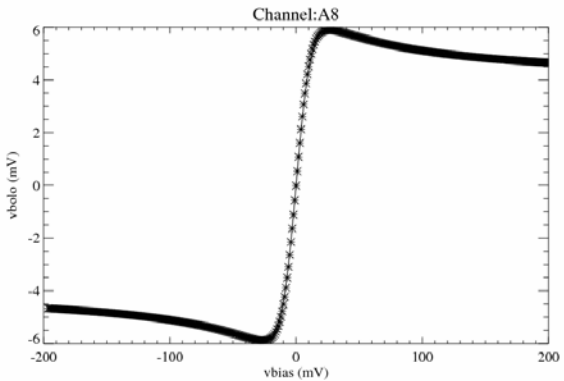


Determine second two parameters with non-linear fit to full dark load curves where Q=0

Example:

$G_0 := 66 \cdot \frac{pW}{K}$

$\beta := 1.5$



$T_0 := 0.3 \cdot K$ fixed reference temperature

$T_C := 0.3 \cdot K$ actual bath temperature

T = bolometer temperature

Responsivity

$$A = -\frac{1}{2}\cdot\sqrt{\frac{\Delta}{T}}$$

$$Z = \frac{\frac{G\cdot T}{-A\cdot P} - 1}{\frac{G\cdot T}{-A\cdot P} + 1}\cdot R$$

Impedance

$$S_{DC} = \frac{1}{2}\cdot\sqrt{\frac{R}{P}}\cdot\frac{1 - \frac{Z}{R}}{1 + \frac{Z}{R_{load}}}$$

Responsivity

SPIRE Detector Noise Performance in PFM5 Test Campaign

(A Progress Report)

Nanyao Lu (NHSC/IPAC)

with contributions from B. Schulz, C. K. Xu (NHSC/IPAC)
and inputs from J. Bock and H. Nguyen (JPL)

Noise Data Considered from PFM5 Tests

Photometer:

OBSID	T_{sub}(K)	f_{bias}(Hz)	V_{bias}(peak)(mV)
02/13/2007 (noises with phase-up):			
30012150	0.286	80.37	0-86 (12 values)
30012151	0.286	110.35	0-86 (12)
30012152	0.286	131.08	0-86 (12)
30012153	0.286	171.33	0-86 (12)
02/19/2007 (noises with phase-up):			
3001226D	0.297	80.37	3-86 (11)
3001226E	0.297	110.35	3-86 (11)
3001226F	0.297	131.08	3-86 (11)
30012270	0.297	171.32	3-86 (11)
30012271	0.297	201.35	3-86 (11)

==> 103 points in the parameter space of (T_{sub}, f_{bias}, V_{bias})

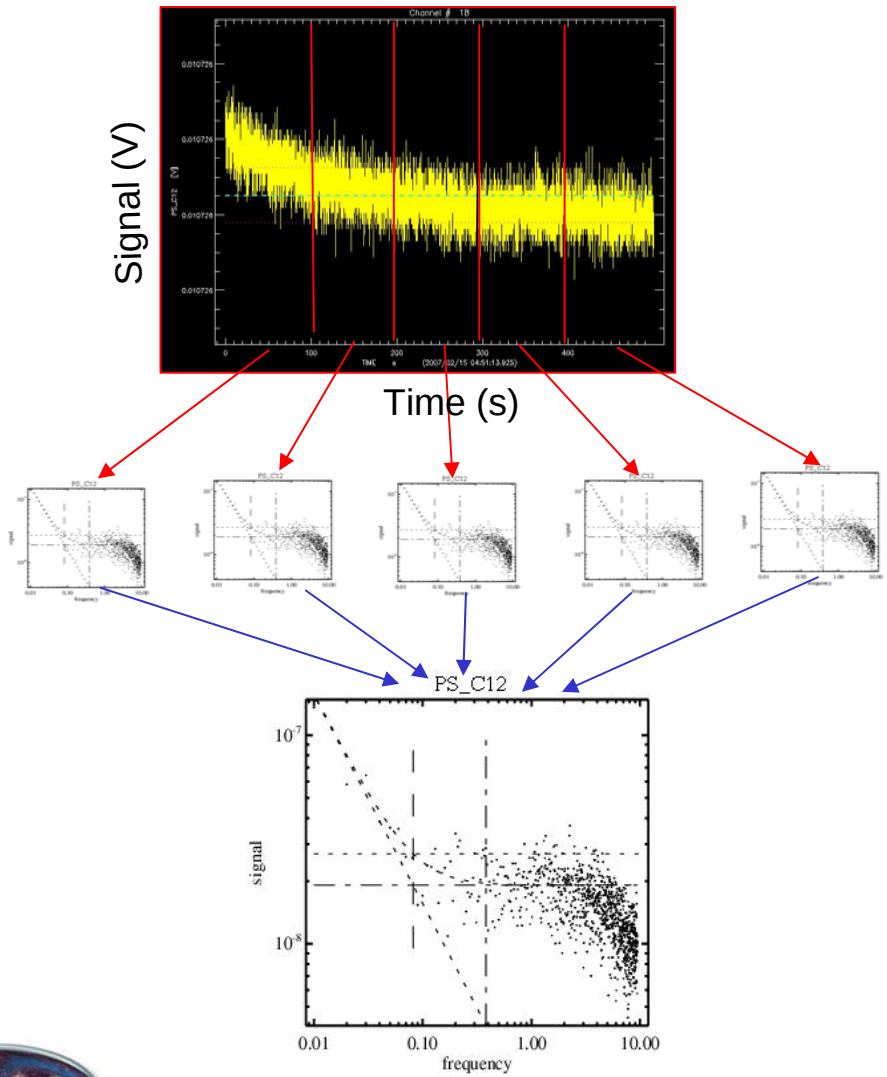
Spectrometer:

OBSID	T_{sub}(K)	f_{bias}(Hz)	V_{bias}(peak)(mV)
02/17/2006 (Noise with phase-up):			
3001223C	0.286	100.68	4.8-171.5 (11 values)
3001223D	0.286	161.42	4.8-128.6 (10)
3001223E	0.286	212.29	4.8-171.5 (11)
3001223F	0.286	275.09	4.8-171.5 (11)
30012240	0.286	305.17	4.84-40.1 (5)
02/17/2007 (noises with phase-up):			
30012242	0.295	100.68	4.84-171.5 (11)
30012243	0.295	161.42	4.84-128.6 (10)
30012244	0.297	212.29	4.84-171.5 (11)
30012245	0.297	275.09	4.84-103.1 (9)
02/21/2007 (dark load curves):			
300122C6	0.2975	100.67	4.8-171.5 (11)
300122C7	0.2973	161.42	4.8-128.6 (10)
300122C8	0.2972	212.29	4.8-171.5 (11)
300122C9	0.2971	275.09	4.8-103.1 (9)
300122CA	0.2970	305.17	4.8-63.0 (7)

==> 96 independent points in the parameter space of (T_{sub}, f_{bias}, V_{bias})

Data Analysis

- IDL-based bolometer analysis software (Zhang & Schulz 2004)
- Detector signals with HK data downloaded per OBSID, deglitched and were further divided into segments per (T_{sub}, f_{bias}, V_{bias}). Each about 500sec in time.
- FFT on sub-segments of 100sec long. Resulting power spectra were added quadratically together.
- Power spectra, 1/f-noise knee frequency and mean plateau noise are derived for each (T_{sub}, f_{bias}, V_{bias}).
- Plateau noises are examined against temperature drifts, frequency features, and model predictions.



Inactive and Noisy Channels

PFM5

Photometer

Dead or non-operational channels:

- PSW: A10, C12, F8, G8.
- PMW: C8, T2, G11, G9, B6, F7.
- PLW: None.

Very noisy channels:

- PSW: J7, G11,
- PS_G11;
- PL_A6.

Spectrometer

Dead or non-operational channels:

- SSW: D5.
- SLW: C2, B3, DK2.

Very noisy channels:

- SS_F4.

PFM4

Photometer

Dead or non-operational channels:

- PSW: A10, C12, F8, G8, B3, J6.
- PMW: C8, T2, G11, G9, B6, DK1.
- PLW: A2, DK1.

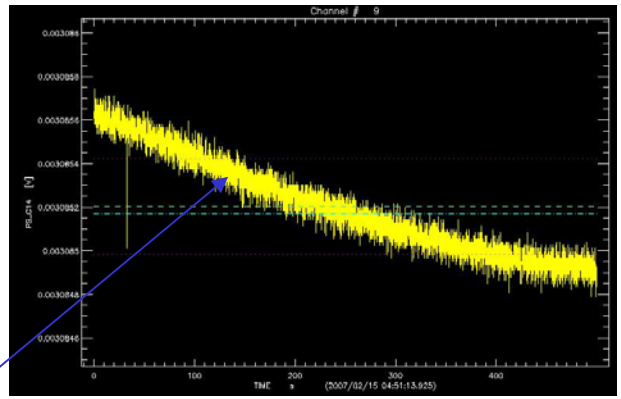
Spectrometer

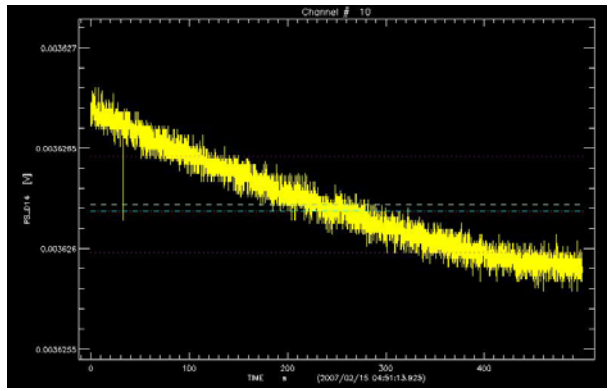
Dead or non-operational channels:

- SSW: D5, D7.
- SLW: C2, B3, DK2.

Examples of Good Test Data

30012153_06 (T_{sub}=286mK, f_{bias}= 171.3Hz, V_{bias}= 20mV)

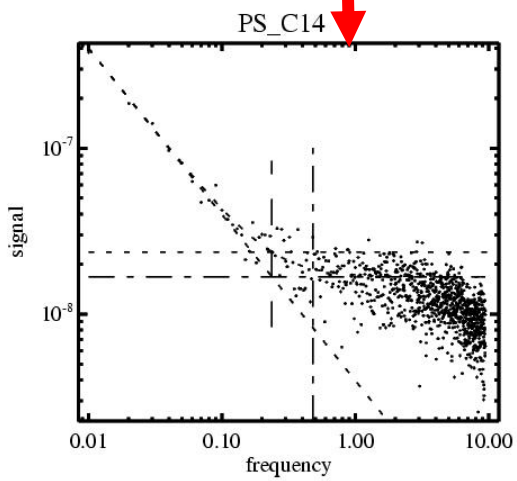


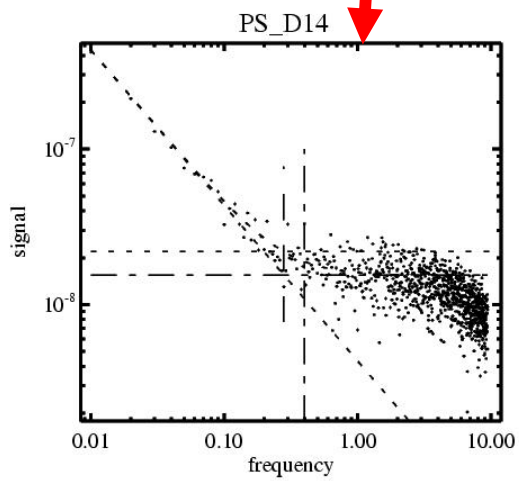


Drift ~ 0.02%

FFT

FFT



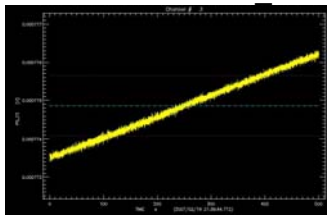


Temperature Drifts

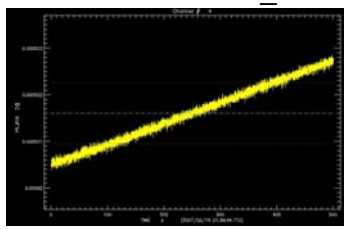
3001226E_02 (T_{sub}=297mK, f_{bias}= 110.35Hz, V_{bias}= 7mV)

Drift ~ 0.5%

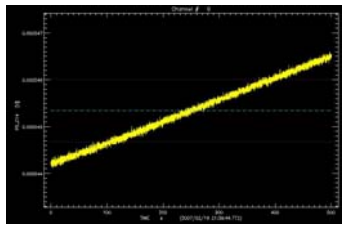
PS_T1



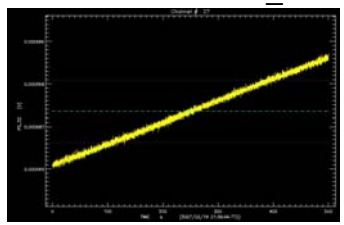
PS_B16



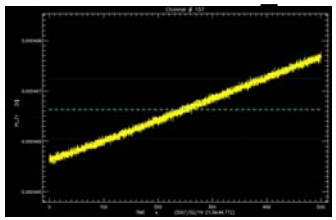
PS_C14



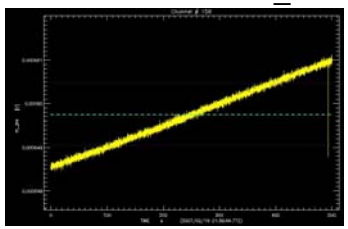
PS_T2



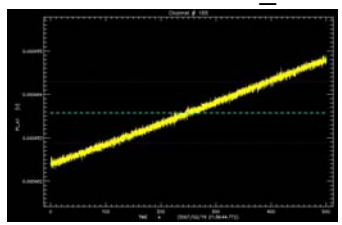
PL_T1



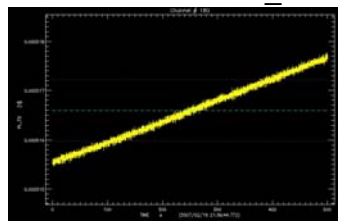
PL_B4



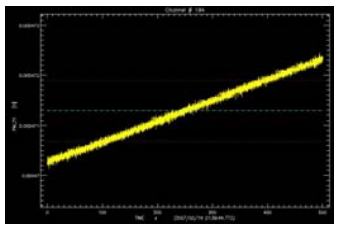
PL_A1



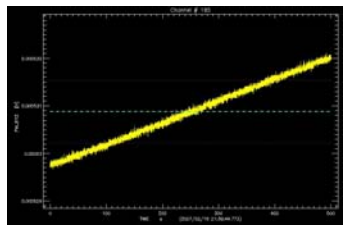
PL_T2



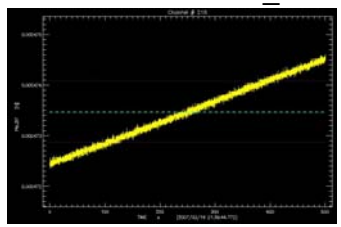
PM_T1



PM_B12



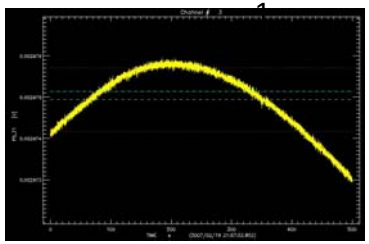
PM_B7



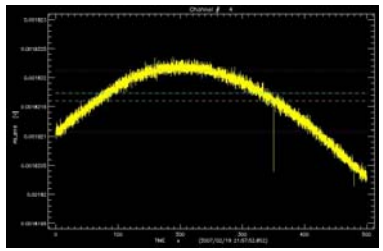
Temperature Drifts

3001226E_04 (T_{sub}=297mK, f_{bias}= 110.35Hz, V_{bias}= 15.5mV)

