A Perspective on US GOES Sounder Development: Some Key Requirements, the HES Sounder, and GIFTS

Hank Revercomb, Dave Tobin, Fred Best, Bob Knuteson, Joe Taylor
University of Wisconsin - Madison
Space Science and Engineering Center (SSEC)

3rd Advanced High Spectral Resolution Infrared Observations Workshop
Madison, Wisconsin, 26-28 April 2006

Topics

A. Introduction

B. Key Requirements
(Issues that arose when specifying HES)

C. Hyperspectral Environmental Suite (HES) Sounder Status

D. Geosynchronous Imaging Fourier Transform Spectrometer (GIFTS) Status

A. Introduction:
where GIFTS and HES fit in

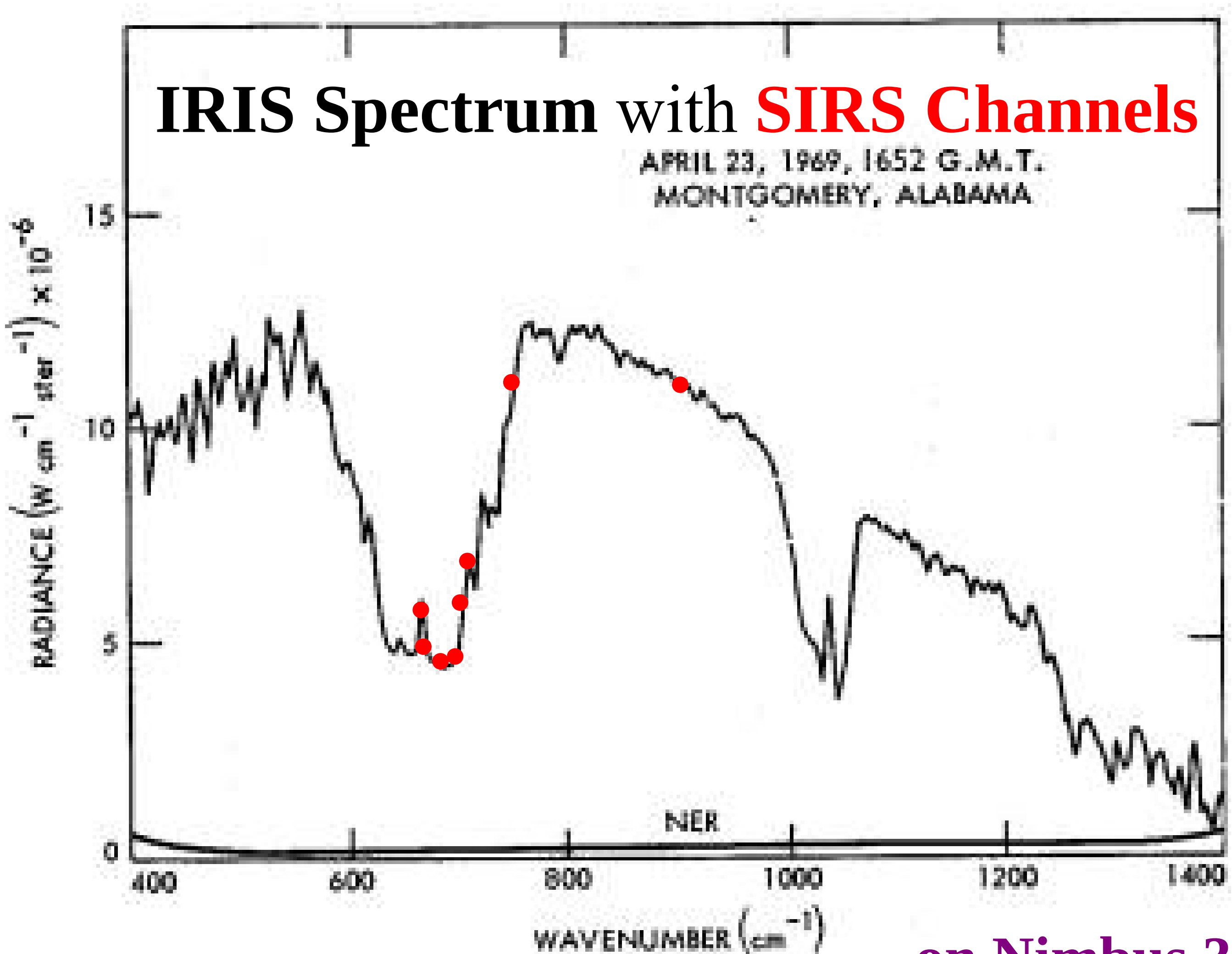
GIFTS represents the research/prototype demonstration that is the most efficient and effective way to realize a new operational system like HES. What GIFTS proves feasible should be incorporated into HES, no less.

(major new technological advances are very slow and expensive to make under the constraints of operational instrument development—"that it can be done" should be demonstrated in "research mode" before embarking on a full operational build)

The 1st Sounders (1969) were Spectrometers

IR Interferometer Spectrometer (**IRIS B**, Rudolf Hanel)

Satellite IR Spectrometer (**SIRS A**, David Wark)



on Nimbus 3 & 4

Temperature & Water Vapor IR Sounder Staircase

Spectral Resolving Power ($\lambda/\Delta\lambda$)

~Resolving Power @ 14 μm

- **(1200)** ***HES, GOES-R*** (2013-)
- **(1200)** ***GIFTS*** (2009 ?)
- **(1200/2800)** **CrIS / IASI** (2006-)

- **(1200)** **AIRS** (2002-)
- **(30)** ***GOES Sounder*** (1994-) **– (3-Axis)**
- **(2000)** ***HIS*** (1986-1998)
- **(30)** ***VAS*** (1980-) **–1st Geo Sounder (Spin-Scan)**
- **(30)** **ITPR,VTPR** (1972) / **HIRS** (1978-)
- **(150-300)** **IRIS / SIRS** (1969-70) **–1st Sounders**

17 yrs

17 yrs

BLUE = Leo ***Purple = Geo*** ***Red = Aircraft***

Temperature & Water Vapor IR Sounder Staircase

~Spatial Footprint (km)

(5-10) ***HES, GOES-R*** (2013-)

→(4) ***GIFTS*** (2009 ?)

(14/12) **CrIS / IASI** (2006-)

(14) **AIRS** (2002-)

(8) ***GOES Sounder*** (1994-) **– (3-Axis)**

17 yrs

(2) ***HIS*** (1986-1998)

(7-14) ***VAS*** (1980-) **–1st Geo Sounder (Spin-Scan)**

17 yrs

(30/20-10) **ITPR,VTPR** (1972) **/ HIRS** (1978-)

(>100/230) **IRIS / SIRS** (1969-70) **–1st Sounders**

nadir only

BLUE = Leo ***Purple = Geo*** ***Red = Aircraft***

B. Key Requirements

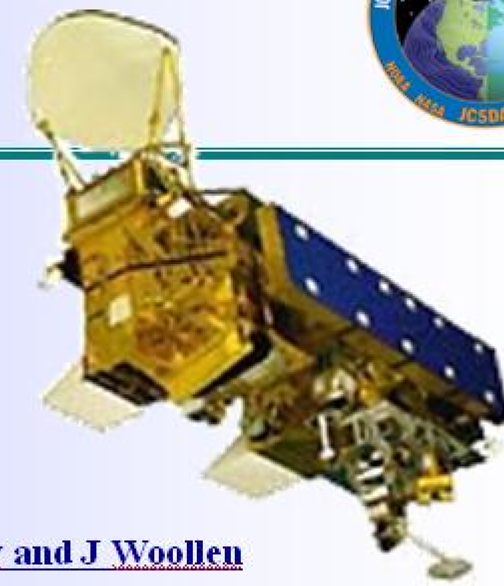
(Issues that arose when specifying HES)

As for GIFTS, Highest priority should be water vapor with

1. High vertical resolution,
2. Small imaging footprint for feature tracking and handling clouds (<5 km)
3. Rapid time sequence capability for key regions (2000x2000 km every 5 minutes)

But, in planning for the next 20-30 years, we really should be working to optimize the value for the full range of anticipated uses and to provide potential for growth

Also, should include operational flexibility of spectral resolution and coverage rates, like GIFTS



AIRS Data Assimilation

J. Le Marshall, J. Jung, J. Derber, R. Treadon, S.J. Lord,
M. Goldberg, W. Wolf and H-S Liu, J. Joiner T. Zapotocny and J Woollen

Positive forecast Impact of High Resolution IR reinforces value of information content

1-31 January 2004

Used operational GFS system as Control

Used Operational GFS system Plus Enhanced AIRS Processing as Experimental System

Clear Positive Impact

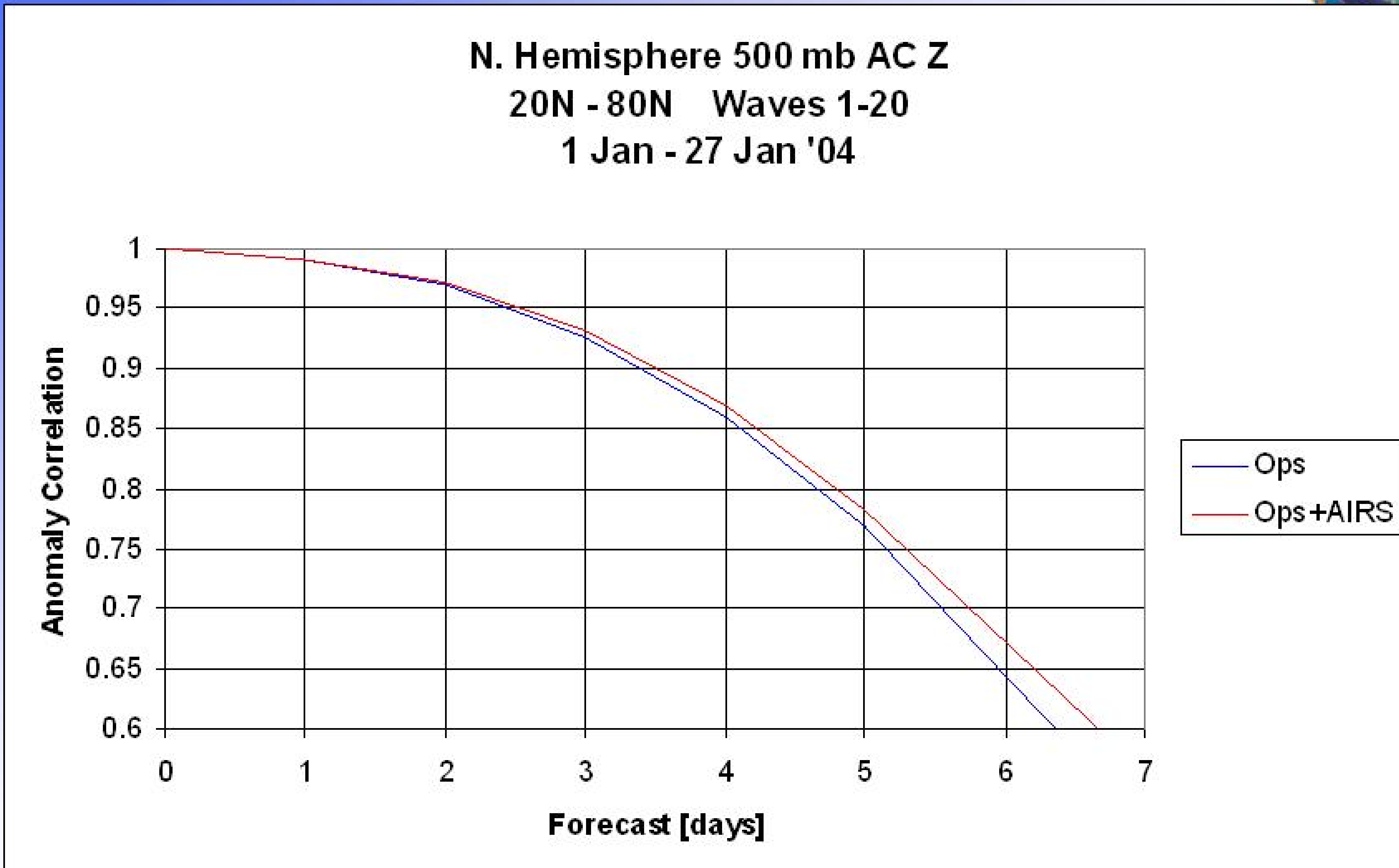
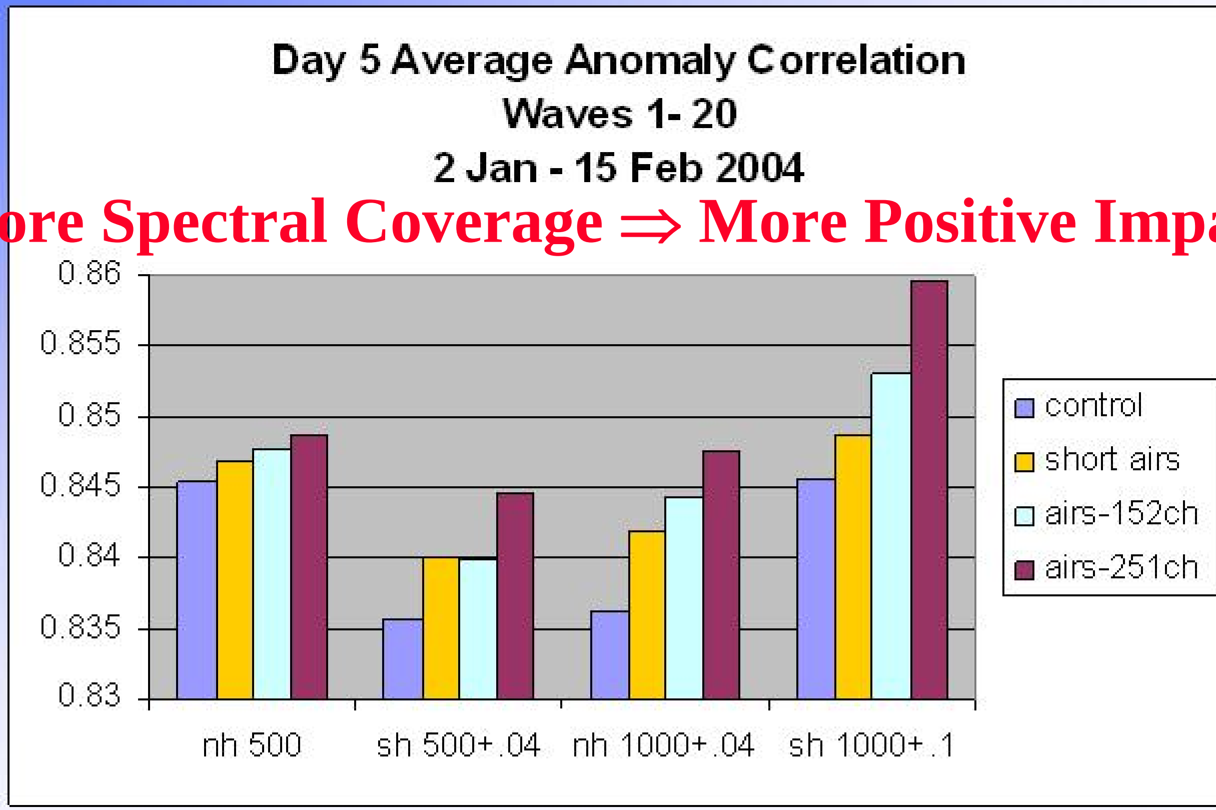


Figure 3(b). 500hPa Z Anomaly Correlations for the GFS with (Ops.+AIRS) and without (Ops.) AIRS data, Northern hemisphere, January 2004

Impact of Spectral Coverage



More Spectral Coverage ⇒ More Positive Impact

1000 and 500hPa Z Anomaly Correlations for the GFS for the Control, Short (using 115 AIRS shortwave channels), airs-152ch using 152 out of the 281 channels available for real time NWP and airs-251ch using 251 out of the 281 channels available for real time NWP, Northern and Southern Hemisphere, January/February, 2004

International TOVS Study Conference - 14
Advanced Sounders Thresholds

			Polar		Geostationary			
Channel cm^{-1}	**$\delta\nu$ cm^{-1}**	**Purpose**	P	δS[1] km	**P**	**δt[2] min**	**δS[3] km**	**Remarks**
660-680	0.6	Strat. Temp.	1	100	-	-	-	Polar satellite only
680-800	0.6	Trop. Temp	1	15	1	30	5	Fundamental Band[4]
800-1000	0.6	T_s, H_2O, Cld	1	15	1	15	5	Fundamental Band[5] Cld, Sfc, T/Emis. & H_2O
1000-1100	0.6	O_3	1	15	3	30	5	O_3, Stratospheric Wind
1100-1590	1.2	T_s, H_2O, Aerosol/Dust	1,2	15	2,1	15	5	Water Vapor Flux Trop. Wind Profiles[6]
1590-2000	1.2	H_2O, T_s, Cld	2,1	15	1,2	15	5	Water Vapor Flux Trop. Wind Profiles[6]
2000-2200	0.6	CO, T_s, Cld	3	15	2	60	5	Trace Gas/Air Quality[7]
2200-2250	2.5	Trop. Temp	2	15	2	15	5	Clear Ocean Day and Land/Ocean Night Utility[8]
2250-2390	2.5	Strat. Temp.	4	100	-	-	-	Night-time Utility[8]
2386-2400	2.5[9]	Trop. Temp	4	15	-	-	-	Night-time Utility[8]
2400-2700	2.5[10]	T_s, Cloud	3	15	-	-	-	Clear ocean and Night Land Utility[8]

Table definitions: $\delta\nu$ (spectral resolution, unapodized for the case of an FTS, assuming an instrument self apodization of less than 5%), P (priority), δt (refresh rate), δS (footprint linear resolution). The values given are the threshold requirements with objectives being better by as much as practical from a technology and cost point of view. Priority 1 measurements are required to fulfill advanced sounding primary objectives.

