Sources and effects of ripple in CrIS Measurements

D. L. Mooney

SUOMI NNP SDR Science and Validated Product Maturity Review

Ringing in CrIS measurements

- **Inherent expected or “truth” ringing**
  - **Essence of calibration**
  - **Odd or even N**
  - **Fourier series approximation error**
  - **ZPD shift for ray spectrum**
- **Processing ringing**
- **Impact on NPP products**
- **Recommendation**

The essence of the calibration is an assumption

- **After corrections for nonlinearity and background removal the calibration is proportional to a simple ratio of measured spectra**

- **Integrals are done optically on the detector and ρ is the complex responsivity, H the FIR filter response, and Sinq is the impulse response of the measurement**

ICT radiance model

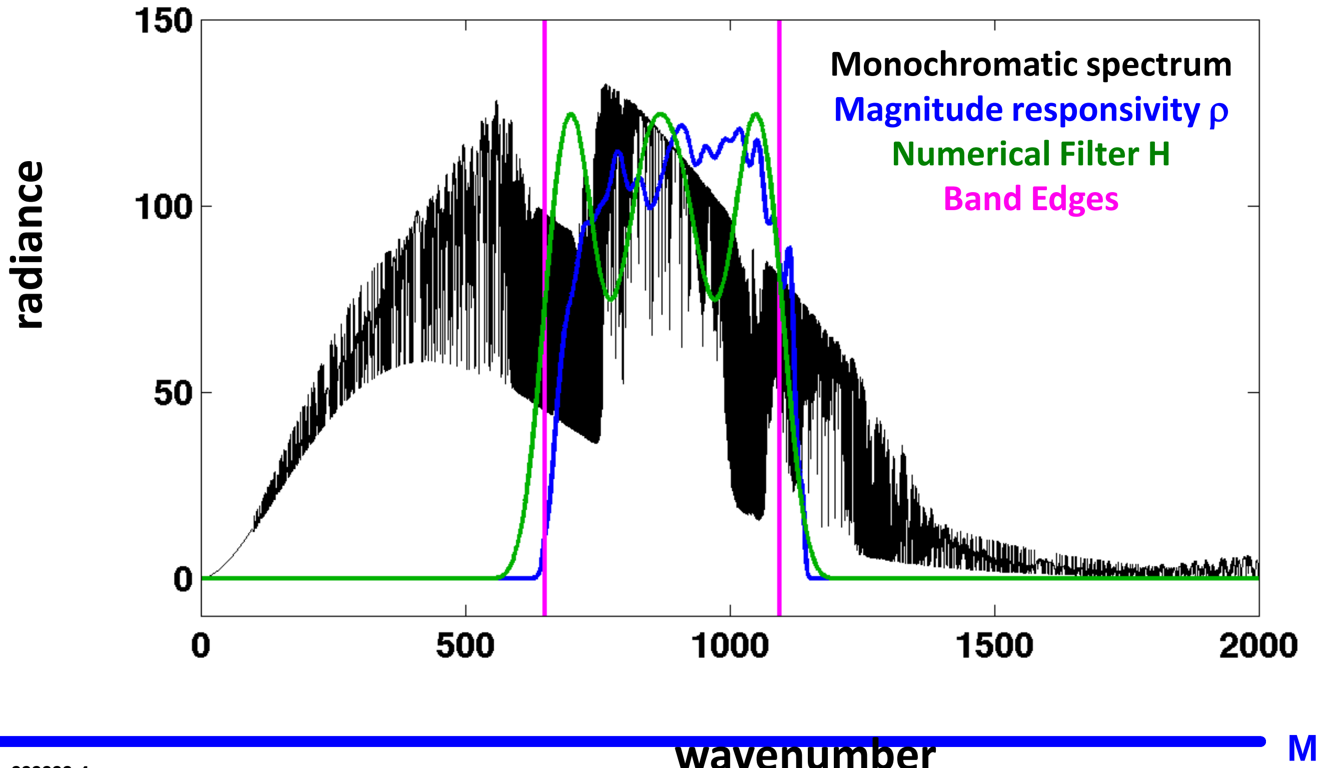
$$N_{Obs}[k] = \left[\frac{\int H_{FIR}(u)\rho(u)e^{i2\pi(k-\frac{u}{\Delta})\Delta\delta ZPD} N_{Scene}(u) Sinq(k-\frac{u}{\Delta})du}{\int H_{FIR}(u)\rho(u)e^{i2\pi(k-\frac{u}{\Delta})\Delta\delta ZPD} N_{ICT}(u) Sinq(k-\frac{u}{\Delta})du} \right] \hat{N}_{ICT}(T_{instrument})$$

$$= \frac{1}{H_{FIR}(u)\rho(k\Delta)} \int N_{Scene}(u')H_{FIR}(u)\rho(u')Sinq(k-\frac{u'}{\Delta})du' \quad + \quad err(\delta ZPD, S_0)$$

The "UWis truth" and the error contain ripple or ringing

Estimate of the ringing error for single ray requires a spectrum and gain g(u) to estimate truth

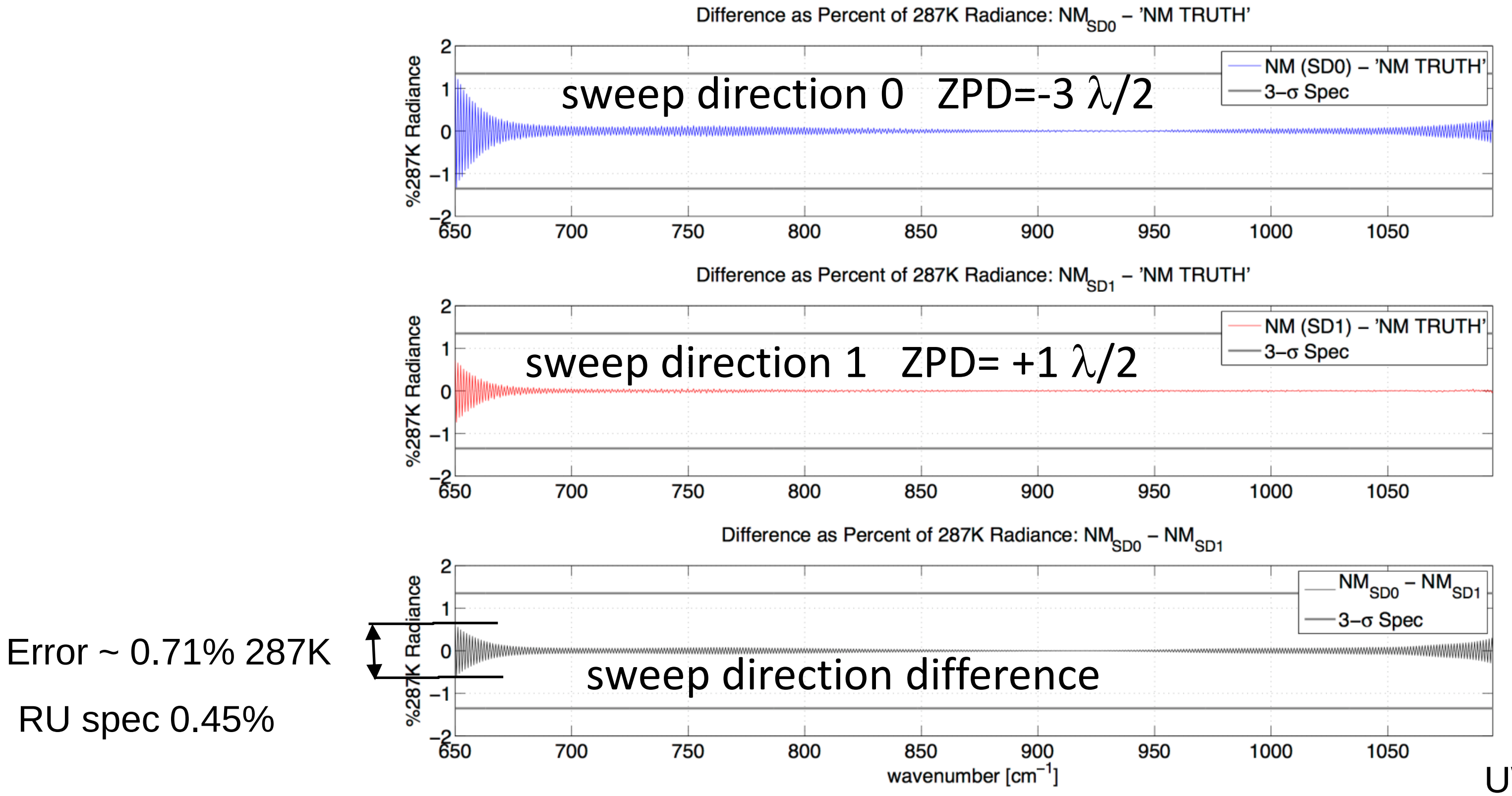
- One fundamental source of Ringing is due to the spectral band limits.
- This should not be viewed as an error or Ringing artifact.
- Calculation of CrIS spectra need to include band limits that accurately represent instrument behavior.
- Specifically the calculations need to use instrument responsivity and FIR filter spectral shapes to band limit spectra, as shown in the figure.



