Correction for Ringing in the Calibrated Spectra of the Cross-track Infrared Sounder (CrIS)

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SSEC

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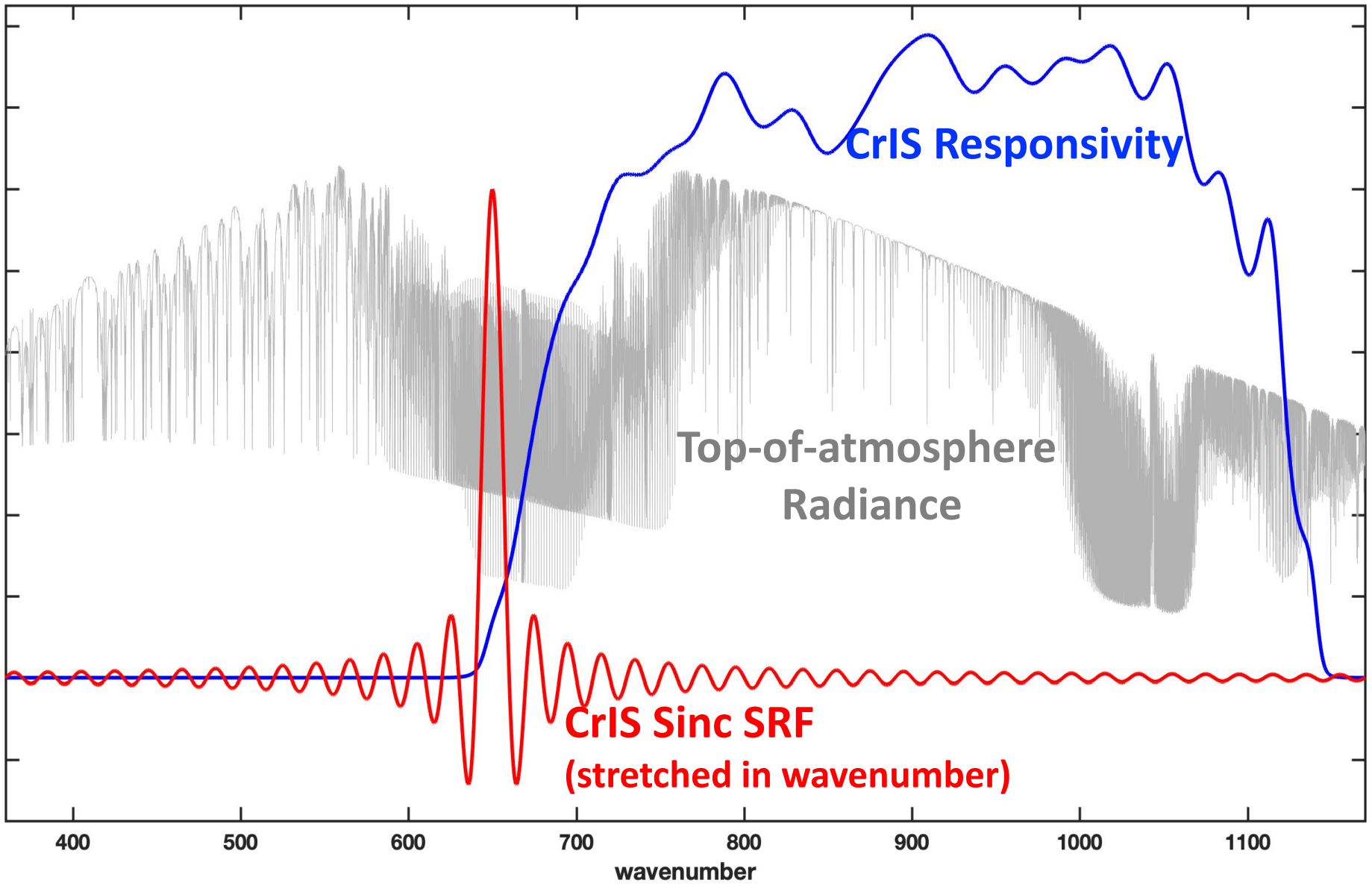
1. What is Ringing?

positive & negative oscillatory features from native Sinc SRF of FTS sensors

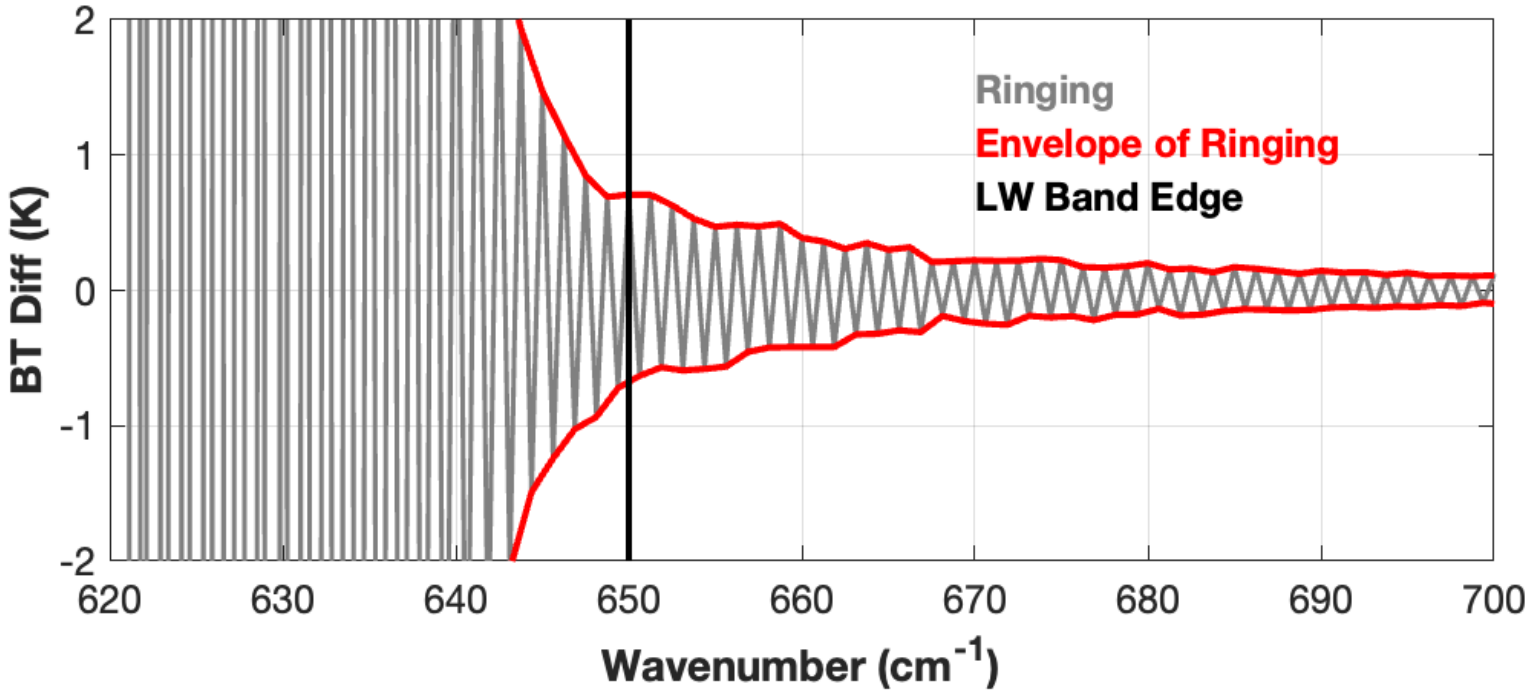
e.g. from convolution of Sinc SRF & finite, non-flat spectral band responsivity

SRF = Spectral Response Function



Ringing Oscillations: Borg et al., 2023

positive & negative oscillatory features from interaction of Sinc SRF & finite, non-flat spectral band responsivity



Borg, L.; Loveless, M.; Knuteson, R.; Revercomb, H.; Taylor, J.; Chen, Y.; Iturbide-Sanchez, F.; Tobin, D.
Simulation of CrIS Radiances Accounting for Realistic Properties of the Instrument Responsivity That Result in Spectral Ringing Features.
Remote Sens. 2023, *15*, 334. https://doi.org/10.3390/rs15020334

See this paper for a prescription for how to accurately include this ringing in calculated CrIS spectra