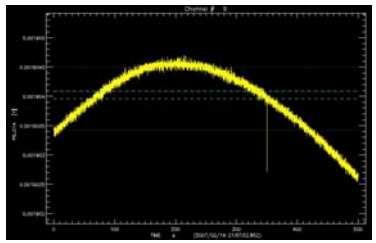
PS_T



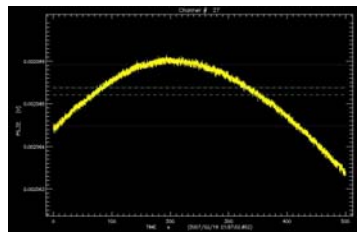
PS_B16



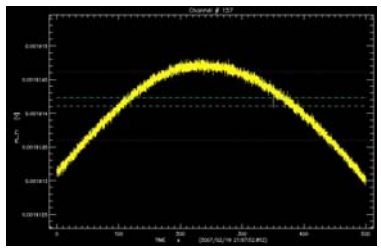
PS_C14



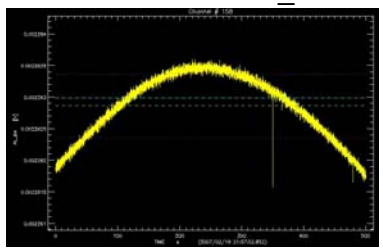
PS_T2



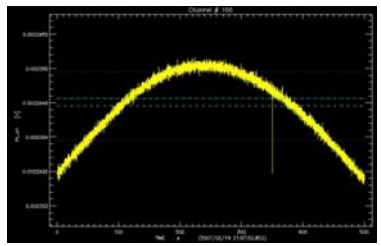
PL_T1



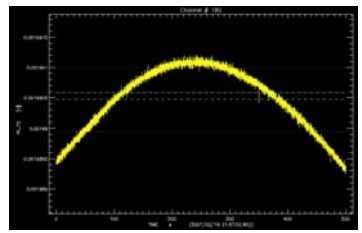
PL_B4



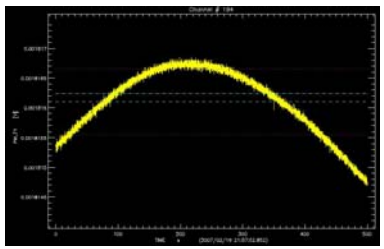
PL_A1



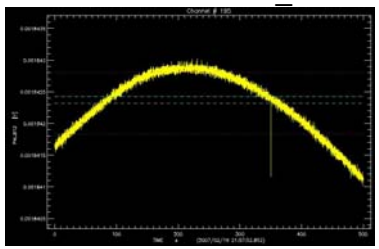
PL_T2



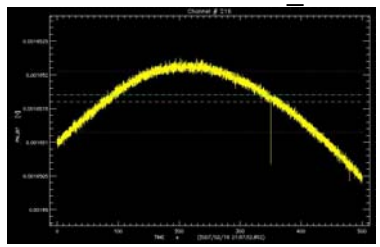
PM_T1



PM_B12



PM_B7

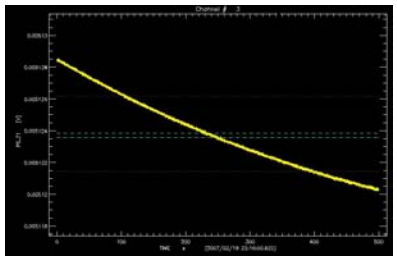


Drift ~ 0.1%

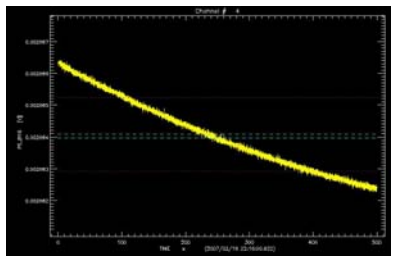
Temperature Drifts

3001226E_06 (T_{sub}=297mK, f_{bias}= 110.35Hz, V_{bias}= 25.5mV)

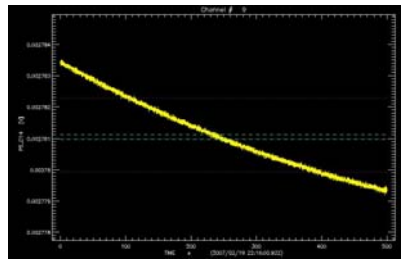
PS_T



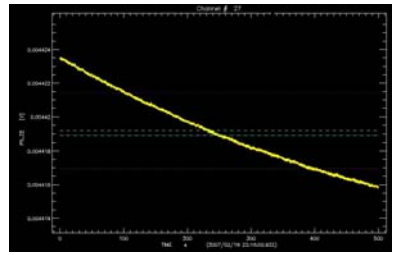
PS_B16



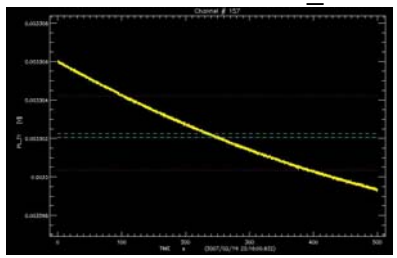
PS_C14



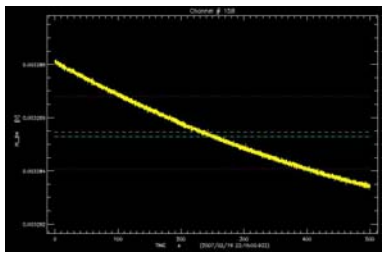
PS_T



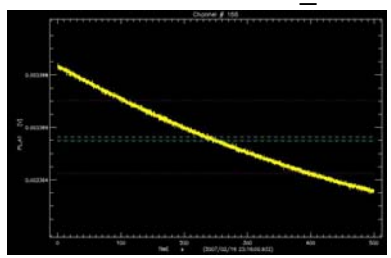
PL_T1



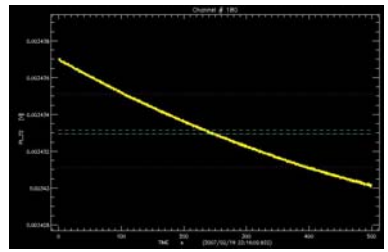
PL_B4



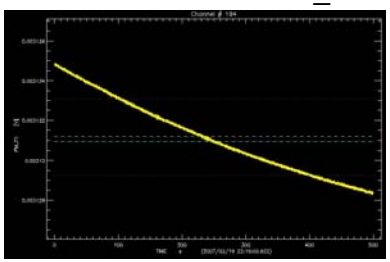
PL_A1



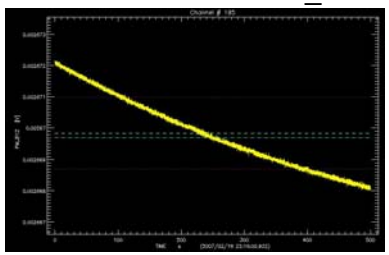
PL_T2



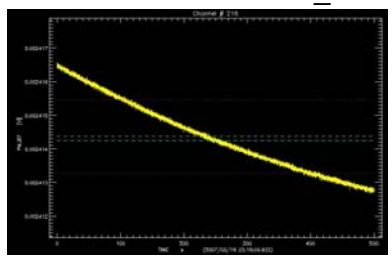
PM_T1



PM_B12



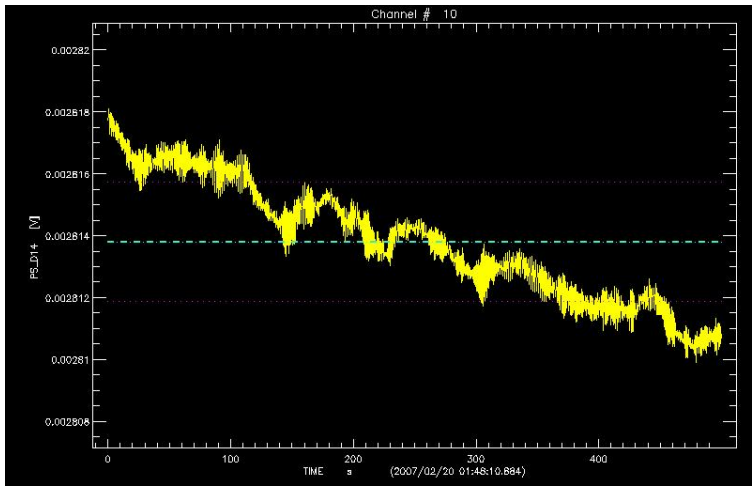
PM_B7

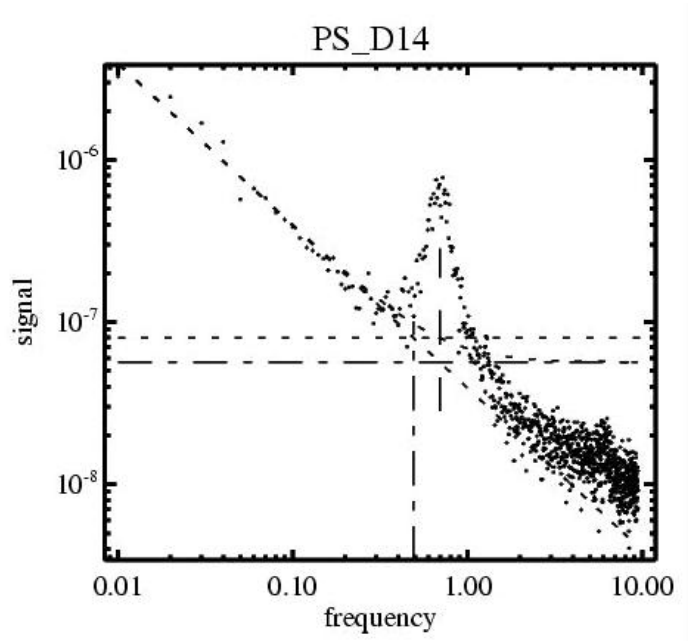


Drift ~ 0.2%

Frequency Features

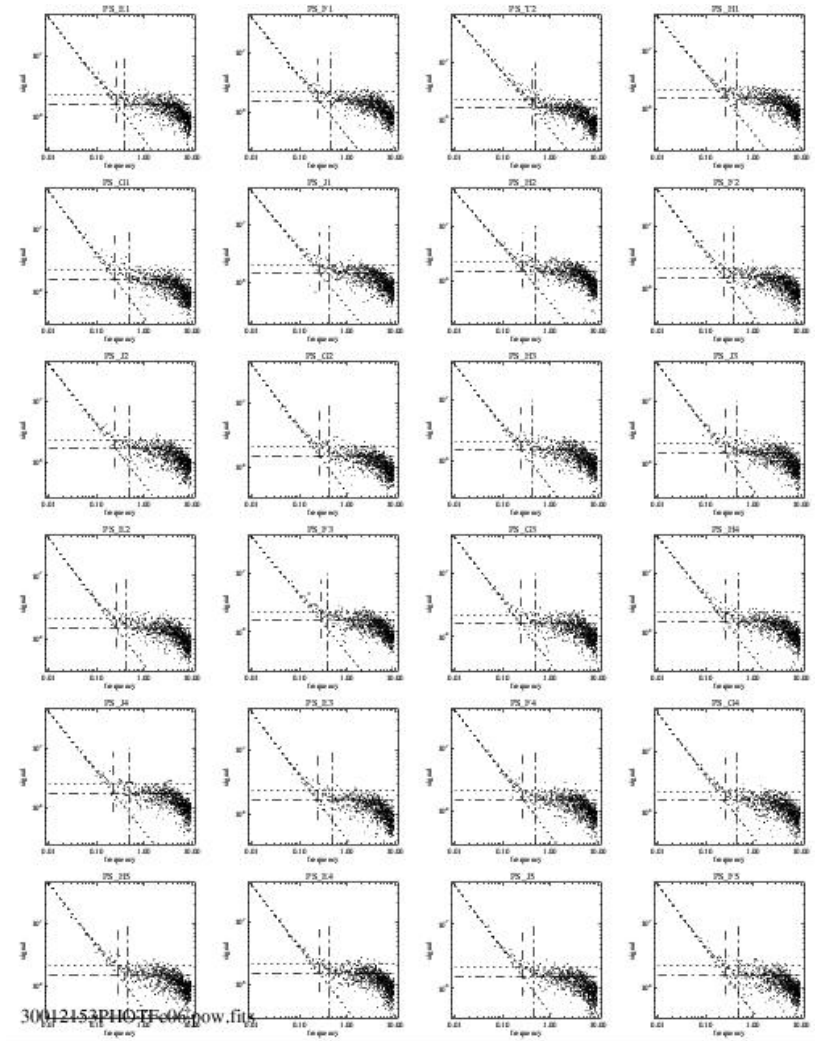
PS_D14





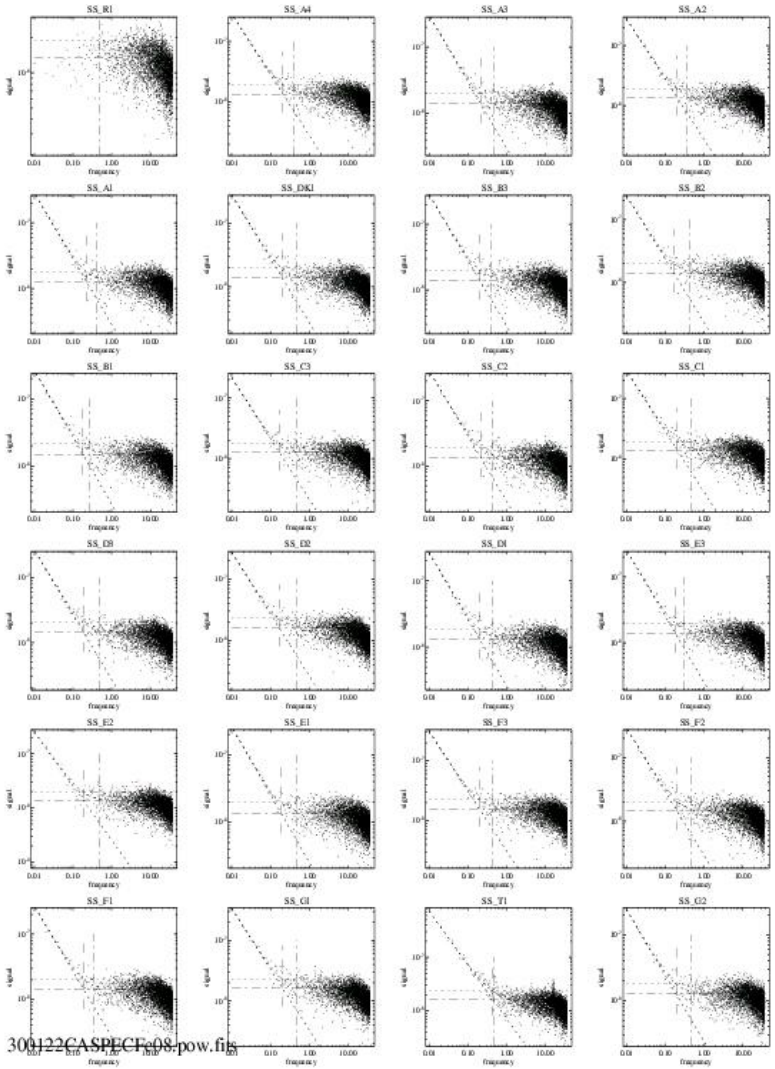
Power Spectra of Photometer

Photometer:
OBSID=30012153;
T_{sub} = 286mK;
f_{bias} = 171.33 Hz;
V_{bias} (peak) = 20mV.