UWisc March 20 2013

Size of LW Spectral Ringing error, compared to Calibration Requirement in terms of Percent of 287K Blackbody Radiance

$$err(\delta ZPD, S_0) = N_{Scene}[k] - N_{Truth}[k]$$



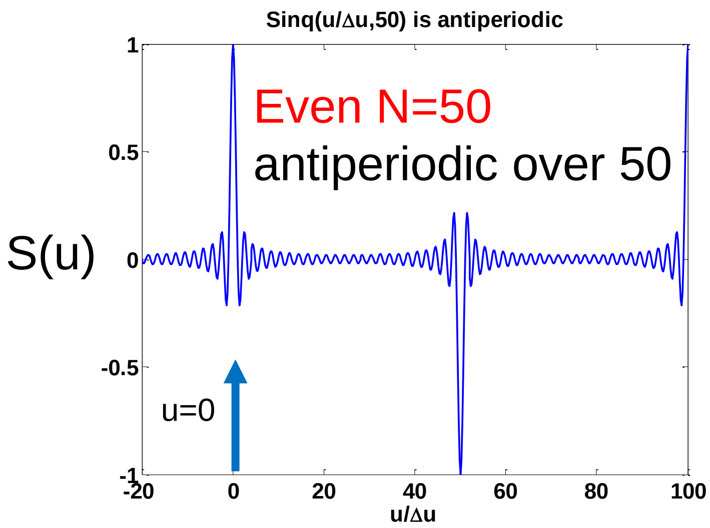
UWisc March 20 2013

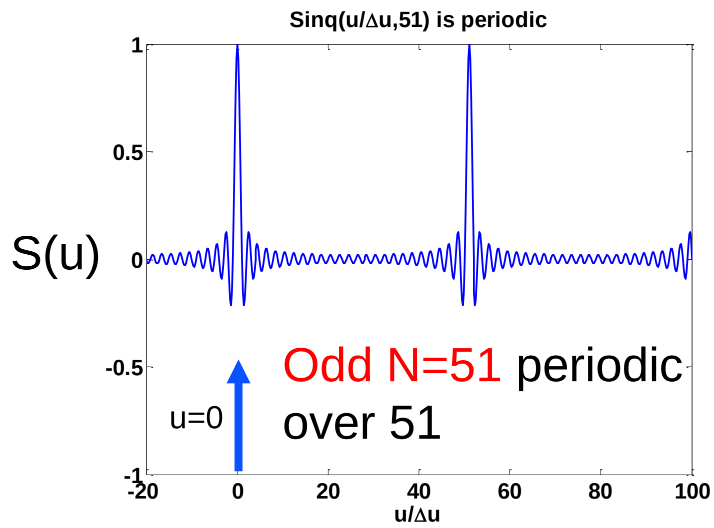
Plots show realistic ringing from a simulation that emulates the application by the instrument of the FTIR filter as a convolution in the interferogram domain

Impulse response of an N point FFT

- Consider radiation from a single wavenumber u into the interferometer
- N-point FFT of the impulse spectrum is anti-periodic for even N, periodic for odd N (scaled Dirichlet function)
- Called “periodic” Sinc

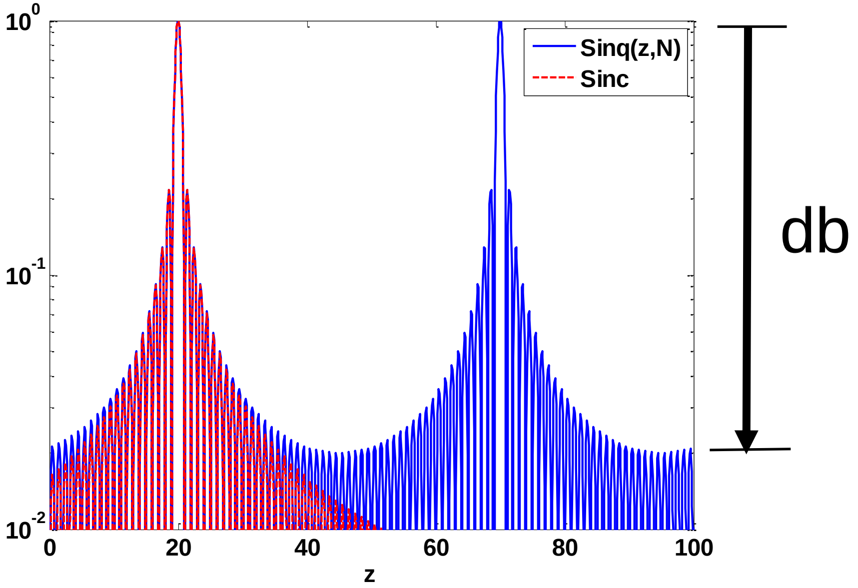
$$Sinq(u) = \frac{1}{N} \sum_{n=-\frac{N-1}{2}}^{\frac{N-1}{2}} \exp(i2\pi \frac{n}{N} uL) = Dirichlet(2\pi \frac{u}{N\Delta u}) = \frac{Sinc(uL)}{Sinc(uL/N)}$$





Ripple far from the peak is expected due to Sinc-like impulse response

- **Sinq function is "periodic Sinc" function**
- **The minimum ripple relative to the peak is (N+1)/2 bins from the peak**



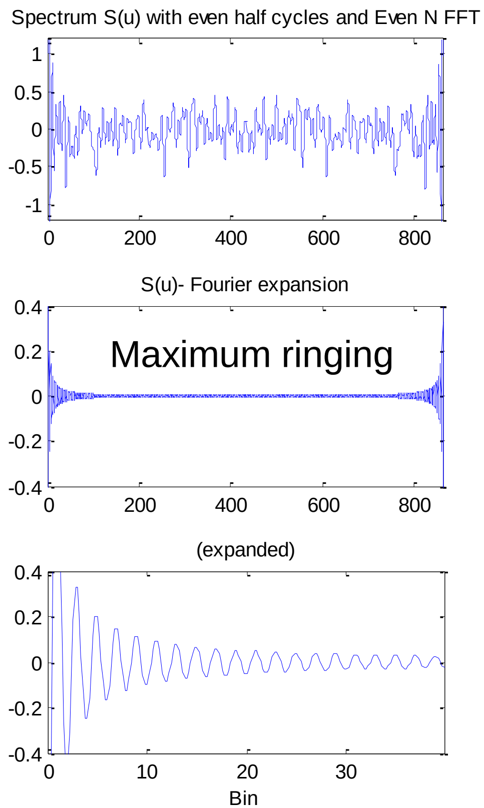
	min/max %	db
LW	0.12	-29.4
MW	0.19	-27.2
SW	0.50	-23.0

- **Inherent ripple far from the peak ~0.1% to 0.5%**

“Truth” ringing in the Fourier spectrum depends of frequency content of high resolution spectra S (u)

