Calibration of Cycles 1 / 2 FORCAST and FLITECAM Grism Spectra

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Calibration Algorithm

The number of electrons detected per sec at pixel *i* is given by

$$N_{e-,i} = A\int\left(\frac{\lambda}{hc}F_\lambda T_\lambda Q_\lambda f\right)\otimes P_\lambda d\lambda_i \approx \frac{Af}{hc}\left\langle(\lambda F_\lambda T_\lambda Q_\lambda)\otimes P_\lambda\right\rangle_i \Delta_i$$

where F_λ is the source flux, T_λ is the atmospheric transmission, Q_λ is the instrument +telescope throughput (response), P_λ is the instrumental profile, f is the fraction of light transmitted through the slit, and Δ is the dispersion. Therefore,

$$N_{e-,i}^{obj} = \frac{Af^{obj}\lambda_i\Delta_i}{hc}\left\langle(F_\lambda^{obj}T_\lambda^{obj}Q_\lambda)\otimes P_\lambda\right\rangle_i$$

and the mean flux from the source at pixel *i* is then

$$\left\langle F_\lambda^{obj}\otimes P_\lambda\right\rangle_i = \frac{hc}{Af^{obj}\lambda_i\Delta_i}\frac{N_{e-,i}^{obj}}{\left\langle(Q_\lambda T_\lambda^{obj})\otimes P_\lambda\right\rangle_i}$$

Similarly, for a standard star,

$$N_{e-,i}^{std} = \frac{Af^{std}\lambda_i\Delta_i}{hc}\left\langle(F_\lambda^{std}T_\lambda^{std}Q_\lambda)\otimes P_\lambda\right\rangle_i$$

But we have models for F^{std}_λ (e.g., Kurucz model for Vega); therefore we can derive the mean throughput at each pixel:

$$\left\langle Q_\lambda T_\lambda^{std} \otimes P_\lambda \right\rangle_i = \frac{hc}{Af^{std}\lambda_i \Delta_i} \frac{N_{e-,i}^{std}}{\left\langle F_\lambda^{std} \otimes P_\lambda \right\rangle_i}$$

With this, and the assumptions that $T_\lambda^{std} \approx T_\lambda^{obj}$ and $f^{obj} \approx f^{std}$ we have for any object:

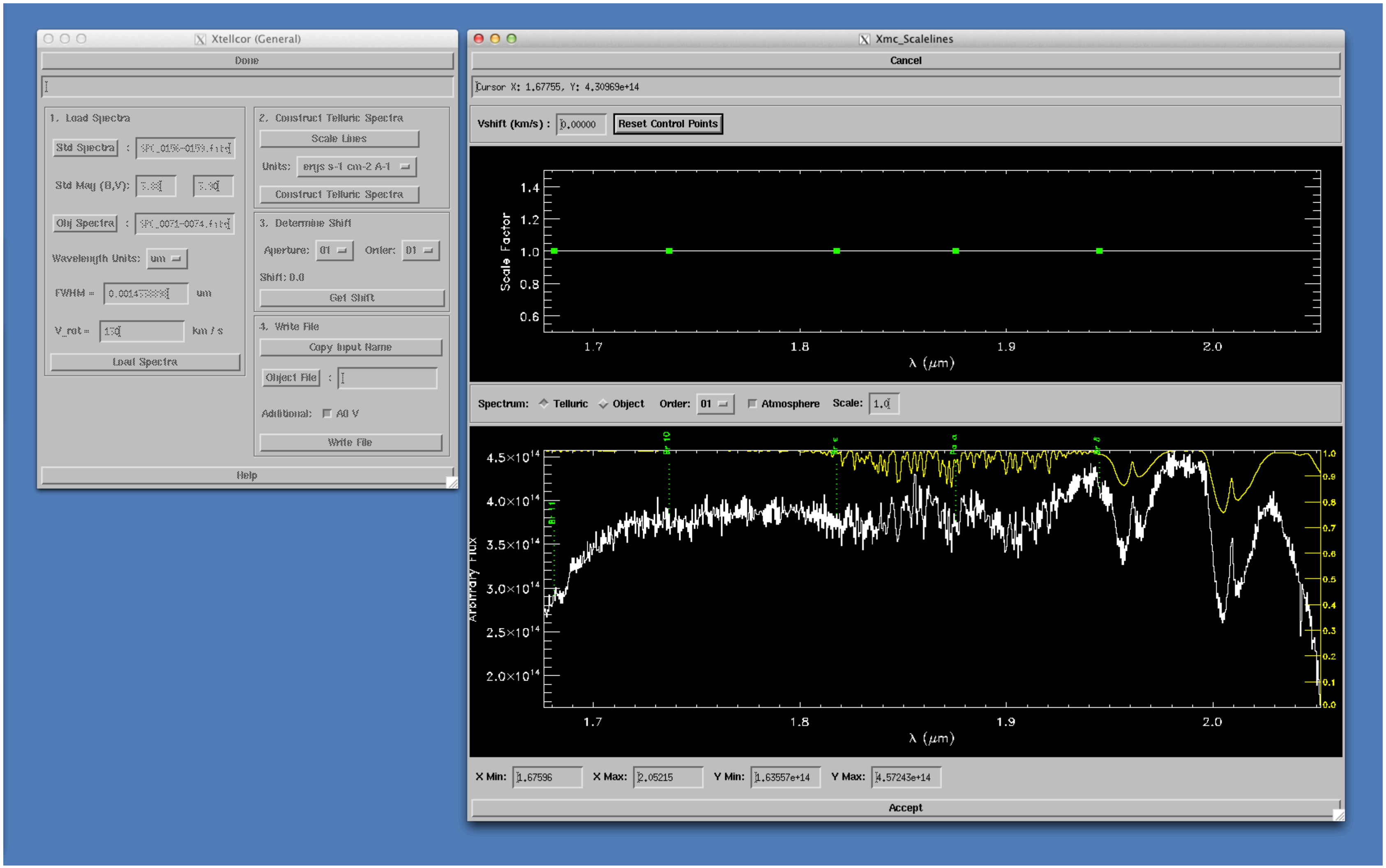
$$\left\langle F_\lambda^{obj} \otimes P_\lambda \right\rangle_i = \frac{N_{e-,i}^{obj}}{N_{e-,i}^{std}} \left\langle F_\lambda^{std} \otimes P_\lambda \right\rangle_i = \frac{N_{e-,i}^{obj}}{C_{\lambda,i}}$$

