Radiometric Performance of the Calibration Demonstration System
Fourier Transform Spectrometer

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Acknowledgments

IR Calibration Demonstration System (CDS) Spectrometer

**Engineering and Technical:**

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**Variable Temperature Blackbody (CORSAIR IIP, SDL)**

**Engineering:**

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CDS Overview

• Objective: Demonstrate brightness temperature measurements with an accuracy of 0.1 K (k=3) in a laboratory environment for scene temperatures of 200-320 K from 200 to 2000 cm\(^{-1}\).

• Key Features:
  – 4-port Fourier transform spectrometer (FTS);
  – Input pupil at calibration blackbody aperture, intermediate pupil at FTS cube corner, exit pupil at FTS output.
  – FTS operated in vacuum housing for thermal and acoustic isolation, elimination of atmospheric absorption, and protection of hygroscopic CsI beamsplitter.
  – Include observations of a variable temperature blackbody source to quantify measurement bias over a range of scene temperatures.
CDS Optical Layout

- Entrance pupil
- Field stops
- Pupil stops
- Ambient, cold, or variable blackbody input
- Reference Input
- Scene Select Mirror
- Bolometer channel
- Pyroelectric channel
Infrared and Metrology Raytrace

CLARREO ALL PATHS (RR, TT, RT, TR)  Scale: 0.22  09-Aug-11

- LED and laser detectors
- Input pupil
- LED and Metrology laser inputs
- Bolometer channel
- Pyroelectric channel
Infrared and Metrology Paths

- Internal Reference
- Metrology laser
- ZPD LED
- Laser Detector
- ZPD Detector
- Input Pupil
- Bolometer Channel
- Pyroelectric Channel
- Internal Reference
Infrared Ray trace

- Beamsplitter & Compensator
- CIRS Scan Mech. and Corner Cube
- Corner Cube
- FTS Ref. Input BB
- Detector Output Ports
- Scene Select Mirror Drive Motor
Optical Bench Temperature Stability

Change in Temperature, K

Time, s
Observation Sequence

• Wait for VTBB temperature to stabilize (2-3 hours).
• Start observation sequence:
  – Position SSM at ABB during FTS flyback (1s);
  – Scan optical path difference (OPD) from +0.25 cm to -0.25 cm while observing ABB (2s);
  – Reposition SSM at CSS during FTS flyback (1s);
  – Scan OPD from +0.25 cm to -0.25 cm at CSS (2s);
  – Reposition SSM at VTBB during flyback (1s);
  – Scan OPD from +1 cm to -1 cm at VTBB (8s);
  – Complete cycle takes 15s; calibration spectra at ¼ resolution, VTBB spectra at full resolution.
• Repeat for ~2 hours (460 VTBB observations).
• Proceed to next VTBB plateau.
After a programmable delay following each positive metrology laser fringe zero crossing, we:
- Sample the bolometer channel output;
- Sample the pyroelectric channel output;
- Record the fringe crossing time for each sample.

Every 200 samples we also sample detector DC levels and other FTS scan-related engineering data.

A broadband LED and detector is used to provide a zero path difference (ZPD) reference location for each interferogram (IGM).
Interferogram preprocessing

• After extracting IGMs from raw data files and performing quality control checks:
  – Correct IGM baselines for transients related to changing scene temperature and electronic time constants;
  – Correct Pyroelectric data for velocity variations by scaling each sample by the ratio of the actual sample rate to the nominal sample rate: \( I'(x) = I(x) \frac{\nu_{act}(x)}{\nu_{nom}}; \)
  – Correct Bolometer data are corrected for responsivity variations proportional to temperature-related changes in bolometer resistance by scaling IGM by the ratio of the nominal detector DC voltage to the actual DC voltage: \( I'(x) = I(x) \frac{V_{nom}}{V_{act}(x)}. \)

• IGMs are centered using the ZPD data and truncated to the proper length:
  – ±2350 points for ABB, CSS;
  – ±9394 points for VTBB.
Bolometer transient modeled with a single time constant (0.18 s) from the preamp DC block filter:

\[ V(t) = V_0(t) + V_T e^{-t/0.18} \]

