Deriving Nonlinearity Coefficients from Changing Background

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Quadratic Nonlinearity Equations

An interferometer with quadratic nonlinearity can be expressed as:

$$I' = (I + V) - a_2(I + V)^2$$

where: *I* = original undistorted interferogram
I' = interferogram distorted with quadratic nonlinearity
V = offset voltage
a_2 = quadratic nonlinearity coefficient

Rearranging the terms yields:

$$\mathrm{I}' = -a_2 I^2 + (1 - 2a_2 V)I + (V - a_2 V^2)$$

This term is just a constant and can be removed before taking the Fourier transform. After taking the Fourier transform the result is:

$$-a_2(S * S) + (1 - 2a_2 V)S$$

where: *S* is the Fourier transform of *I*, and convolution is indicated by $*$.
If the spectrum is band limited, the first term can be ignored, resulting in:

$$(1 - 2a_2 V)S$$

This is the desired spectrum, *S*, multiplied by a gain term

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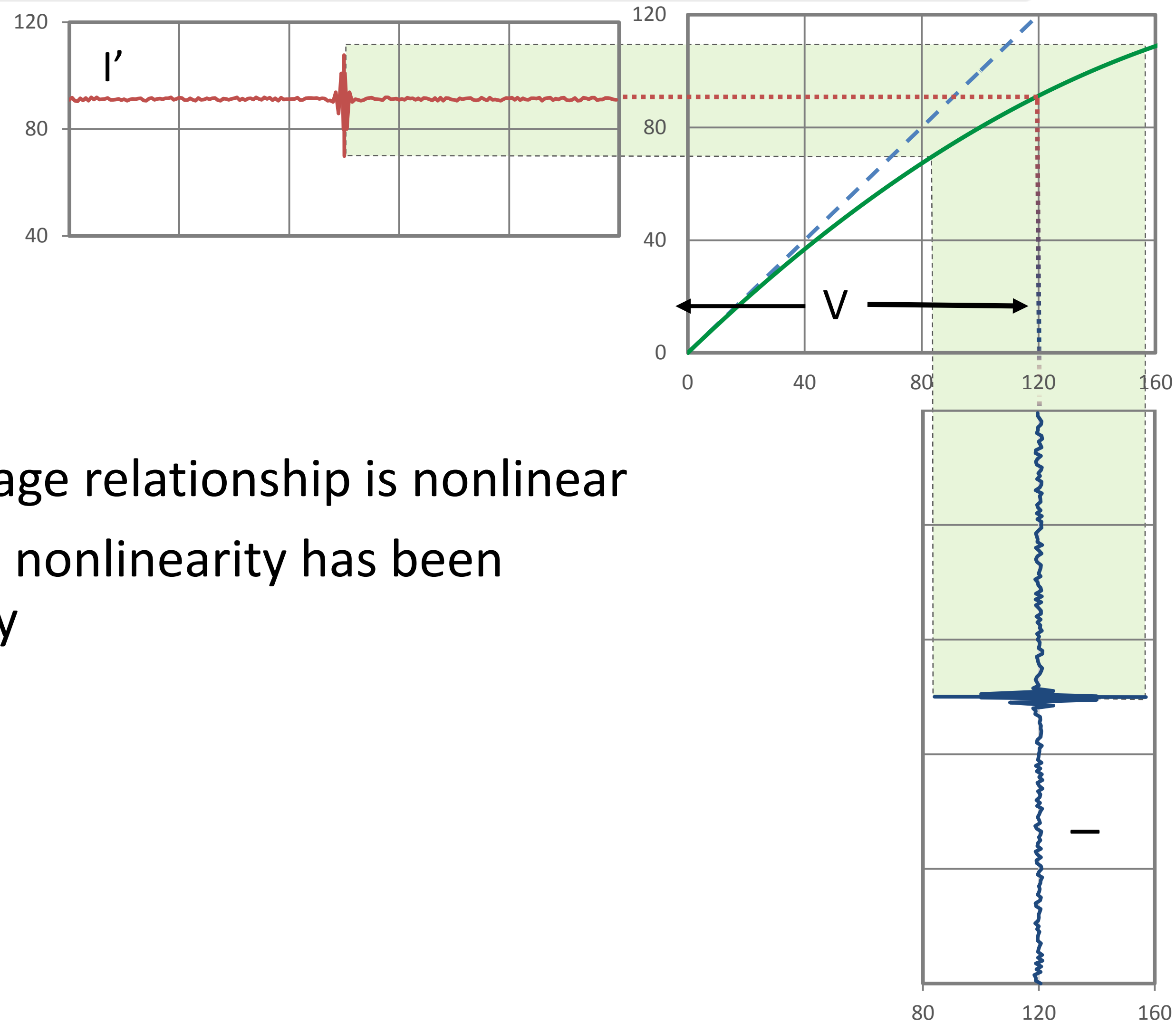
Graphical Representation of Nonlinearity

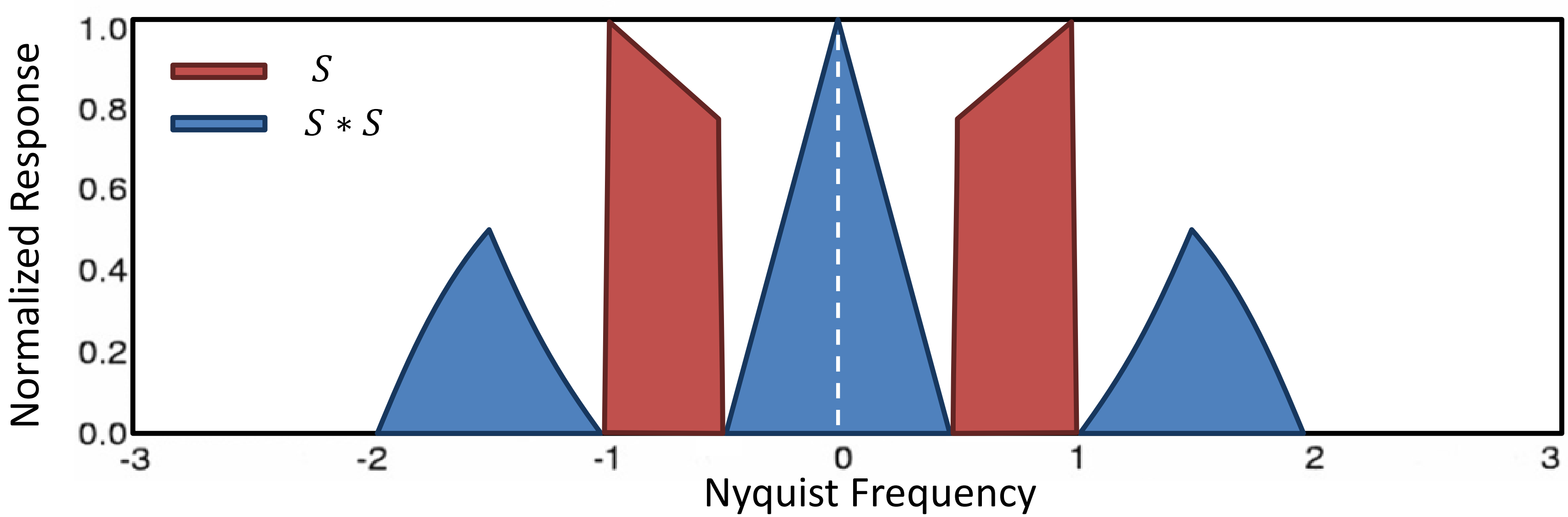
$I' = (I + V) - a_2(I + V)^2$

V -- Voltage Offset
a_2 -- Quadratic Nonlinearity Coefficient
I -- Linear Input Interferogram
I' -- Nonlinear Interferogram



