Improving the longest SI traceable hyperspectral infrared record from space: AIRS

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An SI-Traceable Space-based Climate Observing System
A CEOS, WMO-GSICS Workshop

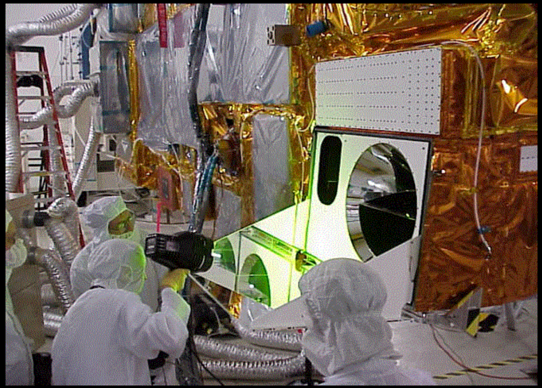
September 9, 2019

Agenda

- NASA AIRS on Aqua
  - AIRS in excellent shape. Expect mission to continue beyond 2022.
  - AIRS designed and tested to produce accurate SI traceable radiances
  - Legacy data set connects to operational weather sounders: CrIS, IASI
  - Interest in AIRS radiance data record growing due to long duration in space and overlap with current sounders.
- AIRS Radiometric Accuracy
  - New Calibration Coefficients for V7
- AIRS In-orbit Stability
  - In-orbit radiometric and spectral stability evaluated
- Additional Topics
  - Spatial Effects Impact Radiometry
  - AIRS Level 1C Product “Cleans-up” Level 1B
  - Lessons Learned for SI-Traceable Space-based Climate Observing System

The Aqua Spacecraft

Launched May 4, 2002



Moderate Resolution Imaging Spectroradiometer (MODIS)
GSFC/Raytheon

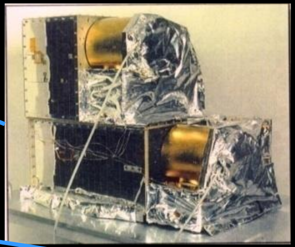
Atmospheric Infrared Sounder (AIRS)
JPL/BAE SYSTEMS

AQUA Spacecraft
GSFC/NGST

Advanced Microwave Scanning Radiometer (AMSR-E)
MSFC/JAXA

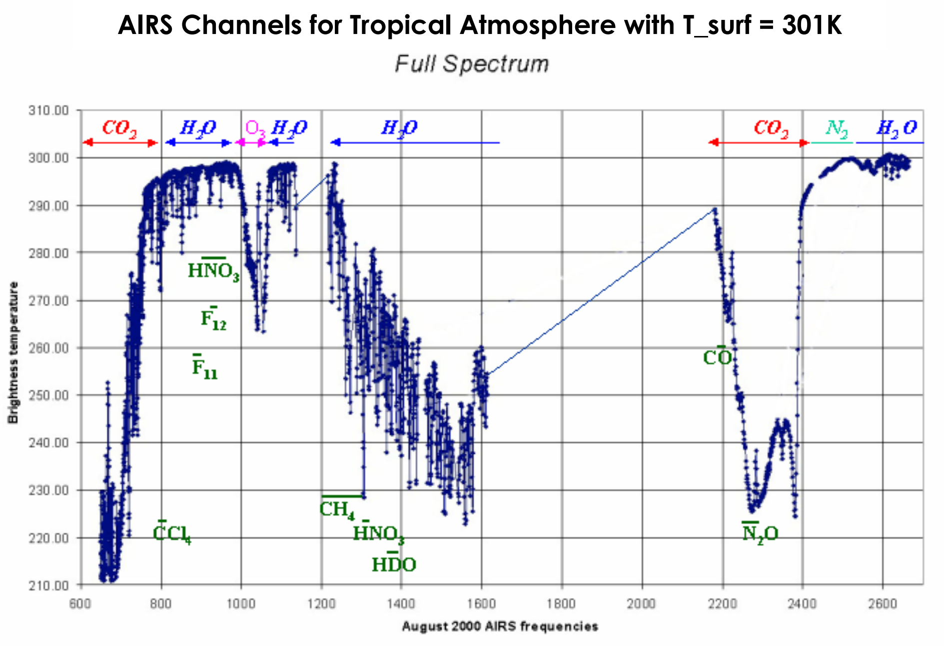
Advanced Microwave Sounding Units (AMSU-A/B)
JPL/Aerojet

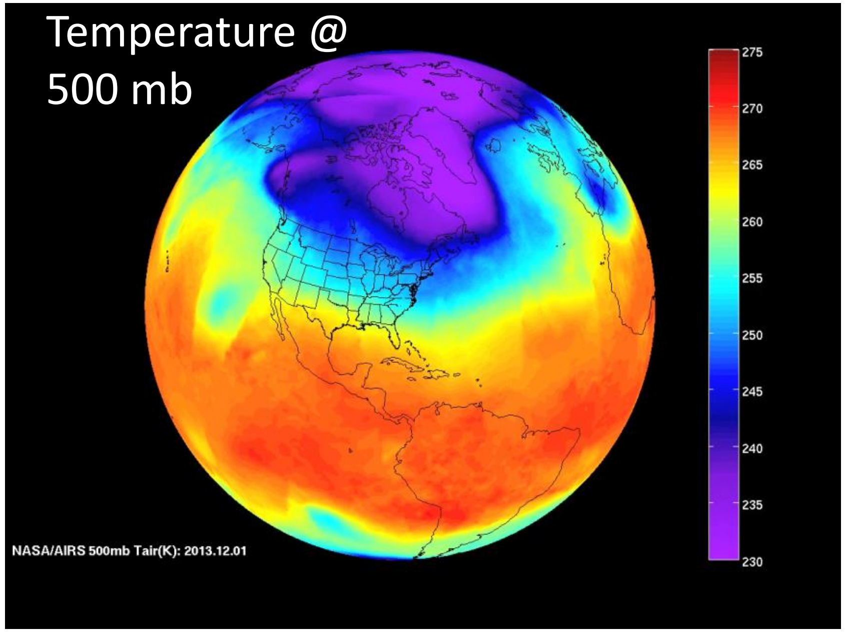
Humidity Sounder from Brazil (HSB)
JPL/Aerojet



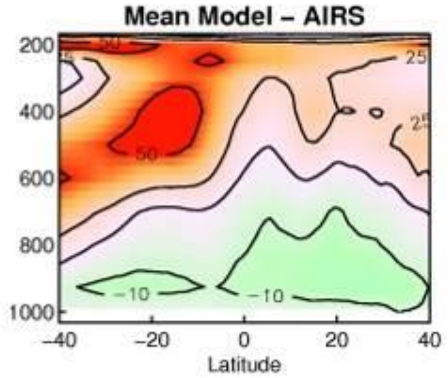
Clouds and Earth Radiant Energy System (CERES)
LaRC/NGST

IR Sounders Support Weather Forecasting and Climate Science





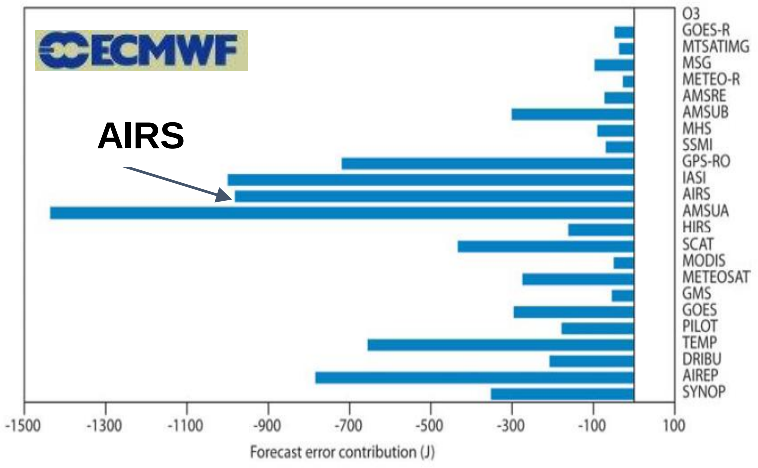
Water Vapor Climatology
(Pierce, Scripps, 2006)

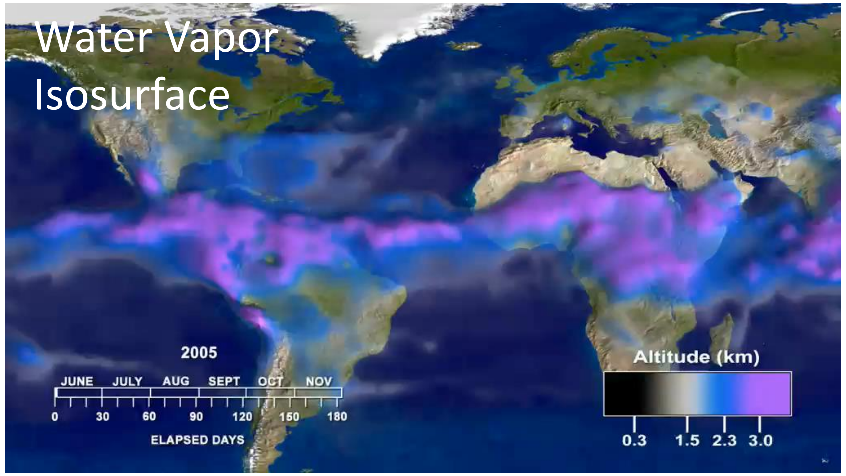


JPL/GSFC

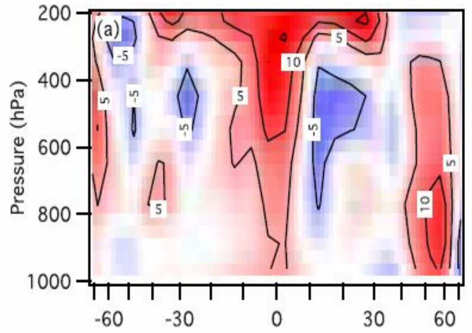
NOAA
NESDIS/NCEP

JCSDA



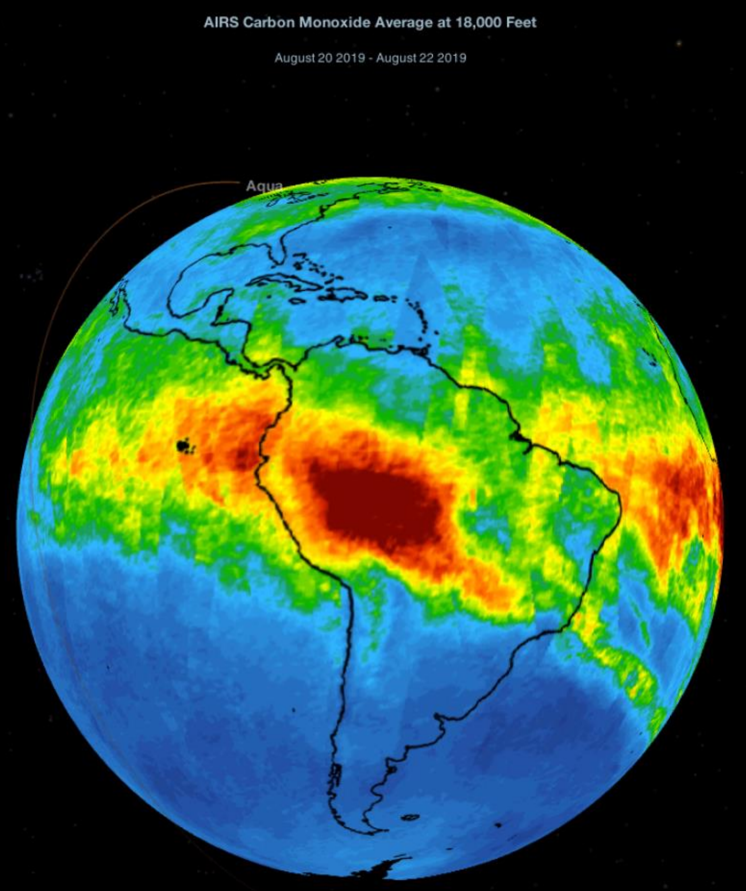


Water Vapor Feedback
(Dessler, Texas A&M, 2008)