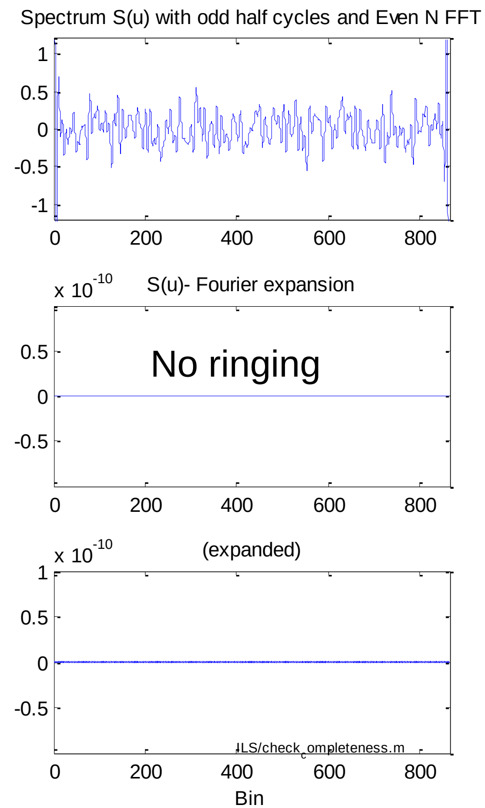
Random spectrum with every wavenumber midway between FFT wavenumbers

N=864



Error in Fourier series expansion =40%

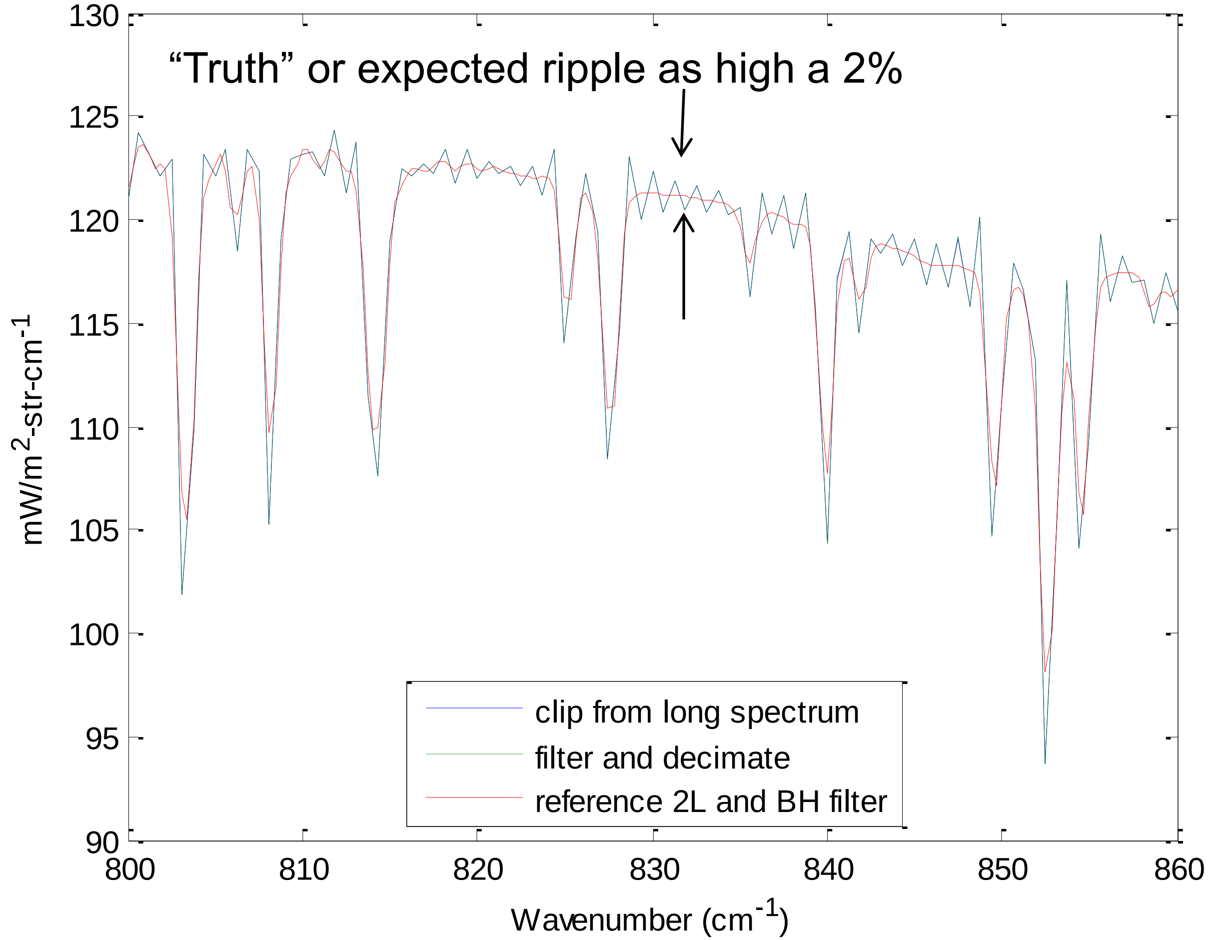
Random spectrum with every wavenumber at FFT wavenumber



Error in Fourier series expansion <1.e-12 %

Discrete FFT wavenumbers = $2\pi(n+1/2)/N$ (even N)

“Truth” ripple occurs across the band, differences due to processing much smaller



Reference has same resolution

Ripple in the “truth” spectrum

- **Ripple in the “truth” spectrum of a finite length sampled interferogram**

$$N_{truth}[k] = \frac{1}{g(u)} \int N_{Scene}(u')g(u')Sinq(k - \frac{u'}{\Delta})du'$$

- **Ripple is contributed by all frequencies between the FFT sample frequencies**
- **Ripple is equally likely in low or high resolution components of the raw high resolution spectra**
- **Suppressing the spectrum at the end points reduces the ripple**

Ringing in CrIS measurements

- Inherent expected or “truth” ringing
- Processing ringing errors
- Impact on NPP products
- Recommendation

Ripple error sources

- **Error is any deviation from the spectrum obtained from a cyclic FFT of the raw spectrum or equivalently a circular FIR filtering**

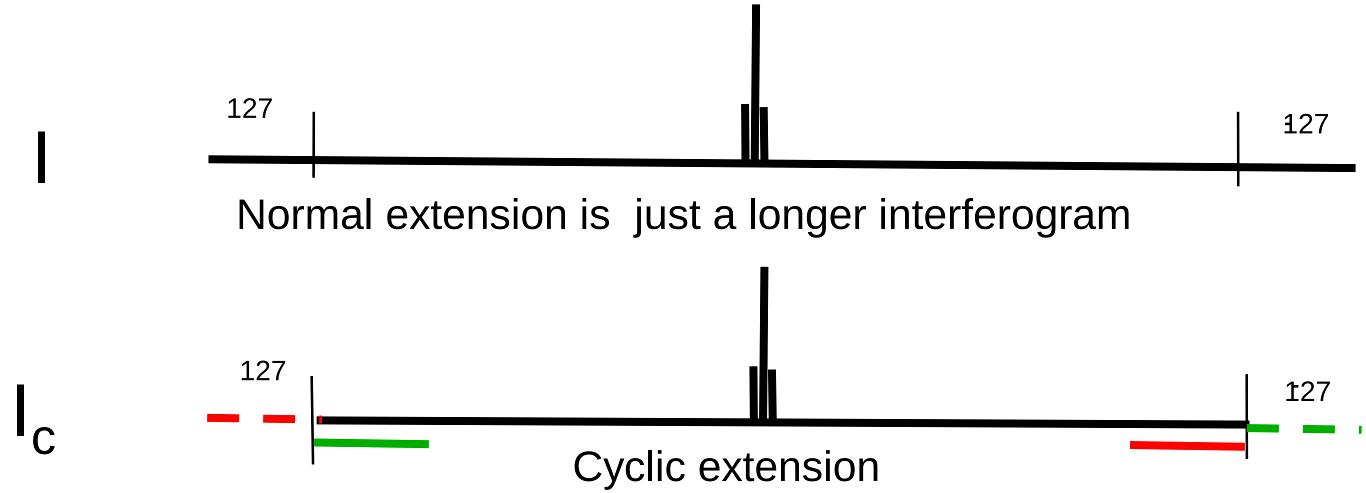
	Ripple class	Ripple type	process	% of 287K worst case	
1	FIR filtering and decimation	end point variation changes	spacecraft	99% pass	band edges
2	Algorithm improvements		ground	99% pass	MW exceedances
3	Delta function approximation		ground	99% pass	MW < 1240 cm-1
4	ZPD shifs and SA^{-1} variability	phase in SA-1 definition	ground	pass	
5	Scan direction ripple differenc	Uncorrected 100 $\lambda/2$ shift	ground	99% pass	MW <1240 cm-1
6	Interpolation	small eigen values in matrix	groind	99% pass	edge differences
7	Laser variation	real time variation in laser wavelength	ground	pass	
8	SA^{-1} definition variability	band edge ripple	ground	pass	