- CrIS's photons to voltage relationship is nonlinear
- The magnitude of the nonlinearity has been exaggerated for clarity

Nonlinear Spectrum



Nonlinear Spectrum

$S' = -a_2(S * S) + (1 - 2a_2V)S$

V -- Voltage Offset
S -- Correct Spectrum
S' -- Nonlinear Spectrum
a_2 -- Quadratic Nonlinearity Coefficient

- When S is band limited as shown, the $(S * S)$ component does not overlap spectrally and can readily be removed
- The nonlinearity corrected spectra is then: $S = S'/(1 - 2a_2V)$

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Standard Nonlinearity Correction Method

- Measure source with known output radiances
  - Need at least two different radiance levels
- Derive nonlinearity coefficients that yield known radiances
- Advantage:
  - Simple intuitive method
- Disadvantage:
  - Radiance of source needs to be known very accurately at different radiance levels

Alternative Nonlinearity Method

- Observe external source (ECT) held at a constant output radiance
  - Although required to be stable, the actual value of radiance is unimportant
- Make measurements with different sensor temperatures
- Internal calibration target (ICT) temperature floats with sensor temperature
- Reprocess the data with different nonlinearity coefficients
- Optimize nonlinearity coefficient by minimizing spread in calculated radiances
- Why it works:
  - Varying background sensor temperature moves up and down the system gain curve
  - Nonlinearity errors cause calibrated radiance to change even though the radiance from source has not changed

Sensor Simulation Model

- Built model to study sensitivities of the method
- Derived nonlinearity a_2 coefficients from simulated data
- Model included:
  - Internal calibration with Deep space (DS) and Internal Calibration Target (ICT)
  - ICT temperature errors
  - Time dependent temperature changes for ICT and ECT
  - Warm instrument background effects
  - Noise
- Results show low sensitivity to all parameters except for Earth Calibration Target (ECT) radiance changes correlated with sensor/ICT variations
- ECT radiance can vary as long as it is not correlated with sensor temperature

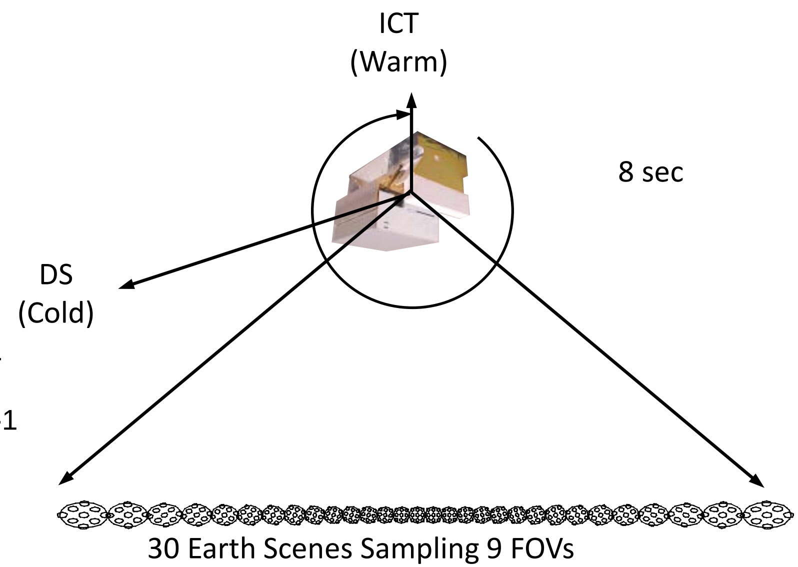
Nonlinearity Correction Method Applied to CrIS

http://www.jpss.noaa.gov/images/media-gallery/gallery-jpss1_1.jpg

- Cross-Track Infrared Sounder (CrIS)
- The CrIS sensor is an infrared Fourier transform spectrometer
- One CrIS instrument is currently flying on the Suomi National Polar-orbiting Partnership (NPP) spacecraft
- Another CrIS (J1) is being preparing for launch in 2017

CrIS Sensor Includes Self Contained Radiance Calibration

- 8-second scans
- 30 Earth locations
  - 9 FOVs per location
  - 3 spectral bands per FOV
    - LWIR 650-1095 cm^{-1}, resolution: 0.625 cm^{-1}
    - MWIR 1210-1750 cm^{-1}, resolution: 1.25 cm^{-1}
    - SWIR 2155-2550 cm^{-1}, resolution: 2.5 cm^{-1}

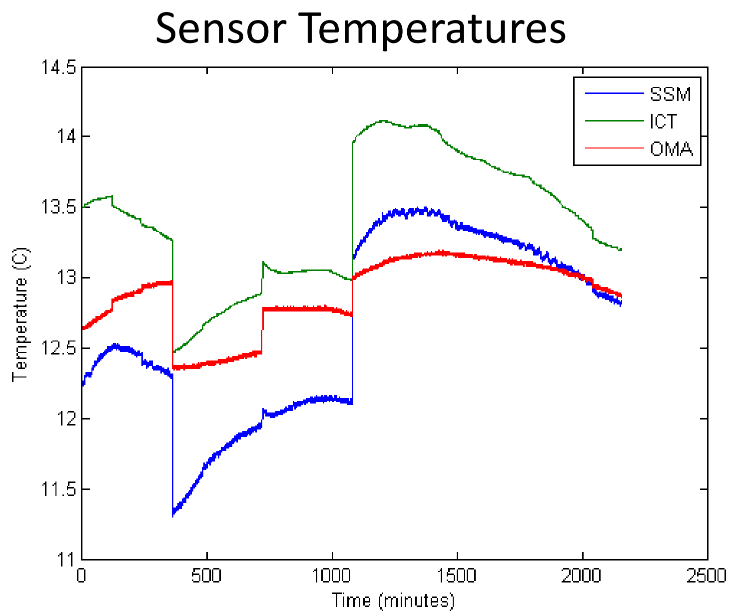


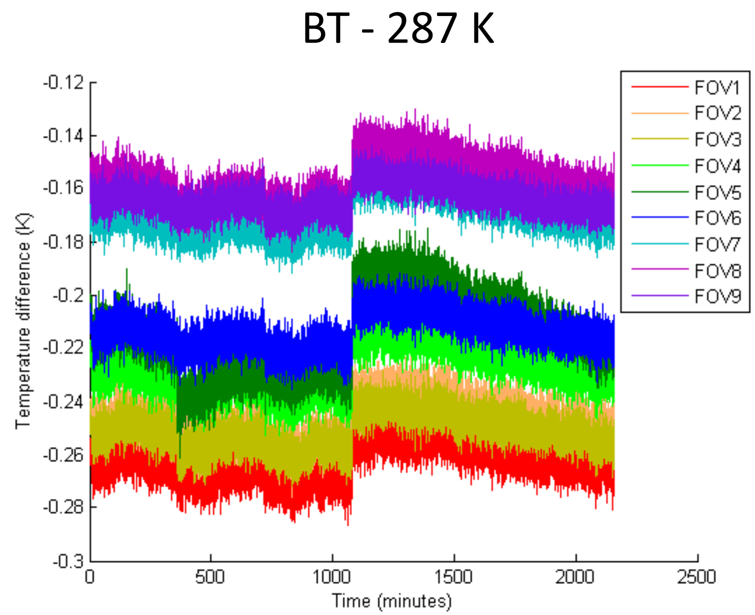
- Two calibration views per scan
  - Internal calibration target (ICT) — Warm (ambient temperature)
  - Deep space (DS) — Cold
  - Separate calibration for two interferometer scan directions
- Two redundant electronic sides

