A Method for Correcting for Telescope Spectral Transmission in the Geosynchronous Imaging Fourier Transform Spectrometer (GIFTS)

John D. Elwell, Deron K. Scott
Space Dynamics Laboratory / Utah State University
GIFTS

• GIFTS mission is to provide water vapor, wind, temperature, and trace gas profiles from geosynchronous orbit
  – Requires highly accurate radiometric and spectral calibration

• Radiometric calibration will be performed during ground calibration and updated in-flight using two on-board cavity blackbody in-flight calibrators (IFCs) and cold space

• Presentation describes how we will correct for two terms in the responsivity calibration
GIFTS Imaging Interferometer Specifications

- Two IR focal planes
  - Short/midwave
    - 4.4 to 6.1 µm
    - 1 K absolute accuracy for scenes >240 K
  - Longwave
    - 8.8 to 14.6 µm
    - 1 K absolute accuracy for scenes >190 K
  - 128 x 128 pixels, 110 µm pitch, 4-km pixel footprints at nadir
  - 7 spectral resolutions from 0.6 cm\(^{-1}\) to 38 cm\(^{-1}\)
  - 0.2 K reproducibility
GIFTS Optical Schematic

Definitions of terms

\( \tau \)  Transmissions (reflectances) of elements
\( \varepsilon \)  Emissivities of elements
\( B \)  Planck radiances at element temperatures
\( C_f \)  Complex response to emissions of the rear optics
\( R_f \)  System responsivity

SDL

Calcon 2003  September 15-18, 2003
GIFTS Optical Schematic

Need to correct for:

τ_t – signal transmission of the telescope mirrors

\[ \tau_t = \tau_1 \cdot \tau_2 \cdot \tau_3 \]

\[ \tau_t = (1 - \varepsilon_1) \cdot (1 - \varepsilon_2) \cdot (1 - \varepsilon_3) \]

τ_m – transmission of the blackbody pick-off mirror
Radiometric Calibration

Scene radiance using inflight calibrators$^1$:

\[
N = \left( \frac{\tau_m}{\tau_t} \right) \cdot R_e \left( \frac{C_e - C_s}{R_f} \right) + B_s \\
\]

where

\[
R_f = \frac{C_h - C_c}{B_h \cdot \varepsilon_h - B_c \cdot \varepsilon_c}
\]

where:

- $N$ Computed scene radiance
- $B_h, B_c$ Planck radiances of hot and cold references
- $\varepsilon_h, \varepsilon_c$ Emissivities of hot and cold references (assumed equal)
- $B_s$ Planck function of cold space (effectively 0 for GIFTS)
- $C_h, C_c, C_e, C_s, C_f$ Measured responses to hot and cold reference, scene, space, and structure (Back end temperatures assumed constant between IFC views)
- $\tau_m$ Blackbody viewing mirror transmission (assumed constant temp)
- $\tau_t$ Telescope transmission (reflectivity)

$^1$ Revercomb, et al., "On Orbit Calibration of the Geostationary Imaging Fourier Transform Spectrometer (GIFTS)", Calcon 200
\( \tau_m \) and \( \tau_t \) Measurement

- Fold mirror \( \tau_m \) and telescope \( \tau_t \) will change during flight, and such changes must be periodically measured.
- The experiments for deriving \( \tau_t \) and \( \tau_m \) will be performed quarterly.
Assumptions Made in Measuring $\tau_m$ and $\tau_t$

- Absorption of gold-coated aluminum telescope mirrors is negligible
- Mirror reflectivities (transmissions) can be computed if mirror emissivities are known
  \[ \tau = 1 - \varepsilon \]
- Mirror emissivities can be estimated by measuring mirror emissions and the mirror temperatures
- $\tau_m$ can be determined in-flight by viewing either IFC at two different fold mirror temperatures
Measuring $\tau_m$ Experimentally

- Collect data viewing an in-flight calibrator at two different flip-in mirror temperatures

- By taking the difference of measured emissions at two different fold mirror temperatures, $\tau_m$ can be computed as:

$$\tau_m = \left[ \frac{B_h - B_c}{C_h - C_c} \cdot \frac{C_{m1} - C_{m2}}{B_{m1} - B_{m2}} \right] + 1 \right]^{-1}$$

- $B_{m1}, B_{m2}, C_{m1}, C_{m2}$ are the Planck radiances and the measured responses to the cold blackbody with the fold mirror at two different temperatures
**τ_m Uncertainties**

- Principle uncertainties in measuring τ_m

<table>
<thead>
<tr>
<th>Error Source</th>
<th>Error</th>
<th>2000 cm⁻¹ τ_m Uncertainty</th>
<th>900 cm⁻¹ τ_m Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>T_m1</td>
<td>1K</td>
<td>0.016</td>
<td>0.046</td>
</tr>
<tr>
<td>T_m2</td>
<td>1K</td>
<td>0.182</td>
<td>0.107</td>
</tr>
<tr>
<td>T_h</td>
<td>0.1 K</td>
<td>0.013</td>
<td>0.010</td>
</tr>
<tr>
<td>T_c</td>
<td>0.1 K</td>
<td>0.005</td>
<td>0.007</td>
</tr>
<tr>
<td>ε_h</td>
<td>0.002</td>
<td>0.008</td>
<td>0.014</td>
</tr>
<tr>
<td>ε_c</td>
<td>0.002</td>
<td>0.002</td>
<td>0.008</td>
</tr>
<tr>
<td>RSS</td>
<td></td>
<td>0.184%</td>
<td>0.118%</td>
</tr>
</tbody>
</table>
Measuring $\tau_t$ Experimentally