15 micron CO_2 & LW window should be considered fundamental bands

Key Spectral Requirements: a perspective

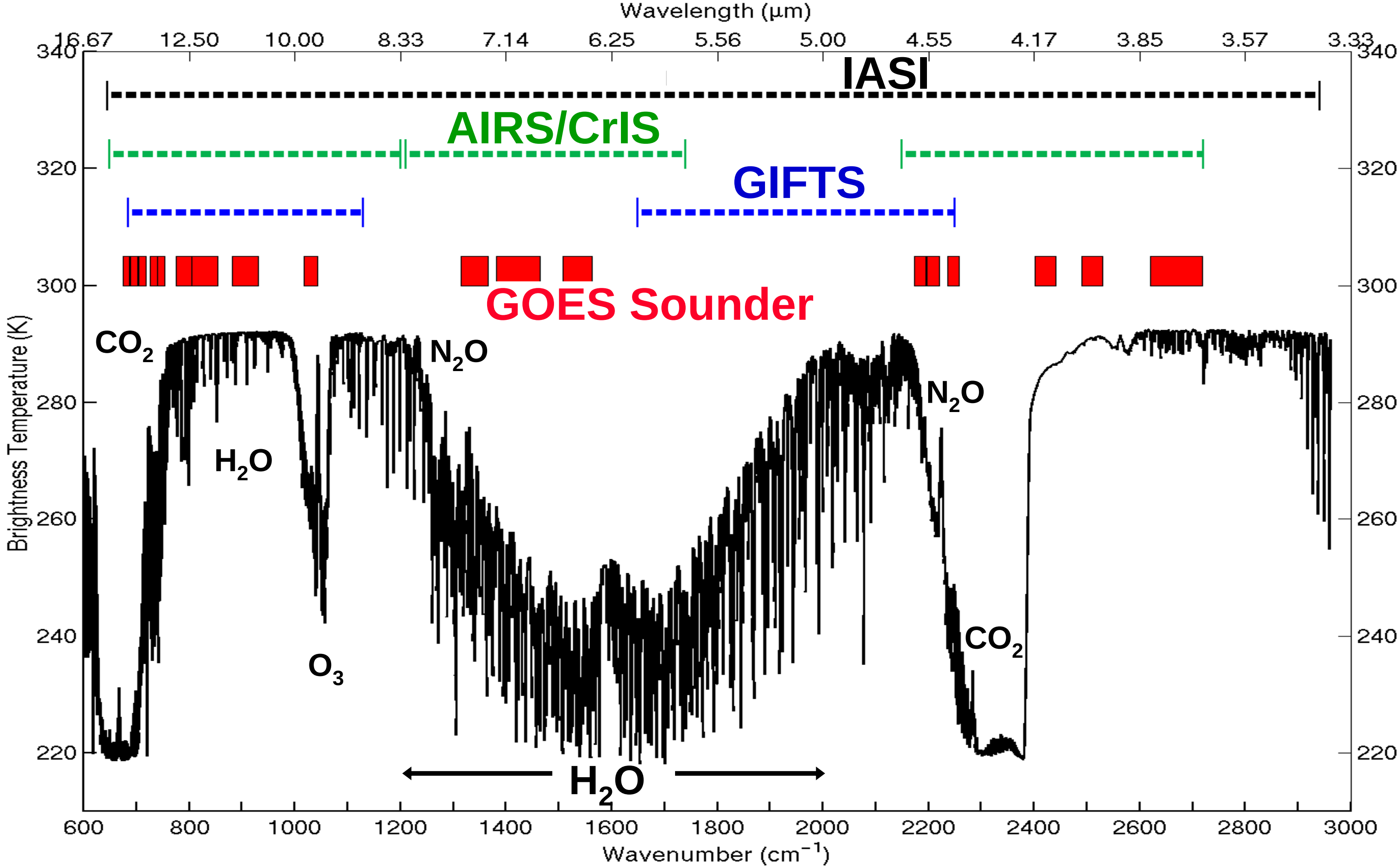
1) Spectral Coverage Considerations
2) Spectral Resolution: FTS/Grating Equivalency
3) Spectral Calibration Knowledge
4) Spectral Instrument Line Shape (ILS) Knowledge and Stability
5) Spectral Sampling, Stability and Scale Standardization

1.) Spectral Coverage: Broad Spectral Coverage, not just High Resolution, is Key

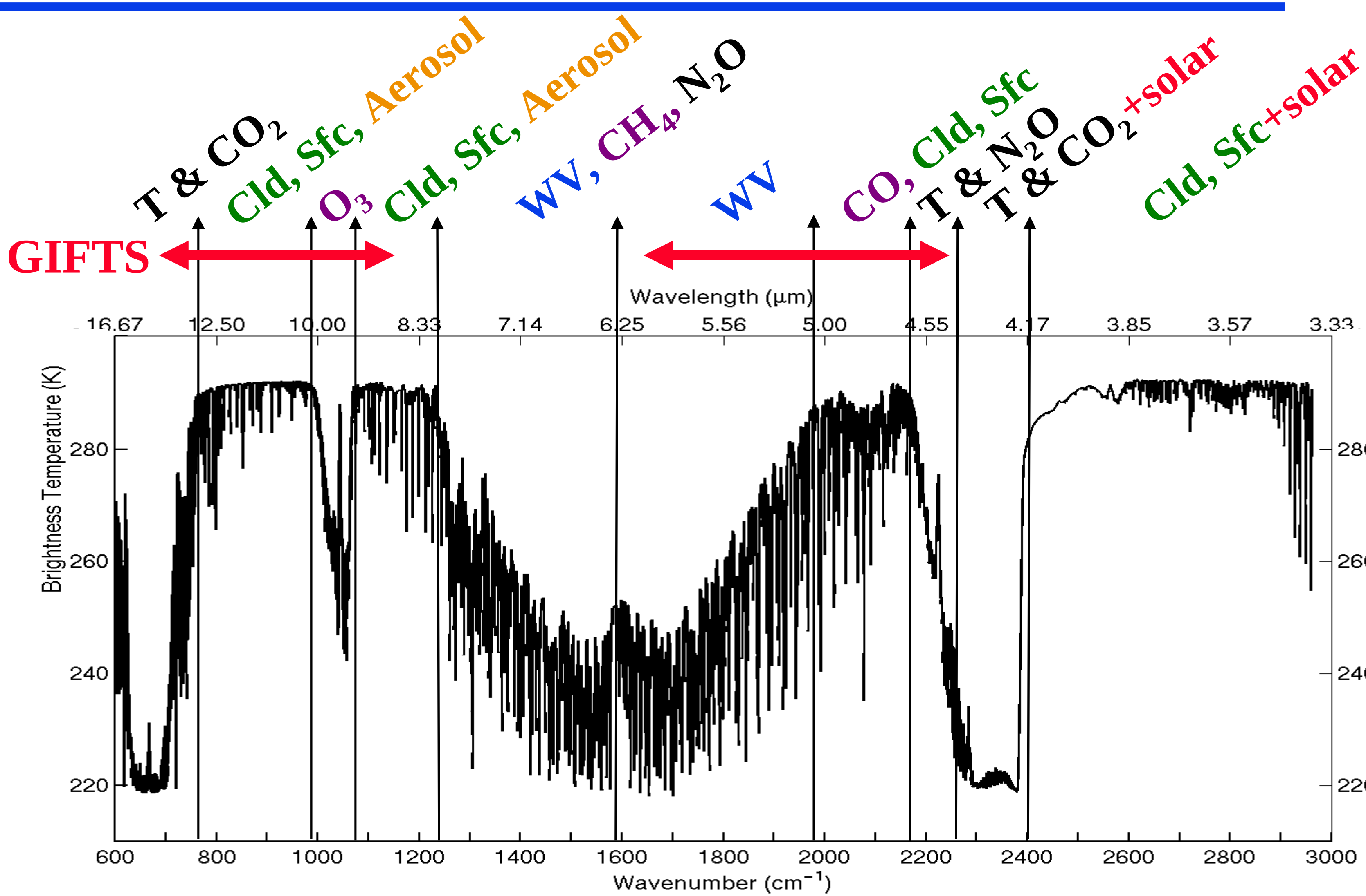
- **Lower Effective Noise for Sounding (based on redundancy of vertical information) that along with spectral resolution improves vertical resolution**
- **Unique information on cloud phase and micro-physical properties, surface emissivity, and trace gases**
- **Allows absolute Calibration Transfer to improve accuracy and consistency among different platforms**
  → e.g. AIRS applied to MODIS

New Era: Spaceborne High-resolution IR

AIRS/IASI/CrIS (LEO) to GIFTS/HES (GEO)



Key Spectral Regions: GIFTS Coverage or Equivalent should be the minimum for future GEO systems

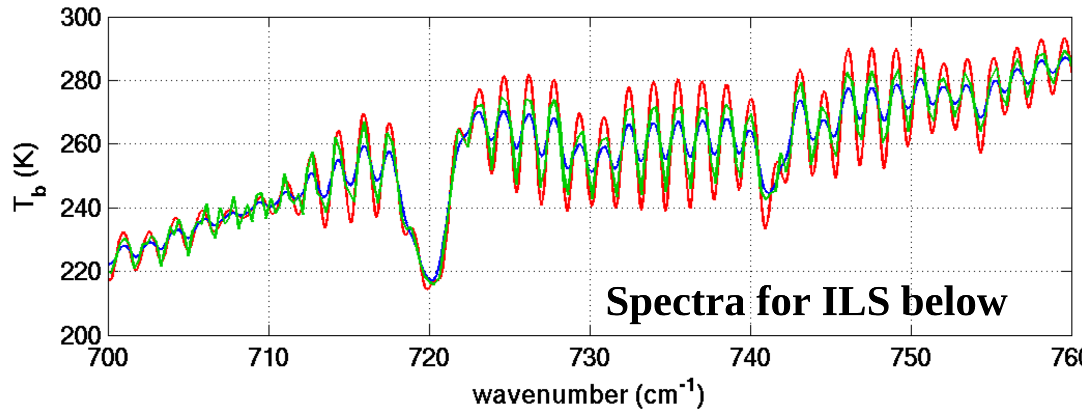


2.) Spectral Resolution:
FTS/Grating Equivalency

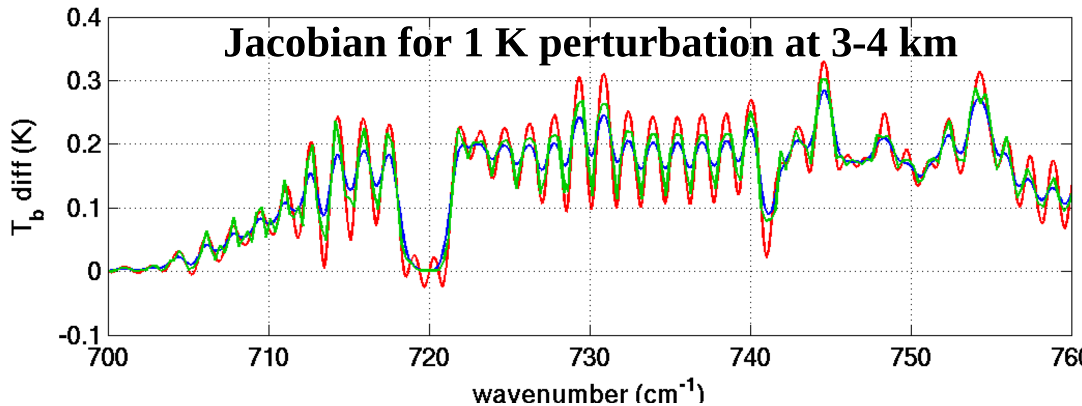
- **Criterion:**
  Jacobian amplitudes (p-p) that are comparable, assuming equivalent noise performance
- **FTS Side-lobes: Not an issue for spectral coverage that is locally contiguous [key is knowing the Instrument Line Shape (ILS), and that is the known from 1st principles for the FTS—must be carefully measured in the laboratory for the grating]**
- **Suggested equivalency:**
  Grating half-width at half-maximum (HWHM) needs to be ≤ to the FTS unapodized resolution
  [$\Delta\nu_{ua}$ = 1/(2*max delay)]

2.) Spectral Resolution:
Long-wave Example

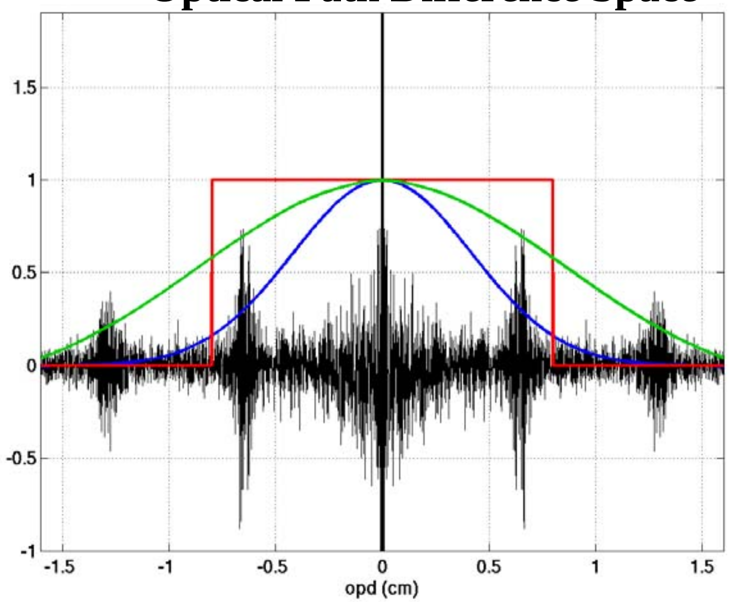
$\Delta\nu$=0.625 cm^{-1}

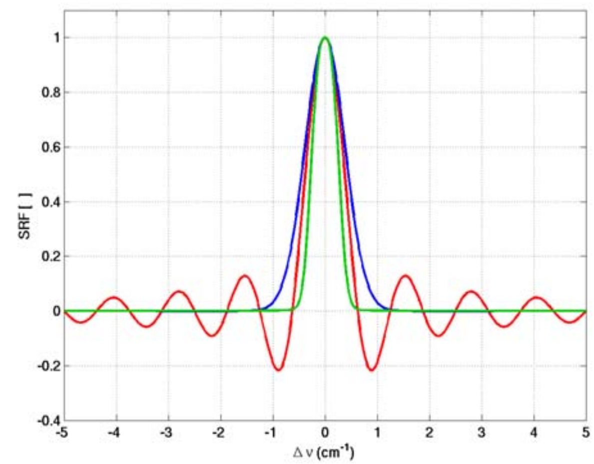


Grating HWHM should be $\leq \Delta\nu_{ua}$ = 1/(2*max delay)]



ILS Equivalent in Optical Path Difference Space





ILS

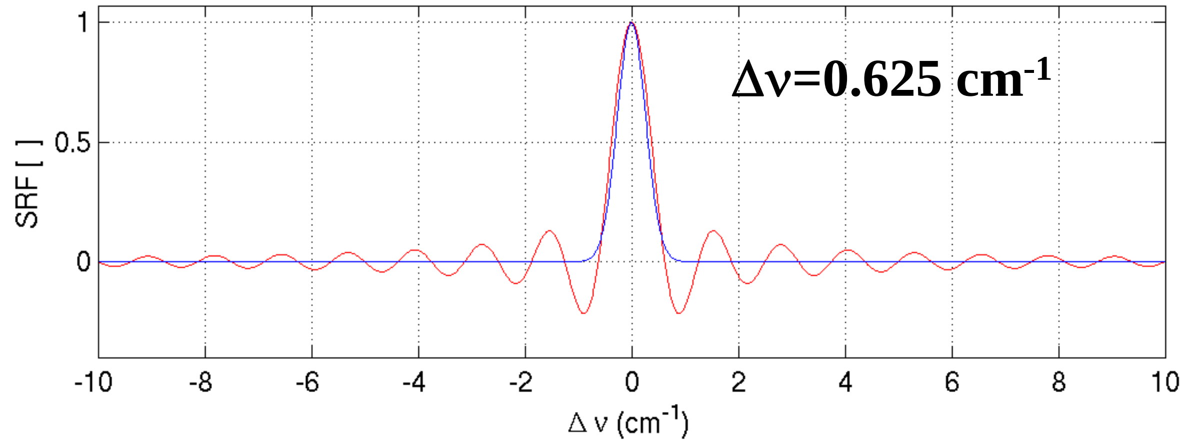
FTS

Grating HWHM

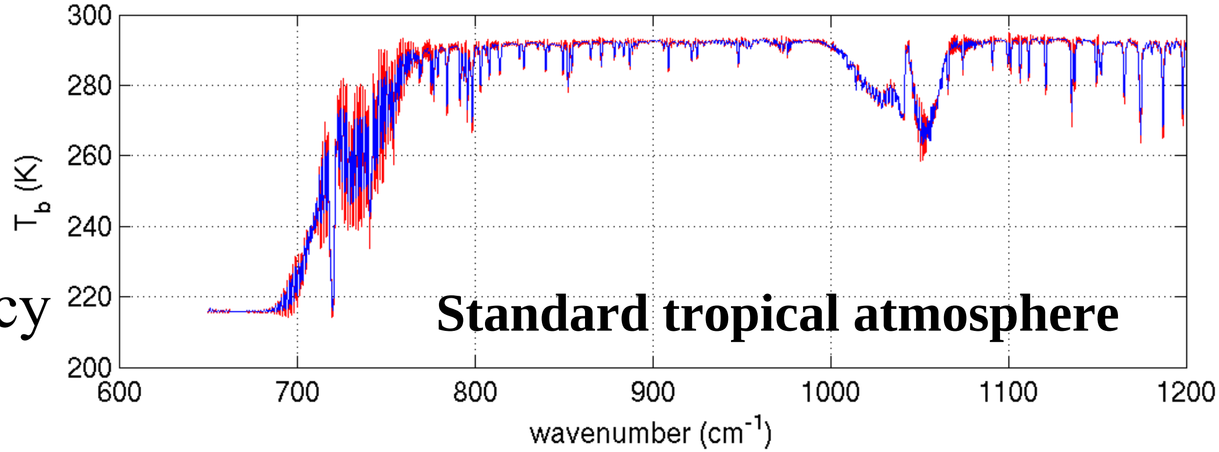
= $\Delta\nu_{ua}$

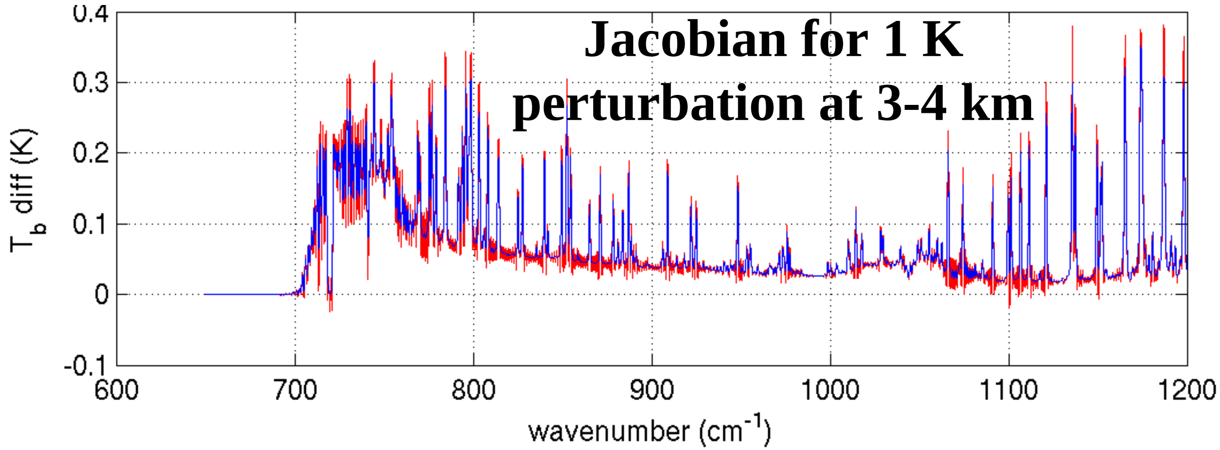
= 1.43 $\Delta\nu_{ua}$

2.) Spectral Resolution:
Long-wave

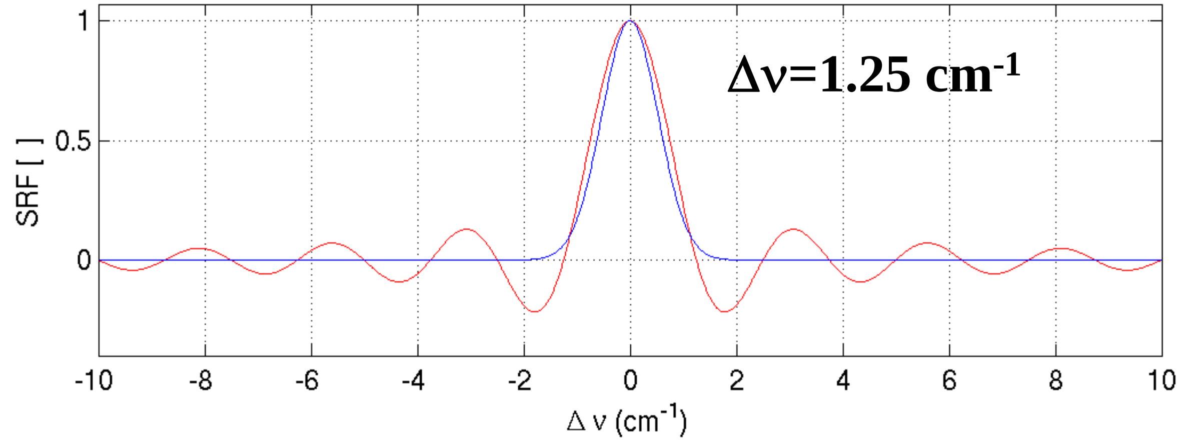


FTS amplitudes are a bit larger than the grating everywhere with the recommended equivalency