Nonlinearity Correction Method Applied to CrIS

- CrIS model J1 has completed thermal vacuum (TVAC) testing
- Long Term Repeatability (LTR) data taken during TVAC
- Provides opportunity to verify method with real sensor data
- LTR data consists of 18 collects each 2 hours long taken over a period of a month
- The LTR gives a metric for the stability of the sensor
- A small LTR means a stable sensor
- LTR is defined as:
  - Average together the 2 hours of spectra in each set
  - Convert to a percentage of a 287 K blackbody
  - Find the standard deviation at each wavenumber
- CrIS J1 meets spec with large margin even without a nonlinearity correction

Time History of LWIR LTR Data





- Temperatures for several sensor elements shown on left
  - SSM (scene select mirror), ICT (internal calibration target), OMA (interferometer or opto-mechanical assembly)
- BT error shown on right
  - Measured brightness temperature minus 287 K
- BT error tracks sensor temperature changes

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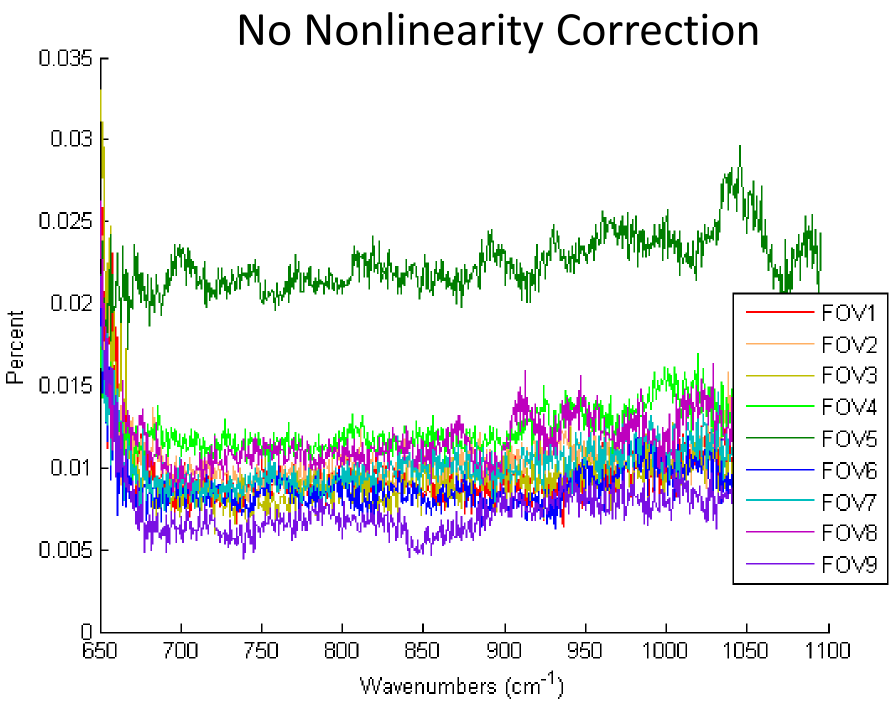
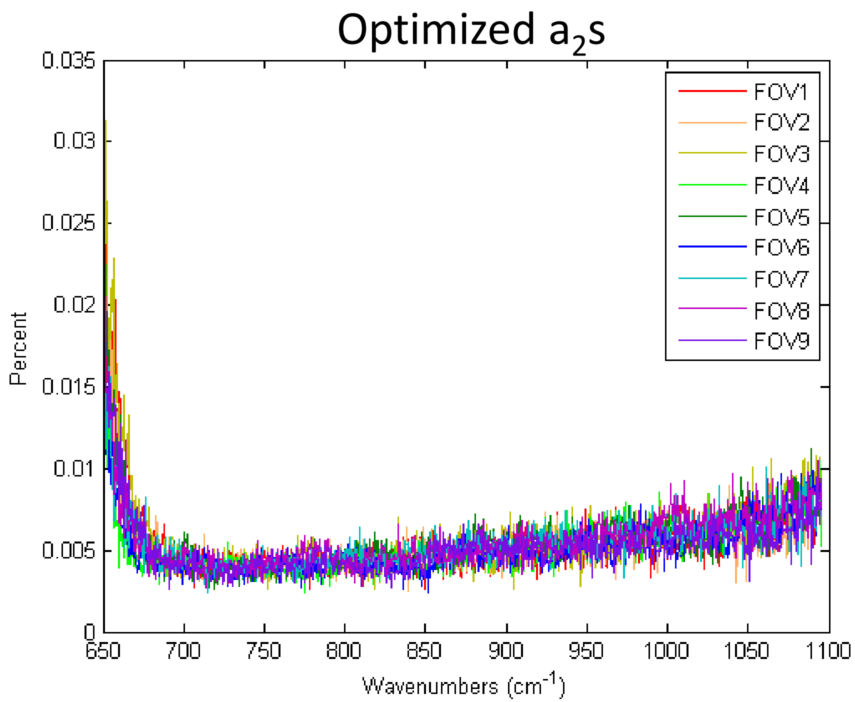
Derive Nonlinearity a_2s from LTR data

- Vary a_2s to minimize LTR using an iterative technique
  - Start with an initial set of a_2s
  - Calculate the LTR
  - Vary a_2s until minimum LTR is found
- Derivation of a_2s uses no explicit temperature knowledge
  - ICT and DS temperatures used by Science Data Record (SDR) algorithm
- Only consider more central regions of each band
  - LWIR 680 – 1020 cm^{-1}, MWIR 1220 – 1600 cm^{-1}, SWIR 2160 – 2400 cm^{-1}
- LTR histories created by concatenated measurements into single time series
- Analysis performed for both electronic sides

LWIR LTR Before and After Nonlinearity Optimization





- LW FOV5 most nonlinear and shows the largest LTR
- After optimization of a_2s, LTR is much lower
- Excellent agreement between FOVs