Non-circular FIR

- **Equivalence of long FFT and clip processing and FIR filtering and decimation is only valid for circular FFT filtering**
- **On board processing is not circular filtering error depends on the end points in the interferogram**
- **Errors below accuracy specification for 99% of band**
- **Differences for scan left-right ~4λ/2**

	LW	MW	SW
wavenumber	830	1370	2550
mW/m^2-str-cm^{-1}	0.072	0.024	0.0028
% of 287K	0.066	0.075	0.510
accuracy (% of 287K)	0.45	0.58	0.77
NEDN (% of 287K)	0.1	0.13	0.35

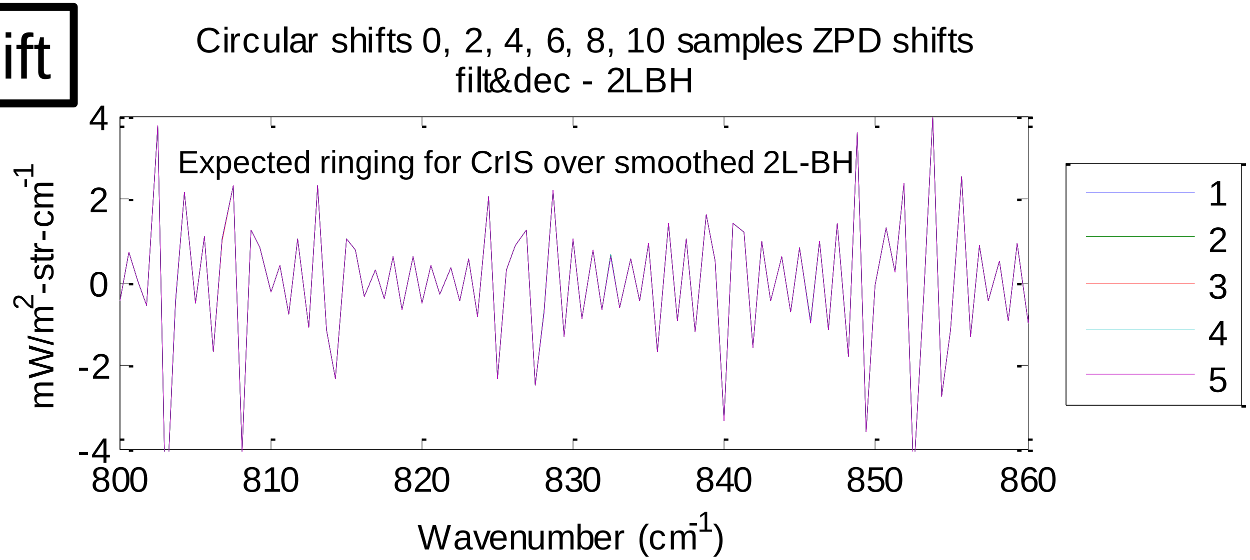
FIR and Decimate (FD) and cyclic extension

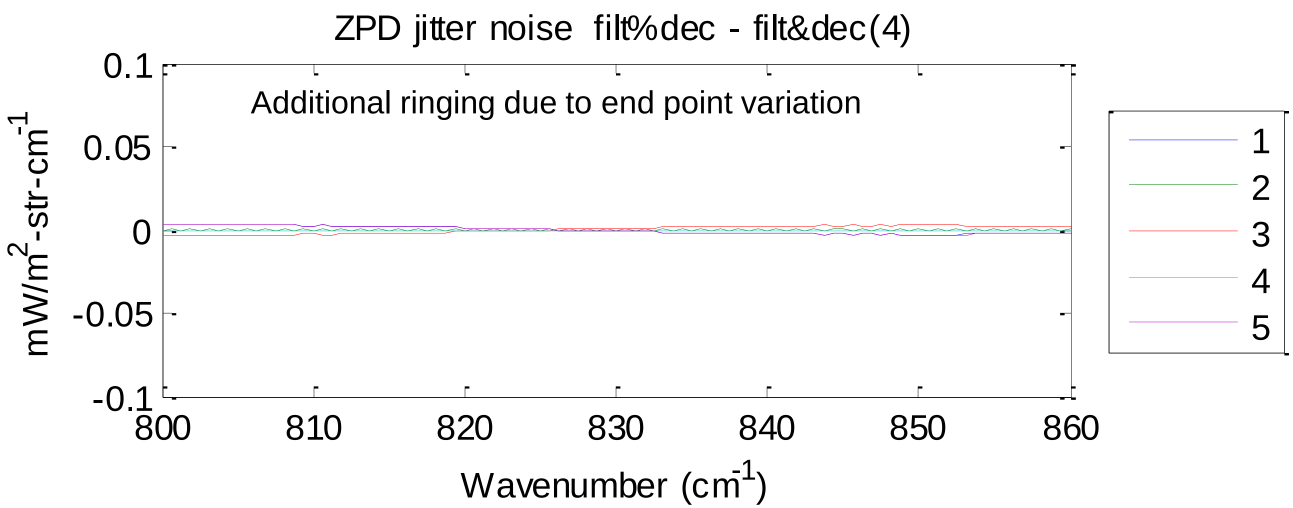


- **FD processing gives reference S_0 only for cyclic extended interferograms**
- **We should only use the middle 24*866 points since they are used to compute S_0 with a long FFT and clip**
- **We violate the assumption with current processing and do not get the reference spectra S_0.**
- **How much of an error do we make?**

LW expected ringing relative to smoothed 2LBH spectrum and smaller end point errors