Power Spectra of Spectrometer

Spectrometer:
OBSID=300122CA;
T_{sub} = 297mK;
f_{bias} = 305.17 Hz;
V_{bias} (peak) = 63 mV.



300122CASPECFe08.pow.fits

Power Spectra of Photometer

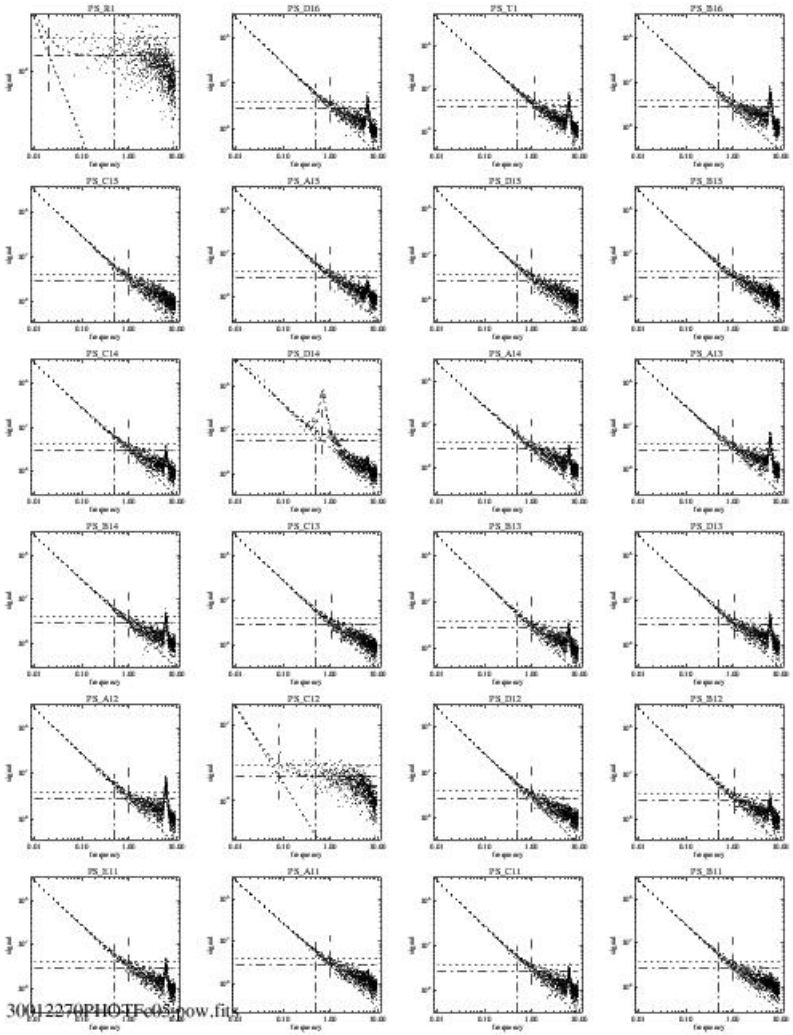
Photometer:

OBSID=30012271;

T_{sub} = 297mK;

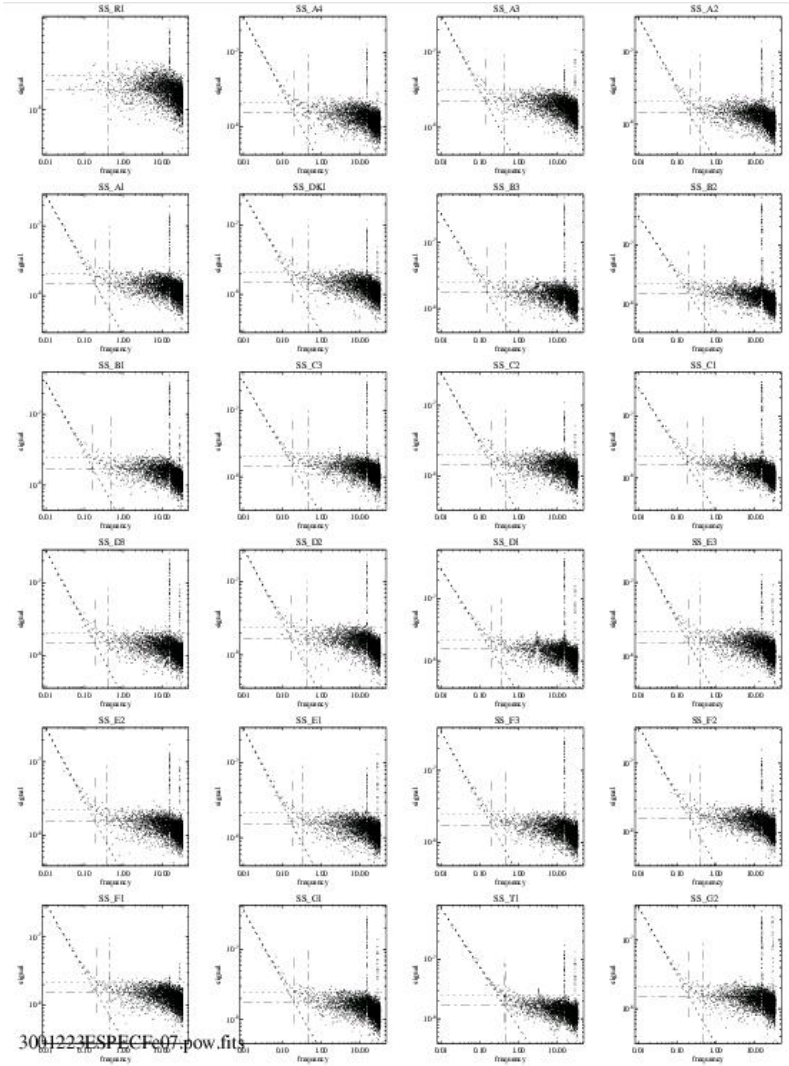
f_{bias} = 171.33 Hz;

V_{bias} (peak) = 20mV.



Power Spectra of Spectrometer

Spectrometer:
OBSID=3001223E;
T_{sub} = 286mK;
f_{bias} = 212.29 Hz;
V_{bias} (peak) = 63 mV.



Detector Noises: Model Predictions

- EIDP simulation from Mather dark model, including noises from detectors and amplifier.
- Inputs: rms bias voltage v_{bias} and the baseplate temperature T_0 for each detector sub-array.
- T_0 is taken as the median temperature of thermister (T1 or T2), derived from the measured resistance.
- The model predicts noise and responsivity (thus NEP) per channel.

Calculated thermister temperatures

Photometer (OBSID=30012150, T_{sub}=286mK, f_{bias}=80.37Hz)

-- Peak Bias Voltage (mV) --			Inferred baseplate temperatures (K)				
PSW	PMW	PLW	PS_T1	PS_T2	PM_T1	PL_T1	PL_T2
0.0000	0.0000	0.0000	...	...	...	...	...
3.0074	3.0265	3.0390	0.330	0.330	0.326	0.326	0.326
7.0172	7.0618	7.0911	0.330	0.330	0.326	0.326	0.326
11.5282	11.6015	11.6496	0.331	0.330	0.326	0.326	0.326
15.5380	15.6368	15.7017	0.331	0.330	0.326	0.326	0.326
20.0491	20.1765	20.2602	0.331	0.331	0.327	0.326	0.326
25.5626	25.7250	25.8318	0.332	0.331	0.327	0.327	0.327
31.5773	31.7780	31.9099	0.332	0.332	0.327	0.327	0.327
40.0982	40.3530	40.5205	0.333	0.332	0.327	0.327	0.327
51.6264	51.9544	52.1701	0.345	0.333	0.328	0.328	0.328
64.1571	64.5647	64.8328	0.366	0.350	0.329	0.329	0.329
85.7098	86.2545	86.6125	0.393	0.377	0.340	0.352	0.359

Spectrometer (OBSID=300123C, T_{sub}=286mK, f_{bias}=100.68Hz)

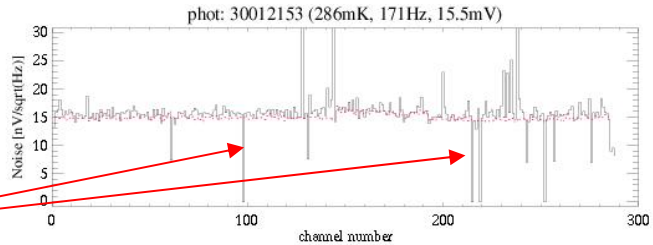
Peak Bias Voltage (mV)		Inferred baseplate temperatures (K)			
SSW	SLW	SS_T1	SS_T2	SL_T1	SL_T2
4.8419	4.8428	0.296	0.296	0.300	0.295
14.5258	14.5285	0.296	0.297	0.301	0.296
22.8263	22.8304	0.297	0.298	0.302	0.296
31.1268	31.1324	0.297	0.299	0.303	0.296
40.1189	40.1262	0.298	0.300	0.304	0.297
51.1862	51.1955	0.299	0.301	0.306	0.297
62.9452	62.9566	0.301	0.308	0.325	0.298
80.2379	80.2524	0.321	0.330	0.349	0.299
103.0642	103.0828	0.338	0.352	0.373	0.301
128.6573	128.6806	0.355	0.372	0.394	0.312
171.5431	171.5741	0.378	0.398	0.423	0.330

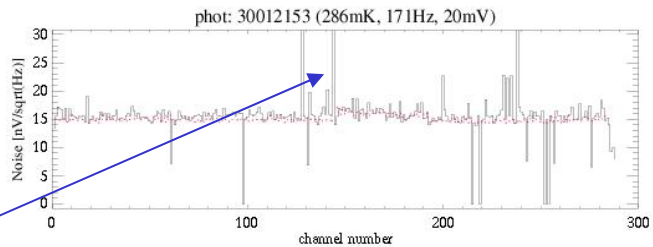
Photometer Noises: Measurements vs. Model