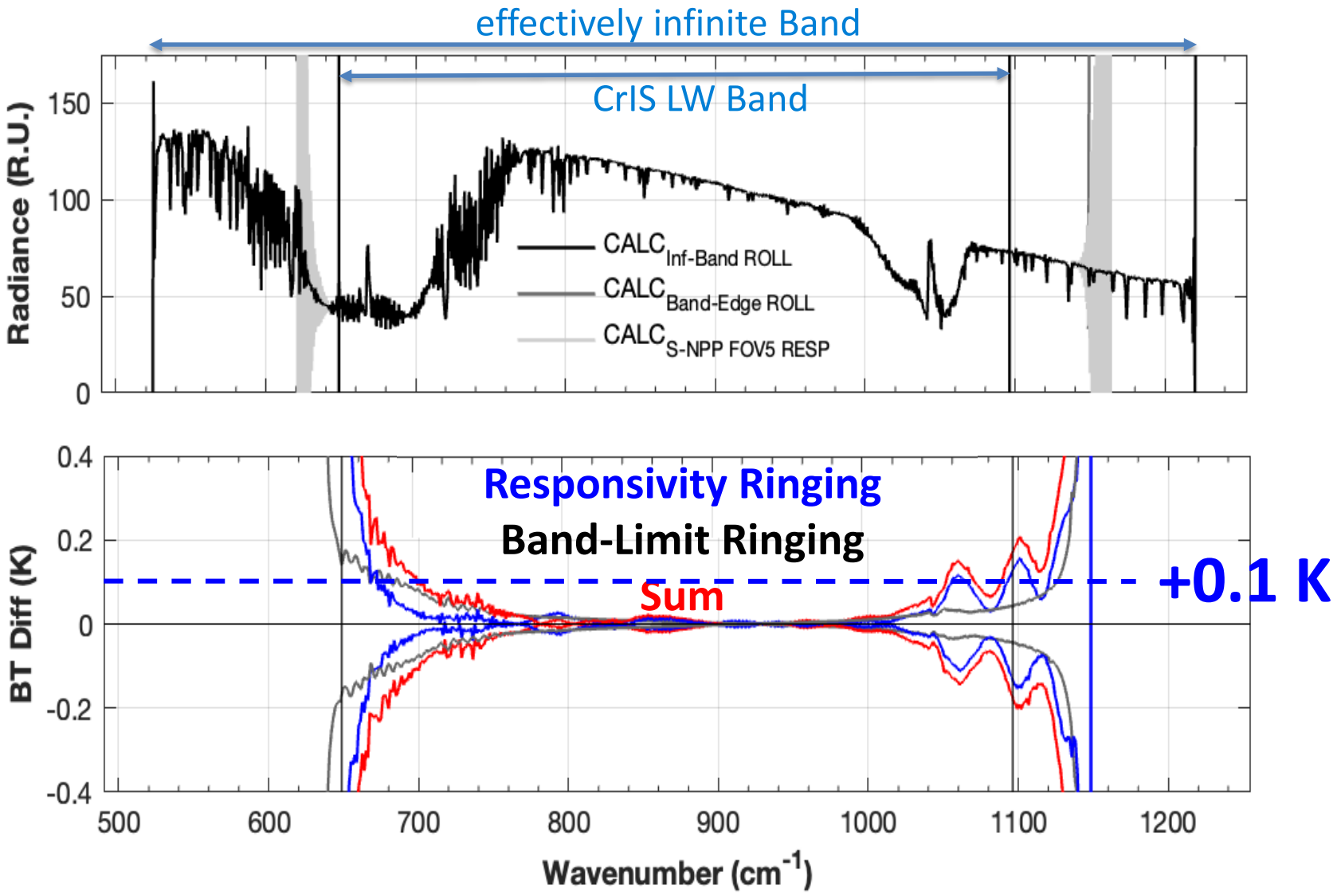
Sources of Ringing

- **Basic ingredient:** Sinc Spectral Response Function from the fundamental FTS approach that truncates the measurements in the Fourier Transform domain (interferogram) at a maximum Optical Path Difference
- **Specific Mechanisms for CrIS**
  - Finite spectral band coverage of measured spectra
  - Non-flat instrument responsivity inside measured bands
  - Artifacts of the spectral resampling and self-apodization correction steps of the calibration algorithm
  - Numerical filter: Lack of perfect circular sampling of original onboard numerical filter.

Black items have been minimized

CrIS Responsivity and Band-Limit Ringing

- These ringing effects are very small
- Matching calculated responsivity and band limiting rolloffs to observations removes biases
- Borg paper shows how to implement this approach
- Observation Correction approach motivated by minimizing burden on user



after Borg et al., 2023

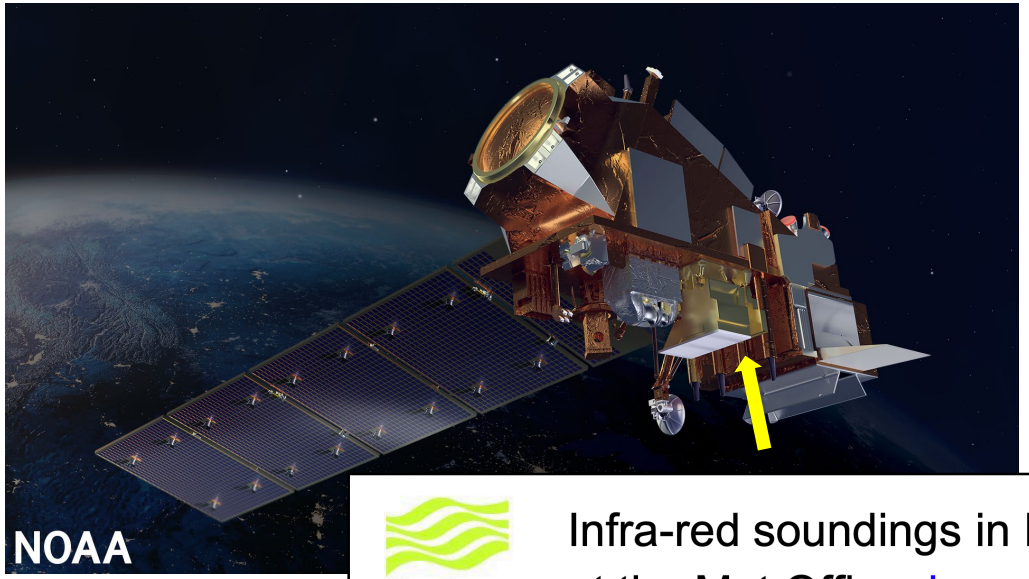
1. Perspective & Review of CrIS

- **Ringing for CrIS is very small and significant (larger than 0.1 K) only in specific spectral regions**

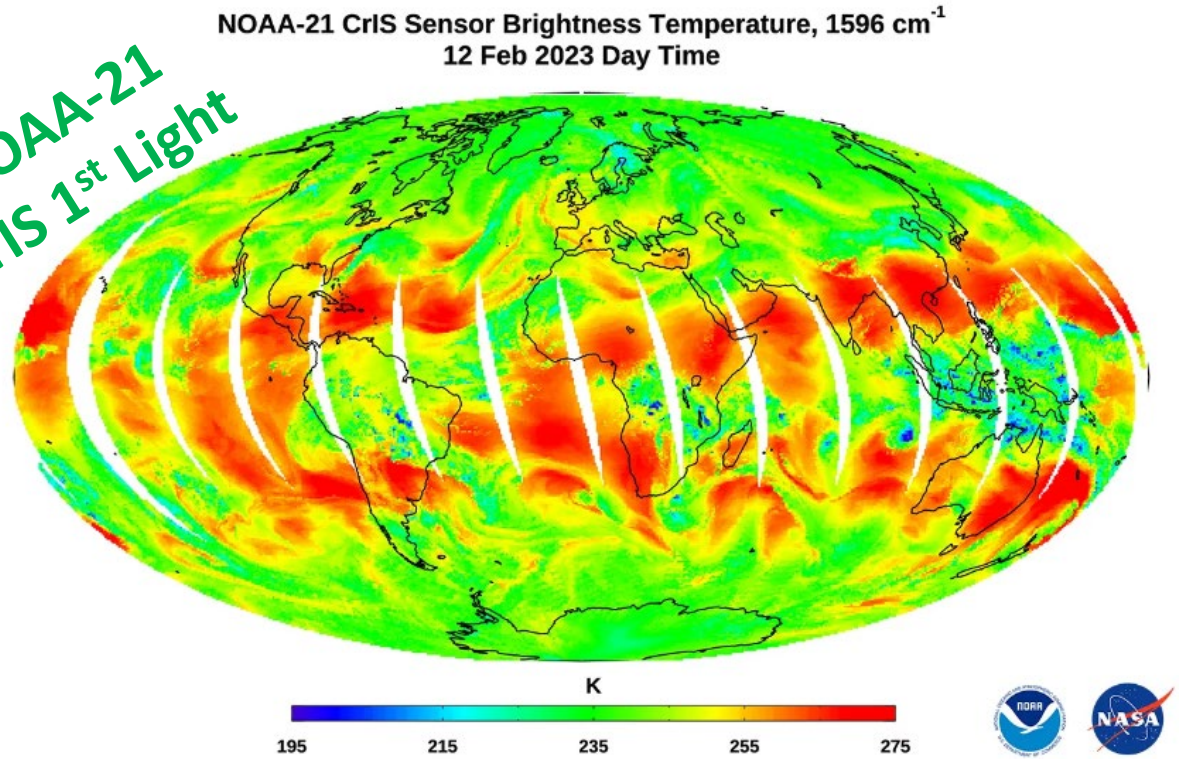
- Ringing is receiving new attention at this point, because the well-defined CrIS Radiometric Uncertainty (RU) is usually < 0.2 K 3-sigma