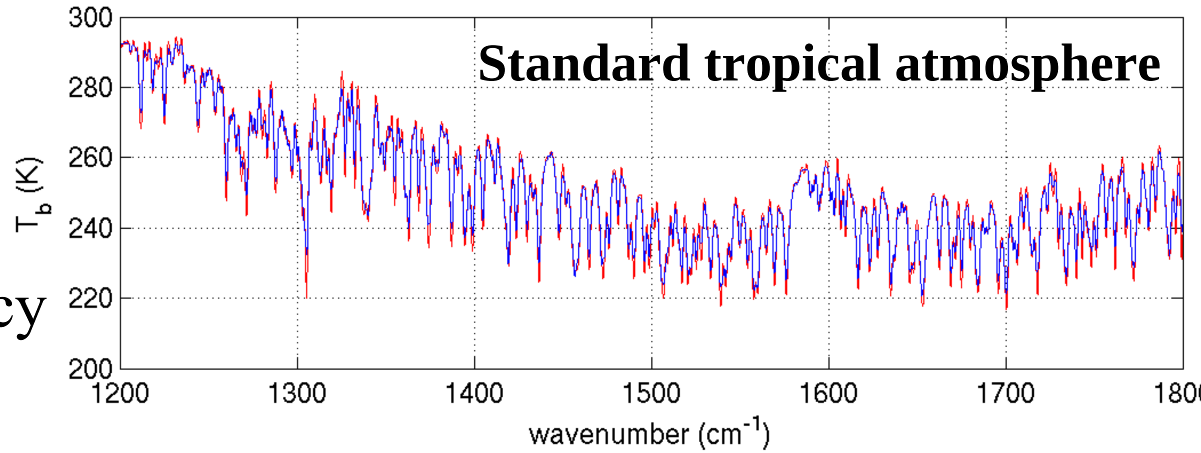


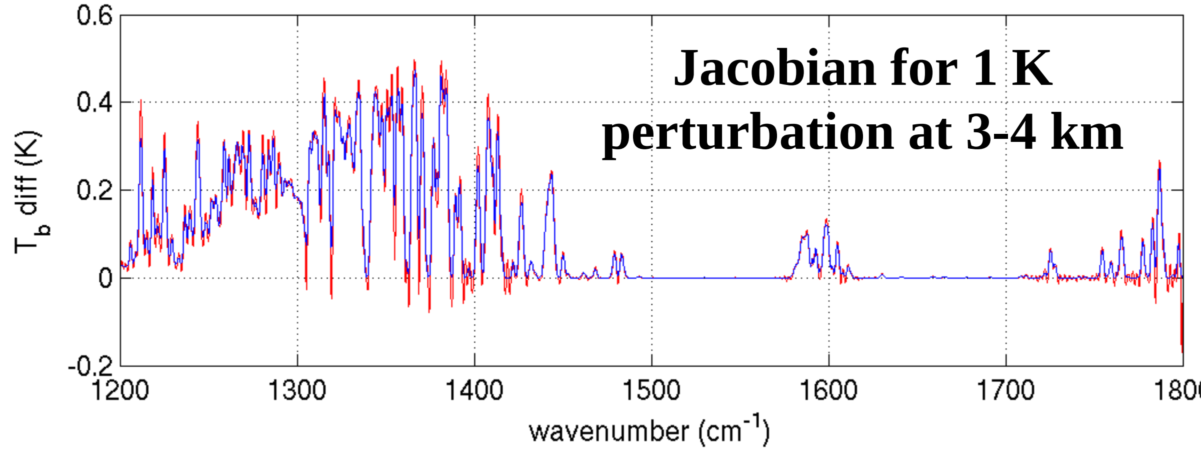


2.) Spectral Resolution: Mid-wave

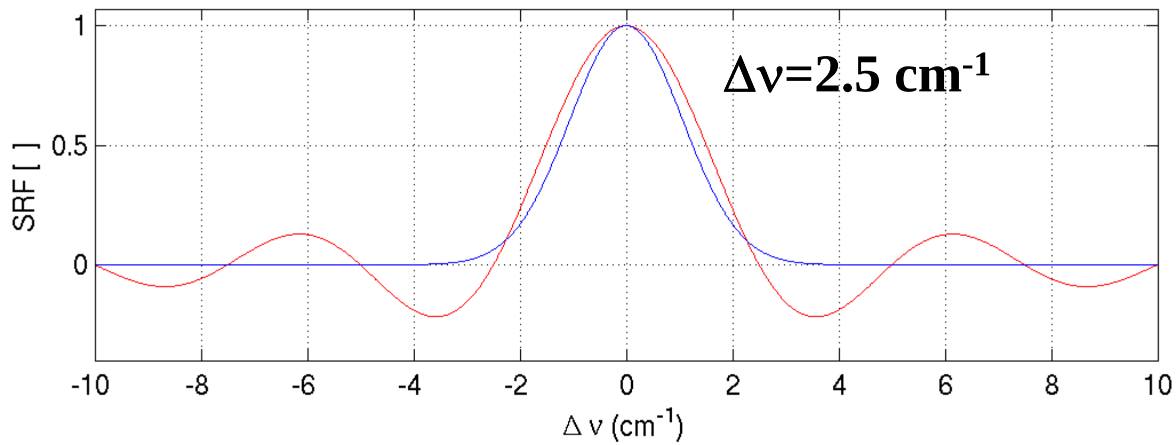


FTS amplitudes are a bit larger than the grating everywhere with the recommended equivalency

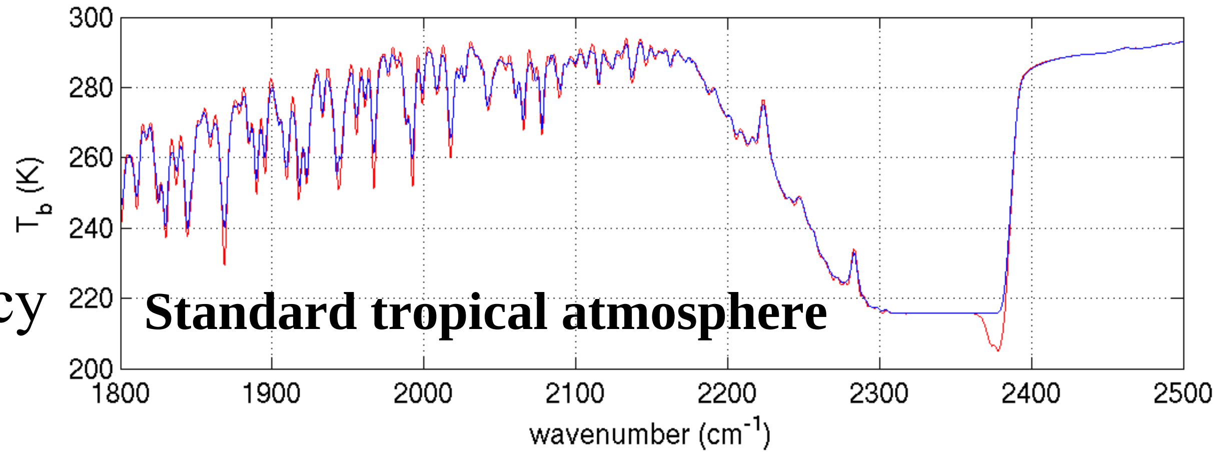


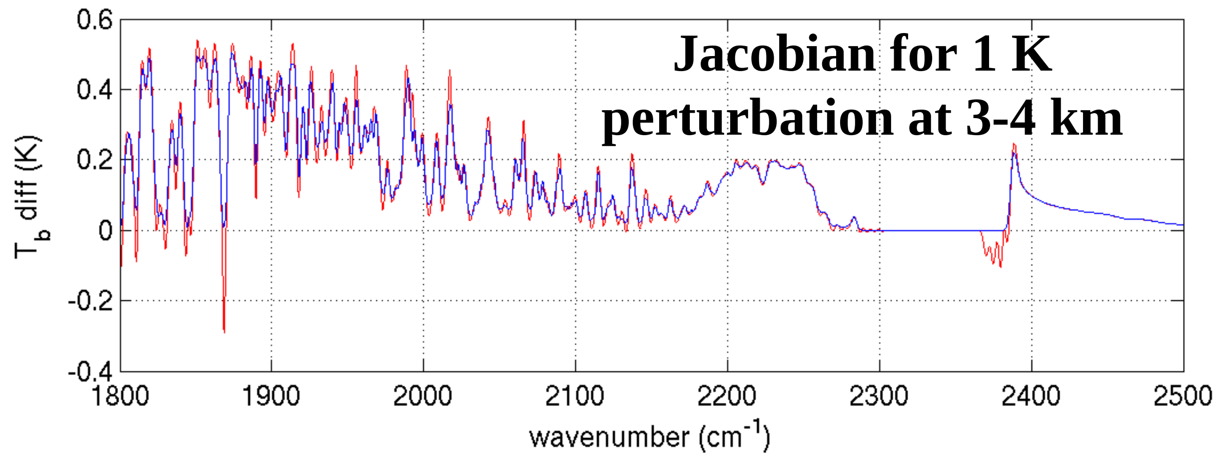


2.) Spectral Resolution:
Short-wave



FTS amplitudes are a bit larger than the grating everywhere with the recommended equivalency





3.) Spectral Calibration Knowledge

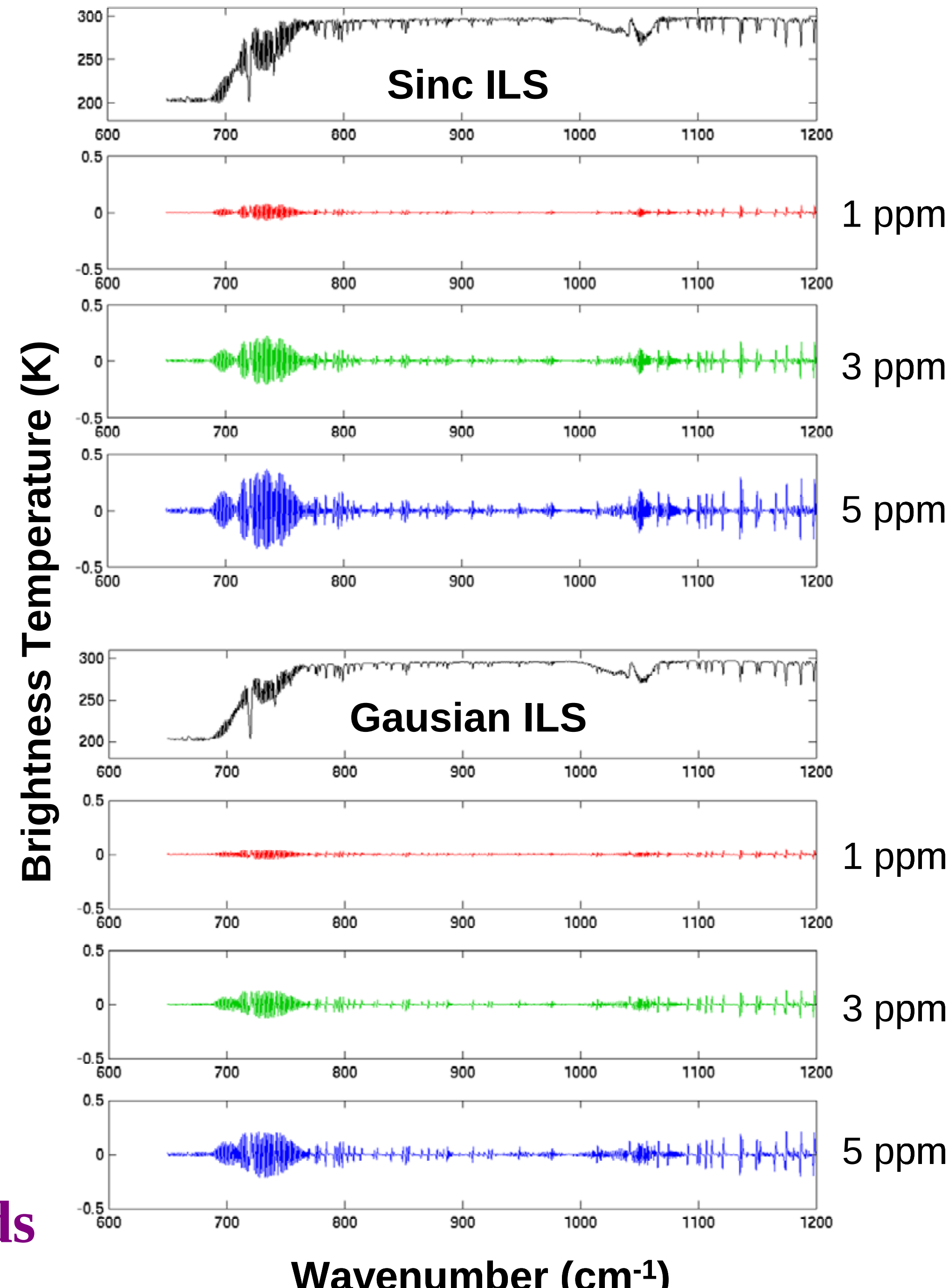
- **Channel Centers need to be known very accurately, <u>with a goal of less than 1 ppm</u>**
- **This is tighter than originally required of AIRS and CrIS (1% of $\Delta\nu = \nu/1200$ implies 8 ppm), although both can meet the tighter goal**
- **Other considerations related to ILS and ultimate spectral scales follow**

3.) Spectral Calibration:
Long-wave, $\Delta\nu$=0.625 cm^{-1}

T_b errors for labeled spectral shift error in ppm

Note that 5 ppm is equivalent to 0.6 % of $\Delta\nu$ at 750 cm^{-1}

Also, note that the larger errors for the sinc ILS are consistent with its larger absorption line amplitudes and sounding sensitivity



Recommend < 3 ppm or 0.3% of $\Delta\nu$ for sounding bands

3.) Spectral Calibration:

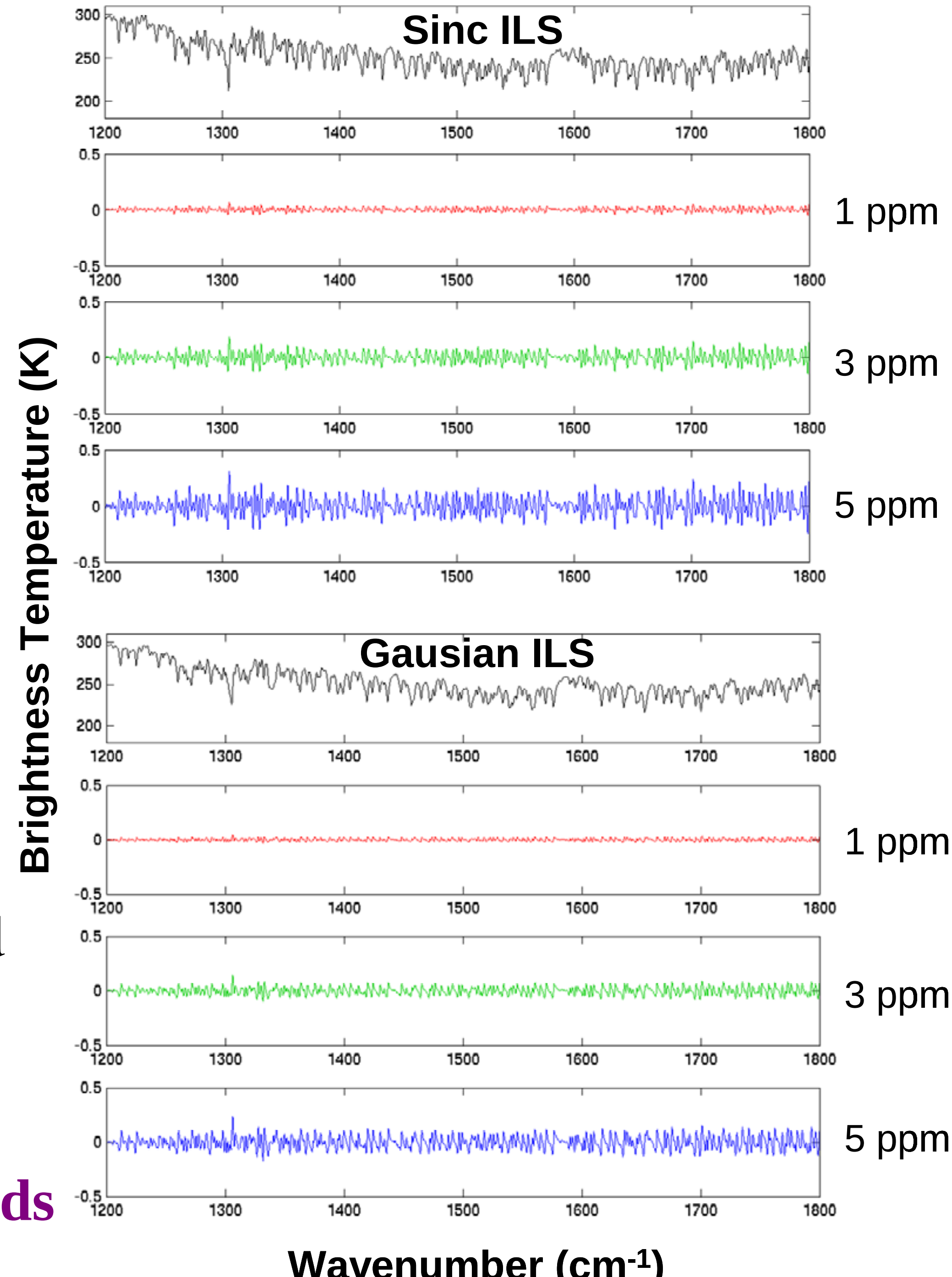
Mid-wave, $\Delta\nu$=1.25 cm^{-1}

T_b errors for labeled spectral shift error in ppm

Note that 5 ppm is equivalent to 0.6 % of $\Delta\nu$ at 1550 cm^{-1}

Also, note that the larger errors for the sinc ILS are consistent with its larger absorption line amplitudes and sounding sensitivity

Recommend < 3 ppm or 0.3% of $\Delta\nu$ for sounding bands



3.) Spectral Calibration:

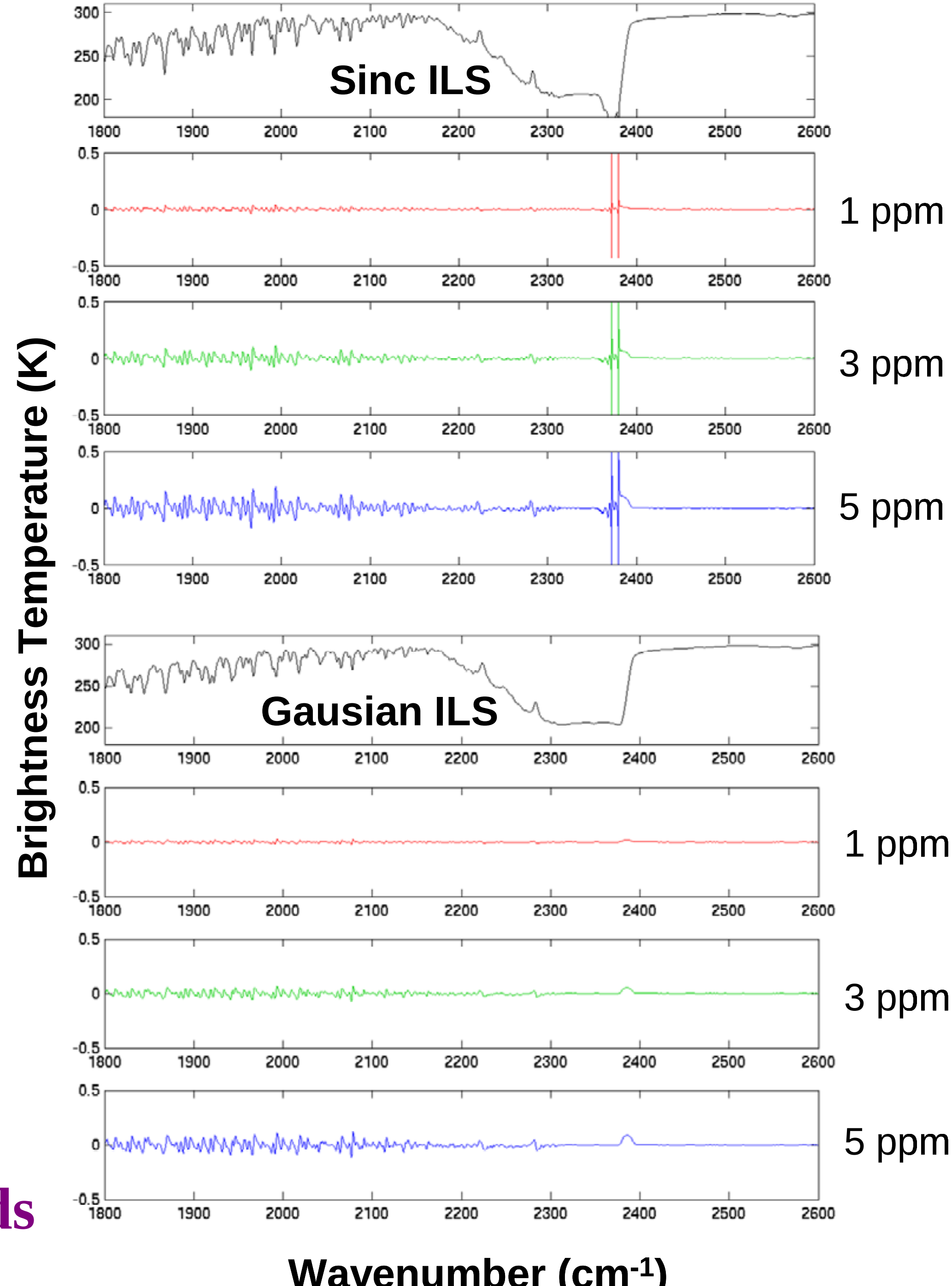
Short-wave, $\Delta\nu$=2.5 cm^{-1}

T_b errors for labeled spectral shift error in ppm

Note that 5 ppm is equivalent to 0.45 % of $\Delta\nu$ at 2250 cm^{-1}

Also, note that the larger errors for the sinc ILS are consistent with its larger absorption line amplitudes and sounding sensitivity

Recommend < 3 ppm or 0.3% of $\Delta\nu$ for sounding bands



4.) Spectral Instrument Line Shape (ILS) Knowledge and Stability

Recommend that errors in calculated spectra arising from ILS uncertainty and stability errors should be less than errors allowed from spectral channel center uncertainty

Note: This statement could be converted into testable limits on the knowledge and stability of ILS width and integrated wing contributions as was done for AIRS

5.) Spectral Sampling, Stability and Scale Standardization

Spectral sampling needs to be adequate to allow spectra with <u>common channel centers</u> to be produced for all pixels in the FOR to within less than the spectral calibration requirements stated above.

