Correction to Remove the Residual Responsivity Dependence of Spectral Instrument-Line-Shapes for Fourier Transform Spectrometers

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Correction to Remove Residual Responsivity Dependence of Spectral ILS for FTS Sensors

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A. **Background: Advantages of FTS for High Accuracy and Climate Trending**

B. **Removing instrument responsivity dependence**

C. **Perspective for CLARREO**

Examples shown for CrIS

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A. Background: Advantages of FTS for High Accuracy and Climate Trending

B. Removing in
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C.

The FTS approach is especially well-suited to NWP and climate benchmarking

Examples shown for CrIS

Advantages of FTS for High Accuracy

- **First order knowledge of ILS:** (or Spectral Response Function) The ILS is established by the FTS approach, mainly depending on a small set of wavelength independent parameters
  Note- AIRS SRFs were determined in ground testing using an FTS

- **Single detector can cover broad spectral bands:** This simplifies optical and detector configurations and avoids uncertainties related to FOV dependence of spectra (e.g. AIRS)

- **Spectral stability:** Insensitivity to instrument T changes

- **On-orbit spectral calibration source practical** (CrIS neon source)

- **Any non-linearity can easily be monitored on orbit** using its out-of-band signature

Other Key Advantages of FTS for NWP & Climate Trending

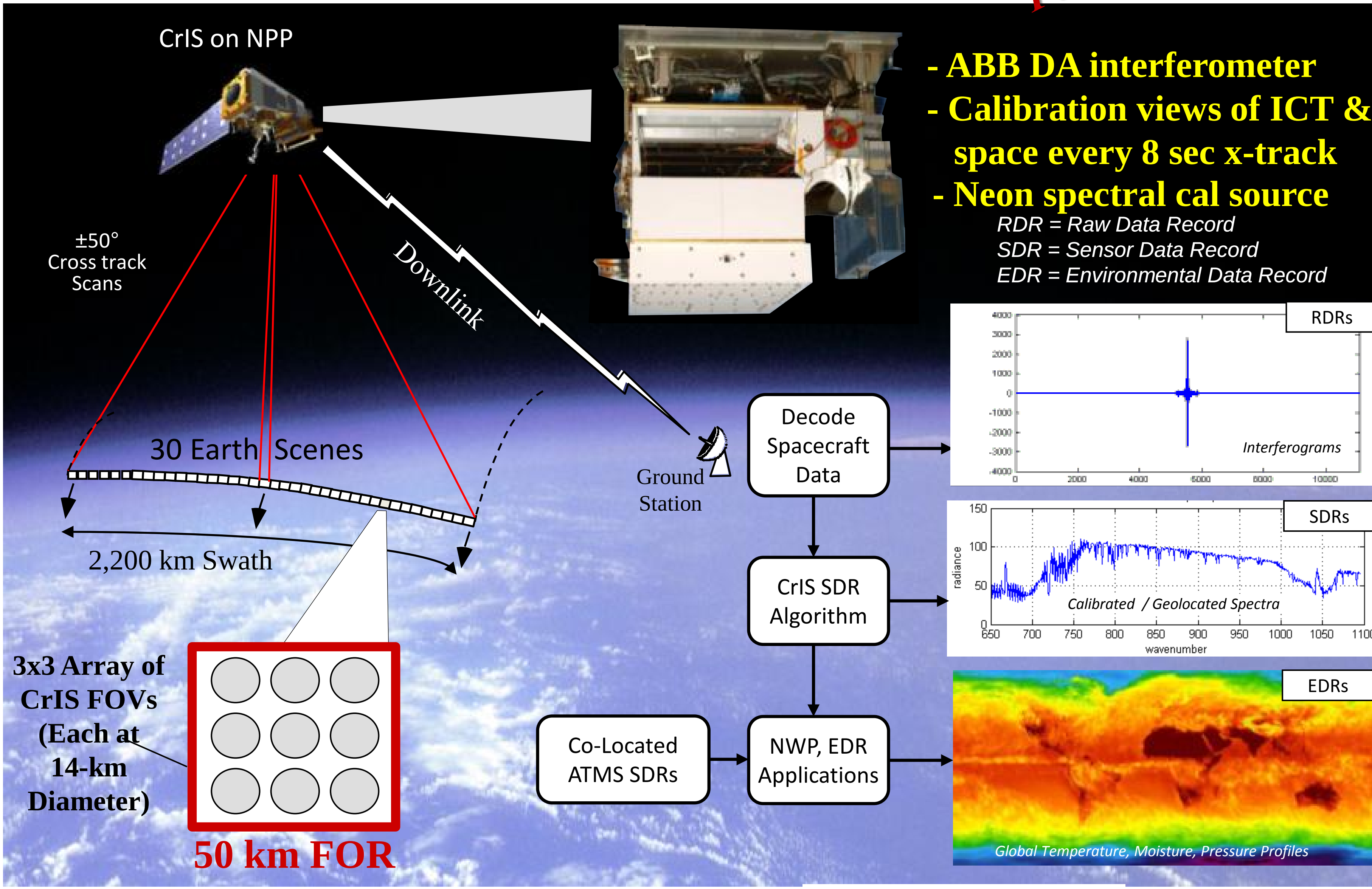
- **Standardization of spectra from different instruments:**
  A rigorous mathematical formalism allows straight forward transformation of one FTS spectrum to another for trending or detailed comparison (e.g. IASI to CrIS, CrIS to CrIS, HIRAS to CrIS, ARI to CrIS).
  Note- lack of a simple reproducible ILS makes AIRS hard to compare to other instruments- we often resort to double-differences with calculations- It would not even be easy to rigorously compare AIRS to a second AIRS

  - **Spectral Scale standardization is straight forward for FTS** that is naturally Nyquist sampled

  - **First order ILS standardization is routine,** and techniques for removal of subtle responsivity influences are being developed in Europe and at UW-SSEC as discussed later

