On-orbit Calibration of the Geostationary Imaging Fourier Transform Spectrometer (GIFTS)

H. E. Revercomb[a], F. A. Best[a], D. C. Tobin[a], R. O. Knuteson[a], R. K. Garcia[a],
D. D. LaPorte[a], G. E. Bingham[b], and W. L Smith[c]

[a]*University of Wisconsin-Madison, Space Science and Engineering Center*
[b]*Utah State University, Space Dynamics Laboratory*
[c]*NASA Langley Research Center*

The Year 2002 Conference on Characterization and Radiometric Calibration for Remote Sensing

April 29 - May 2, 2002
Space Dynamics Laboratory / Utah State University

Abstract

The NASA New Millennium Program’s Geostationary Imaging Fourier Transform Spectrometer (GIFTS) requires highly accurate radiometric and spectral calibration in order to carry out its mission to provide water vapor, wind, temperature, and trace gas profiling from geostationary orbit. A calibration approach has been developed for the formulation phase GIFTS instrument design. The in-flight calibration is performed using views of two on-board blackbody sources along with cold space. A radiometric calibration uncertainty analysis has been developed and used to show that the expected performance for GIFTS exceeds its top level requirement to measure brightness temperature to better than 1 K.

The spectral calibration is established by the highly stable diode laser used as the reference for interferogram sampling, and verified with comparisons to atmospheric calculations. Algorithms that normalize spectral sampling have been developed to correct for off-axis effects. A baseline approach defining the role that ground measurements play in the on-orbit calibration has been established.

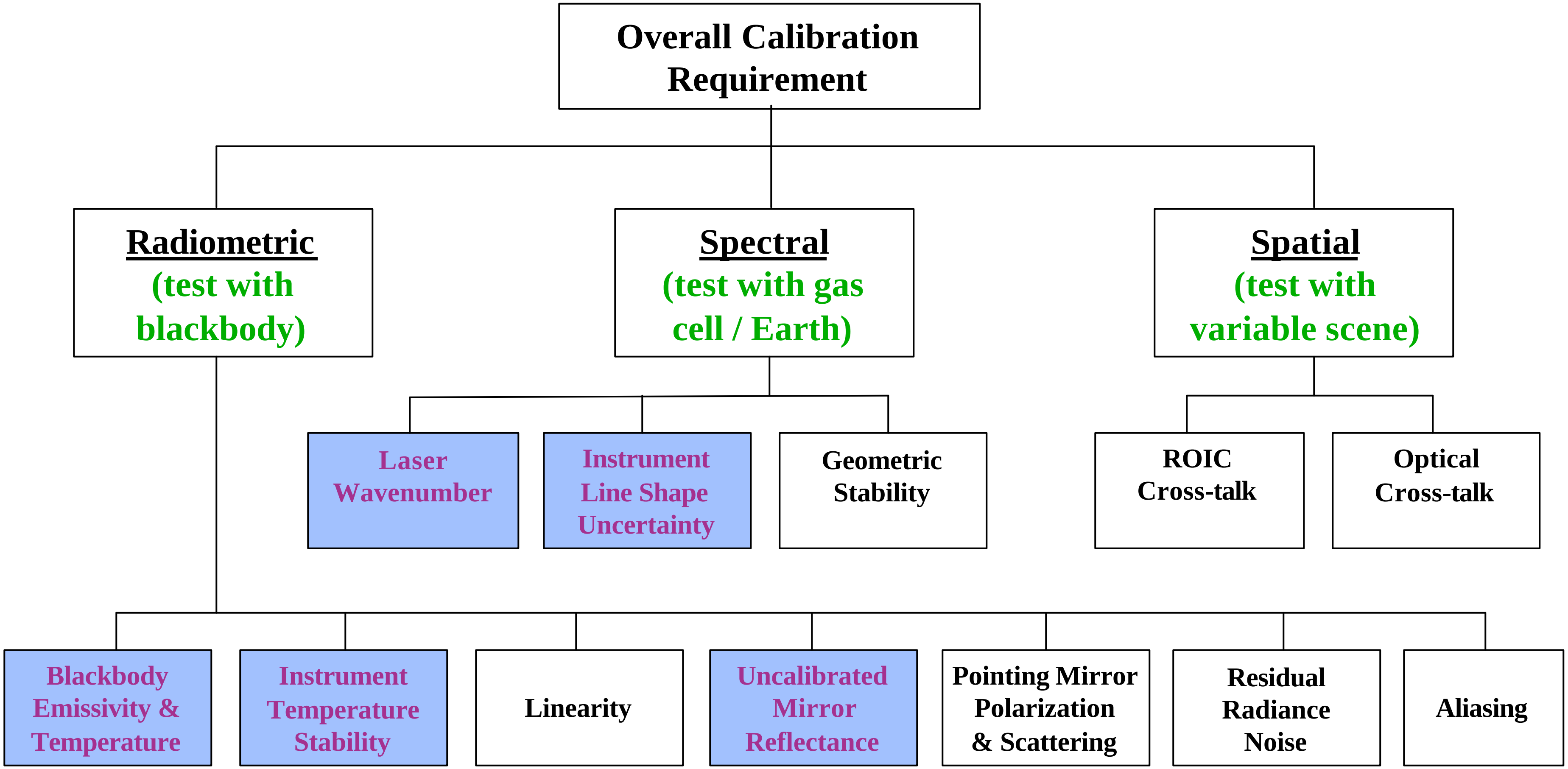
GIFTS Measurement Concept

Combine Advanced Measurement Technologies On a Geosynchronous Satellite to Obtain 4-D Observations of the Atmosphere

- **Horizontal**: *Large detector arrays give near instantaneous wide 2-D geographical coverage*
- **Vertical**: *Michelson interferometer (FTS) gives high spectral resolution that yields high vertical resolution*
- **Temporal**: *Geosynchronous orbit allows high time resolution (i.e., motion observations)*

UW-SSEC

GIFTS Calibration Overview



Overall Calibration Requirement

Radiometric (test with blackbody)

- Blackbody Emissivity & Temperature
- Instrument Temperature Stability
- Linearity
- Uncalibrated Mirror Reflectance
- Pointing Mirror Polarization & Scattering
- Residual Radiance Noise
- Aliasing

Spectral (test with gas cell / Earth)

- Laser Wavenumber
- Instrument Line Shape Uncertainty
- Geometric Stability

Spatial (test with variable scene)

- ROIC Cross-talk
- Optical Cross-talk

Items to be addressed quantitatively in this talk.

Radiometric Calibration

Topics - On-orbit Radiometric Calibration

- Top level requirements
- In-flight Radiometric Calibration Concept for GIFTS
- Predicted Radiometric Performance
- In-flight Calibrator Baseline Design
- Heritage

GIFTS Blackbody Top Level Requirements

Calibration Accuracy [From the GIRD §5.5.1 (GIR398)]

The absolute calibration accuracy of the GIFTS Instrument shall be =1K brightness temperature for Earth scene brightness temperatures >240K (SW/MW channel) and >190K (LW channel) and shall be traceable to the National Institute of Standards and Technology (NIST). The reproducibility shall be =0.2K for the same conditions.

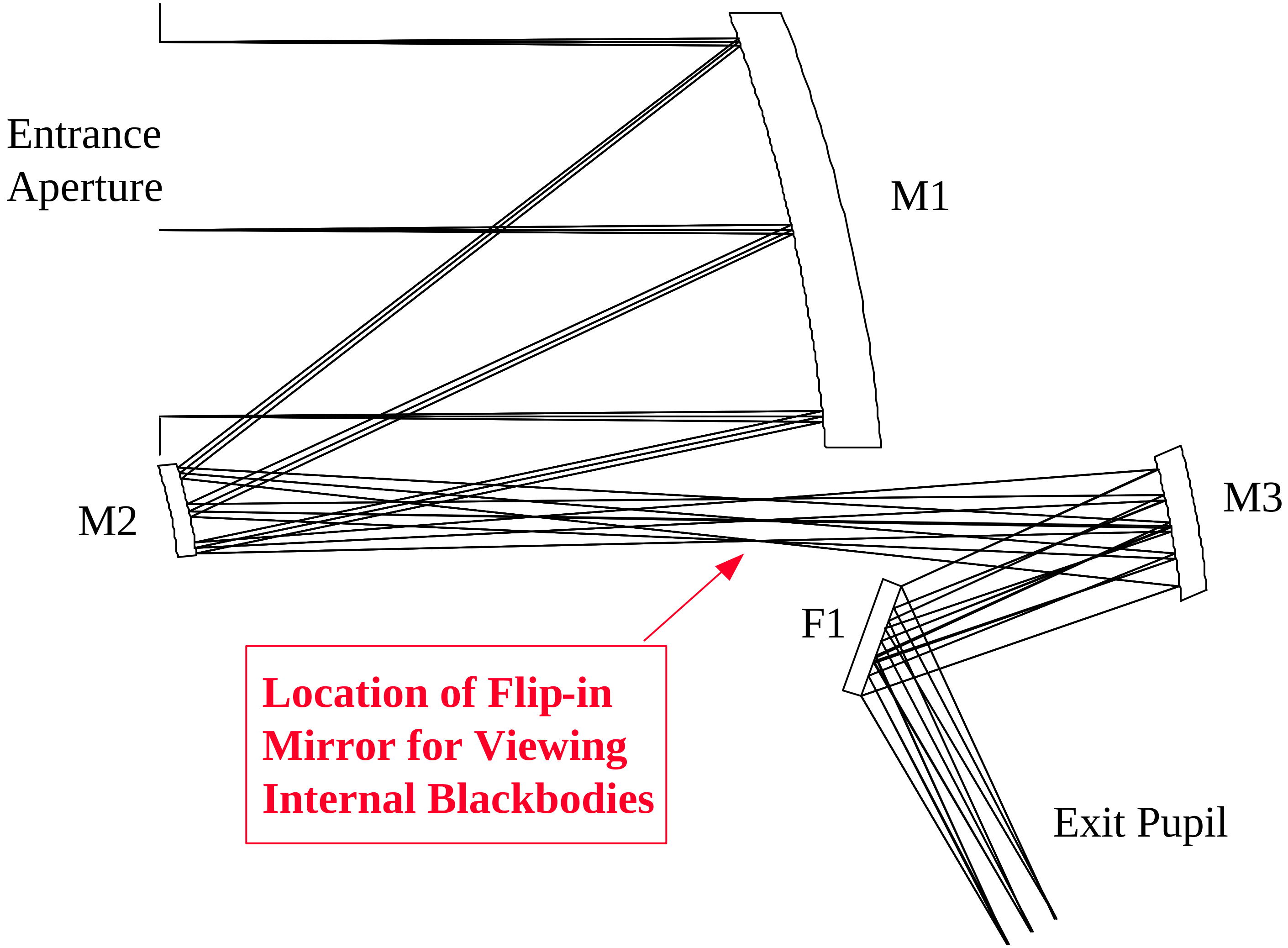
On-Board Calibration [From the GIRD §5.5.3 (GIR400)]

The GIFTS instrument shall provide three calibration reference sources that shall be viewable at regular, programmable intervals. Two of these sources shall be blackbodies at temperatures chosen to optimize calibration accuracy over the life of the mission. The instrument shall include the capability of viewing space as a third calibration source…