Spectral stability or sampling shall be such that the channel centers can be mapped onto one (or a small number of) <u>standard channel center grids</u> with errors that do not exceed the spectral calibration requirements stated above.

[Nyquist sampling is direct way to meet this need]

C. HES Sounder Status

- **Three industries are competing to build HES:**
  Ball, BAE, and ITT each have $20 M contracts to chose between an FTS and a grating approach and to perform an advanced phase A design (my description)
- **Common requirements for FTS and grating:**
  Strong attempt to limit requirements to those perceived to be achievable by both approaches.
- **Spectral coverage trades under consideration:**
  Options for spectral coverage are being explored to minimize complexity, risk and cost (and performance)
- **Process is just past mid-way:**
  A delta-Mid Term Review is planned for mid-May
  A winner is expected to be chosen next year

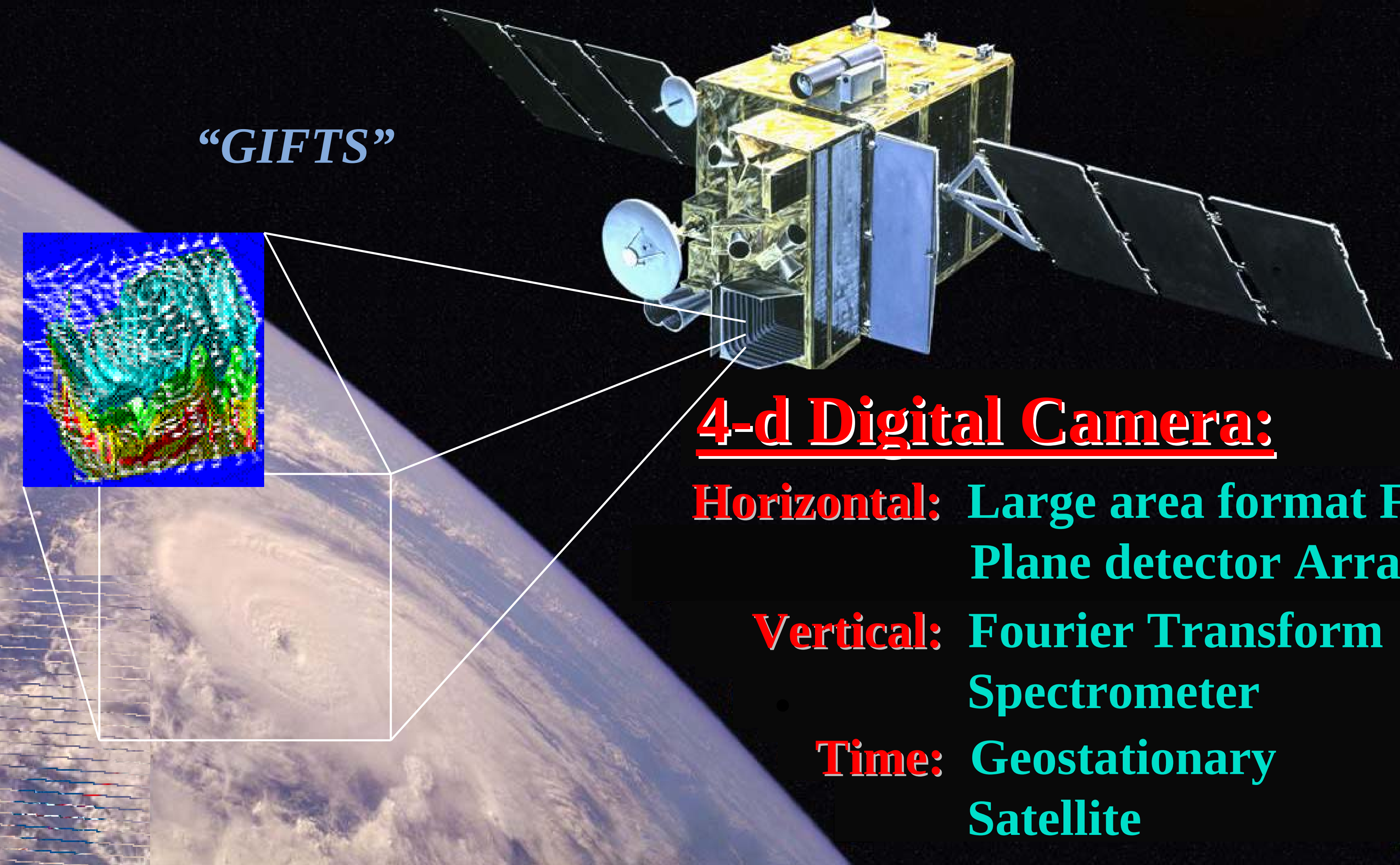
D. GIFTS Status

1. General Concept
2. Instrument Summary
3. Performance

Geostationary Imaging Fourier Transform Spectrometer

New Technology for Atmospheric Temperature, Moisture, Chemistry, &
Winds

"GIFTS"



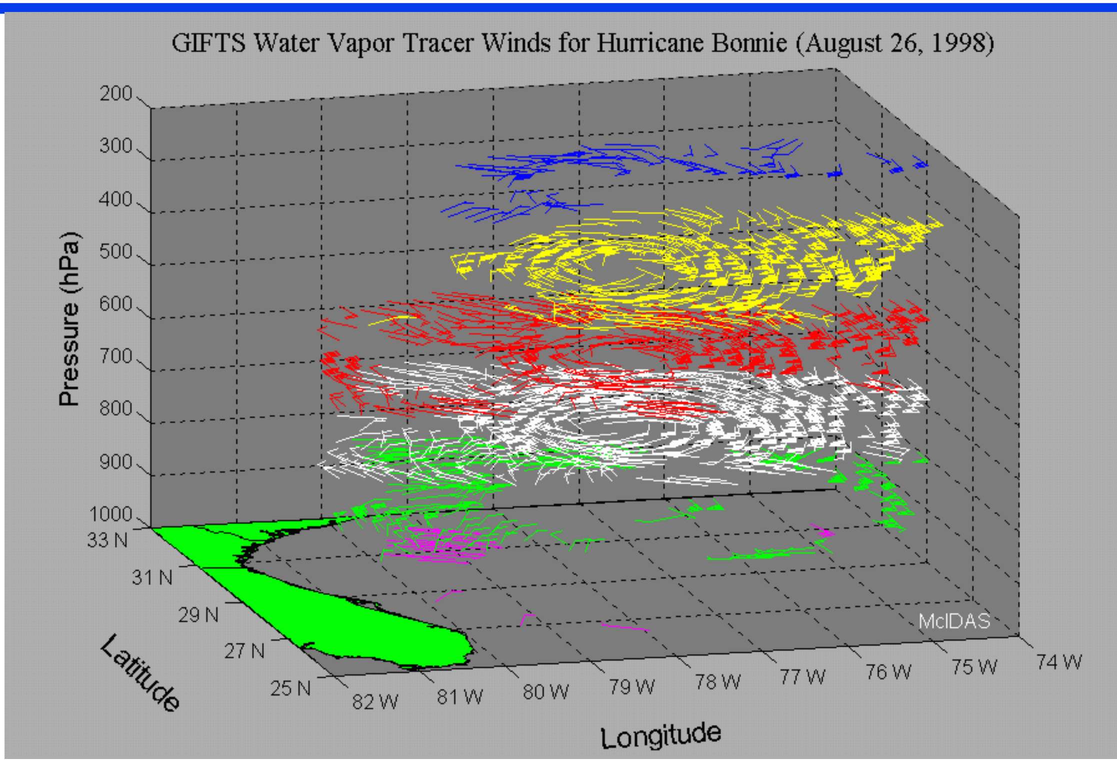
4-d Digital Camera:

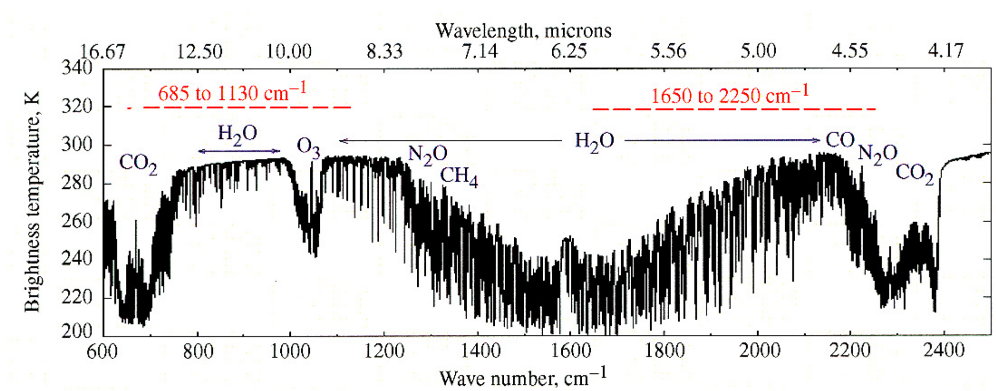
Horizontal: Large area format Focal Plane detector Arrays

Vertical: Fourier Transform Spectrometer

Time: Geostationary Satellite

GIFTS Winds from Water Vapor Retrieval Tracking





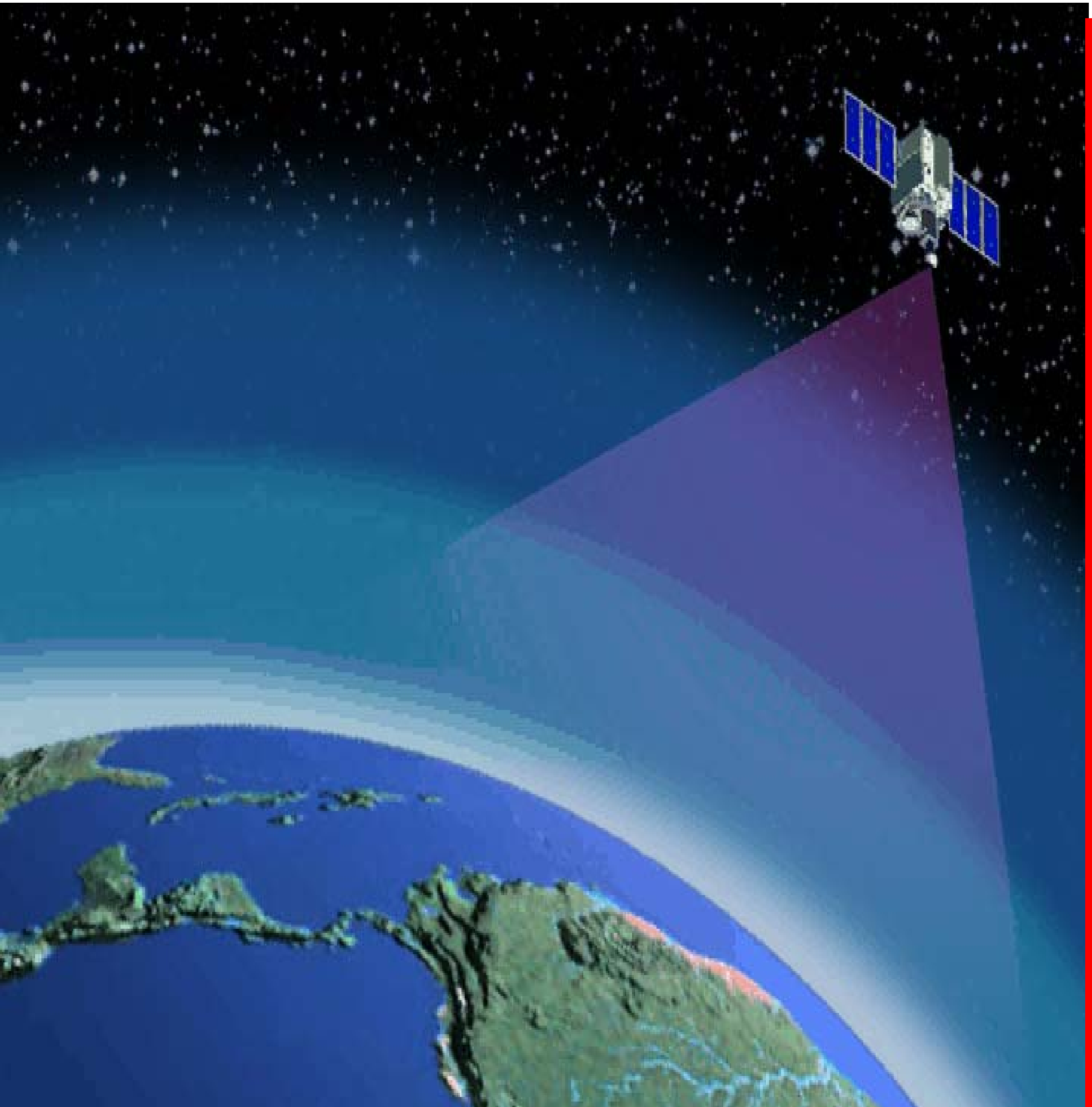
16,000 Temperature, Humidity & Trace Gas Profiles in 10 sec

Global Sounding in < 10 min

High resolution Sounding: 6000 x 6000 km in 30 min

Dense Wind Observations, tracked from Water Vapor Soundings

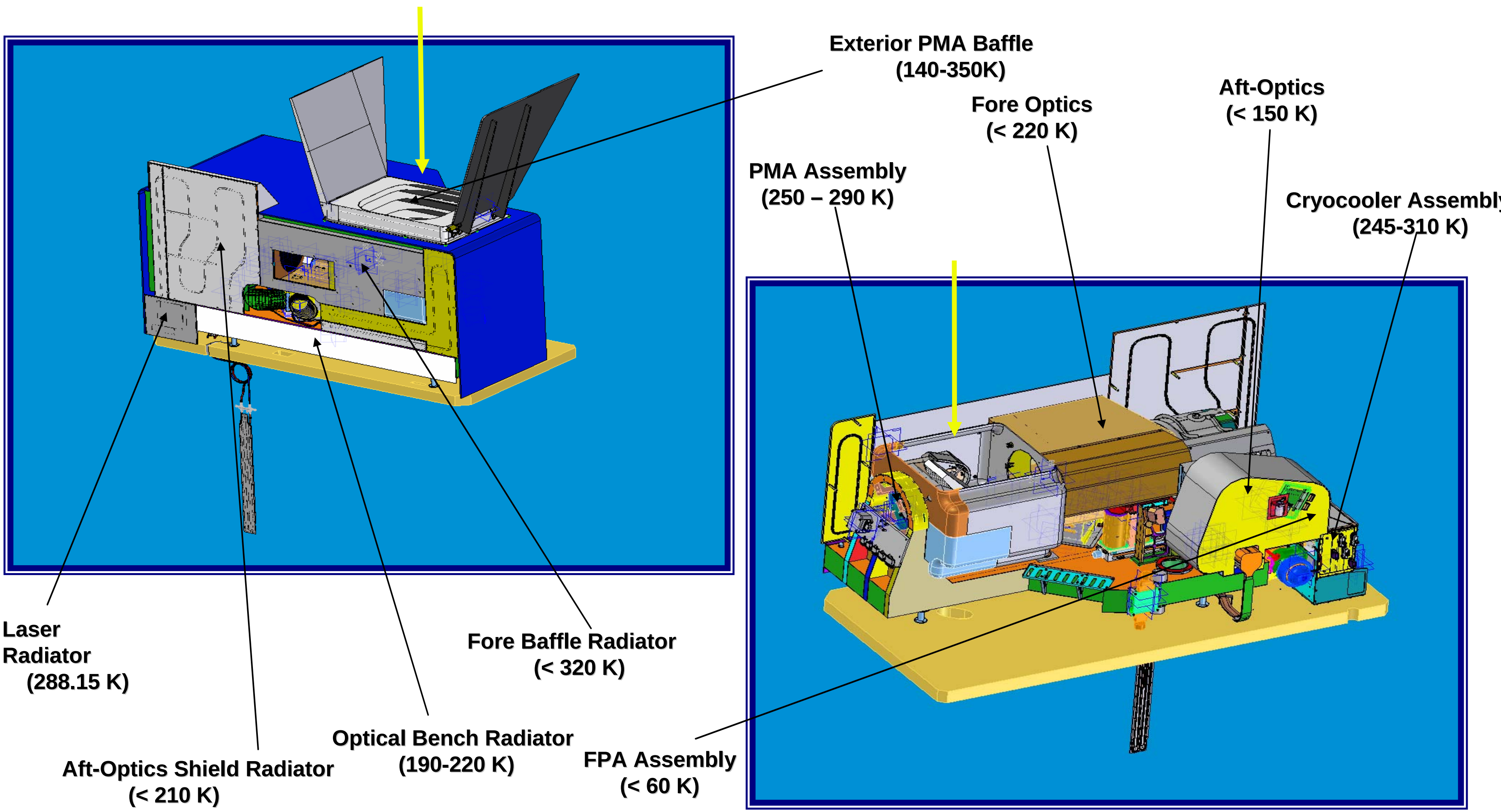
GIFTS Sampling Characteristics



- Two 128x 128 Infrared focal plane detector arrays with 4 km footprint size
- A 512 x 512 Visible focal plane detector arrays with 1 km footprint size
- Field of Regard 512 km x 512 km at satellite sub-point
- Eleven second full spectral resolution integration time per Field of Regard
- ~ 80,000 Atmospheric Soundings every minute