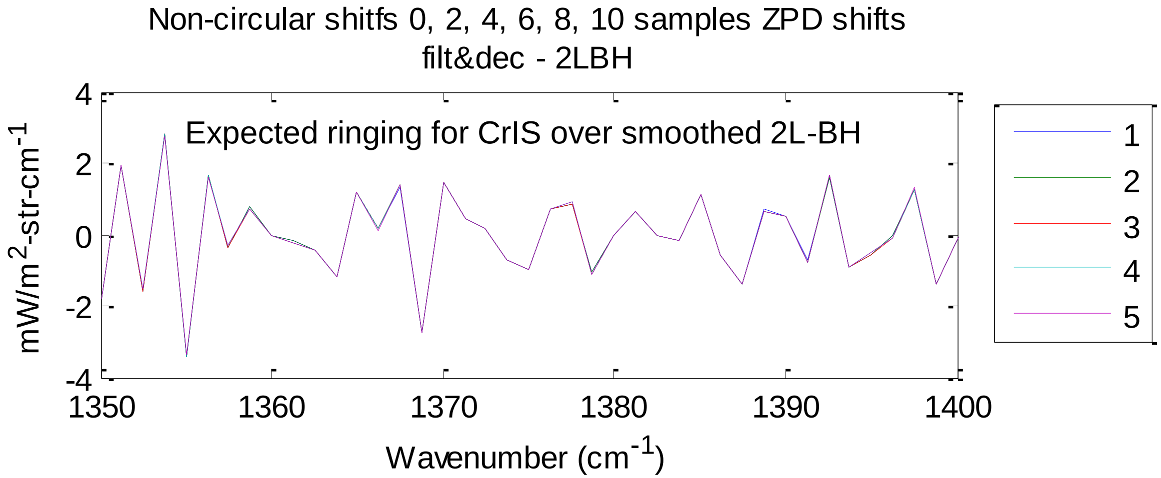
cyclic shift

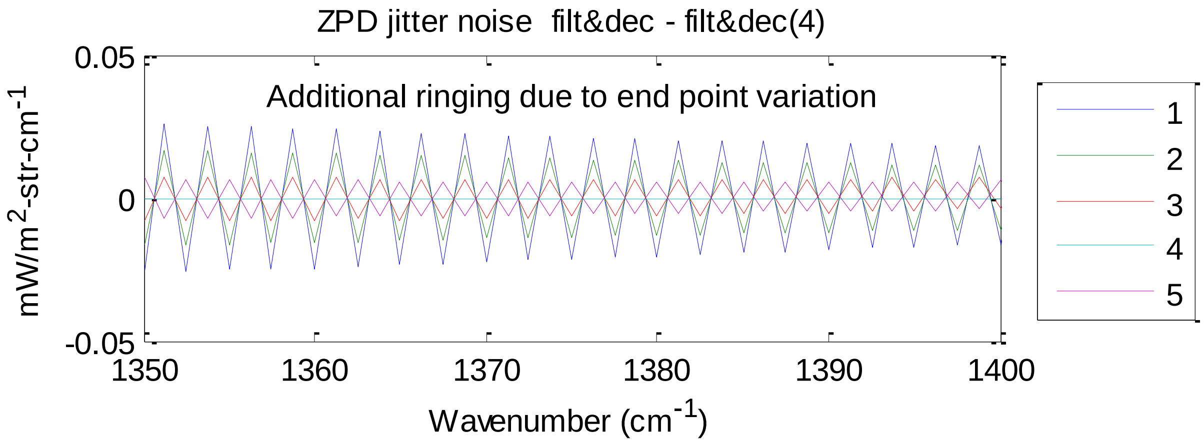




MW expected ringing relative to smoothed 2LBH spectrum and smaller end point errors

Non-cyclic shift





Algorithm improvements

- IDPS algorithm Based on early definition of processing and is not internally consistent
- Steps in processing should undo what the interferometer does to the signal in reverse order
- Other processing approaches have been evaluated
- Utility of processing options for extended resolution processing still being evaluated
- Ringing differences exists between various options but are below the accuracy specification in most cases

Calibration approach differences

Member	CMO pricipals	Calibration	Comment
IDPS	$SA_u^{-1}, F_{s\to u}$	$N = (SA_u^{-1} \cdot F_{s\to u} \cdot f_{ATBD}) \cdot \left\{ \frac{S_E - S_{SP}}{S_{ICT} - S_{SP}} ICT(T, u_{sensor*(1+delta)}) \right\}$	SA^{-1} in user grid, Calibration wavenumber is shifted off-axis empirically. No ILS correction for imaginary part
Exelis (old)	$SA_u^{-1}, F_{s\to u}$	$N = \left(SA_u^{-1} F_{s\to u} \cdot f_{ATBD}\right) \left\{ \frac{S_E - S_{SP}}{S_{ICT} - S_{SP}} f_{BH} \cdot \left[SA_u^{-1} \cdot F_{s\to u} \right]^{-1} \cdot ICT(T, u_{sensor}) \right\}$	SA^{-1} in user grid, Calibration wavenumber is sensor grid. ILS for real & imag
Exelis(new)	$SA_u^{-1}, F_{s\to u}$	$N = \frac{(SA_u^{-1} \cdot F_{s\to u})(S_E - S_{SP})}{(SA_u^{-1} \cdot F_{s\to u})(S_{ICT} - S_{SP})} \cdot ICT(T, u_{user})$	SA^{-1} in user grid, Calibration wavenumber is sensor grid
LL(old)*	$SA_s^{-1}, F_{s\to u}$	$N = \frac{M \cdot \left(FIR^{-1} \cdot (S_E - S_{SP})\right)}{M \cdot \left(FIR^{-1} \cdot (S_{ICT} - S_{SP})\right)} \cdot ICT(T, u_{user})$	M calculated as single matrix from off-axis sensor to on-axis user, close to $F*SA^{-1}$
Proposed	$SA_s^{-1}, F_{s\to u}$	$N = F_{s\to u} \left\{ f_{ATBD} \cdot \left[\frac{SA_s^{-1} \cdot \left(FIR^{-1} \cdot (S_E - S_{SP})\right)}{SA_s^{-1} \cdot \left(FIR^{-1} \cdot (S_{ICT} - S_{SP})\right)} \cdot ICT(T, u_{sensor}) \right] \right\}$	SA^{-1} in sensor grid, Calibration wavenumber is sensor grid, FIR 3db wider
ADL/CSPP (IDPS translation)	$SA_u^{-1}, F_{s\to u}$	$N = (SA_u^{-1} \cdot F_{s\to u} \cdot f_{ATBD}) \cdot \left\{ \frac{S_E - S_{SP}}{S_{ICT} - S_{SP}} ICT(T, u_{sensor*(1+delta)}) \right\}$	SA-1 in user grid, Calibration wavenumber is shifted off-axis by corner, edge, center
UMBC/UW** option A	$SA_u^{-1}, F_{s\to u}$	$N = F_{s\to u} \cdot \left(f \cdot SA_s^{-1} \cdot \left\{ f \cdot \frac{(S_E - S_{SP})}{(S_{ICT} - S_{SP})} ICT(T, u_{sensor*<\cos>}) \right\} \right)$	SA-1 in user grid, Calibration wavenumber shifted uniquely by FOV and band
UMBC/UW** option B	$SA_s^{-1}, F'_{s\to u}$	$N = F_{s\to u} \cdot \left(f \cdot ICT(T, u_{sensor}) \cdot SA_s^{-1} \cdot \left\{ f \cdot \frac{(S_E - S_{SP})}{(S_{ICT} - S_{SP})} \right\} \right)$	SA^{-1} in sensor grid, Calibration wavenumber is sensor grid

F=interpolation matrix
SA^{-1}=inverse self apodization matrix
f = band trimming filter
f_{BH} =Blackmann Harris filter

* M is single calculation from off-axis sensor to on-axis user grid

** F may be Sinc or FFT based, f may be ATBD or raised cosine

Two primary processing approaches

- **Two primary processing classes**
  - **1. Calibrate off-axis then convert to on-axis user grid (Exelis-old, IDPS, ADL, CSPP) based on Bomem attempt to reduce computation**

$$SA_u^{-1} \cdot F_{s \to u} \left\{ \frac{(S_{scene} - S_{space})}{(S_{scene} - S_{space})} R_{ICI}(T, u_{off-axis}) \right\}$$

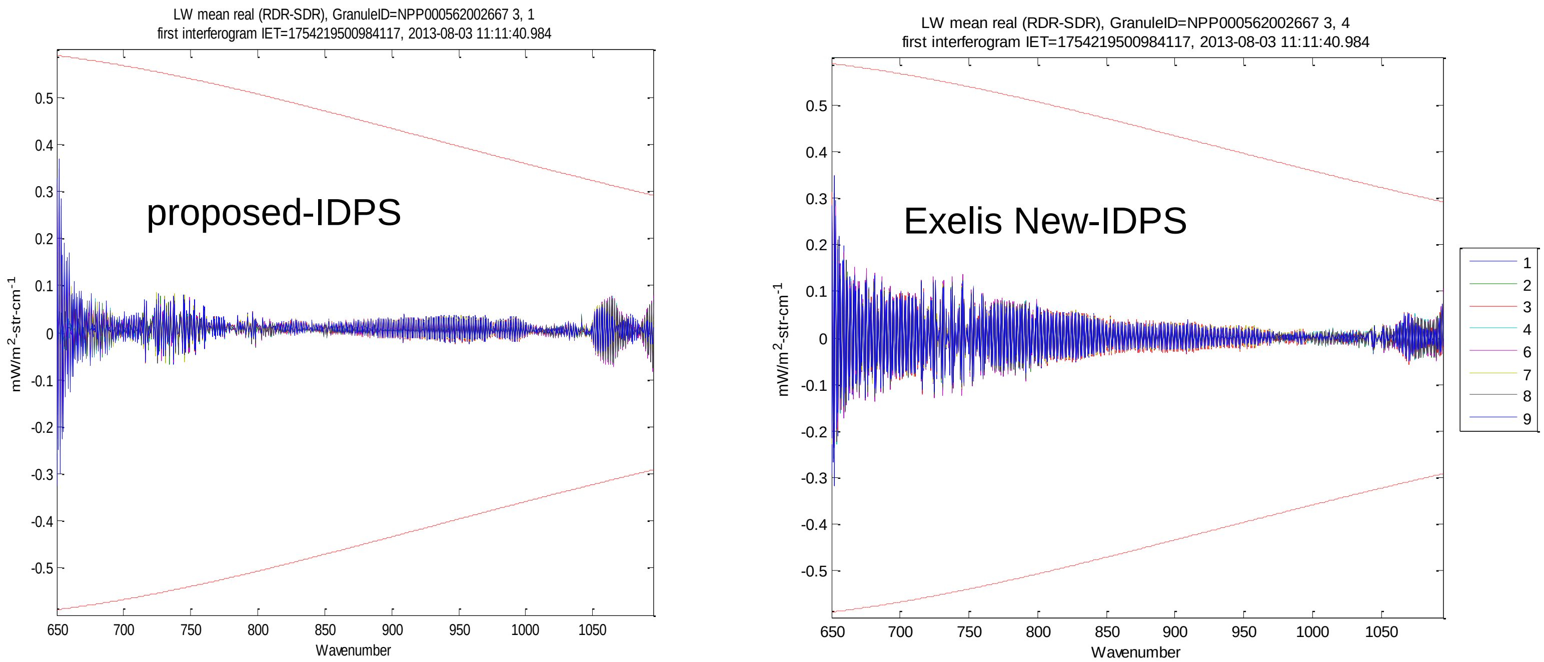
  - **2. Convert to on-axis grid then calibrate (Exelis-new, proposed,LL)**