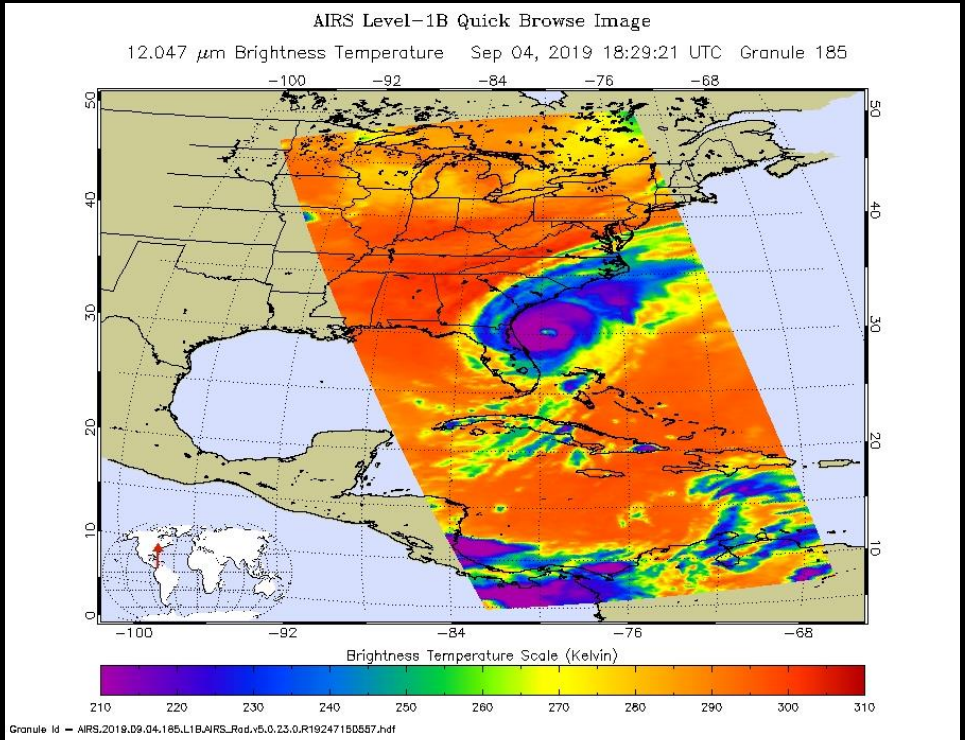


AIRS Recent Events

CO: August 2019, Amazon Wildfires

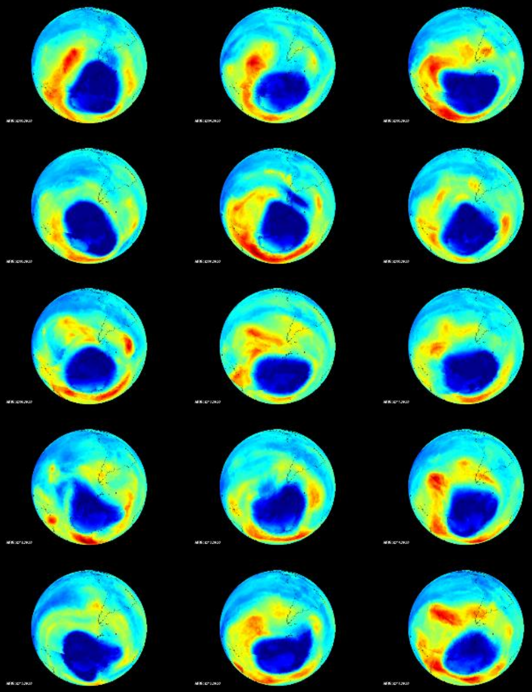


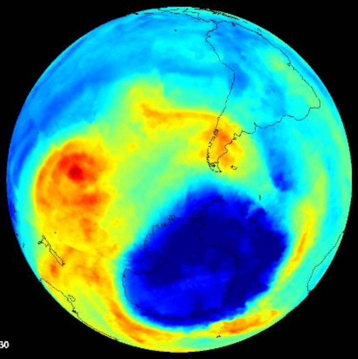
Hurricane Dorian: September 4, 2019



AIRS Provides a Long Record of Atmospheric Products (e.g. O_3)

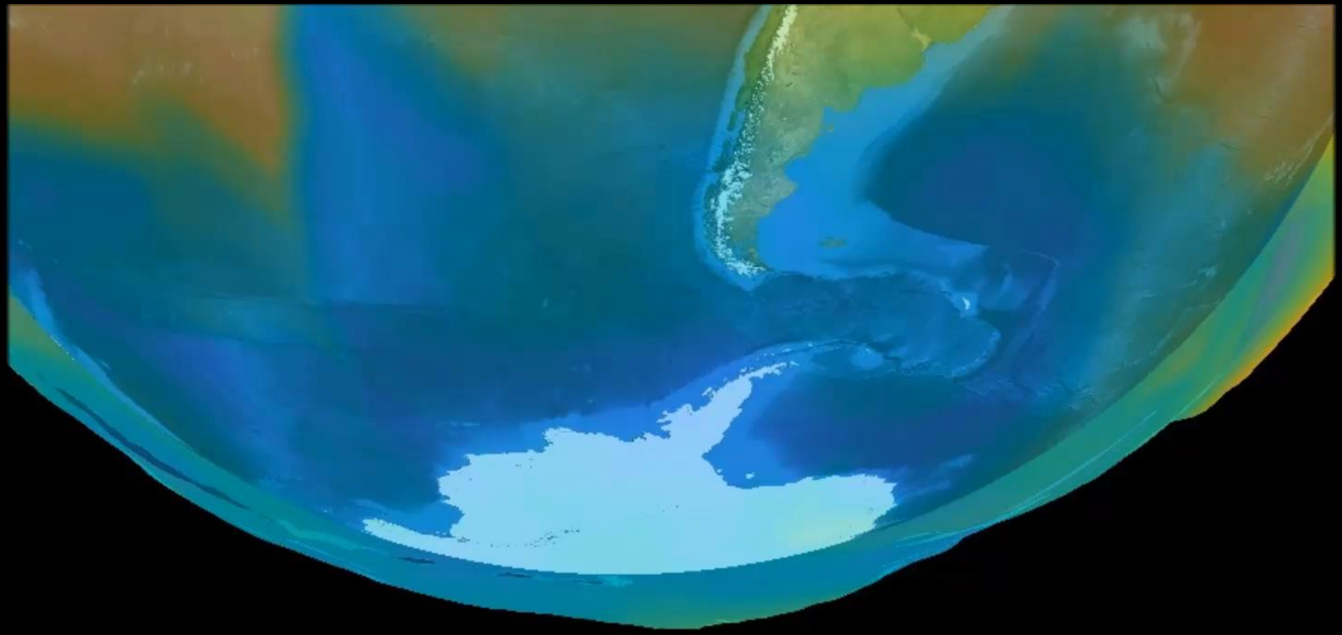
AIRS O_3 16 Years





AIRS: 2018.09.30

O3: Fall 2018, Ozone Hole Formation



AIRS.2018.08.01

AIRS Confirms Global Warming

The Washington Post

Satellite confirms key NASA temperature data: The planet is warming — and fast

SCIENTIFIC AMERICAN

It's A Match: Satellite and Ground Measurements Agree on Warming

This figure from Susskind et al. was shown in Washington Post story.

AIRS time series of global mean surface temperature anomalies confirms global warming from in situ (GISS) and reanalysis (ECMWF) data.

AIRS shows more warming in poorly-instrumented Arctic regions (Arctic amplification), suggesting previous datasets may underestimate warming (not shown).

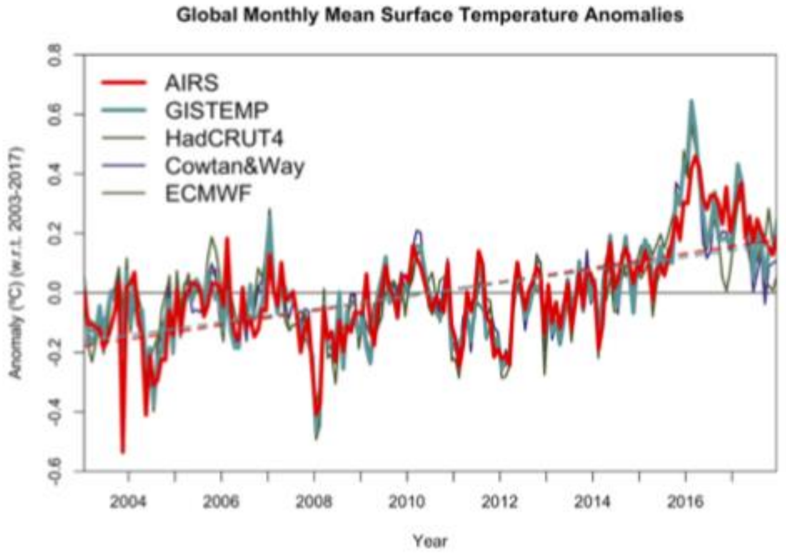


Figure 1. Global mean anomalies for the AIRS and GISTEMP data sets for January 2003 through December 2017 along with three other selected *in situ* data products (HadCRUT4, Cowtan and Way, and ECMWF). Dashed lines are the ordinary least squares trends of the anomaly time series for AIRS and GISTEMP over this time period.

Susskind, J., A. Schmidt, J. N. Lee and L. Iredell, (2019) Recent global warming as confirmed by AIRS, *Environmental Research Letters,* 14, 044030.

AIRS Key Climate Related Publications

Arctic Processes and Trends

- Boisvert, L. N., and J. C. Stroeve (2015), The Arctic is becoming warmer and wetter as revealed by the Atmospheric Infrared Sounder, *Geophys. Res. Lett., 42,* doi:10.1002/2015GL063775.
- Devasthale, A., J. Sedlar, B. H. Kahn, M. Tjernström, E. J. Fetzer, B. Tian, J. Teixeira, and T. S. Pagano (2016), A decade of spaceborne observations of the Arctic atmosphere: novel insights from NASA's AIRS Instrument, *Bulletin of the American Meteorological Society, 97(11)*, 2163-2176.

Climate Model Assessment and Verifications

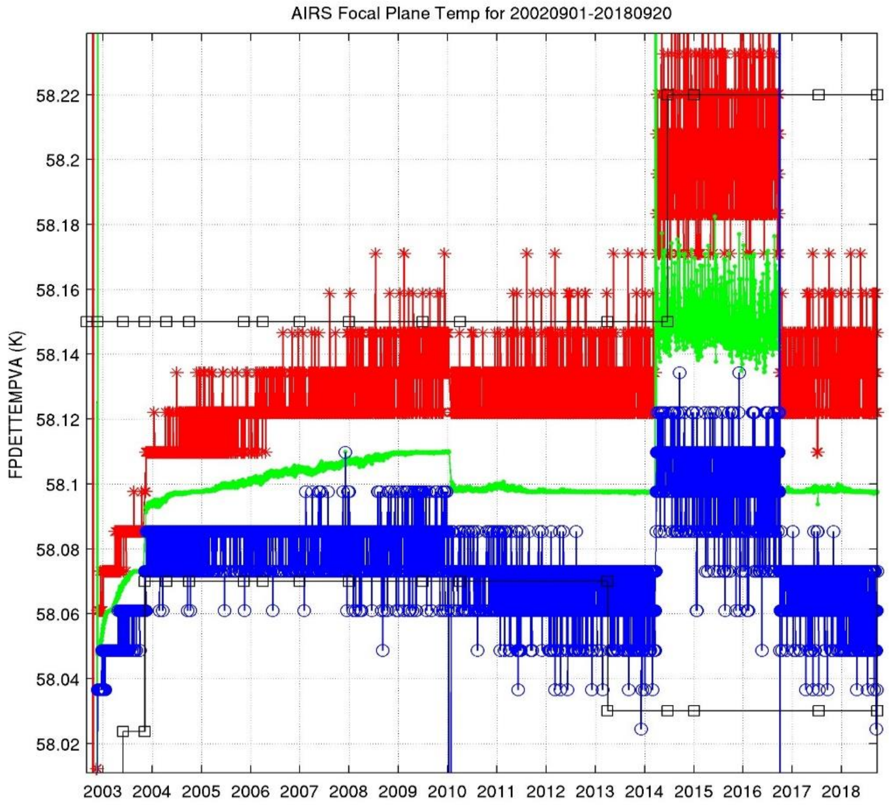
- Dessler, A. E., Z. Zhang, and P. Yang (2008), Water-vapor climate feedback inferred from climate fluctuations, 2003-2008, Geophys. Res. Lett., 35, L20704, doi:10.1029/2008GL035333.
- Fasullo, J. T., and K. E. Trenberth (2012) A Less Cloudy Future: The Role of Subtropical Subsidence in Climate Sensitivity, *Science,* DOI: 10.1126/science.1227465.
- Pierce, D. W., T. P. Barnett, E. J. Fetzer, and P. J. Gleckler (2006), Three-dimensional tropospheric water vapor in coupled climate models compared with observations from the AIRS satellite system, *Geophys. Res. Lett.*, *33*, L21701, doi:10.1029/2006GL027060.