where

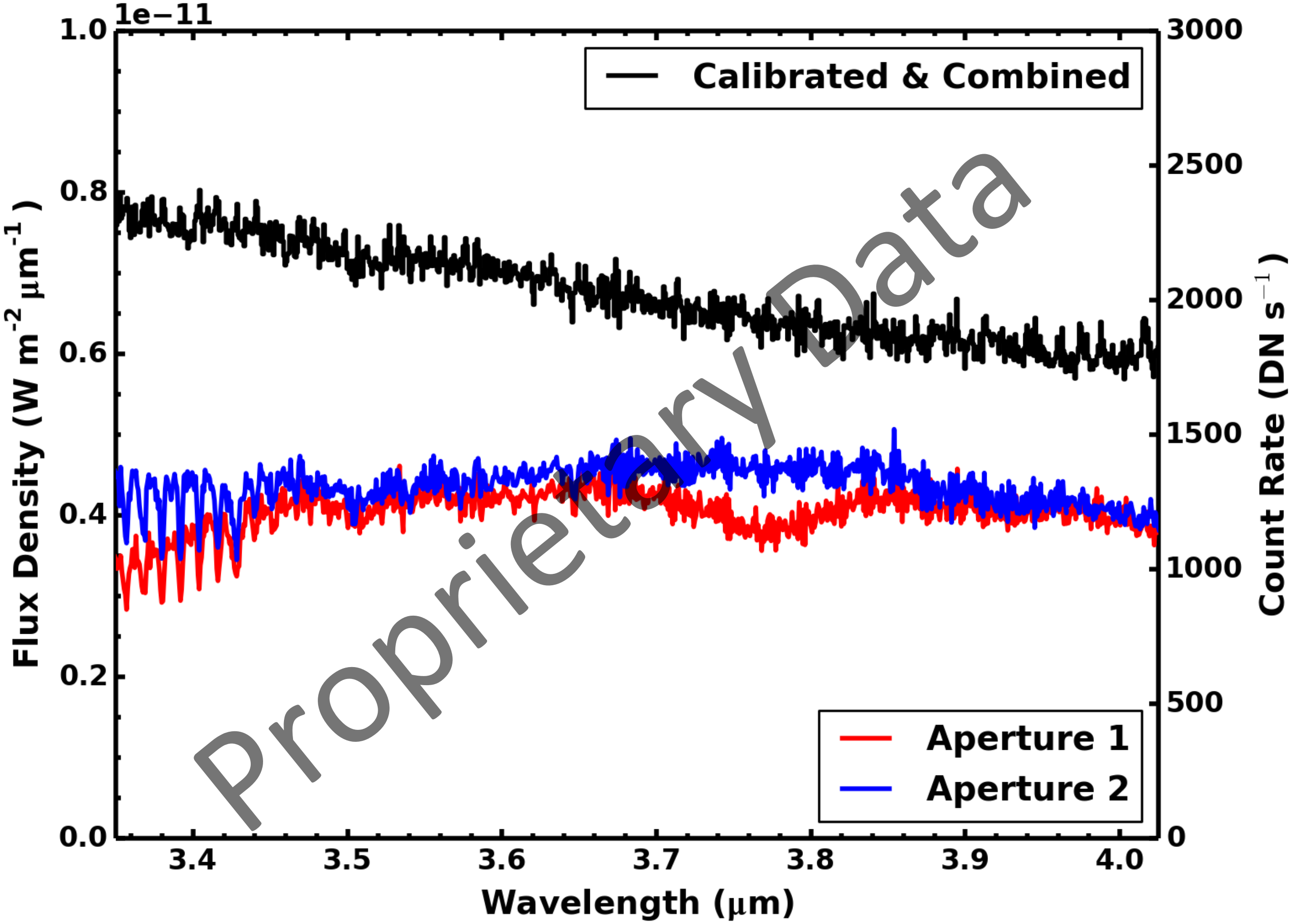
$$C_{\lambda,i} = \frac{N_{e-,i}^{std}}{\left\langle F_\lambda^{std} \otimes P_\lambda \right\rangle_i} = \frac{Af^{std}\lambda_i \Delta_i}{hc} \left\langle Q_\lambda T_\lambda^{std} \otimes P_\lambda \right\rangle_i$$

is the 'telluric correction function' at each pixel *i* in electrons/s/($Wm^{-2}\mu m^{-1}$), or electron/s/Jy. Note that we need the resolving power in order to compute P_λ. The *xtellcor_general* program (developed for the calibration of IRTF/SpeX data; Vacca et al. 2003) allows users to perform the calibration steps with a gui. It assumes the standard star is an A0V that can be modeled as a scaled, reddened, shifted, velocity broadened version of the Kurucz Vega model spectrum.

Calibration of FLITECAM grism data – modified version of *xtellcor_general*



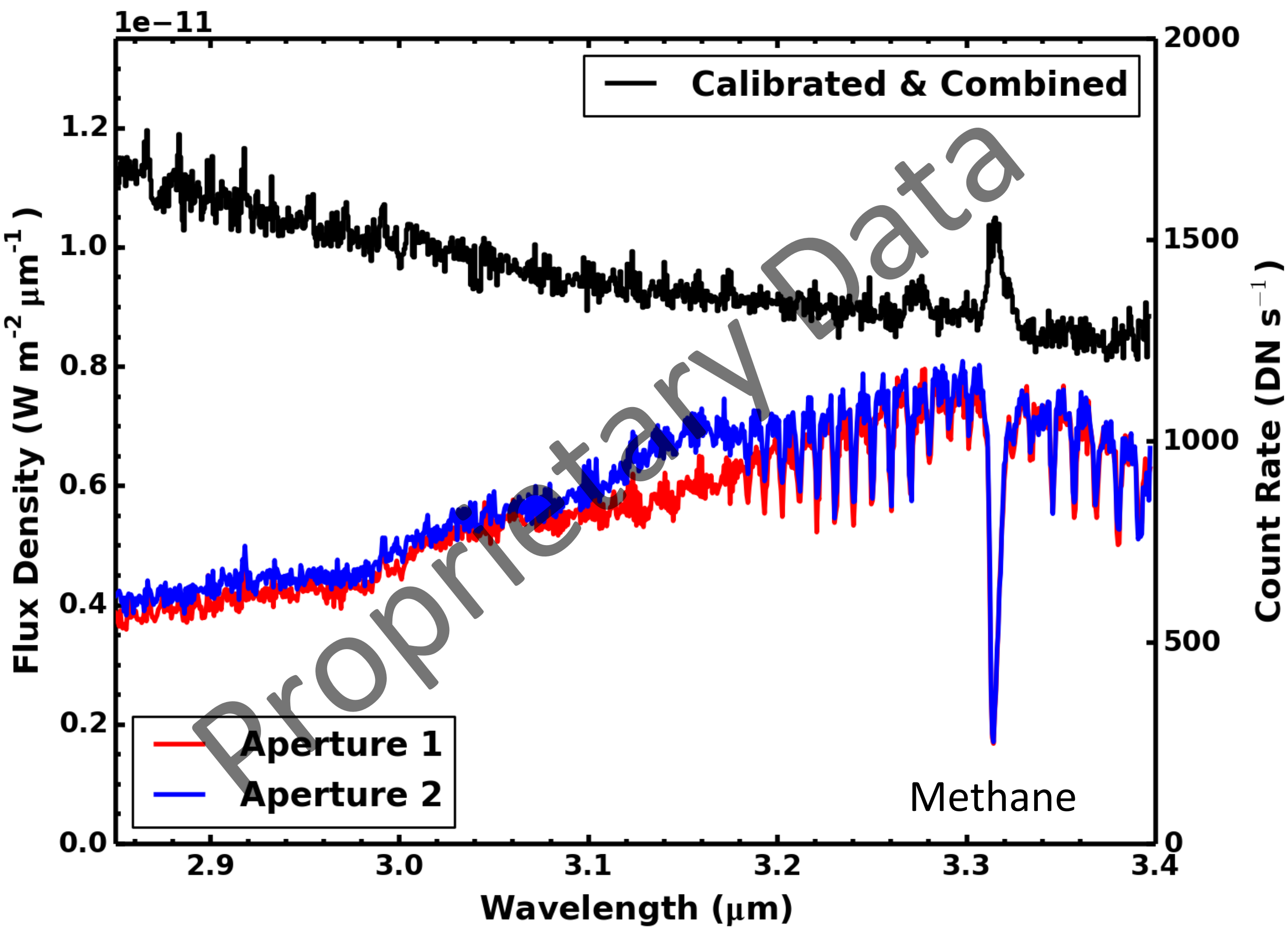
Example of results: U Mon



Calibrator taken on a different flight, at a different altitude, and different ZA

Example of results: U Mon

“Well, sometimes the magic works. Sometimes, it doesn't.” – Little Big Man



Calibrator taken on a different flight, at a different altitude, and different ZA

FLITECAM Grism Calibration Issues

- *Xtellcor_general* does not currently account for differences in airmass (ZA) or altitude
  - Either modify code to incorporate corrections based on telluric models, or change procedure (e.g., implement procedure similar to that for FORCAST grism data, in which ATRAN models are used along with an ‘invariant’ response curve for each grism)
  - Both require time and effort
  - Often have only one observation of an A0V in a given grism
- *Xtellcor_general* is not automated, so all calibrations have to be done manually
  - All reductions to date have been done by R. Hamilton

Calibration Algorithm

The number of electrons detected per sec at pixel *i* is given by

$$N_{e-,i} = A\int\left(\frac{\lambda}{hc}F_\lambda T_\lambda Q_\lambda f\right)\otimes P_\lambda d\lambda_i \approx \frac{Af}{hc}\left\langle(\lambda F_\lambda T_\lambda Q_\lambda)\otimes P_\lambda\right\rangle_i \Delta_i$$

where F_λ is the source flux, T_λ is the atmospheric transmission, Q_λ is the instrument +telescope throughput (response), P_λ is the instrumental profile, f is the fraction of light transmitted through the slit, and Δ is the dispersion. Therefore,

$$N_{e-,i}^{obj} = \frac{Af^{obj}\lambda_i\Delta_i}{hc}\left\langle(F_\lambda^{obj}T_\lambda^{obj}Q_\lambda)\otimes P_\lambda\right\rangle_i$$

and the mean flux from the source at pixel *i* is then

$$\left\langle F_\lambda^{obj}\otimes P_\lambda\right\rangle_i = \frac{hc}{Af^{obj}\lambda_i\Delta_i}\frac{N_{e-,i}^{obj}}{\left\langle(Q_\lambda T_\lambda^{obj})\otimes P_\lambda\right\rangle_i}$$