Pyroelectric transient modeled with two time constants: one (0.18 s) from the preamp DC block filter, and another (1 s) from the detector electronic time constant:

\[ V(t) = V_0(t) + V_{T1} e^{-t/0.18} + V_{T2} e^{-t} \]
Due to the $1/f$ response of the pyroelectric detector, relative response is proportional to $1/(\text{relative velocity})$. Because we record the time for individual samples, we can estimate the instantaneous velocity and correct for the effect of velocity variations.
The bolometer is a thermal detector that responds to a change in radiative input by a change in temperature. The change in temperature causes a change in bolometer resistance that is in turn proportional to resistance, resulting in nonlinear response that can be corrected by normalizing by the instantaneous resistance (or relative DC voltage as shown above).
Calibration Process

- After preprocessing:
  - Linear fit of CSS IGMs within 130s of VTBB IGM to estimate average at time of VTBB observation;
  - Use CSS radiance model to estimate $L_{CSS}$ at time of VTBB observation;
  - Linear fit of ABB IGMs within 130s of VTBB IGM to estimate average at time of VTBB observation;
  - Use ABB radiance model to estimate $L_{ABB}$ at time of VTBB observation;
  - Use VTBB radiance model to estimate $L_{VTBB}$ for later comparison with calibrated spectrum $L'_{VTBB}$;
  - Zero-pad ABB and CSS IGMs to length of VTBB IGM;
  - Calculate Fourier transforms (FT) and calibrate:

$$L'_{VTBB} = L_{CSS} + (L_{ABB} - L_{CSS}) \times \frac{FT(I_{VTBB} - I_{CSS})}{FT(I_{ABB} - I_{CSS})}.$$
• Excess noise in ZPD region caused by small random sample position error, roughly 2x the noise floor.
\[ B_s \equiv \frac{B_p + \rho_s B_c}{(1 + \rho_s)}; \]

\[ L_{ABB} = (1 - \rho_d) B_s + \rho_d \left( 0.954 B_c + 0.039 B_A + 0.007 B_I \right). \]

\[ B_x \equiv \frac{\alpha \tilde{V}^3}{e^{\beta \tilde{V}/T_x} - 1}; \alpha \equiv 2hc^2; \beta \equiv hc/k. \]
Brightness temperature differences are not significant.
CSS Radiance Model

\[ B_s \equiv \frac{B_p + \rho_s B_r}{1 + \rho_s}; \]

\[ L_{CSS} = (1 - \rho_d) B_s + \rho_d \left( 0.892 B_r + 0.083 B_f + 0.013 B_A + 0.012 B_I \right). \]

\[ B_x \equiv \frac{\alpha \bar{V}^3}{\left( e^{\beta \bar{V}/T_x} - 1 \right)}; \alpha \equiv 2hc^2; \beta \equiv hc/k. \]
Although brightness temperature differences are large at high wavenumber, the radiance difference is insignificant.
\[ B_s \equiv \frac{B_p + \rho_s B_c}{1 + \rho_s}; \]
\[ L_{VTBB} = (1 - \rho_d) B_s + \rho_d \left( 0.965 B_c + 0.027 B_s + 0.004 B_{ep} + 0.004 B_I \right). \]
Comparison with Virial STEEP3

Preliminary results calculated from temperatures measured during cooldown, resulting in large gradients. Some of the discrepancy results from different interpretations of the surface temperature distribution implied by the temperature measurements. Calculations will be repeated with equilibrium temperature values.
CHILR 10.6 μm CSS reflectance: $0.5 \times 10^{-4}$
Model: $1.6 \pm 1.0 \times 10^{-4}$

CHILR 4 μm CSS reflectance: $5.5 \times 10^{-4}$
Model (5 μm): $6.6 \pm 1.0 \times 10^{-4}$