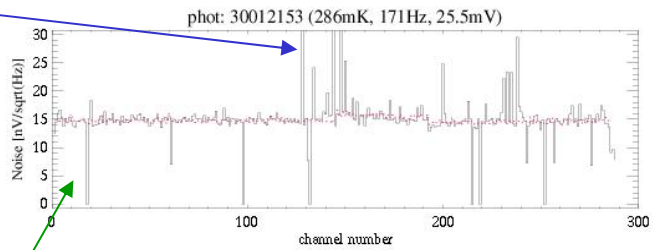
inactive channels

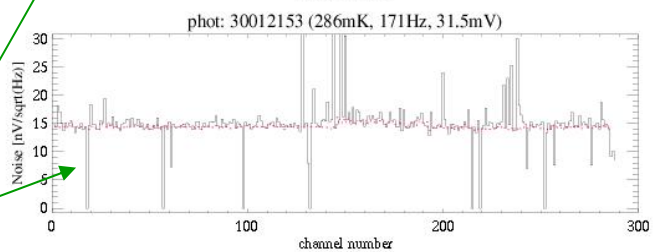
noisy channels

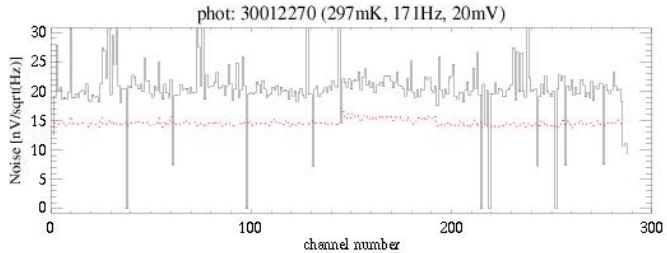
No data

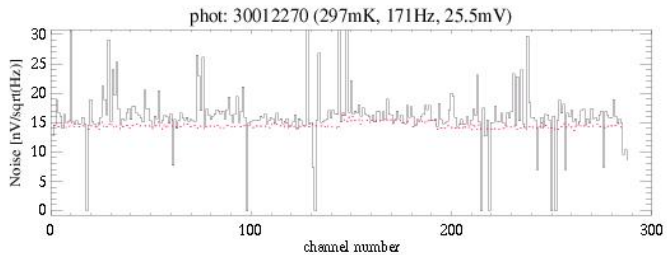


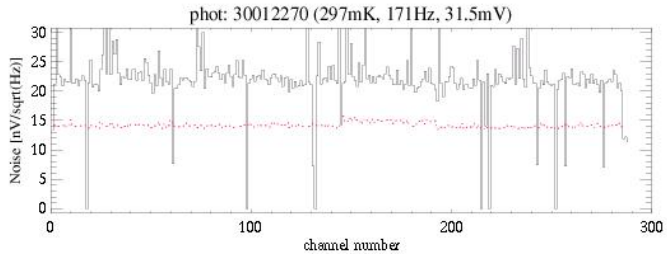


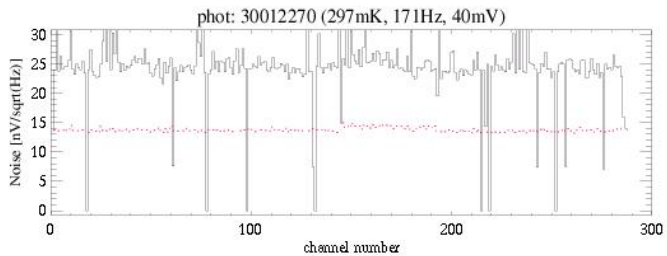




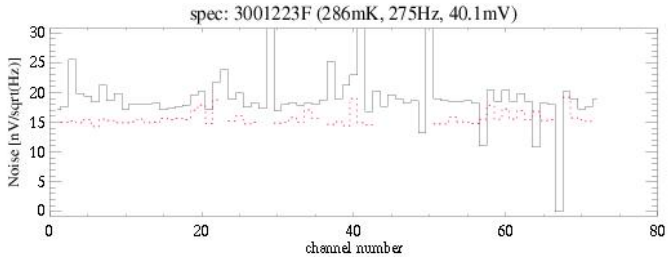


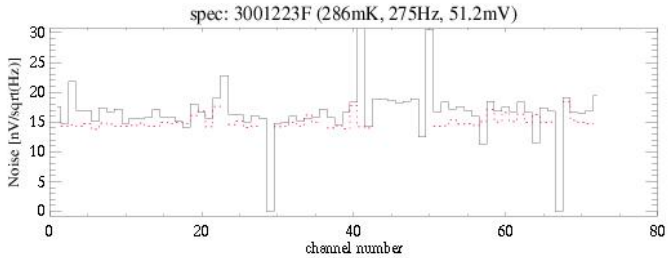


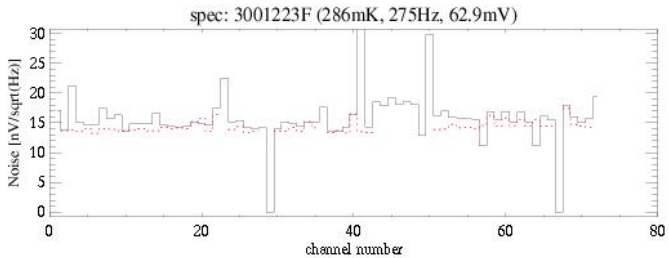


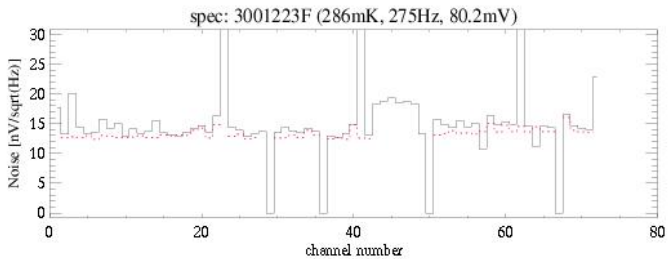


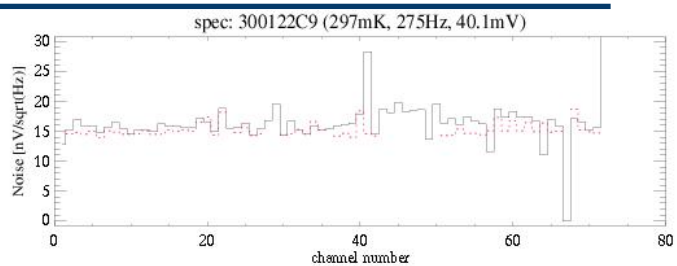
Spectrometer Noises: Measurements vs. Model

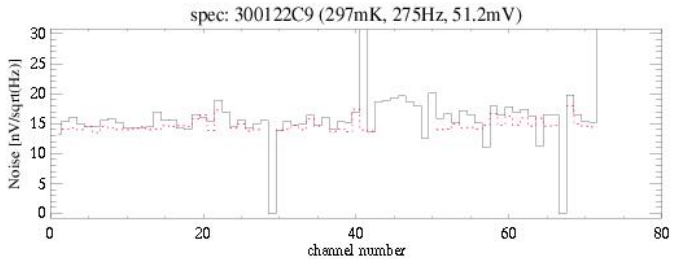


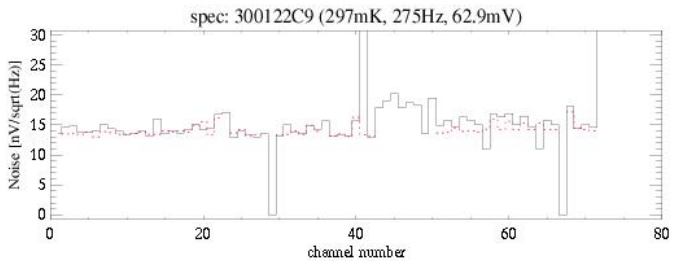


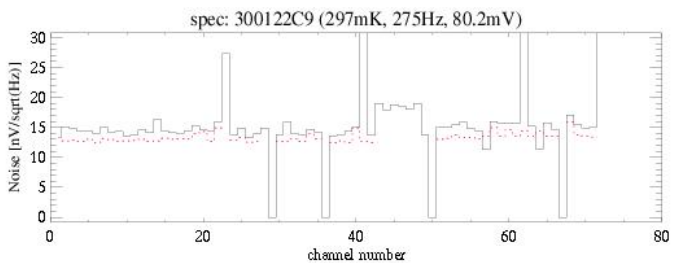








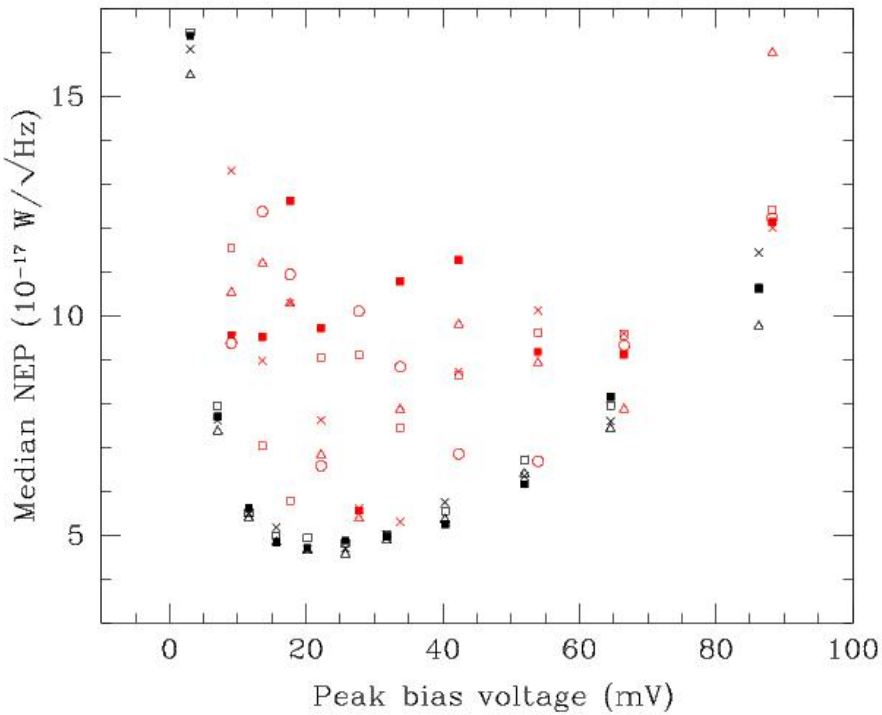


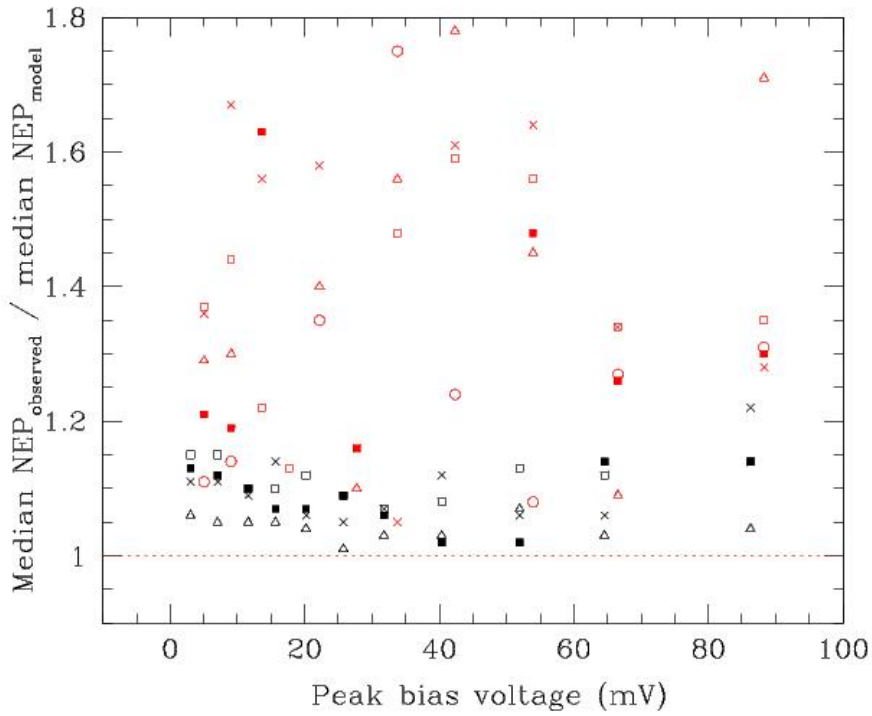


Minimum Frontier of Overall Median NEPs for Photometer

NEP = (noise in V) / (model responsivity)

Black points: T_{sub} = 286 mK;
Red points: T_{sub} = 297 mK;



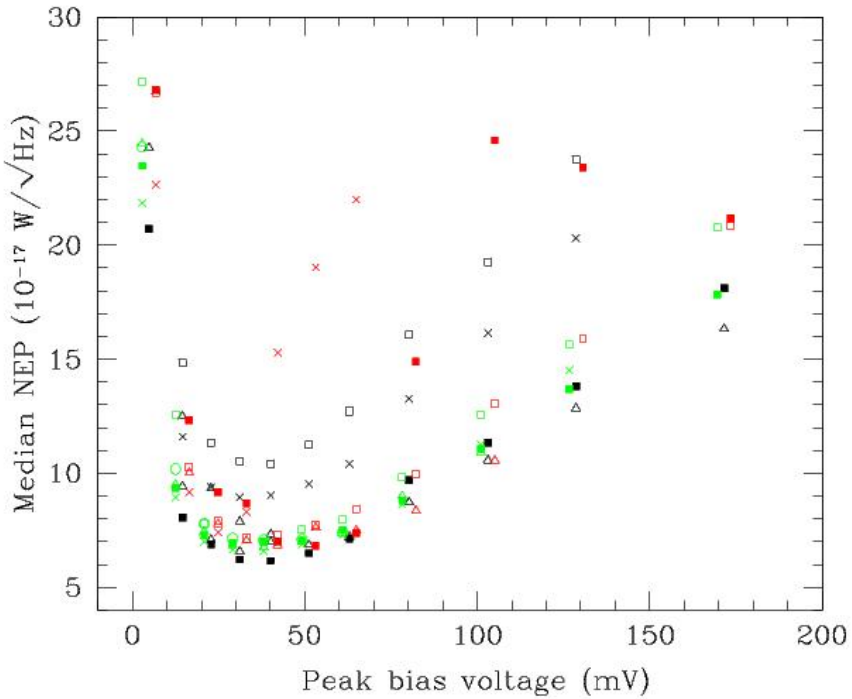


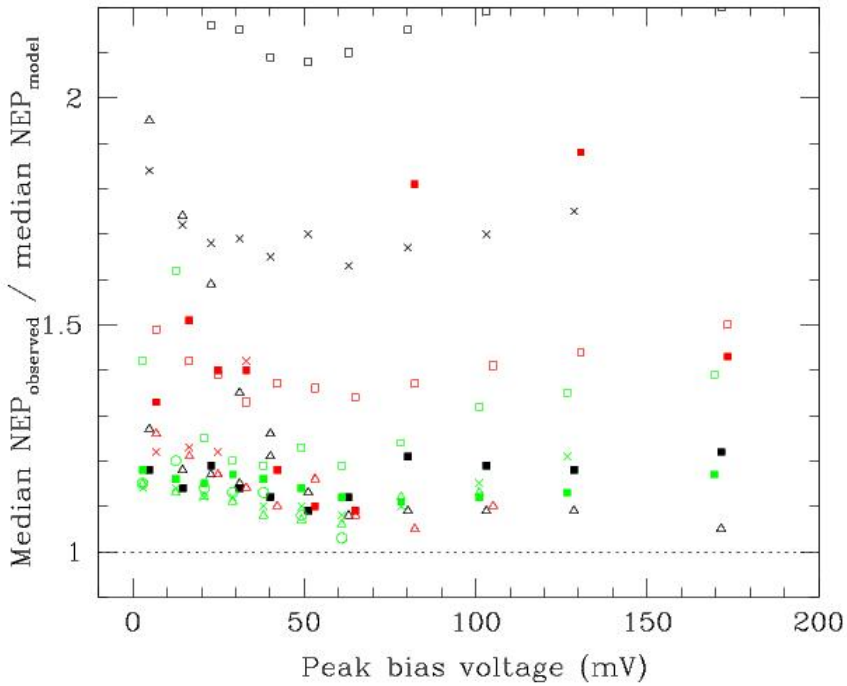
Symbols indicates bias frequencies: 80 Hz (open squares), 110 Hz (crosses), 131 Hz (filled squares), 171 Hz (triangles), or 201 Hz (circles).

Note: Median is for PSW,PMW & PLW together.

Minimum Frontier of Overall Median NEPs for Spectrometer

Black points: T_{sub} = 286 mK;
Red points: T_{sub} = 297 mK (noise tests);
Green points: T_{sub} = 297 mK (dark load curves).





Symbols indicates bias frequencies: 100 Hz (open squares), 161 Hz (crosses), 212 Hz (filled squares), 275 Hz (triangles), or 305 Hz (circles).

Note: Median is for SSW and SLW together.

Summary

- There are fewer dead or non-operational channels in PFM5 than in PFM4.
- The optimal bias settings achieved *overall* NEPs of 4.5x and $6x10^{-17}$W/sqrt(Hz) for photometer and spectrometer, respectively. These minimum NEPs are within ~5 and 10% of the respective model predictions. The optimal biases appear to be within the range of 15-30mV for photometer and of 30-50mV for spectrometer.
- Temperature drifts are a serious problem in many of these tests. We plan to remove the drifts (see Kevin Xu's presentation on Friday) to better characterize the underlying noises.

PFM5 Noise Tests

Photometer

- Dates: 2/13/07, 2/19/07.
- Two bath temperatures:
  T_{sub}= 286 & 297 mK.
- Up to 5 bias frequencies:
  f_{bias}= 80 - 201 Hz.
- 11 bias voltages:
  V_{bia}(peak) = 3 - 86 mV.
- With phase-up.

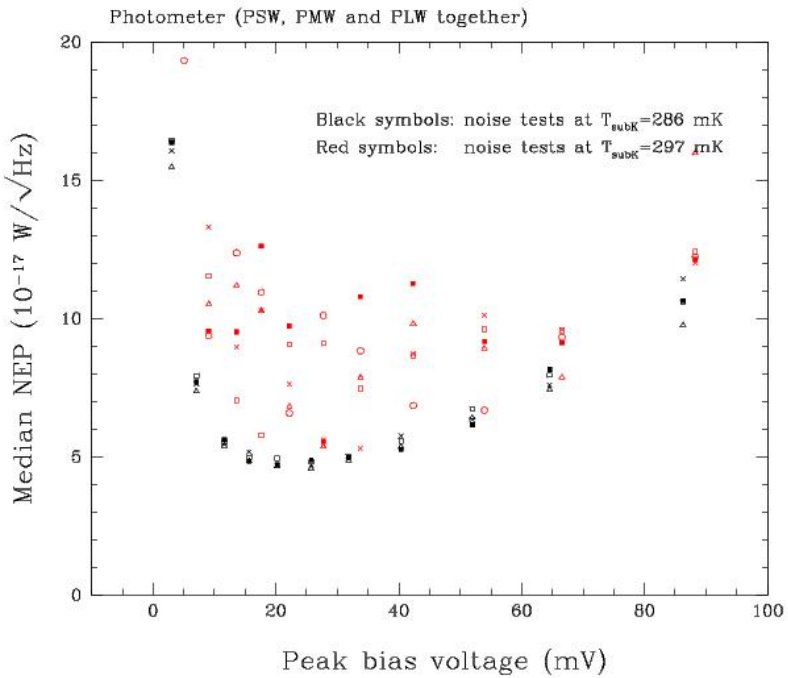
Spectrometer

- Dates: 2/17/06, 2/21/07.
- Two bath temps:
  T_{sub}= 286 & 297 mK.
- Up to 5 bias frequencies:
  f_{bias}= 80 - 201 Hz.
- Up to 11 bias voltages:
  V_{bias}(peak) = 3 - 171 mV.
- With phase-up.
- Including dark load curve measurements.

