STAR JPSS 2015 Annual Science Team Meeting
Session 6c
CrIS Calibration Algorithm Analysis

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Day 3, August 27 2014
Background

• In late 2014 it became clear we were comparing results based on different low level interpretations of the calibration algorithm in the ATBD

• A list of 11 equations were clearly identified

• We have reduced to five and testing rigorously

• What are we measuring?
  – An extended FOV off-axis interferogram on sensor sampling grid

• What is the product we are delivering?
  – An equivalent on-axis, single ray spectrum corrected for extended FOV apodization and sensor sampling, with responsivity and FIR filter removed by a two point calibration and with non-linearity corrected
  – The details of the process define different algorithms
# Five surviving algorithms

<table>
<thead>
<tr>
<th>Algorithm</th>
<th>Parameters</th>
<th>Comment</th>
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<tbody>
<tr>
<td><strong>NOAA A1</strong></td>
<td>$N = (SA^{-1} \cdot F_{\text{s-to-u}} \cdot f_{\text{ATBD}}) \cdot \left{ \frac{S_E - \langle S_{SP} \rangle}{S_{ICT} - \langle S_{SP} \rangle} \cdot ICT(T,u)_{\text{sensor}}^{\text{ATBD}} (1 + \text{delay}) \right}$</td>
<td>ISA – Sincq, Small N&lt;br&gt;F – Mooney, Small N&lt;br&gt;f – ATBD band limiting filter&lt;br&gt;ISA = $SA^{-1}$&lt;br&gt;Baseline delivered in Jan 2015&lt;br&gt;Ratio before ISA&lt;br&gt;F and ISA reversed&lt;br&gt;Calibrated in off-axis grid</td>
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<td><strong>CCAST</strong></td>
<td>$N = F_{\text{s-to-u}} \cdot ICT(T,u)<em>{\text{sensor}} \cdot f</em>{\text{raised cos}} \cdot SA^{-1} \cdot f_{\text{raised cos}} \cdot \left{ \frac{S_E - \langle S_{SP} \rangle}{S_{ICT} - \langle S_{SP} \rangle} \right}$</td>
<td>ISA – Sincq, Large N&lt;br&gt;F – double FFT&lt;br&gt;f – raised cos filter&lt;br&gt;Calibration ratio first&lt;br&gt;F &amp; ISA next&lt;br&gt;Calibrate on sensor grid</td>
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<td><strong>NOAA A2</strong></td>
<td>$N = ICT(T,u) \cdot \left{ \frac{F_{\text{s-to-u}} \cdot f_{\text{ATBD}} \cdot SA^{-1} \cdot f_{\text{ATBD}} \cdot \Delta S_1}{F_{\text{s-to-u}} \cdot f_{\text{ATBD}} \cdot SA^{-1} \cdot f_{\text{ATBD}} \cdot \Delta S_2} \right}$</td>
<td>ISA – Sincq, Small N&lt;br&gt;F – Mooney, Small N&lt;br&gt;f – ATBD band limiting filter&lt;br&gt;ISA correction and interpolation&lt;br&gt;Before calibration ratio&lt;br&gt;Small N F and ISA&lt;br&gt;Calibrate on user grid</td>
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<tr>
<td><strong>NOAA A3</strong></td>
<td>$N = ICT(T,u) \cdot \left{ \frac{F_{\text{s-to-u}} \cdot f_{\text{ATBD}} \cdot SA^{-1} \cdot f_{\text{ATBD}} \cdot \Delta S_1}{F_{\text{s-to-u}} \cdot f_{\text{ATBD}} \cdot SA^{-1} \cdot f_{\text{ATBD}} \cdot \Delta S_2} \right}$</td>
<td>ISA – Sincq, Large N&lt;br&gt;F – Mooney, Large N&lt;br&gt;f – ATBD band limiting filter&lt;br&gt;NOAA 2 + large N F and ISA</td>
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<tr>
<td><strong>NOAA A4</strong></td>
<td>$N = ICT(T,u) \cdot \frac{F_{\text{s-to-u}} \cdot f_{\text{ATBD}} \cdot SA^{-1} \cdot f_{\text{ATBD}} \cdot \begin{bmatrix} \Delta S_1 \ \Delta S_2 \end{bmatrix}}{F_{\text{s-to-u}} \cdot f_{\text{ATBD}} \cdot SA^{-1} \cdot f_{\text{ATBD}} \cdot \begin{bmatrix} \Delta S_1 \ \Delta S_2 \end{bmatrix}}$</td>
<td>$\Delta S_1 = FIR^{-1} \cdot (S_E - \langle S_{SP} \rangle)$&lt;br&gt;$\Delta S_2 = FIR^{-1} \cdot (S_{ICT} - \langle S_{SP} \rangle)$&lt;br&gt;Same as NOAA 3 plus rephasing&lt;br&gt;Remove phase due to ZPD shift&lt;br&gt;Before calibration&lt;br&gt;Calibrate on user grid</td>
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$SA^{-1}$ and F are $(N \times N)$ matrices, f is a band limiting filter
Formal overview of calibration for all algorithms