**Estimated uncertainty of 0.008 in SOC diffuse reflectance measurements**
<table>
<thead>
<tr>
<th>Source</th>
<th>Standard Uncertainty ($u_j$)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>ITS90 TP ($H_2O$) (Type A)</td>
<td>0.03 mK</td>
<td>NIST IR5319</td>
</tr>
<tr>
<td>SPRT Calibration (k=1)</td>
<td>0.25 mK</td>
<td>Hart Scientific calibration report</td>
</tr>
<tr>
<td>Superthermometer SPRT ratio (k=1)</td>
<td>0.08 mK</td>
<td>Hart Scientific technical guide (1594A)</td>
</tr>
<tr>
<td>SPRT drift (type B, rect)</td>
<td>0.29 mK</td>
<td>Checked with LaRC TPW cell</td>
</tr>
<tr>
<td>Cal bath gradients (type B, rect)</td>
<td>1.15 mK</td>
<td>LaRC estimate from hysteresis</td>
</tr>
<tr>
<td>Superthermometer thermistor ratio (k=1)</td>
<td>0.008 mK</td>
<td>Hart Scientific technical guide (1594A)</td>
</tr>
<tr>
<td>Thermistor repeatability (type B, rect)</td>
<td>1.04 mK</td>
<td>Estimate from LaRC experience</td>
</tr>
<tr>
<td>Steinhart-Hart fit error (type B, rect)</td>
<td>0.4 mK</td>
<td>Estimate from fit residuals</td>
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<tr>
<td><strong>Total Calibration:</strong></td>
<td><strong>1.65 mK</strong></td>
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<tr>
<td>Blackstack accuracy (type B, rect)</td>
<td>4.2 mK</td>
<td>5K thermistor at 295K; Hart Scientific 1560 + 2564 literature</td>
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<tr>
<td><strong>Total</strong></td>
<td><strong>4.5 mK, k=1</strong></td>
<td><strong>9 mK, k=2</strong></td>
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<tr>
<td>Source</td>
<td>Standard Uncertainty ($u_j$)</td>
<td>Reference</td>
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<tr>
<td>--------------------------------------------------</td>
<td>------------------------------</td>
<td>------------------------------------------------</td>
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<tr>
<td>ITS90 TP (Ar) (Type A)</td>
<td>0.05 mK</td>
<td>NIST IR5319</td>
</tr>
<tr>
<td>PRT repeatability (Type B, rect)</td>
<td>2.9 mK</td>
<td>Lake Shore PT 103 literature</td>
</tr>
<tr>
<td>PRT calibration (k=1)</td>
<td>5.6 mK</td>
<td>Lake Shore PT 103 literature</td>
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<tr>
<td>Mounting change correction uncertainty (type B, rect)</td>
<td>0.4 mK</td>
<td>Space Dynamics Lab estimate</td>
</tr>
<tr>
<td>Drift (type B, rect)</td>
<td>0.6 mK</td>
<td>Space Dynamics Lab estimate</td>
</tr>
<tr>
<td>Hysteresis (type B, rect)</td>
<td>1.7 mK</td>
<td>Space Dynamics Lab estimate</td>
</tr>
<tr>
<td><strong>Total Calibration (77 K)</strong></td>
<td><strong>6.6 mK</strong></td>
<td></td>
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<tr>
<td>Blackstack accuracy (type B, rect)</td>
<td>1.4 mK</td>
<td>Hart Scientific literature, 1560 + 2562 PRT module</td>
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<tr>
<td>Self heating uncertainty (type B, rect)</td>
<td>6 mK</td>
<td>Space Dynamics Lab estimate</td>
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<tr>
<td>Blackbody gradients (type B, rect)</td>
<td>12 mK</td>
<td>Space Dynamics Lab worst case model estimate</td>
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<td><strong>Total</strong></td>
<td><strong>15 mK, k=1</strong></td>
<td><strong>(30 mK, k=2)</strong></td>
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<tr>
<td>Source</td>
<td>Standard Uncertainty, $u_j$ (mK)</td>
<td>Reference</td>
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<td>---------------------------------------------</td>
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<tr>
<td>SPRT Calibration (k=1)</td>
<td>2.5 2.5 2.5</td>
<td>Space Dynamics Lab test report</td>
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<td>Blackstack SPRT readout accuracy (type B, rect)</td>
<td>3.9 5.3 6.7</td>
<td>Hart Scientific literature</td>
</tr>
<tr>
<td>Blackstack thermistor readout accuracy (type B, rect)</td>
<td>1.9 1.1 2.9</td>
<td>Hart Scientific literature (results for 2.5 kΩ thermistor)</td>
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<tr>
<td>SPRT drift (type B, rect)</td>
<td>1.2 1.2 1.2</td>
<td>Space Dynamics Lab estimate</td>
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<tr>
<td>Cal bath gradients (type B, rect)</td>
<td>1.2 1.2 1.2</td>
<td>LaRC estimate from ABB cal</td>
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<tr>
<td>Repeatability (type B, rect)</td>
<td>1.0 1.0 1.0</td>
<td>LaRC estimate from ABB cal</td>
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<tr>
<td>Steinhart-Hart fit error (type B, rect)</td>
<td>0.4 0.4 0.4</td>
<td>LaRC estimate from ABB cal</td>
</tr>
<tr>
<td><strong>Total Calibration</strong></td>
<td><strong>5.4 6.3 8.0</strong></td>
<td>-</td>
</tr>
<tr>
<td>Blackbody gradients (type B, rect)</td>
<td>4.9 4.9 4.9</td>
<td>Space Dynamics Lab model estimate</td>
</tr>
<tr>
<td>Blackstack thermistor readout (type B, rect)</td>
<td>1.9 1.1 2.9</td>
<td>Hart Scientific literature; self heating included in original calibration</td>
</tr>
<tr>
<td>Total, k=1</td>
<td>7.6 8.1 9.8</td>
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</tr>
<tr>
<td><strong>Total, k=2</strong></td>
<td><strong>15 16 20</strong></td>
<td>-</td>
</tr>
</tbody>
</table>
Blackbody Gradients and Drift