- And new Imaging FTS instruments like MTG-IRS and the NOAA GXO Sounder bring new challenges to the forefront

3rd CrIS now on-orbit showing excellent performance

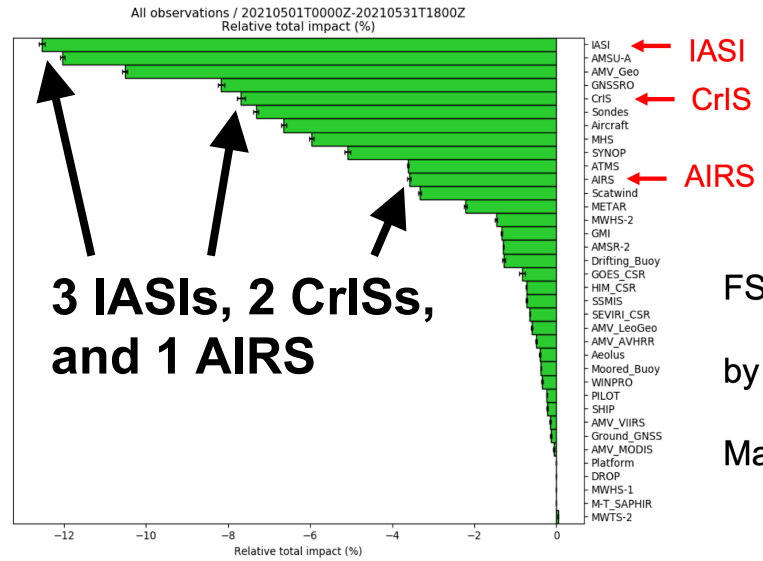


NOAA-21 CrIS 1st Light



Met Office

Infra-red soundings in NWP at the Met Office: impact (2)



IASI

CrIS

AIRS

3 IASIs, 2 CrISs, and 1 AIRS

FSOI impacts by instrument May 2021

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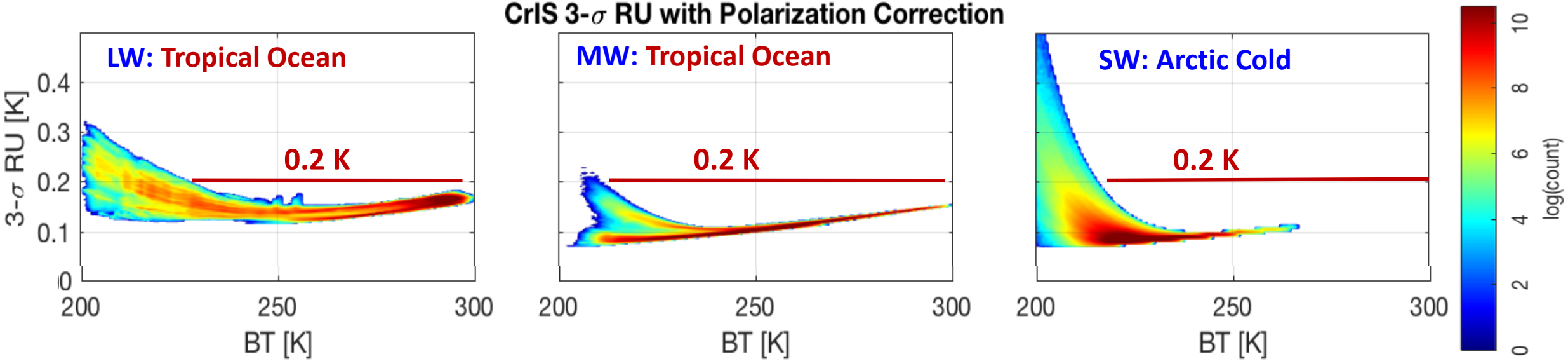
CrIS FSOI impacts at Met Office and ECMWF comparable to larger IASI & AIRS instruments

CrIS On-orbit 3-σ Accuracy (or RU)

Density plots of T_b uncertainty at scene T_b



NOAA20, 1 April 2018 granules all spectral channels and FOVs

Blackbody RU for all bands: Approximately MW lower bound

LW extra: Non-linearity

MW extra: Non-linearity, plus Polarization

SW extra: Polarization

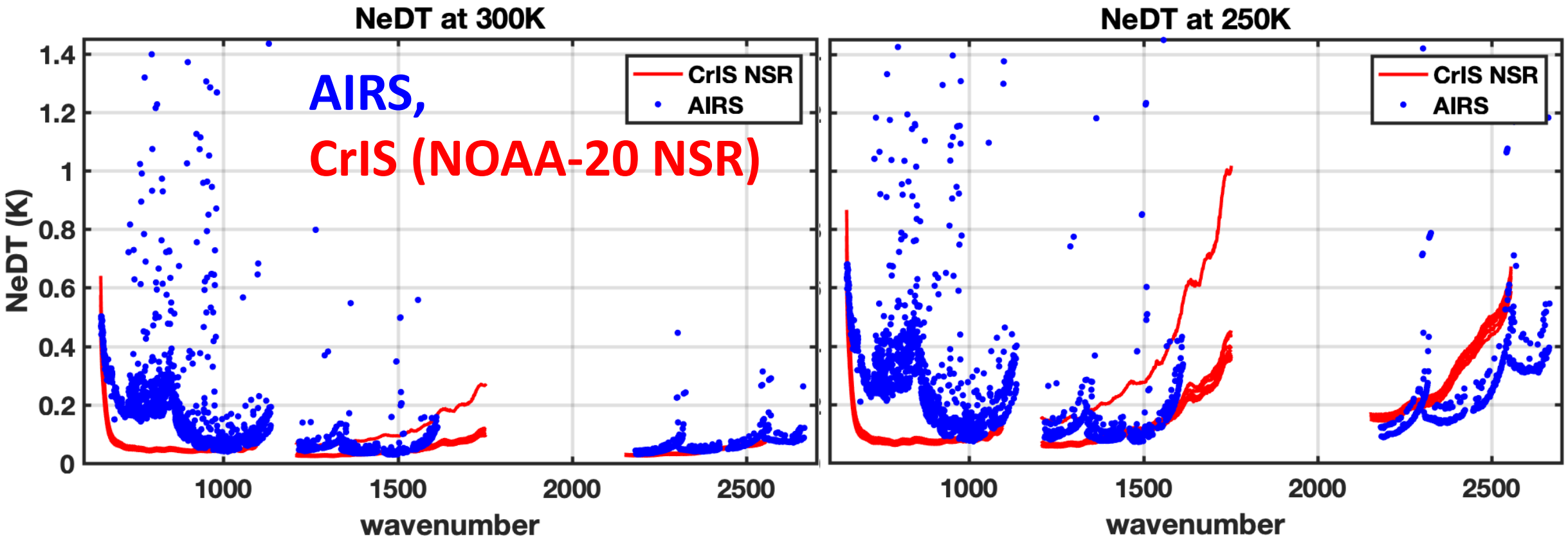
RU availability for every spectrum enhances value as key climate record

CrIS RU, the product of many years of development

- **Spectral Fidelity of Basic Fourier Transform approach: stems from broad spectral band coverage of each detector, well-known SRFs, & robust spectral scale from laser reference (1970s)**
  - As realized and emphasized by Jim Brault early on
  - Chosen for sounding by Bill Smith at U of Wisconsin
  - Implemented with robust dynamic alignment by Henry Buijs, Bomem/ABB