CrIS Operational Concept

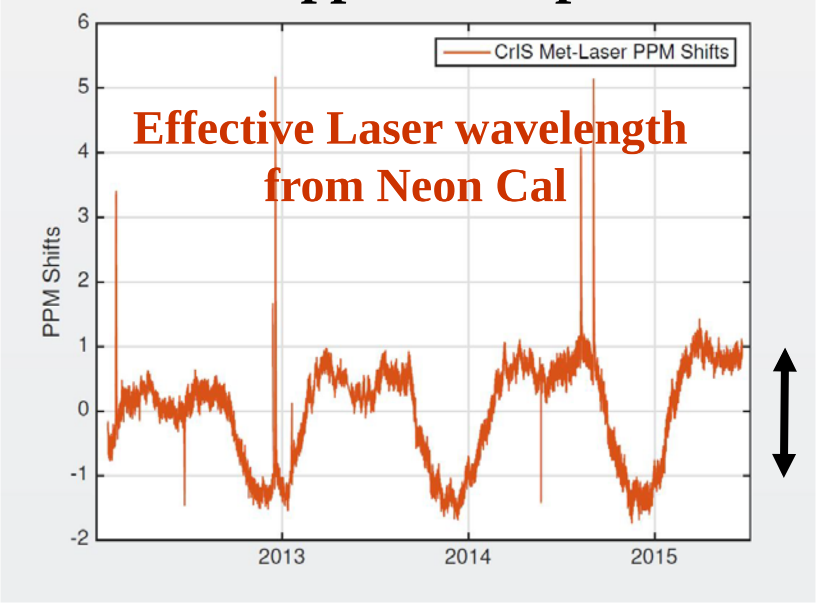
Example Performance



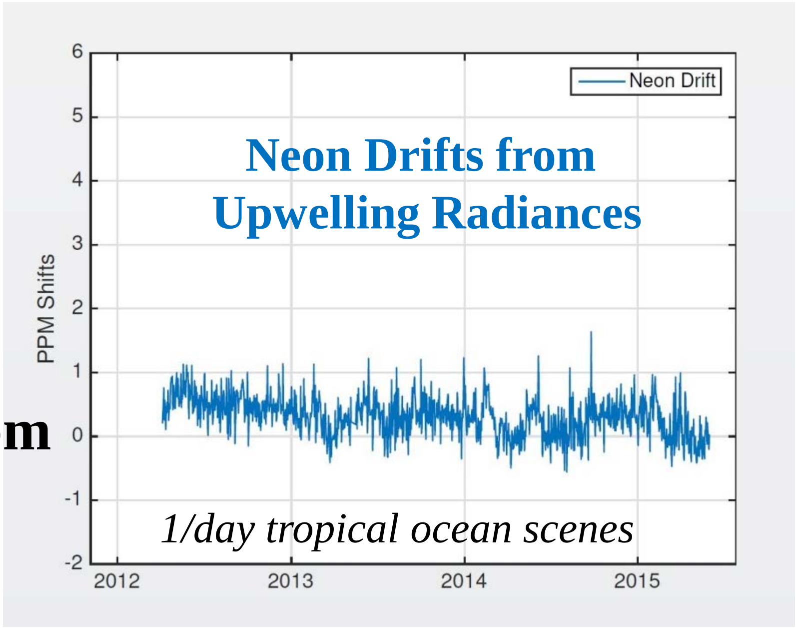
CrIS Spectral Calibration is very Stable

from Larrabee Strow, Aug 2015

Just 3 ppm/ ΔK optics



2 ppm



Variation of FTS effective metrology laser wavelength calibrated with stable onboard Neon source <u>reduces final error to </u>< 1 ppm!

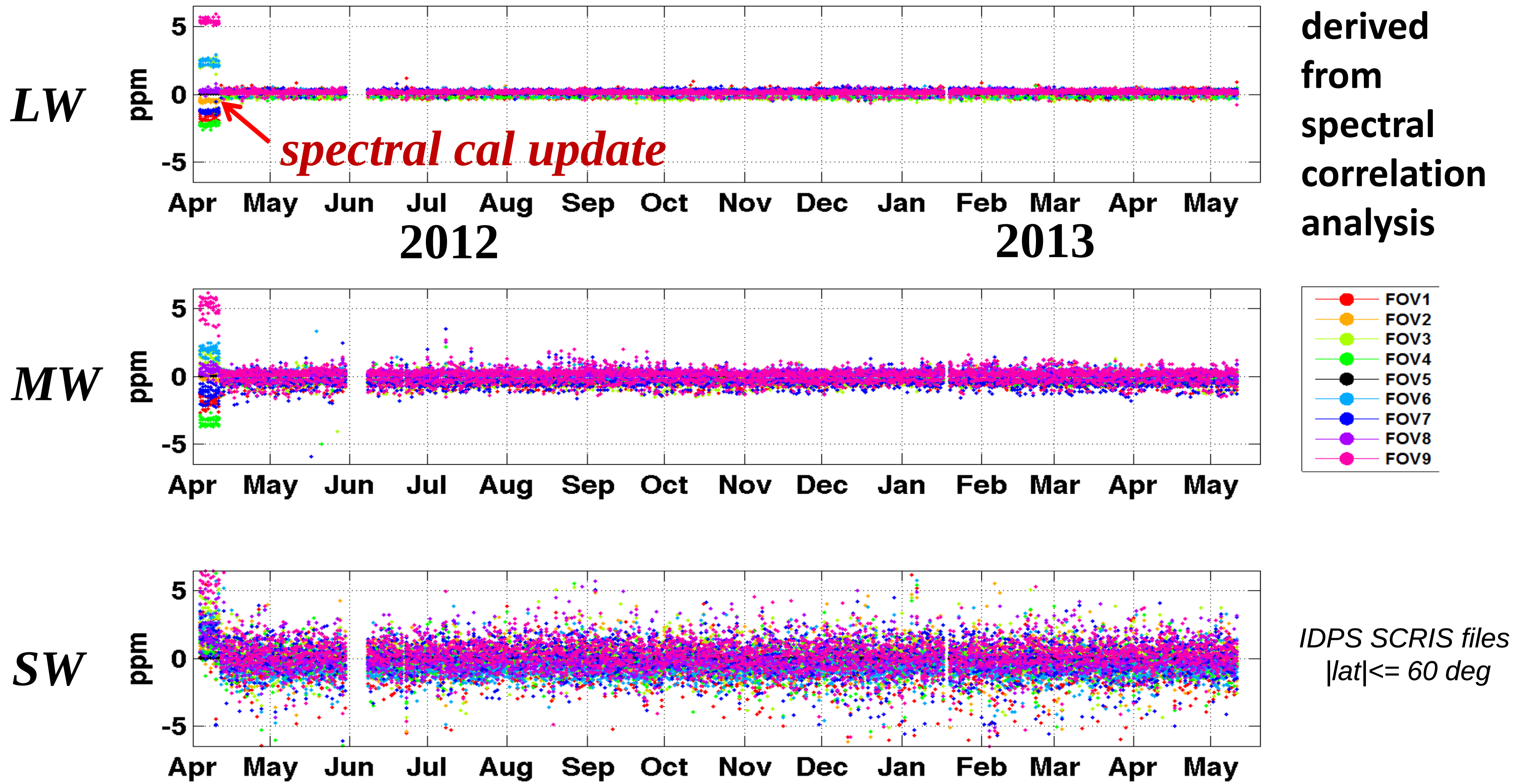
Note: (1) Daily variation is generally < 0.5 ppm