Climate Processes and Characterization

- Huang, X., X. Chen, G.L. Potter, L. Oreopoulos, J.N. Cole, D. Lee, and N.G. Loeb, 2014: A Global Climatology of Outgoing Longwave Spectral Cloud Radiative Effect and Associated Effective Cloud Properties, *J. Climate,* 27, 7475–7492, **https://doi.org/10.1175/JCLI-D-13-00663.1**
- Kahn, B. H., X. Huang, G. L. Stephens, W. D. Collins, D. R. Feldman, H. Su, S. Wong, and Q. Yue (2016), ENSO regulation of far- and mid-infrared contributions to clear-sky OLR, *Geophys. Res. Lett., 43,* doi:10.1002/ 2016GL070263.
- Kahn, B. H., Takahashi, H., Stephens, G. L., Yue, Q., Delanoë, J., Manipon, G., Manning, E. M., and Heymsfield, A. J.: Ice cloud microphysical trends observed by the Atmospheric Infrared Sounder, *Atmos. Chem. Phys., 18*, 10715–10739, https://doi.org/10.5194/acp-18-10715-2018, 2018.
- Stephens, G.L., B.H. Kahn, and M. Richardson, 2016: The Super Greenhouse Effect in a Changing Climate, *J. Climate,* 29, 5469–5482, https://doi.org/10.1175/JCLI-D-15-0234.1
- Su, H., J. H. Jiang, C. Zhai, T. J. Shen, J. D. Neelin, G. L. Stephens, and Y. L. Yung (2014), Weakening and strengthening structures in the Hadley Circulation change under global warming and implications for cloud response and climate sensitivity, *J. Geophys. Res. Atmos., 119,* doi:10.1002/2014JD021642.

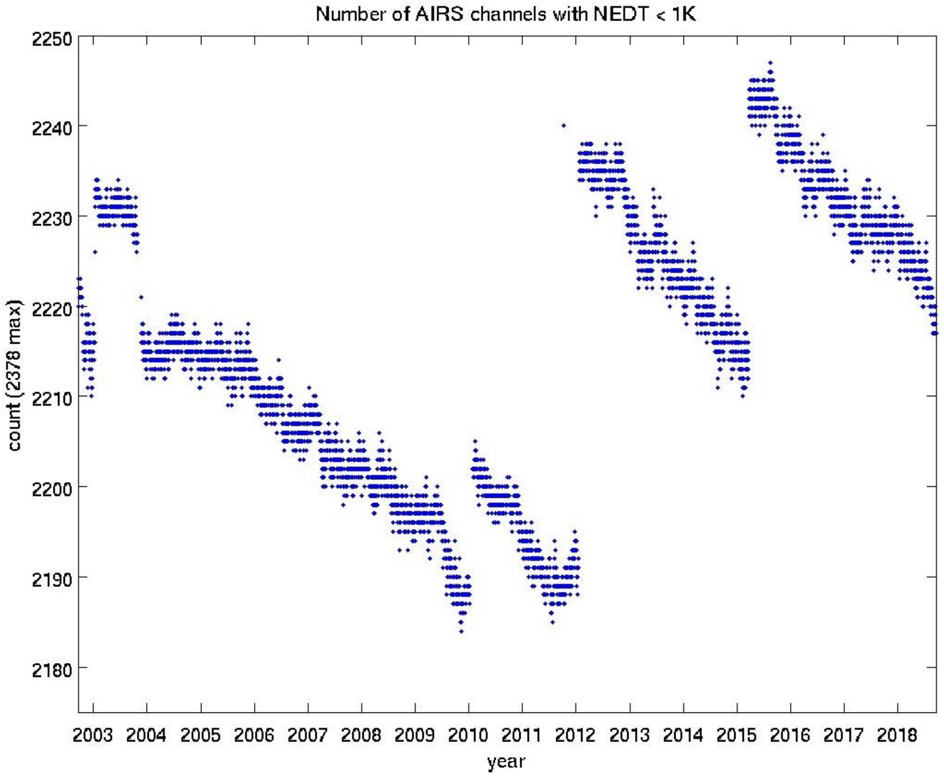
AIRS Remains Healthy

Minimal Trends in Instrument Telemetry



Focal Plane temperature has remained within a 0.25 K range throughout the AIRS mission. Note: Median temperature (green) rose ~0.06 K during 2014-2016 Cooler A anomaly

Detector Operability Maintained Throughout the Mission

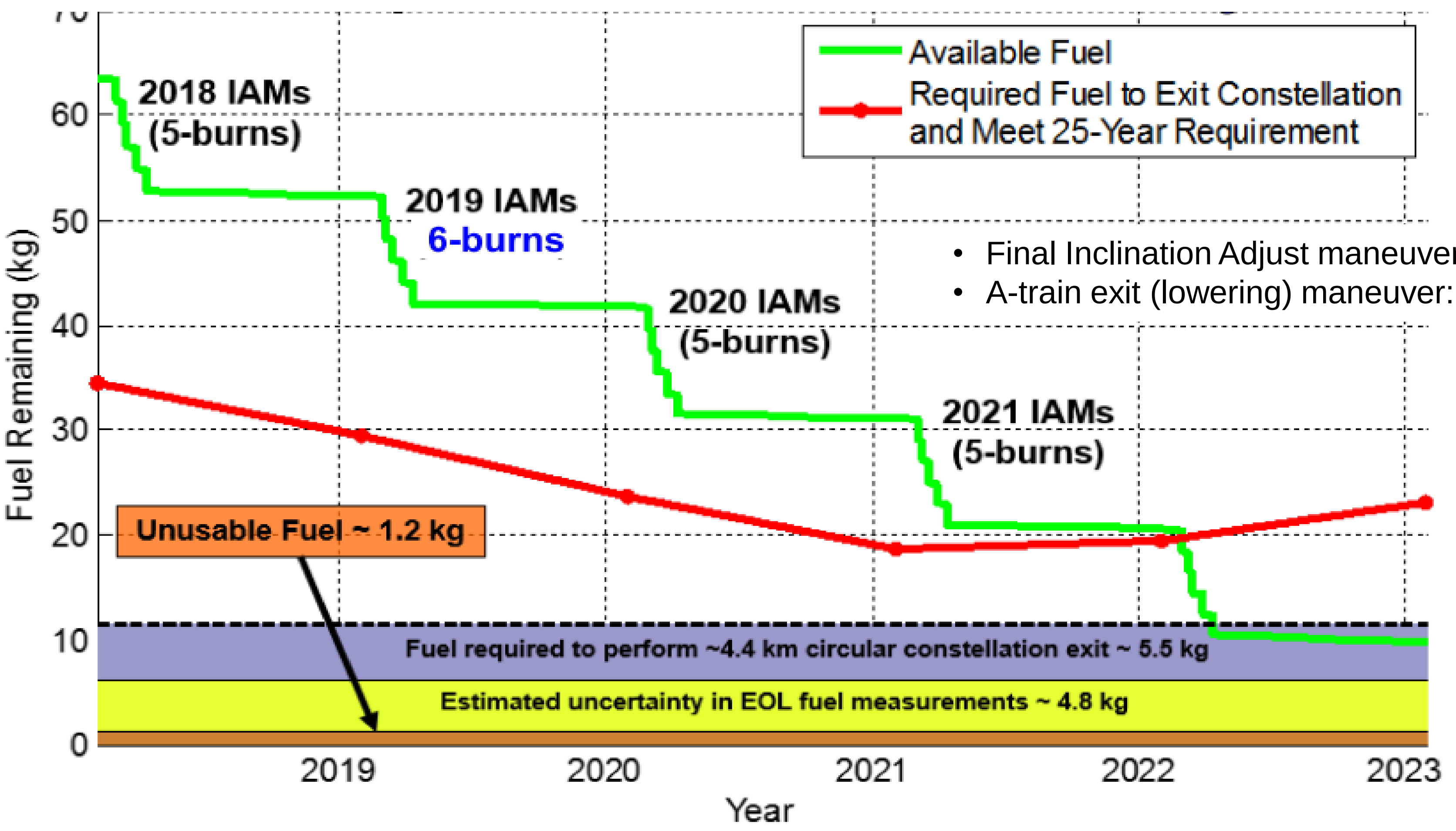


GainTable loads

2003-01-10	2013-06-10
2003-11-18	2015-03-23
2012-01-21	2018-xx-xx

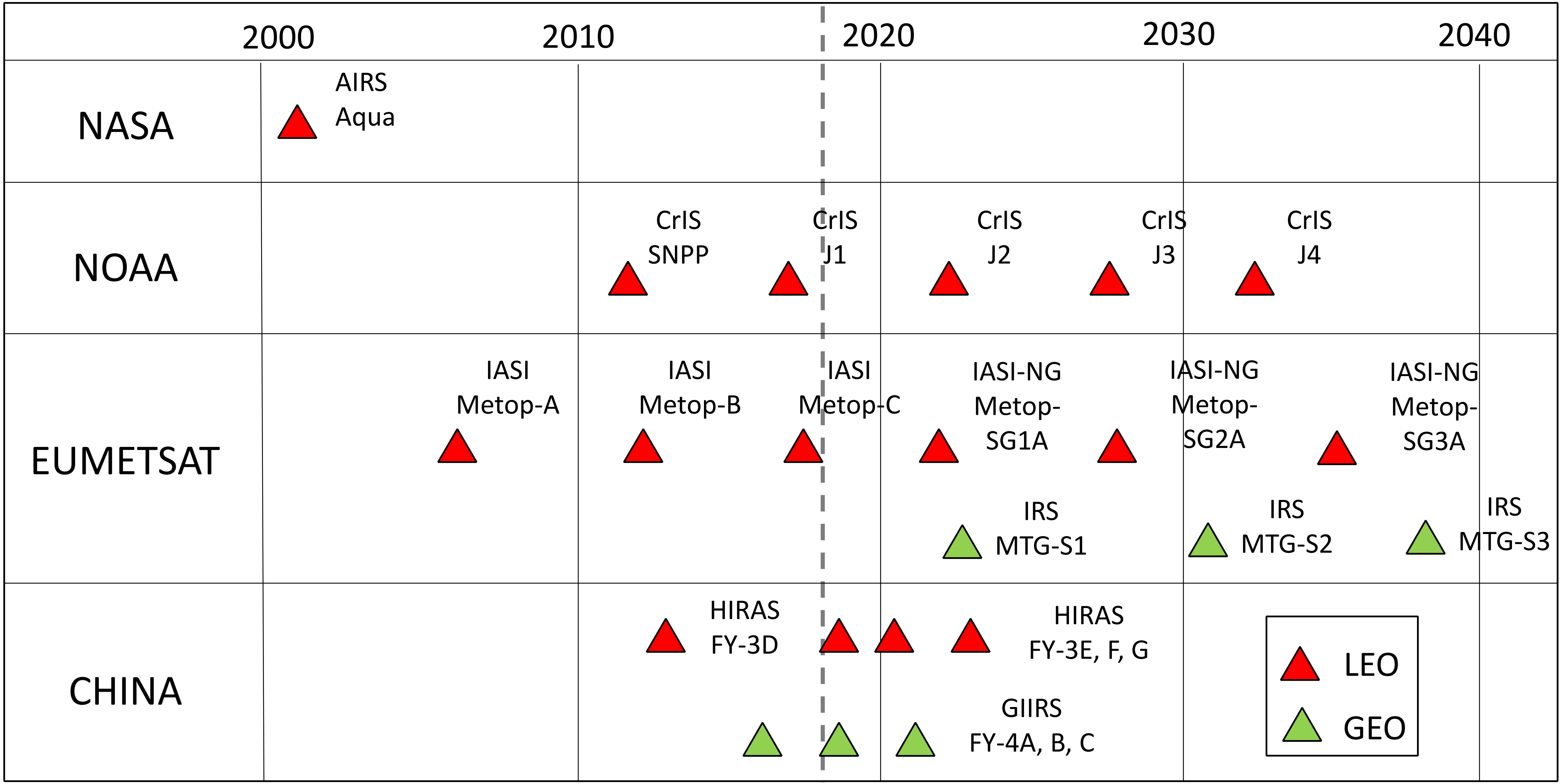
Aqua and AIRS Expected to Last beyond 2022

- Aqua Flight Operations Team is continuing to test alternate orbit-lowering maneuver(s)
- Post-2022 orbit will also have thermal impact on AIRS – specifically, 2nd stage heater will need to draw more power to maintain spectrometer temperature
- AIRS is expected to last the life of the spacecraft



- Final Inclination Adjust maneuvers: March-April 2021
- A-train exit (lowering) maneuver: March 2022