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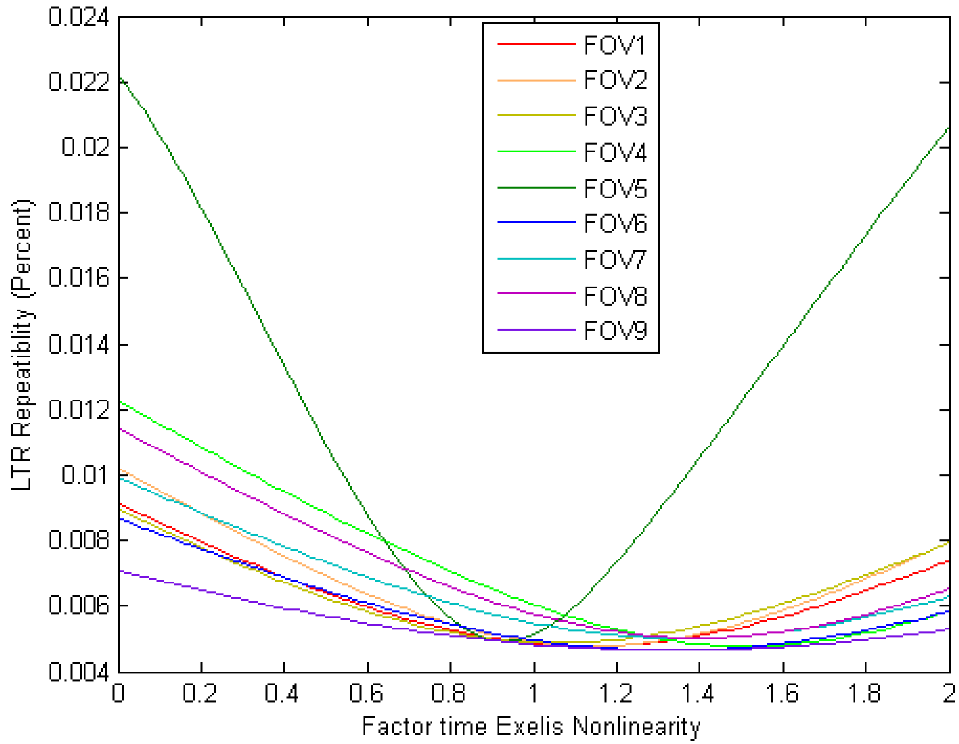
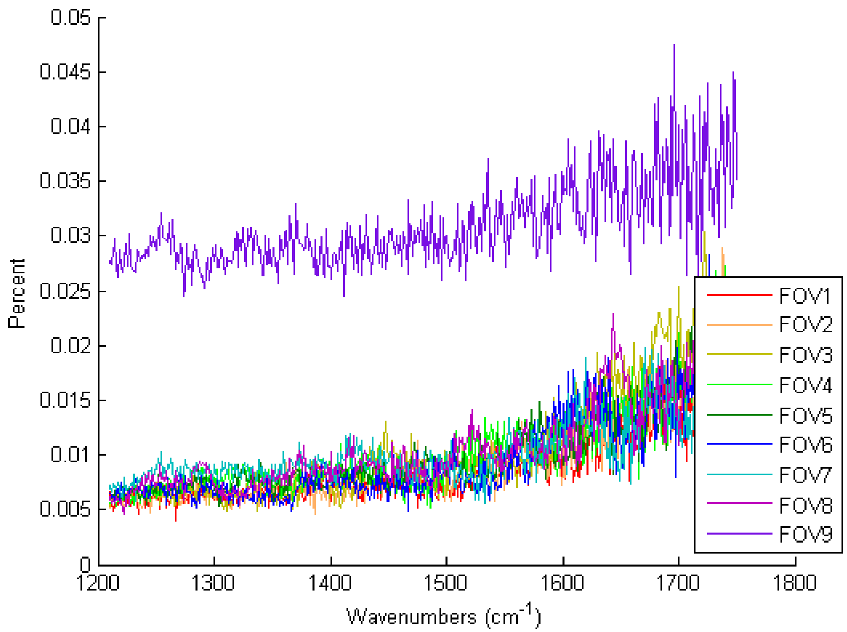
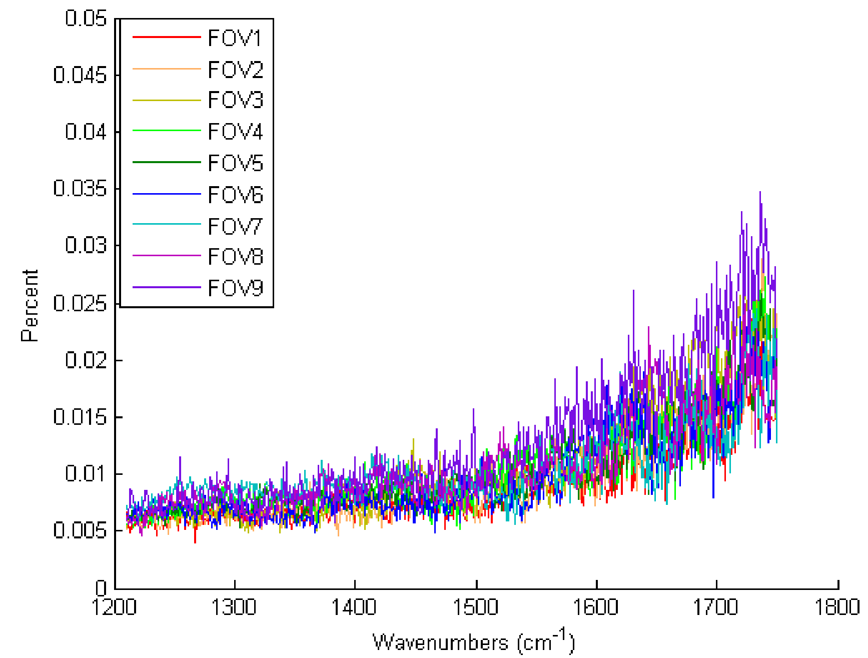
Magnitude of LTR with Different a_2s



- LTR calculated with a factor times preliminary Exelis a_2s
- Calculated at a number of points then spline interpolated
- Solved for factor that minimizes LTR for each FOV

MWIR LTR Before and After Optimization





- Only MW FOV9 has significant nonlinearity
- Only FOV9 a_2 optimized, all other MW a_2s set to zero