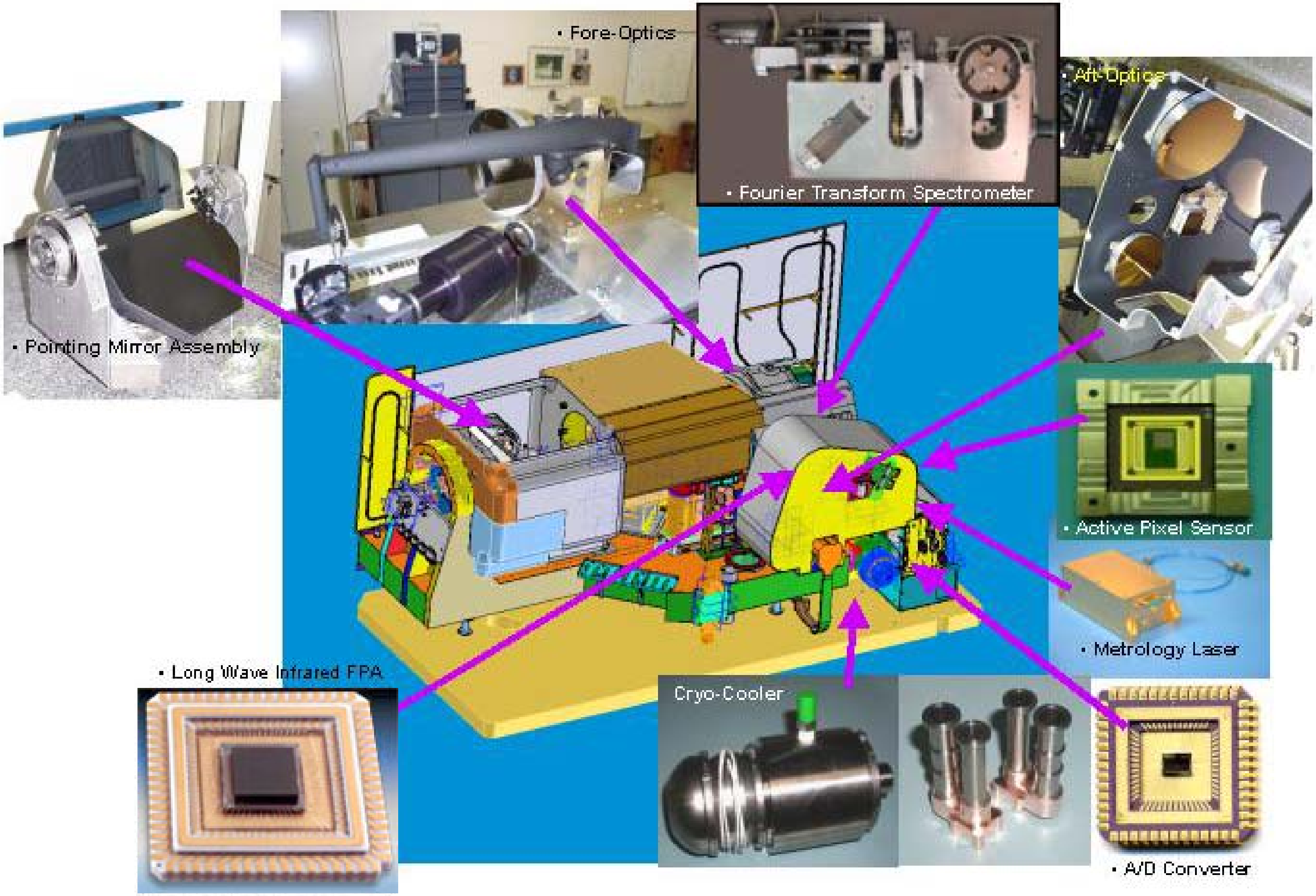
D. GIFTS Status:
Instrument Summary

GIFTS Sensor Module on S/C Nadir Deck



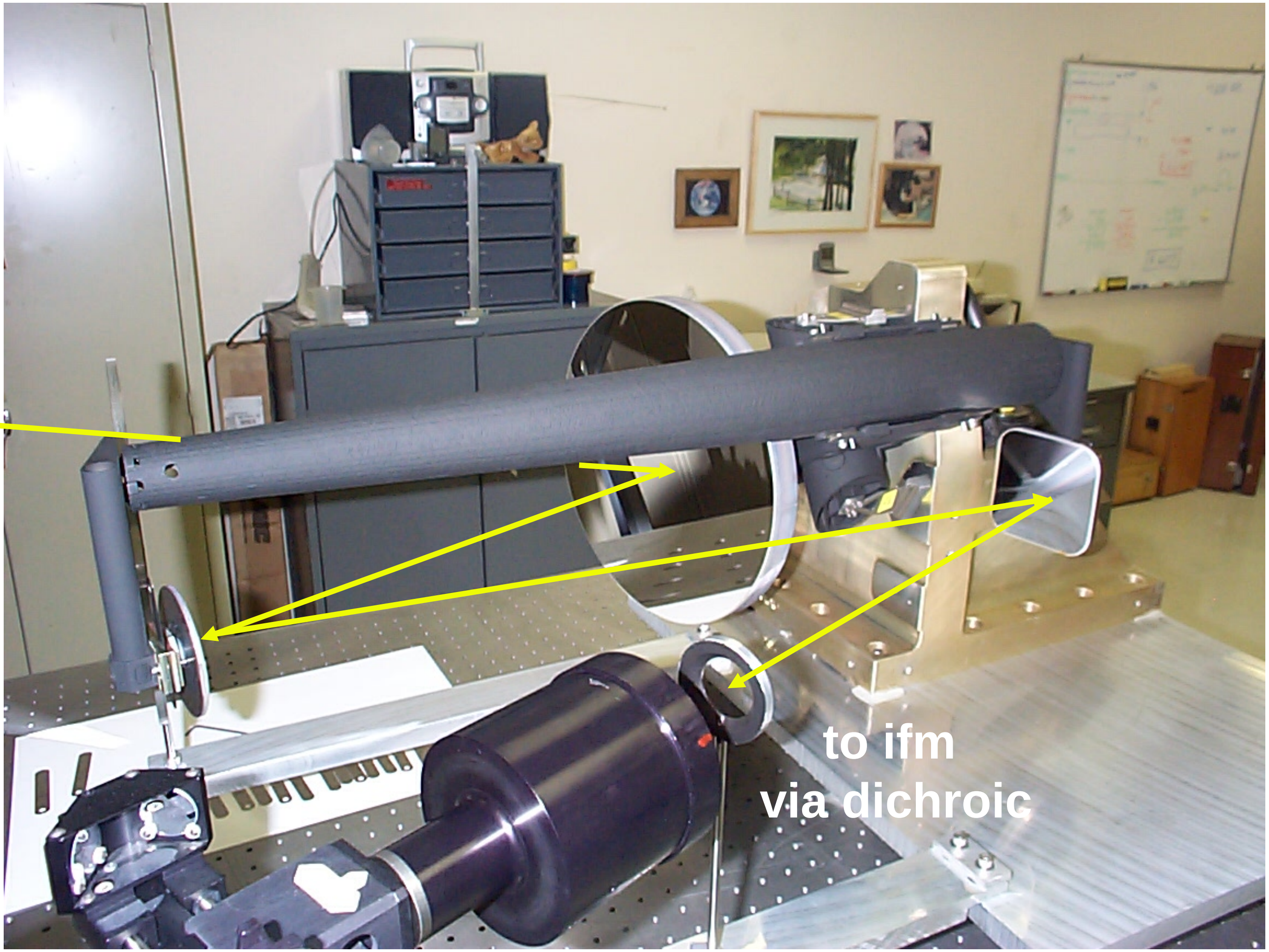
CBE Mass: 150 Kg ; Power: 330 W

GIFTS Sensor Module Technologies



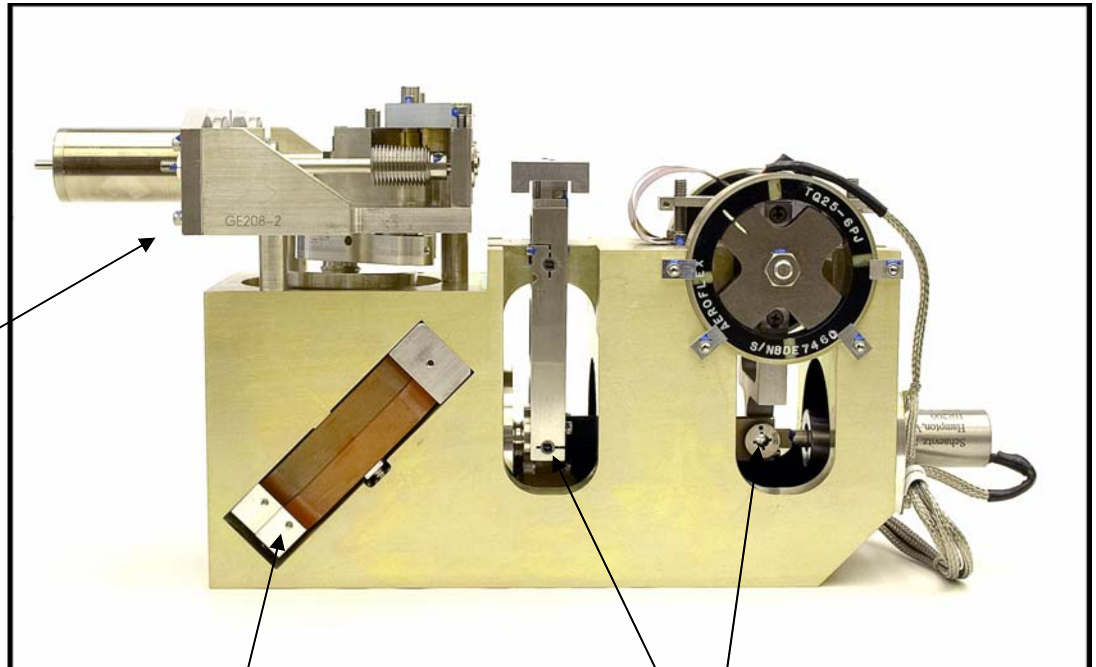
Telescope from SSG:
lightweight, 3-element Silicon Carbide

from Pointing Mirror



F/0.74 primary, 6.86 afocal ratio

Michelson Interferometer (SDL):
Cryogenic Plane-Mirror



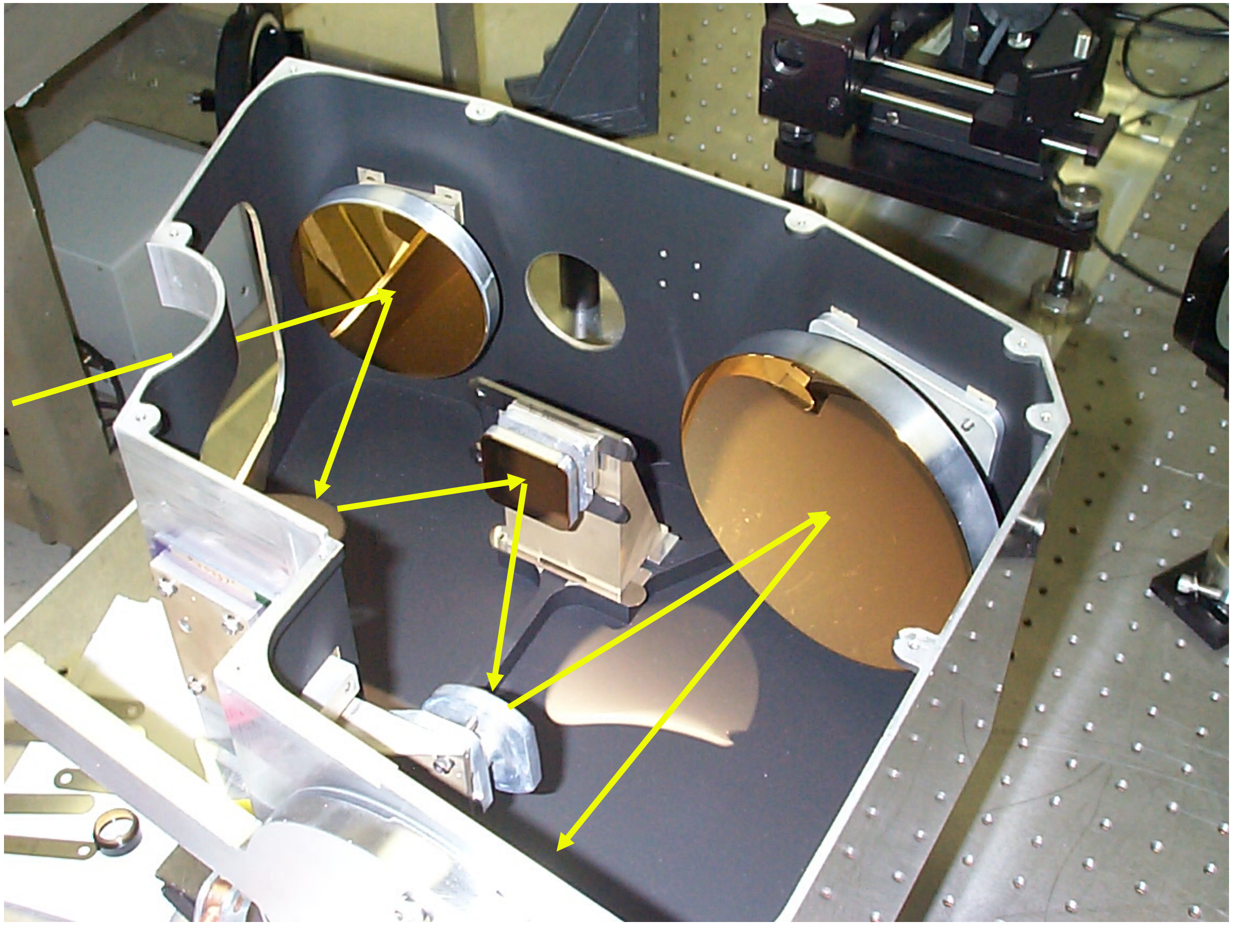
Remote alignment assembly

Beamsplitter assembly

Moving-mirror assembly

Aft-Optics from SSG:
5-element, reflective

from ifm
via dichroic

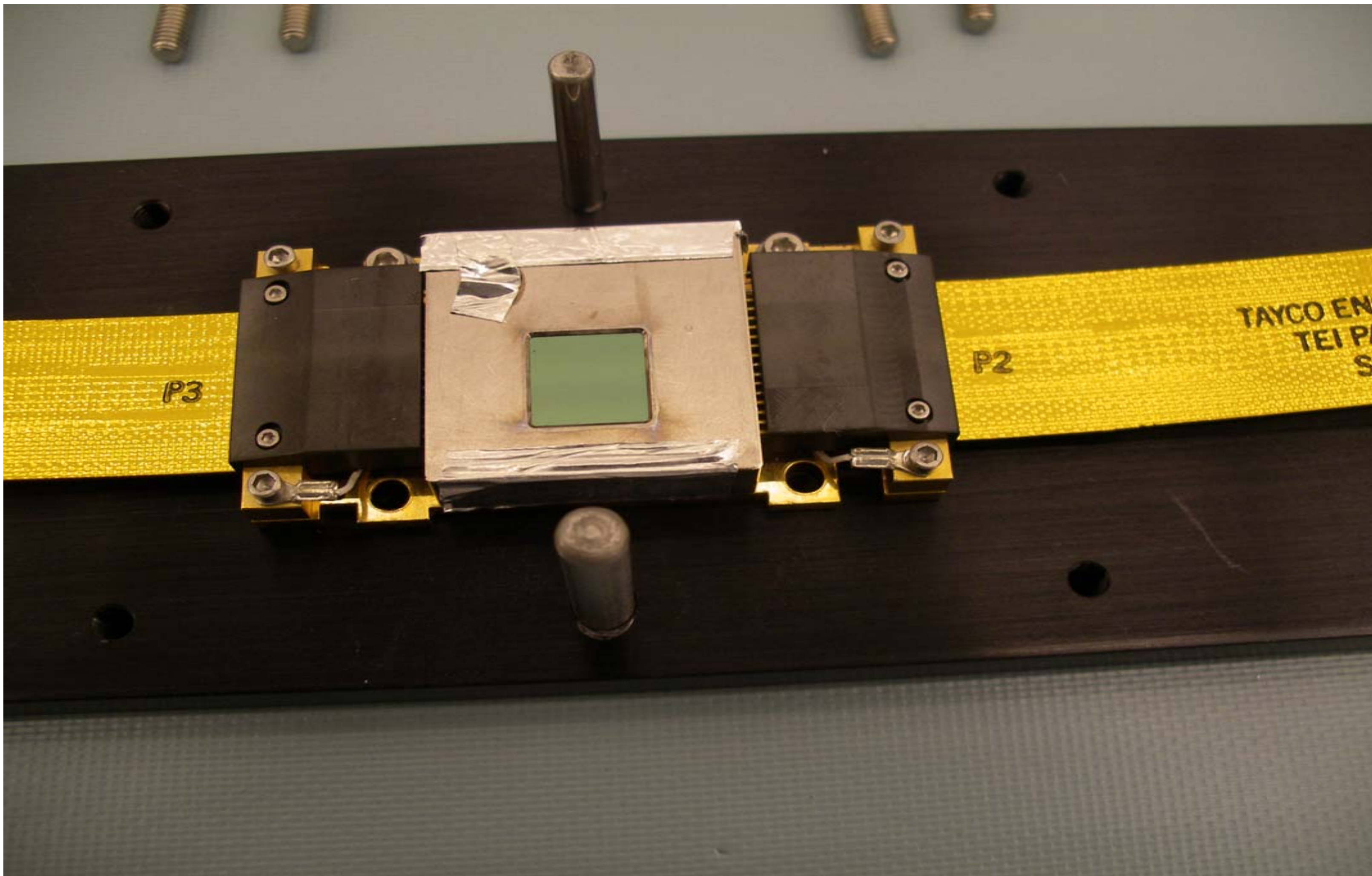


to Lyot stop & detectors

Optical System Wavefront error & Ensquared Energy meet requirements

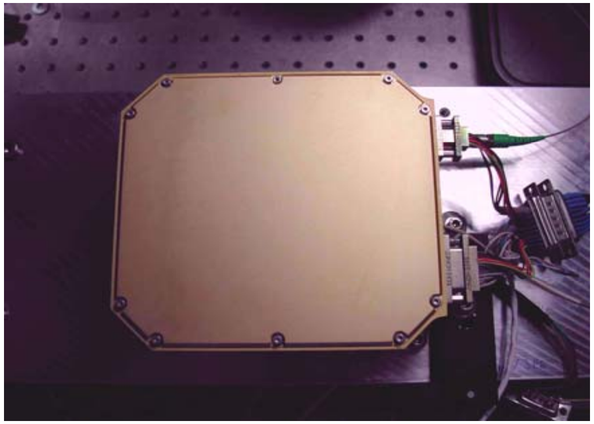
IR FPA Assembly (BAE):

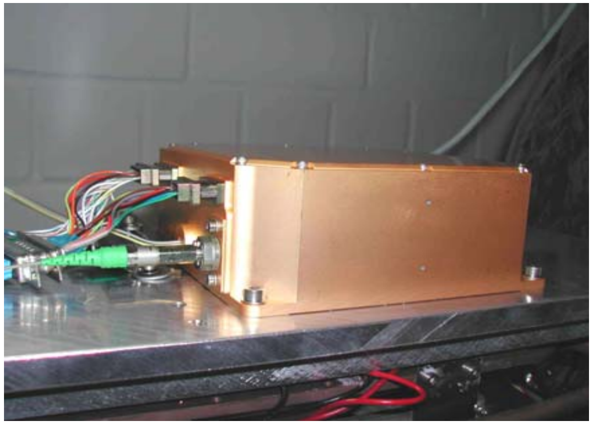
128x 128 pixels, 1 LW, 1 M/SW



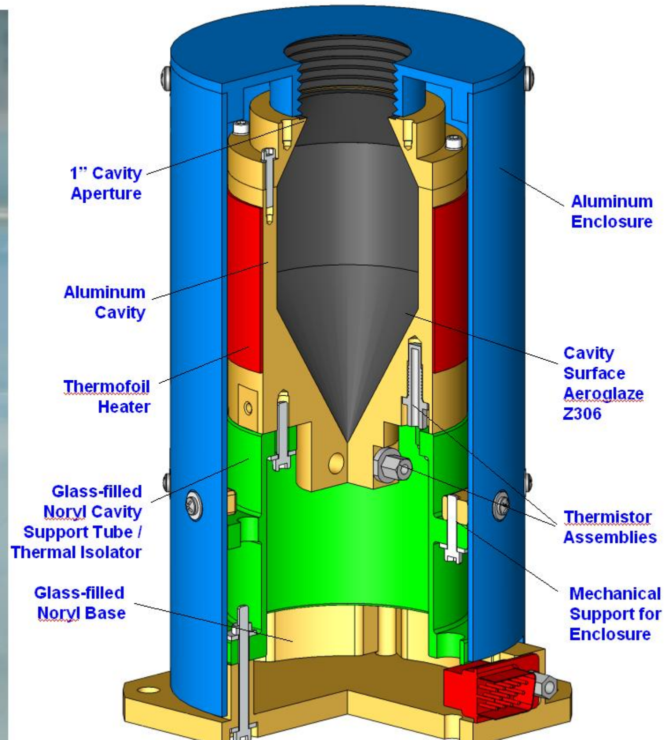
Long-lived, Stable Laser
(Tesat, Germany)