(2) Annual variation is < 3 ppm uncorrected

(3) Neon cal results in < 1 ppm spectral cal error

see also Chen, Han, and Weng, 2017

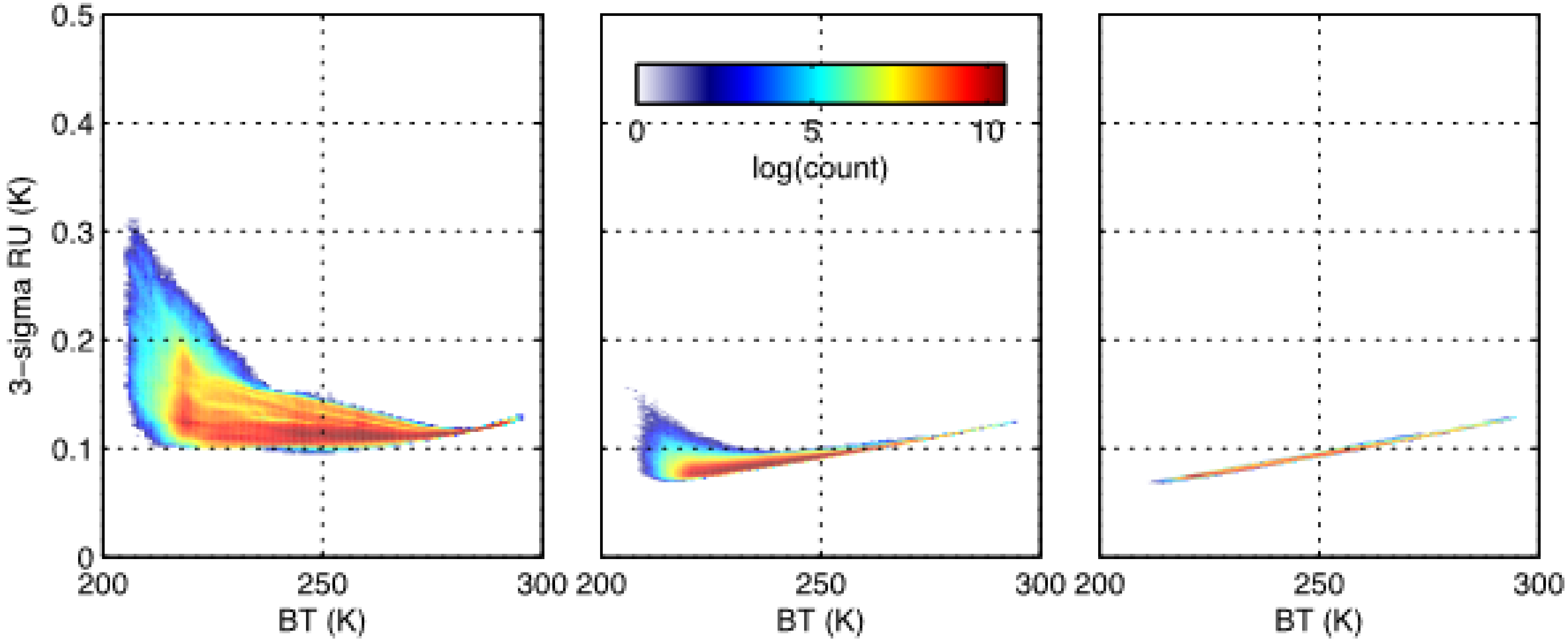
CrIS Spectral Calibration Shifts w/r/t FOV5



All FOVs agree to significantly better than 1 ppm!

On-Orbit Radiometric Uncertainty (RU) Estimates for CrIS (3-sigma)

Density plot for one orbit includes all spectral channels and FOVs



RU for atmospheric spectra only exceeds 0.2 K 3-sigma for a few cold LW spectra

Exceptions that can exceed 0.2 K under limited and rare conditions

- **FOV5 anomaly** (unexplained error in FOV5)
  Large at 668 cm^{-1} Q-branch for some cold scenes
  (only major anomaly without identified root cause)

- **Ringing** (every other point oscillation - spectrally local)
  - **Numerical filter induced:** mechanism identified and rigorous correction developed
  - **Self-apodization correction ringing artifacts:**
    New research algorithm essentially eliminates this effect
  - **Responsivity related source identified as "true ringing" and handled in calculations:**
    New correction approach is the main subject here

See Joe Taylor et al. poster for more comprehensive information, especially including the status of polarization correction

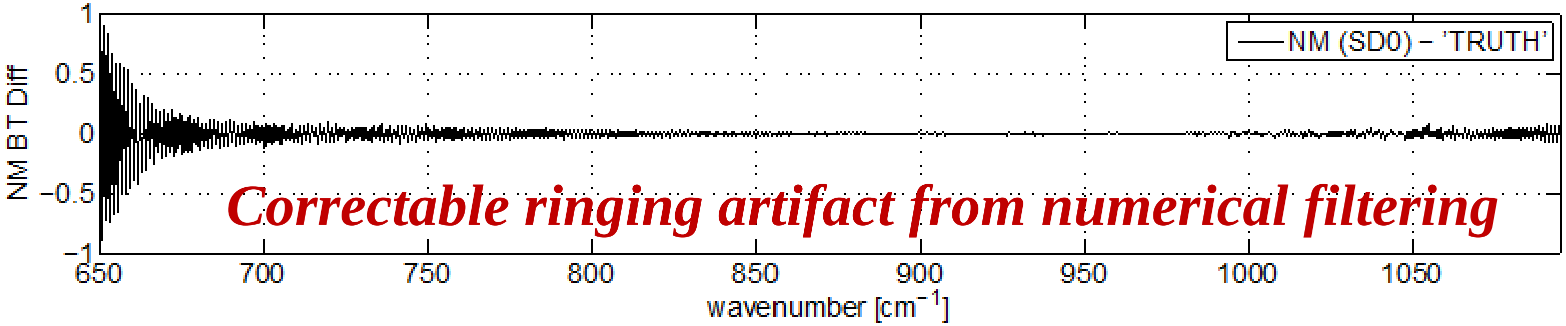
New Self-apodization Correction Summary

- A new, rigorous correction algorithm has been defined
- The new relationship for the self-apodized interferogram has been tested by using a simulation to compare it to the result derived from a high resolution spectrum with the angular weighting handled rigorously –<u>Excellent agreement proven</u>
- Also, we have the correction algorithm integrated into the full CrIS calibration algorithm with a modified spectral calibration and are making comparisons with results using the SA^{-1} matrix
- <u>Preliminary results suggest that ringing artifacts in the MW and SW bands are significantly reduced</u>
- Paper in progress

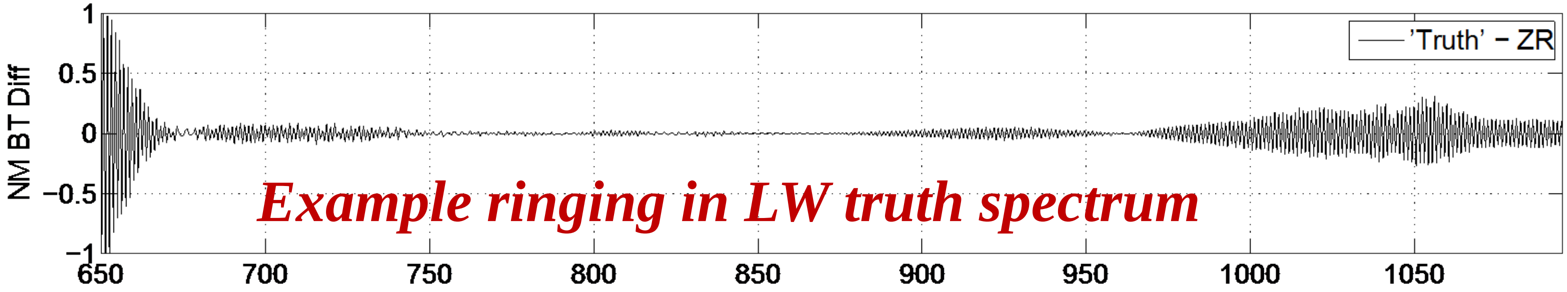
See Joe Taylor et al. poster

Gibbs Ringing: Truth and Artifact

- **Numerical Filter Ringing Artifacts:**
  Correctable ringing artifacts result at LW end of LW band



- **Responsivity band limits cause "truth" spectra to ring:**
  Calculation of "truth" spectra with CrIS Responsivity removes obs-calc artifacts