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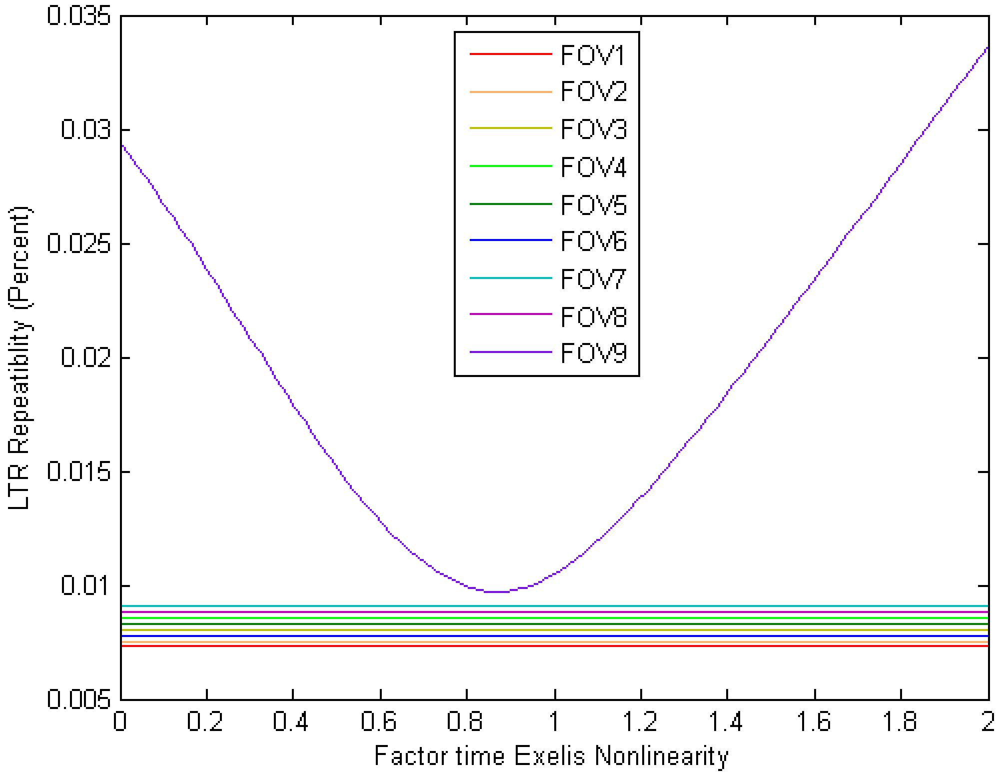
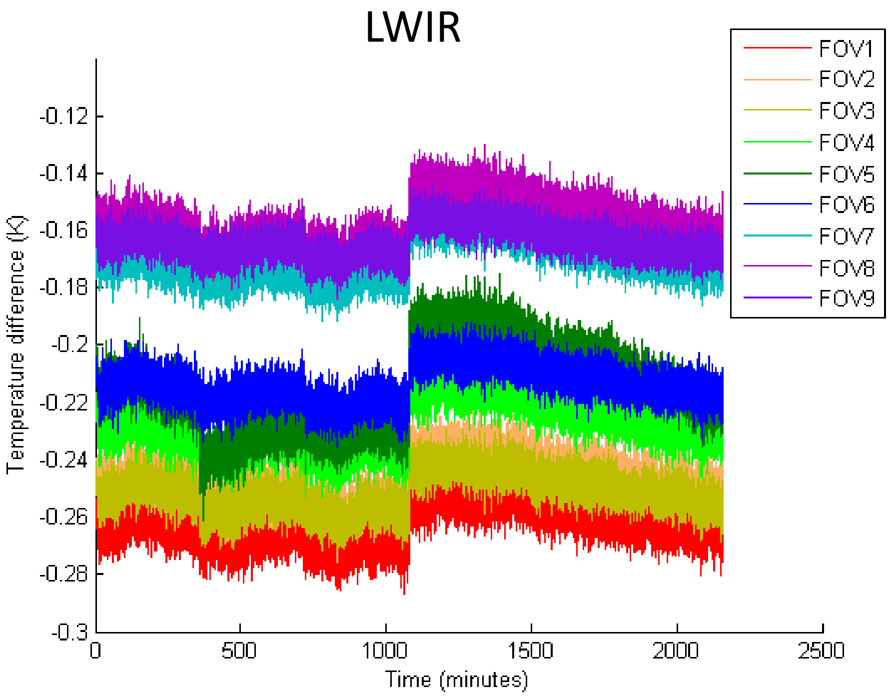
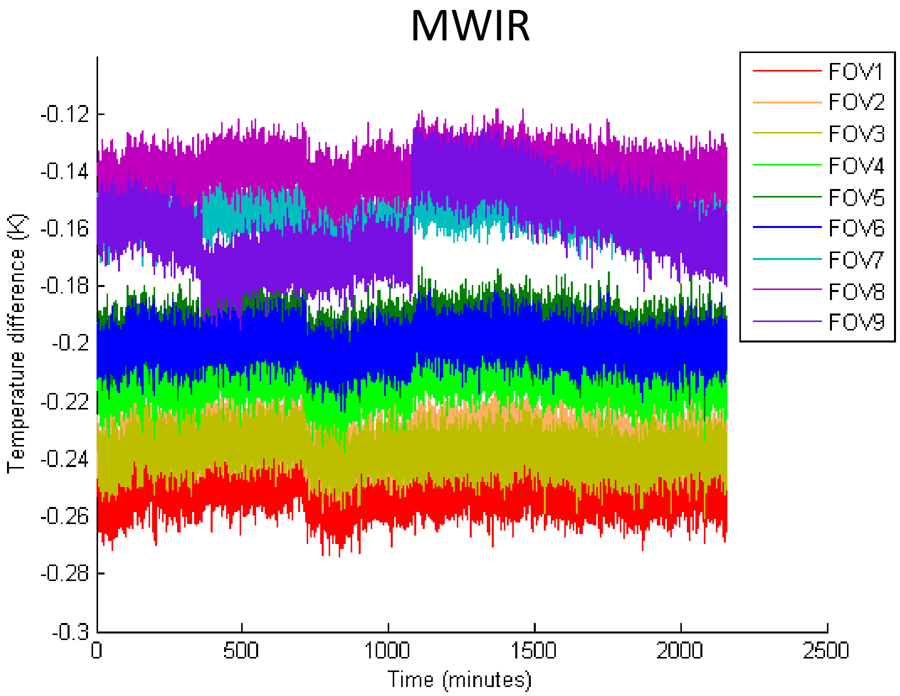
MWIR LTR



- Only MW FOV9 a_2 varied, other a_2s set to zero
- MWIR side 1 data

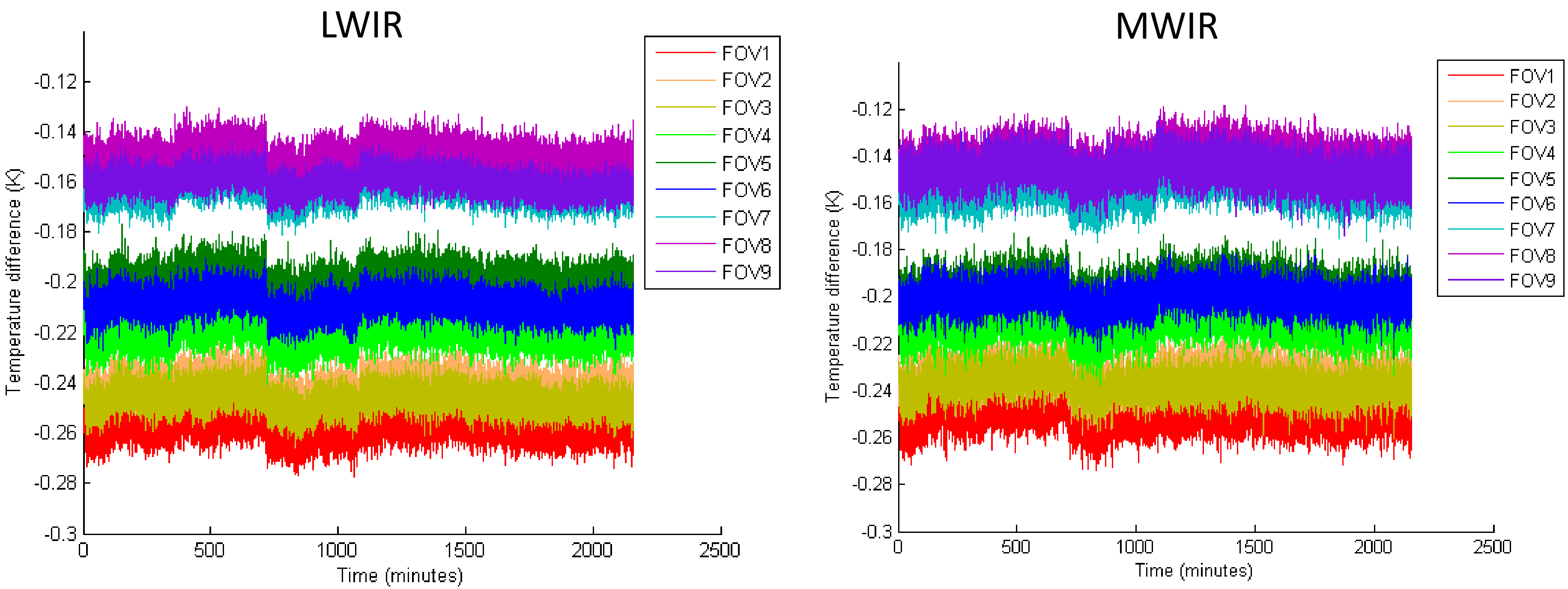
LTR Before Nonlinearity Optimization





- LW FOV5 and MW FOV9 brightness temperature differences on order of 50 mK
- Radiance jump at center of test apparent with nonlinear FOVs