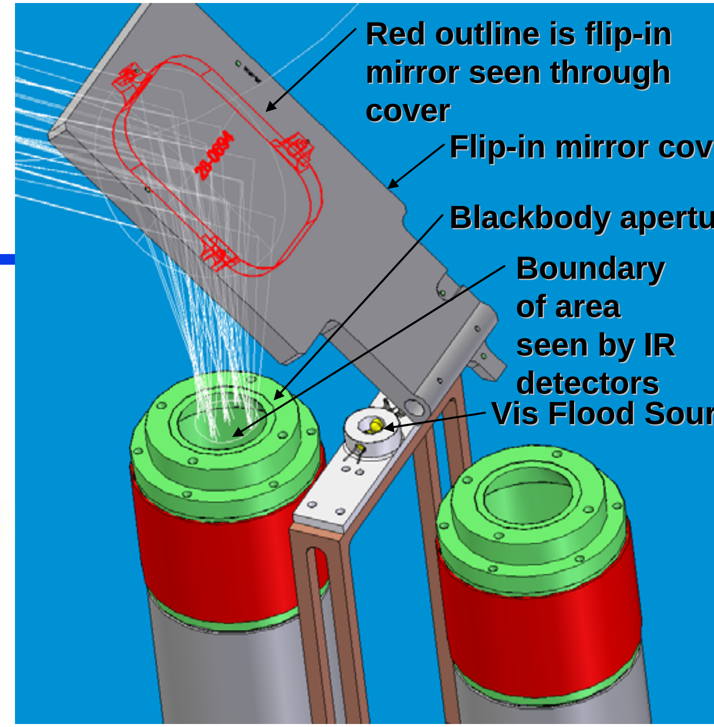
- Wavelength: 1064.49 – 1064.62 nm in vacuum
- Wavelength Stability over 24 hrs: +/- 1.9 E-4 nm (+/- 50 MHz freq)
- Output Power: > 25 – 35 mW
- Output: PM single mode fiber
- Total Radiation: 75 krad (Si)
- Reliability: 0.97 @ 7 years operation



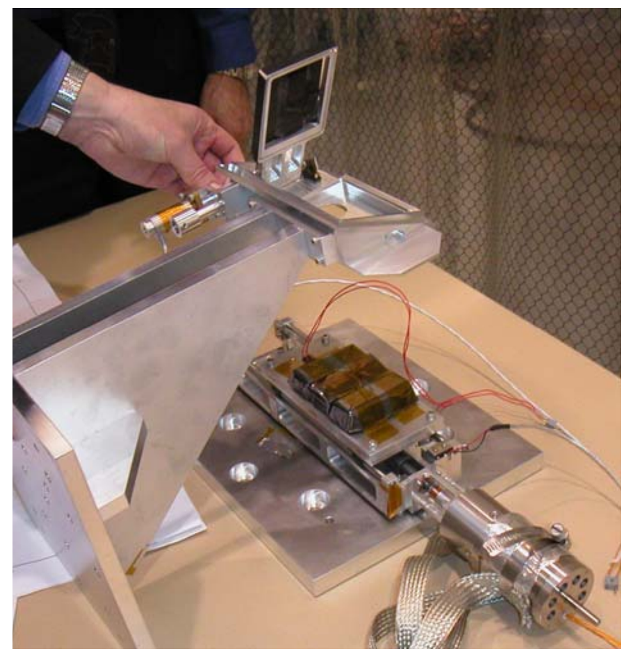


Internal Blackbody References

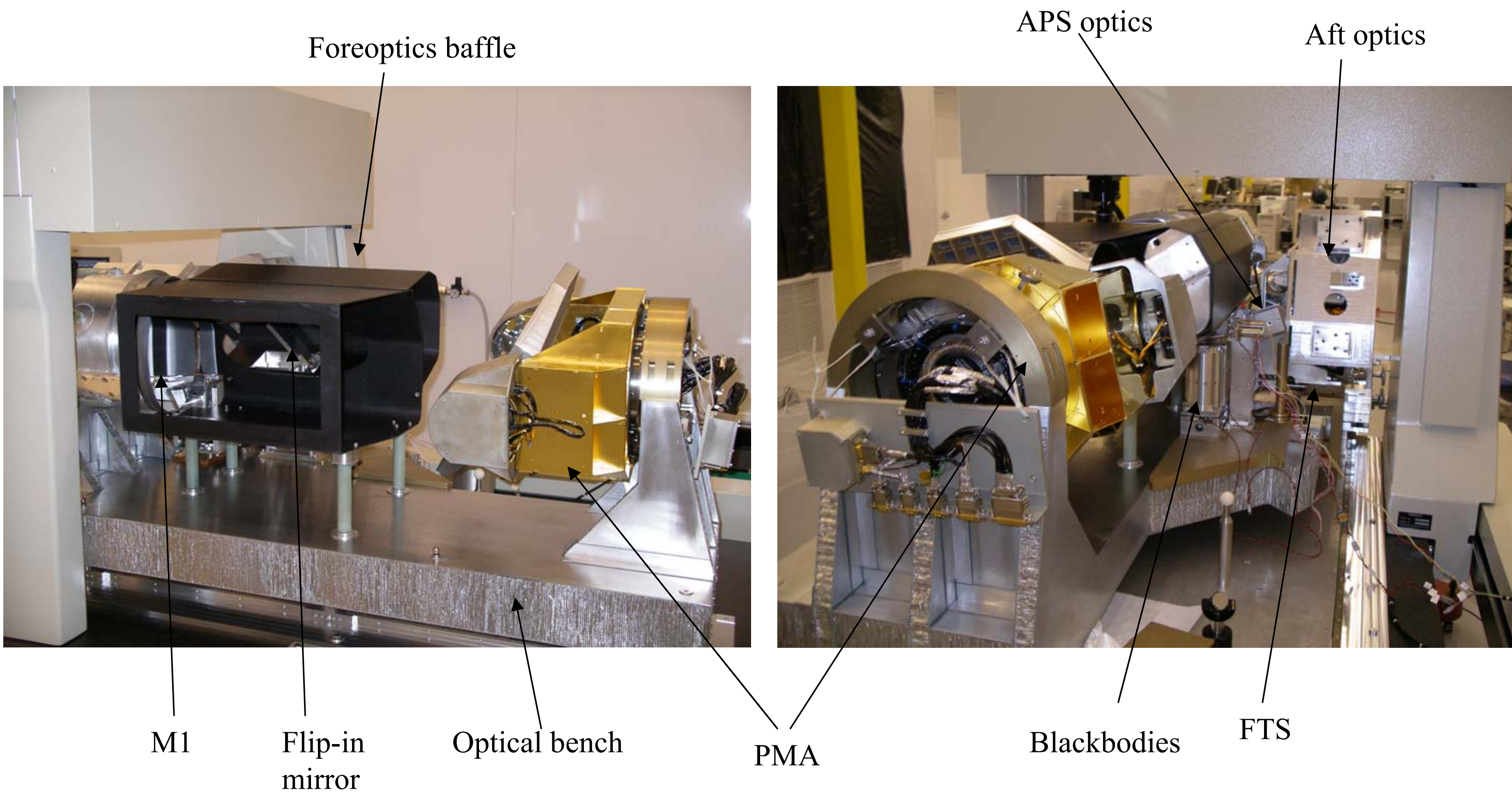




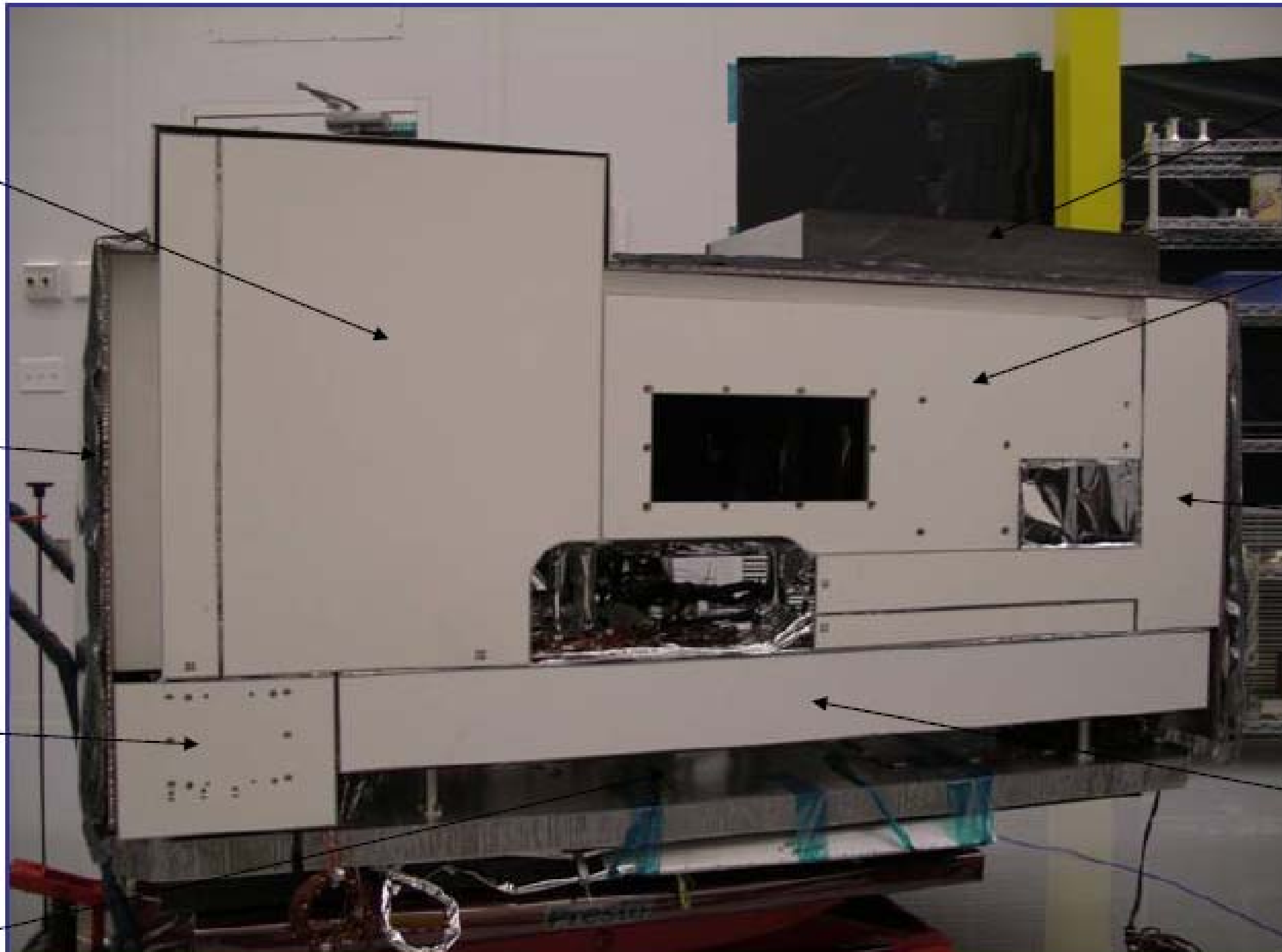
	Specification	Estimate
Temperature Uncertainty	< 0.1 K (3 σ)	< 0.056 K
Blackbody Emissivity	> 0.996	> 0.999
Emissivity Uncertainty	< 0.002 (3 σ)	< 0.00072



GIFTS EDU Assembly



GIFTS EDU: Radiator view

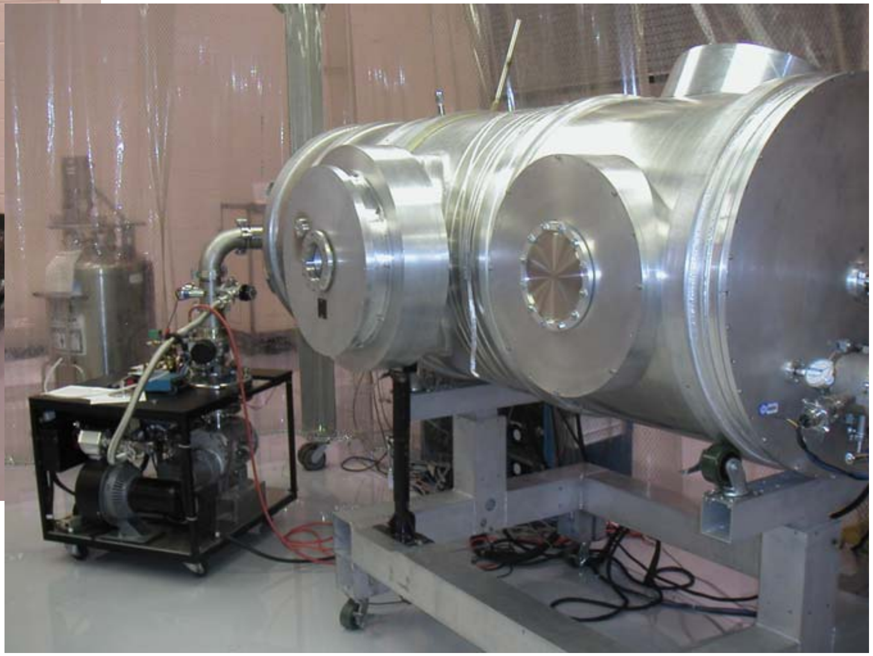


GIFTS: Wrapped up for Thermal Vacuum Testing at SDL

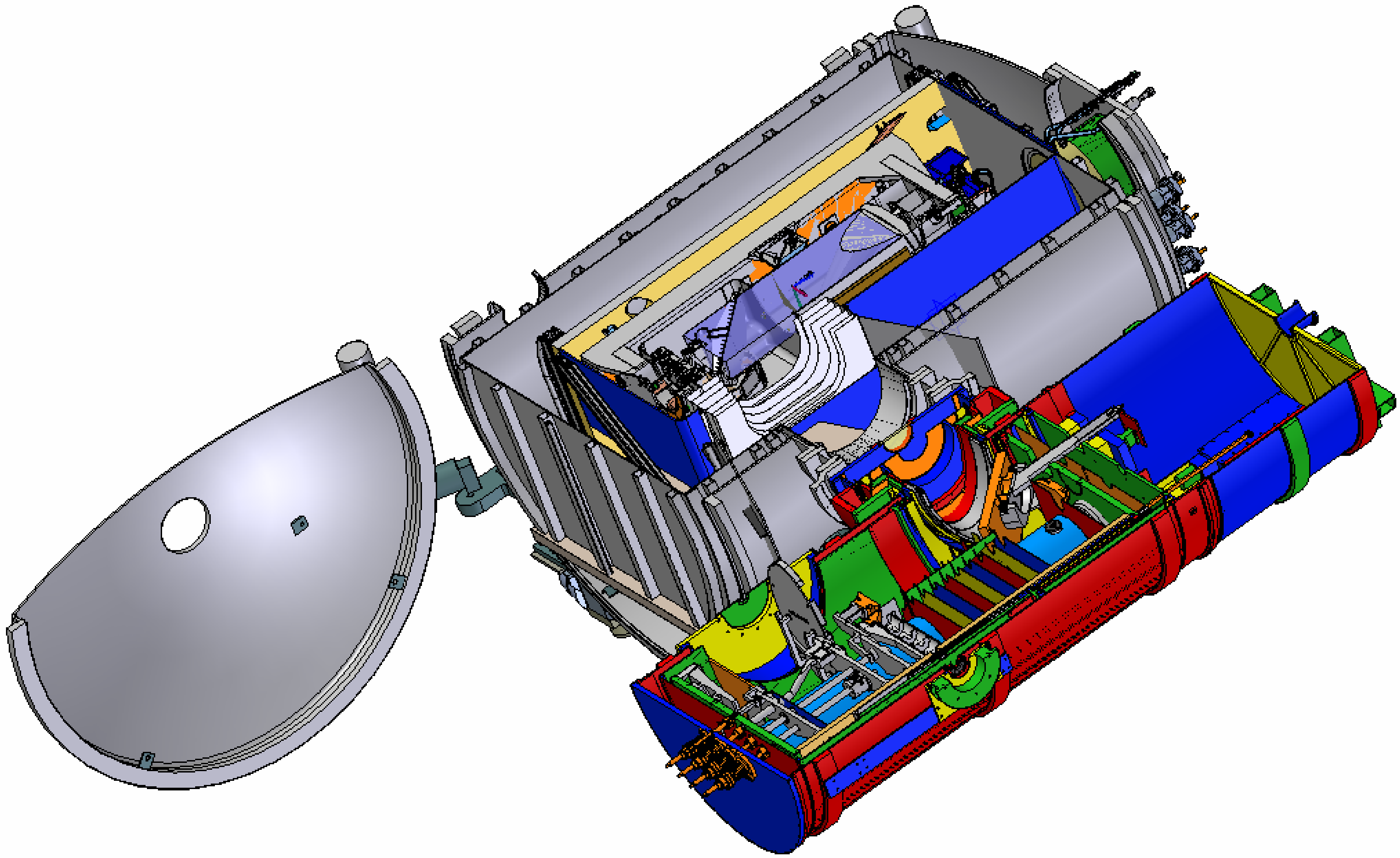
SDL Test Facilities for GIFTS

GIFTS Chamber

"MIC2"
Multi-function IR Calibrator

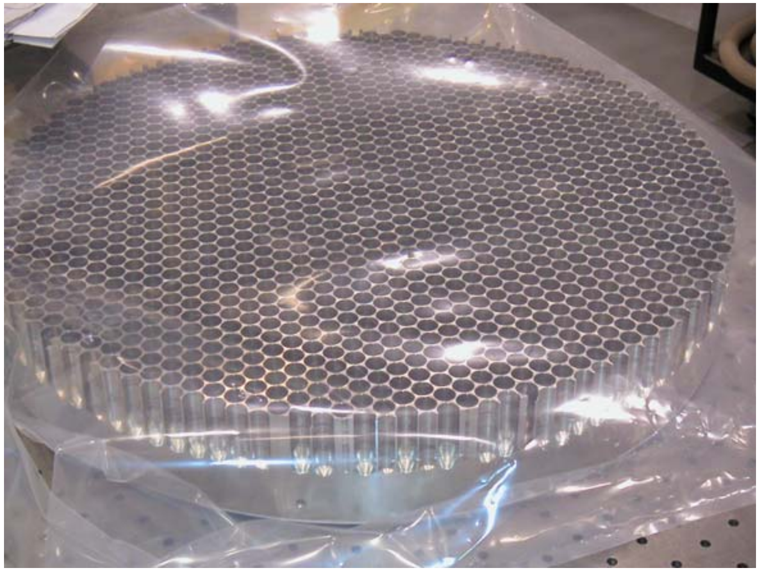


MIC2-Chamber Interface



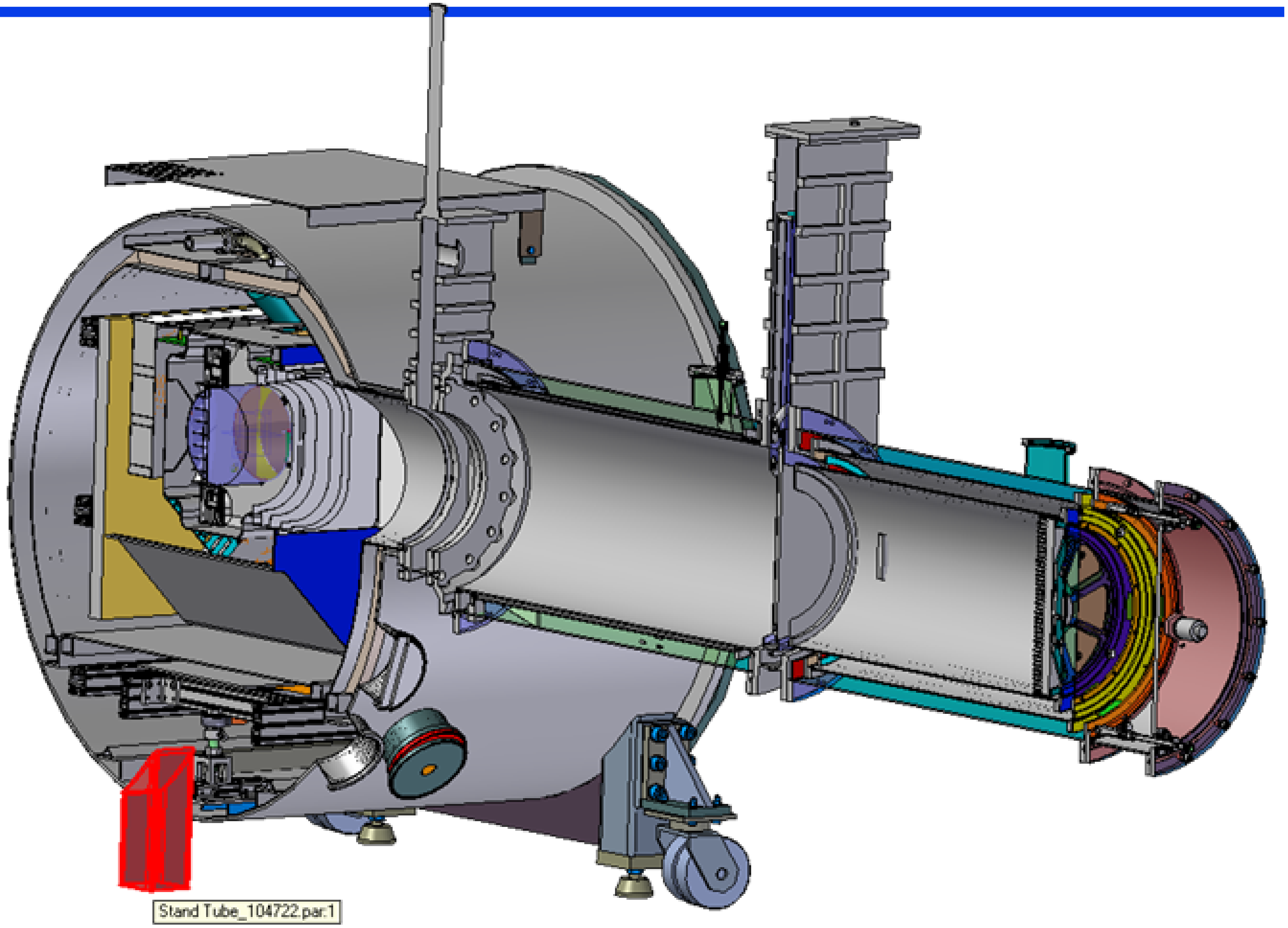
Large External Blackbody Sources (LN2 and Warm) for T/V Testing at SDL