GIFTS Radiometric Calibration Concept

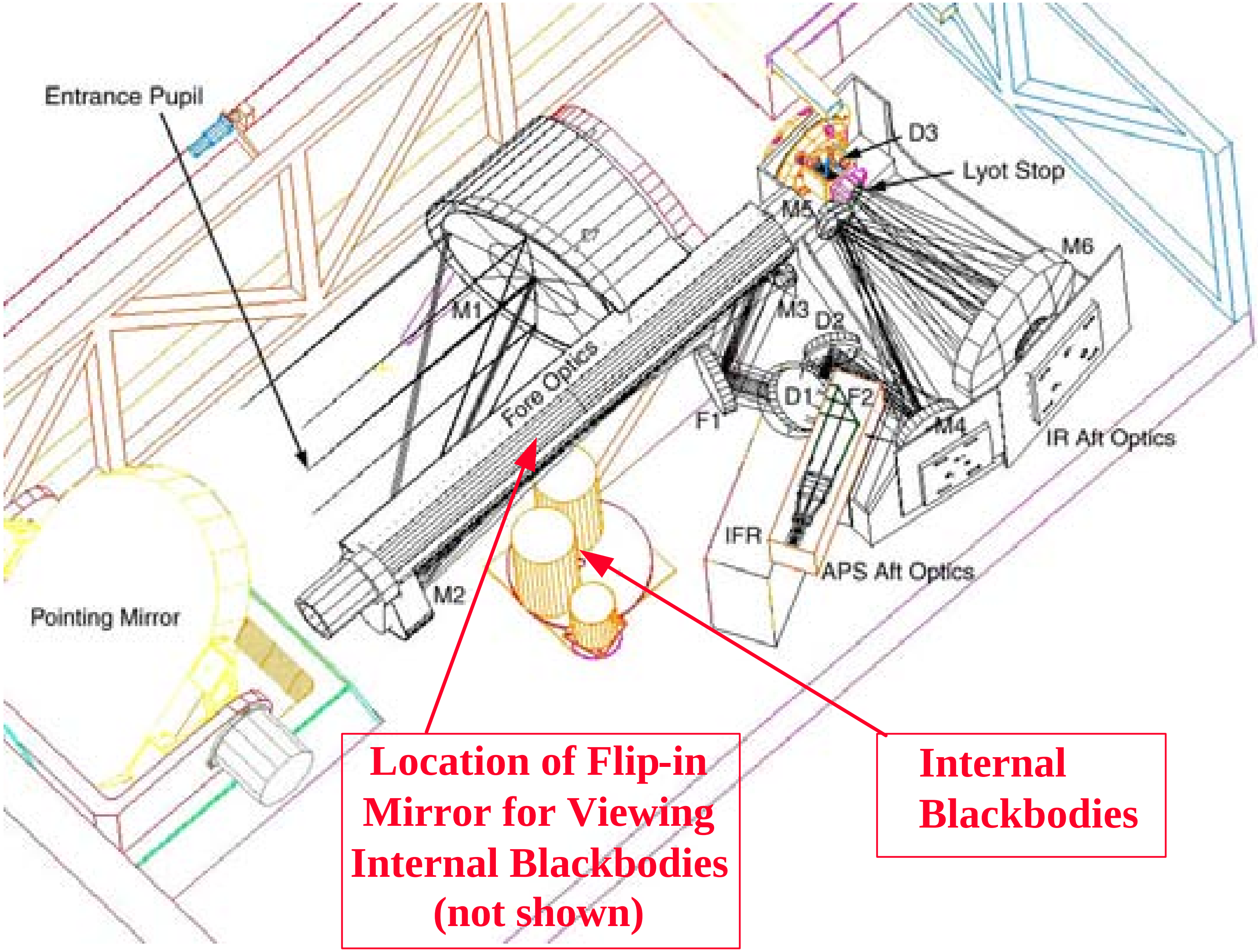
- Two small reference Blackbodies located behind telescope, combined with Space View.
- Blackbody design is scaled from the UW ground-based AERI and NAST / S-HIS aircraft instruments.
- Constraints on original S/C prevented traditional external large aperture blackbody configuration.
- Advantages compared to large external blackbody:
  (1) higher emissivity is practical with small size
  (2) protection from solar forcing.

Fore Optics (Afocal Telescope)



Location of Flip-in Mirror for Viewing Internal Blackbodies

Oblique View of Optical Subsystem



Location of Flip-in Mirror for Viewing Internal Blackbodies (not shown)

Internal Blackbodies

GIFTS Radiometric Calibration Concept

$$N = \left(\frac{t_m}{t_t}\right)(B_H - B_C)\,Re\left(\frac{C_E - C_S}{C_H - C_C}\right) + B_S$$

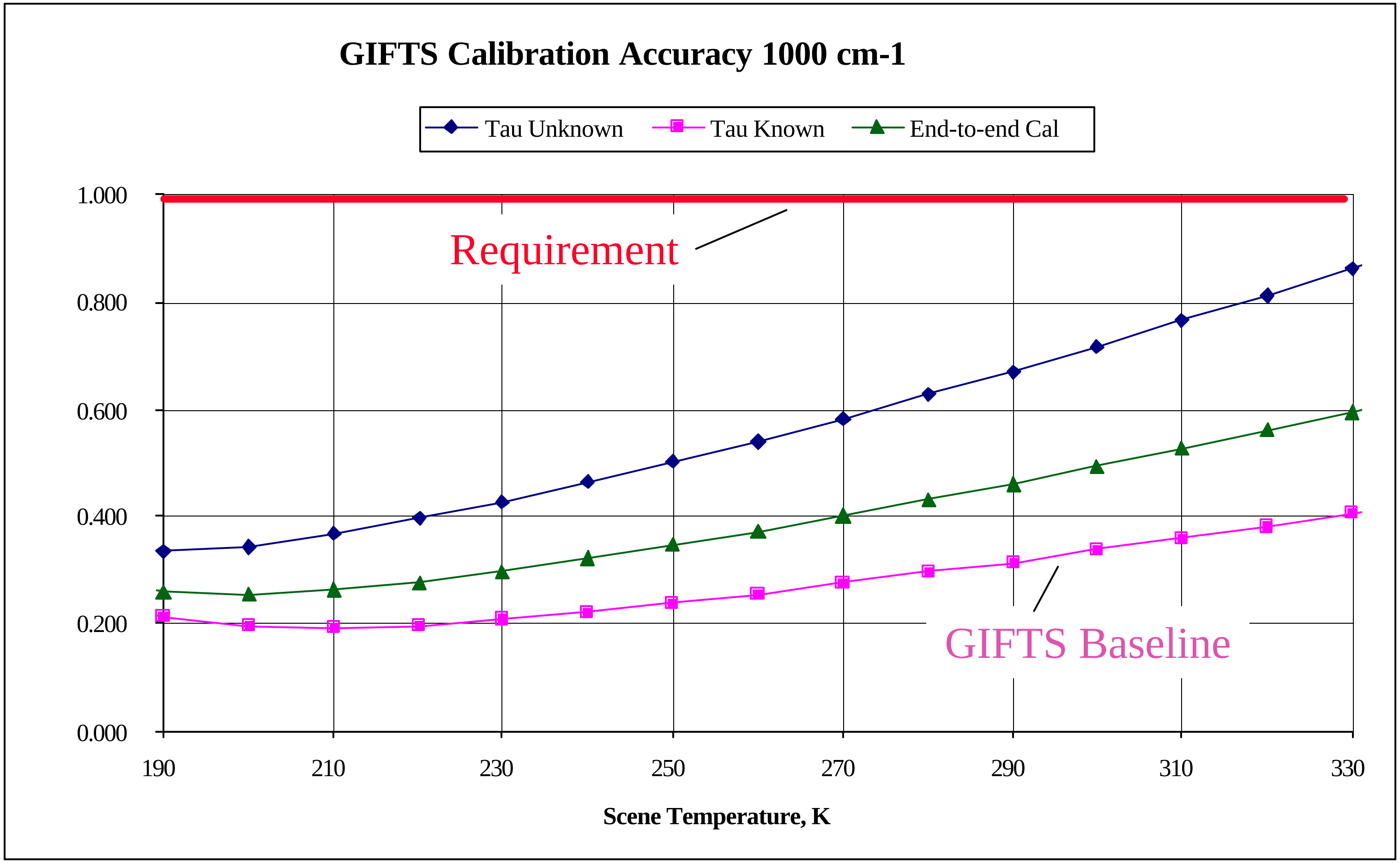
- Radiance N derived from raw spectra of Earth (C_E), Space (C_S), and the internal Hot (C_H) and Cold (C_C) Blackbodies
- t_t is the signal transmission of the telescope mirrors &
  t_m is the transmission of the Blackbody pick-off mirror
- B is the Planck Radiance from the Hot, Cold, and Space References

GIFTS Radiometric Calibration Parameters

Absolute Calibration Uncertainties

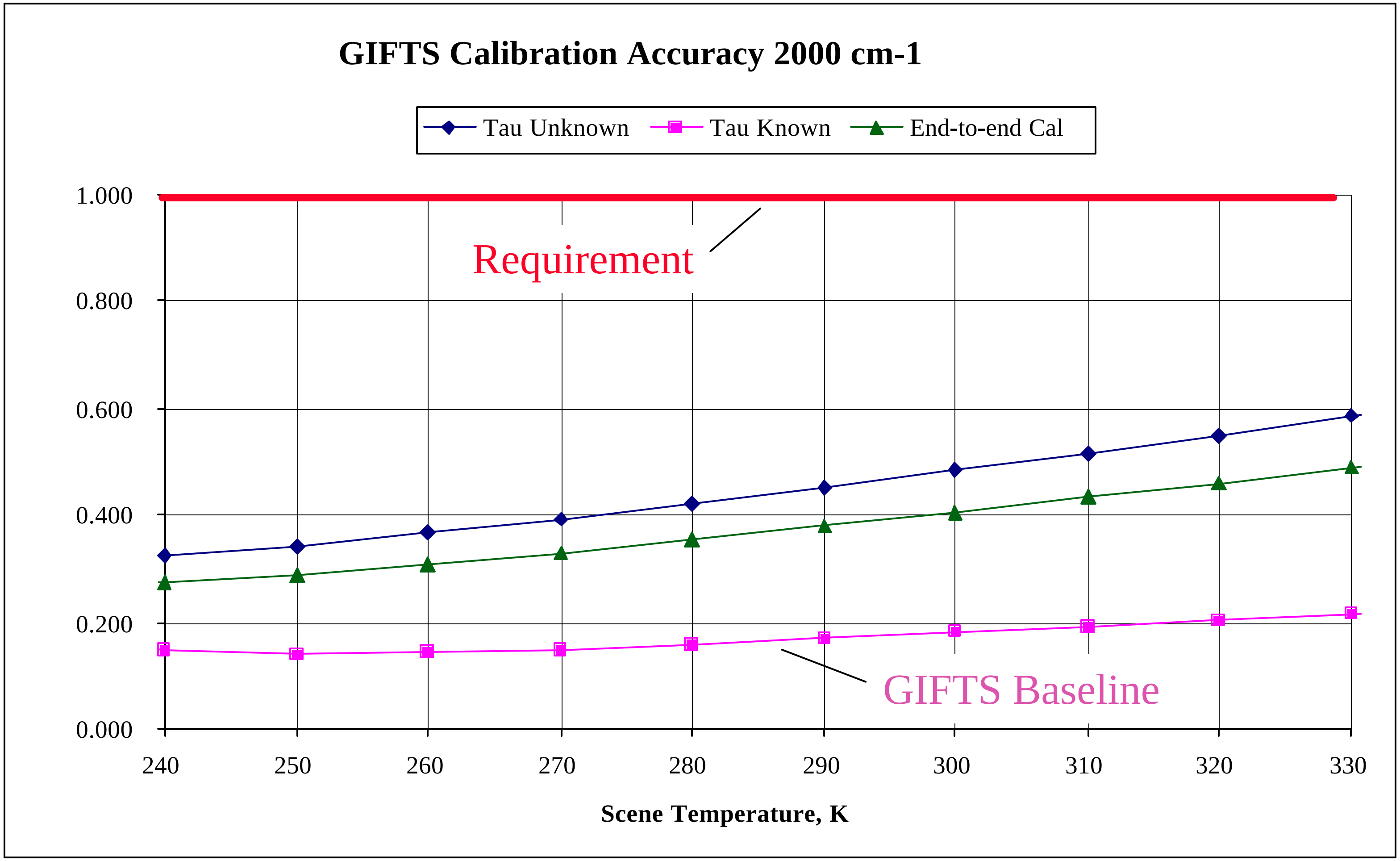
Input Parameters			Parameter Uncertainties	
wn	1000	Wavenumber, [cm-1]		
TauTel	0.913	Transmission of Telescope (2) plus front flat (1)	^{2}TauRatio	0.0020
TauBBmirror	0.970	Transmission of BB mirror	^{2}TauBBmirror	0.010
Thbb	300	Temp. of Hot Blackbody, [K]	^{2}Thbb	0.1
Tcbb	265	Temp. of Cold Blackbody, [K]	^{2}Tcbb	0.1
Tspace	4.0	Temp. of Space View, [K]		
Ttel	265	Temp. of Front Telescope, [K]	^{2}Ttel	2.00
Tbbmirror	220	Temp. of blackbody mirror, [K]	^{2}Tbbmirror	2.00
Tstr	250	Temp. of Structure Reflecting into BB's, [K]	^{2}Tstr	5.00
Ehbb	0.996	Emissivity of HBB, [-]	^{2}Ehbb	0.002
Ecbb	0.996	Emissivity of CBB, [-]	^{2}Ecbb	0.002
Espace	1.0	Effective Emissivity of Space View, [-]		
Parameters Used For Temperature Stability Affects				
TtelChange	0.4	Change in Telescope Temp Between Earth & Space Views		
TbbmirChange	2.0	Change in BB Mirror Temp Between Hot and Cold Views		