LTR After Nonlinearity Optimization



- Excellent agreement between LWIR and MWIR time histories
- ECT gradients rows FOVs 1-2-3 to 7-8-9 clearly visible
- Remaining structure probably ECT temperature instability
  - Equal magnitude for all bands

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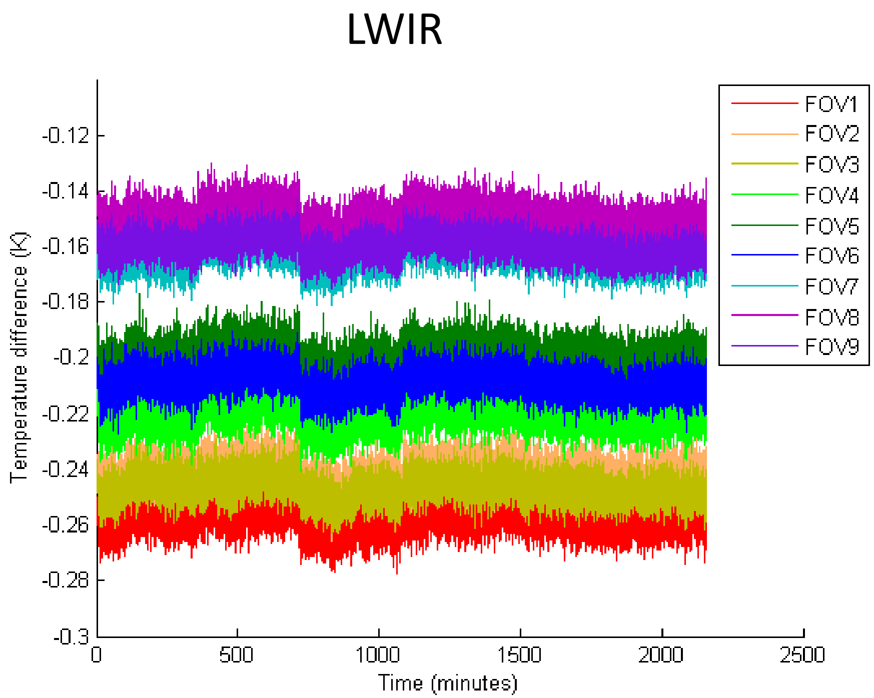
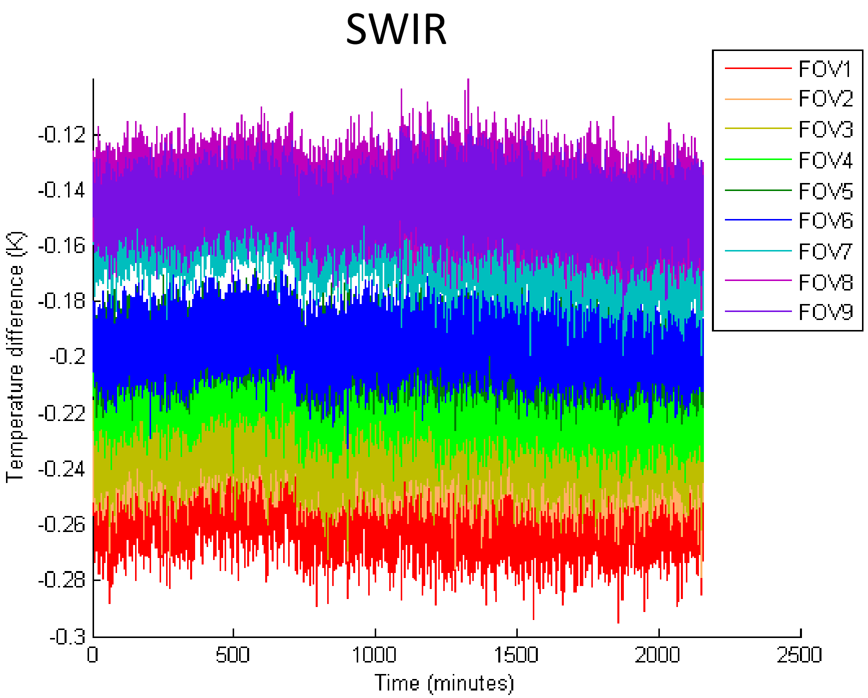
LTR After Nonlinearity Optimization





- Excellent agreement between LWIR and SWIR
- SWIR has higher noise
- No nonlinearity correction for SWIR

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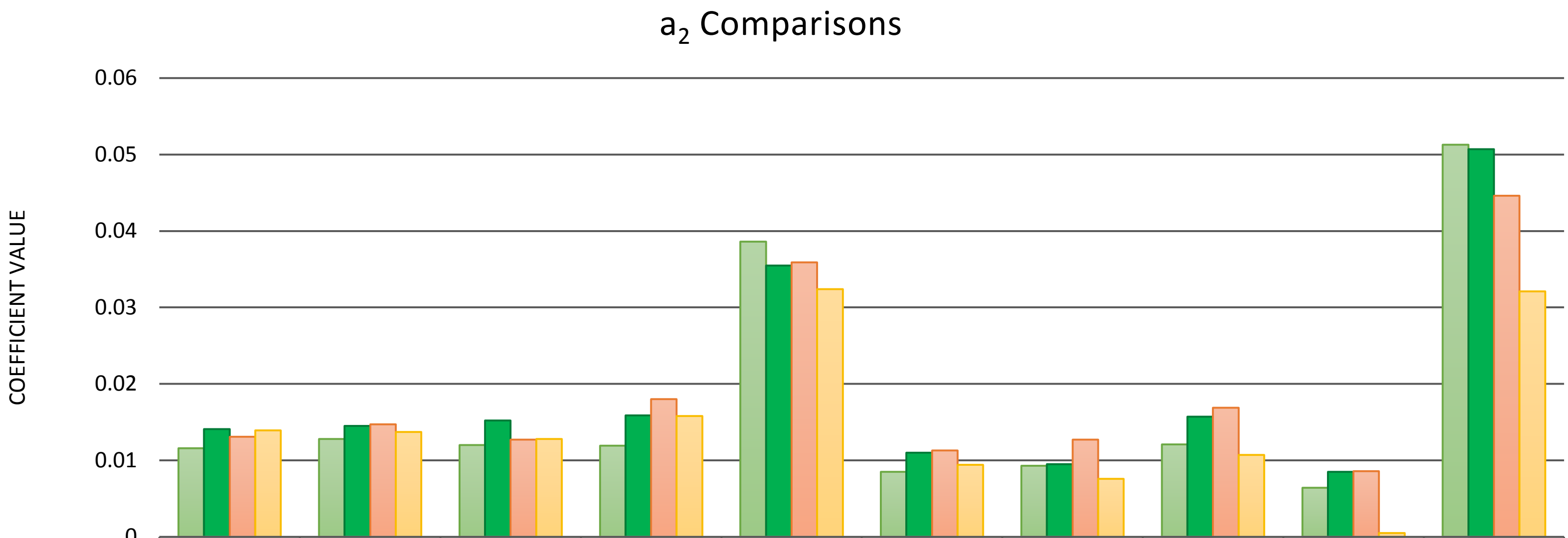
Derived a_2s