"HAES15"
(High Accuracy Extended Source)



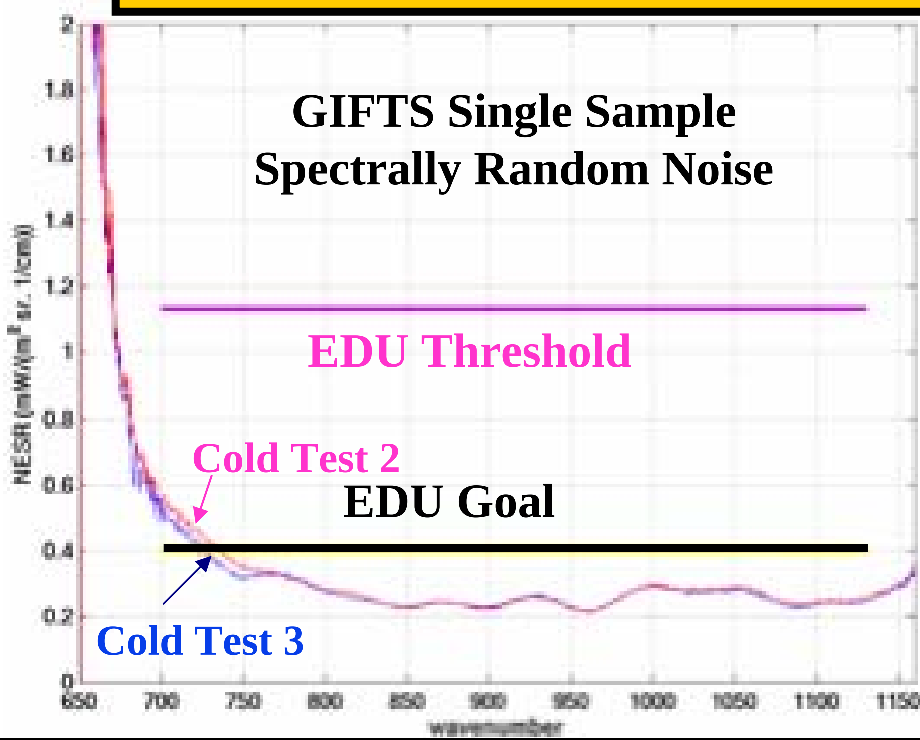
Testing will verify internal calibration and refine fore-optics parameters

HAES15-Chamber Interface

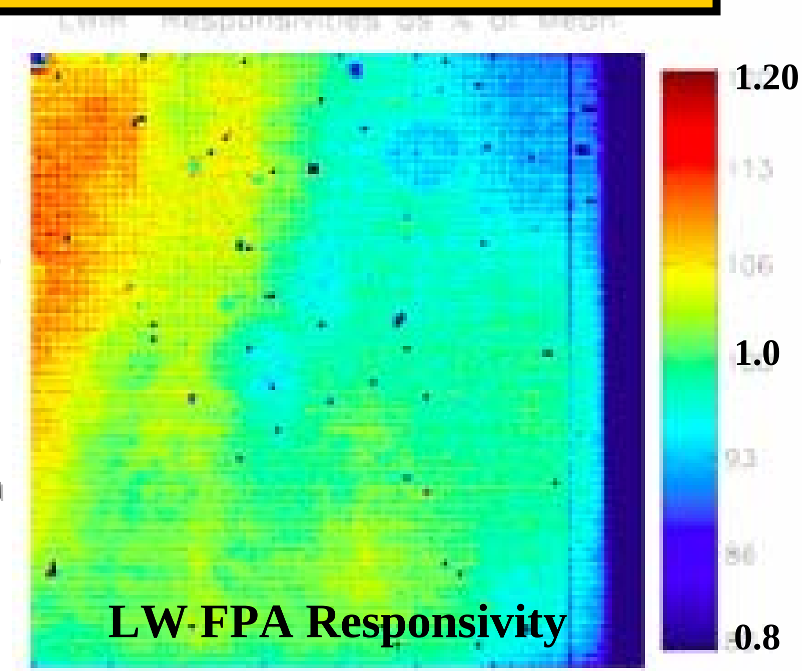


D. GIFTS Status:
Performance
(Results from recent testing)

GIFTS T-V Tests Show That HES LW Band Measurements With Required S/N & High Operability Are Practical



LW FPA Operability



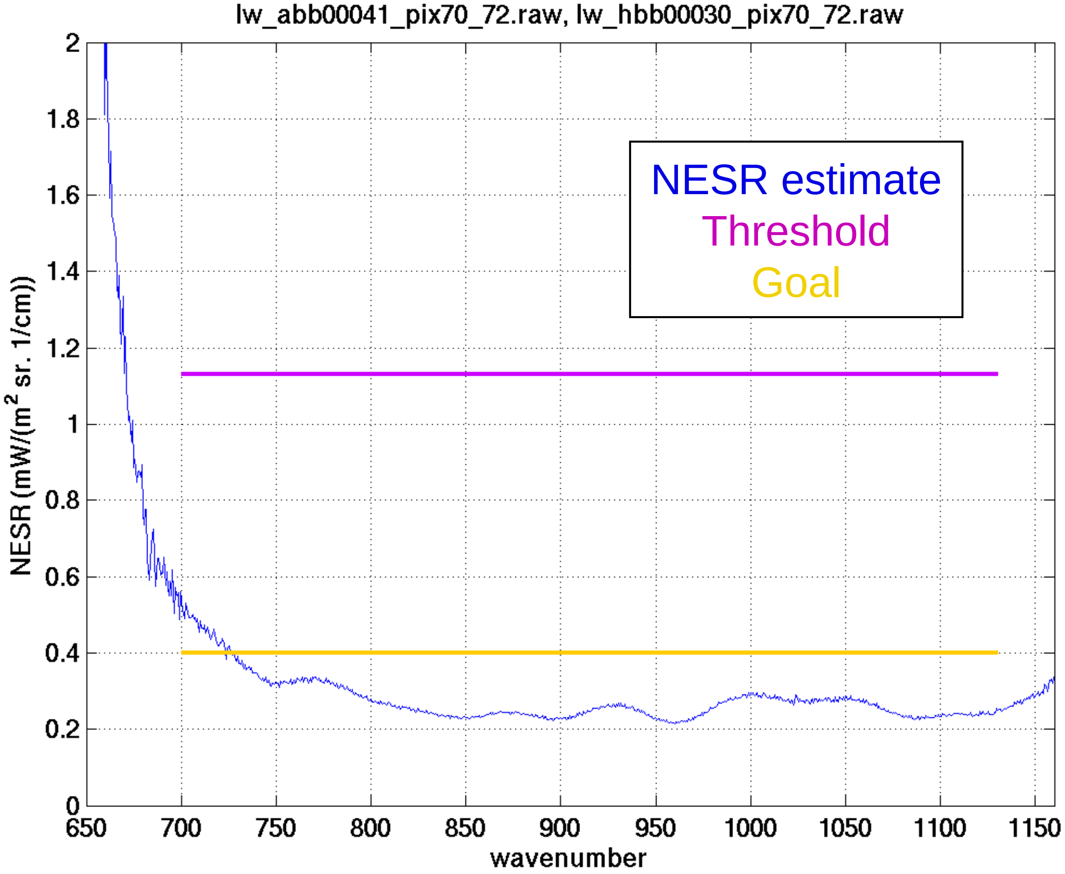
Pixels with responsivity in range 80%-120% of mean	98.2%
Pixels with noise less than 3X mean noise	96.3%
Active pixels (those that meet both responsivity & noise criteria)	95.9%

Significance:

- Can achieve AIRS-like performance for 4 km spatial footprints covering 500x500 km field every 12 seconds.
- Coverage about 40 x faster than GOES,
5-6 times faster at full spectral resolution, all with spatial footprints that are 4 times smaller in area and contiguous.

THE UNIVERSITY of WISCONSIN MADISON

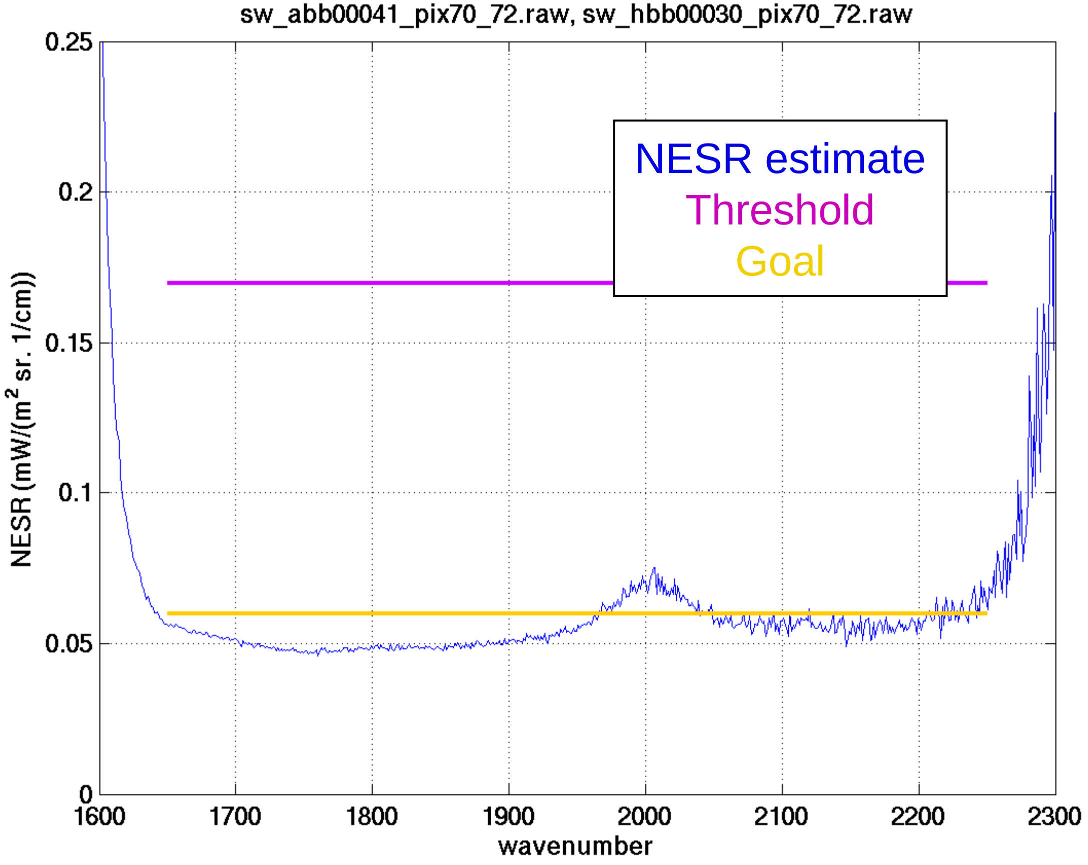
Cold Test 3, LW Random (spectrally uncorrelated) Noise



Meets goal for total NESR at all but the longest wavelength end of the band

- Count Noise computed from STDDEV of real part of complex spectra in out-of-band region (4000-4500 cm^{-1}) (~279 counts) and then divided by the magnitude responsivity to get random (spectrally uncorrelated) NESR:

ColdTest 3, SW Random (spectrally uncorrelated) Noise

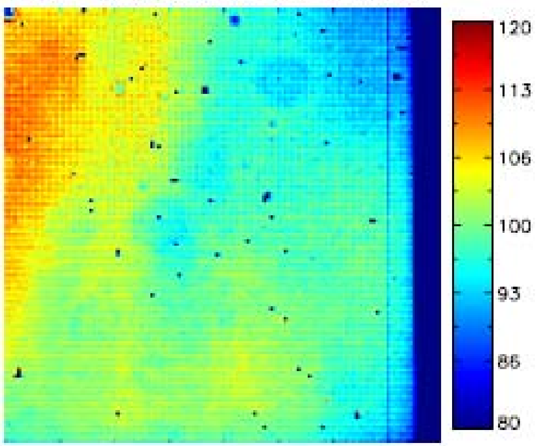


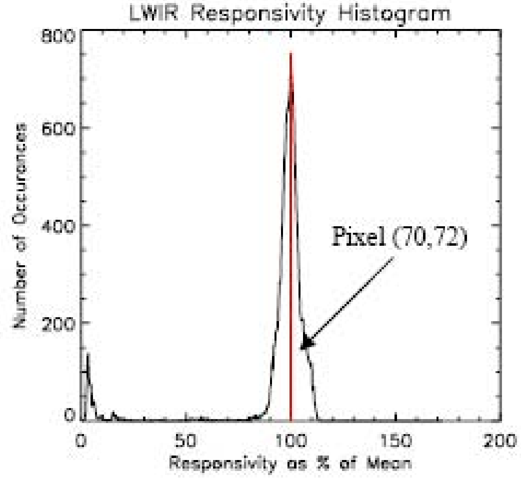
Meets goal for total NESR over most of the band

- Count Noise computed from STDDEV of real part of complex spectra in out-of-band region (4000-4500 cm^{-1}) (~266 counts) and then divided by the magnitude responsivity to get random (spectrally uncorrelated) NESR:

LWIR Cold Test 3 Active Pixel Inventory Radiometer Mode

LWIR Responsivities as % of Mean

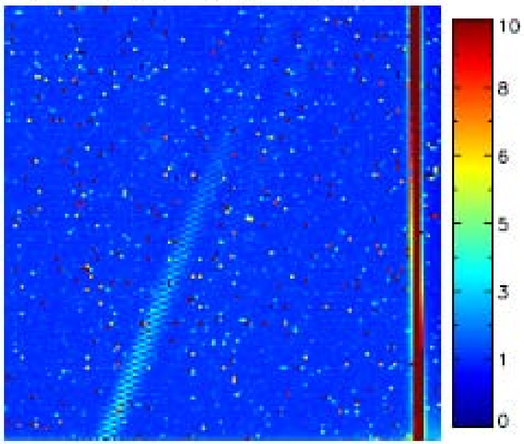


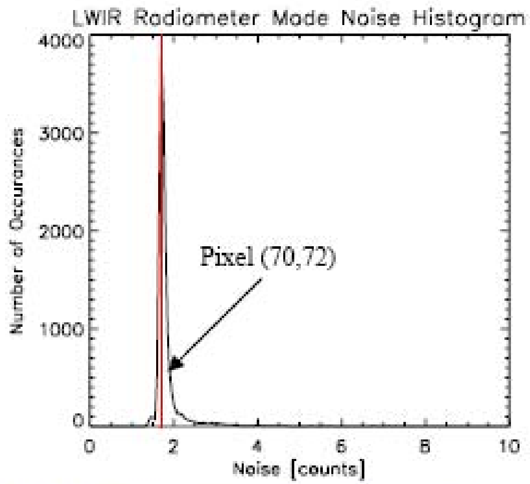


LWIR FPA Statistics

Vignetted pixels excluded from statistics	768
Pixels with responsivity in range 80%-120% of mean	98.2%
Pixels with noise less than 3X mean noise	96.3%
Active pixels (those that meet both responsivity & noise criteria)	95.9%

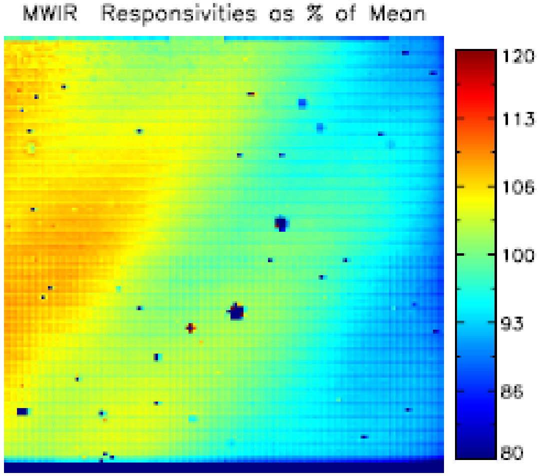
LWIR Radiometer Mode Noise [counts]

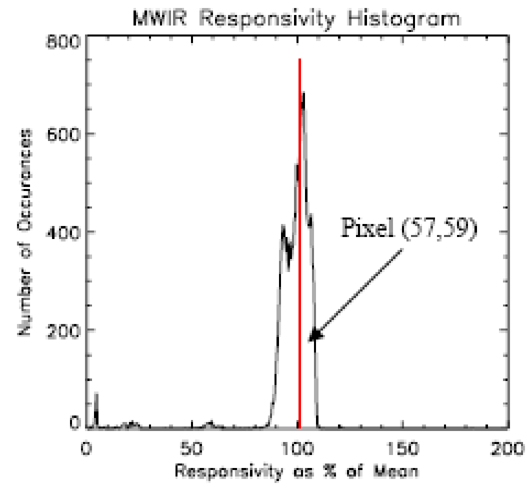




Pixel (70,72) shown on later slides for responsivity and NESR

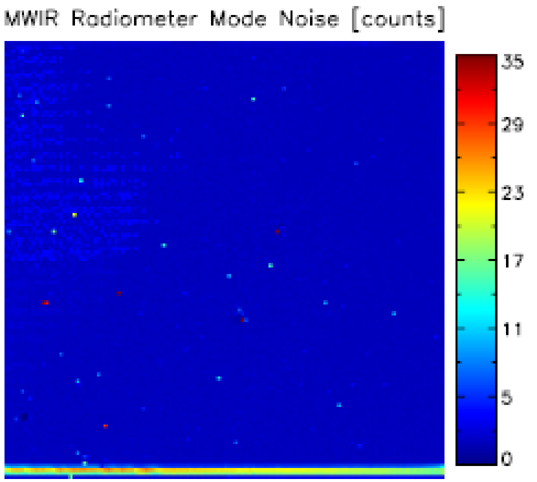
SMWIR Cold Test 3 Active Pixel Inventory Radiometer Mode

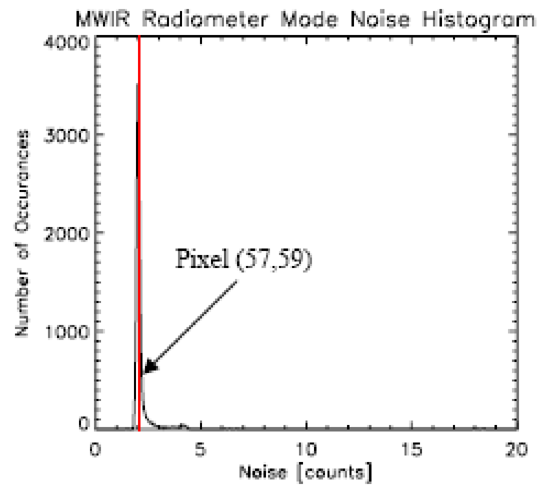




MWIR FPA Statistics

Vignetted pixels excluded from statistics	640
Pixels with responsivity in range 80%-120% of mean	99.6%
Pixels with noise less than 3X mean noise	99.8%
Active pixels (those that meet both responsivity & noise criteria)	99.4%

