Expected Calibration Performance of the NPP Cross-track Infrared Sounder (CrIS)

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This presentation includes independent analysis of CrIS Flight Model 1 thermal vacuum test data performed by the SSEC/UW-Madison under IPO support and summarizes our view of the expected radiometric performance and accuracy of the sensor
(More detail presented at Vancouver OSA, 27-30 April 2009 by Tobin et al., HMC1 and Taylor et al., FMA4)
1. **Introduction to CrIS**

2. **Flight Model Calibration Issues:**
   Identified early in 2008 and subsequently fixed
   - *Unexpectedly low Internal Calibration Target (ICT) emissivity led to replacement with EDU ICT*
   - *Correction developed for higher than expected non-linearity*

3. **Absolute Accuracy Expectations for CrIS:**
   Thermal Vacuum Test Results
   *In-flight and testing uncertainty separately identified*

   Preview: Uncertainty generally <0.2 K 3-sigma
1. Introduction to CrIS

- The operational follow-on to AIRS PM Sounder
- IASI provides AM Soundings
Cross-track Infrared Sounder (CrIS) for NPP / NPOESS

Current Generation
HIRS (20 ch)

Next Generation
CrIS (1307 ch)

Volume: < 71 x 80 x 95 cm
Mass: < 152 kg
Power: < 124 W
Data Rate: <1.5 Mbps

from Williams, Glumb and Predina, ITT, August 2005 SPIE
**CrlS:**

- Part of the Crosstrack Infrared and Microwave Sensor Suite (CrlMSS) on NPP and NPOESS to produce all-weather high vertical resolution vertical profiles of temperature, moisture, and pressure
- Plane-Mirror Interferometer With DAPS
- Large 8 cm Clear Aperture
- Three Spectral Bands
  - LWIR: 650-1095 cm\(^{-1}\) (0.625 cm\(^{-1}\) res.)
  - MWIR: 1210-1750 cm\(^{-1}\) (1.25 cm\(^{-1}\) res.)
  - SWIR: 2155-2550 cm\(^{-1}\) (2.5 cm\(^{-1}\) res.)
- 1305 Total Spectral Channels
- 3x3 FOVs at 14 km Diameter for each Band
- Photovoltaic Detectors in All 3 Bands
- 4-Stage Passive Detector Cooler (81K)
- Internal Laser Wavelength Calibration
- Deep-Cavity Internal Calibration Target
- Passive Vibration Isolation System Allows Robust Operation
- Modular Construction

*Partially unfolded CrlS optical system shows flow of signal radiance to detectors*
Flight Model 1 (FM1) Status

• **Primary Thermal Vacuum (TVAC) testing complete & in Pre-ship review process**
  – Vibration & EMI tests
  – FOV Shape / Co-registration
  – ILS / Spectral Accuracy
  – NEDN
  – Short Term Repeatability
  – Long Term Repeatability
  – Radiometric uncertainty and linearity testing

• **NIST post TVAC External Calibration Target validation being planned**

• **FM1 expected to ship to the spacecraft for integration testing later this year**

• **NPP launch in early 2011**
Calibration Accuracy Requirements

- **CrIS sensor Radiometric Specifications**
  
  are primarily driven by weather applications. Expressed as (1-sigma) percent radiance uncertainty with respect to Planck 287K radiance [i.e. 100\cdot dR/B(287K)]:
  
  - Longwave: 0.45%
  - Midwave: 0.58%
  - Shortwave: 0.77%
  
  for B(233K) to B(287K)

- **Climate Applications**
  
  typically desire better accuracy
  
  e.g. AIRS spec was 3% radiance, but cal/val has shown much lower uncertainty. Similarly for IASI.