Correction approach is the main subject of this presentation

Perspective on Ringing Artifacts

- These ringing artifacts in some regions of the spectrum can be large compared to other radiometric uncertainties and could limit future NWP application of these channels
- People sometimes minimize the importance of ringing errors by pointing out that ringing can be removed by apodization and that NWP centers for example use apodized spectra
- However, it should be noted that if off-diagonal error covariance matrices are applied to prevent the loss of high resolution information, optimum estimation techniques essentially remove the apodization to create independent errors
- Therefore, the normal application of apodization does not really eliminate ringing artifacts, and rigorous corrections should be applied whenever possible

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B. Removing instrument responsivity dependence

C. Perspective f

Examples shown for CrIS

Small, residual dependence on instrument responsivity can be removed

Introduction

- **CrIS Paradigm to date:** Create calibrated spectra compatible with calculated spectra that are band-limited by the CrIS responsivity, which inherently yields an ILS weakly dependent on responsivity (i.e. obs & calcs both contain “true” ringing)
- **Approach for MTG-IRS imaging FTS:** EUMETSAT is investigating removing the ILS responsivity dependence of MTG-IRS (that, unlike CrIS, is expected to be reasonably large) by using
  (1) a spectrally local apodization correction, and
  (2) a weak apodization to minimize un-invertible contributions from where the responsivity goes to zero
- **New Approach:** We have identified a new way to accomplish step (1) that may have significant accuracy and efficiency advantages
- **Potential:** The significance of this type of correction is that it will be possible to create NWP radiances and climate radiance products that are truly independent of which instrument collected the data

Math Formalism: Setting up

First, define a measured interferogram as

$$F_{meas}(x) = F_E - F_S = \left[\int d\nu\, N(\nu)\, R(\nu)\, e^{-i2\pi\nu x}\right] \cdot boxcar(x) \qquad (1)$$

where F_E and F_S are the measured Earth and Space view interferograms, *N* is the Earth spectrum, *R* is the instrument responsivity, and the boxcar function represents the normal interferogram truncation that creates an unapodized spectral Instrument Line Shape given by ILS = sinc($2\pi\nu X$) with X being the maximum OPD or the sinq, its discrete sampling equivalent. The square bracketed term in Equation 1 is the Inverse Fourier Transform (***ift***) of $N(\nu)\, R(\nu)$.

By applying the forward Fourier Transform (***ft***) to Equation 1 and using the convolution theorem, the spectral domain version of this relationship becomes

$$S_{meas}(\nu) = [N(\nu) \cdot R(\nu)] \otimes ILS(\nu)\text{, or}$$

$$S_{meas}(\nu) = \int d\nu'\, N(\nu')\, R(\nu')\, sinc[2\pi X(\nu' - \nu)] \qquad (2)$$

Math Formalism: the Taylor Series

$$S_{meas}(\nu) = [N(\nu) \cdot R(\nu)] \otimes ILS(\nu) \text{, or}$$

$$S_{meas}(\nu) = \int d\nu' \, N(\nu') \, R(\nu') \, sinc[2\pi X(\nu' - \nu)] \qquad (2)$$

Then, to separate the dependence on the responsivity from the spectrum itself we expand *R* as a general Taylor series $R(\nu') = R(\nu) + (\nu' - \nu)\, R'(\nu)/1! + (\nu' - \nu)^2 R''(\nu)/2! + \ldots$, yielding

$$S_{meas}(\nu) = R(\nu) \cdot [N(\nu) \otimes ILS(\nu)] + R'(\nu) \cdot \{N(\nu) \otimes [\nu \cdot ILS(\nu)]\}$$

$$+ \tfrac{1}{2} R''(\nu) \cdot \{N(\nu) \otimes [\nu^2 \cdot ILS(\nu)]\} + \cdots \qquad (3)$$

where the primes on *R* represent differentiation.

Using the identity $\{N(\nu) \otimes [\nu^n \cdot ILS(\nu)]\} = \boldsymbol{ft}\{F(x) \cdot \boldsymbol{ift}[\nu^n \cdot ILS(\nu)]\}$ and $F(x) = \boldsymbol{ift}[N(\nu)]$ Equation 3 can also be written as

$$S_{meas}(\nu) = R(\nu) \cdot ft\{F(x) \cdot boxcar(x)\} + R'(\nu) \cdot ft\{F(x) \cdot ift[\nu \cdot ILS(\nu)]\}$$

$$+ \tfrac{1}{2} R''(\nu) \cdot ft\{F(x) \cdot ift[\nu^2 \cdot ILS(\nu)]\} + \cdots \qquad (4)$$

Math Formalism: Calibration & Correction

Now we can rewrite Equations 3 and 4 in terms of calibrated spectra by dividing by $R(\nu)$ and defining the responsivity dependent calibrated spectrum as $N_{meas} = S_{meas}(\nu)/R(\nu)$ and the responsivity independent corrected spectrum as $N_{cor} = N(\nu) \otimes ILS(\nu) = \boldsymbol{ft}\{F(x) \cdot boxcar(x)\}$, yielding

$$\boldsymbol{N_{meas}(\nu) = N_{cor}(\nu) + \left[\frac{R'(\nu)}{R(\nu)}\right] \cdot \{N(\nu) \otimes [\nu \cdot ILS(\nu)]\} + ½ \left[\frac{R''(\nu)}{R(\nu)}\right] \cdot \{N(\nu) \otimes [\nu^2 \cdot ILS(\nu)]\} + \cdots}$$

$$\boldsymbol{= N_{cor}(\nu) + \left[\frac{R'(\nu)}{R(\nu)}\right] \cdot ft\{F(x) \cdot ift[\nu \cdot ILS(\nu)]\} + ½ \left[\frac{R''(\nu)}{R(\nu)}\right] \cdot ft\{F(x) \cdot ift[\nu^2 \cdot ILS(\nu)]\} + \cdots} \qquad (5)$$

To put Equation 5 in the form of a correction, we solve for N_{cor} and iterate the solution, starting with letting $N(\nu) = N_{meas}$ or $F(x) = F_{meas}(x) = \boldsymbol{ift}[N_{meas}(\nu)]$.

$$\boldsymbol{N_{cor}(\nu) = N_{meas}(\nu) - \left[\frac{R'(\nu)}{R(\nu)}\right] \cdot \{N_{meas} \otimes [\nu \cdot ILS(\nu)]\} - ½ \left[\frac{R''(\nu)}{R(\nu)}\right] \cdot \{N_{meas} \otimes [\nu^2 \cdot ILS(\nu)]\} - \cdots}$$

$$\boldsymbol{= N_{meas}(\nu) - \left[\frac{R'(\nu)}{R(\nu)}\right] \cdot ft\{F_{meas}(x) \cdot ift[\nu \cdot ILS(\nu)]\} - ½ \left[\frac{R''(\nu)}{R(\nu)}\right] \cdot ft\{F_{meas}(x) \cdot ift[\nu^2 \cdot ILS(\nu)]\} - \cdots} \qquad (6)$$