GIFTS Calibration Accuracy-Longwave

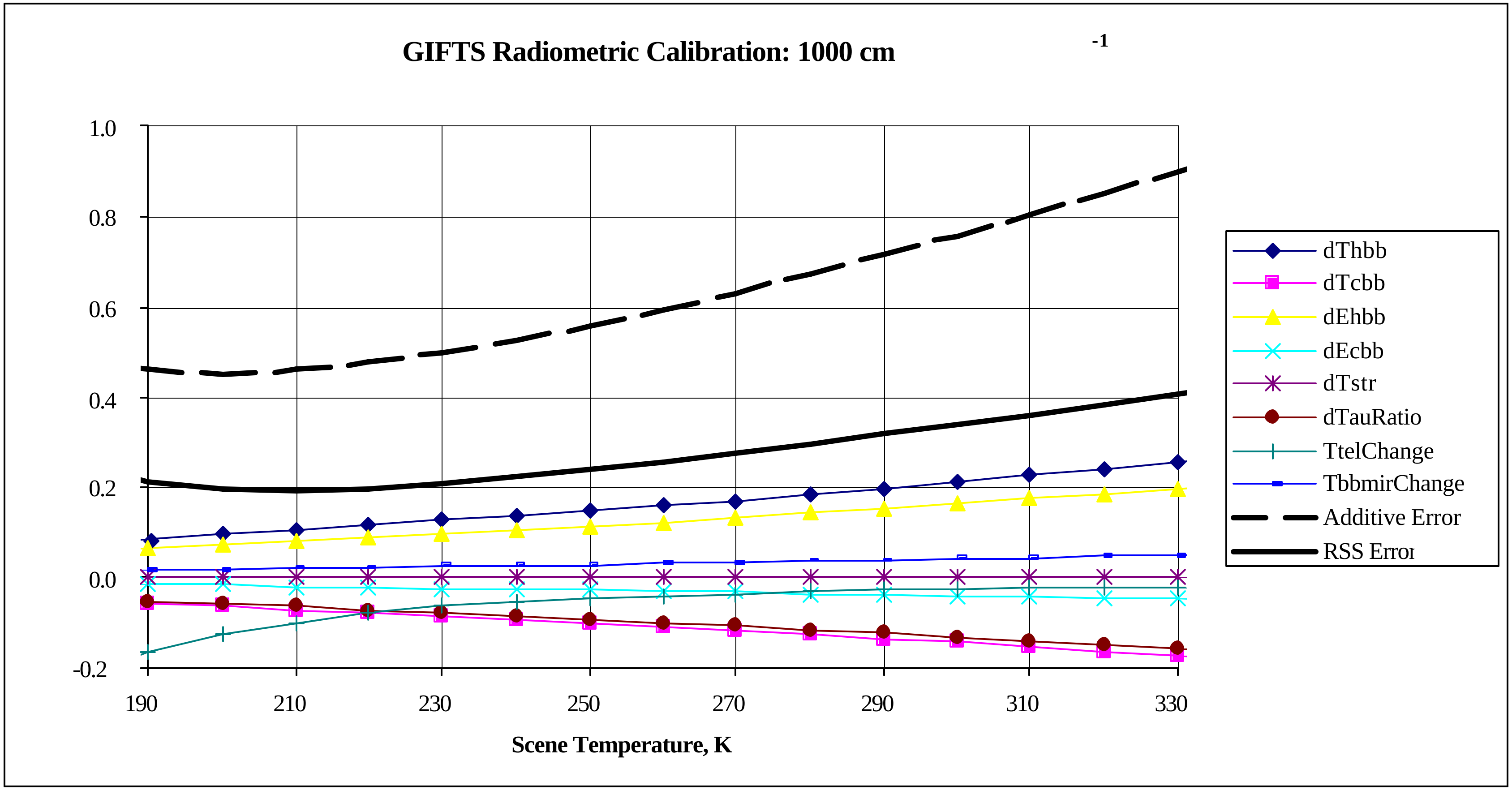


UW-SSEC

GIFTS Calibration Accuracy-Shortwave

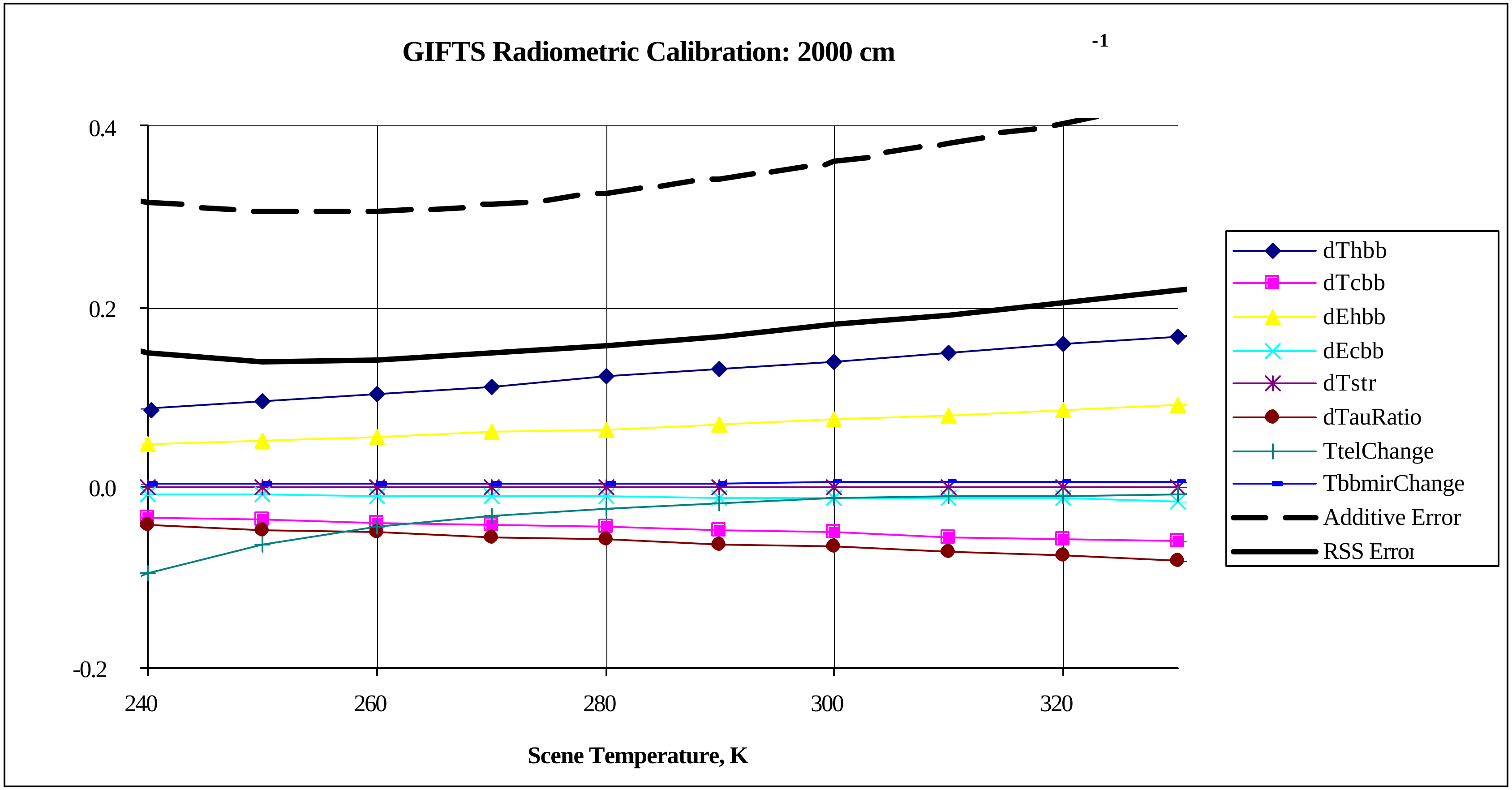


GIFTS Calibration Errors-Longwave



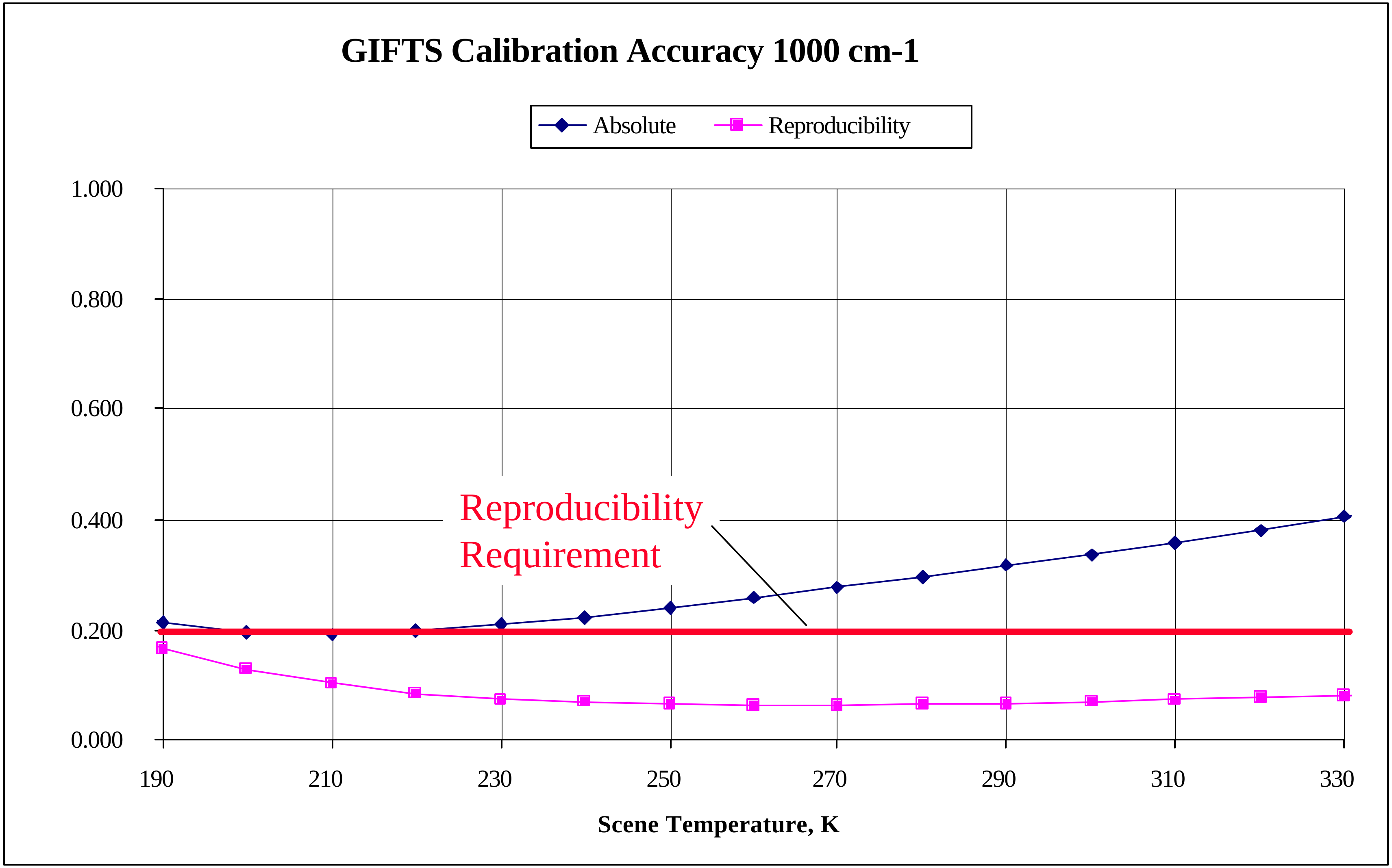
UW-SSEC

GIFTS Calibration Errors-Shortwave

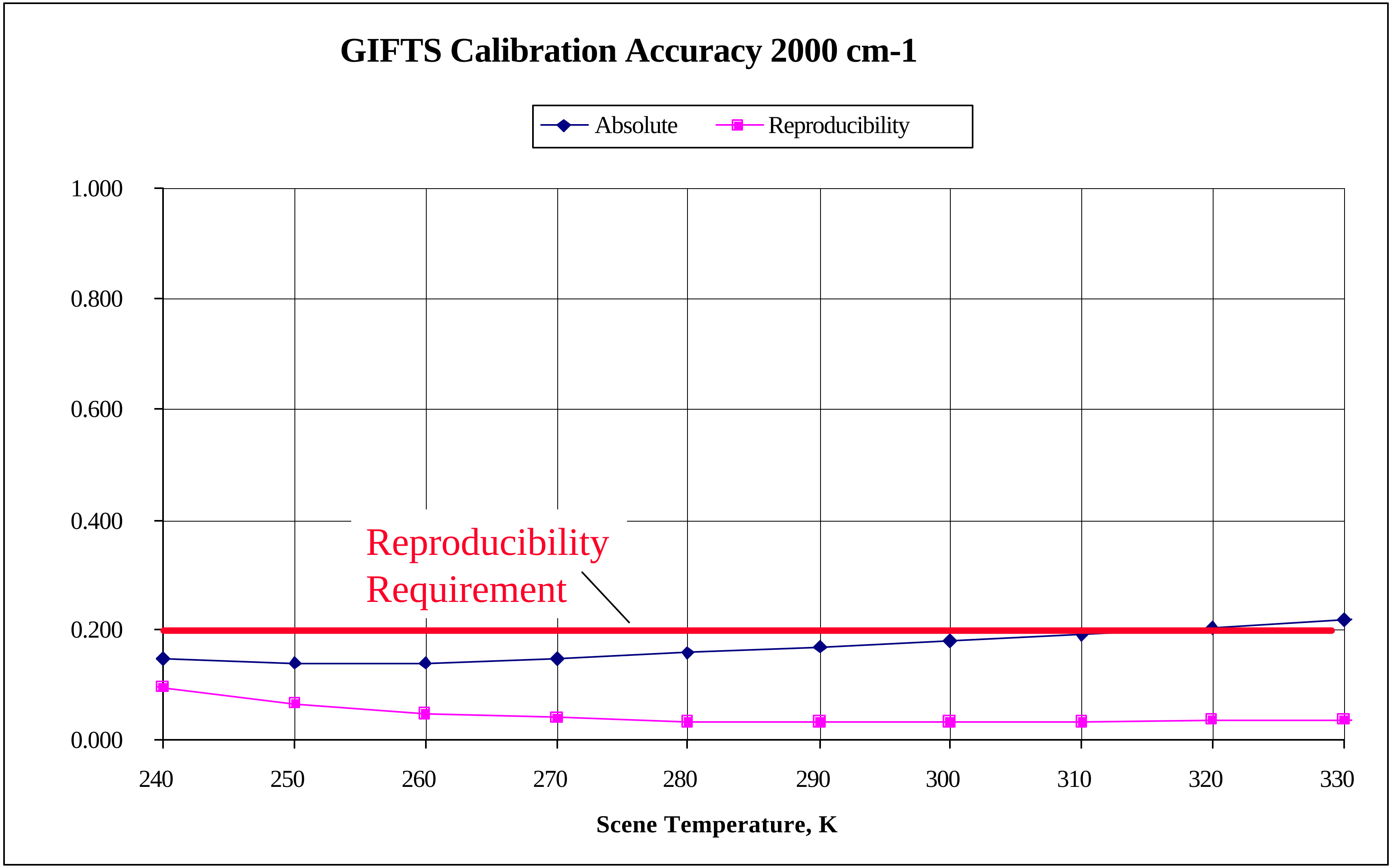


UW-SSEC

Reproducibility-Longwave



Reproducibility-Shortwave



UW-SSEC

GIFTS Blackbody Requirements

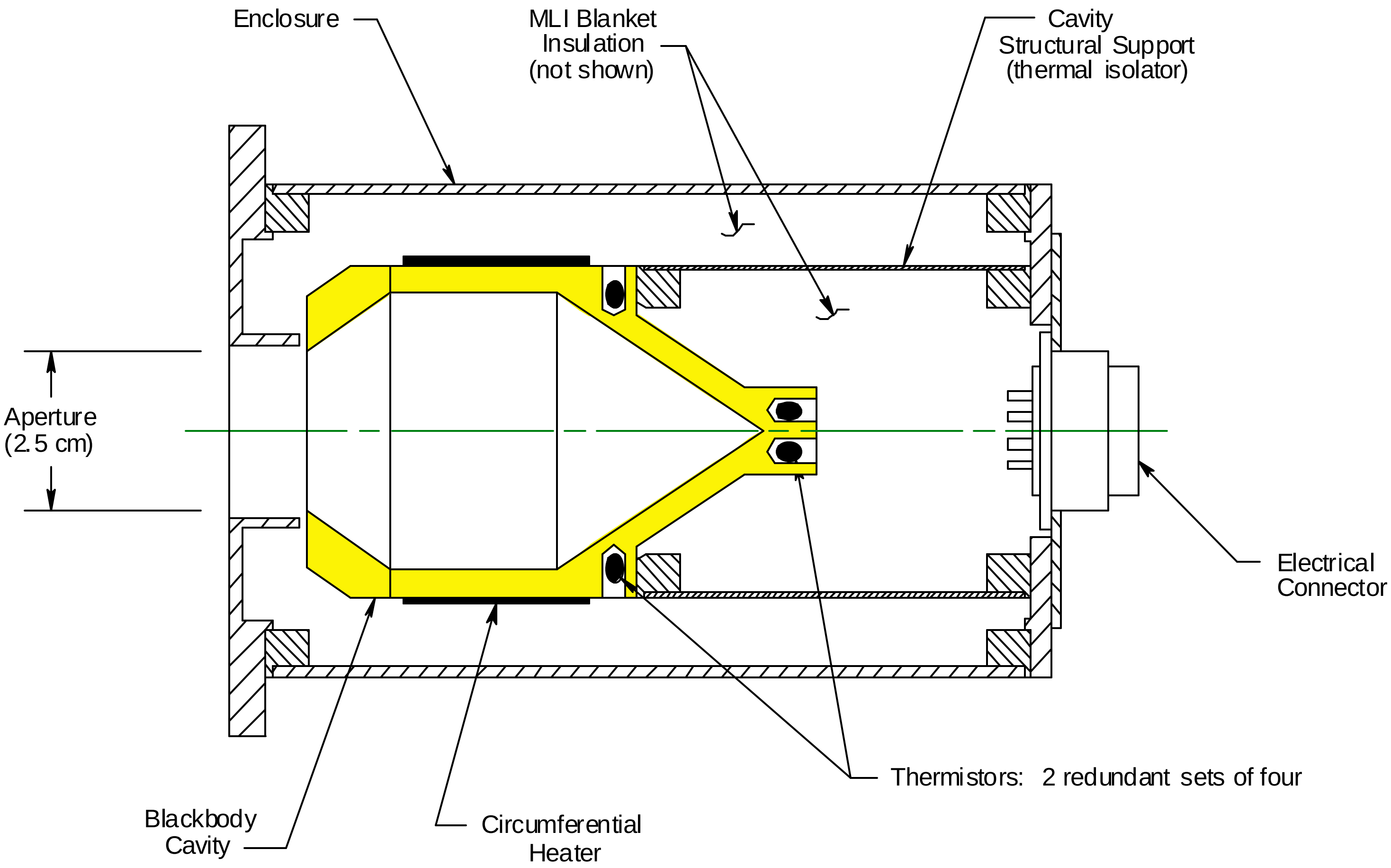