Similarly, for a standard star,

$$N_{e-,i}^{std} = \frac{Af^{std}\lambda_i\Delta_i}{hc}\left\langle(F_\lambda^{std}T_\lambda^{std}Q_\lambda)\otimes P_\lambda\right\rangle_i$$

But we have models for both F^{std}_λ (e.g., Herschel) and T^{std}_λ (e.g., ATRAN); therefore we can derive the mean instrumental throughput at each pixel:

$$\left\langle Q_\lambda \otimes P_\lambda \right\rangle_i = \frac{hc}{Af^{std}\lambda_i \Delta_i} \frac{N^{std}_{e-,i}}{\left\langle (F^{std}_\lambda T^{std}_\lambda) \otimes P_\lambda \right\rangle_i}$$

With this, we have for any object:

$$\left\langle F^{obj}_\lambda \otimes P_\lambda \right\rangle_i = \frac{N^{obj}_{e-,i}}{N^{std}_{e-,i}} \frac{\left\langle (F^{std}_\lambda T^{std}_\lambda) \otimes P_\lambda \right\rangle_i}{\left\langle T^{obj}_\lambda \otimes P_\lambda \right\rangle_i} = \frac{N^{obj}_{e-,i}}{\left\langle T^{obj}_\lambda \otimes P_\lambda \right\rangle_i R_{\lambda,i}} = \frac{N^{obj}_{e-,i}}{C_{\lambda,i}}$$

where

$$R_{\lambda,i} = \frac{N^{std}_{e-,i}}{\left\langle (F^{std}_\lambda T^{std}_\lambda) \otimes P_\lambda \right\rangle_i}$$

is the 'response function' at each pixel *i* in electrons/s/($Wm^{-2}\mu m^{-1}$), or electron/s/Jy, which should not vary from observation to observation as long as the instrument parameters do not change. Note that we need the resolving power in order to compute P_λ and an accurate wavelength calibration to compute T_λ. This assumes that the image quality is the same for both sets of observations, $f^{obj} = f^{std}$. The 'total' correction function at each pixel is then given by:

$$C_{\lambda,i} = \left\langle T^{obj}_\lambda \otimes P_\lambda \right\rangle_i R_{\lambda,i}$$

Note that there are similar equations for extended sources. In this case, the number of electrons detected per second per spatial and spectral pixel from a source with uniform surface brightness I_λ is given by:

$$N_{e-,i}^{obj} = \frac{A\lambda_i \Delta_i sp}{hc} \left\langle (I_\lambda^{obj} T_\lambda^{obj} Q_\lambda) \otimes P_\lambda \right\rangle_i$$

where s is the slit size and p is the pixel scale. Therefore,

$$\left\langle I_\lambda^{obj} \otimes P_\lambda \right\rangle_i = \frac{hc}{A\lambda_i \Delta_i sp} \frac{N_{e-,i}^{obj}}{\left\langle (Q_\lambda T_\lambda^{obj}) \otimes P_\lambda \right\rangle_i} = \frac{N_{e-,i}^{obj}}{C_{\lambda,i}^{ext}}$$

By analogy with point sources,

$$\left\langle I_\lambda^{obj} \otimes P_\lambda \right\rangle_i = \frac{f^{std}}{sp} \frac{N_{e-,i}^{obj}}{N_{e-,i}^{std}} \frac{\left\langle (F_\lambda^{std} T_\lambda^{std}) \otimes P_\lambda \right\rangle_i}{\left\langle T_\lambda^{obj} \otimes P_\lambda \right\rangle_i} = \frac{N_{e-,i}^{obj}}{\left\langle T_\lambda^{obj} \otimes P_\lambda \right\rangle_i R_{\lambda,i}^{ext}} = \frac{N_{e-,i}^{obj}}{C_{\lambda,i}^{ext}}$$

So that for extended sources

$$R_{\lambda,i}^{ext} = R_{\lambda,i}^{ps} \frac{sp}{f^{std}} \quad \text{and} \quad C_{\lambda,i}^{ext} = C_{\lambda,i}^{ps} \frac{sp}{f^{std}}$$

FORCAST Calibration Procedure:

- Retrieve Level 2 spectra of standard (alpha Boo) from DCS
- Correct for telluric absorption by dividing by a model of telluric transmission, generated from ATRAN, for observing altitude and ZA, smoothed (convolved to FORCAST grism resolution) and sampled at observed pixel spacing
- Compute response curve by dividing by a smoothed and sampled stellar model (from Herschel calibration program)
- Compute mean response function (Me/s/Jy) by averaging all response curves and smoothing

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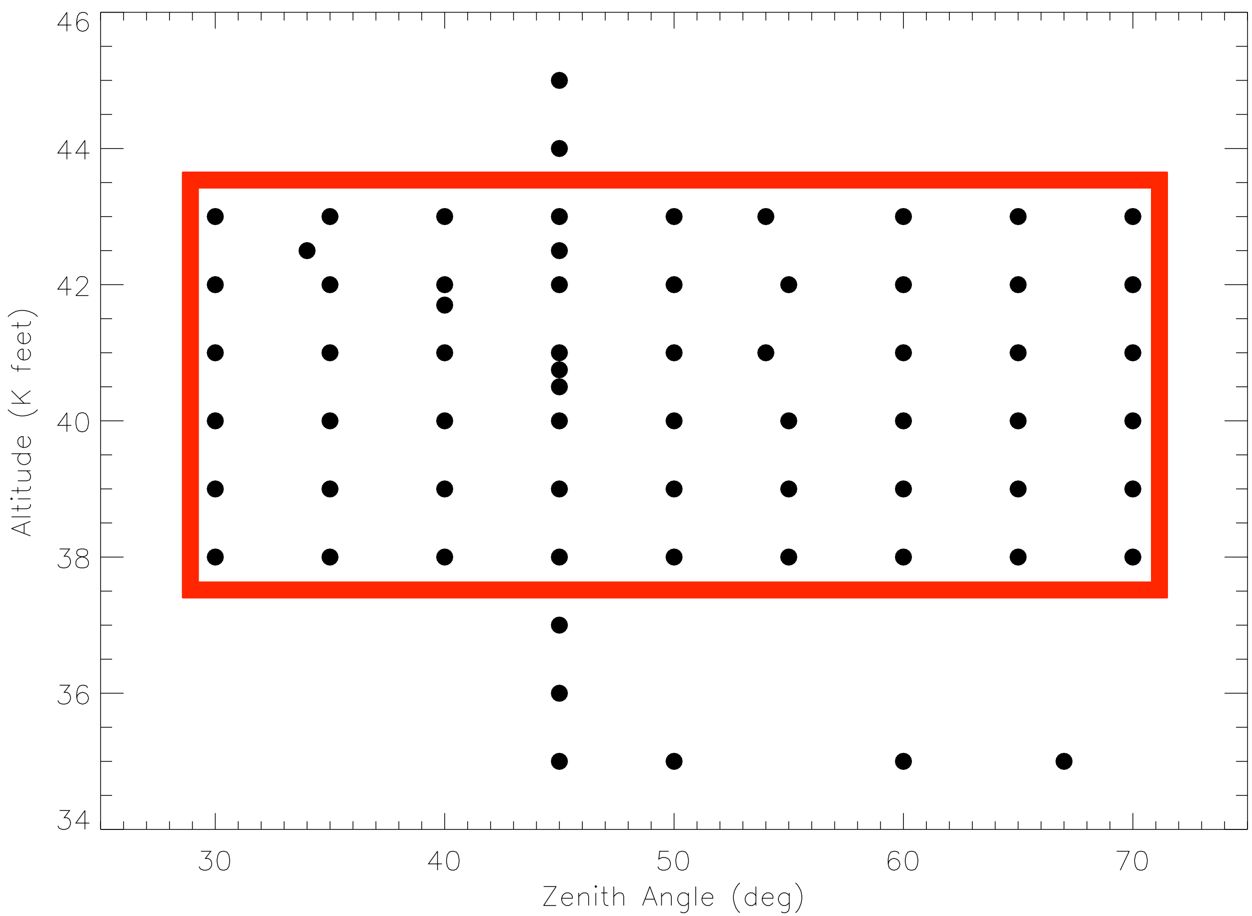
- Correct Level 2 object spectrum for telluric absorption by dividing by a smoothed and sampled model of telluric transmission generated from ATRAN for object altitude and ZA
- Compute flux calibrated object spectrum by dividing by the appropriate response curve to convert Me/s to Jy