- Formal expression for the FFT of the measured extended FOV interferogram with non-circular FIR before truncation (CrIS processing on spacecraft)
  - Double integral over angular extent of the Field stop and wavenumber
  - Both the FIR filter and responsivity are inside an integral
  - If H were constant in the pass band it could be easily removed (come back to this later)

\[
S_{NCF}[k] = \int_{a_1}^{a_2} P(a) \cos(a) \int_{u_1}^{u_2} S_{\text{highres}}(u') \rho(u') H(u' \cos(a)) L \sinq(Lu' \cos(a) - k), N) du' da
\]

- For circular FIR filtering H is already outside the integral (not CrIS)

\[
S_{CF}[k] = H[k] \int_{a_1}^{a_2} P(a) \cos(a) \int_{u_1}^{u_2} S_{\text{highres}}(u') \rho(u') L \sinq(Lu' \cos(a) - k), N) du'
\]

- H and responsivity removed by a two-point calibration that implicitly assumes both can be brought out from the interval.

\[
S_{\text{cal}}[k] \propto \frac{S_{\text{scene}}[k] - S_{\text{space}}[k]}{S_{\text{ICT}}[k] - S_{\text{space}}[k]}
\]

- "Truth" (UW) is defined using single ray on-axis interferograms in user grid (no FOV integration over angle) with a two-point calibration

\[
S_{\text{Truth}}[k] = \int_{u_1}^{u_2} S_{\text{highres}}(u') \rho(u') L \sinq(Lu' - k), N) du'
\]
Unpeeling the Onion

- March 12 2014, UW proposed correction for non-circular FIR
- April 9 2014, STAR Alternate method to correct non-circular FIR
- May 28 2014, UW, working definition of Truth
- Dec 17 2014, CCAST compared to NOAA using clear earth scenes
- Sept 10 2014, LL & Logistikos, correcting ATBD resampling
- Sept 10 2014, LL, Sinc decimation properties
- Sept 24 2014, UW, results for non-circular FIR ringing correction
- Oct 10, 2014, STAR, Optimized ringing correction using resampling
- Jan 14 2015, LL, Exact F computation using analytic approach
- Jan 28 2015, Chen & Han, SA correction of gas cell data picks large N periodic Sinc as basis for SA\(^{-1}\)
- Feb 25 2015, Logistikos, Phase correction before calibration NOAA A4, with half the computation time
- March 11 2015, LL, Full simulation side by side comparisons
- March 25 2015, STAR, comparison studies rang NOAA 4 highest
- April 15 2015, STAR, Fill LBL simulation (ECMWF) compared to clear ocean
- April 29 2015, UW, Obs minus calc find NOAA 3 & 4 best match
- June 15 2015, LL, Full simulation shows little difference long or short N
Compare NOAA A4 with CCAST using full up simulation

- **Simulation**
  - Interferograms for scene, ICT, cold space for LBL spectra
  - Full accurate integration of extended FOV
  - Accurate calculation of SA and F transformation matrices
- **Full algorithm based calibration**
- **Effects considered**
  - Computational methods for F and ISA
  - Circular and Non-circular filtering
  - Long and Short Sinq(Lu-k,N)
  - Aliasing
  - Band pass filter settings
Simulated interferograms

- LBL spectrum & interpolated UW responsivity
- Compute scene, ICT, space for all FOV for each option
- Three types of interferograms: on-axis user, on-axis sensor, extended FOV sensor
- Full double integration over u and field stop for extended FOV

Idealized “Truth”

\[ I_u[n] = \sum_{m=1}^{M} W_m S_{LBL}(u_m) \rho(u_m) e^{i2\pi n\Delta u_m} \Delta u_{LBL} \]

\[ I_s[n] = \sum_{m=1}^{M} W_m S_{LBL}(u_m) \rho(u_m) e^{i2\pi n\Delta u_m} \Delta u_{LBL} \]