- Onboard Cavity Blackbody: HIS, AERI, AIRS, CrIS (1980s -)
- Complex Calibration: HIS Aircraft instrument (1988)
- Non-linearity Correction: Ground-based AERI and Scanning HIS Aircraft instruments (1990s)
- Polarization Correction: AIRS (1990s) & S/C flip maneuver (2012 -)

CrIS Noise is Excellent too



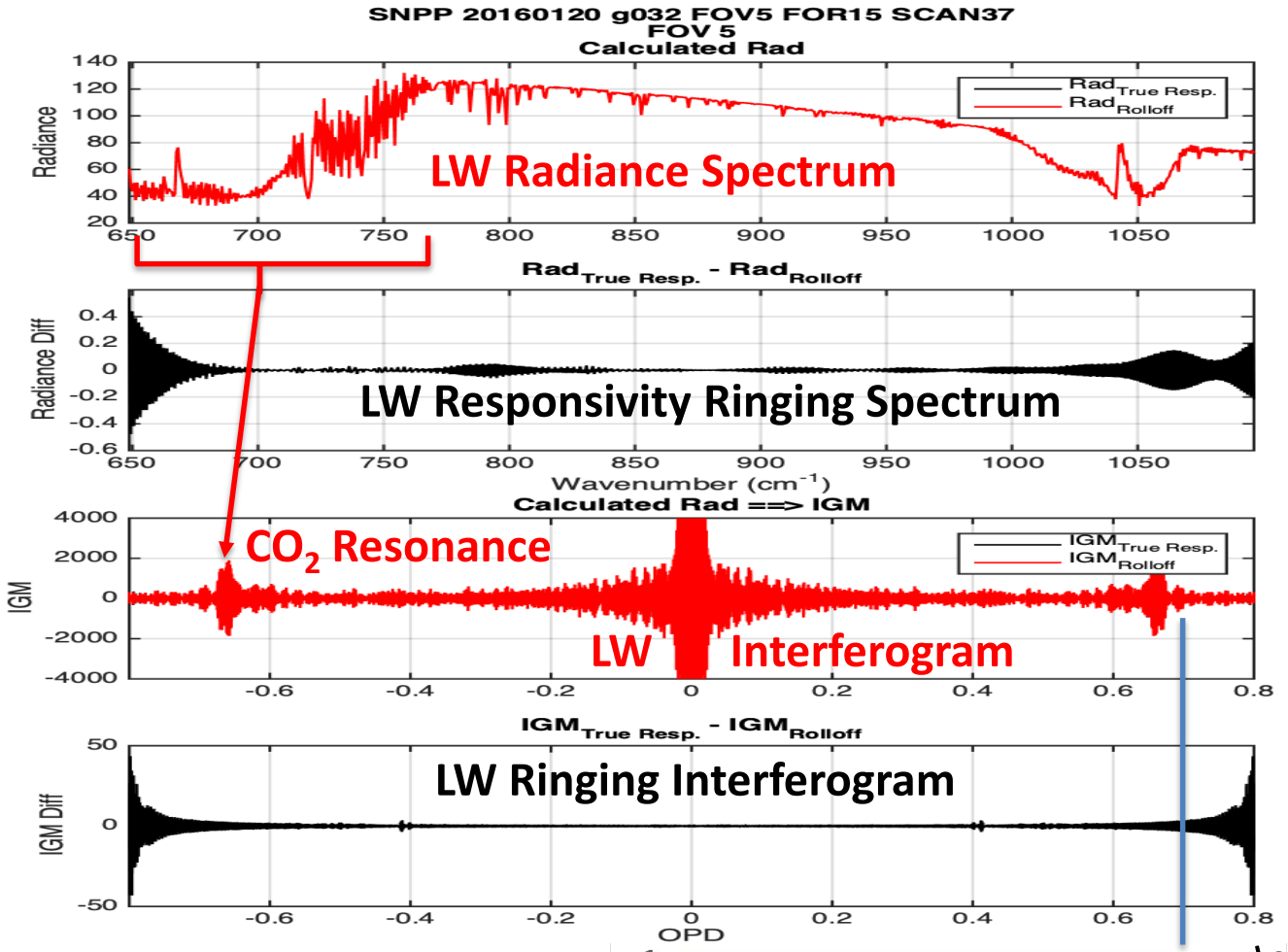
CrIS noise better than or comparable to AIRS in all 3 spectral bands

3. Basis for New Ringing Correction

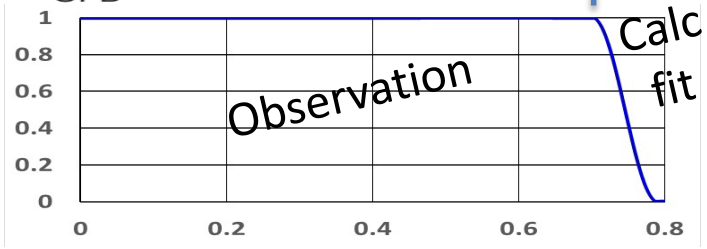
- Outgrowth of a responsivity ringing correction originally presented at ITSC-21, 2017 hosted by EUMETSAT
  - That correction did not work well, as pointed out by Nigel Atkinson (Thanks). We identified the problem as using the observed spectrum for the first guess for iteration. A first guess free of responsivity-induced ringing was needed.
  - Our first guess idea actually became this correction
- Ringing originates from the high delay end of the interferogram, because it is a high resolution effect. So the correction replaces the high delay region of the Fourier Transform of observed spectra with approximations generated from calculations. A smoothly varying cosine weighting is used to transition from the observed to a calculated interferogram at high delays.
- Here, the calculated option uses Principal Components (PCs) from calculated spectra to approximate the observed spectrum. The number of PCs used is selected to avoid fitting ringing features not included in the training.

Choice of Weighting Function W (1)

- Choose cosine weight W of interferogram that
  (1) Removes most ringing artifacts at large delays
  (2) Minimizes delays replaced with calculation (1-W)
- Starting W cutoff > 0.7 cm avoids LW CO_2 resonance near x= 0.66 $\pm$ 0.03 cm
- W =1 from x=0 to x=xs cm and reaches W=0 at 0.79 cm
- Effect of noise correlation from weak apodization is will be small

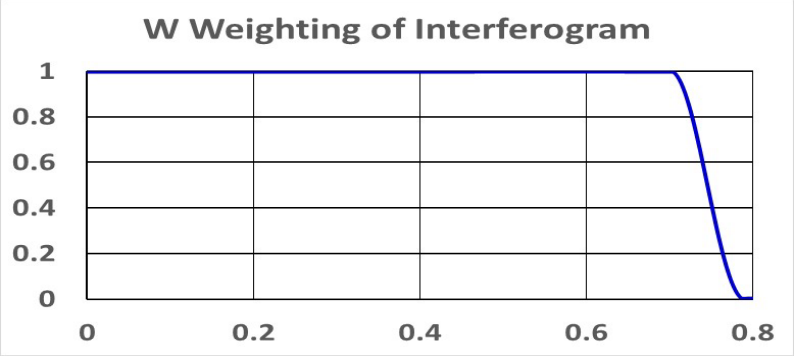


Weight W removes ringing & keeps CO_2



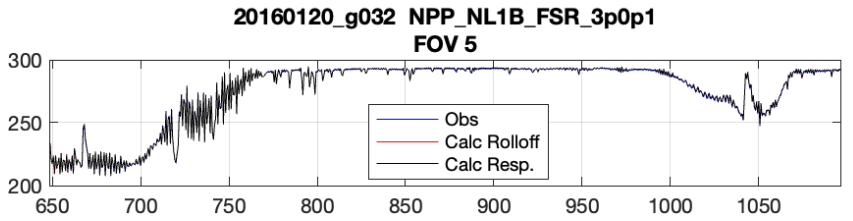
Choice of Weighting Function W(2)

- Choose cosine weight W of interferogram that
  (1) Removes most ringing artifacts at large delays
  (2) Minimizes delays replaced with calculation (1-W)
- Starting W cutoff > 0.7 cm avoids LW CO_2 resonance near x= 0.66 ± 0.03 cm
- W =1 from x=0 to x=xs cm and reaches W=0 at 0.79 cm