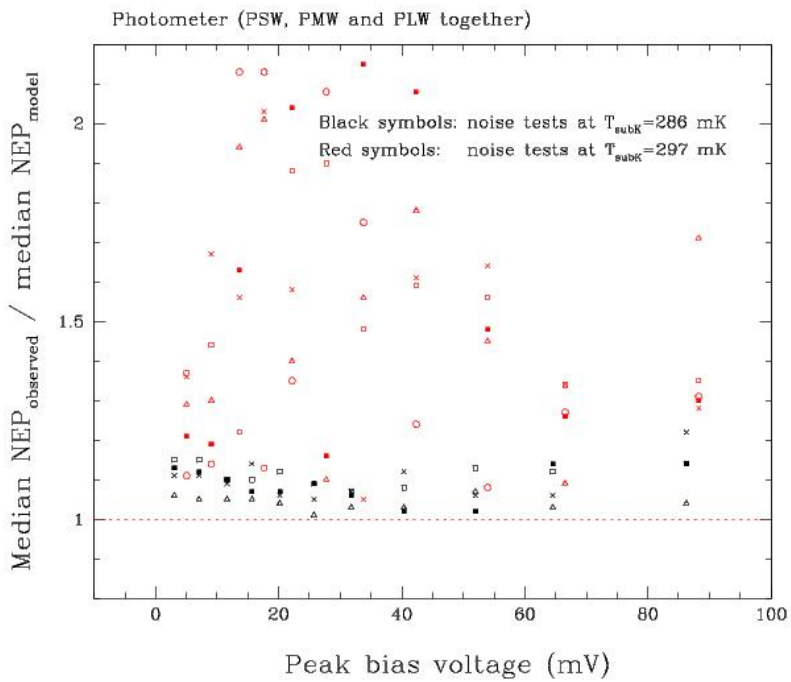
(plus microphonics tests.)

Minimum Overall Median Photometer NEP's

Simply plots and legend please!



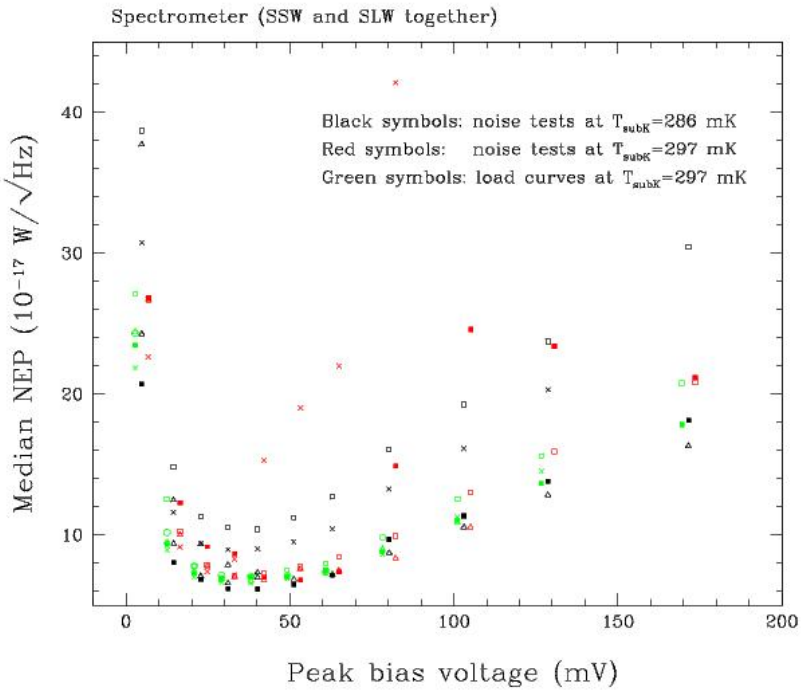
Symbols indicate bias frequencies: 80 Hz (open squares), 110 Hz (crosses), 131 Hz (filled squares), 171 Hz (triangles), or 201 Hz (circles).



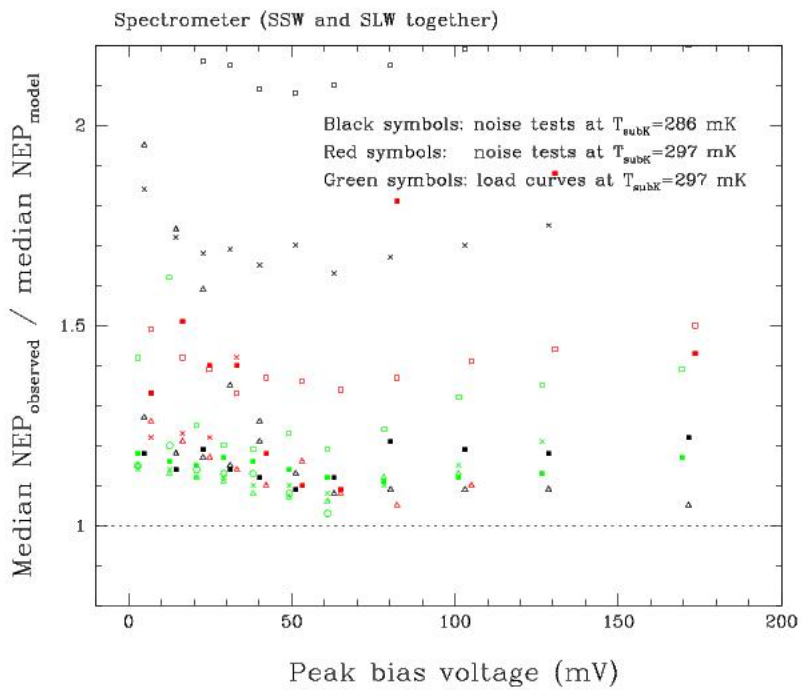
Symbols indicate bias frequencies: 80 Hz (open squares), 110 Hz (crosses), 131 Hz (filled squares), 171 Hz (triangles), or 201 Hz (circles).

Minimum Overall Median Spectrometer NEP's

Simply plots and legend please!



Symbols indicate bias frequencies: 100 Hz (open squares), 161 Hz (crosses) 212 Hz (filled squares), 275 Hz (triangles), or 305 Hz (circles).



Symbols indicate bias frequencies: 100 Hz (open squares), 161 Hz (crosses) 212 Hz (filled squares), 275 Hz (triangles), or 305 Hz (circles).

Telescope Compensation

SPIRE Spectrometer Workshop

15 May 2007

Trevor Fulton

Contents

- Transmission Profiles
- Spatial uniformity for SCAL2, SCAL4
- ZPD locations

Transmission Profiles

Observation	Temperatures [K]			
	CBB	SCAL	SCAL2	SCAL4
300114CA	**6.7**	**4.5**	**4.7**	**4.6**
30011720	7.2	4.5	4.7	4.6
30011724	7.7	4.5	4.7	4.6
30011728	8.2	4.5	4.7	4.6
3001172B	8.7	4.5	4.7	4.6
300114CF	9.0	4.5	4.6	4.6
300114D7	6.7	4.5	9.2	4.6
300114DD	6.7	4.5	14.2	4.6
300114E3	6.7	4.5	20.2	4.6
30011760	6.7	4.5	25.9	4.7
300113B4	6.7	4.5	4.6	9.1
300113BB	6.7	4.5	4.7	15.0
300113BE	6.7	4.5	4.7	20.1
300114EC	6.7	4.5	4.7	20.2

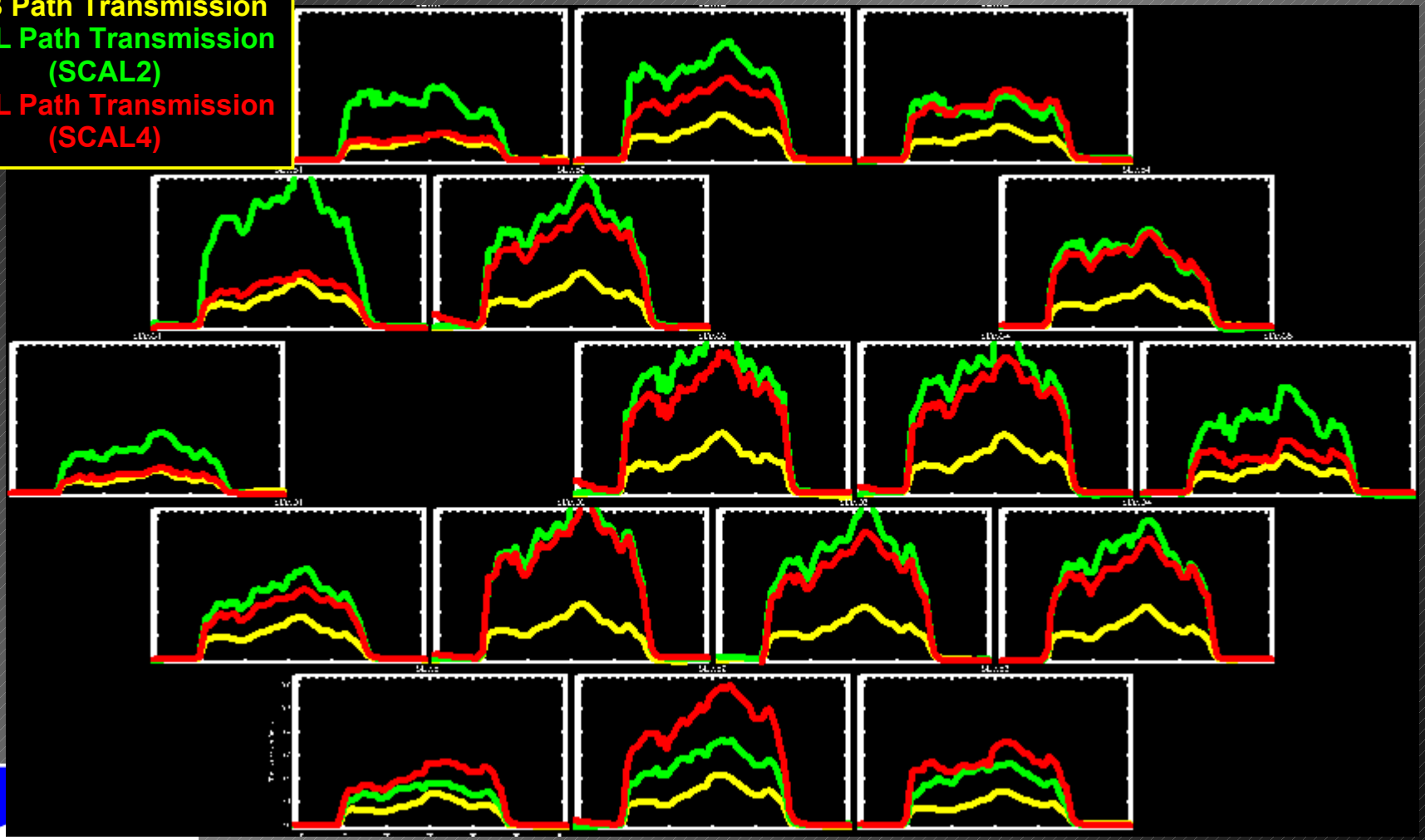
A list of the PFM4 observations used for the transmission analysis. 300114CA was used as the reference observation. The observations in **yellow** were used to determine the CBB/telescope path transmission; the observations shown in **green** were used to determine the SCAL path transmission (SCAL2); the observations shown in **red** were used to determine the SCAL path transmission (SCAL4). In theory, the transmission for SCAL2 and SCAL4 *ought* to be identical.

Transmission Profiles

- The observations studied for this analysis were those in which one of the CBB, SCAL2, and SCAL4 temperatures at a time.
- Common aspects between the observations allowed for a differential analysis on the resultant spectra.
- The relative transmission was determined for each of the “hot” cases. An average relative transmission was then derived for each element (CBB, SCAL2, and SCAL4).
- Plots of these average relative transmission curves are shown in the following slides.

Transmission Profiles

CBB Path Transmission
SCAL Path Transmission (SCAL2)
SCAL Path Transmission (SCAL4)

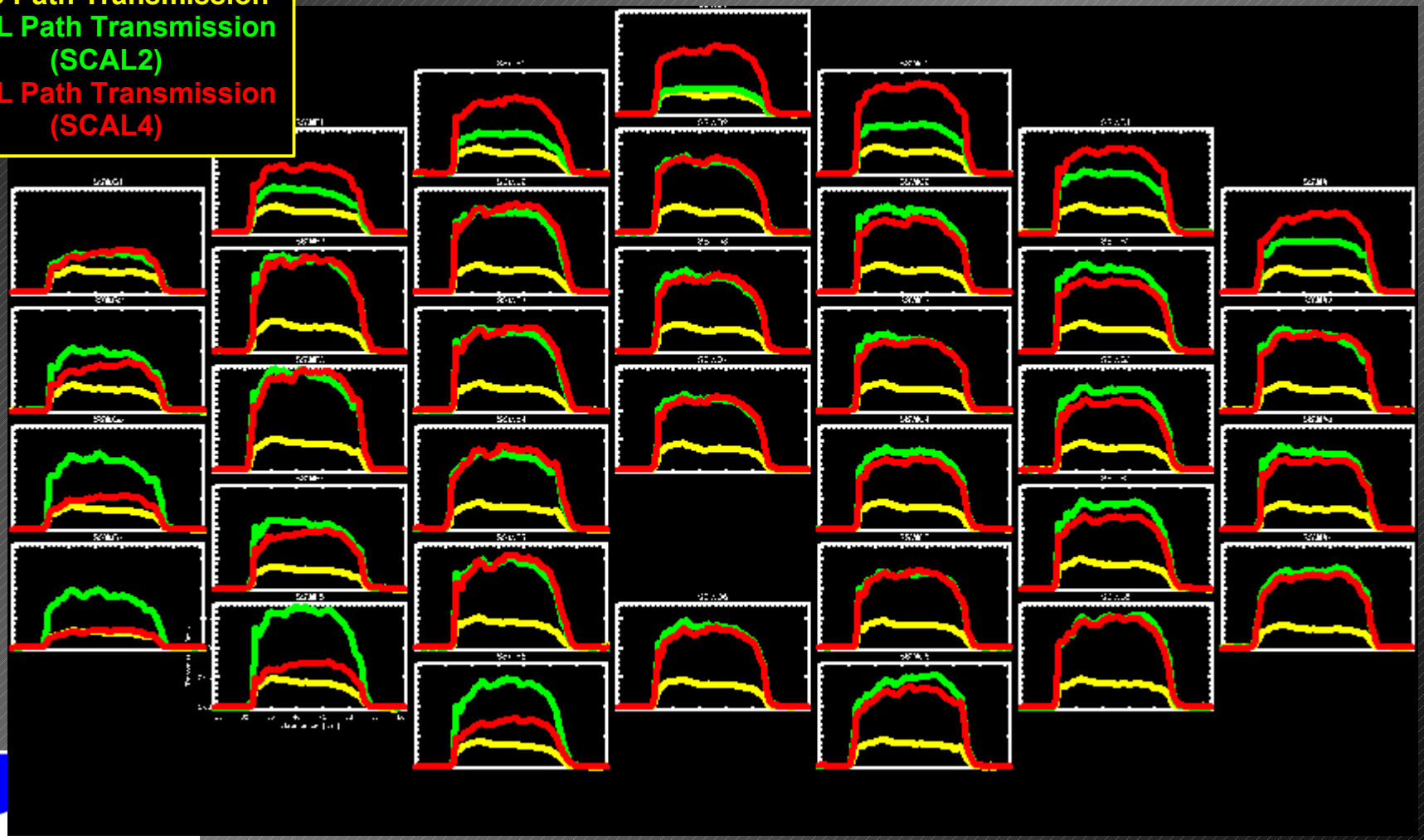


SPIRE

CSA ASC

Transmission Profiles

CBB Path Transmission
SCAL Path Transmission (SCAL2)
SCAL Path Transmission (SCAL4)