CrIS Measured

\[ I_x[n] = \sum_{1}^{128} w_q P(a_q) \cos(a_q) \sum_{m=1}^{M} W_m S_{LBL}(u_m) \rho(u_m) e^{i2\pi n\Delta u_m} \cos(a_q) \Delta u_{LBL} \]
Improved transformation matrices (2015)

- SA\(^{-1}\) matrix corrects extended FOV spectral distortion

\[
SA[k, k'] = \int_{a_{\min}}^{a_{\max}} P(a) \int_{z_1}^{z_2} \sinq(z - k, N) \sinq^* \left( \frac{z}{\cos(a)} - k', N \right) dz \, da
\]

- F matrix maps from sensor grid (L/N) to user grid (L'/N)

\[
F[k, k'] = \int_{z_1}^{z_3} \sinq(z - k, N) \sinq^* \left( \frac{zL'}{L - k'}, N \right) dz
\]

- High accuracy methods of computation developed

<table>
<thead>
<tr>
<th>type</th>
<th>z1</th>
<th>z2</th>
<th>z3</th>
<th>N</th>
<th>error</th>
</tr>
</thead>
<tbody>
<tr>
<td>SA short</td>
<td>sinq uL\cos(a)</td>
<td>Z1+Nb</td>
<td>na.</td>
<td>Nb</td>
<td>Exact analytic 1.e-14</td>
</tr>
<tr>
<td>SA long</td>
<td>sinq uL\cos(a)-Nb</td>
<td>Z1+2Nb</td>
<td>na.</td>
<td>NbNd</td>
<td>GL quadrature 1.e-12</td>
</tr>
<tr>
<td>F long</td>
<td>sinq 0</td>
<td>NbNd</td>
<td>uL+Nb</td>
<td>Nb</td>
<td>Exact analytic 1.e-14</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Band</th>
<th>Decimated interferogram length Nb</th>
<th>Decimation factor Nd</th>
<th>Long interferogram length Nb*Nd</th>
</tr>
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<tbody>
<tr>
<td>LW</td>
<td>864</td>
<td>24</td>
<td>20736</td>
</tr>
<tr>
<td>MW</td>
<td>1050</td>
<td>20</td>
<td>21000</td>
</tr>
<tr>
<td>SW</td>
<td>797</td>
<td>26</td>
<td>20722</td>
</tr>
</tbody>
</table>
SA\(^{-1}\) correction is a matrix operation

LW example

Short N=864
Decimated by 24

Long N= 864*24

Use bigger matrix to reduce edge effects.
20736^2=429,981,696 double integration matrix elements is prohibitive (72 C_CPS for 36 hours)

Spectra in one of 24 decimation intervals
Simulated process to convert extended FOV sensor grid to calibrated on-axis user grid spectra

Interferograms

- Long Extended FOV Sensor grid w/FIR $I_x[n]$
- Long On-axis user grid wo/FIR $I_u[n]$

On-orbit data

- Sample
- Sample, FIR, Decimate

CrIS Diagnostic (limited) stream

CrIS Full normal data stream

Ground algorithms

- 2-pt cal with SA$^{-1}$ FOV correction
- 2-pt cal with SA$^{-1}$ FOV correction

Calibrated Spectra

- $DI_{xeu}$
- $FD_{xeu}$

CrIS “Truth” estimate

- $DI_u$
- $FD_u$

“Truth”

Sample, FIR, Decimate

- 2-point calibration
- 2-point calibration

ISA – correction for extended FOR

- Short FFT, Non linear corr
- Long FFT & clip, Non linear corr
Even with a circular FIR we have an error

FD- Truth NOAA A4

- **FD on-axis:** convolution theorem gives nearly zero error

- **extended FOV FD** compared to extended FOV DI

- **Bottom:** extended FOV FD compared to truth (on-axis D) (THIS IS CrIS)
  - This is the expected ringing due to the full calibration and comparison with truth

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**CrIS Note:** scale increased by 50

- < 1 mK
- < 10 mK
- < 500 mK
LW raw scene spectra and band limiting filters

**Graphs:**

- **LW HiRes ISA and F correction**
  - Various spectral curves with annotations:
    -Raw FOV 1
    -F and ISA corr FOV 1
    -f NOAAA4
    -f raised cos
    -alias fold point
    -user range
  - Wavenumber range: 800 to 1200 cm⁻¹