AIRS Success Followed by Numerous Operational Sounders Worldwide



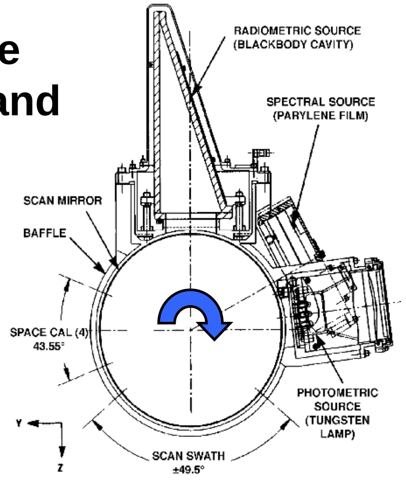
AIRS Demonstrates Key IR Sounding Technologies

AIRS Features

- Orbit: 705 km, 1:30pm, Sun Synch
- Pupil Imaging IFOV : 1.1° x 0.6° (13.5 km x 7.4 km)
- Scanner Rotates about Optical Axis (Constant AOI on Mirror)
- Full Aperture OBC Blackbody, ε>0.998
- Full Aperture Space View
- Solid State Grating Spectrometer
- Temperature Controlled Spectrometer: 158K
- Actively Cooled FPAs: 60K
- No. Channels: 2378 IR, 4 Vis/NIR
- Mass: 177Kg,
  Power: 256 Watts,
  Life: 5 years (7 years goal)

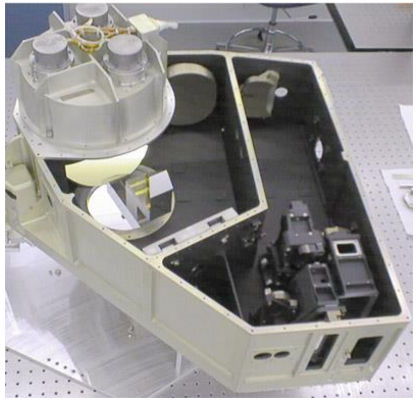
Full Aperture Blackbody and Space View

Isolated Scan Cavity



Temperature Controlled Instrument

Active Detector Cooling

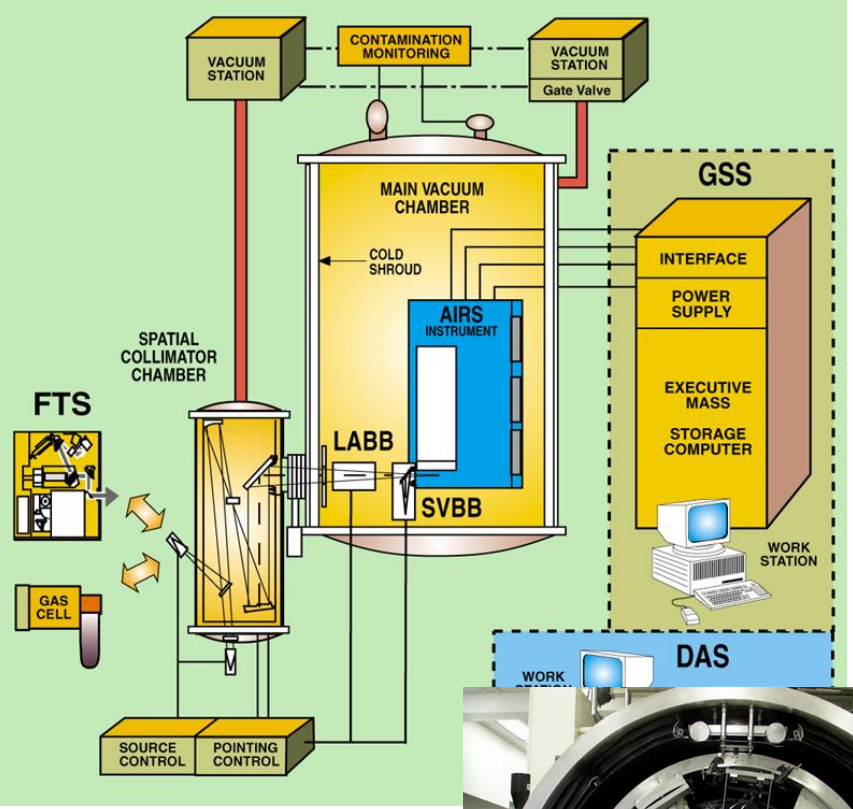


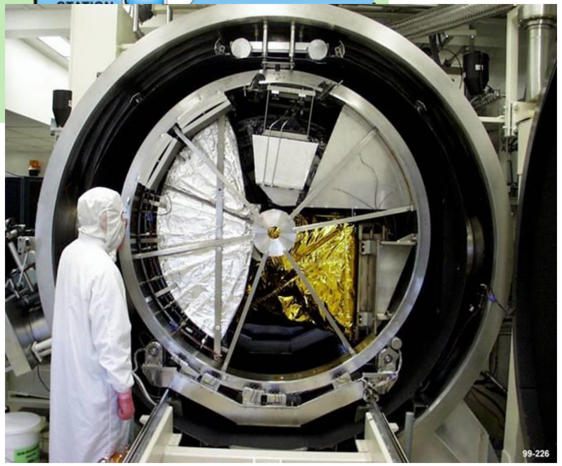
Grating Spectrometer

IR Spectral Range:
3.74-4.61 µm, 6.2-8.22 µm,
8.8-15.4 µm
IR Spectral Resolution:
≈ 1200 (λ/Δλ)
No. IR Channels: 2378 IR

Extensive Pre-flight Calibration on AIRS Ties to NIST Standards

- Radiometric Response
  - Emissivity, Nonlinearity
  - Stray Light, Polarization
  - Scan Angle Dependence in TVAC
  - Transfer to On-Board Blackbody
  - 2 TVAC Cycles
- Spectral Response
  - SRF Characterization with FTS
  - Channel Spectra Characterized
- Spatial Response
  - Top-hat Functions All Channels
  - Stray Light Excellent
  - Far Field Response Excellent
- Good Documentation
  - Over 400 Design File Memos





AIRS Radiometric Transfer Equations

Scene Radiance

$$L_{ev} = L_o(\theta) + \frac{c_1'(dn_{ev} - dn_{sv}) + c_2(dn_{ev} - dn_{sv})^2}{[1 + p_r p_t cos2(\theta - \delta)]}$$

Mirror Polarization Contribution

$$L_o(\theta) = \frac{L_{sm} p_r p_t [cos2(\theta - \delta) - cos2(\theta_{sv,i} - \delta)]}{[1 + p_r p_t cos2(\theta - \delta)]}$$

Gain Term

$$c_1{}' = \frac{[\varepsilon_{obc} P_{obc} - L_o(\theta_{obc})][1 + p_r p_t cos2\delta] - c_2(dn_{obc} - dn_{sv})^2}{(dn_{obc} - dn_{sv})}$$

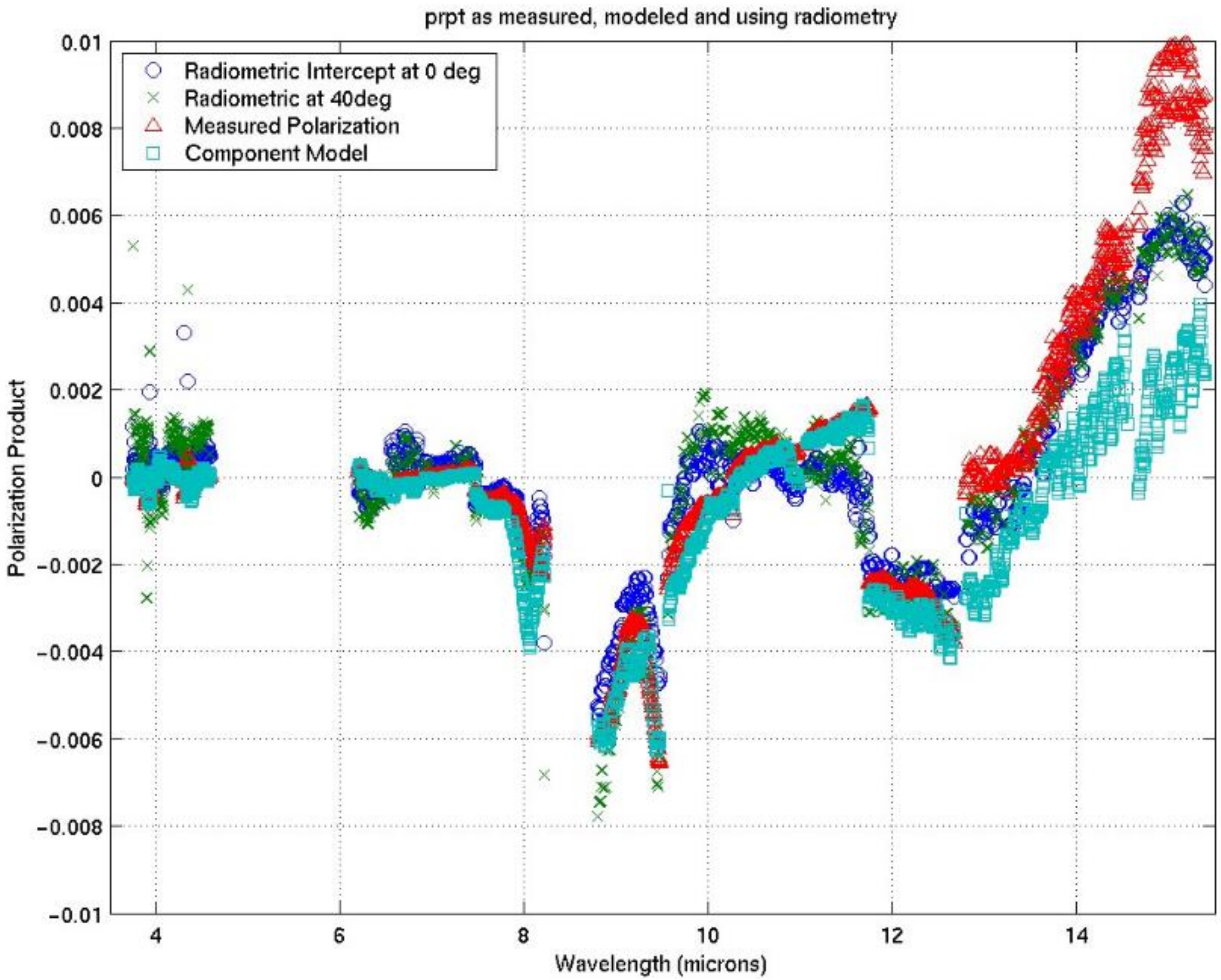
L_{ev} = Spectral Radiance in the Earth Viewport (W/m2-sr-µm)
L_{sm} = Spectral Radiance of the Scan Mirror for Unity Emissivity at T_{sm} (W/m^2-sr-µm)
L_o = Spectral Radiance Correction for Scan Mirror (W/m^2-sr-µm)
c_1 = Instrument gain (W/m^2-sr- µm-counts)
c_2 = Instrument nonlinearity (W/m^2-sr- µm-counts^2)
dn_{ev} = Digital counts while viewing Earth for each footprint and scan (counts)
dn_{sv} = Digital counts while viewing Space for each scan (counts)
$p_r p_t$ =Product of scan mirror and spectrometer polarization diattenuation (unitless)
θ = Scan Angle measured from nadir (radians)
δ = Phase of spectrometer polarization (radians)
P_{obc} = Plank Blackbody function of the OBC blackbody at temperature T_{obc} (W/m^2-sr-µm)
T_{obc} = Telemetered temperature of the OBC blackbody (K) with correction of +0.3K.
ε_{obc} = Effective Emissivity of the blackbody
dn_{obc} = Digital number signal from the AIRS while viewing the OBC Blackbody

V7k

- T. Pagano et al., "Reducing uncertainty in the AIRS radiometric calibration", Proc. SPIE 10764-23, San Diego, CA (2018)
- T. Pagano et al., "Pre-Launch and In-flight Radiometric Calibration of the Atmospheric Infrared Sounder (AIRS)," IEEE TGRS, Volume 41, No. 2, February 2003, p. 265
- T. Pagano, H. Aumann, K. Overoye, "Level 1B Products from the Atmospheric Infrared Sounder (AIRS) on the EOS Aqua Spacecraft", Proc. ITOVS, October 2003