**AIRS Specification (3%)**

Brightness Temperature differences at 287K corresponding to the CrIS Radiometric Uncertainty Specification

Will show expected CrIS 3-sigma accuracy is less than the 1-sigma specification
Original Expectations

- **General Design:** Incorporates a high emissivity (>0.99), ambient temperature Internal Calibration Target (ICT), giving a high degree of insensitivity to the ICT emissivity ($e_{\text{effective}}$ very close to 1)

- **Linearity:** Photovoltaic detectors would be highly linear, requiring no correction

- **NIST:** Confirmation of ICT and External Calibration Target characteristics and radiance uncertainty budget prior to TVAC testing

But, NIST Blackbody testing was not performed and early FM1 TVAC results (Jan-May 2008) showed major departures
2. Flight Model Calibration Issues:
Identified early in 2008 and subsequently fixed

- Unexpectedly low Internal Calibration Target (ICT) MW/SW emissivity led to replacement with EDU ICT
- Correction developed for higher than expected non-linearity
TVAC MN results circa June 2006 (original ICT) using linear calibrations

1. ICT emissivity
Original FM1 ICT emissivity

Reflectivity in MW/SW >10 x higher than expected!

Emissivity & Cold Background Fraction (f) required to match CrIS radiance for 299 K Blackbody Target

 Observed spectra explained by:
(a) implausibly large cold background fraction, or
(b) very low cavity/surface emissivity

Proven answer
Current FM1 ICT emissivity

- Defective ICT replaced by EDU3 ICT
- ITT transfer radiometer (TSSR) measured 4 µm emissivity
- Special TVAC test measured spectrum

Emissivity from UW analysis of CrIS PQH@315K dataset
We conservatively assume 0.01 1-sigma (0.03 3-sigma) uncertainty, largely constrained by TSSR and spectral dependence from background T uncertainty.
Reflected Component of Predicted ICT Radiance

View factors accurately determined by ITT, yielding the following simplified picture:

The predicted ICT Radiance, used in the calibration equation, is:

$$ R_{ICT} = \varepsilon_{ICT} B(T_{ICT}) + (1-\varepsilon_{ICT}) R_{ICT,Reflected} $$

where $(1-\varepsilon_{ICT}) R_{ICT,Reflected}$ is the reflected term.

Contributions to $R_{ICT,Reflected}$ fall into three groups

1. Ambient temperature components with active temperature sensors, accounting for $\sim 47.5\%$ view factor.
2. Near ambient temperature components without representative temperature monitoring, accounting for $\sim 50.8\%$ view factor. Thermal modeling predicts orbital variation of $\sim 5.5K$ peak-to-peak variation in these components.
3. Cold view components, accounting for $\sim 1.8\%$ view factor.
TVAC results circa June 2008 (original ICT) using linear calibrations

2. Nonlinearity
The LW and MW ECT view residuals (calibrated minus predicted) using linear calibrations display spread among FOVs and mean residuals which are negative for $T_{ECT} > T_{ICT}$ and positive for $T_{ECT} < T_{ECT}$. Minimal spread and near zero mean residual for $T_{ECT} \approx T_{ICT}$. SW linear.

Out-of-band harmonic analyses utilizing Diagnostic Mode (DM) data collections show the nonlinearity to be purely quadratic for the LW and MW bands, and linear for the SW.

UW Correction (developed for PC MCT detectors) applied to all CrIS LW & MW interferograms

$$C_{LIN} = (1+2\ a_2 \ V_{DC}) \ C_{MEAS}$$

where $C_{MEAS}$ is the measured (nonlinear) complex spectrum, $a_2$ is the quadratic nonlinearity coefficient, and $V_{DC}$ is the DC level.

$V_{DC}$ is modeled based on measurements from CrIS. $a_2$ is estimated for each LW and MW FOV using in-band ECT view data and out-of-band harmonic analysis.
Non-linearity Parameters \((a_2)\)
From DM data & TVAC (Low, Nominal, High)

Final estimates (“Opt”) are mean of estimates for each FOV

1-sigma uncertainty from estimate variability:
- 9.6% for LW
- 15.5% for MW

Yield very conservative 3-sigma estimates
MN (T~296K) Brightness Temperature residuals without NLC