	LW 1	LW 2	LW 3	LW 4	LW 5	LW 6	LW 7	LW 8	LW 9	MW 9
Preliminary	0.0116	0.0128	0.012	0.0119	0.0386	0.0085	0.0093	0.0121	0.0064	0.0513
Flight	0.0141	0.0145	0.0152	0.0159	0.0355	0.011	0.0095	0.0157	0.0085	0.0507
S1	0.0131	0.0147	0.0127	0.018	0.0359	0.0113	0.0127	0.0169	0.0086	0.0446
S2	0.0139	0.0137	0.0128	0.0158	0.0324	0.0094	0.0076	0.0107	0.0005	0.0321

FOV #

- Side1: a_2s derived from side 1 LTR data
- Side2: a_2s derived from side 2 LTR data
- Results consistent with a_2s generated with conventional method

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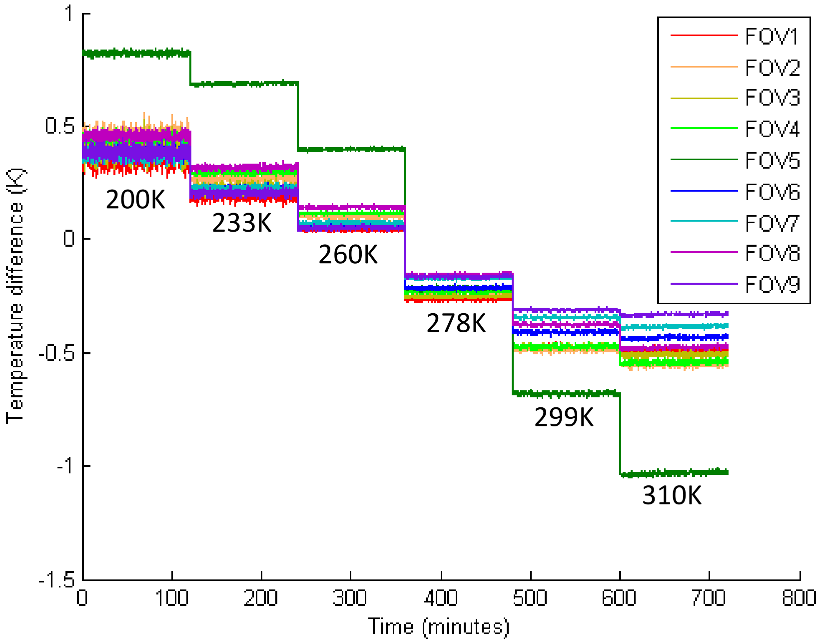
Check of LTR Derived Nonlinearity a_2s

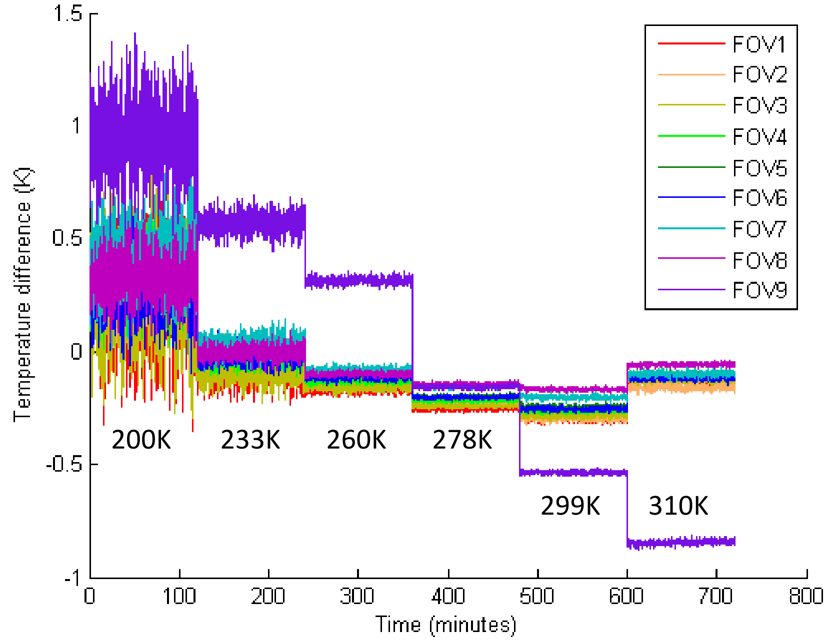
- Conventional method of determining nonlinearity uses the ECT stepped through a range of temperatures
- Plot stepped blackbody brightness temperatures similar to LTR time histories
- Combine data into a time series subtract ECT set point temperature
- Again integrate over spectral content
  - LWIR 680 – 1020 cm^{-1}
  - MWIR 1220 – 1600 cm^{-1}
  - SWIR 2160 – 2400 cm^{-1}
- No correction for ECT gradients or temperature errors
- Side 1 a_2s consistent with stepped blackbody data

Stepped Blackbody No Nonlinearity Correction

LWIR



MWIR



- No nonlinearity correction
- Nonlinearity of LW FOV5 and MW FOV9 clearly visible
- Mission Nominal Temperature (MN) stepped blackbody, side 1