The derived In-flight calibrator subsystem requirements are:

- Temperature knowledge: ±0.1 K
- Emissivity knowledge: better than ±0.2%
- Temperature gradient : knowledge within 0.1 K

GIFTS Instrument imposed requirements and allocations:

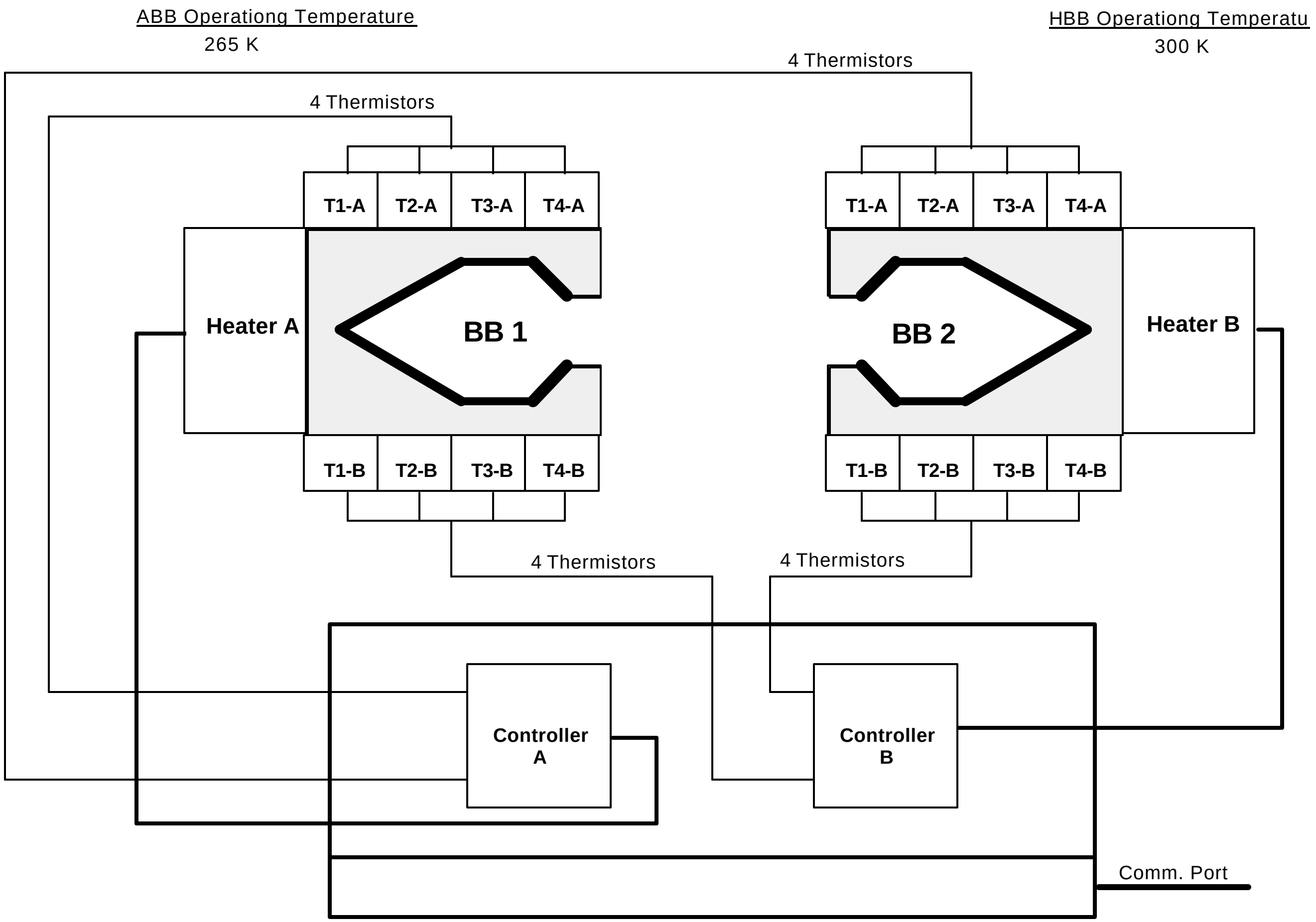
- Source Aperture: 2.54 cm
- Envelope: 8.0 cm Dia. X 14 cm long
- Operating Temperature: 265 to 300 K
- Mass (2 BB's and Controllers): < 2.4 kg
- Power (2 BB's and Controller): < 3.0 W