Computed ATRAN Models

45 models; ΔZA = 5 degrees; Δalt = 1000 feet; 4-50 μm



Absolutely Calibrated Herschel Model Spectra

Star	Flux @ 11 μm (Jy)
alpha Boo	591
alpha Cet	180
alpha CMa	120
alpha Tau	526
beta And	209
beta Peg	312
beta UMi	104
gamma Dra	124
sigma Lib	162

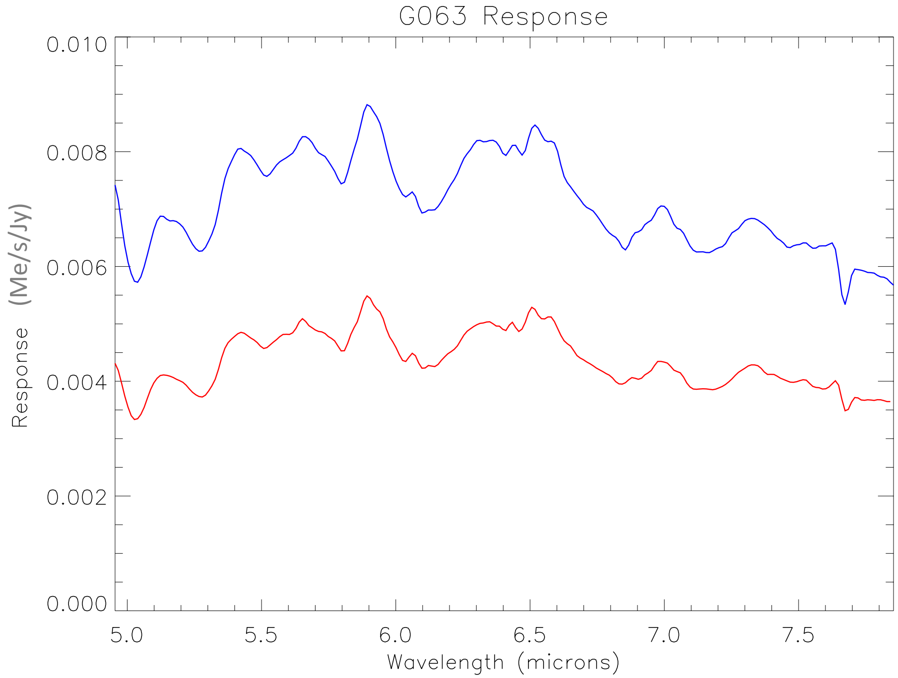
Not used due to variability of ~8%

Adopted FORCAST Grism Resolutions

Grism	Slit	R = λ/Δλ
G063	LS24 = 2.4”	180 - nominal
G063	LS47 = 4.7”	125
G111	LS24	300 - nominal
G111	LS47	150
G227	LS24	140 - nominal
G227	LS47	90
G329	LS24	220 - nominal
G329	LS47	130

Resolutions not well constrained by fitting telluric features. LS24 resolutions should be determined accurately from unresolved lines in celestial sources. LS47 resolutions are set by image quality, which can be estimated during spectral extraction. Variations in R with wavelength not yet measured or accounted for.

Response Curves – SWC, Cy 2

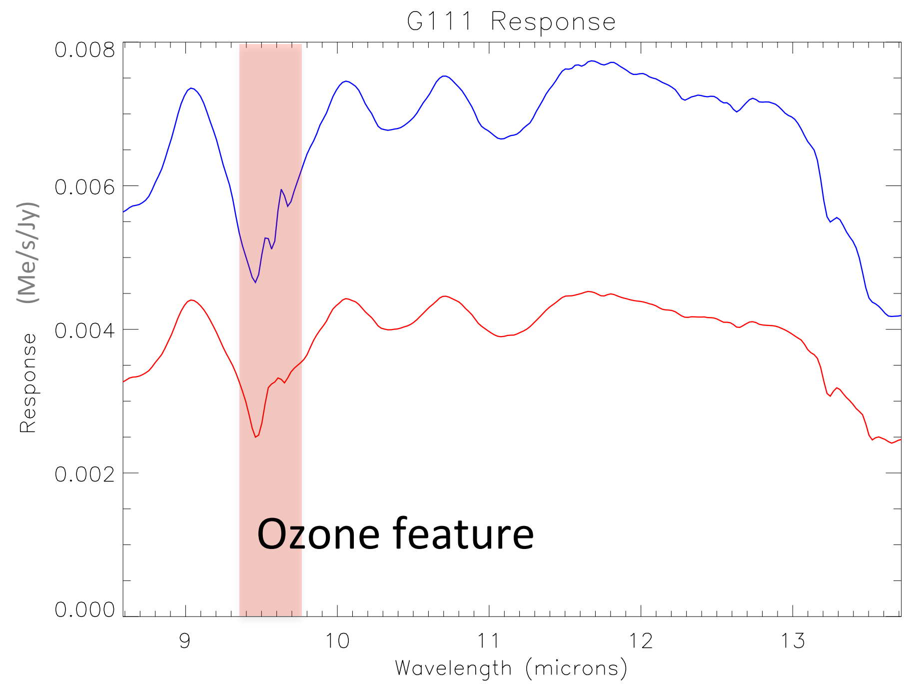


LS47 – wide slit = 4.7”

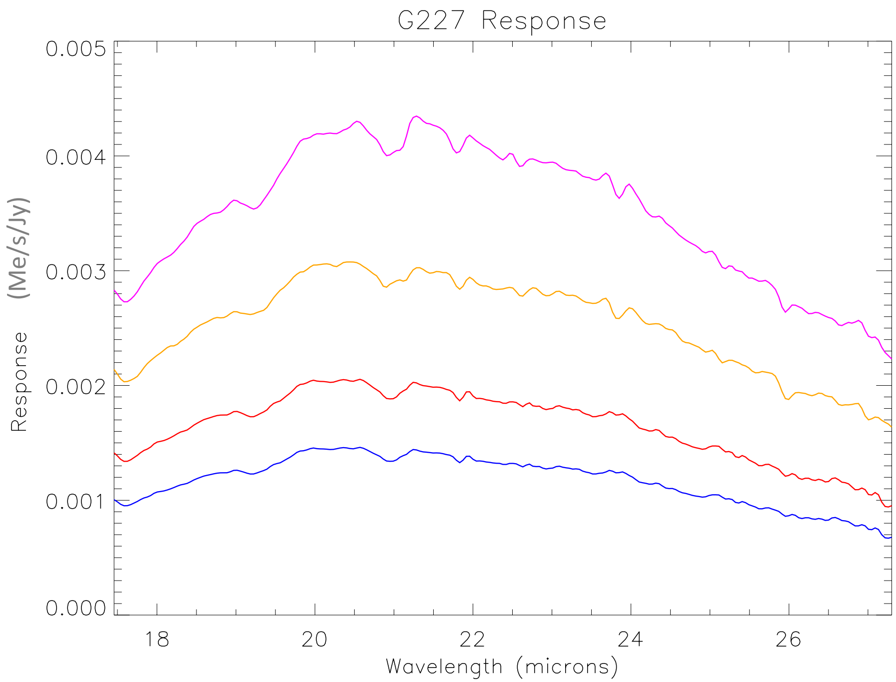
LS24 – narrow slit = 2.4”