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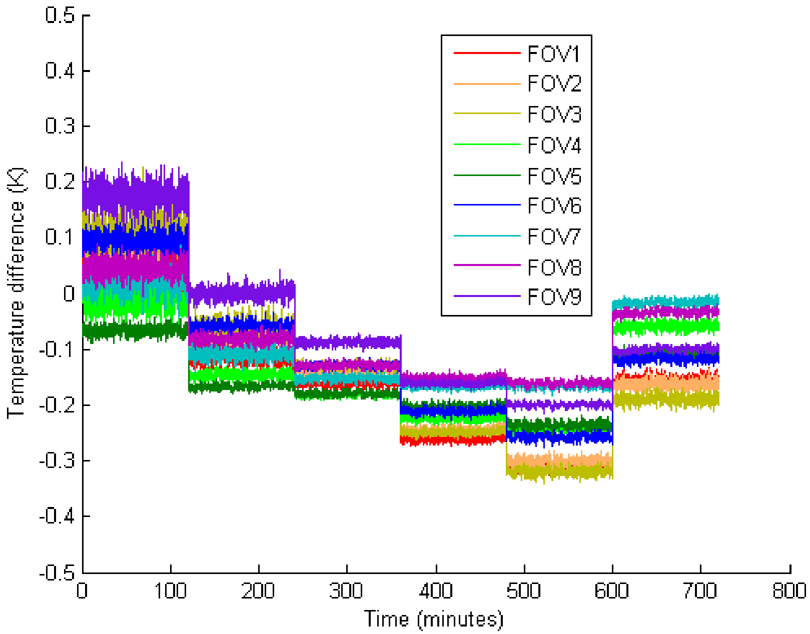
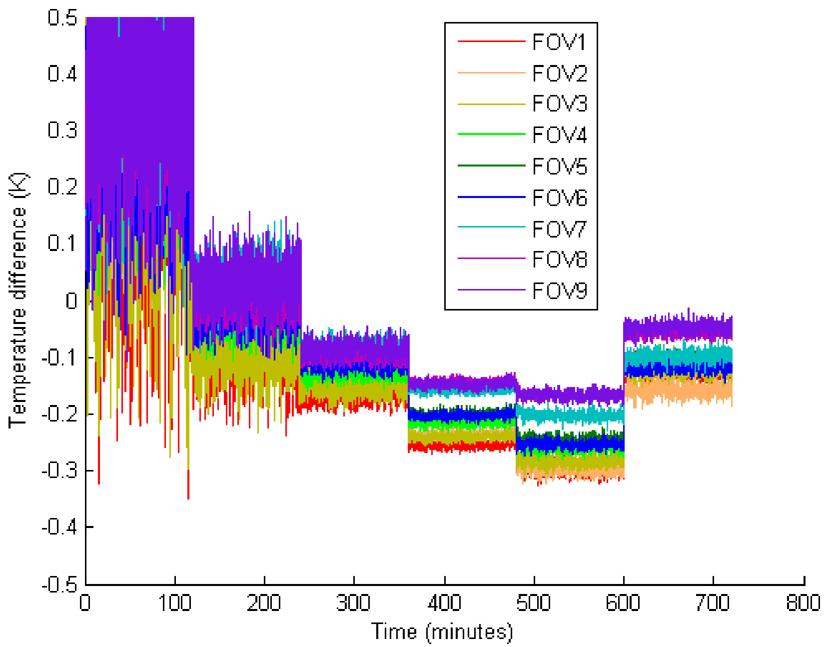
With Nonlinearity Correction

LWIR



MWIR



- Note the scale change from the preceding slide
- Good agreement between LW and MW
- a_2s derived from side 1 LTR

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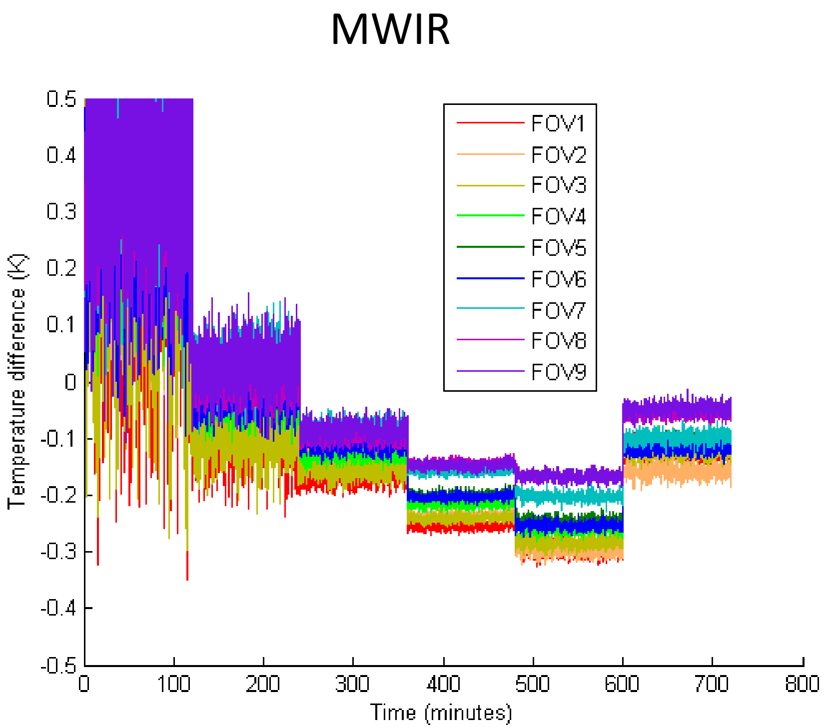
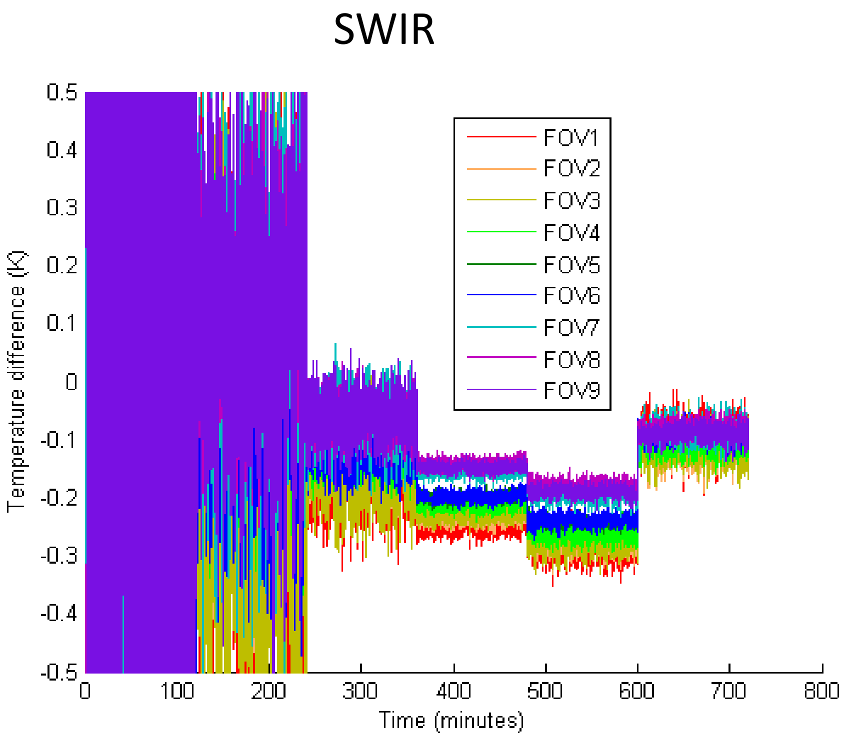
MWIR Compared to SWIR





- Good agreement with SWIR
- High noise for cold temperatures with MWIR and SWIR

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Discussion

- Method works well even though sensor temperature difference was only on the order of 1.5 K
- Larger change in sensor temperature expected to produce more accurate a_2s
- Variations in observed brightness temperature used to derive a_2s smaller than ECT gradients
- With quadratic nonlinearity large temperature differences are not needed
- However, side 2 LTR has less temperature variation and derived a_2s not as consistent with stepped blackbody
- Method relies on relative differences not absolute differences
- Method can still work with ECT temperature variation if they are not correlated with the sensor temperature variations

Conclusion

- a_2 nonlinearity coefficients can be derived using alternate method
  - Potential on-orbit application with uniform temperature scene
- Derived a_2s consistent with stepped blackbody
- Side 1 LTR data showed larger brightness temperature differences and resulted in better a_2s
- Potentially higher accuracy since method can partially compensates for inaccuracies of other coefficients and model
- Probably only practical with system like CrIS with self contained calibration