$$R_{ICI}(T, u_u) \cdot \frac{F_{s \to u} \cdot SA^{-1} \cdot (S_{scene} - S_{space})}{F_{s \to u} \cdot SA^{-1} \cdot (S_{scene} - S_{space})} \qquad F_{s \to u} \cdot \left[\frac{SA_s^{-1} \cdot (S_{scene} - S_{space})}{SA_s^{-1} \cdot (S_{scene} - S_{space})} \cdot R_{ICI}(T, u_{sensor}) \right]$$

- **Differences in bias and ripple but below accuracy specification**

- **Second approach is more consistent**

Typical LW ringing differences between processing options



Different detailed differences between options are being systematically compared

Check the delta function approximation

- **Delta function approximation**

$$\int_{0}^{N} \mathrm{Sinc}(\ xR - z)\,\mathrm{Sinc}(\ y - z)\,dz \cong \mathrm{Sinc}(\ xR - y)$$

- **Case 1: R=1, equality hold exactly**
  - **Known exact result**
  - **Quadrature test results show that for 2N points the worst case error is 1.e-12 using Gauss-Legendre quadrature or trapezoid rule**

- **Case 2: R NOT 1**
  - **No analytic solution;**
  - **R=1.001977,1.020532,1.00507 for LW,MW,SW bands**

$$R = \frac{\Delta u_{ref}}{\Delta u_{\lambda} \cos(\ a)}$$

  - **Quadrature checked by multiple algorithems**
  - **Delta function approximation has significant error**

Delta function approx error summary

- **The approximation**

$$\int_0^N \mathrm{Sinc}(xR - z)\,\mathrm{Sinc}^*(y - z)\,dz \cong \mathrm{Sinc}(xR - y)$$

- **The errors**

Case 1: R=	1.00000	1.00000	1.00000
delta approx errors	1.E-14	1.E-14	1.E-14
Case 2: R=	1.001977	1.020532	1.00507
Max delta approx errors	0.002	0.010	0.005

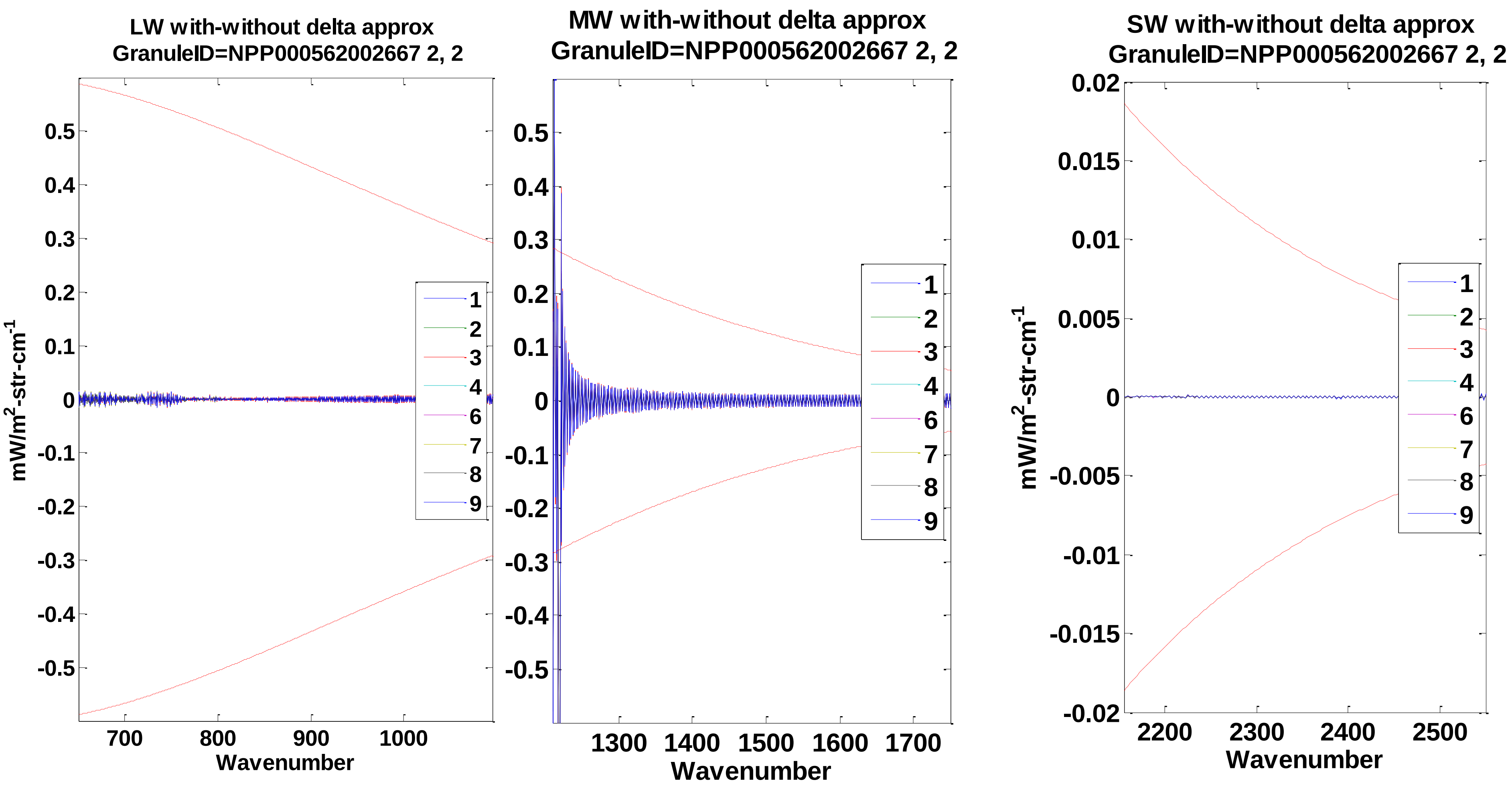
- **The errors occur across the band and are ripples**

- **There is a large amount of summing and cancelation and results are best compared by processing NPP spectra with and without approximation**

- **Changes are well below accuracy except for ~ MW 1260 cm-1**

With and without delta function approximation using IDPS algorithm

LW MW SW



Effects of ZPD on SA^{-1} are negligible

- **Compare self apodization corrected off-axis spectra SA and on-axis spectra on sensor grid**

- **18 Dec 2012 Briefing "Change in Calibration for different ZPD assumptions (2)"**

- **Changed ZPD by +/- 50 λ/2 and compute SA matrix**

$$SA^{-1} = \sum_a P(a) \sum_m \mathbf{exp(i2\pi u_m \delta ZPD(cos(a)-1))} \frac{\Delta u_{spec}}{\Delta u_a} Sinq\left(\frac{u_m}{\Delta u_a} - k, N\right) Sinq^*\left(\frac{u_m}{\Delta u_{spec}} - k', N\right) w_m$$