Correction terms take the form $\left[\frac{R^{n^{th}der}(\nu)}{R(\nu)}\right] \cdot ft\{F_{meas}(x) \cdot ift[\nu^n \cdot ILS(\nu)]\}$,

so we explore the nature of $ift[\nu^n \cdot ILS(\nu)]$

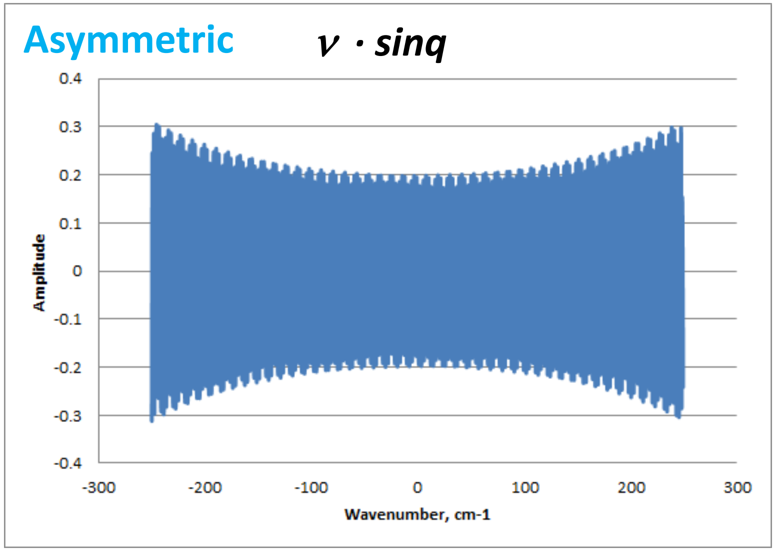
Parameters Used in Simulation approximate FIR filtered data

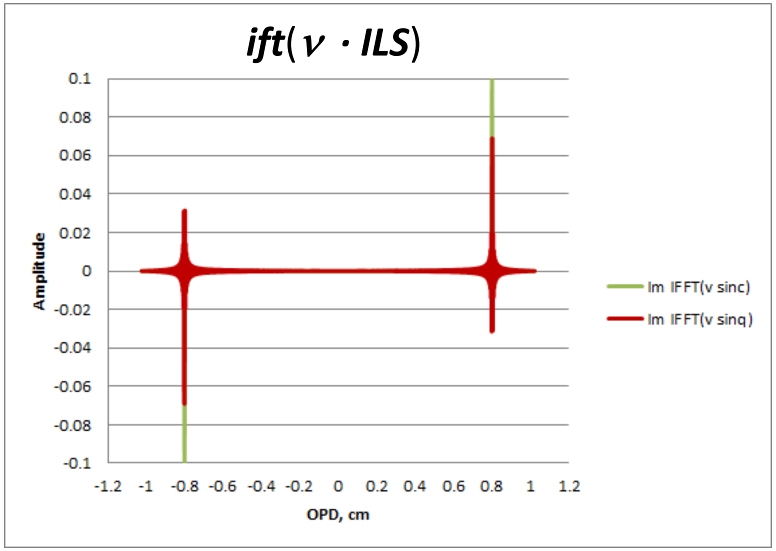
Xsinc	**0.8**		dw	0.48828125
N	**512**		dx	0.002
wny	**250**		X	1.024
K	801			
Nlyons	1024			

CrIS						
CrIS laser wavelength		**1.556**	**microns**	LW sampled twice per fringe		
LW sample interval		0.0000778	cm	**0.001867**	**cm**	**Filtered**
LW Nyquist wn		6426.735219	cm-1	**267.7806**	**cm-1**	
reductionfactor, LW		**24**				
Filtered point number		**864**	876 before FCC correction			
max delay		0.8066304	0.806291956			

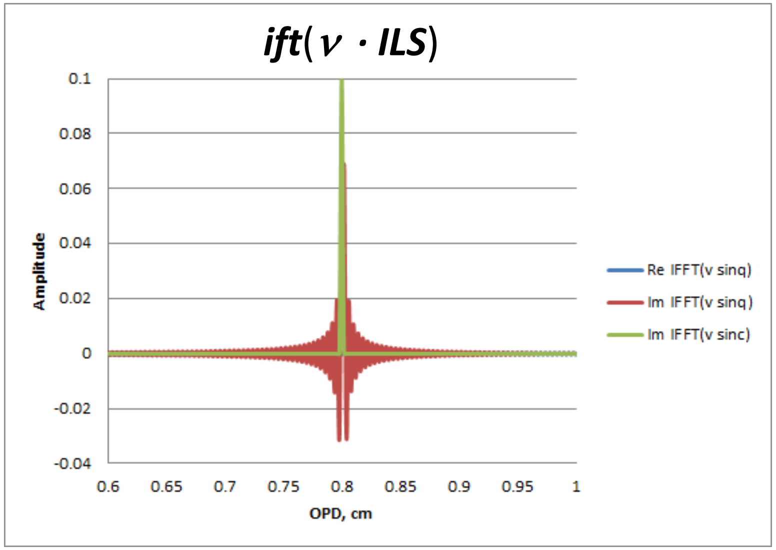
Correction terms take the form $\left[\frac{R^{n^{th}der}(\nu)}{R(\nu)}\right] \cdot ft\{F_{meas}(x) \cdot ift[\nu^n \cdot ILS(\nu)]\}$,

so we explore the nature of $ift[\nu^n \cdot ILS(\nu)]$ **n =1, Imaginary**



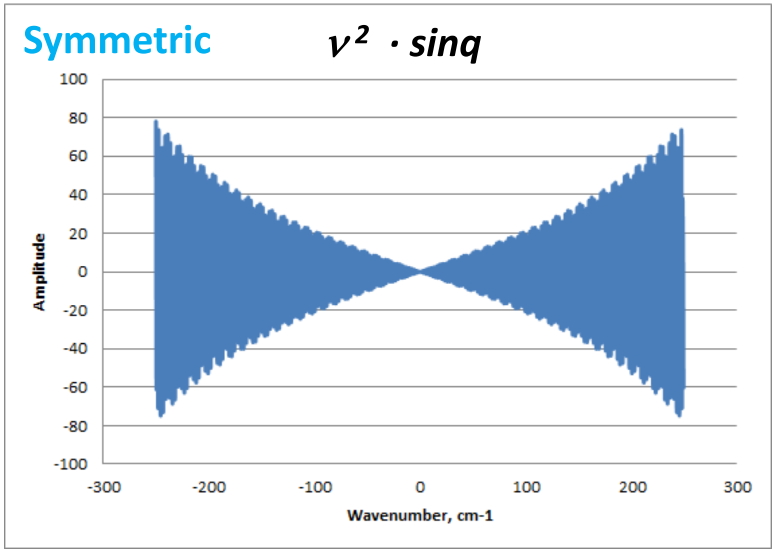


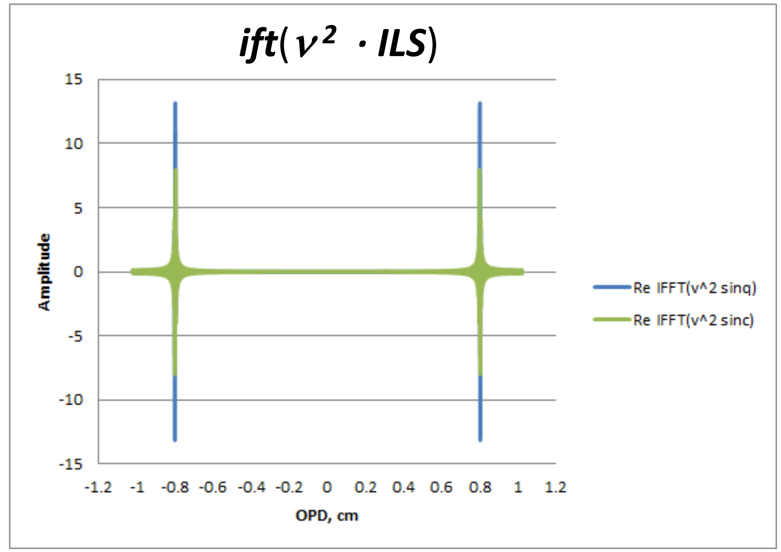
Note that this type of artifact affects the ends of interferograms, thereby creating ringing-type spectral artifacts, consistent with the characteristics of the responsivity-limited "truth" spectra shown earlier