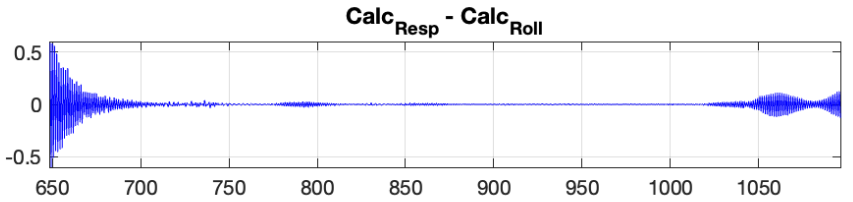


cm OPD

LW Tb Spectrum



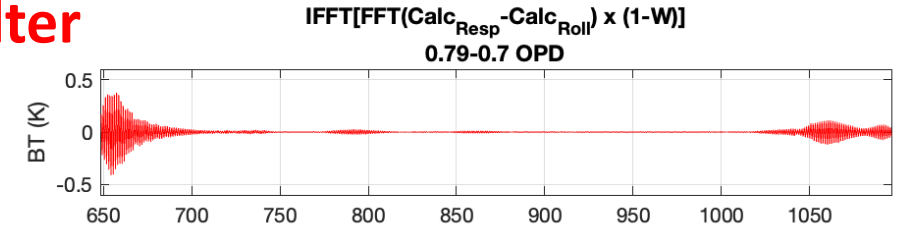
Calculated Responsivity Ringing



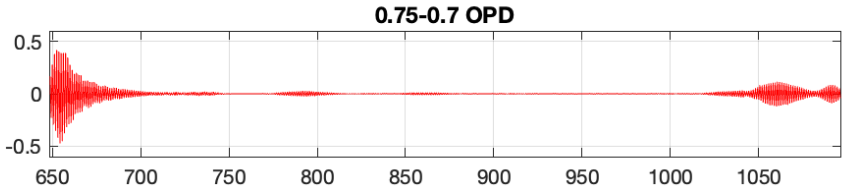
Captured by 1-W filter

0.70 – 0.79 cm

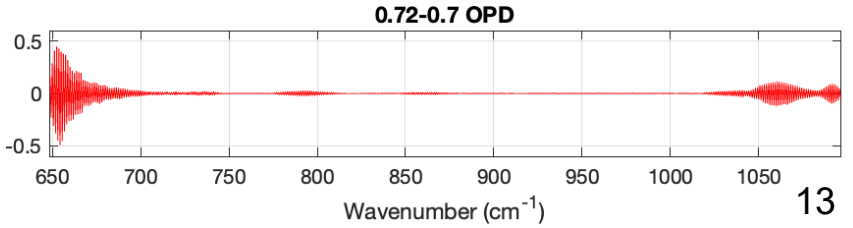
Selected xs



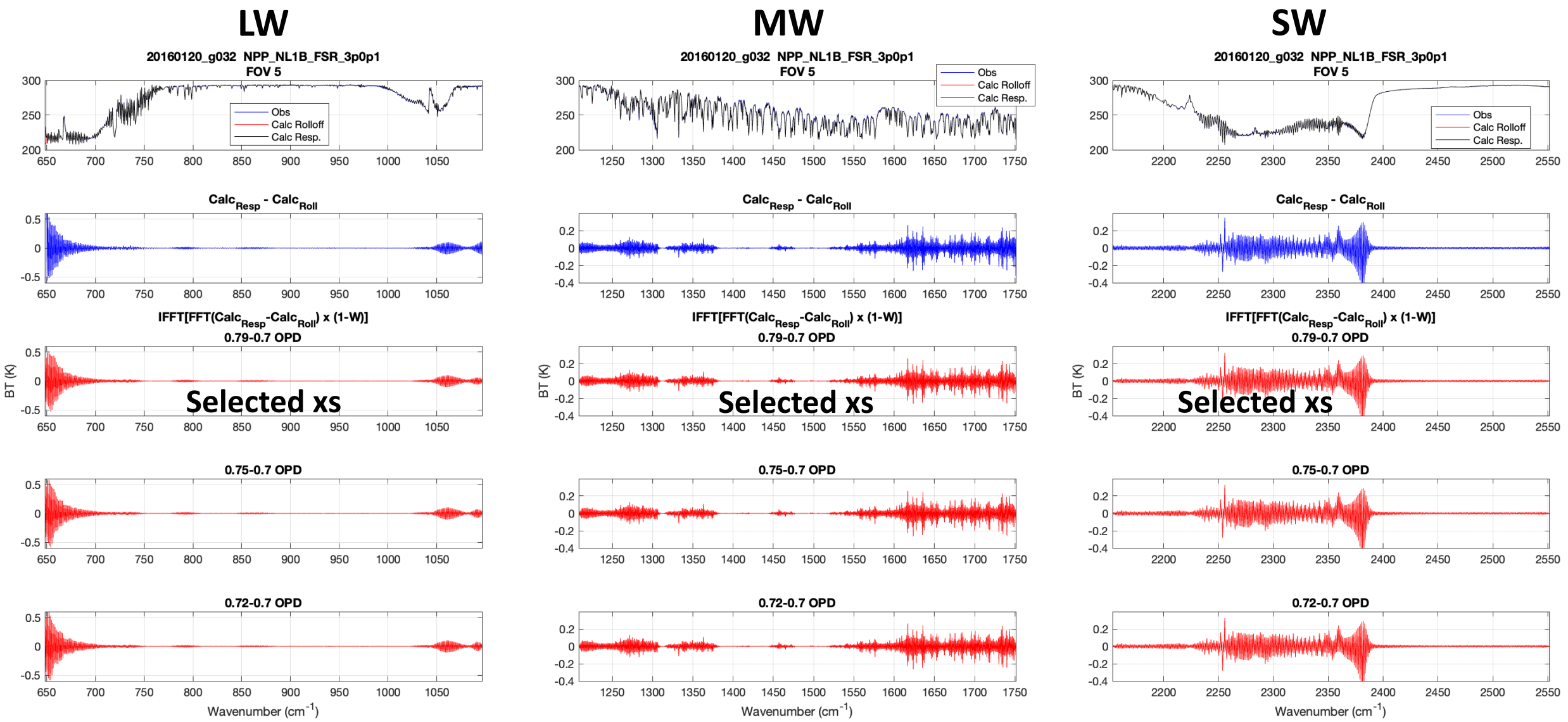
0.70 – 0.75 cm



0.70 – 0.72 cm



Choice of Weighting Function W, all bands



Replacement Rolloffs

Choice of PC Number for the fit

- Following comparisons suggest that reasonable choices of PC number are between 200 and about 500 PCs for the LW
- Criteria
  (1) too few PCs can distort true atmospheric spectral features, and
  (2) too many PCs start fitting the ringing features to be removed with the correction
- Generally, fits to higher Optical Path Differences (delays) improve as the number of PCs is increased

Joe Taylor's effort making use of Elisabeth Weisz's implementation of Bill Smith's DRDA retrievals