Multiple Methods Used to Determine $p_r p_t$ in V5

V5 Coefficients Determined Pre-Launch and Not Changed Since

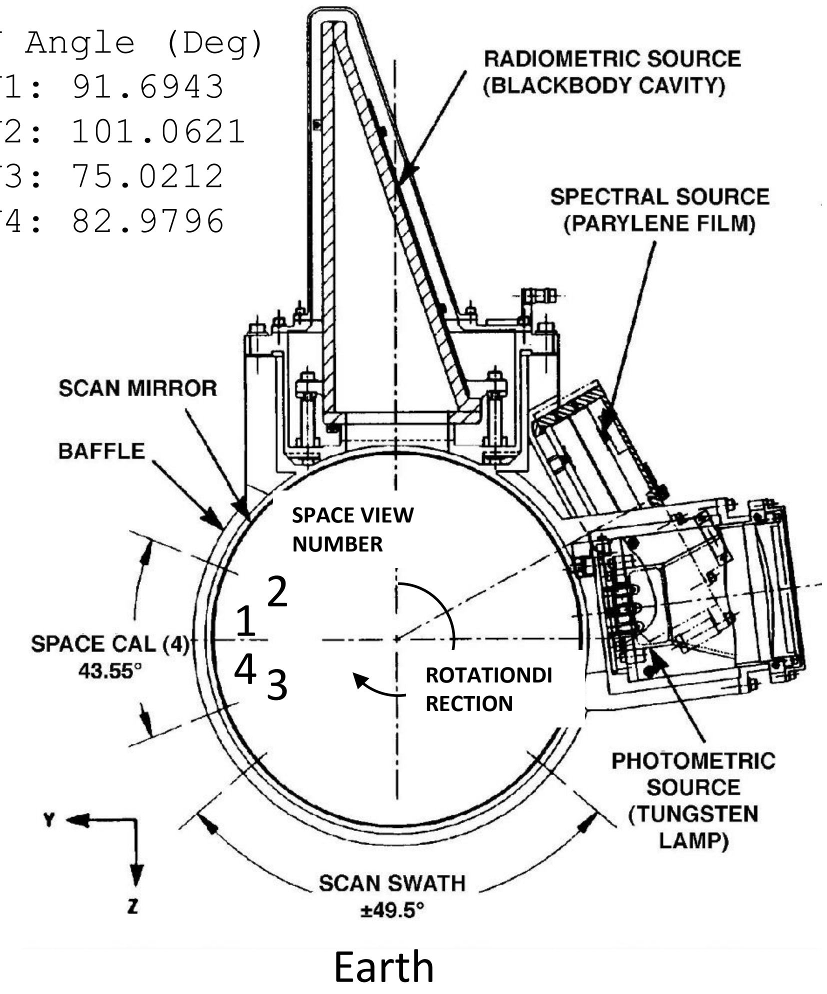


High Uncertainty Especially in LWIR

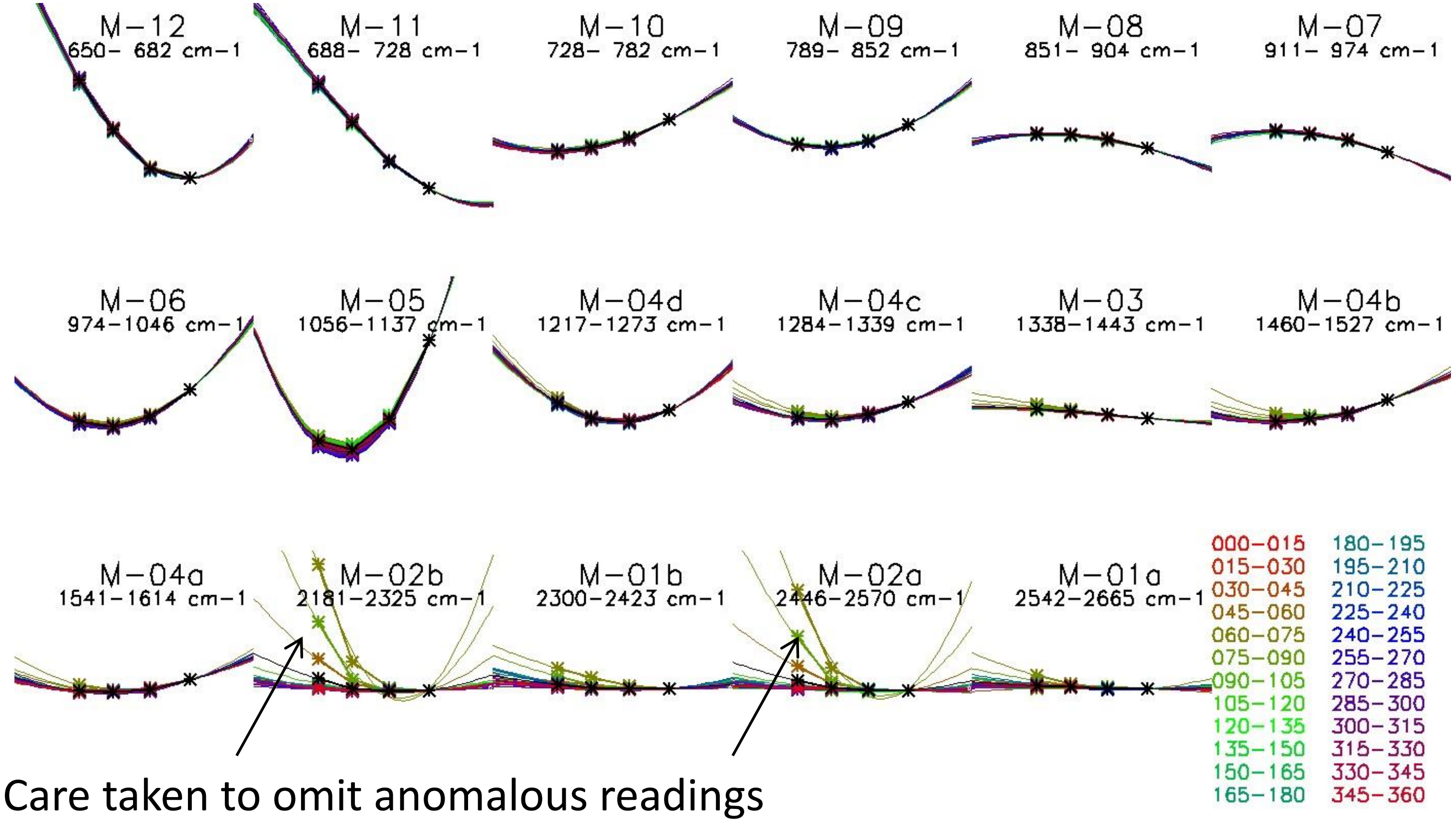
V5 is average of "Measured" and "Modeled" polarization, with Phase = 0

New Method Uses Multiple Space Views to Derive Polarization

SV Angle (Deg)
SV1: 91.6943
SV2: 101.0621
SV3: 75.0212
SV4: 82.9796



Every space view in the mission used to give 171 monthly averages

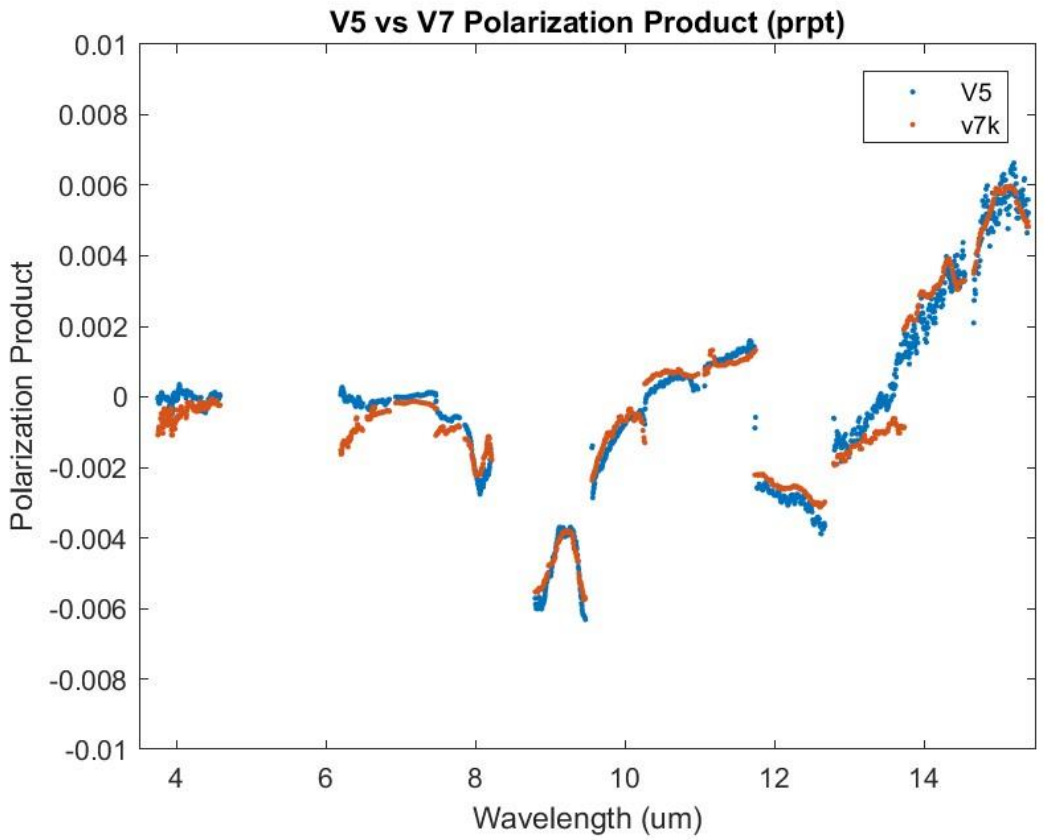


Care taken to omit anomalous readings

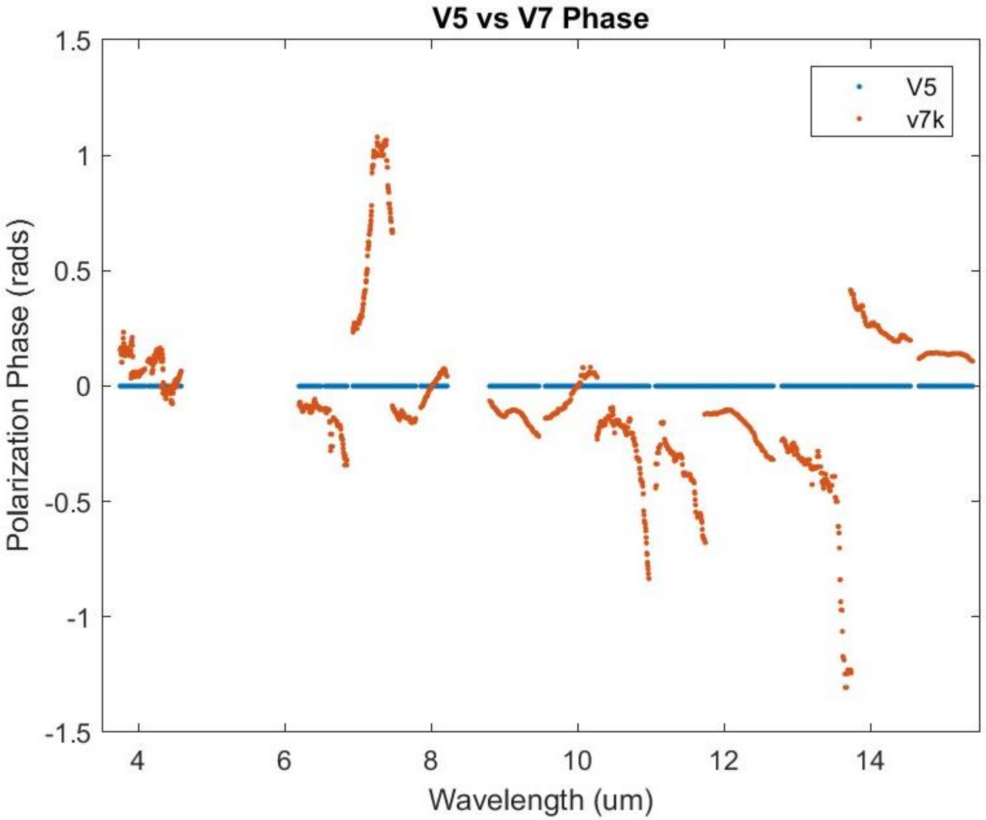
$$(dn_{sv,i} - dn_{sv,1})c_1' = -L_{sm}p_r p_t\left[cos2\theta_{sv,i}cos2\delta + sin2\theta_{sv,i}sin2\delta + cos2\delta\right]$$