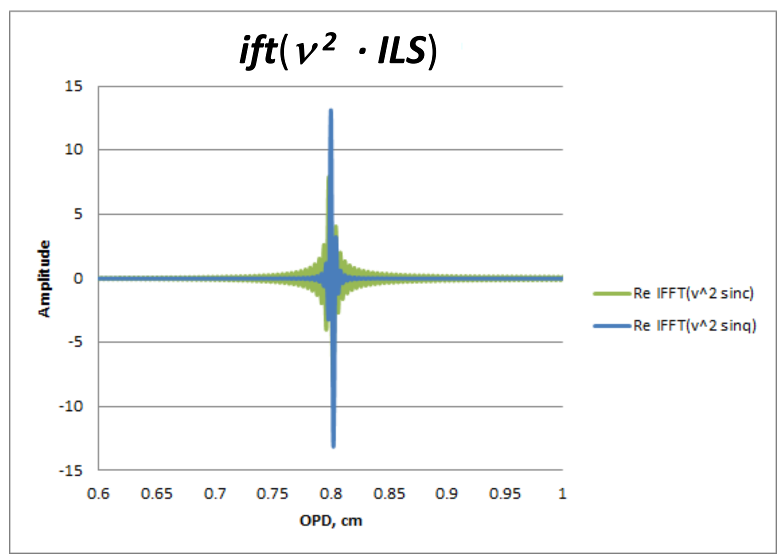


Correction terms take the form $\left[\frac{R^{n^{th}der}(\nu)}{R(\nu)}\right] \cdot ft\{F_{meas}(x) \cdot ift[\nu^n \cdot ILS(\nu)]\}$,