LS47

LS24

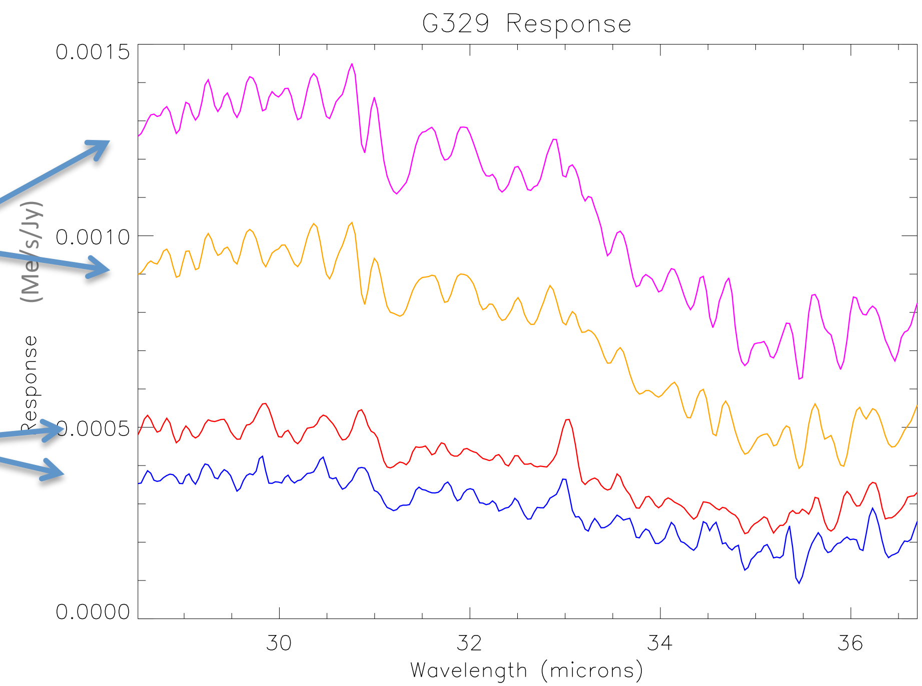


Response Curves – LWC, Cy 2



LS 47 / Det Bias 1.23 V
LS 47 / Det Bias 1.42 V

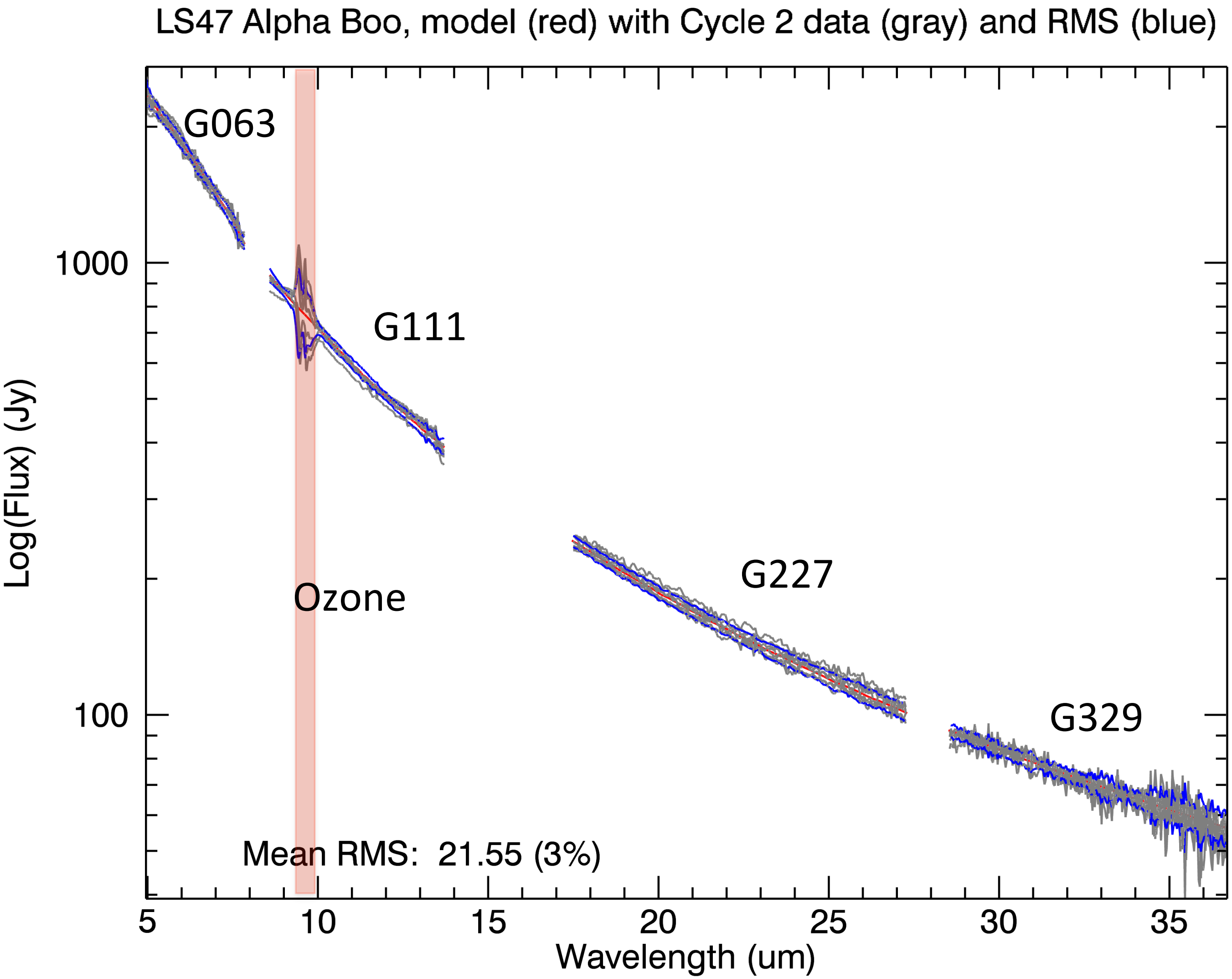
LS 24 / Det Bias 1.23 V
LS 24 / Det Bias 1.36 V