Fitting Observed Radiances with PCs from Calculations

100 PCs

100 PCs not enough

Interferogram doesn't look like Ringing

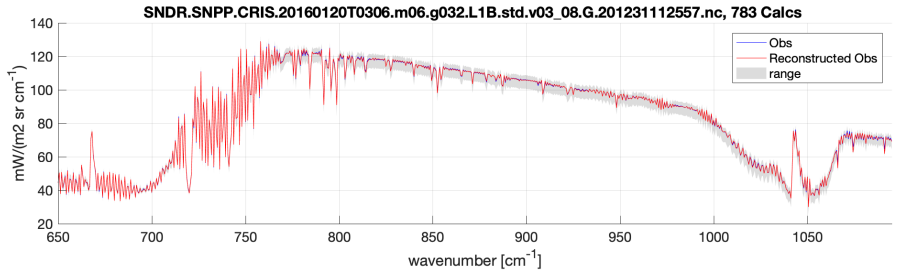
Spectrum is Not Pure Ringing

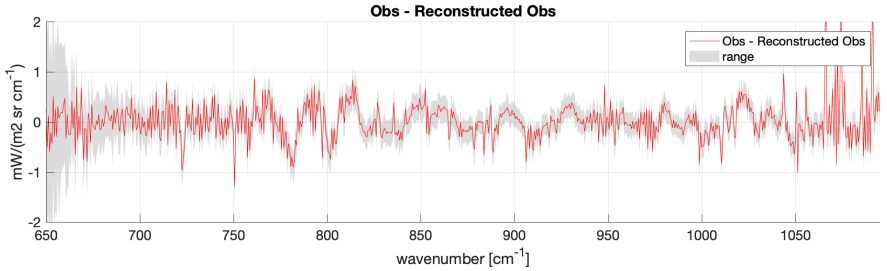
Total Spectral Residuals

Interferogram Residuals & Cosine Weight W

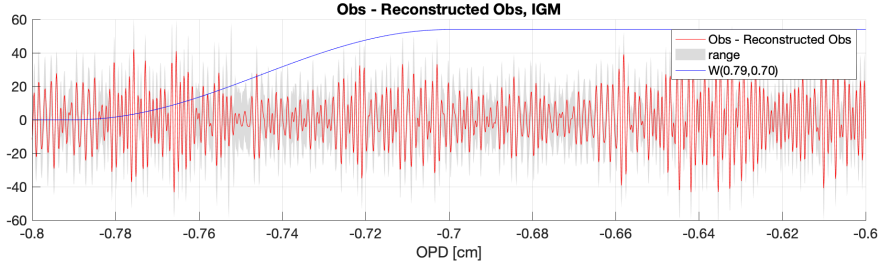
Spectral Residual from I x W

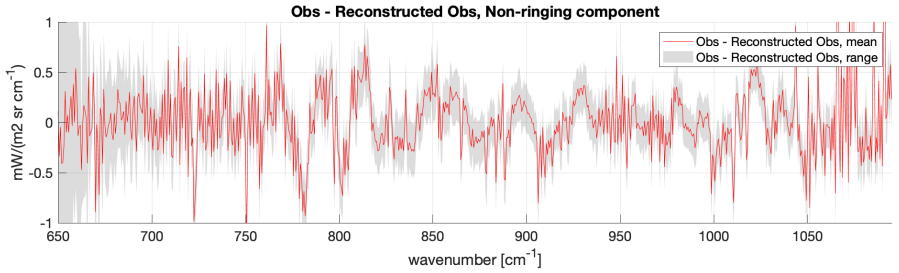
Spectral Correction from I x (1-W)



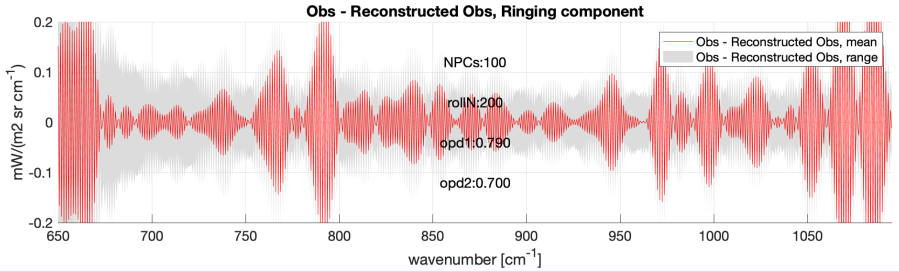


±2





±1



±0.2

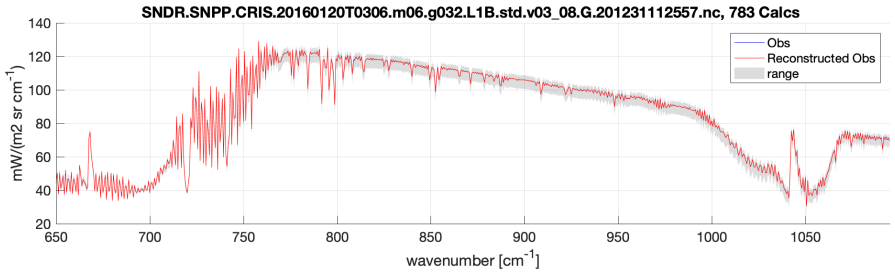
Observed Radiance – PCRTM Reconstructed Radiance

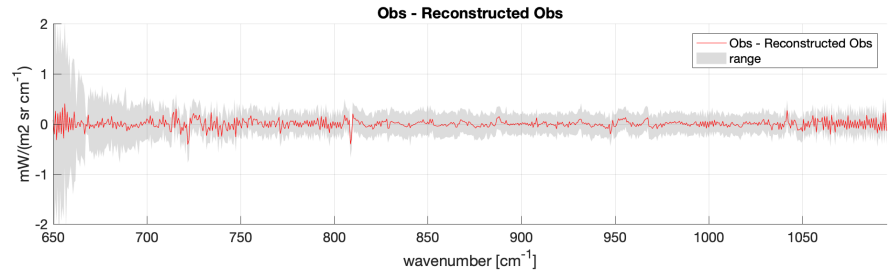
Fitting Observed Radiances with PCs from Calculations

200 PCs

200 PCs looking good
- note noise signature

Total Spectral Residuals

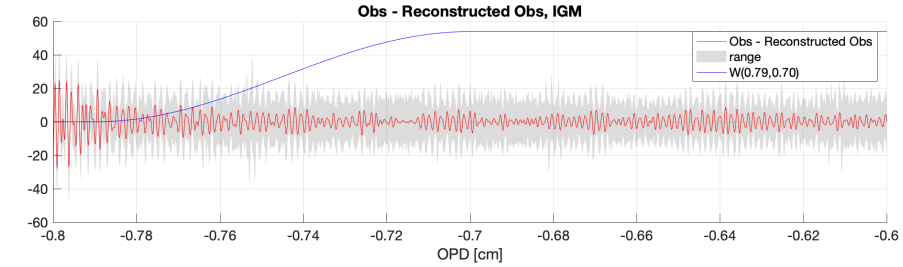




±2

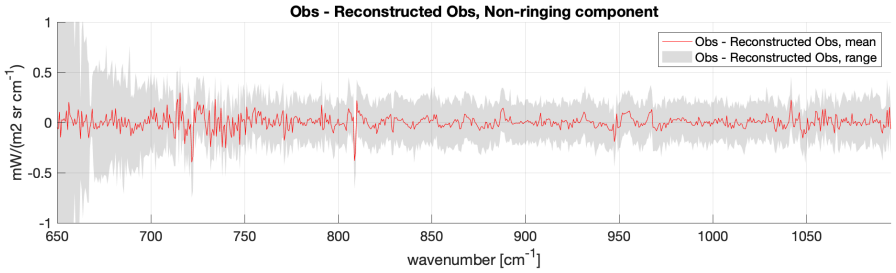
Interferogram looks like Ringing

Interferogram Residuals & Cosine Weight W



Verifies Good fit

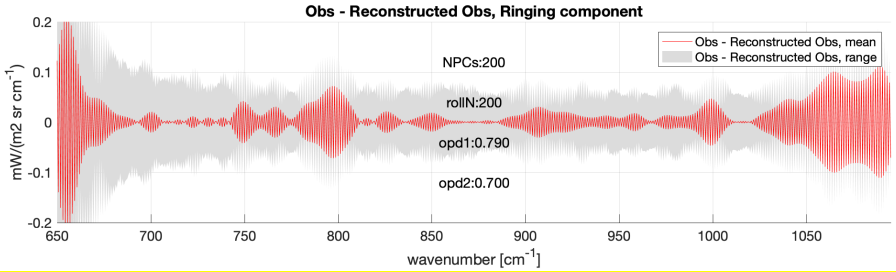
Spectral Residual from I x W



±1

Responsivity Ringing Spectral Signature
-should provide good correction

Spectral Correction from I x (1-W)



±0.2

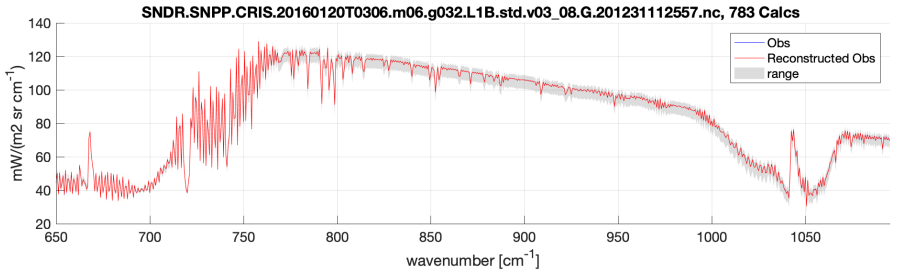
Observed Radiance – PCRTM Reconstructed Radiance

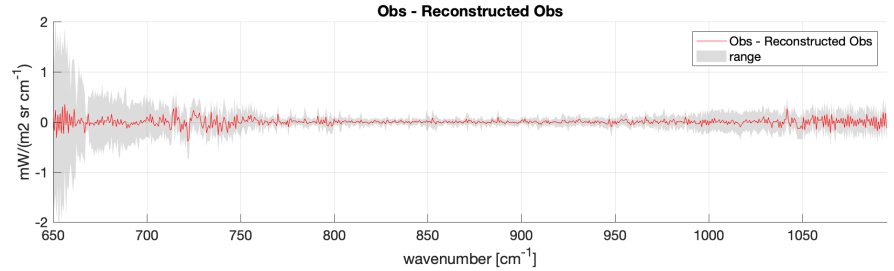
Fitting Observed Radiances with PCs from Calculations