so we explore the nature of $ift[\nu^n \cdot ILS(\nu)]$ **n =2, Real**

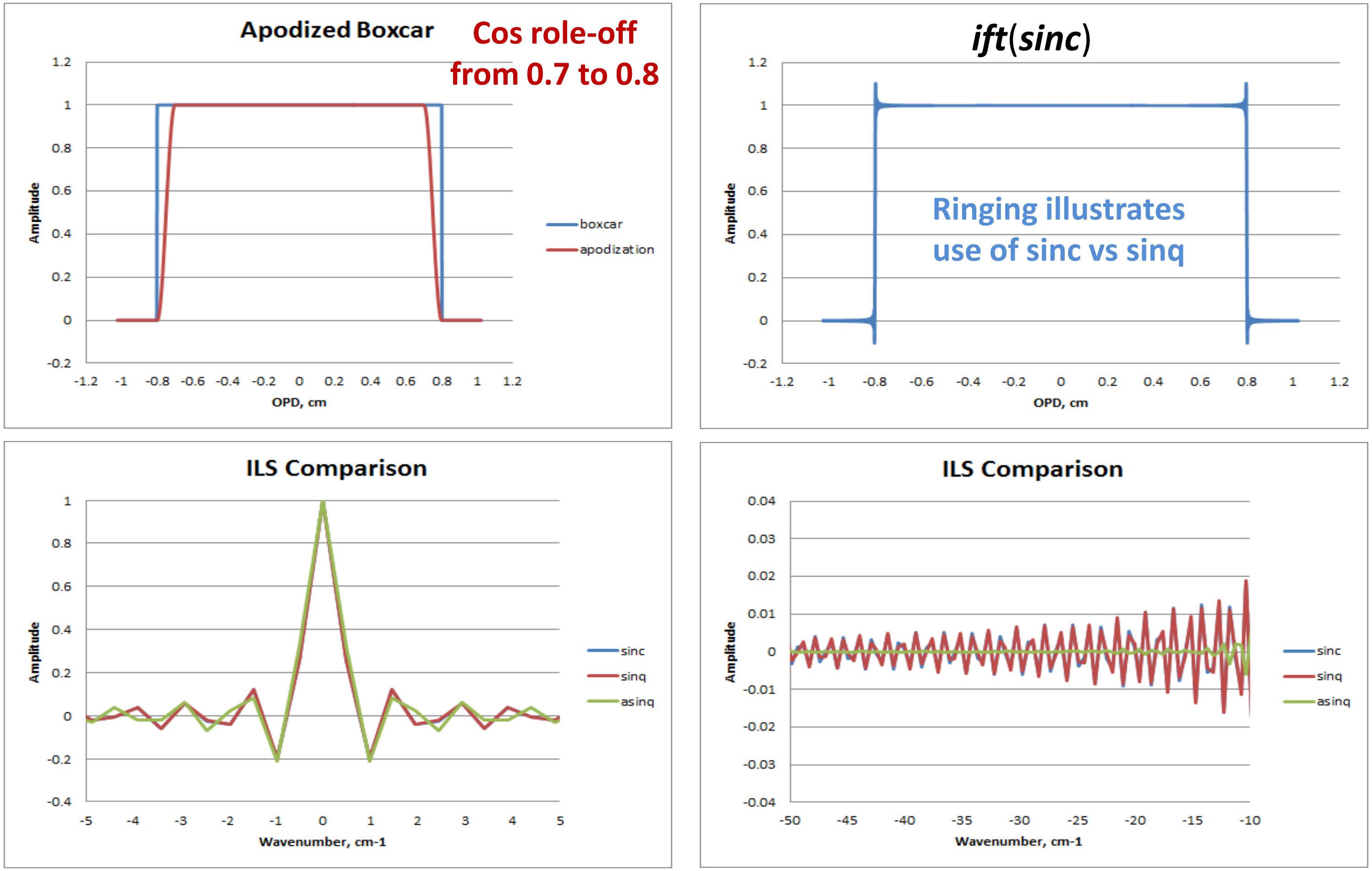






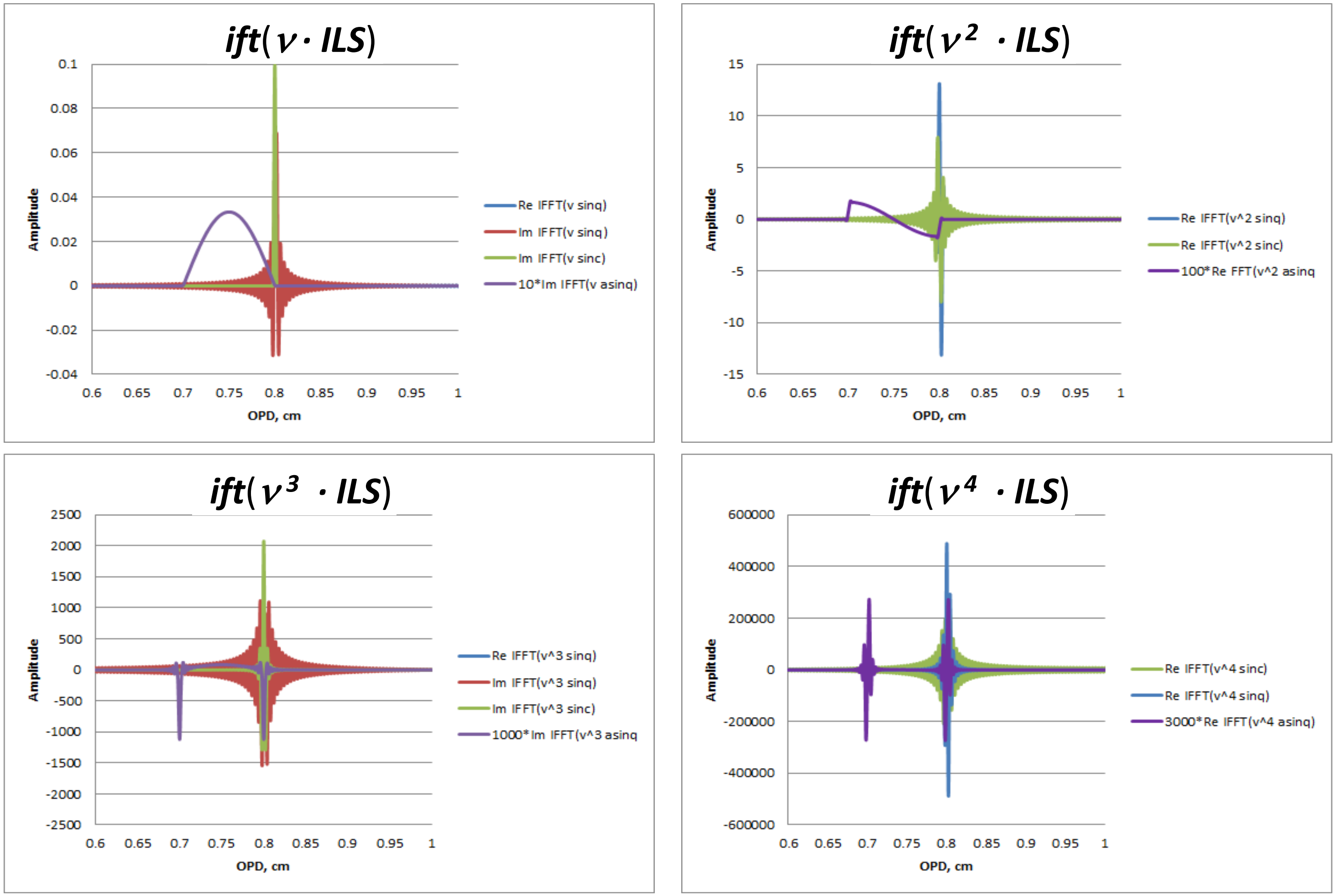
Again, this type of artifact affects the ends of interferograms, thereby creating ringing-type spectral artifacts, consistent with the characteristics of the responsivity-limited "truth" spectra shown earlier

Information related to the number of points needed in the interferogram domain and whether apodization is needed (1)



Example limited apodization that would not truncate the 15 micron CO_2 resonance centered near 0.63 cm

Information related to the number of points needed in the interferogram domain and whether apodization is needed (2)



Note that with this apodization, fewer points spill over the nominal ends of the interferogram

Next Steps

- **Perform simulations to explore**
  - Sampling requirements by varying the Nyquist wavenumber & maximum Optical Path Difference
  - Appropriate definition of the unapodized ILS (sinq)
  - Apodization required to eliminate un-invertible out-of-band contributions
- **Application to CrIS Data**
  Apply the best unapodized and apodized options to CrIS using the data sets already developed to study obs-calc differences and evaluate residuals for non-band-limited calculations
- **EUMETSAT Approach:** Implement and compare

Correction to Remove Residual Responsivity Dependence of Spectral ILS for FTS Sensors

CLARREO IR can make excellent operational sensors even better and leverage their record

A. Backgroun…

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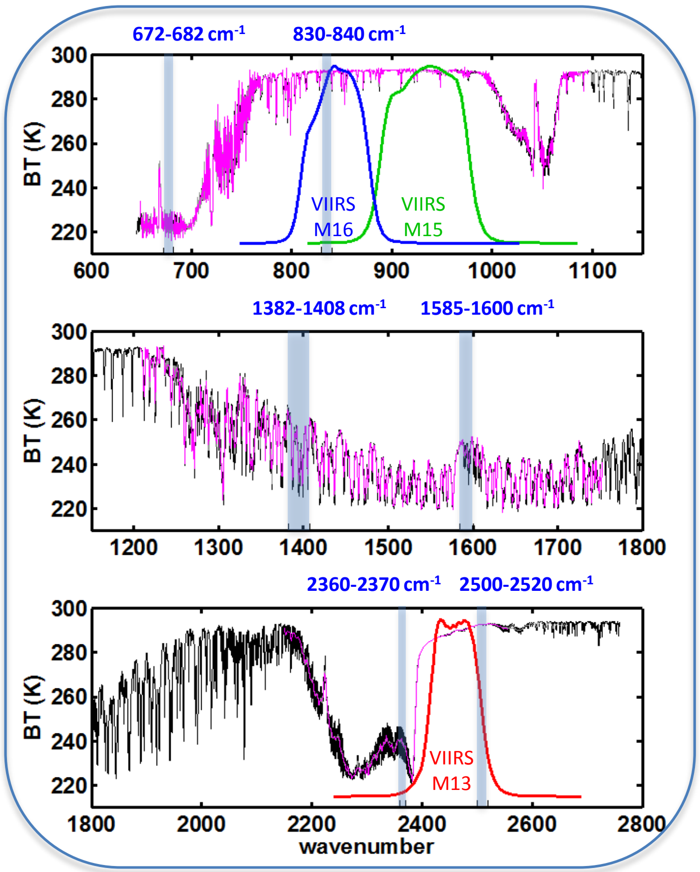
…nsivity dependence