V7k Compared to V5: Polarization and Phase

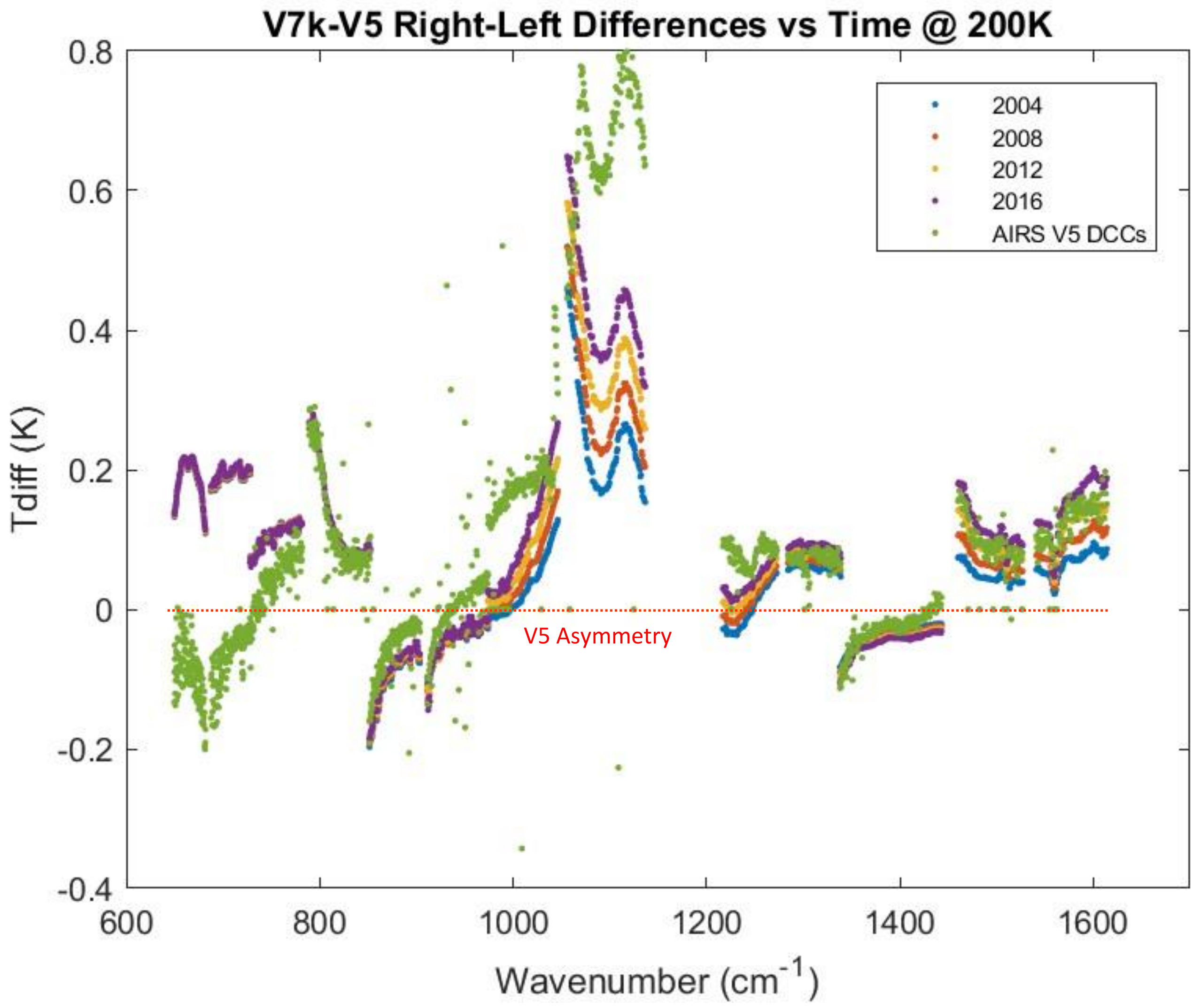
$p_r p_t$

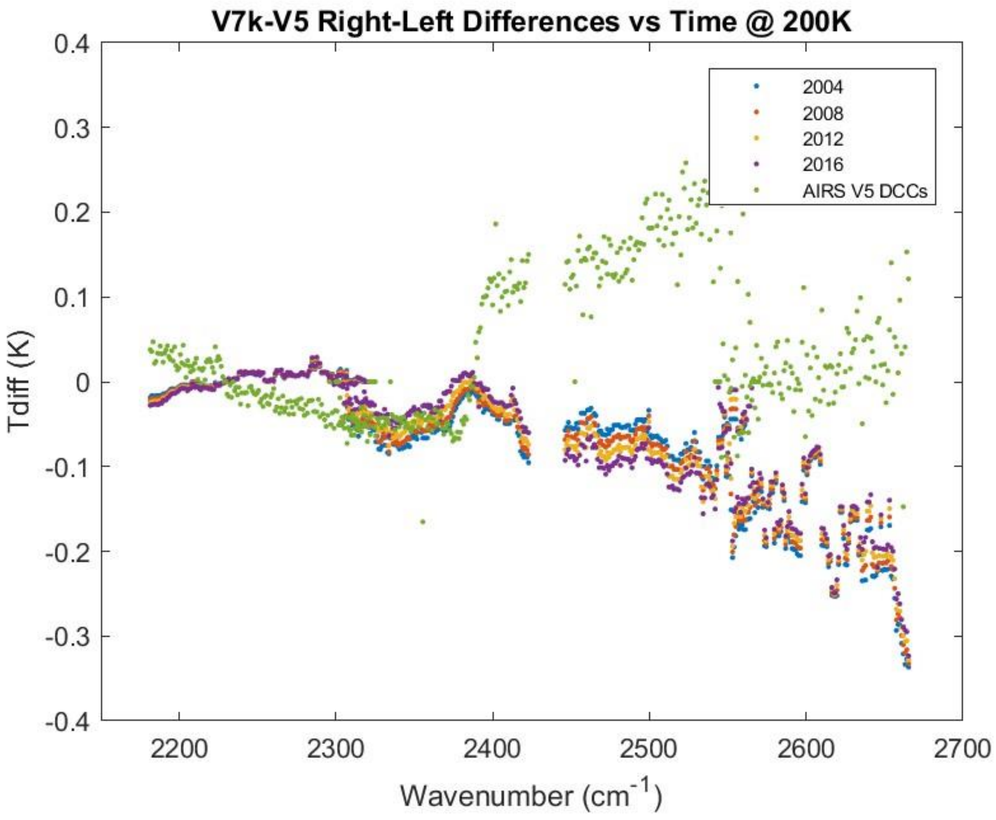


phase



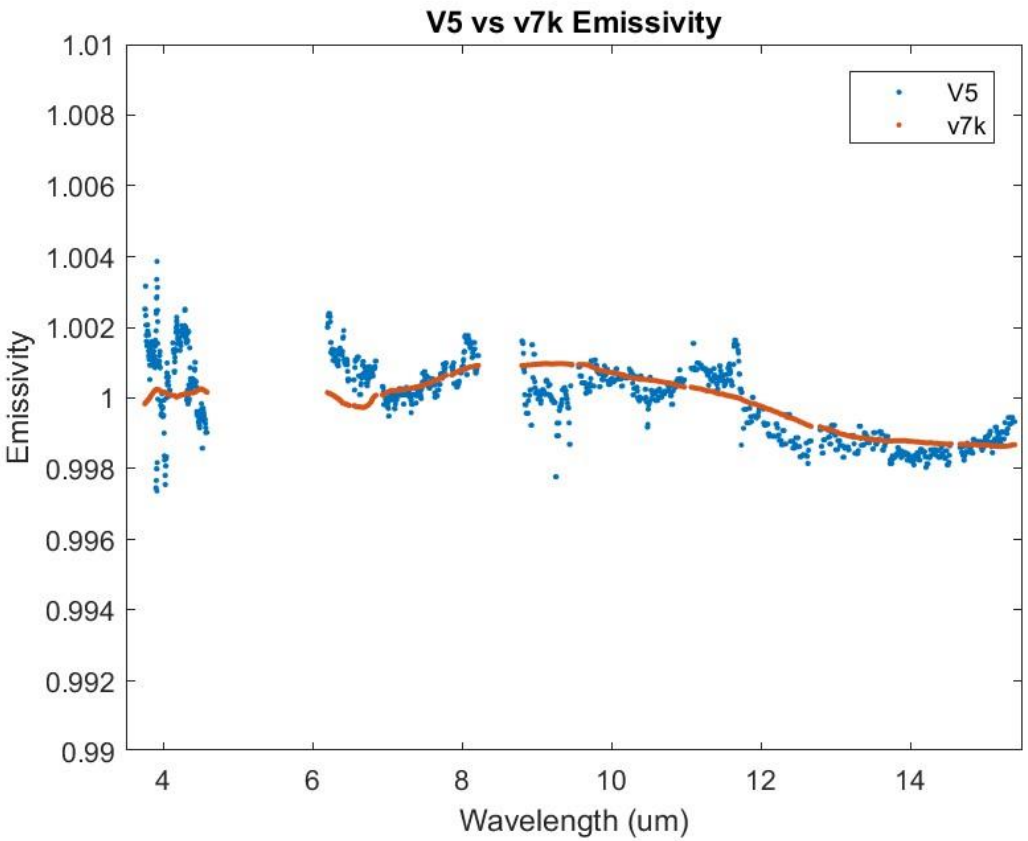
L/R Asymmetries V7k Compared to V5 DCCs



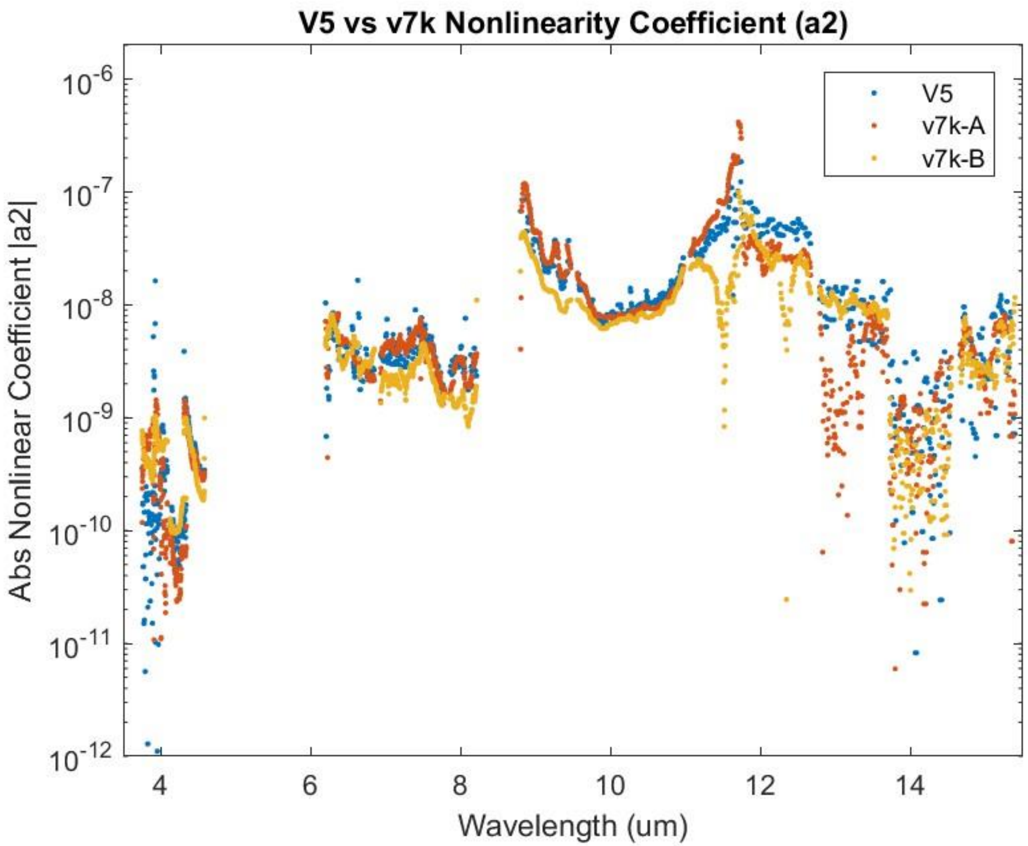


Changes Made to Emissivity and Nonlinearity

V7k Emissivity Smoothed over Channels



V7k Uses Separate A & B Nonlinearity



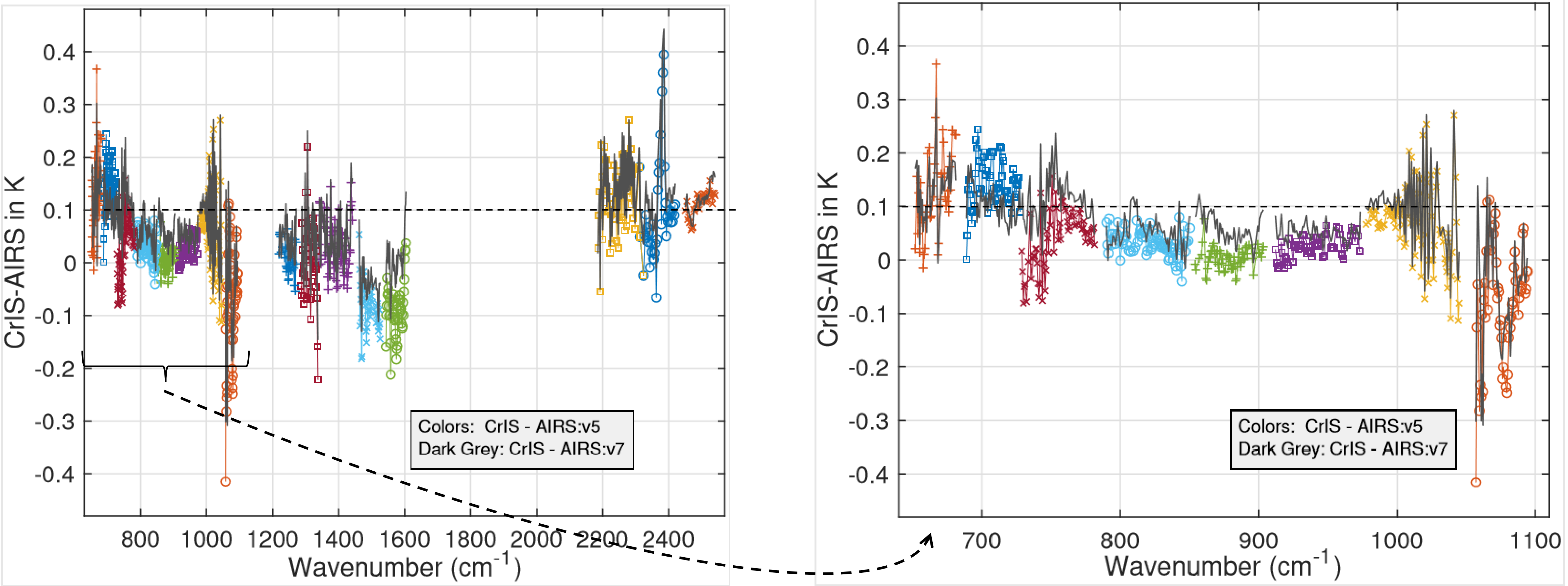
CrIS-AIRS Shows Bias Improvement with V7k