Blackbody Temperature Gradients and Drift

VTBB cone 1 - 258.62
VTBB cone 2 - 258.62
CSB cone 1 - 77.63
CSB cone 2 - 77.63
ABB plate 1 - 294.97
ABB plate 2 - 294.97
ABB plate 3 - 294.97

Temperature difference, K

Time, s
• Accuracy is affected by low or rapidly changing responsivity.
• Bolometer channel responsivity shows strong absorption features from polypropylene detector dewar window.
• Pyroelectric channel shows steep rolloff due to electronic frequency response, and absorption from 1400-1600 cm$^{-1}$ from protective parylene coating on CsI detector window.
Calibrated Radiance

• Acquired roughly 2 hours of data at each dwell temperature
  – 460 variable temperature blackbody spectra at 0.5 cm\(^{-1}\) resolution.
  – 460 cold and ambient calibration blackbody views at 2 cm\(^{-1}\) resolution.
• Also binned spectrally: 10 points (5 cm\(^{-1}\)) for bolometer, 50 points (25 cm\(^{-1}\)) for pyroelectric.
• Standard errors (k=1) shown.
• Expect best bolometer results below 1350 cm⁻¹ due to window absorption
• Expect best pyro results below 1350 cm⁻¹ due to detector window coating absorption and high frequency rolloff.
• Calculation includes scattering; note curvature at 200K
• Scale expanded 40x relative to previous calibrated radiance plot.
• Green line is origin for each offset plot.
• Systematic bolometer error and variation with temperature suggests uncorrected nonlinear behavior.
• Red line is origin for each offset plot; green lines indicate ±0.1K.

• k=1 error includes statistical error and error in modeling calibration and variable temperature blackbody radiance.

• Best results for high responsivity region below 1350 cm⁻¹
Comments and Observations

• We use single detectors to cover the entire thermal spectrum, so:
  – Small nonlinearities will alias radiance from the blackbody peak to other parts of the observed spectrum;
  – Real and Imaginary bolometer radiance differences show this;
  – Using separate detectors to cover the shortwave part of the spectrum (as in the CLARREO mission concept design) will reduce the consequences by reducing the required dynamic range and putting aliased power out-of-band.

• For the tested range of 200K to 320K scene temperature, over the spectral range 250-1350 cm\(^{-1}\) where responsivity for both channels is high:
  – Radiance bias is generally less than 0.00015 W/m\(^2\) sr cm\(^{-1}\);
  – Brightness temperature bias is generally less than 0.2K;
  – Bolometer bias is dominated by uncorrected nonlinearity;
  – There may still be a source of bias in the pyroelectric channel that is not yet accounted for.