C. Perspective for CLARREO

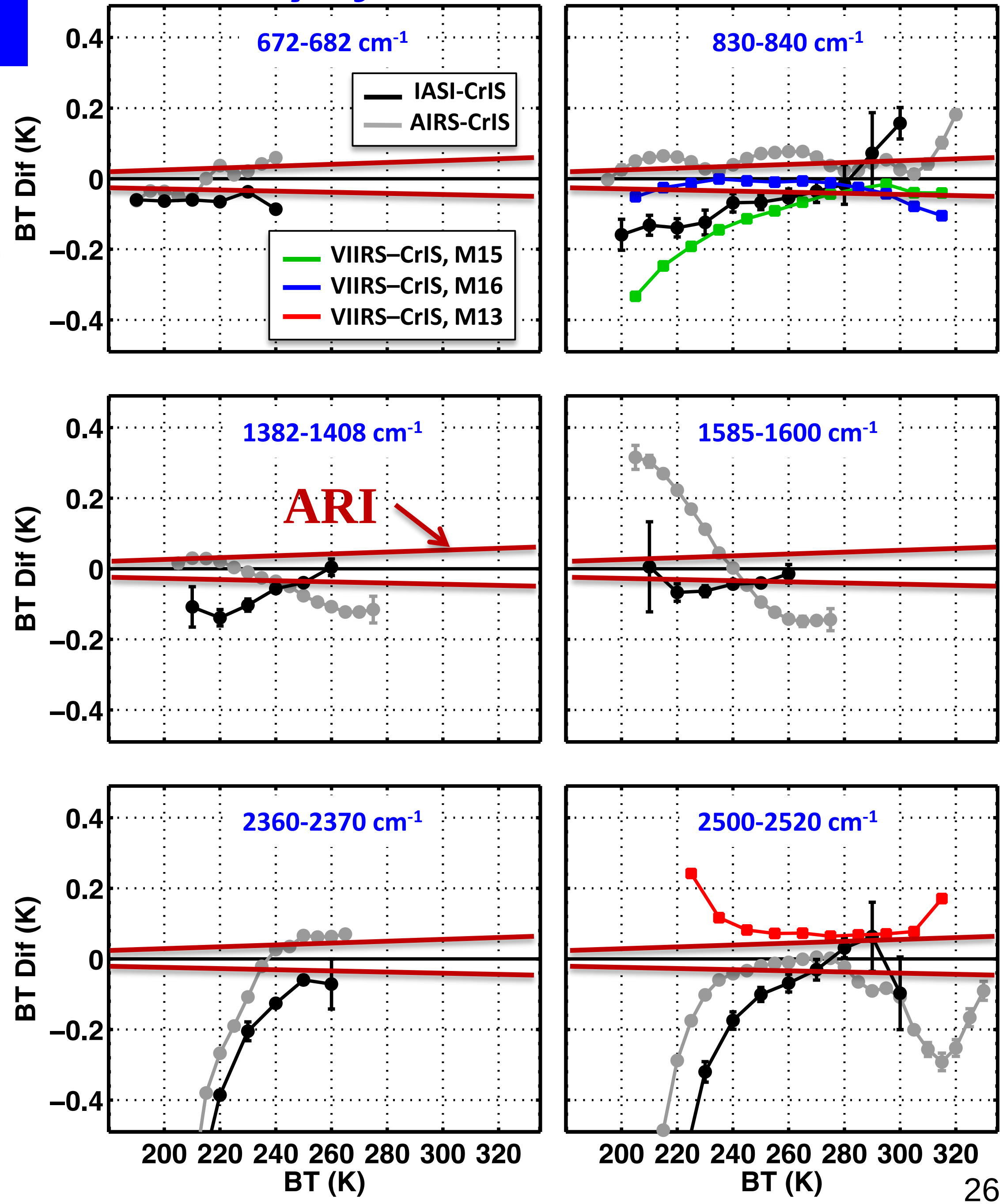
Examples shown for CrIS

CLARREO Mission Offers highly Valuable On-orbit Standard

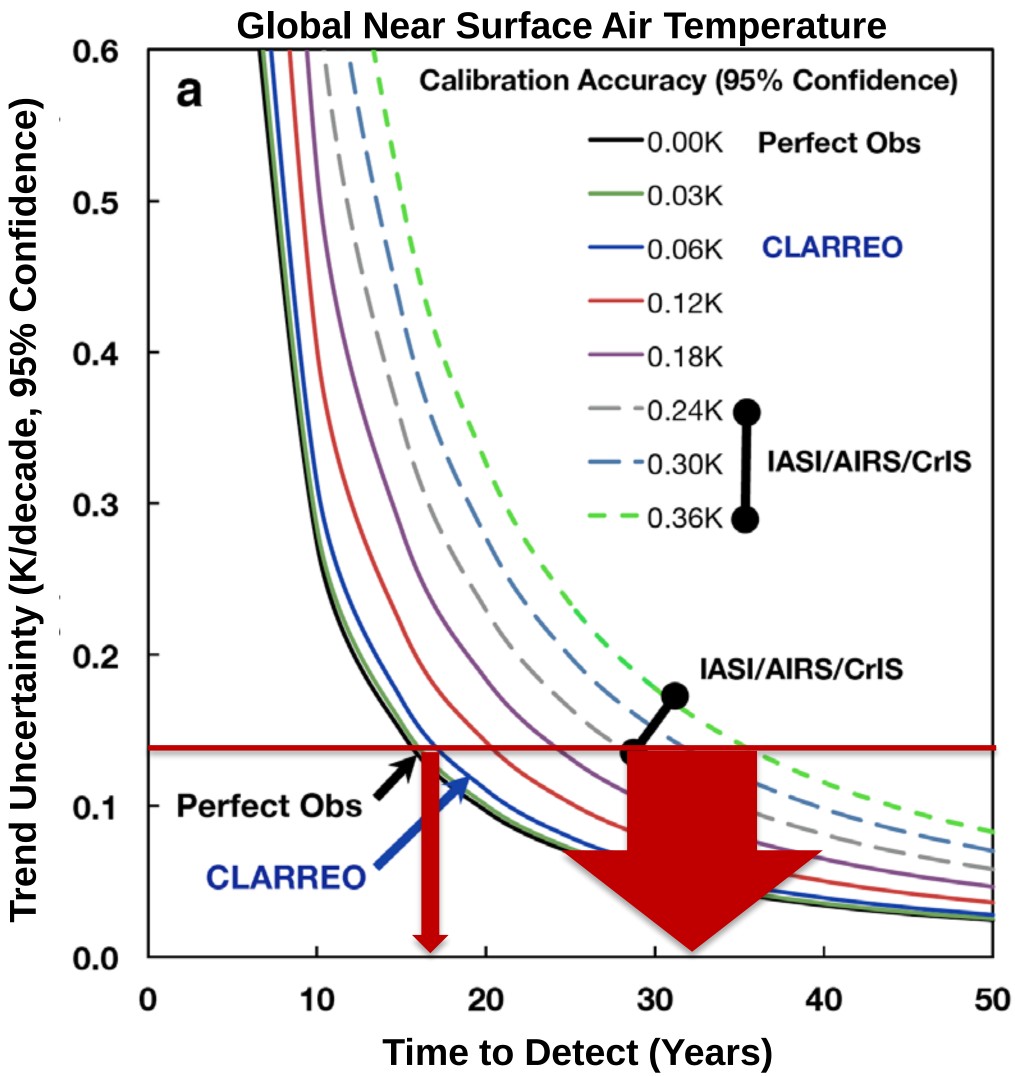
- **ARI 0.1 K not-to-exceed RU provides better "truth"**
- **Residual from CrIS for:**
  - **AIRS**
  - **IASI**
  - **VIIRS: M13, M15, M16**



Summary of Inter-calibrations Results



CLARREO/ARI Accuracy Offers Substantially Reduced Time to Detect Global Climate Change



Example with ~ factor of 2 shorter Time to Detect

Wielicki et al., BAMS, 2013

Huge Financial benefit shown by Cooke and Wielicki

Summary

- **The choice to use FTS for the operational IR sounder fleet world-wide** (CrIS, IASI, & FY3 HIRAS) **and for CLARREO has become even more strongly justified the more we learn**
- **New techniques for rigorously (1) normalizing the Spectral Instrument Line shape (ILS) functions and (2) removing the ringing artifacts from spectral variations of instrument responsivity and from spectral band limitations further strengthen the rationale**
- **Therefore, FTS observations can now be made essentially free of instrument-to-instrument and detector-to-detector dependencies, making them especially well suited for combining in NWP and Climate Benchmarking applications**
- **Flying an even more accurate FTS reference (e.g. the IR part of the CLARREO pathfinder) would be especially valuable to society for dealing with issues of climate change**