- **LW HighRes ISA and F correction**
  - Two sub-plots:
    - Left: Wavenumber range: 600 to 660 cm⁻¹
    - Right: Wavenumber range: 1090 to 1160 cm⁻¹
  - Various spectral curves with annotations:
    -Raw FOV 1
    -F and ISA corr FOV 1
    -f NOAAA4
    -f raised cos
    -nominal clip
    -alias fold point
    -user start
LW A4 and CCAST FD – Truth

Nyquist ringing envelopes

Filtered and decimated off axis spectra (full cal) – long interferogram spectra (full cal)

Dashed line - NEDN
LW color temperature difference for A4 and CCAST relative to TRUTH

LW circular FIR FDXeu-Dlu (ringing envelopes)

A4, circ FIR)

LW non-circular FIR FDXeu-Dlu (ringing envelopes)

A4, noncirc FIR

LW non-circular FIR FDXeuCCAST-Dlu (ringing envelopes)

CCAST noncirc FIR
LW A4 and UMBC Differences: FOV – FOV5
LL simulation

NOAA 4

UBMC

NOAA 4

UBMC
A4 and UMBC Differences: FOV-2-FOV
Consistence: \[(BT_{obs} - BT_{lbl})_{fovi} - (BT_{obs} - BT_{lbl})_{fov5}\]

Larger ringing from A-UMBC among corner FOVs

Han & Chen STAR June 10, 2015
relative test overview

noaa 3-day test, all FOVs minus FOV 5

ccast 3-day test, all FOVs minus FOV 5

ccast minus noaa 3-day test, all FOVs

wavenumber
MW raw Scene spectra and band limiting filters

MW HiRes ISA and F correction

MW HighRes ISA and F correction

MW HighRes ISA and F correction

MW HiRes ISA and F correction

MW FD – Truth  NOAA4 and CCAST
Nyquist ringing envelopes

MW HiRes FDxeu-Dlu

NOAA 4, circ FIR

MW HiRes FDxeu-Dlu

NOAA 4, noncirc FIR

MW HiRes FDxeuCCAST-Dlu

CCAST noncirc FIR

Dashed line - NEDN
MW Color temperature difference for NOAA4 and CCAST relative to TRUTH

MW circular FIR FDxeu-Dlu (ringing envelopes)

MW non-circular FIR FDxeu-Dlu (ringing envelopes)

MW non-circular FIR FDxeuCCAST-Dlu (ringing envelopes)
MW A4 and UMBC Differences: FOV –2 – FOV5
LL simulation
A4 and UMBC Differences: FOV-2-FOV
Consistence: $(B_{\text{obs}} - B_{\text{lbl}})_{\text{fov,2}} - (B_{\text{obs}} - B_{\text{lbl}})_{\text{fov,5}}$

Larger difference from A-UMBC among Side FOVs
relative test overview
SW band raw spectrum and band limiting filters

![Graphs showing SW HiRes ISA and F correction for different wave numbers and power levels.](Image)
SW non-circ FIR A4 and CCAST Nyquist ringing envelopes

Dashed line - NEDN
SW Color temperature difference for A4 and CCAST relative to TRUTH

NOAA 4, circ FIR

NOAA 4, noncirc FIR

CCAST noncirc FIR
SW A4 and UMBC Differences: FOV –2 – FOV5 LL simulation

![Graphs comparing SW non-circular FIR FDxu-Dlu and SW non-circular FDxuCCAST-Dlu for NOAA 4 and UBMC](image)
A4 and UMBC Differences: FOV-2-FOV
Consistence: \((BT_{\text{obs}} - BT_{\text{lbl}})_{\text{fov}_i} - (BT_{\text{obs}} - BT_{\text{lbl}})_{\text{fov}_5}\)
FD – Truth FOVs- FOV5
UMBC ops minus calc Aug 5 2015

relative test overview

noaa 3–day test, all FOVs minus FOV 5

ccast 3–day test, all FOVs minus FOV 5

ccast minus noaa 3–day test, all FOVs
Summary

• Significant improvement in understanding, precision, and speed of the numerical calibration

• Focusing on NOAA and CCAST performance optimization

• Ongoing work
  – Flat passband FIR filters to get closer to circular filter result
  – Aliasing of MW and SW spectra

• Incorporating optimizations into production code