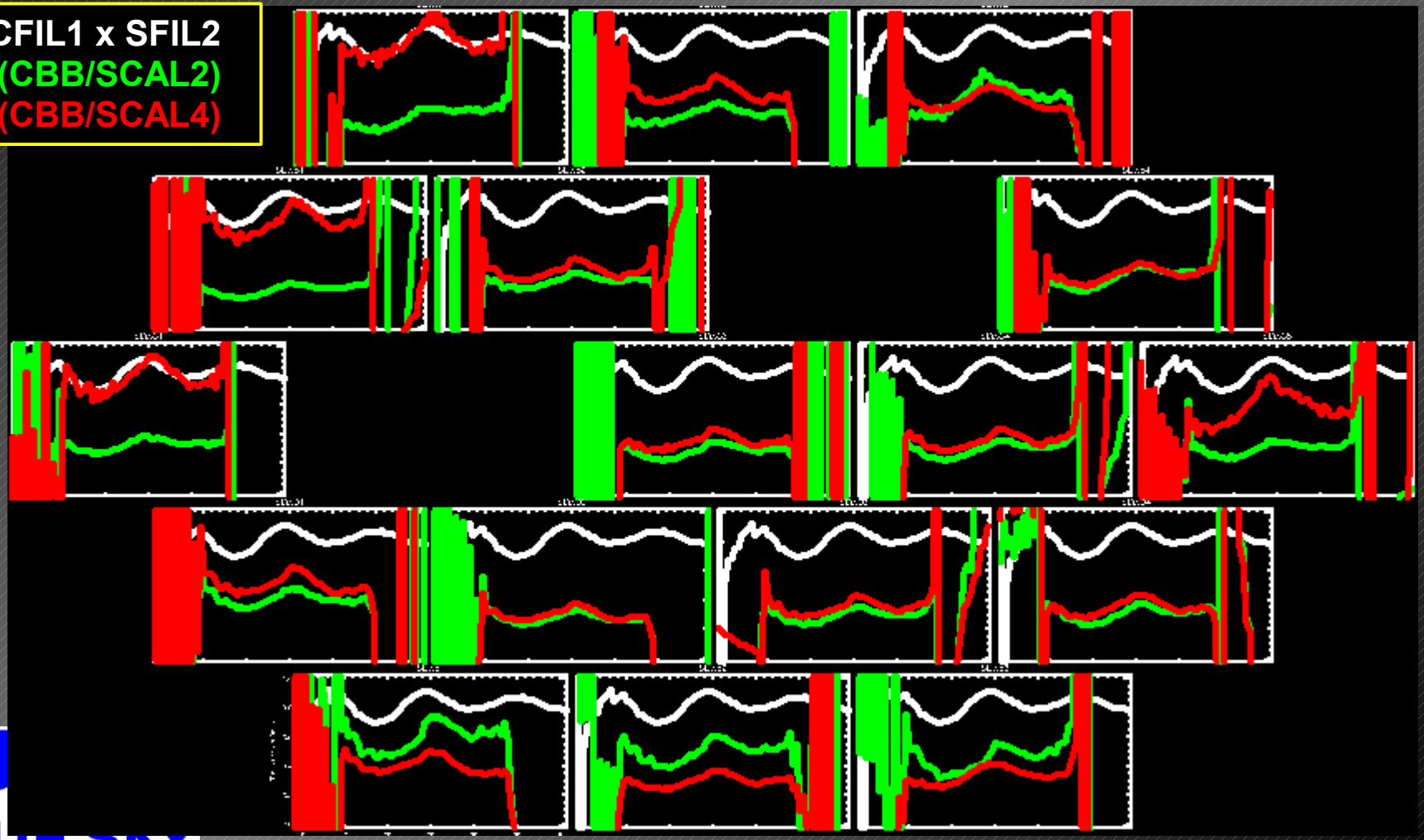
BLUE SKY SPECTROSCOPY

Spatial Uniformity

- A plot of the ratio of the measured transmission for the CBB path to that for the SCAL path should be similar in shape to the product of the transmission of the two extra filters (CFIL1xSFIL2).

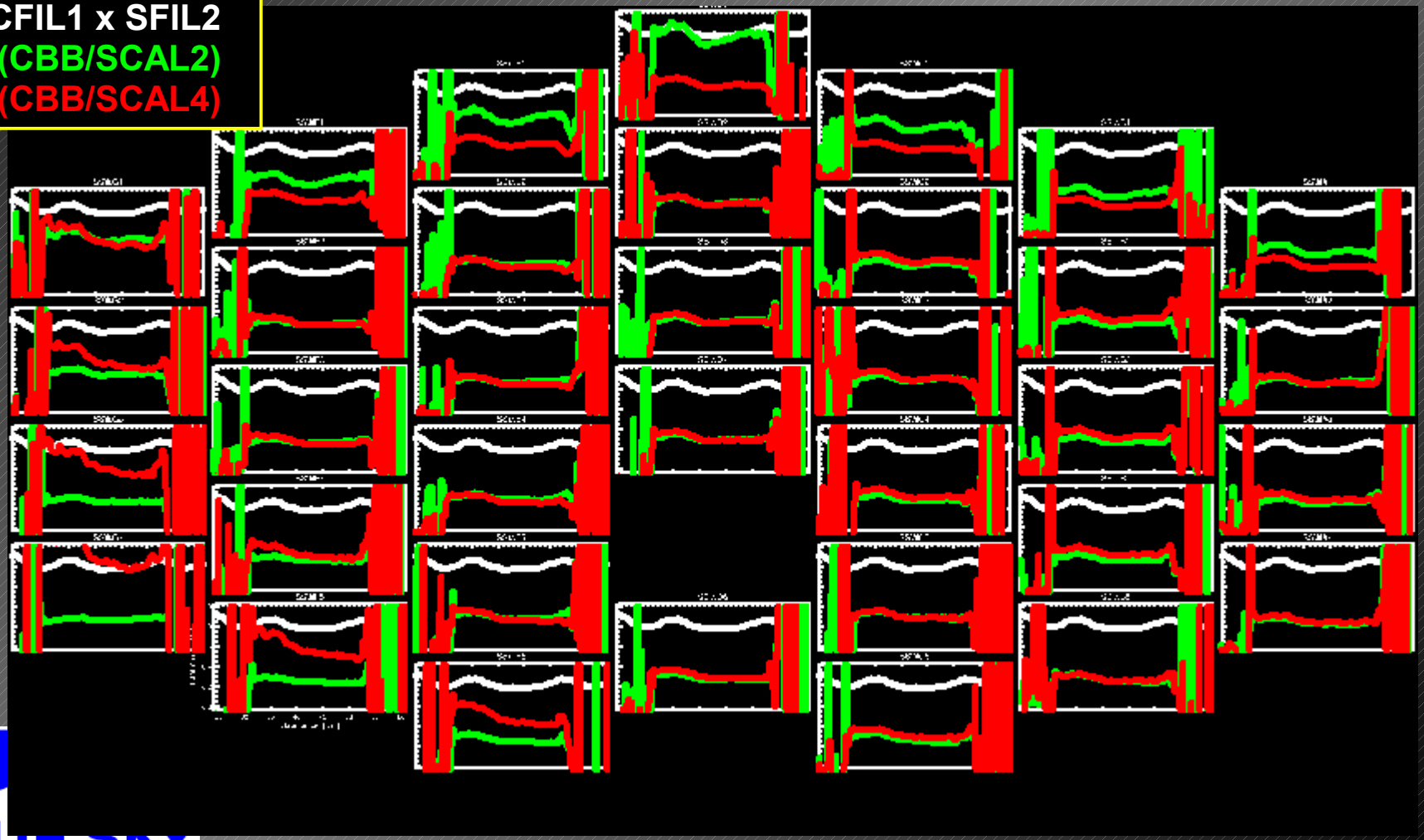
Spatial Uniformity

CFIL1 x SFIL2
(CBB/SCAL2)
(CBB/SCAL4)



Spatial Uniformity

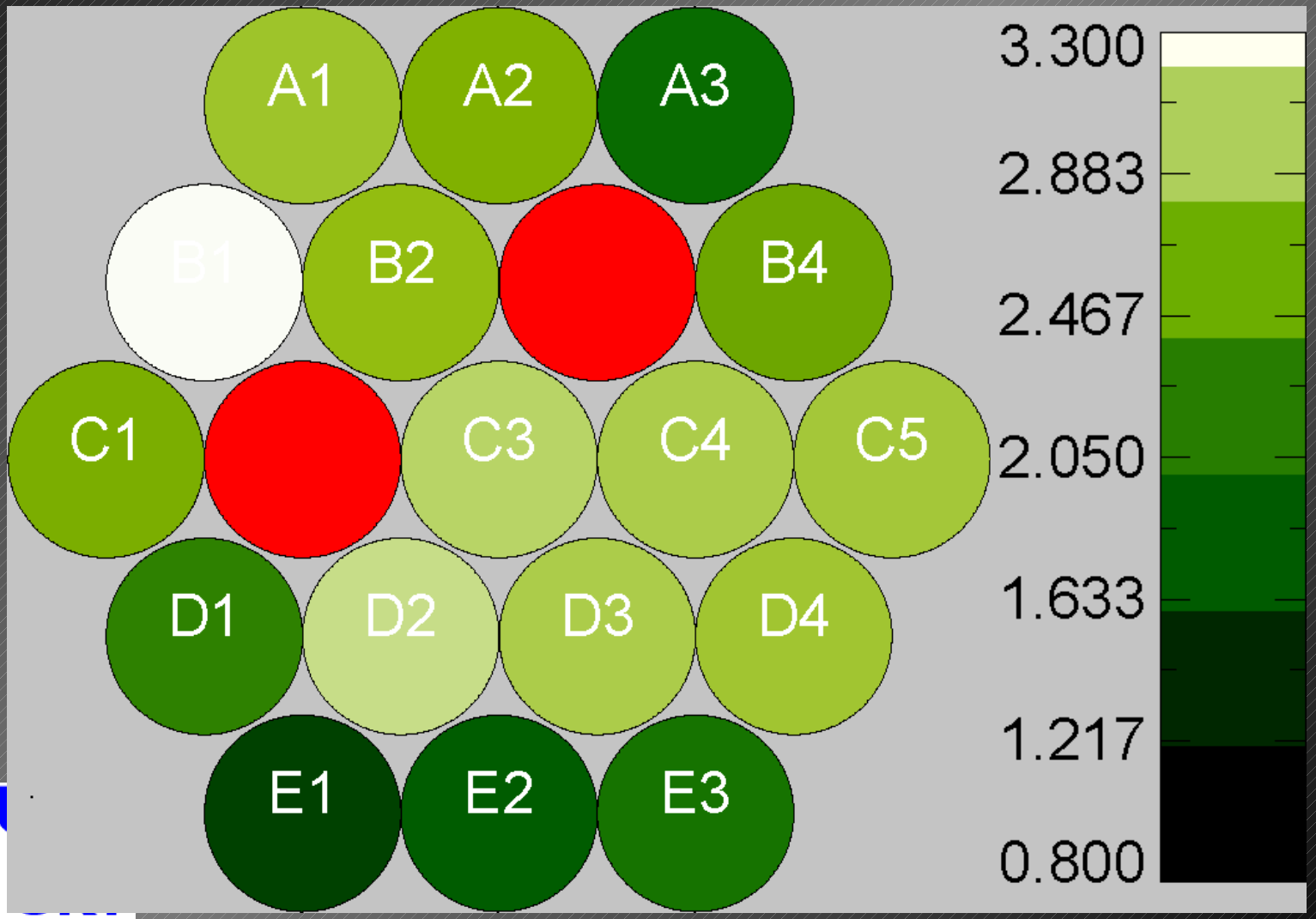
CFIL1 x SFIL2
(CBB/SCAL2)
(CBB/SCAL4)