700 PCs

700 PCs fitting noise
-slight over fitting

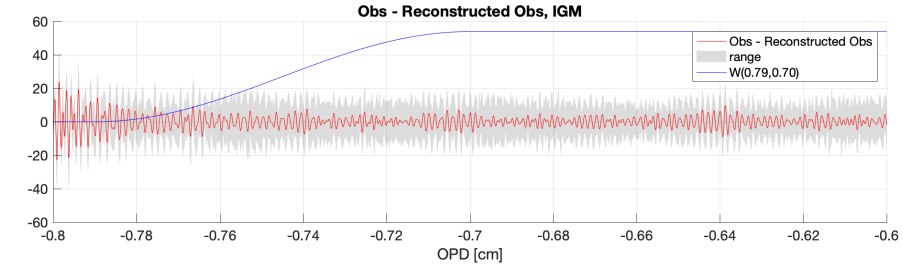
Total Spectral Residuals



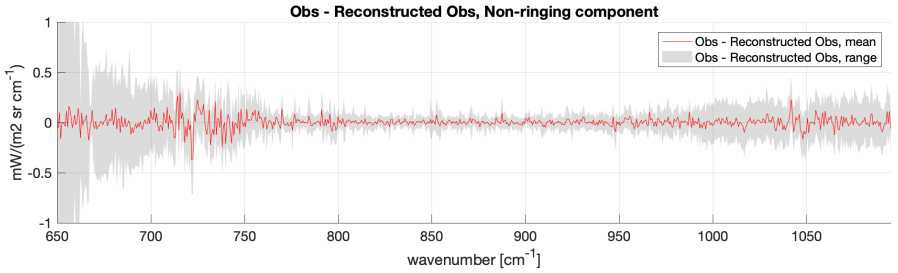


±2

Interferogram Residuals
& Cosine Weight W



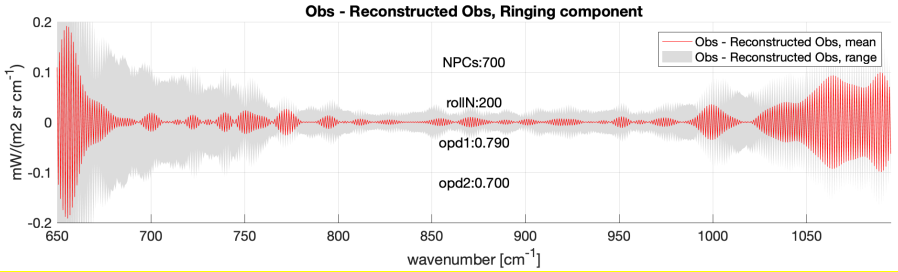
Spectral Residual
from I x W



±1

Slightly fitting
Responsivity Ringing

Spectral Correction
from I x (1-W)



±0.2

Observed Radiance – PCRTM Reconstructed Radiance

Fitting Observed Radiances with PCs from Calculations

1100 PCs

1100 PCs fitting noise -more over fitting

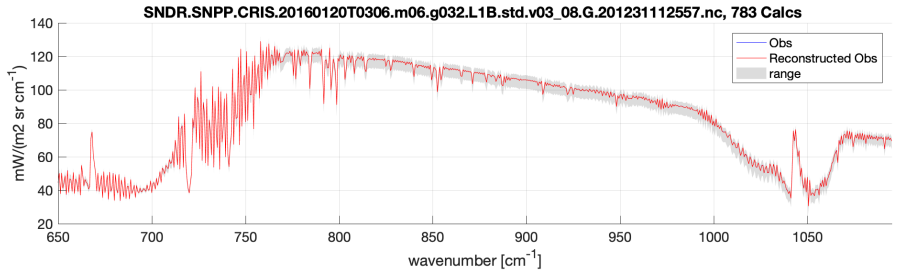
Total Spectral Residuals

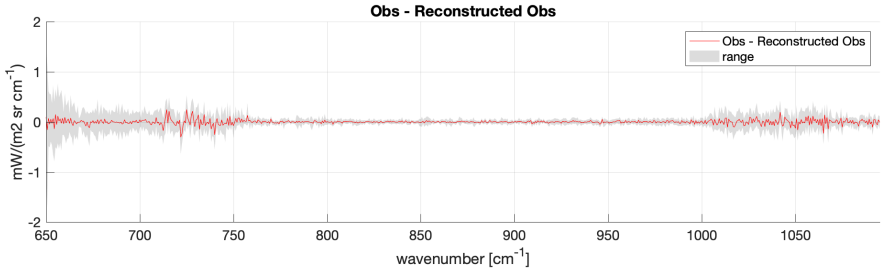
Interferogram Residuals & Cosine Weight W

Spectral Residual from I x W

Fitting too much of Responsivity Ringing

Spectral Correction from I x (1-W)





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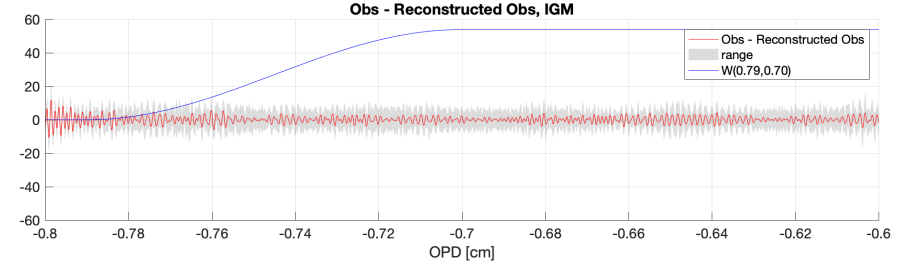
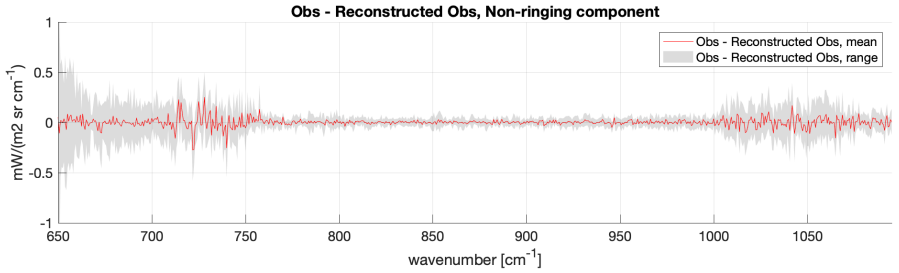
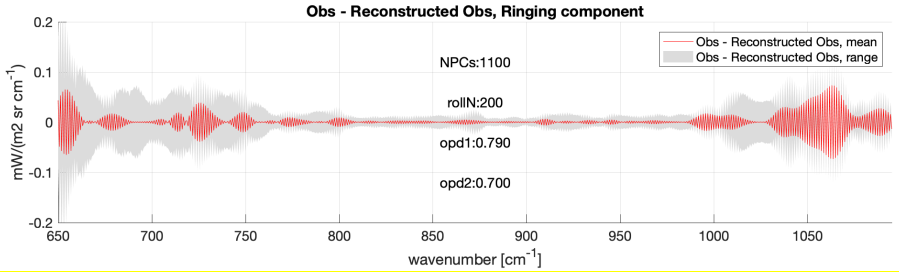