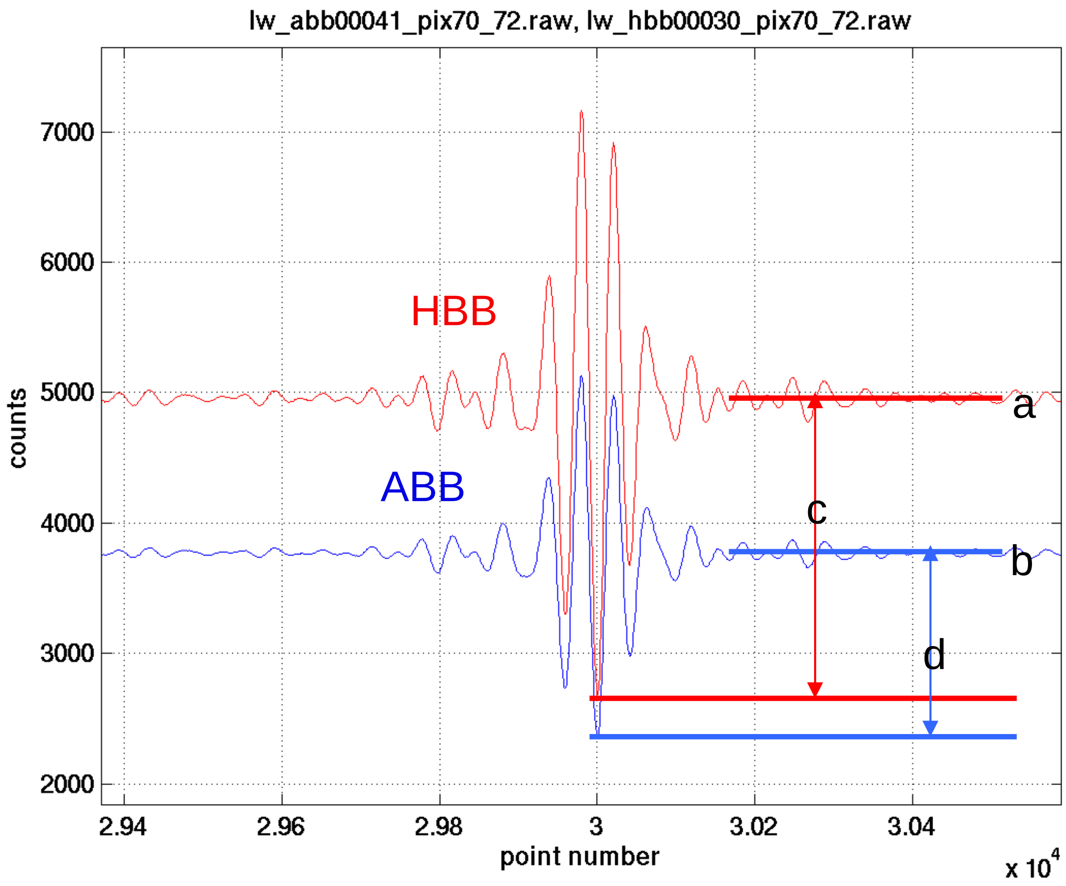




Pixel (57,59) shown on later slides for responsivity and NESR

Cold Test 3, Interferometer LW Modulation Efficiency

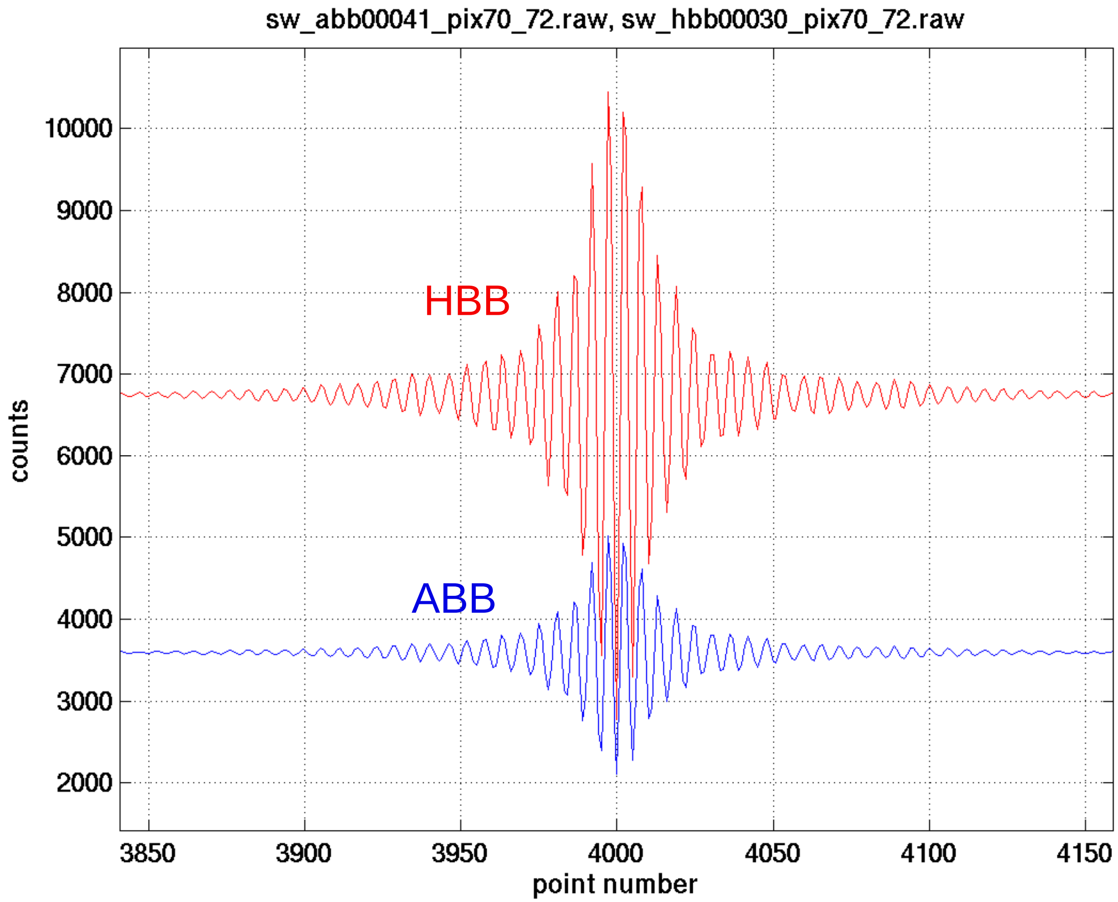
- Modulation Efficiency = (c-d)/(a-b) = 72.6% (was 71.9% for coldtest 2)



Approach gives lower bound because wavenumber dependent phase variations are not accounted for.

Cold Test 3, Interferometer SW Modulation Efficiency

- Modulation Efficiency = (c-d)/(a-b) = 78.9% (was 71.1% for coldtest 2)



SW Modulation efficiency is good, but we expect that the LW value should be greater than the SW, suggesting that that analysis accounting for phase variations may affect the LW the most.

D. GIFTS: Future Potential

SSEC

GIFTS Needs to be Flown!

- **National Academies Decadal Survey Interim report, April 2005:**
  "NASA and NOAA should complete the fabrication, testing, and space qualification of the GIFTS instrument and should support the international effort to launch this instrument by 2008."
- **But, Co-Chair, Berrien Moore testified before House Committee on Science, 2 March 2006:**
  after summarizing the Interim Report support for GIFTS, stated "…(NASA) FY '07 budget does not provide the additional funding that would be necessary to complete GIFTS."
- **Hopefully NOAA or NASA will see the light:**
  And reap the benefits of flying GIFTS ASAP

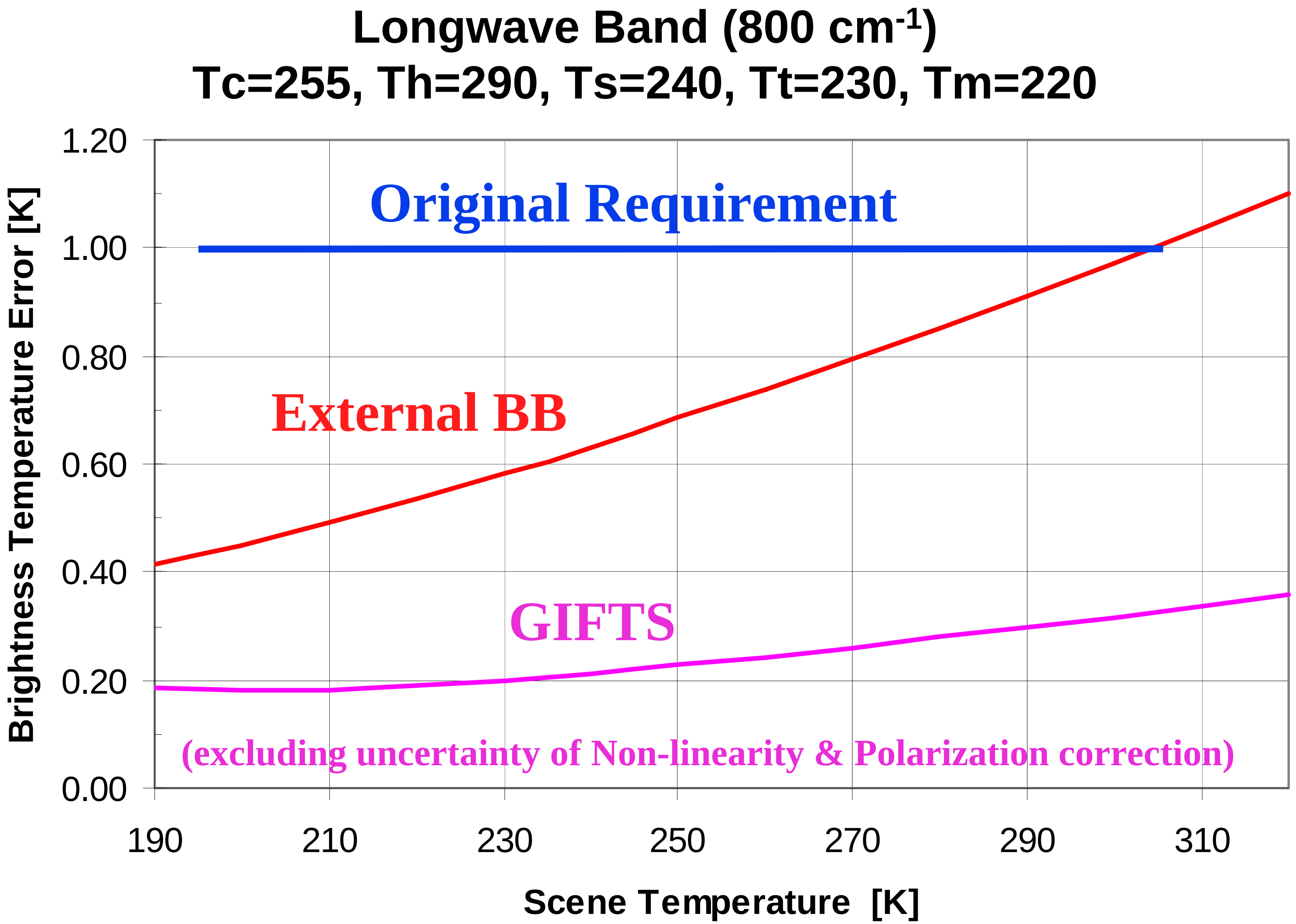
GIFTS FLIGHT OPTIONS

All require upgrade to flight model

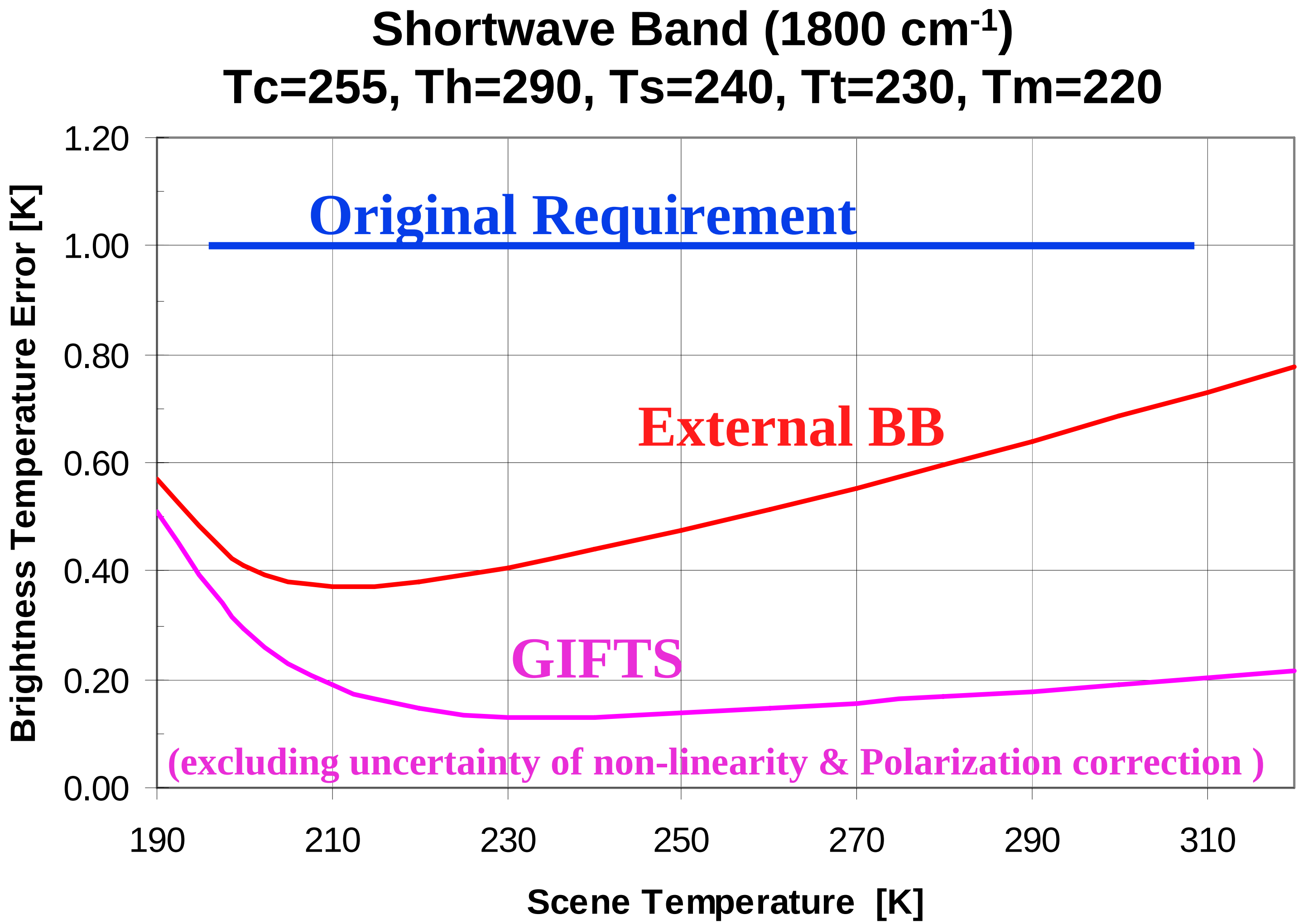
- **Dedicated Mission**
  - NASA or NOAA covers the cost of upgrade, launch and science
- **GOES R HES Risk Reduction**
  - NASA works with NOAA to fly GIFTS as GPP
- **International Geostationary Laboratory (IGEOLAB)**
  - Concept developed by the international Coordinating Group on Operational Satellites (CGOS) – of which NESDIS is a partner
  - Objective: to share costs of developing the next generation of GEO observational satellites
  - Payoff: provide contributors with next generation data and operational experience as they develop their own systems
  - Interested parties include Russia, India, Korea, China, EUMETSAT

Backup Slides:

GIFTS Absolute Calibration-Longwave

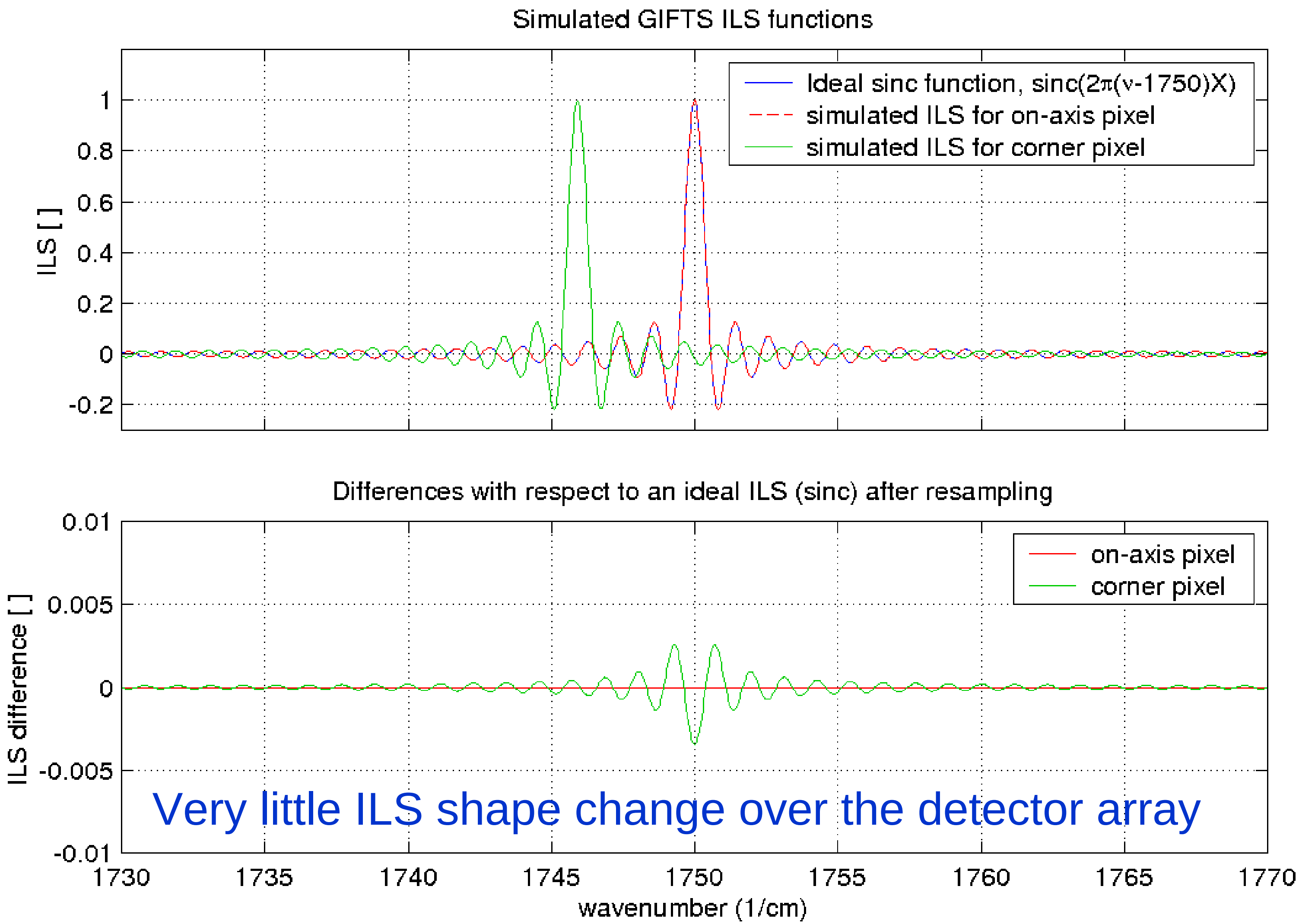


GIFTS Absolute Calibration-Shortwave



GIFTS ILS:

$$F(x,\theta) = \int d\nu N(\nu) e^{i2\pi\nu x\left(1-\frac{\theta^2+b^2}{2}\right)} \mathrm{sinc}(2\pi\nu x b\theta)$$



Very little ILS shape change over the detector array

<0.05 K Tb effect, with no correction