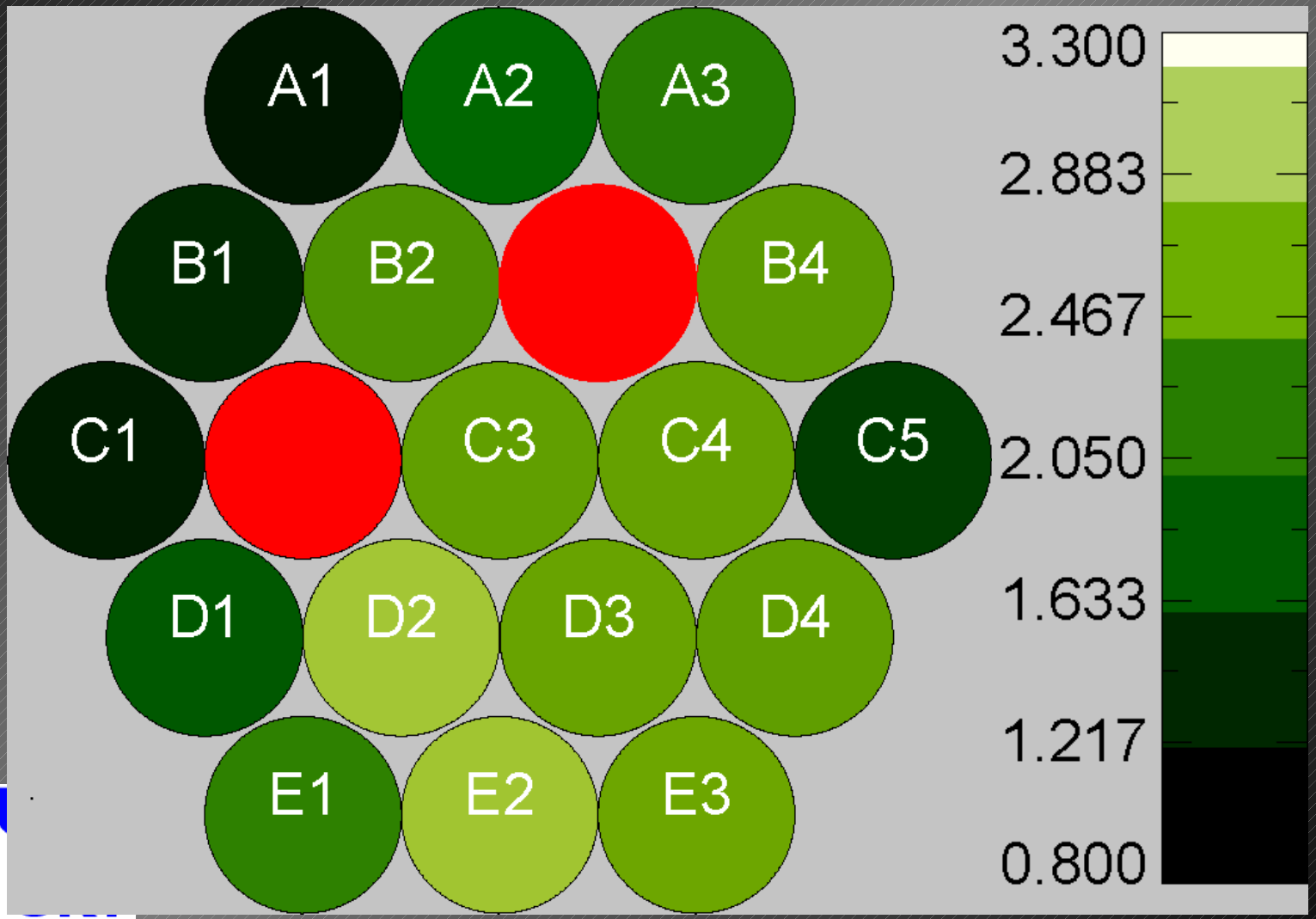
Spatial Uniformity

- The shape of the CBB/SCAL2 transmission ratios and the CBB/SCAL4 transmission ratios is indeed similar to the shape of CFIL1xSFIL2, in particular for the pixels in the unvignetted FOV.
- The measured ratios still differ from the expected ratio by a scaling factor.
- The following figures show the derived scaling factor for each detector. (pixels shown in **red** were not active during the PFM4 test campaign)