GIFTS In-flight Calibrator Baseline Design



Paint surface is Chemglaze Z306

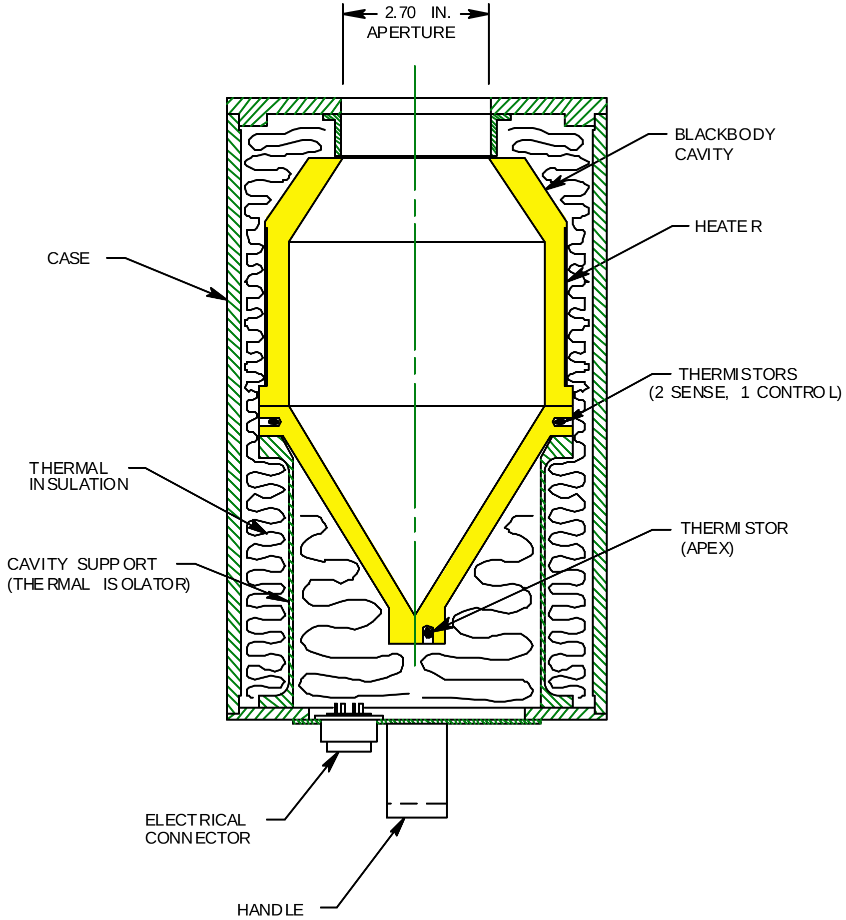
GIFTS BB Block Diagram

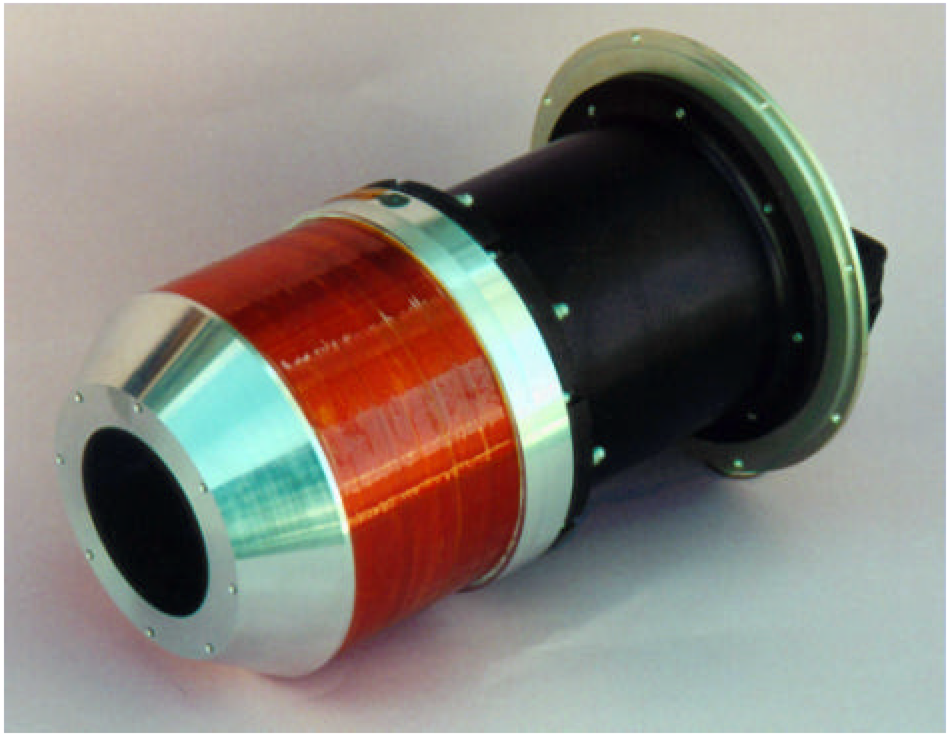


Blackbody Subsystem Heritage

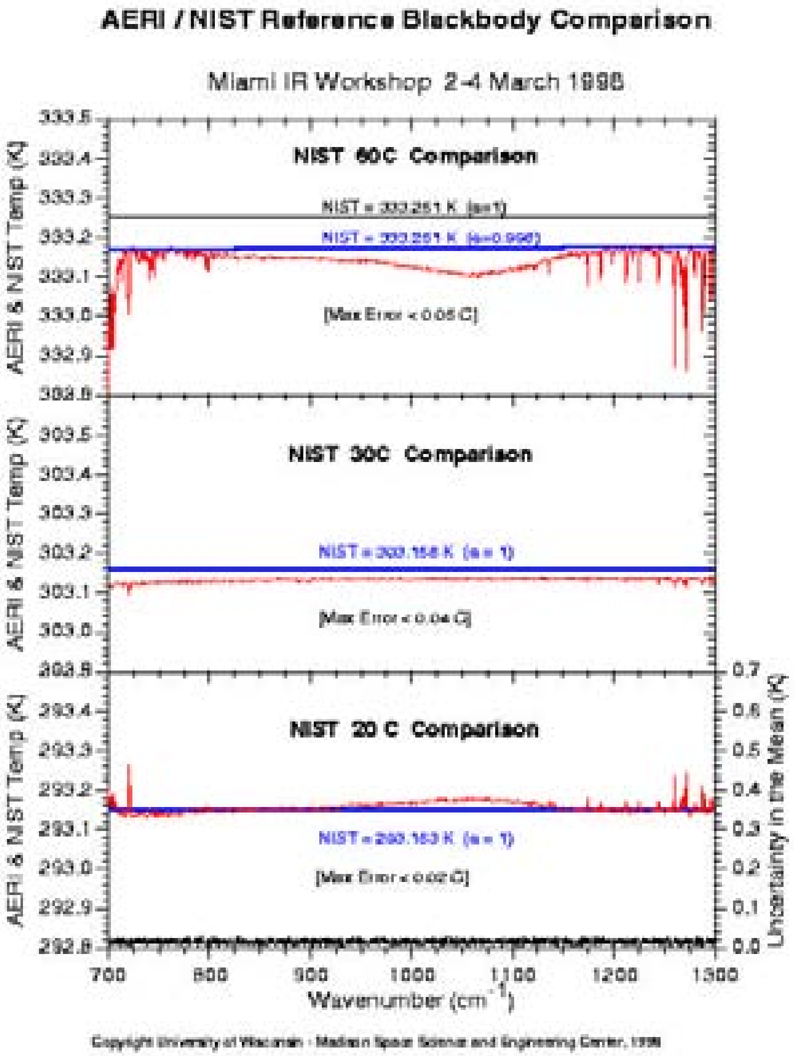
- UW Developed AERI (groundbased) and S-HIS (aircraft) FTIR Instruments have demonstrated Radiometric Performance with accuracies better than 1 K.
- These programs have demonstrated the methodologies of integrating instrument Radiometric Models with Calibration Techniques and Error Budgets to produce the required radiometric accuracies.

AERI Blackbody





AERI / NIST Blackbody Intercomparison



Copyright University of Wisconsin - Madison Space Science and Engineering Center, 1998

@ 333K, Max Error <0.05K

@ 303K, Max Error <0.04K

@ 293K, Max Error <0.02K

Summary - Radiometric Calibration

- In-flight radiometric calibration makes use of two small internal blackbody cavities (located near the field stop), plus a space view.
- A combination of the internal blackbodies and the space view allow tracking of any in-flight changes of the fore-optics transmission.
- Internal high-emissivity Blackbodies offer:
  - Better absolute calibration
  - Easier implementation - smaller range of pointing mirror angles

Spectral Calibration

GIFTS On-Orbit Spectral Calibration

Philosophy

- Pre-flight spectral calibration parameters determined during ground calibration.
- Highly stable laser serves as an in-flight calibration reference.
- Verify in-flight using known atmospheric absorption lines.

Discussion Topics

- In-flight wavenumber scale verification.
- The Instrument Line Shape (ILS) correction.
- Off-axis wavenumber scale renormalization.

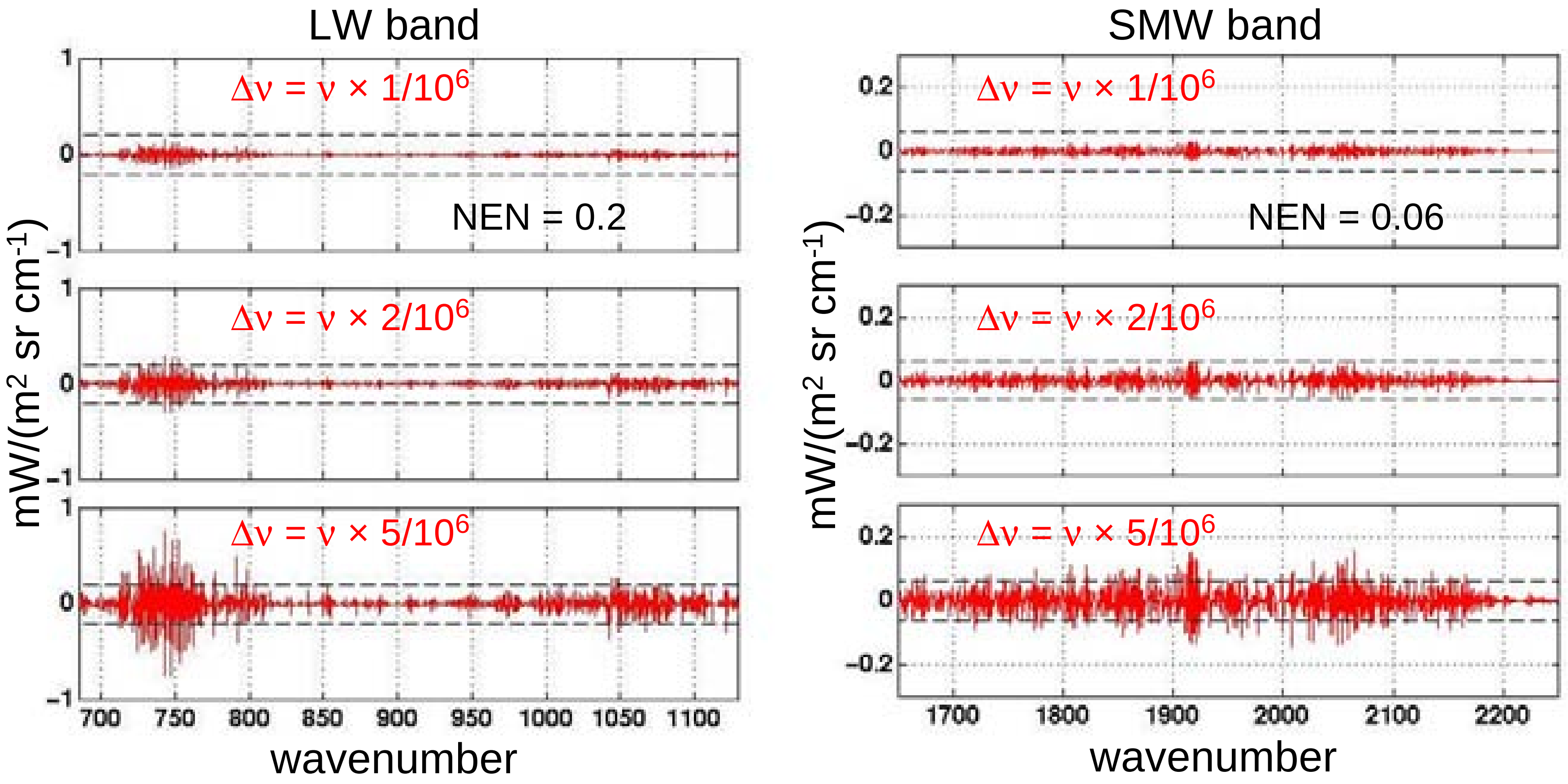
In-flight Wavenumber Scale Validation

- The GIFTS spectral scale is referenced to the on-board laser used to trigger interferogram sampling, as in a normal FTS.
- In a Michelson inteferometer, sampling at equal intervals in optical path delay leads (after Fourier Transform) to equal sampling in wavenumber.
- The actual wavenumber sampling interval depends on both the wavelength of the laser used to sample the interferogram and the angle between the path of the laser and the IR beam for each detector.

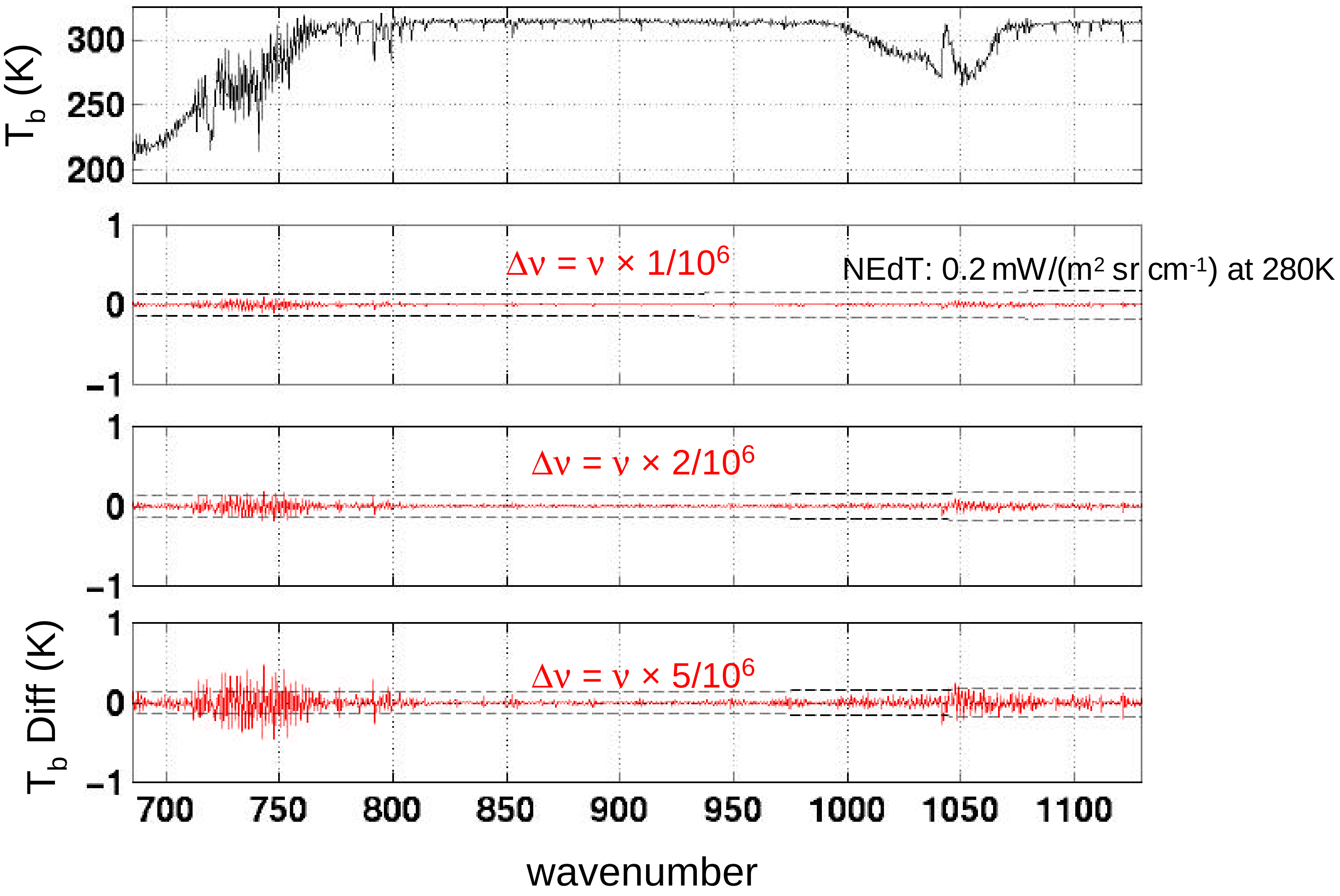
GIFTS Spectral Calibration Requirements

- The effective radiometric errors associated with spectral calibration are included under the overall 1 K absolute calibration specification.
- An objective for GIFTS is to provide a laser stability better than 1 part in 10^6 (3 σ) over a month time period.