Original figures and analysis by L. Strow

- Improvement of 50-200 mK seen in all modules
- Mostly due to smoothed emissivity
- Reduction of Module Boundary Differences
- Residual CrIS-AIRS bias seen approaching 100 mK

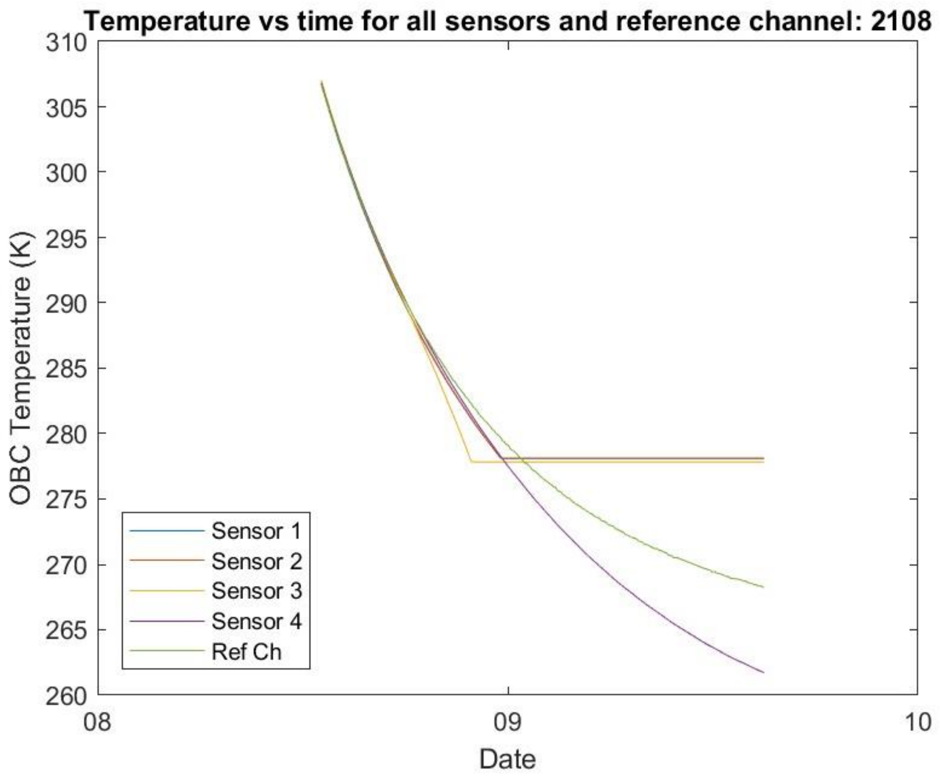
Module Boundary Differences

Module	M5	M6	M7	M8	M9	M10	M11
Module	M6	M7	M8	M9	M10	M11	M12
(cm-1)	1045.5	973.2	903.3	851.6	781.3	727.9	681.8
V5 (mK)	300	50	5	100	50	80	250
V7k (mK)	300	10	5	0	5	0	60

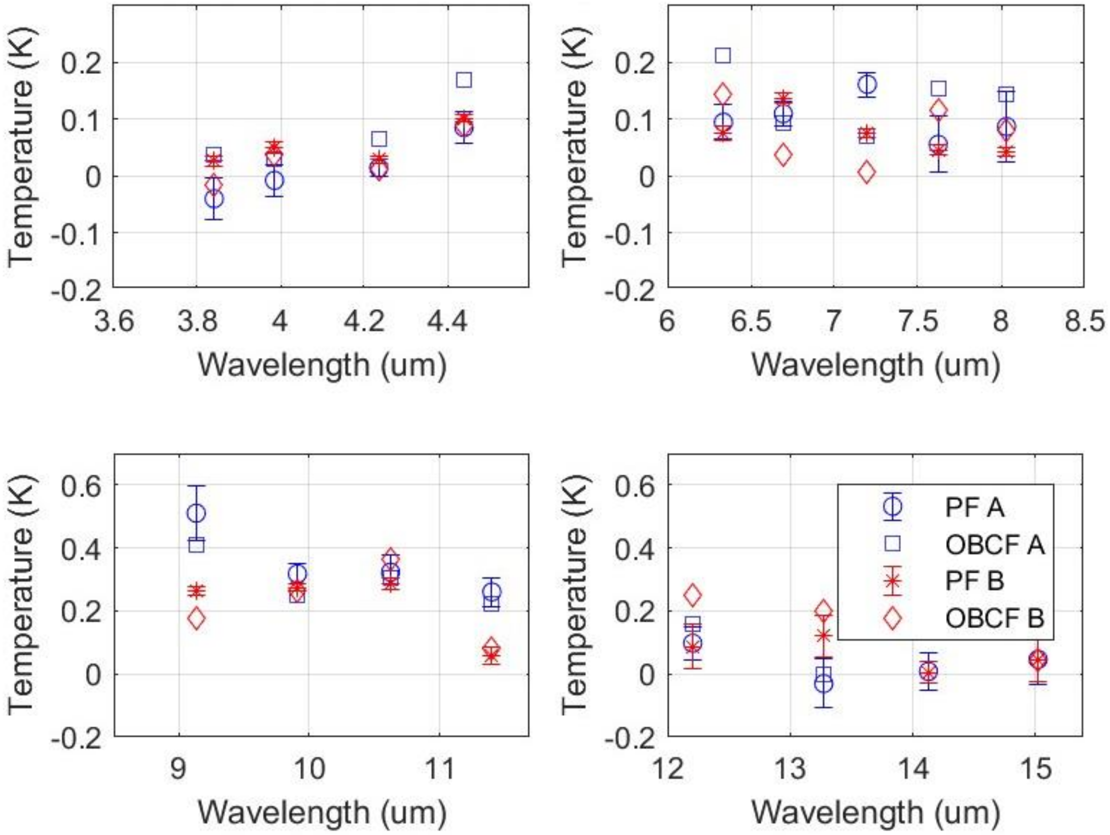


OBC Float Test Confirms A/B Unique Nonlinearity Coefficients

In-flight OBC Float test Temperatures



Nonlinearity Contribution at 250K
Error Bars are 1-sigma Uncertainty Pre-Flight

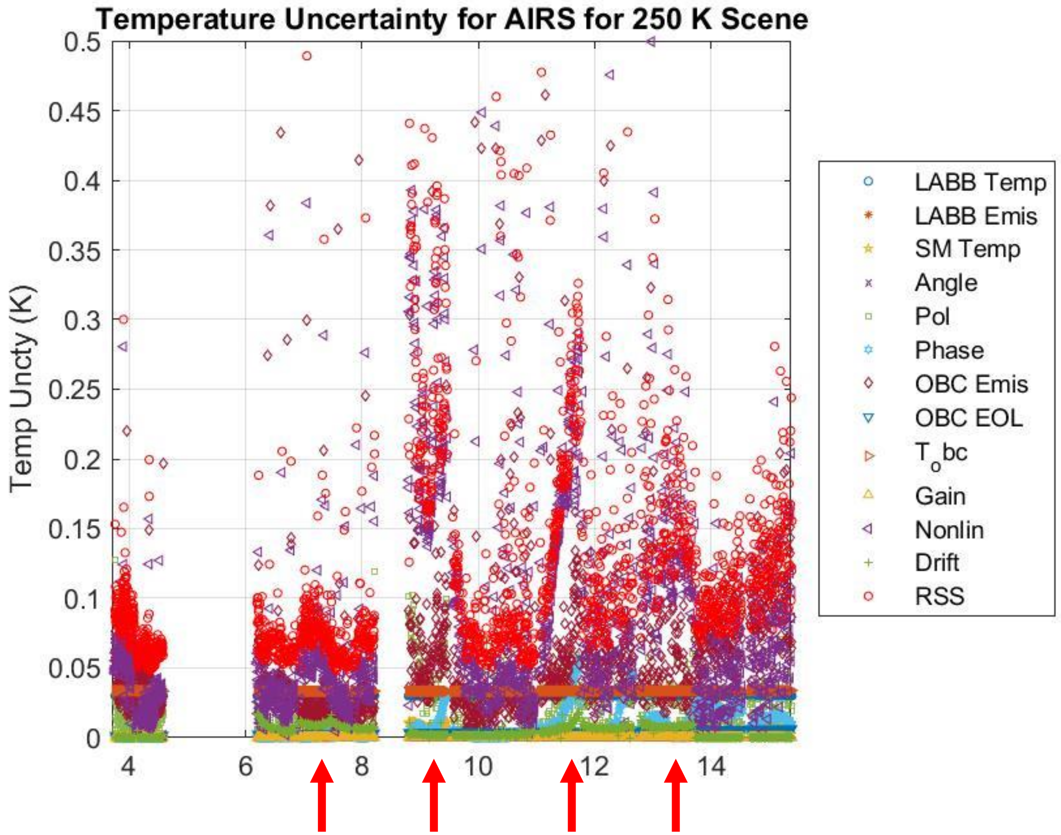


Pagano, T. S. et al., "Checking AIRS nonlinearity in flight", Proc SPIE 11127-43, San Diego, CA (2019)

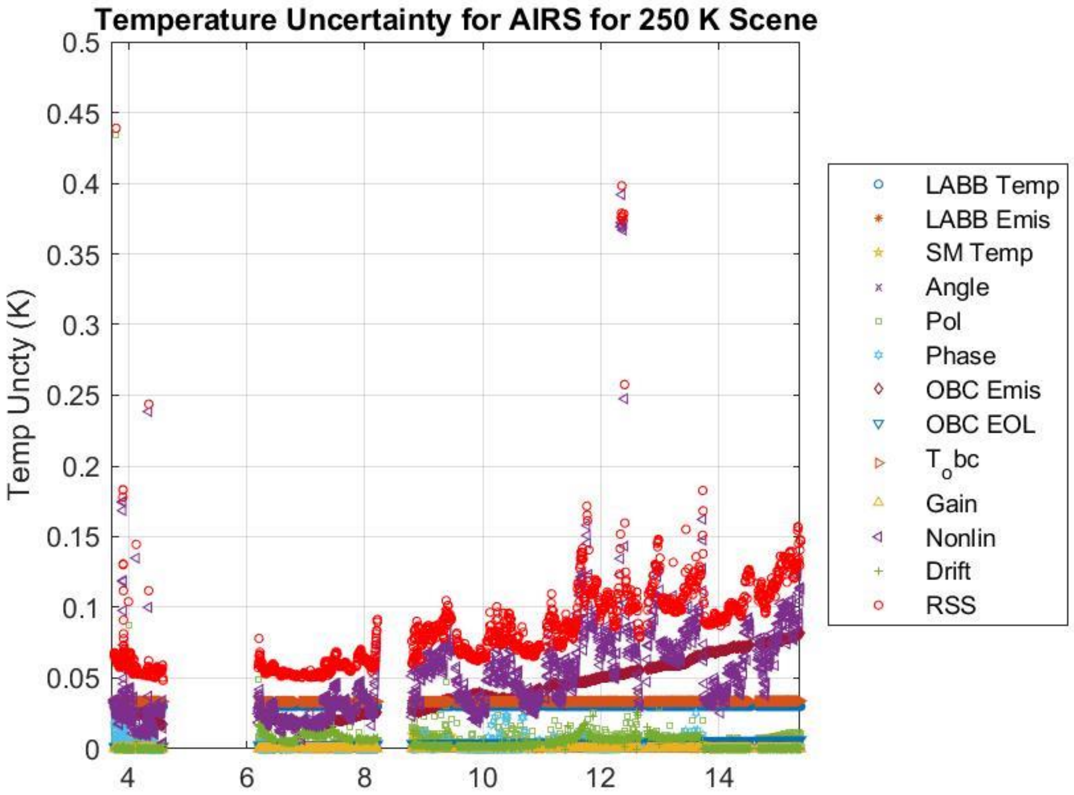
V7k Reduces Radiometric Uncertainty (1σ)