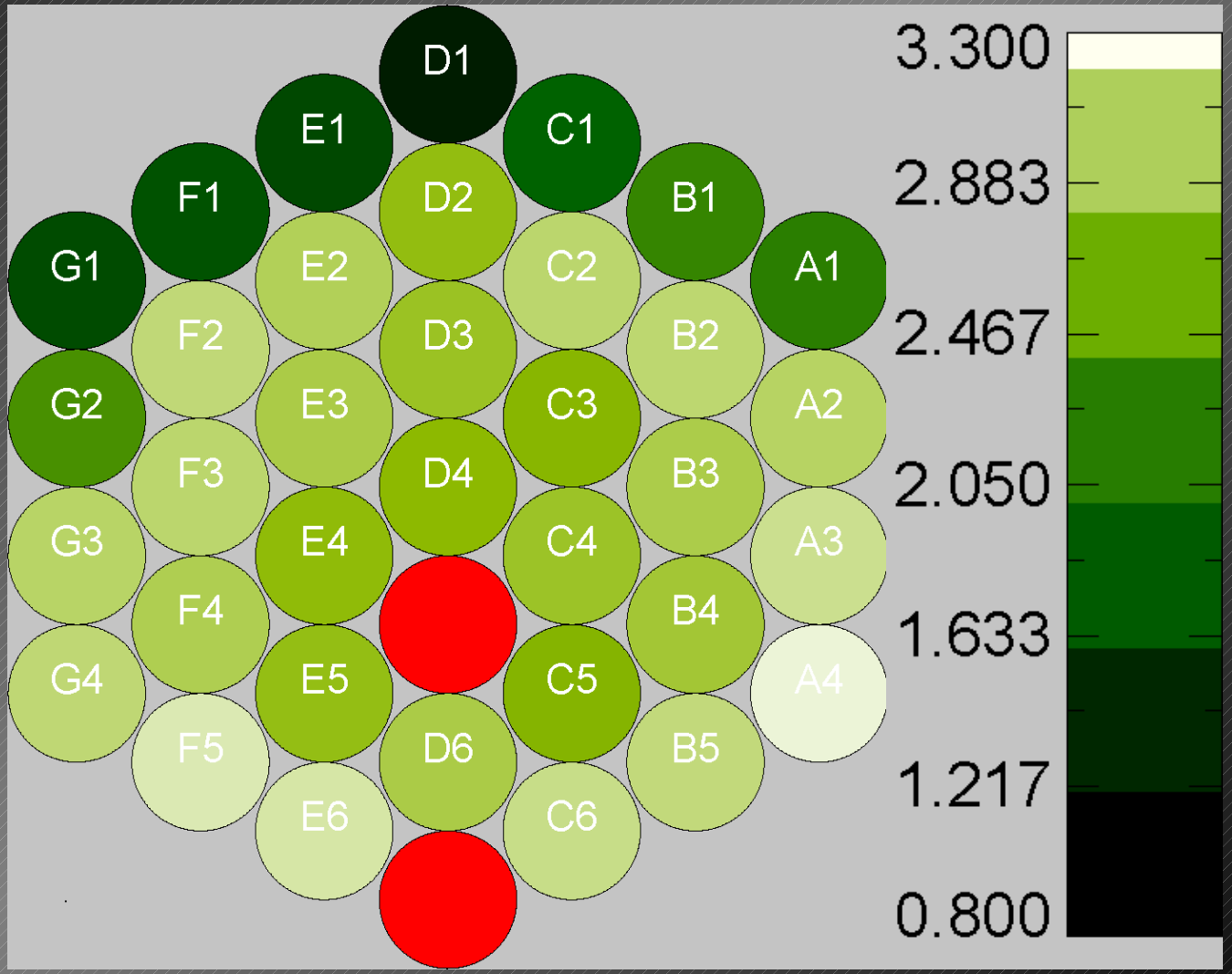
Spatial Uniformity, SCAL2



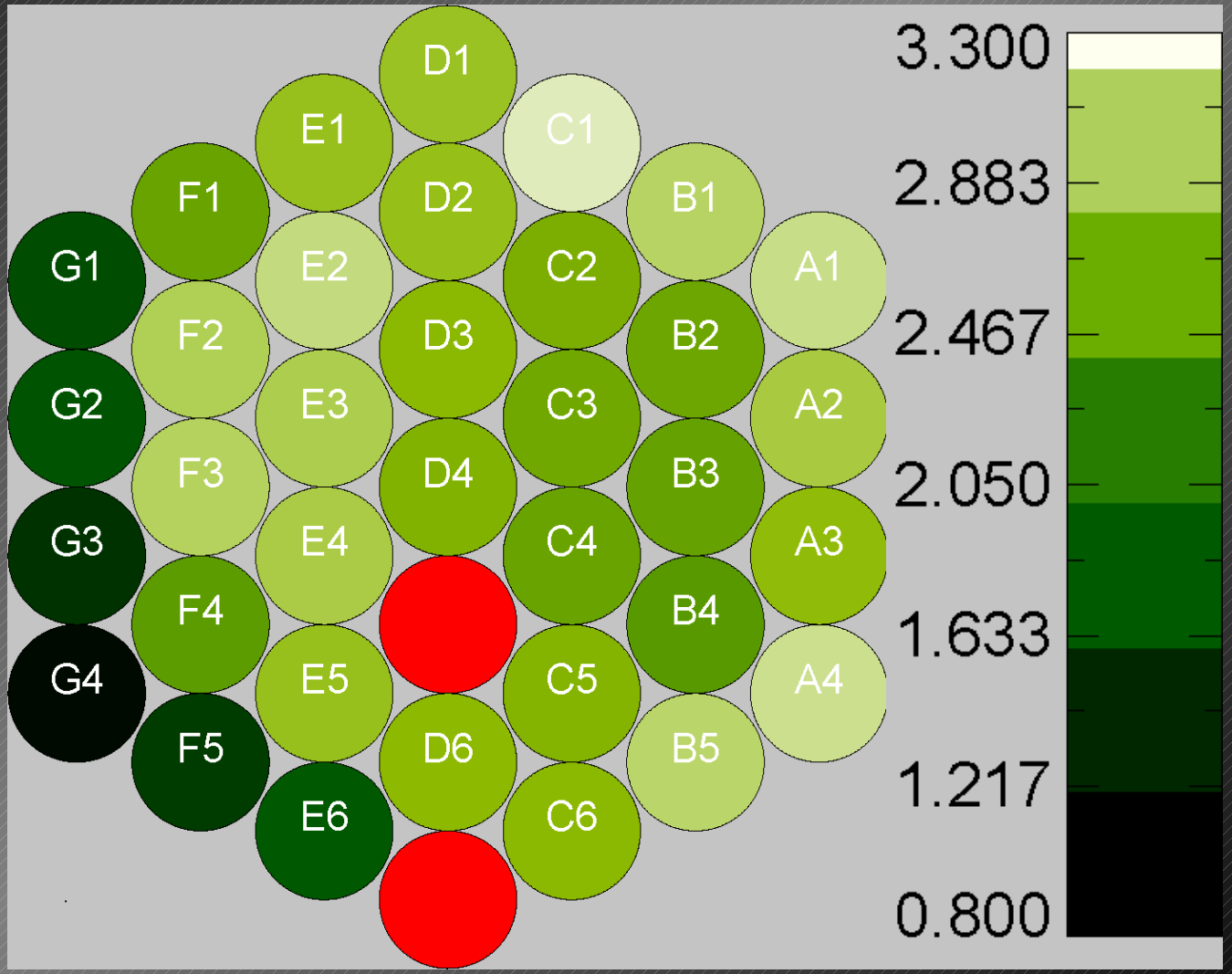
Spatial Uniformity, SCAL4



Spatial Uniformity, SCAL2

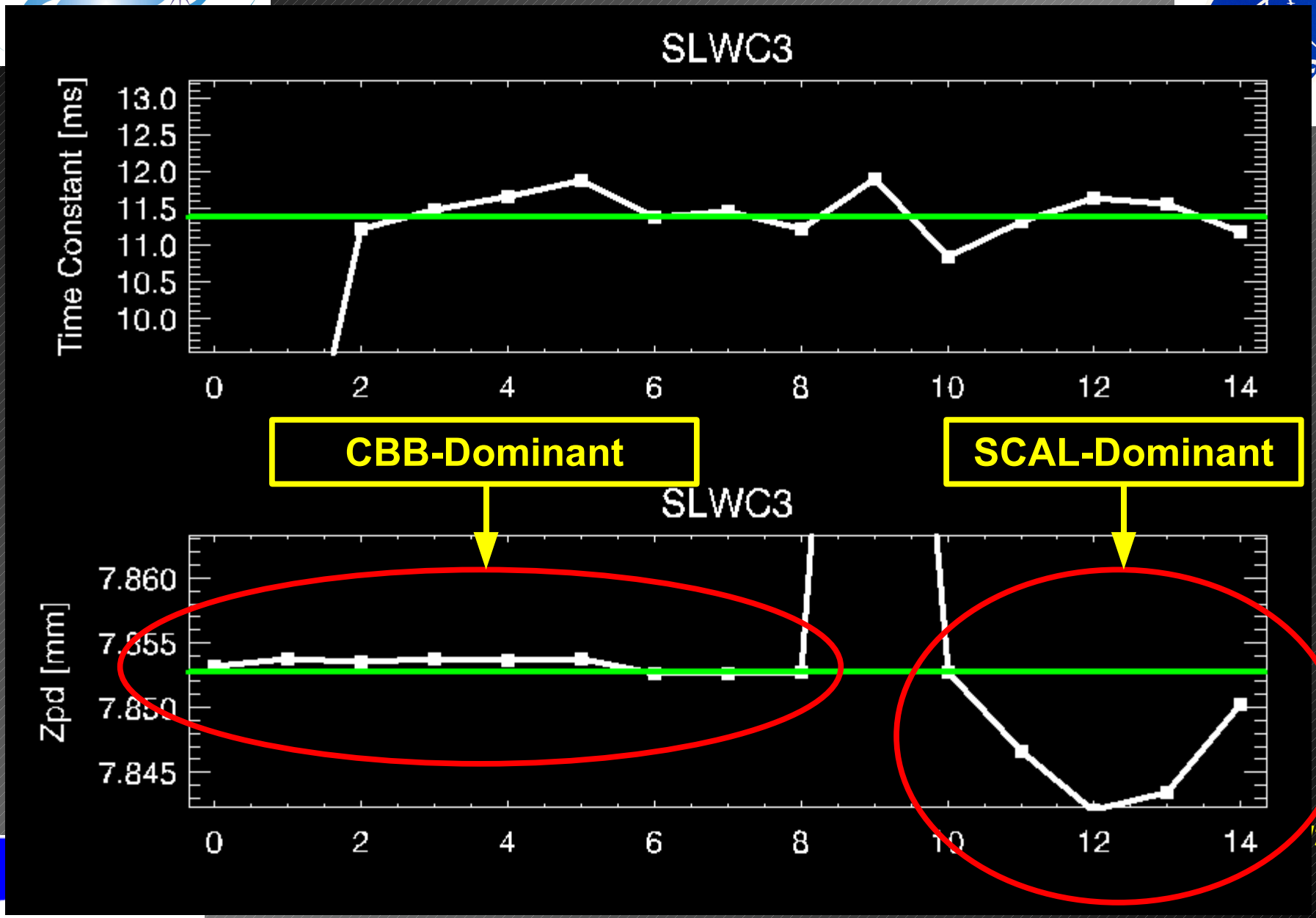


Spatial Uniformity, SCAL4



ZPD Locations

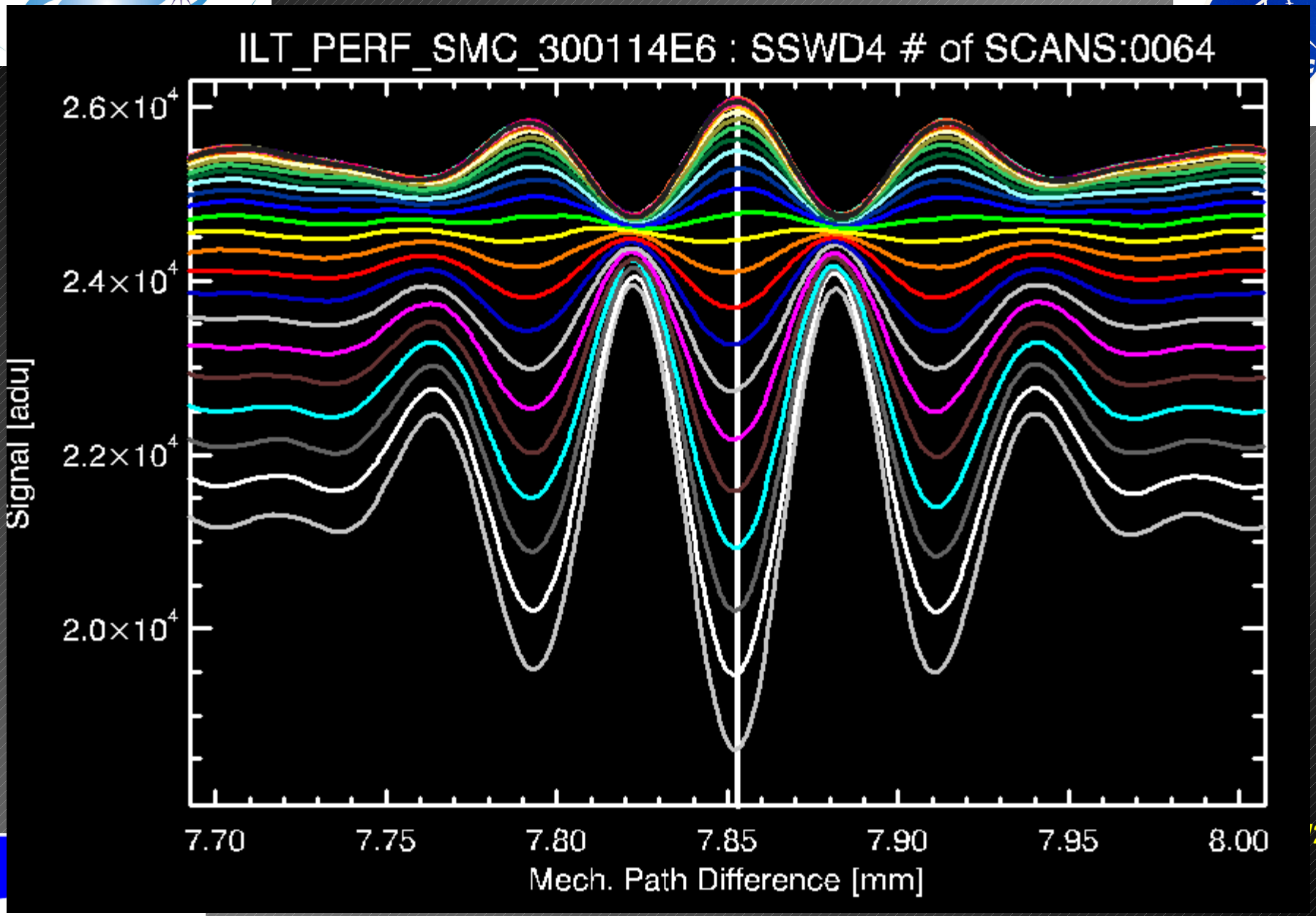
- For the pixels in the unvignetted FOV:
  - The transmission derived using SCAL2 and that derived using SCAL4 are self-consistent within the unvignetted FOV.
  - The measured SCAL path transmission ~2.5 times that of the CBB path, which is consistent with results from PFM1 and PFM3 data.
  - The measured SCAL2 transmission appears to be slightly higher relative to SCAL4 in the SLW array, whereas there is good agreement in the SSW array (this needs further study).



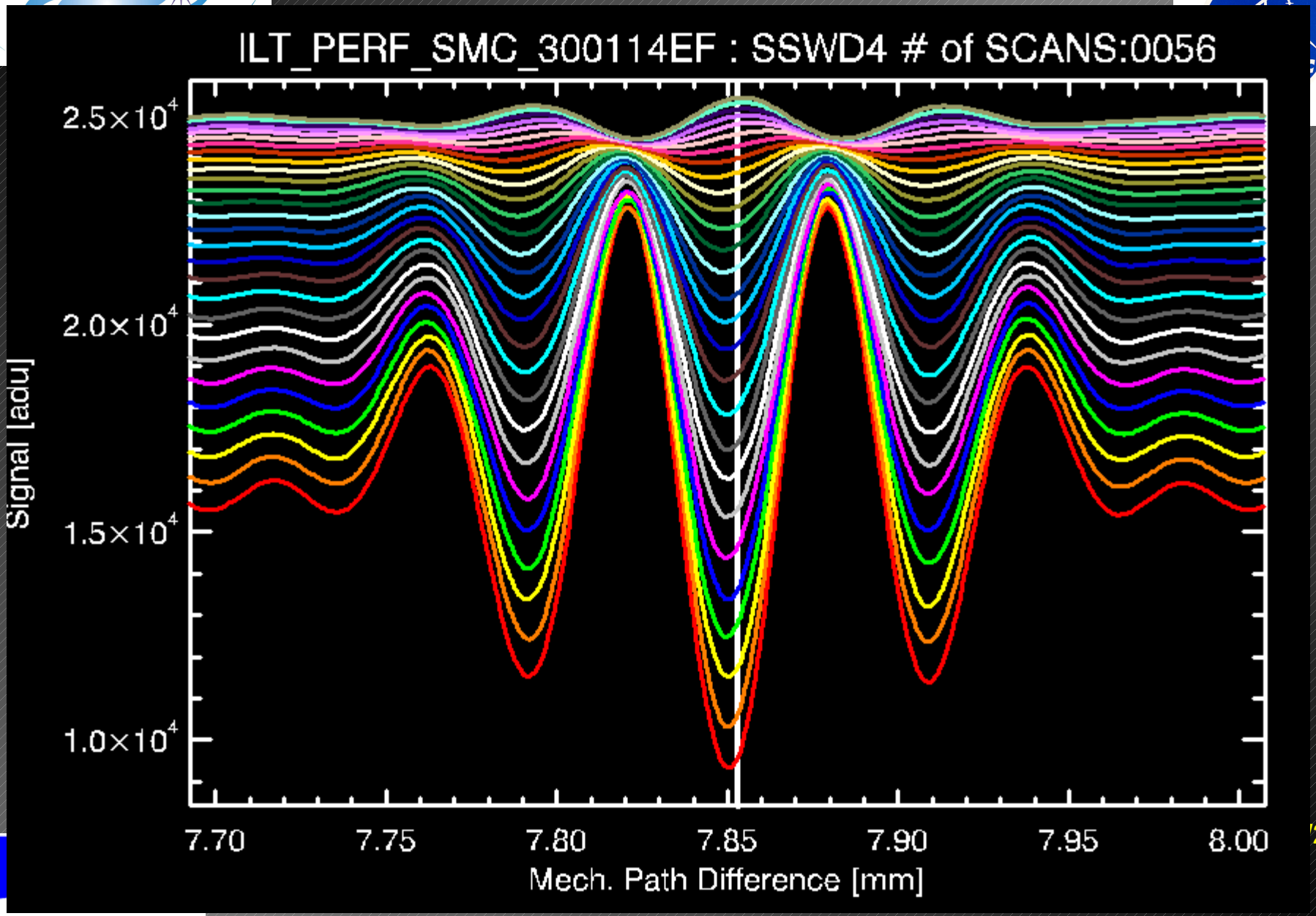
BLUE SKY SPECTROSCOPY

ZPD Positions

- Consider two observations from PFM4:
  - OBSID=0x300114E6: CBB, SCAL, SCAL4 constant, SCAL2 variable.
  - OBSID=0x300114EF: CBB, SCAL, SCAL2 constant, SCAL4 variable.
- In these observations, the input source changes from SCAL (2 or 4) dominant to CBB dominant over the course of ~50 MR scans.



BLUE SKY SPECTROSCOPY



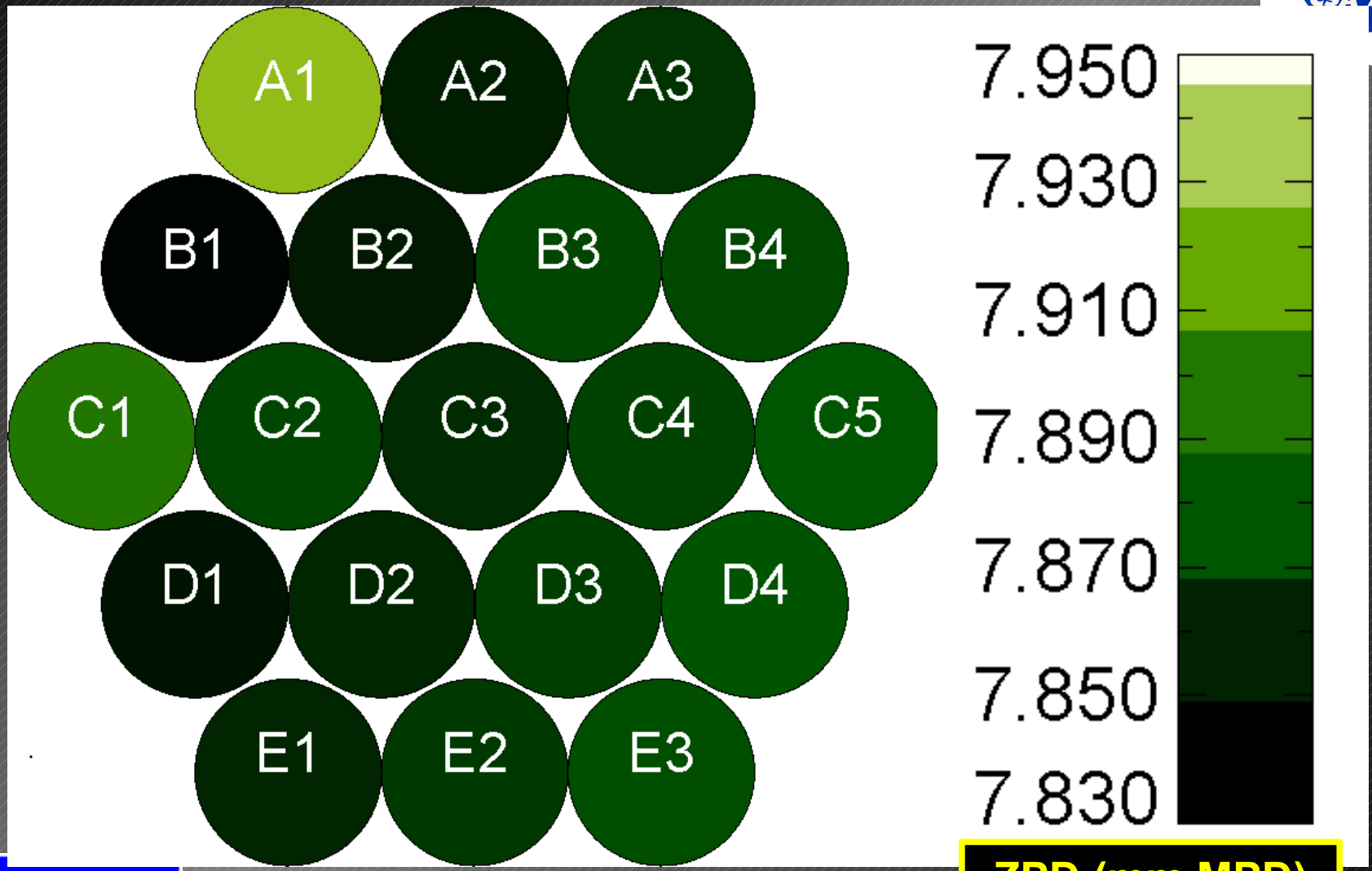
BLUE SKY SPECTROSCOPY

21

SPIRE

ILT_PERF_SMC_300114EC

CSA ASC

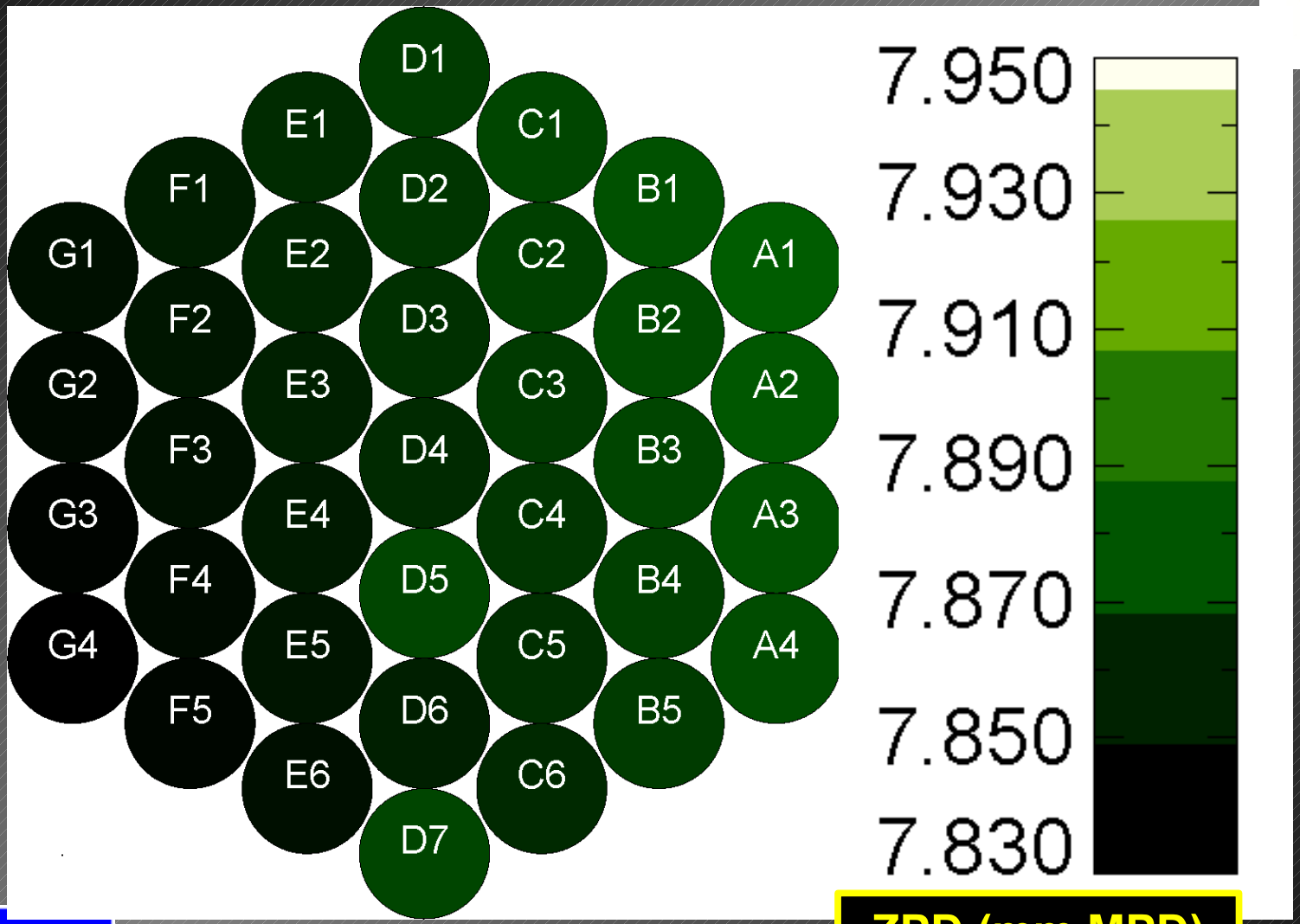


BLUE SKY SPECTROSCOPY

SPIRE

ILT_PERF_SMC_300114EC

CSA ASC



BLUE SKY SPECTROSCOPY