» Simulated Errors due to wavenumber scale uncertainties:

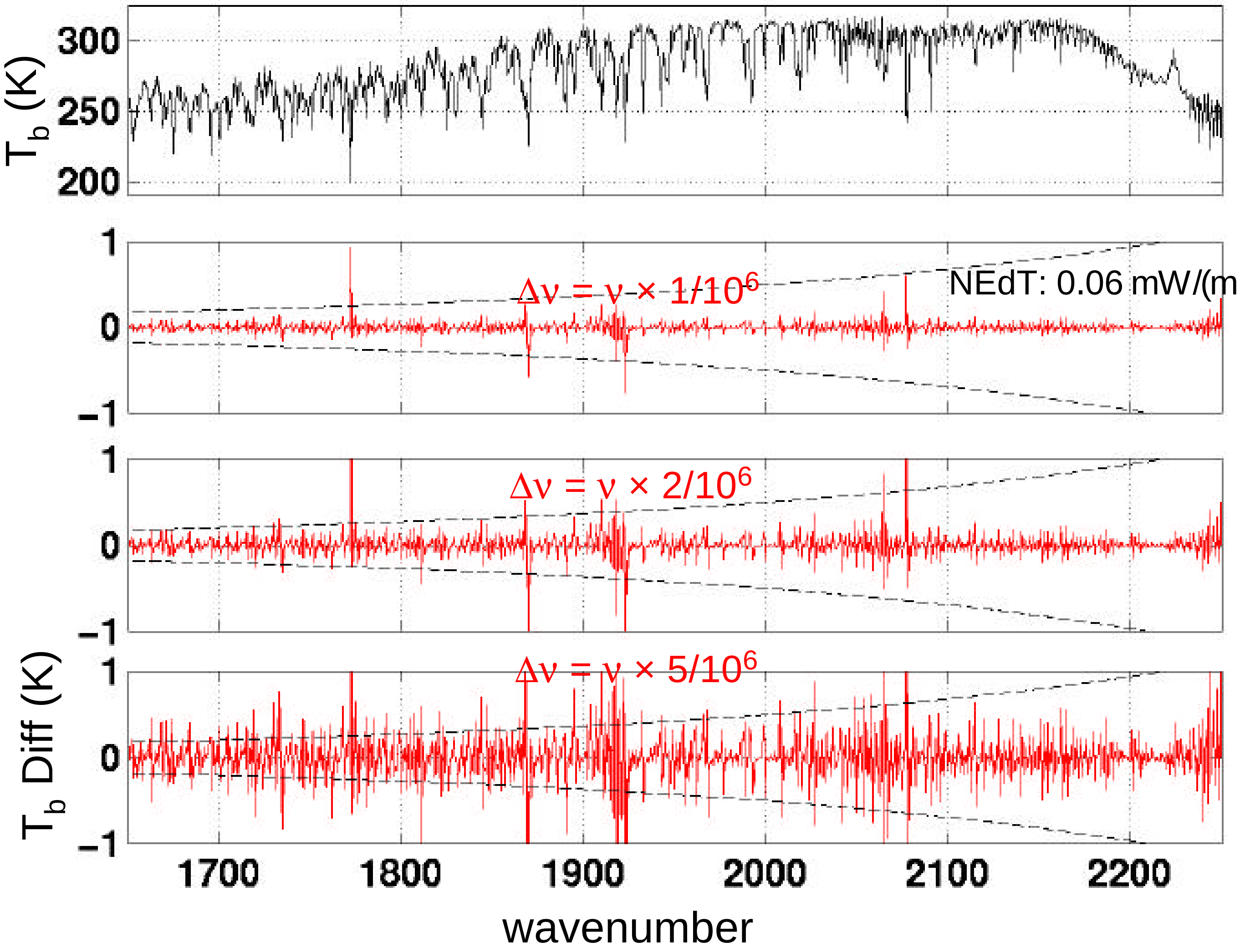


LW band Tb



T_b (K)
300
250
200
1
0
−1
$\Delta\nu = \nu \times 1/10^6$
NEdT: 0.2 mW/(m² sr cm⁻¹) at 280K
1
0
−1
$\Delta\nu = \nu \times 2/10^6$
1
0
−1
$\Delta\nu = \nu \times 5/10^6$
T_b Diff (K)
700
750
800
850
900
950
1000
1050
1100
wavenumber

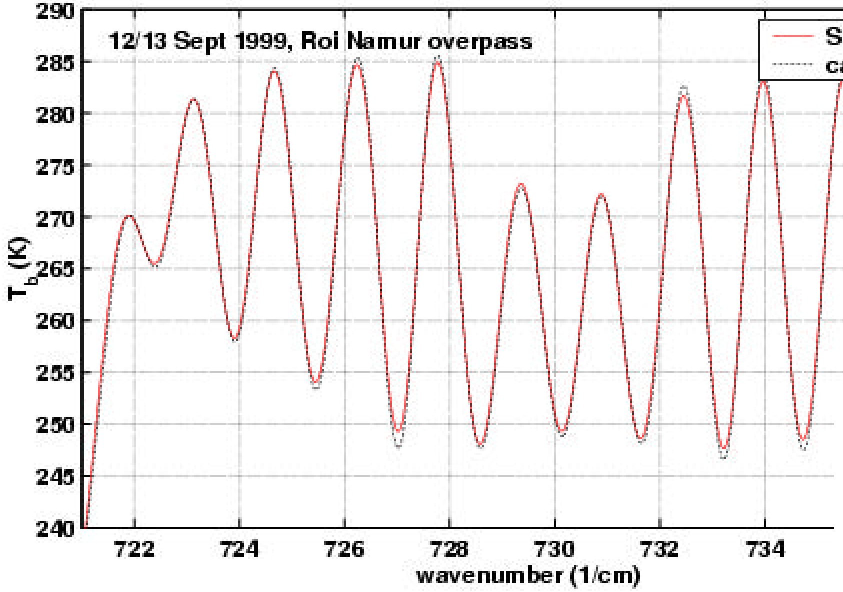
SMW band Tb



NEdT: 0.06 mW/(m^2 sr cm^{-1}) at 280K

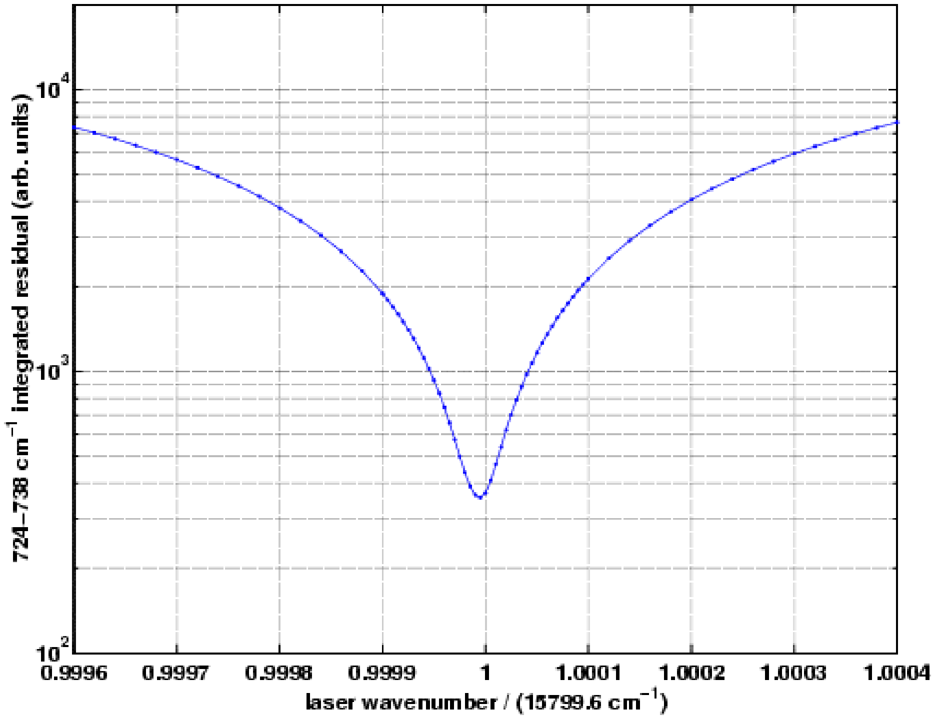
UW-SSEC

Example Spectral Calibration: S-HIS

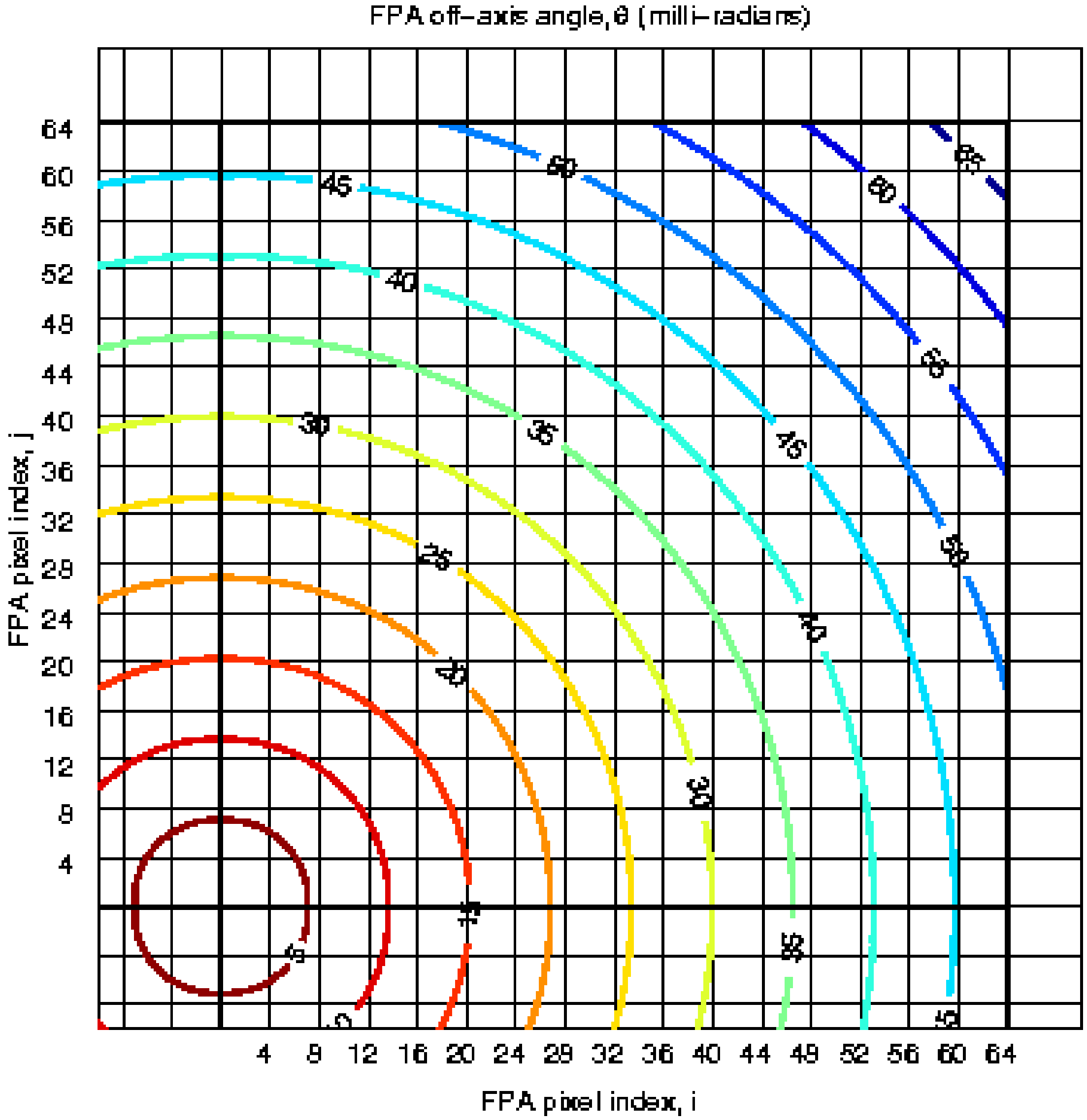


Atmospheric CO_2 lines from S-HIS and from using HITRAN2000.