LS 47 / Det Bias 1.23 V
LS 47 / Det Bias 1.42 V

LS 24 / Det Bias 1.23 V
LS 24 / Det Bias 1.36 V

‘Internal accuracy’ of response curves – Wide Slit

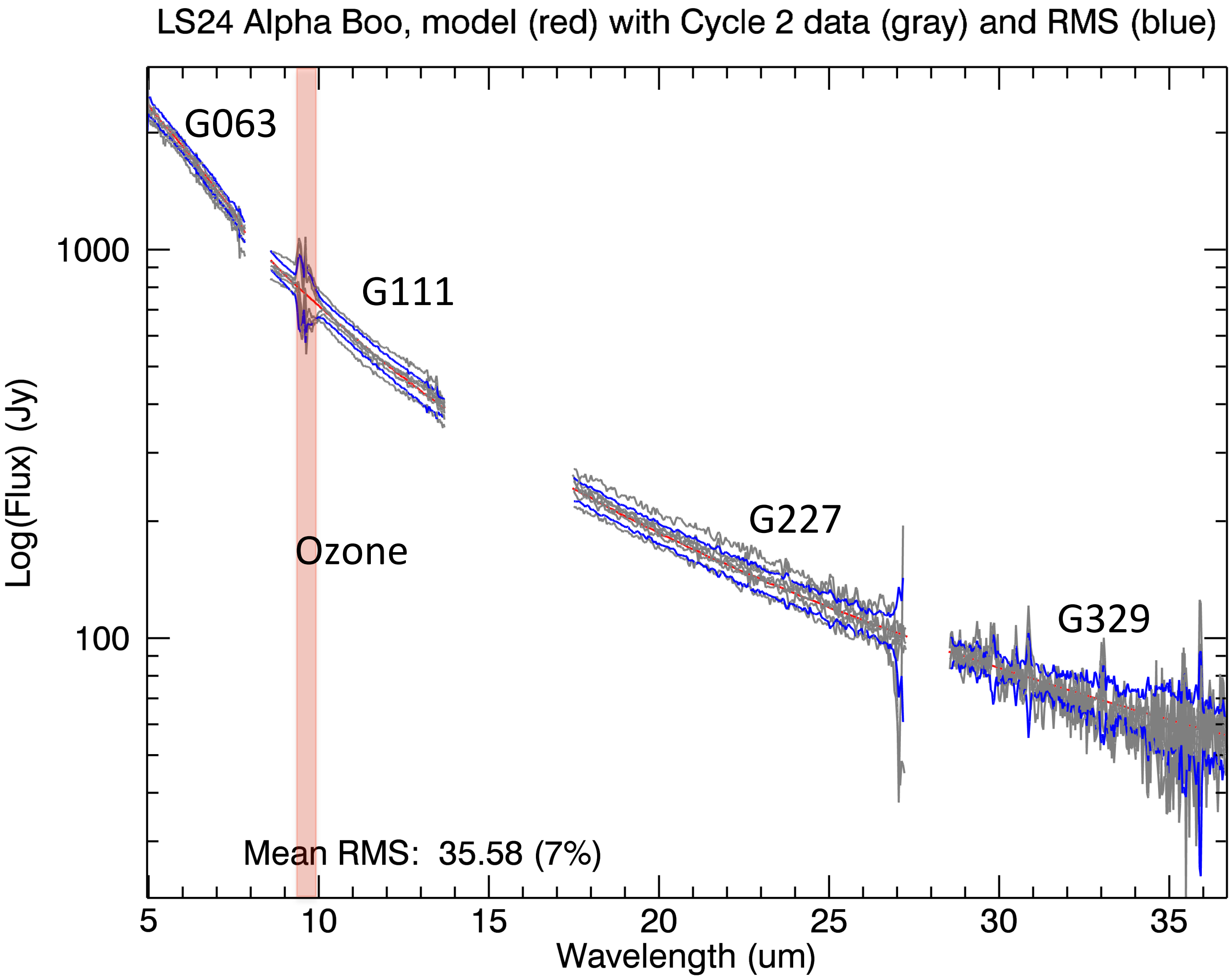


Mean RMS:

G063: 3%
G111: 3%
G227: 3%
G329: 4%

All : 3%

‘Internal accuracy’ of response curves – Narrow Slit

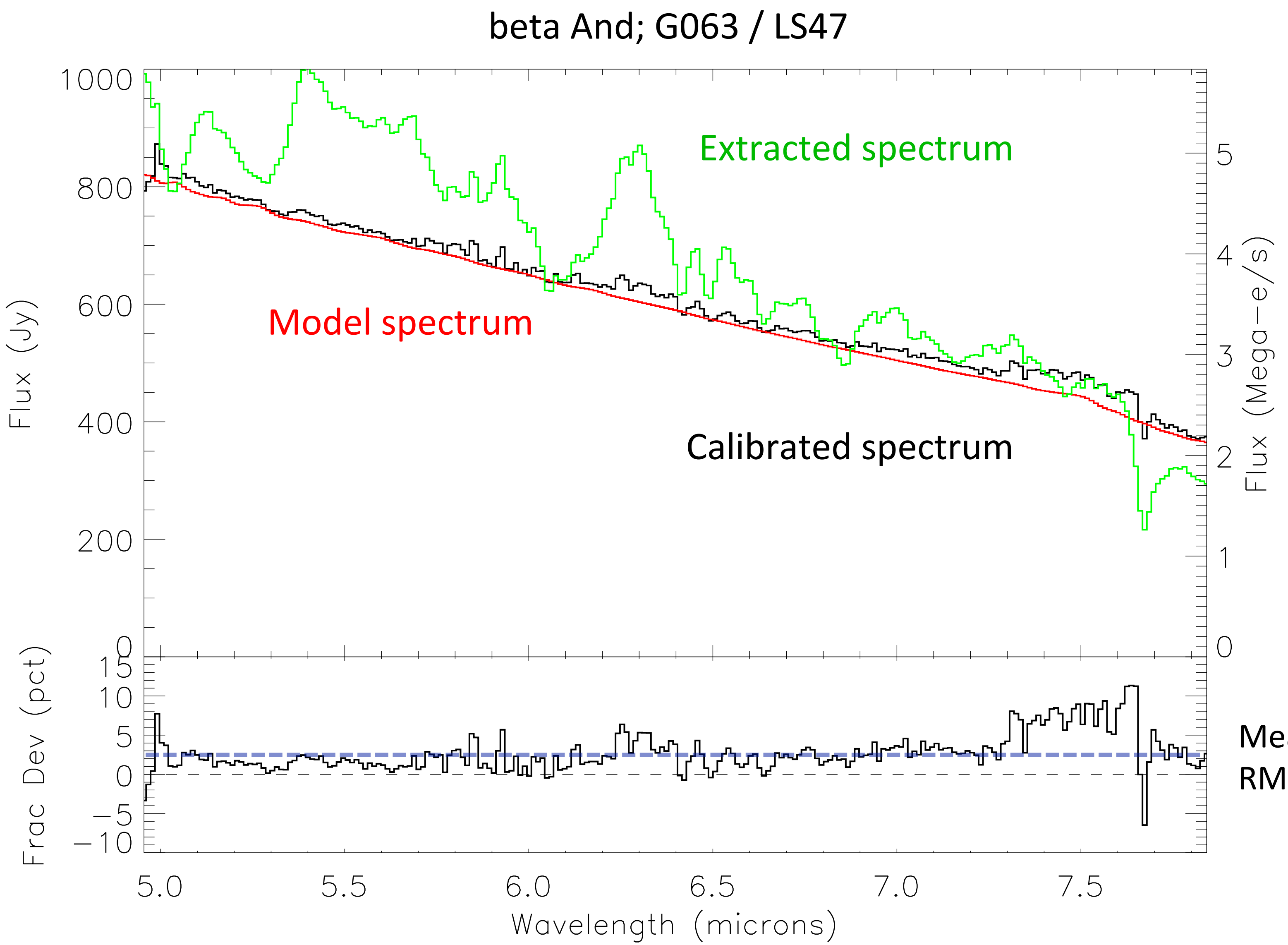


Mean RMS:

G063: 4%
G111: 6%
G227: 7%
G329: 10%

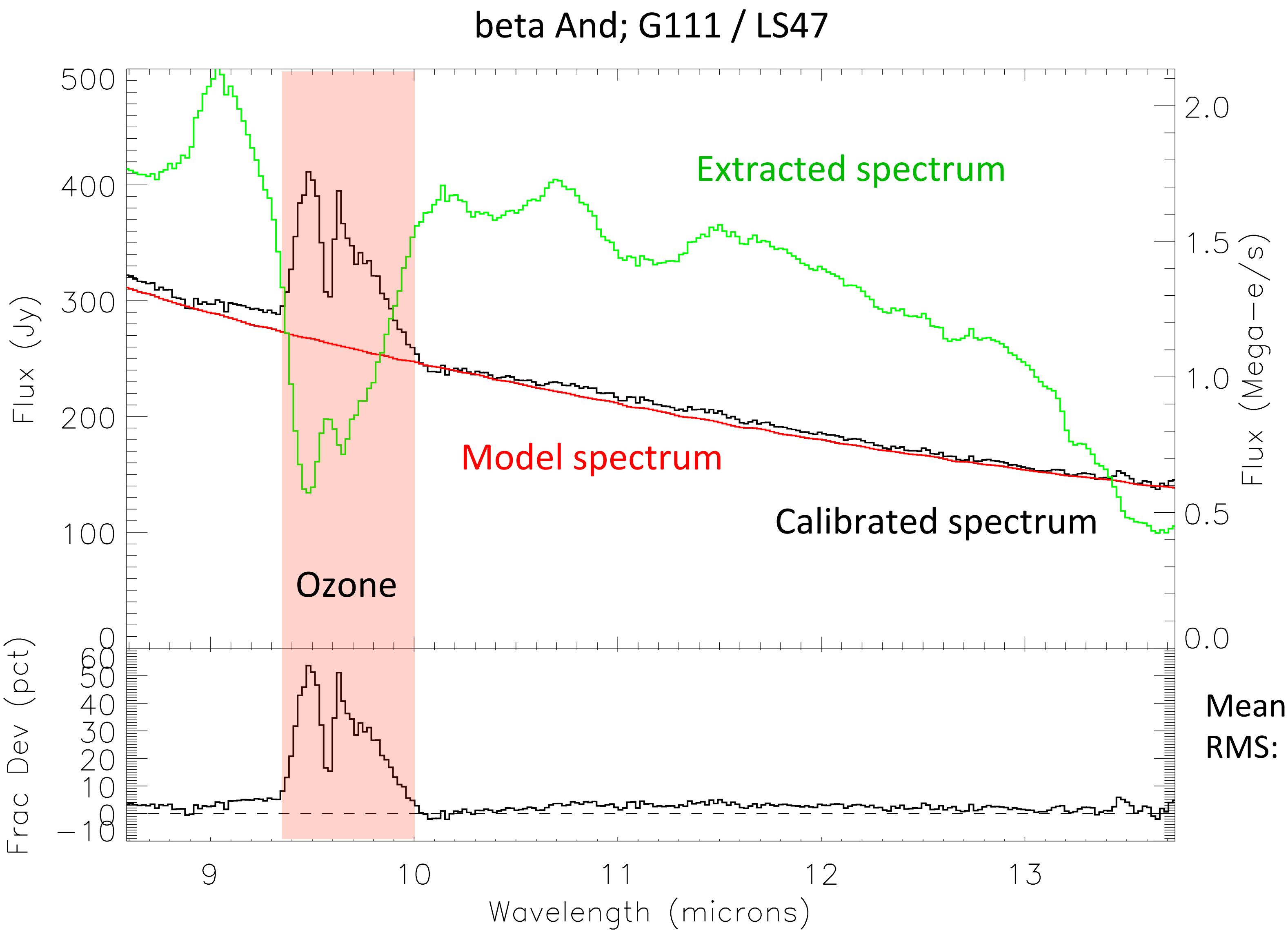
All : 7%

Absolute Accuracy of Grism Response Curves



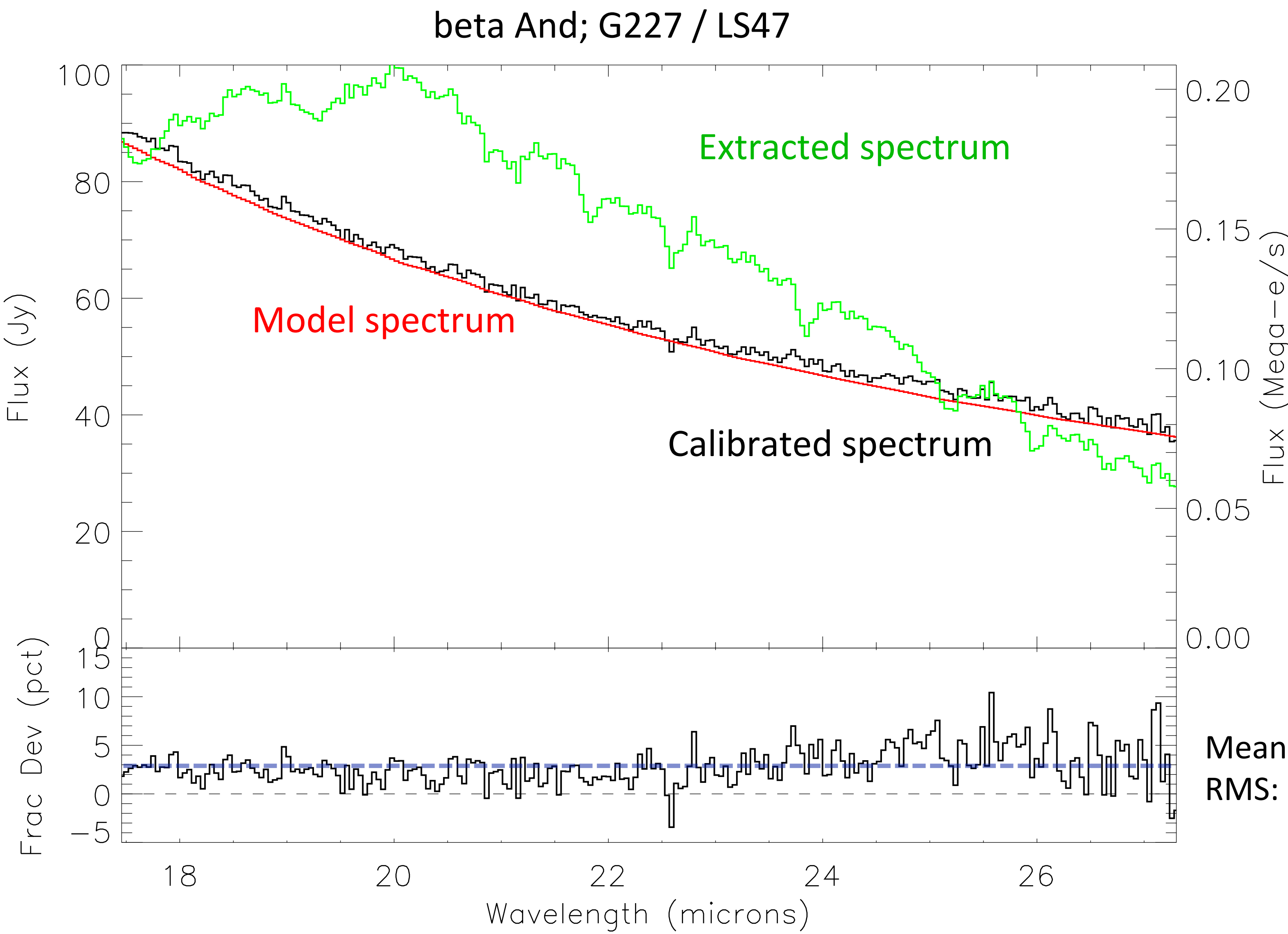
Mean Residuals: 2.8%
RMS: 2.4%

Absolute Accuracy of Grism Response Curves



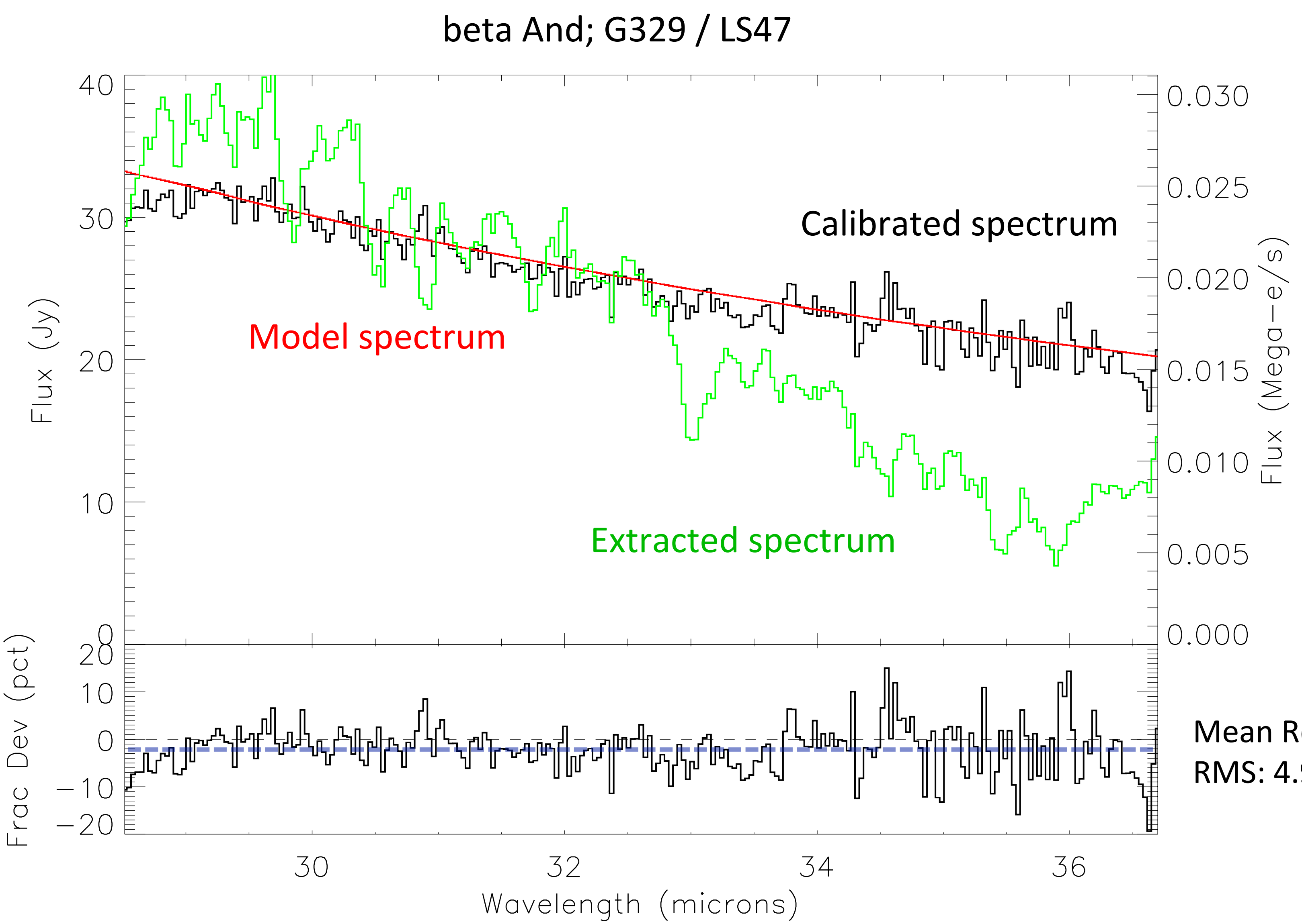
Mean Residuals: 5.6%
RMS: 9.9%

Absolute Accuracy of Grism Response Curves



Mean Residuals: 2.9%
RMS: 2.0%

Absolute Accuracy of Grism Response Curves



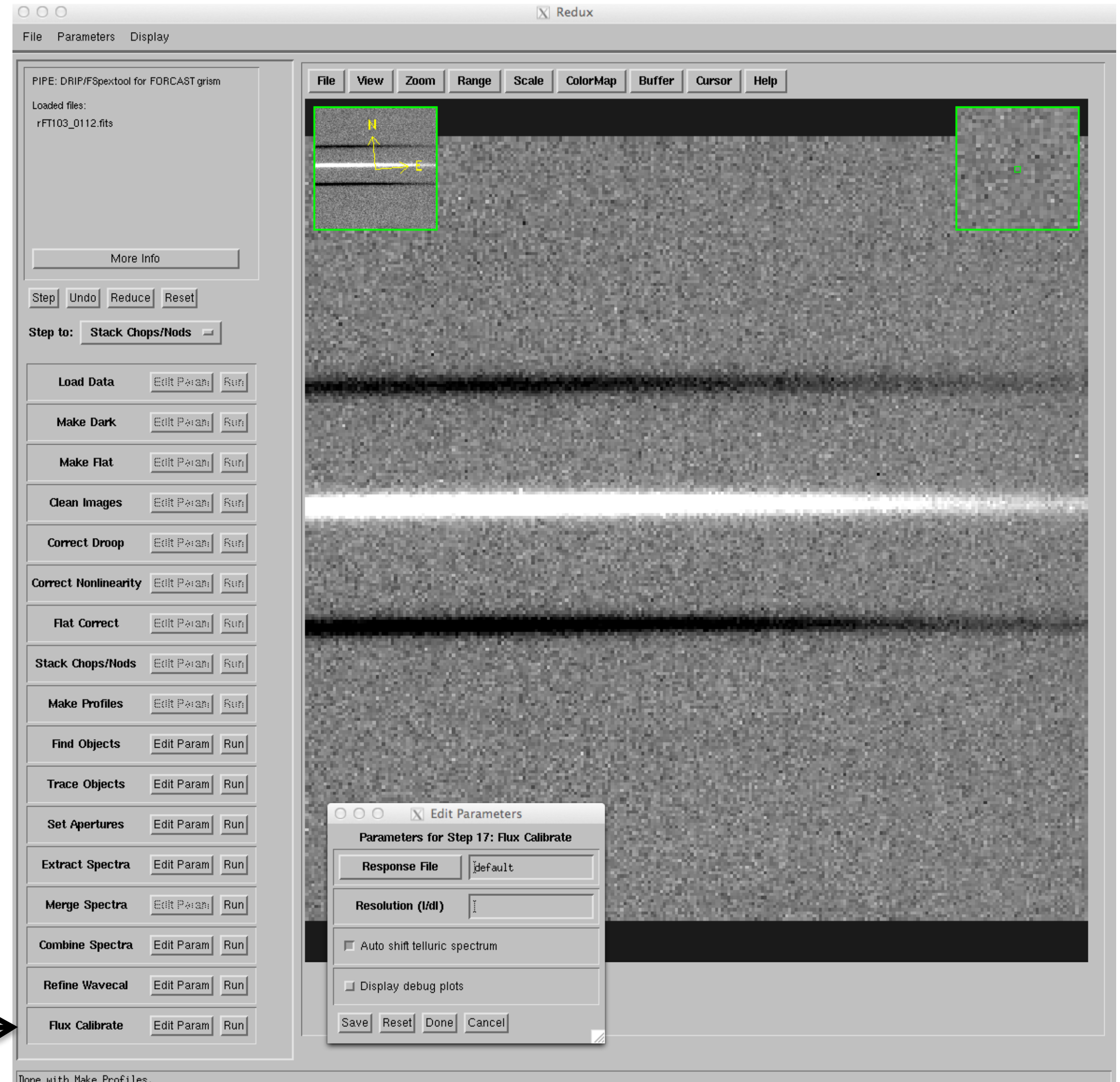
Mean Residuals: 2.1%
RMS: 4.9%

Implementation into Redux

Steps:

1. Read ZA and altitude of target from header and automatically determine the closest ATRAN model (in terms of ZA and altitude) from the stored library of models
2. Adopt default or user-specified resolution and smooth/sample telluric model
3. Choose response curve appropriate for camera (SWC/LWC), grism, slit, and date (detector bias)
4. Compute total correction curve by multiplying response by telluric model
5. Compute optimal λ shift of correction curve relative to target spectrum from x-correlation
6. Divide by total correction curve

Level 3 flux calibration step



FORCAST Grism Calibration Issues

- Resolution of each mode is not well constrained.
  - Resolution of narrow slit modes not known accurately
  - Resolution of wide slit modes set by image quality
  - Produces residuals in telluric corrected spectra
- Wavelengths may not be accurate enough
  - Produces residuals in telluric corrected spectra
- Relies on ATRAN models of telluric transmission as function of ZA and altitude
  - No other external inputs (e.g., WVM data)
  - Does not accurately model the ozone feature at 9.6 μm
- No incorporation of Flat Fields
  - Grism flat fields only recently available
  - Cy 2, Level 2 data reduced without flat fields
  - Some of the (small scale) structure seen in response curves due to flat response