±1

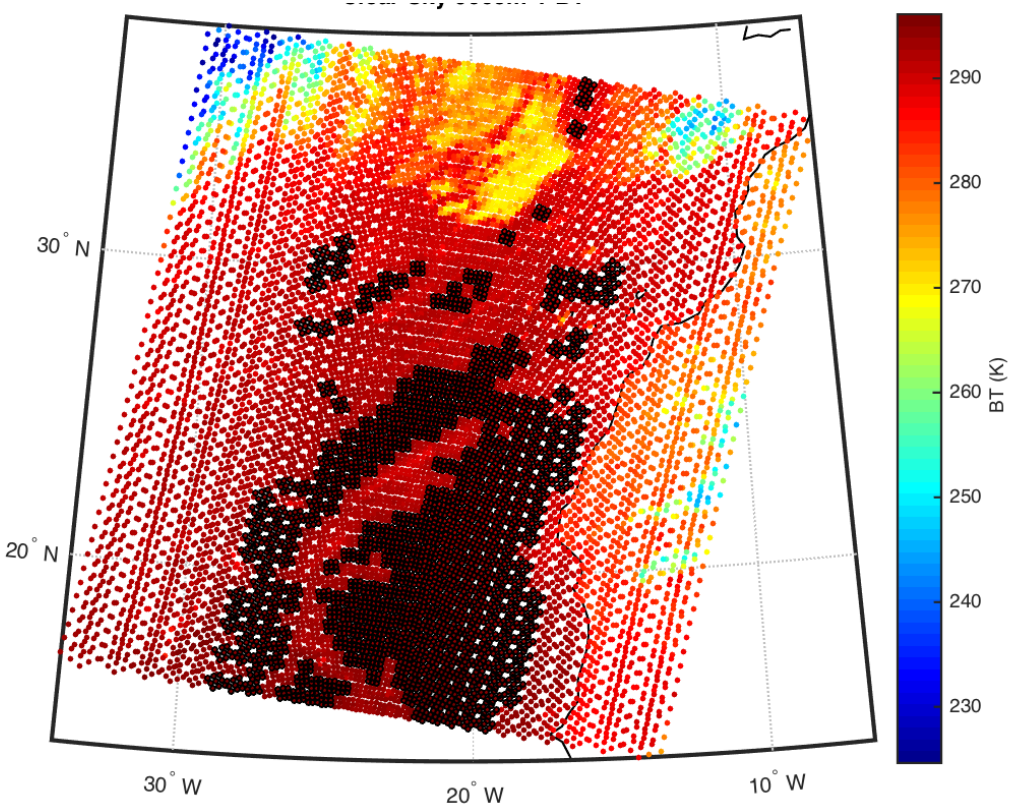


±0.2

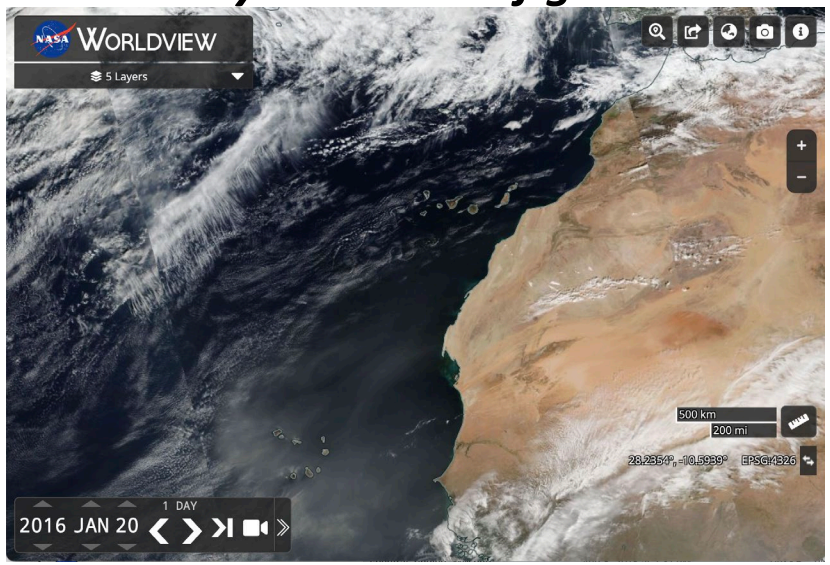
Observed Radiance – PCRTM Reconstructed Radiance

4. New Ringing Correction Results

- Using Suomi NPP granule from Borg, et al. Ringing Paper, 20 Jan 2016
  Nighttime, Clear Ocean
  900 cm^{-1}



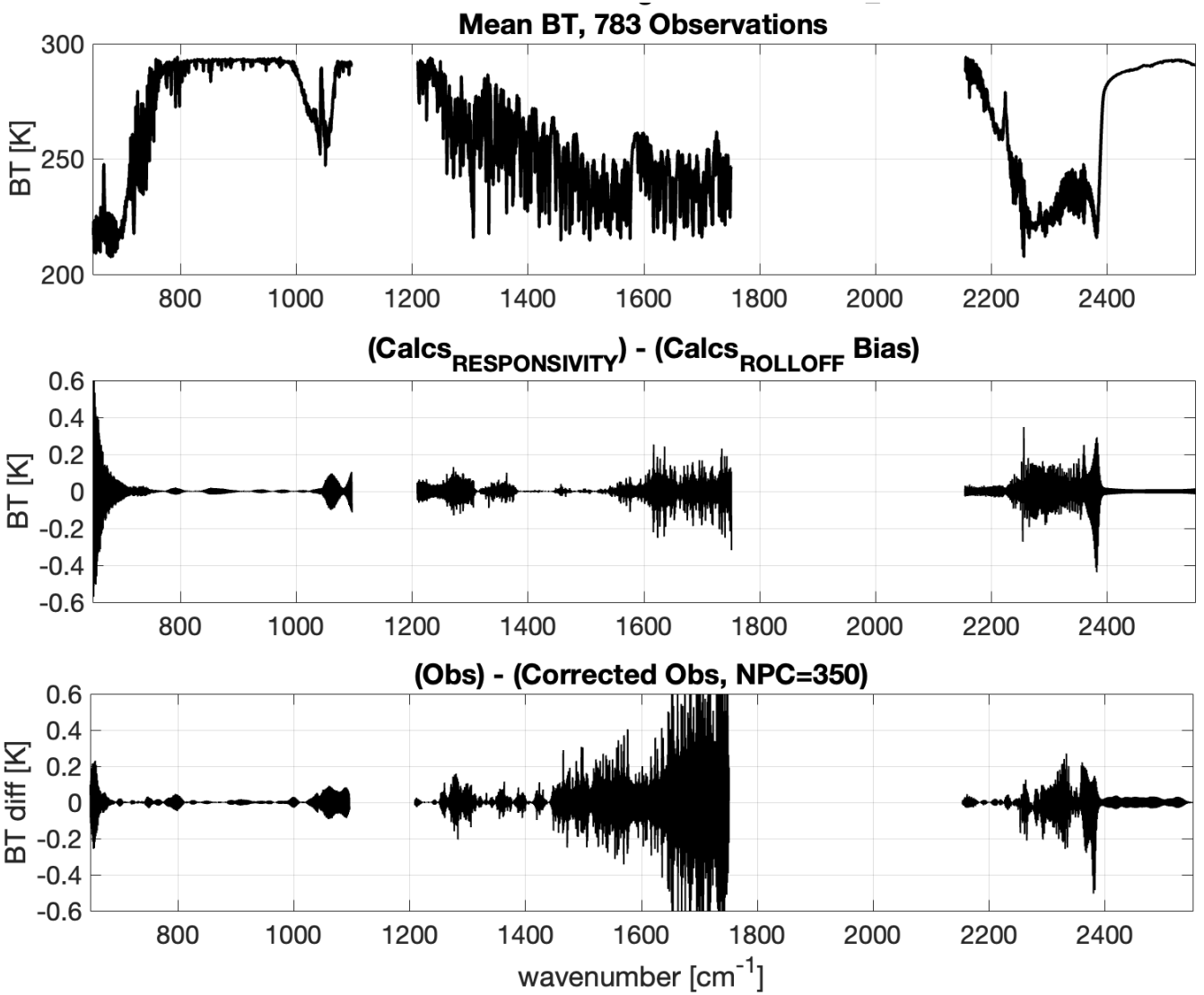
Daytime view of granule



Std. Dev(900cm^{-1} Radiance) < 0.3
(900cm^{-1} BT – ECMWF Skt) < 2 K

- **Results suggest some new ringing contributions may exist**

Ringing Correction, Suomi NPP, 350 PCs



Note that the small size of (Obs – Obs corrected) & its similarity to known Ringing signatures shows that very little observed information is being lost

Calc responsivity – Calc rolloff

Obs – Obs corrected

Region of major differences in MW band suggest some new ringing contributions may exist, but small deficiencies of the calculated PCs are possible and still need to be investigated

5. New Ringing Correction Summary

- The new approach basically applies a very weak apodization, but replaces the small lost interferogram region with a fit to the observation using calculated PCs
- The primary information content is retained, while most ringing features are forced to agree with calculations, leaving Obs-Calcs largely free of ringing
- This is certainly still a "work in progress", but promises to remove most remaining ringing features
- Note: An instrument responsivity with high frequency channeling side-bands like that recently explored by Dussarrat et al for MTG-IRS will probably not be adequately handled by this approach that depends on ringing dominantly affecting large delays where little primary information resides. Their correction for channeling could be followed by this type of correction, if necessary.
- Final note: While the application of commonly used apodization like Hamming may appear to remove ringing, any rigorous use that preserves information content also preserves ringing, and is not an effective correction