Observed wavenumber scale factor chosen to minimize difference with radiative transfer Calculation.

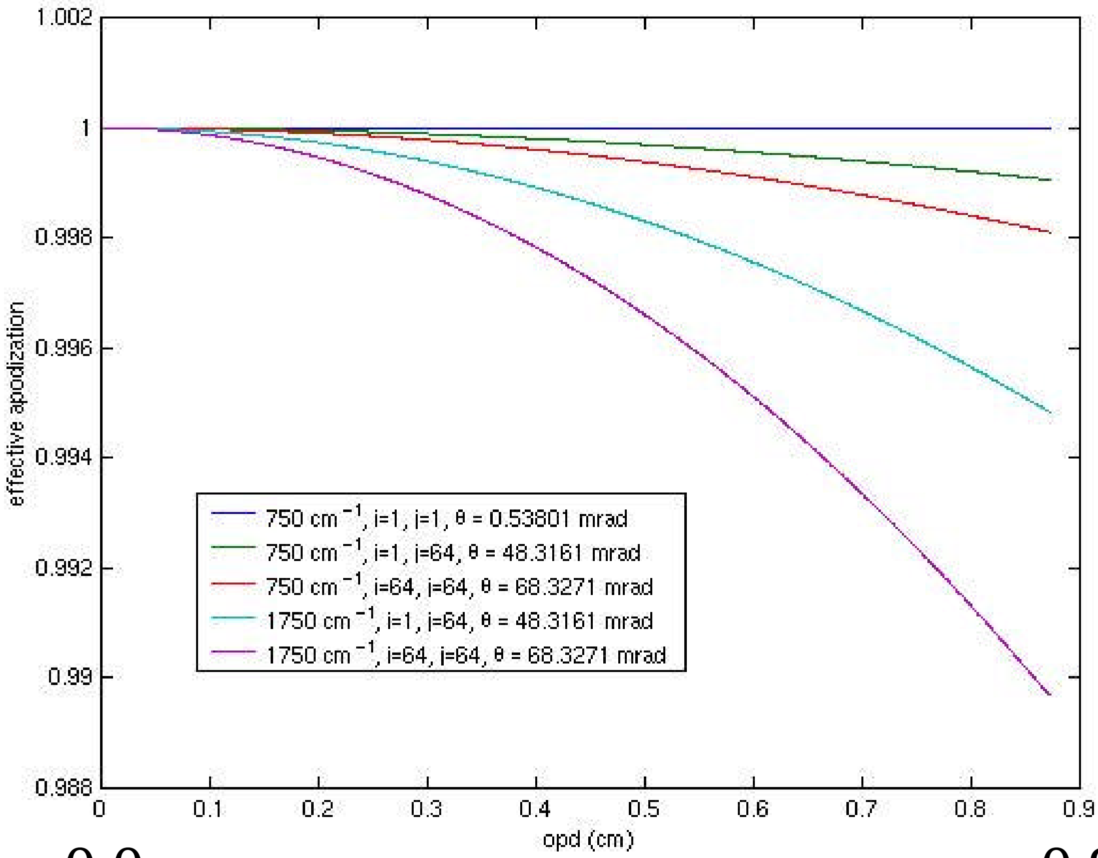


Off-Axis GIFTS Focal Plane Array Angle



Self-Apodization due to finite detector size

Self-Apodization



1.00

0.99

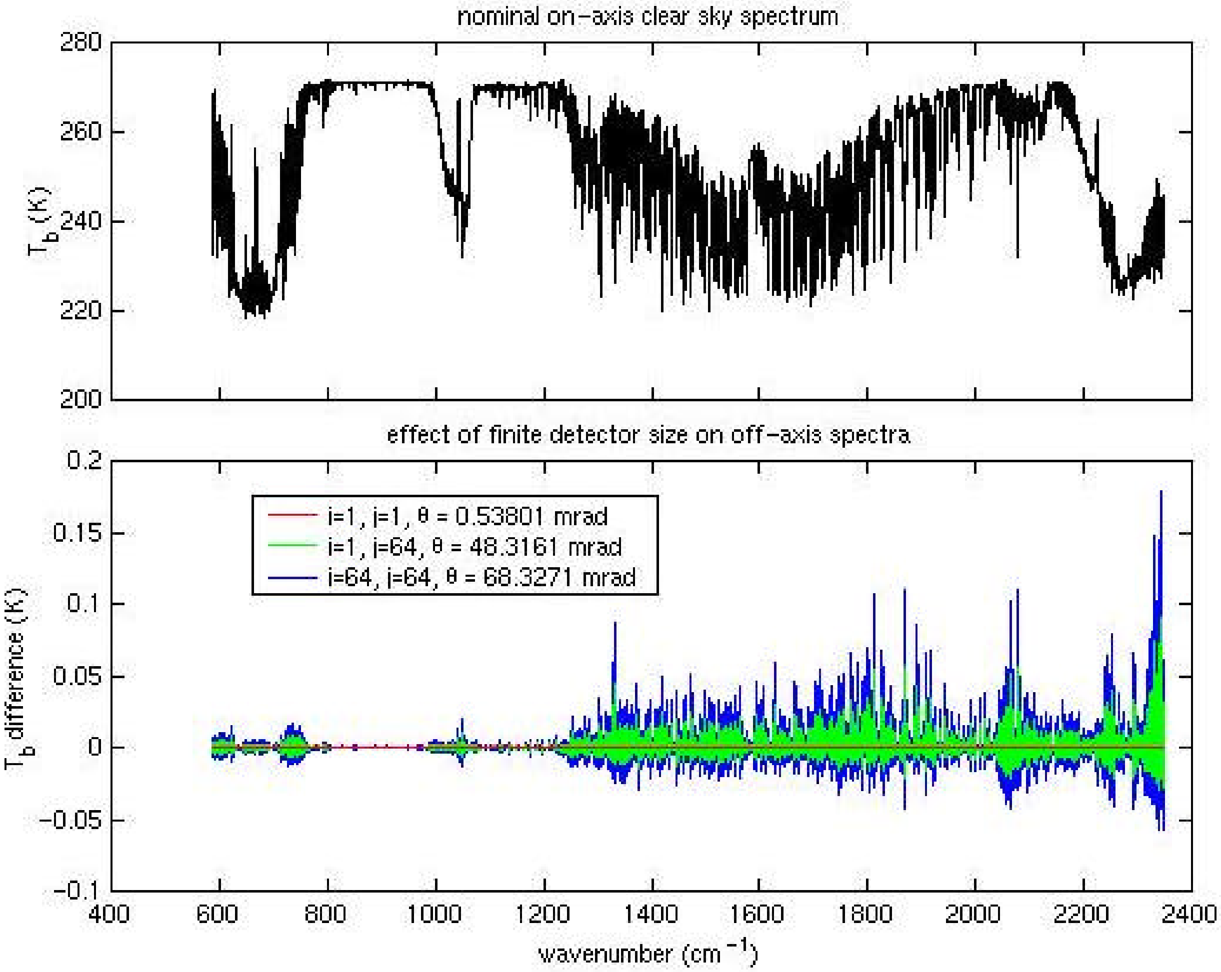
0.0

OPD (cm)

0.9

Self-apodization effect is less than 1% for GIFTS detectors.

Effect of Uncorrected ILS variations



Equivalent temperature error less than 0.1K even without correction!

UW-SSEC

ILS Correction Process

- In expression for the measured interferogram, *F(x)*, expand sinc function as a power series of (2πνxbθ):

$$F(x)=\int d\nu N(\nu)e^{i2\pi\nu x}-\frac{(2\pi x b\theta)^2}{3!}\cdot\int d\nu N(\nu)\nu^2 e^{i2\pi\nu x}+\frac{(2\pi x b\theta)^4}{5!}\cdot\int d\nu N(\nu)\nu^4 e^{i2\pi\nu x}-\ldots$$

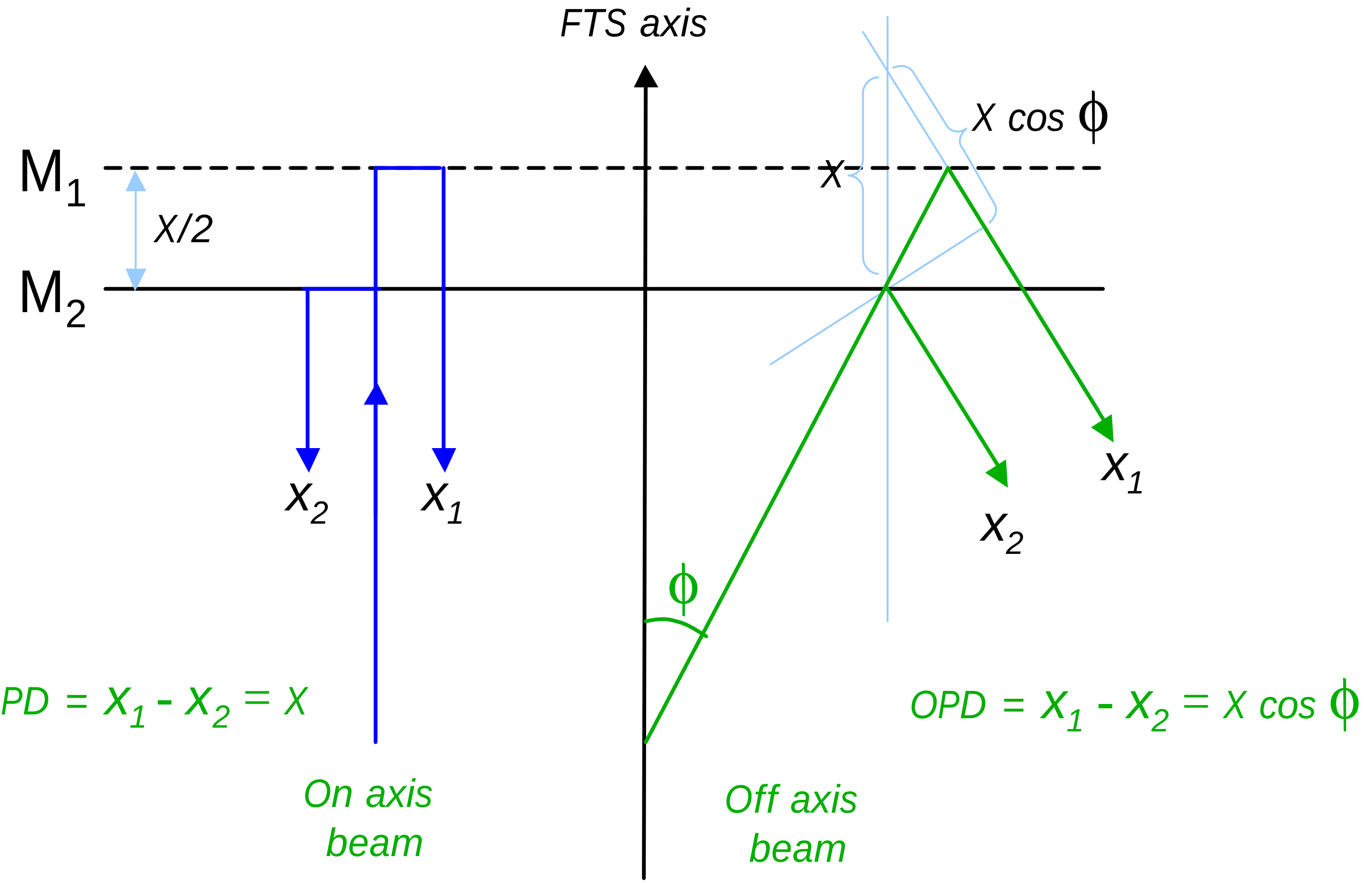
- Compute perturbation terms and subtract from measured interferogram.

» Similar process is currently performed for UW FTS airborne and ground based instruments (S-HIS/AERI).