- Response curves must be generated for Cycle 1 data
  - Instrument parameters (tilts, wavelengths, bias) changed between Cy1 and Cy2
- Responses for XD mode have not yet been computed
  - G2xG1 has 8 separate orders with poorly constrained λ's in bottom orders
- S/N of alpha Boo spectra in longest λ grism mode (G329) is fairly poor
  - G329/LS24 (narrow slit) mode particularly bad; recommend not offering mode
  - alpha Boo is brightest MIR standard in sky – need longer exp time or brighter objects (asteroids)

Summary

- FLITECAM grism data have been calibrated using a modified version of xtellcor_general, a model of Vega, and observations of A0V stars
- FORCAST data have been calibrated using software developed in-house, ATRAN models, and Herschel models of standard stars
- Telluric models have been generated for a large set of observing altitudes and ZAs, covering the wavelength range of the FORCAST grisms
- Response curves have been derived for single order FORCAST grism modes (G063, G111, G227, G329) with both slits (and for 2 detector bias settings) for Cy 2 data using observed spectra, telluric models, and model spectra of alpha Boo
- Implemented calibration method provides calibrated spectra good to better than ~10% for single order grism modes with the wide slit (LS47) for Cy 2 data
- Similar results found for LS 24 spectra, but…
  - Lower S/N
  - Subject to variable slit losses
- Highly accurate slit spectroscopy always requires imaging photometry for normalization of absolute flux levels
  - All MIR standard stars are intrinsically variable!
  - Calibration is only as good as models of standard stars
  - Need more cross-calibration of standards
- Algorithm/code have been incorporated into pipeline (Redux)
  - Ready to proceed with calibration of single-order Cy 2 spectra
  - Response curves for single order Cy 1 data and XD modes are underway