- Collect a minimum of three measurements with each optical element at different temperatures
- The following steps will be performed to collect data
  - Turn off telescope cooling loop and collect data for 24 hours
  - Collect emission data by viewing cold space
  - After each emissions data collection, close the fold mirror and collect tail-end optics emissions data by looking at the cold blackbody
Deriving $\tau_t$

- Cold space response:

$$C_s = (B_s \cdot \tau_t + L_t) \cdot R_f + C_f$$

- $B_s$ Planck radiance of space (4 K), assumed to be 0
- $\tau_t$ Telescope transmission
- $L_t$ Total emission from telescope
- $R_f$ System responsivity
- $C_f$ Complex emission from optics behind the telescope

With $B_s=0$, the unknowns are the telescope emission, $L_t$, and the complex emissions from the rear optics, $C_f$
Deriving $\tau_t$

• $C_f$ can be measured for each telescope emission measurement by looking at the cold IFC

$$C_f = C_c - \left[ \left( B_c \cdot \varepsilon_c \right) + B_{str} \cdot \left( 1 - \varepsilon_c \right) \right] \cdot \tau_m + B_m \cdot \left( 1 - \tau_m \right) \cdot R_f$$

• $L_t$, total telescope emission, is the sum:

$$L_t = B_{pm} \cdot \varepsilon_{pm} \cdot \left( 1 - \varepsilon_{m1} \right) \cdot \left( 1 - \varepsilon_{m2} \right) + B_{m1} \cdot \varepsilon_{m1} \cdot \left( 1 - \varepsilon_{m2} \right) + B_{m2} \cdot \varepsilon_{m2}$$

• This can be linearized with the substitutions:

$$\alpha_1 = \varepsilon_{pm} \cdot \left( 1 - \varepsilon_{m1} \right) \cdot \left( 1 - \varepsilon_{m2} \right) \quad \alpha_2 = \varepsilon_{m1} \cdot \left( 1 - \varepsilon_{m2} \right) \quad \alpha_3 = \varepsilon_{m2}$$
Deriving $\tau_t$

A set of simultaneous linear equations can be set up to solve for $L_t$

$$\frac{C_s - C_f}{R_f} = B_{pm} \cdot \alpha_1 + B_{m1} \cdot \alpha_2 + B_{m2} \cdot \alpha_3$$

- The values on the left side are known
- The $B$ values are computed from element temperatures
- With more than three samples, these equations are then solved using a least-squared error approach for $\alpha_1$, $\alpha_2$, and $\alpha_3$
- The resulting mirror emissivities can be computed as:

$$\varepsilon_{pm} = \frac{\alpha_1}{(1 - \varepsilon_{m2}) \cdot (1 - \varepsilon_{m3})} \quad \varepsilon_{m1} = \frac{\alpha_2}{1 - \varepsilon_{m2}} \quad \varepsilon_{m2} = \alpha_3$$
### $\tau_t$ Uncertainties

- Principle uncertainties in measuring $\tau_t$

<table>
<thead>
<tr>
<th>Error Source</th>
<th>Error</th>
<th>$\tau_t$ Uncertainty</th>
<th>$\tau_t$ Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_{pm}$</td>
<td>1K</td>
<td>0.067</td>
<td>0.030</td>
</tr>
<tr>
<td>$T_{m1}$</td>
<td>1K</td>
<td>0.064</td>
<td>0.030</td>
</tr>
<tr>
<td>$T_{m2}$</td>
<td>1K</td>
<td>0.067</td>
<td>0.031</td>
</tr>
<tr>
<td>$T_h$</td>
<td>0.1 K</td>
<td>0.021</td>
<td>0.016</td>
</tr>
<tr>
<td>$T_c$</td>
<td>0.1 K</td>
<td>0.007</td>
<td>0.011</td>
</tr>
<tr>
<td>$\varepsilon_h$</td>
<td>0.002</td>
<td>0.006</td>
<td>0.011</td>
</tr>
<tr>
<td>$\varepsilon_c$</td>
<td>0.002</td>
<td>0.002</td>
<td>0.006</td>
</tr>
<tr>
<td>RSS</td>
<td></td>
<td>0.117</td>
<td>0.057</td>
</tr>
</tbody>
</table>
Overall Radiance Calibration

- The combined uncertainty of the radiance calibration and derivation of $\tau_t$ and $\tau_m$ has been modeled
• Responsivity must be computed separately for each pixel, therefore multiple scans must be collected to do any averaging

• $\tau_m$ and $\tau_t$ are applicable to all pixels
  – A single scan of interferometer data will provide about 16000 samples over which $\tau_m$ and $\tau_t$ can be averaged

• Still to be addressed
  – Residual nonlinearity
  – Changes in responsivity over 24-hour telescope thermal cycle