- ECT@310K
- ECT@299K, $T_{ECT} \sim T_{ICT}$
- ECT@287K
- ECT@260K
- ECT@233K
- ECT@200K

Δ BT(K)

wavenumber (cm$^{-1}$)
MN: Brightness Temperature residuals w/ NLC and “Opt” $a_2$ values

ECT@310K
ECT@299K, $T_{ECT} \sim T_{ICT}$
ECT@287K
ECT@260K
ECT@233K
ECT@200K

[Graph showing brightness temperature residuals for different temperatures with a range of wavenumbers from 600 to 2600 cm$^{-1}$]
3. Absolute Accuracy Expectations for CrIS: Thermal Vacuum Test Results

- In-flight calibration uncertainty
- Thermal Vacuum Testing Uncertainty
On-orbit radiometric calibration equation:

\[ R_{Earth} = R e \{ \frac{(C'_{Earth} - C'_{Space})}{(C'_{ICT} - C'_{Space})} \} (R_{ICT} - R_{Space}) + R_{Space} \]

with:

\[ R_{ICT} = \varepsilon_{ICT} B(T_{ICT}) + (1-\varepsilon_{ICT}) R_{ICT,Reflected} \]

\[ R_{Space} = B(T_{Space}) \]

\[ C' = C \ (1+2 \ a_2 V_{DC}) \]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>1-( \sigma ) uncertainty</th>
<th>3-( \sigma ) uncertainty</th>
<th>Source/Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>( T_{ICT} ) (K)</td>
<td>37.5 mK</td>
<td>112.5 mK</td>
<td>Bomem/ITT eng. estimate (w/o known readout issue)</td>
</tr>
<tr>
<td>( \varepsilon_{ICT} )</td>
<td>0.01</td>
<td>0.03</td>
<td>Independent measurement (TSSR) at 2500 cm(^{-1}) plus Analysis</td>
</tr>
<tr>
<td>( T_{refl,measured} ) (K)</td>
<td>0.5 K</td>
<td>1.5 K</td>
<td>Temperature monitored components (Frame, OMA, BS, ICT Baffle)</td>
</tr>
<tr>
<td>( T_{refl,modelled} ) (K)</td>
<td>2 K</td>
<td>6 K</td>
<td>Worst case estimate of unmonitored SSM Baffle T variations</td>
</tr>
<tr>
<td>( a_2 ) (1/counts)</td>
<td>9.6% Longwave 15.5% Midwave</td>
<td>28.8% Longwave 46.5% Midwave</td>
<td>DM and ECT view analysis</td>
</tr>
</tbody>
</table>
CrIS FM1 In-flight Radiometric Uncertainty (3-sigma Tb)
Example for Small MW non-linearity (FOV 9)

ECT @ 287K, FOV 9

1-sigma Uncertainty
- dT_ICT=−37.5 mK
- dT_Refl=−0.5K
- dT_SSMBaffle=−2K
- de_ICT=−0.01
- da2=9.6%LW,15.5%MW
- RSS
CrIS FM1 In-flight Radiometric Uncertainty (3-sigma Tb)
Example for Largest MW non-linearity (FOV 7)

ECT @ 287K, FOV 7

1-sigma Uncertainty

- $d_{T\_ICT} = -37.5$ mK
- $d_{T\_Refl} = -0.5$ K
- $d_{T\_SSMBaffle} = -2$ K
- $d_{e\_ICT} = -0.01$
- $da2 = 9.6\%$ \(\text{LW, 15.5}\%\) MW
- RSS
CrIS FM1 In-flight Radiometric Uncertainty (3-sigma Tb)
Example for Largest MW non-linearity (FOV 7)

ECT @ 260K, FOV 7

1-sigma Uncertainty

- dT_ICT=-37.5 mK
- dT_Refl=-0.5K
- dT_SSMBaffle=-2K
- de_ICT=-0.01
- da2=9.6%LW,15.5%MW
- RSS
CrIS FM1 In-flight Radiometric Uncertainty (3-sigma Tb) versus scene T for all FOVs at ~mid-band