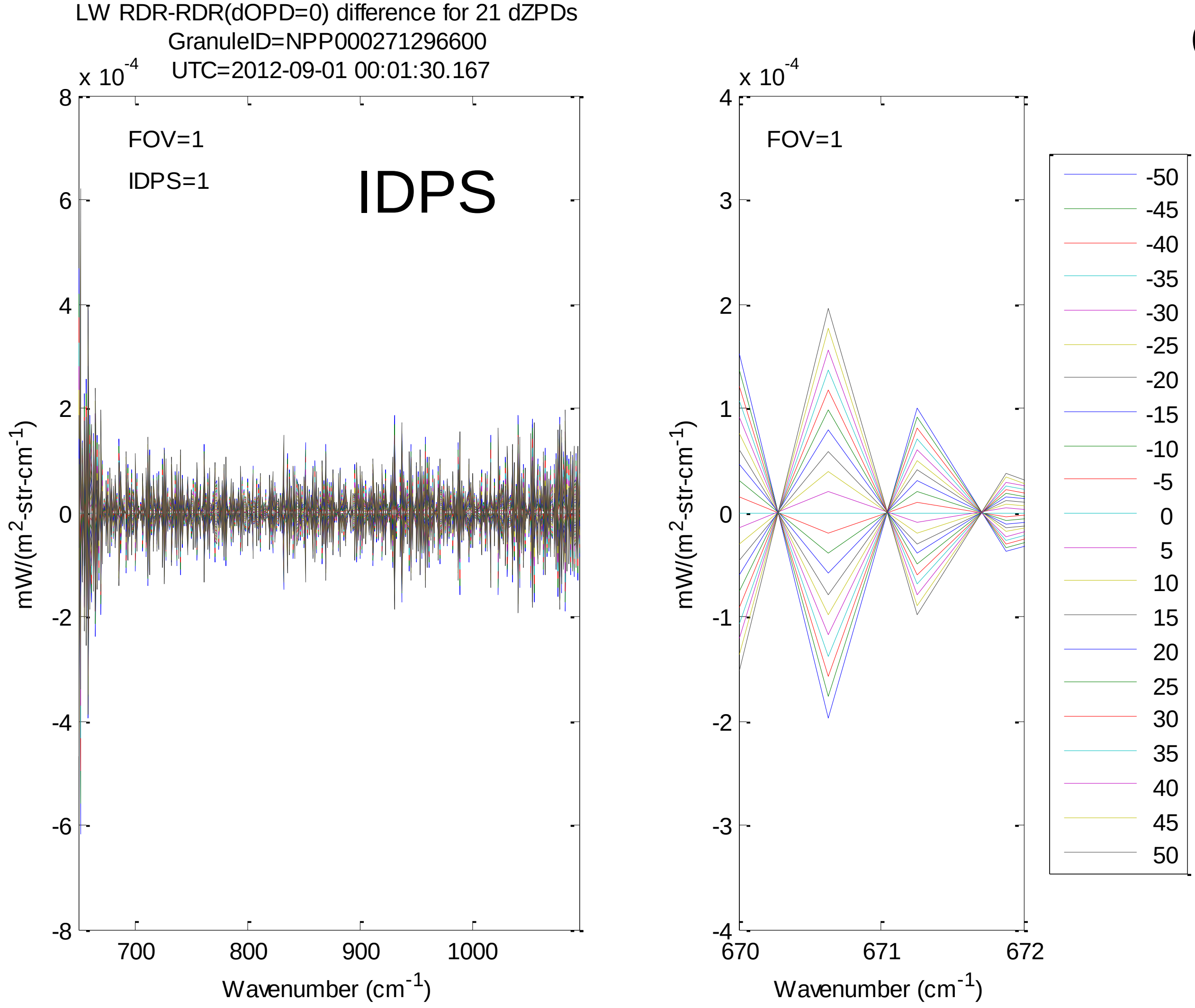
- **Changes are small due to incorrect self apodization correction, well below the NEDN**

Band	Max error +/- 50 λ/2	NEDN level
LW	4.00E-04	4.00E-01
MW	3.00E-03	4.00E-02
SW	1.00E-05	5.00E-03

Change in calibrated LW spectra for ZDP change over +/- 50 λ/2

Case 1

NEDN ≈ 0.1



Scan direction ripple

- **Large ripple first observed with older FIR filter associated with different large filter residuals**
- **Modification of FIR filter reduced the scan direction ripple but did not eliminate it**
- **Detailed analysis of clear ocean scenes show small residual scan direction ripple**
- **Thought to be caused by FIR filtering**
- **Effect is small for 99% of the channels and difficult to isolate and analyze in the measurement data**

Estimate of scan direction ringing differences from measured clear ocean scenes

- **Data evaluated using double difference (Strow UBMC)**

- **S1=Measured spectrum with sinc window-RTA with sinc window removes most of ringing and leaves bias and ringing**

$$S1(\delta ZPD, S_0) \approx N_{Obs}[k] - \int N_{RTA}(u) Sinc(k - \frac{u}{\Delta}) du$$

- **S2=Measured spectrum with Hamming window-RTA with hamming window removes most of ringing and leaves bias**

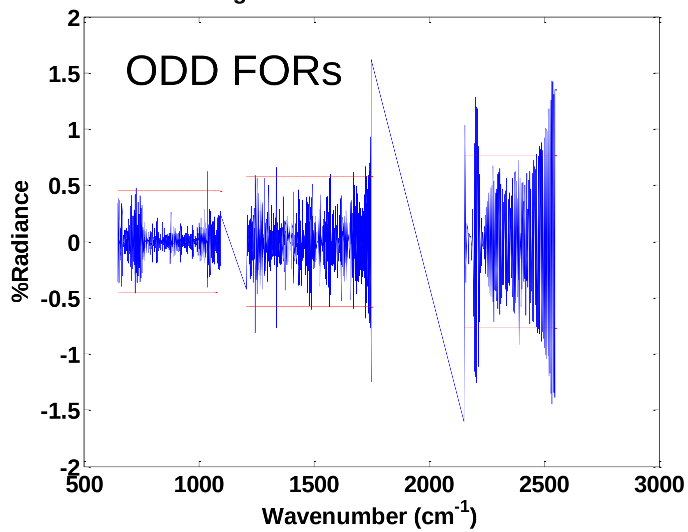
$$S2(\delta ZPD, S_0) \approx \sum \left(N_{Obs} \otimes H\right)[k'] - \int N_{RTA}(u) H(k - \frac{u}{\Delta}) du$$

- **S=S1-S2 is essentially error ringing with some Hamming residual truth ringing**

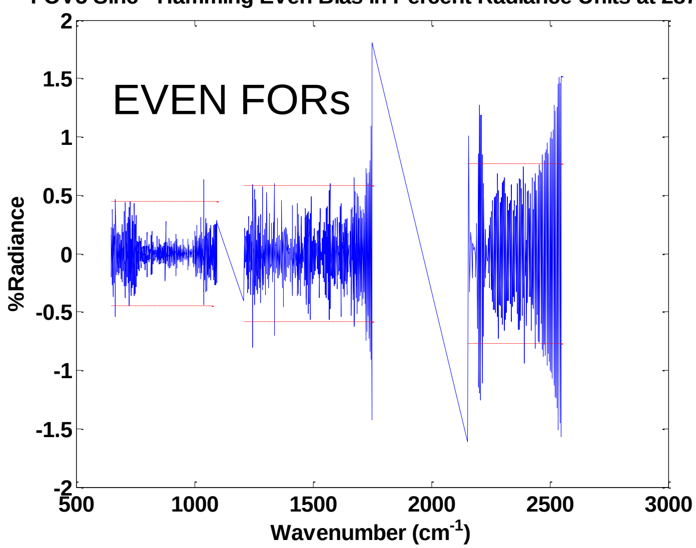
- **Left-right ringing is well below “not to exceed” x3 accuracy specification, meets accuracy specification except below 660 cm-1**