Off-Axis Effects: Wavenumber Scale

- The beams of light reaching each detector in the focal plane array pass through the interferometer at different angles, ϕ.
- With respect to the on-axis beam, the off-axis beams have slightly shorter OPDs:
  $\mathrm{OPD}(\phi) = \mathrm{OPD}(0)\cos(\phi)$.
- The varying OPD scale across the focal plane array leads to slightly different wavenumber scales for each detector in the focal plane array.
- Ground processing will be used to interpolate the radiance spectrum from each pixel onto a reference wavenumber scale.

Off-axis Effects



$OPD = x_1 - x_2 = X$

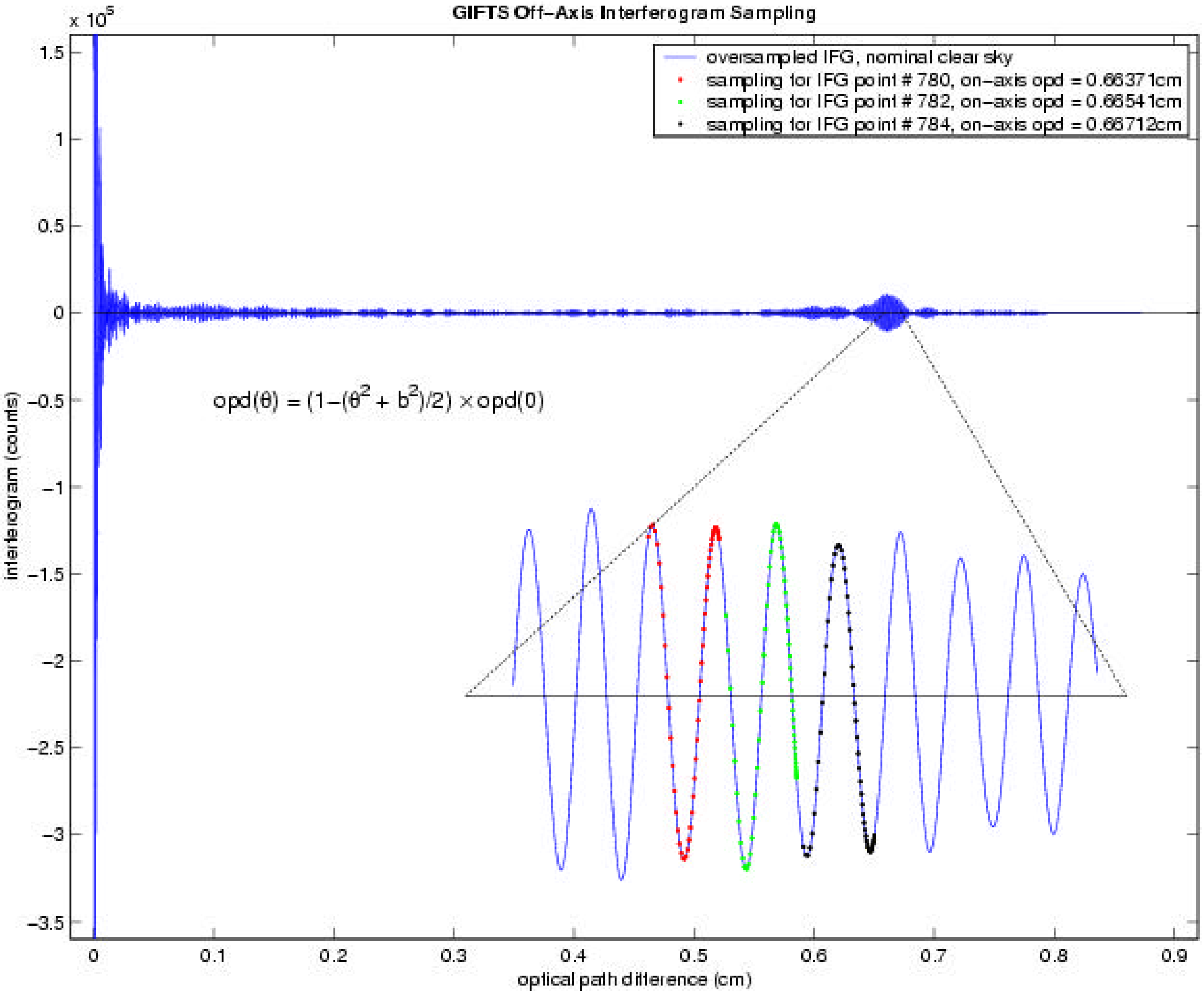
On axis beam

$OPD = x_1 - x_2 = X \cos \phi$

Off axis beam

from Fourier Transform Spectrometry, James W. Brault

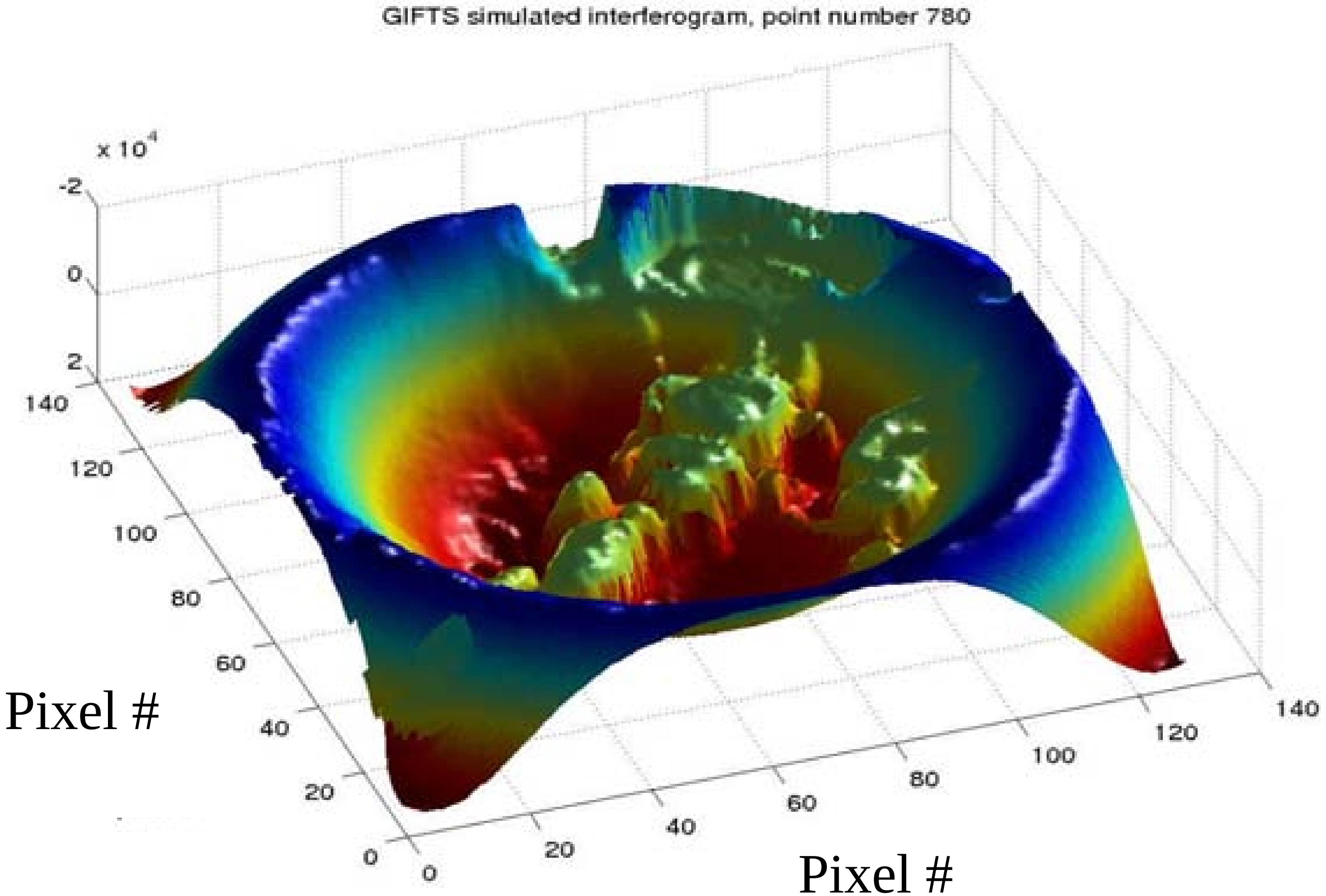
GIFTS Off-Axis Interferogram Sampling



All sampled points lie on the same continuous interferogram

GIFTS Data Cube Simulation

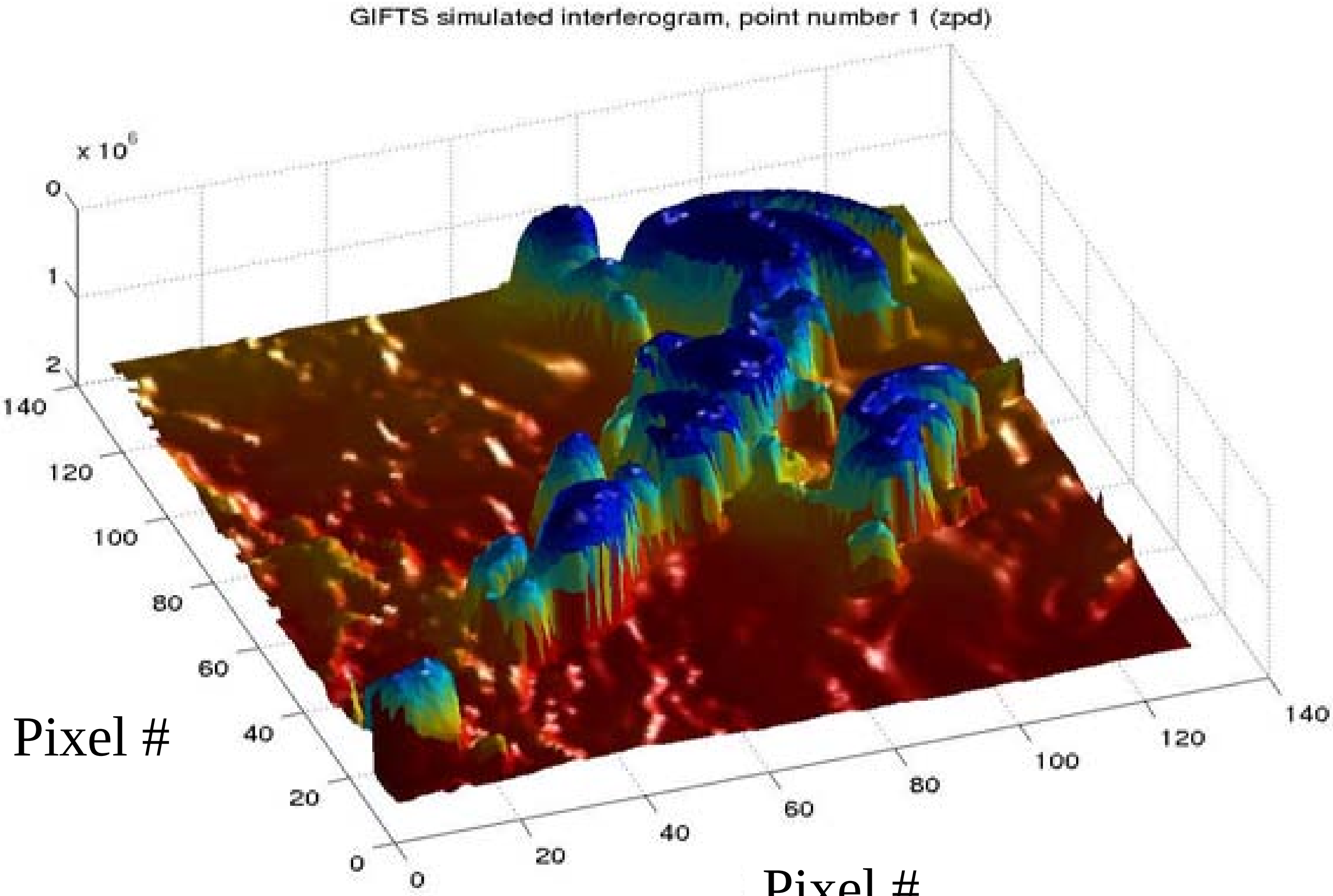
Image of interferogram point #780 (CO_2 resonance)



UW-SSEC

GIFTS Data Cube Simulation

Image of interferogram point #1 (ZPD)



Pixel #

Pixel #

Summary - Spectral Calibration

- Primary issues to be addressed by the spectral calibration are ILS changes and wavenumber scale “stretch” across the array.
- ILS effects are negligible because of the small angular size of individual pixels.
- The wavenumber scale stretch variation over the array is large, but is physically well understood and can easily be removed.
- The spectral calibration will be routinely monitored using atmospheric emission lines during flight.
- Real-time ground data processing will produce a continuous stream of spectrally calibrated radiance observations on a standard wavenumber scale.