Uncertainty generally <0.2 K 3-sigma
CrIS FM1 In-flight Radiometric Uncertainty (3-sigma Tb) versus scene T for all FOVs at ~mid-band

Uncertainty for FOVs with larger non-linearity will be reduced from inflight data
CrIS TVAC Testing Radiometric Uncertainty

TVAC calibration equation for ECT view:

\[ R_{ECT} = Re\left\{\frac{(C'_{ECT} - C'_{ST})}{(C'_{ICT} - C'_{ST})}\right\}(R_{ICT} - R_{ST}) + R_{ST} \]

with:

\[ R_{ST} = \varepsilon_{ST} B(T_{ST}) + (1-\varepsilon_{ST}) B(T_{ST,Reflected}) \]
\[ R_{ICT} = \varepsilon_{ICT} B(T_{ICT}) + (1-\varepsilon_{ICT}) R_{ICT,Reflected} \]
\[ C' = C (1+2 a_2 V_{DC}) \]

TVAC “truth”: ECT view predicted:

\[ R_{ECT} = \varepsilon_{ECT} B(T_{ECT}) + (1-\varepsilon_{ECT}) B(T_{ECT,Reflected}) \]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>1-(\sigma) uncertainty</th>
<th>3-(\sigma) uncertainty</th>
<th>Source/Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>(T_{ECT}) (K)</td>
<td>200-310 K</td>
<td>29.7 mK</td>
<td>89.1 mK</td>
<td>Bomem/ITT estimate recent new Hart/UW absolute cal info, and without spatial gradients</td>
</tr>
<tr>
<td>(\varepsilon_{ECT})</td>
<td>0.9995</td>
<td>0.0003</td>
<td>0.0009</td>
<td>Bomem report</td>
</tr>
<tr>
<td>(T_{ECT,Reflected}) (K)</td>
<td>(T_{ICT})</td>
<td>3 K</td>
<td>9 K</td>
<td>Conservative estimate</td>
</tr>
<tr>
<td>(T_{ST}) (K)</td>
<td>105 K</td>
<td>2 K</td>
<td>6 K</td>
<td>Conservative estimate</td>
</tr>
<tr>
<td>(\varepsilon_{ST})</td>
<td>0.9995</td>
<td>0.0003</td>
<td>0.0009</td>
<td>Bomem report</td>
</tr>
<tr>
<td>(T_{ST,Reflected}) (K)</td>
<td>(T_{ICT})</td>
<td>3 K</td>
<td>9 K</td>
<td>Conservative estimate</td>
</tr>
</tbody>
</table>
TVAC Testing 3-sigma Radiometric Uncertainty
Example for FOV 7 & 260 K

ECT @ 260K, FOV 7

1-sigma Uncertainty
- $dT_{ST}=2K$
- $de_{ST}=0.0003$
- $dT_{refl_{ST}}=3K$
- $dT_{ECT}=29.7mK$
- $de_{ECT}=0.0003$
- $dT_{refl_{ECT}}=3K$
- RSS

wavenumber (cm$^{-1}$)
TVAC Testing 3-sigma Radiometric Uncertainty
Compared to CrIS Calibration Uncertainty

- **Colored, Filled, Circles** = CrIS Inflight Uncertainty
- **Solid Black Line** = TVAC testing Uncertainty
TVAC Testing 3-sigma Radiometric Uncertainty
Compared to CrIS Calibration Uncertainty

- **Colored, Filled, Circles** = CrIS Inflight Uncertainty
- **Colored, Open, Squares** = TVAC Residuals (absolute value)
- **Solid Black Line** = TVAC testing Uncertainty
Summary/Conclusions

- Two main issues encountered and addressed during the CrIS FM1 TVAC testing campaign were presented here:
  - Low emissivity of the original FM1 ICT
  - Significant nonlinearity in the LW and MW FOVs

- The In-flight Radiometric Uncertainty of CrIS FM1 is estimated to be very good, with 3-sigma BT RU estimates below ~0.2K for the large majority of FOVs and channels