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:

\[ I' = -a_2 I^2 + (1 - 2a_2 V)I + (V - a_2 V^2) \]

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.
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

\[ S' = -a_2 (S \ast S) + (1 - 2a_2 V)S \]

- When S is band limited as shown, the \((S \ast S)\) component does not overlap spectrally and can readily be removed.
- The nonlinearity corrected spectra is then: \( S = S'/(1 - 2a_2 V) \)
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

- 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
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 $a_2$s, LTR is much lower
- Excellent agreement between FOVs
Magnitude of LTR with Different $a_2$s

- LTR calculated with a factor times preliminary Exelis $a_2$s
- 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 $a_2$s set to zero
• Only MW FOV9 $a_2$ varied, other $a_2$s 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
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
• Excellent agreement between LWIR and SWIR
• SWIR has higher noise
• No nonlinearity correction for SWIR
Derived $a_2$s

- Side1: $a_2$s derived from side 1 LTR data
- Side2: $a_2$s derived from side 2 LTR data
- Results consistent with $a_2$s generated with conventional method
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 \( a_{2s} \)s consistent with stepped blackbody data
Stepped Blackbody No Nonlinearity Correction

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

- Note the scale change from the preceding slide
- Good agreement between LW and MW
- $a_2$s derived from side 1 LTR
MWIR Compared to SWIR

- Good agreement with SWIR
- High noise for cold temperatures with MWIR and SWIR
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 $a_2$s
• Variations in observed brightness temperature used to derive $a_2$s smaller than ECT gradients
• With quadratic nonlinearity large temperature differences are not needed
• However, side 2 LTR has less temperature variation and derived $a_2$s 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 $a_2$s consistent with stepped blackbody
• Side 1 LTR data showed larger brightness temperature differences and resulted in better $a_2$s
• 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