Double difference processing of clear ocean scenes

FOV5 Sinc - Hamming Odd Bias in Percent Radiance Units at 287K

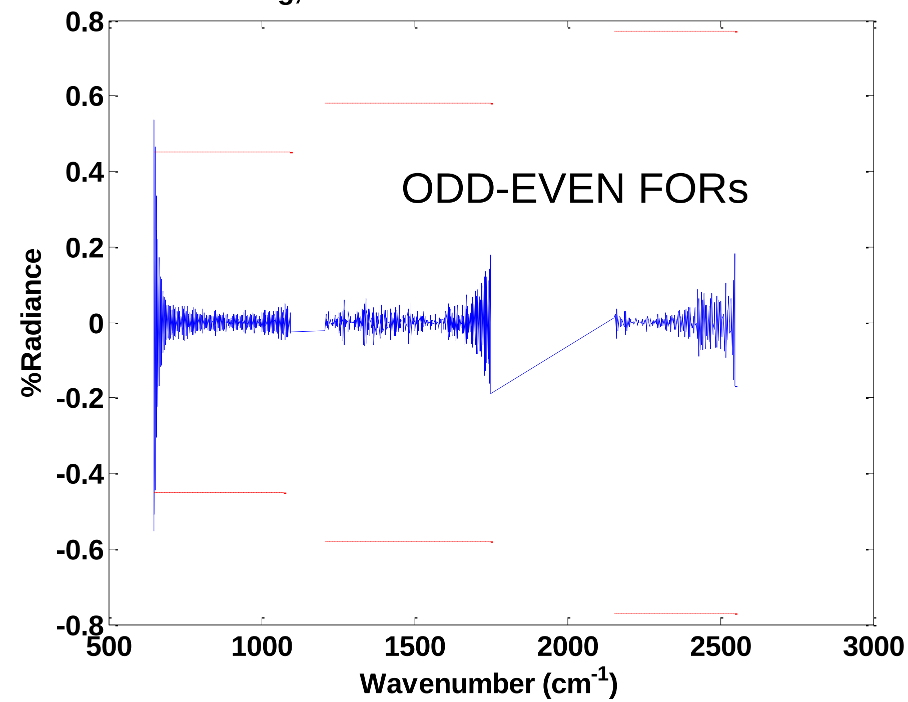


FOV5 Sinc - Hamming Even Bias in Percent Radiance Units at 287K



	LW	MW	SW
Accuracy (% of 287K)	0.45	0.58	0.77
NEDN (% of 287K)	0.10	0.13	0.35

FOV5 Sinc-Hamming, Odd-Even Bias in Percent Radiance Units at 287K



from L. Strow, UMBC

Interpolation matrix F

- **Interpolation matrix from sensor grid is ill-conditional**

$$S_u[k'] = F(k',k)S_s[k]$$

$$F[k',k] = \frac{\Delta_s}{\Delta_u} Sinq(\frac{k\Delta_s}{\Delta_u} - k')$$

- **Various numerical methods used to deal with it**
- **Underlying problem is the spectral range of the sensor and user grid is different**
- **Empirical filtering in IDPS used to minimize ripple below specification**

Calibration differences with metrology laser shifts

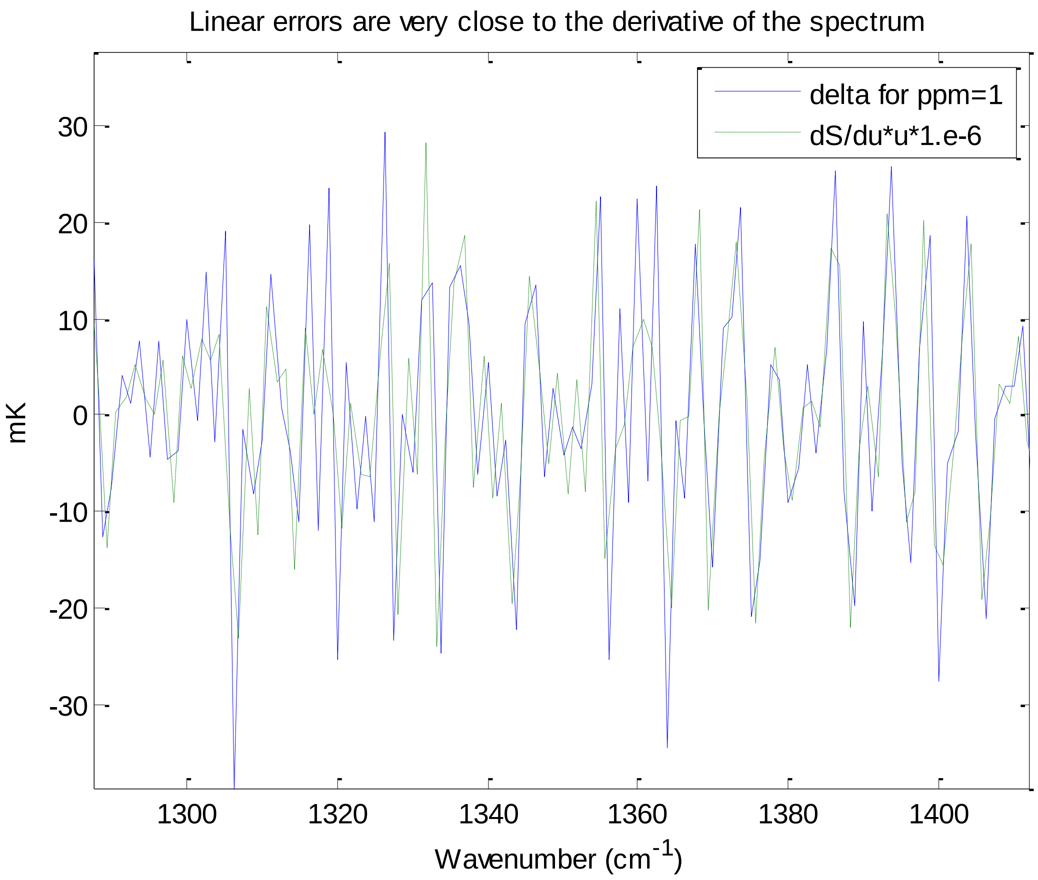
- Interpolation matrix is laser wavelength dependent
  – Nominal measured wavelength used as baseline

- Parameterize ppm offset, recomputed M, and recalibrate RDR
  – PPM shift = -5, -4, -3, -2, -1, 0, 1, 2, 3, 4, 5

- Abs Peak errors for 1 PPM shift well below accuracy specification
  – LW 45 mK 0.064 % of 287K
  – MW 30 mK 0.072 % at 287K
  – SW 15 mK 0.068% at 287K

- Errors roughly equal to the numerical derivative times (wavenumber*ppm*1.e-6) but not good enough to make a correction

MW error is very similar to the derivative of the spectra (PPM=1)



SA^{-1} matrix variability

- Multiple definitions of self apodization matrix exist
- Processing difference is a ripple
- Ripple errors tend to group FOV into corners, edges , and the center
- Differences are less than the RU (accuracy) specificaton
- Continued evaluation of SA matric computation to reduce ripple

Ripple error sources

- **Error is any deviation from the spectrum obtained from a cyclic FFT of the raw spectrum or equivalently a circular FIR filtering**

	Ripple class	Ripple type	process	% of 287K worst case	
1	FIR filtering and decimation	end point variation changes	spacecraft	99% pass	band edges
2	Algorithm improvements		ground	99% pass	MW exceedances
3	Delta function approximation		ground	99% pass	MW < 1240 cm-1
4	ZPD shifs and SA^{-1} variability	phase in SA-1 definition	ground	pass	
5	Scan direction ripple differenc	Uncorrected 100 $\lambda/2$ shift	ground	99% pass	MW <1240 cm-1
6	Interpolation	small eigen values in matrix	groind	99% pass	edge differences
7	Laser variation	real time variation in laser wavelength	ground	pass	
8	SA^{-1} definition variability	band edge ripple	ground	pass	

Impact on NPP products

- All prior EDR studies used Blackman-Harris filtered spectra
- All EDR requirements were met
- Blackman-Harris or more preferably the invertible Hamming filtering reduces ringing to negligible levels
- There is no EDR impact for the present level of ringing error

Summary and conclusions

- Ripple error is caused by many different steps but for the most part ripple is below the accuracy specification
- Only significant operational ripple variation in the IDPS processing is the scan direction variation and thought to be due to onboard FIR filtering implementation
- Ripple can be almost completely eliminated by Hamming filtering
- All CrIS EDRs can be met with filtered spectra and normal resolution
- Ripple may be a problem with extended resolution and science studies and optimal processing methods are being evaluated