- Accuracy assumes A and B differences in nonlinearity seen pre-flight are real
- OBC Float Test Needed to Verify A vs B Nonlinearity

V5



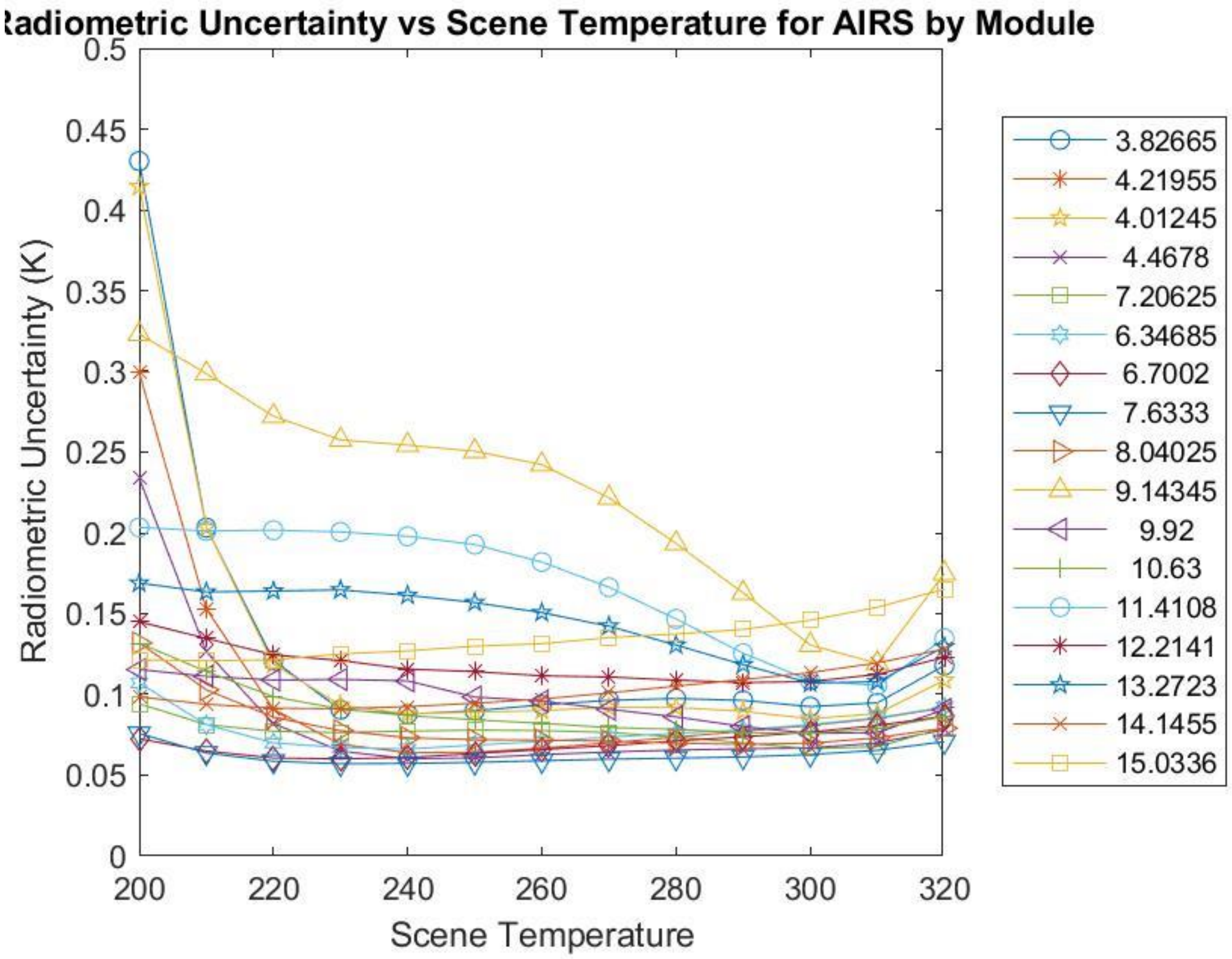
V7k



V5 Radiometric Uncertainty (1-sigma)

Radiometric Uncertainty Inputs at 9.14 µm and Impact to Calibration at 260K

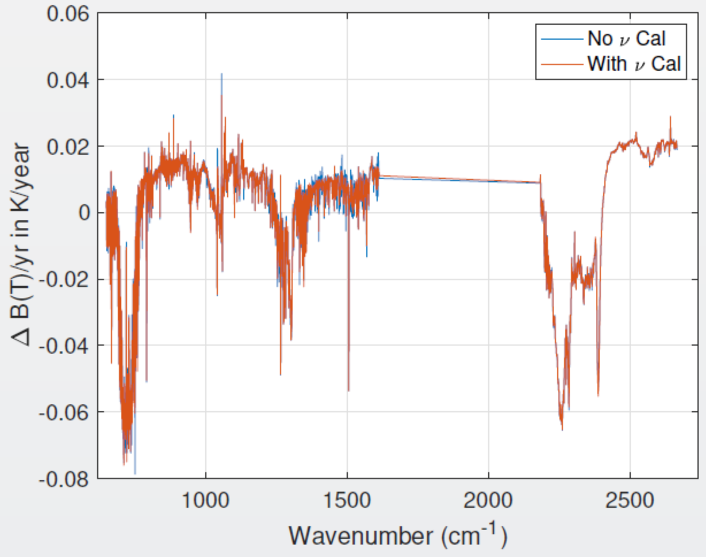
Parameter	1-σ Parameter Uncty	1-σ Radiometric Uncty (K)
Version	V5	V5
Uncertainty in LABB Temperature	0.03K	0.03K
Uncertainty in LABB Emissivity	0.00005	0.002K
Uncertainty in Scan Mirror Temperature	1.25K	0.006K
Uncertainty in Polarization Amplitude	.0009	0.04K
Uncertainty in Polarization Phase	.08	0.005K
Uncertainty in OBC Blackbody Emissivity	.002	0.07K
Uncertainty in OBC Blackbody Emissivity (EOL)	0.0001	0.004K
Uncertainty in OBC Blackbody Temperature	0.05K	.04K
Uncertainty in Nonlinearity	2.7%*	0.21K
Uncertainty in drift in space view	0.04dn	0.001K
Total Uncertainty at 260K		0.24K



UMBC Exploring Stability of AIRS Radiances

AIRS Radiance Stability is Excellent

Stability: Clear Ocean Trends



- This is AIRS 16-year clear ocean BT trend
- Shortwave has issues, not used for science trending
- Compare to ERA vs latitude for "good channels"
- Modify ERA SST to account for effect of water vapor on BT trends

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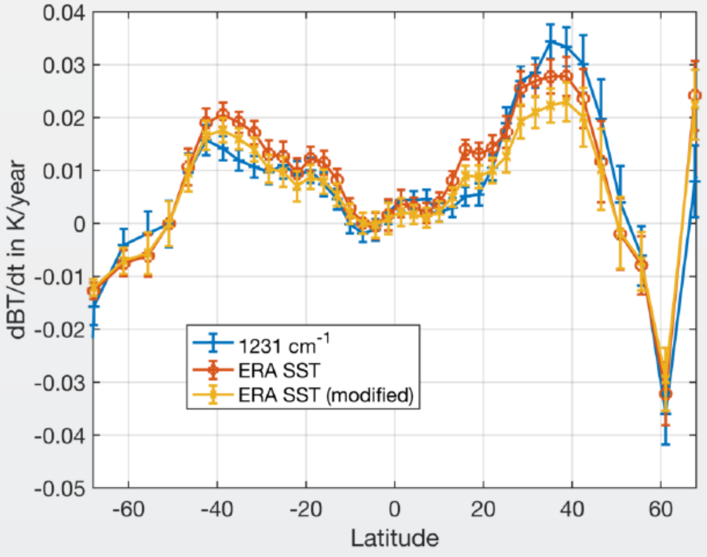
AIRS Radiance Trends Follow Model

Stability: AIRS 1231 cm^{-1} Trends vs ERA SST Trends



- ERA SST modification due to water vapor absorption
- These are quite accurate, use Aumann's "split-window" to correct
- AIRS trending hotter by ~0.003K/year
- Differences mostly 30-40 deg. lat??, look at time-dependence

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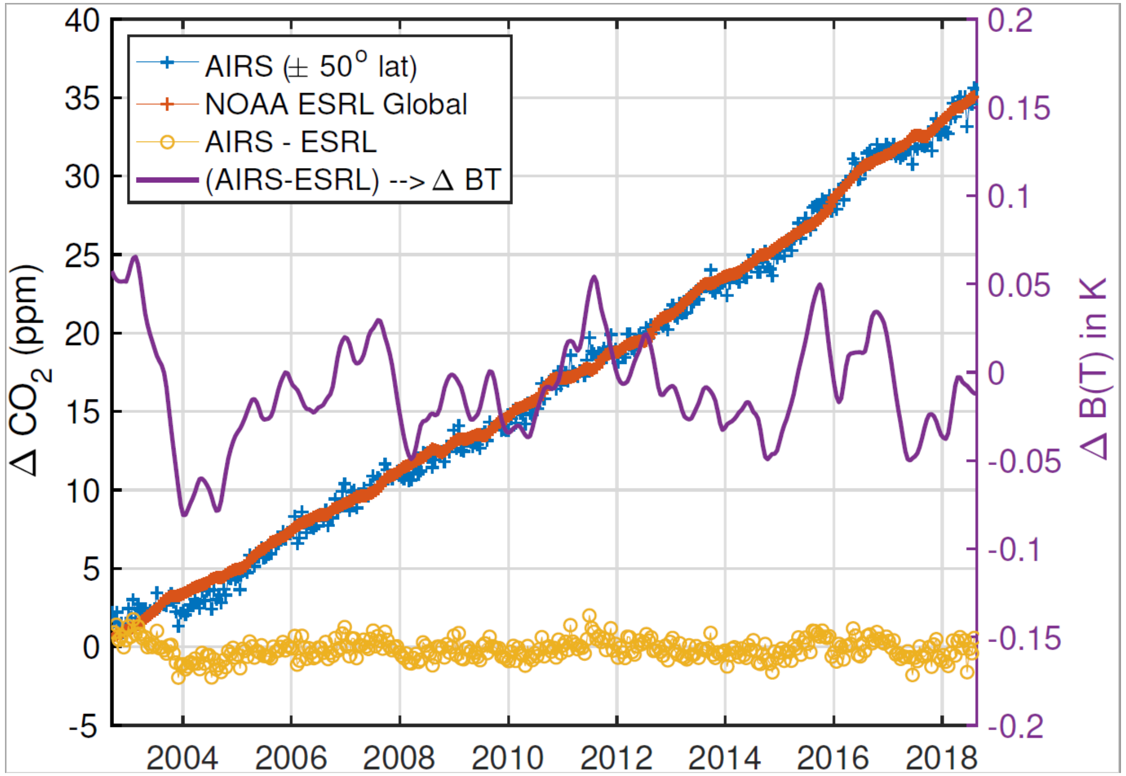
AIRS Radiometric Stability via CO_2 Trends



- CO2 well mixed and can be used for AIRS stability tests
- CO2 in-situ measurement stability below 1mK/year in B(T) units (16 years)
- Collect AIRS ocean-only clear scenes and create 16 day averages (over 40 latitude bins).
- Remove seasonal variability and form B(T) anomaly.
- Use an optimal-estimation retrievals to compute CO_2(t), other trace gases, and T(z,t), H_2O(z,t), O_3(z,t), SST, etc.
- Compare retrieved CO_2 ramp to in-situ (SI traceable) CO_2 measurements from NOAA ESRL

- Results show good agreement.
- Offsets near Nov 2003 understood.
- Results suggest near zero trends with a statistical uncertainty of about 0.004K/year.

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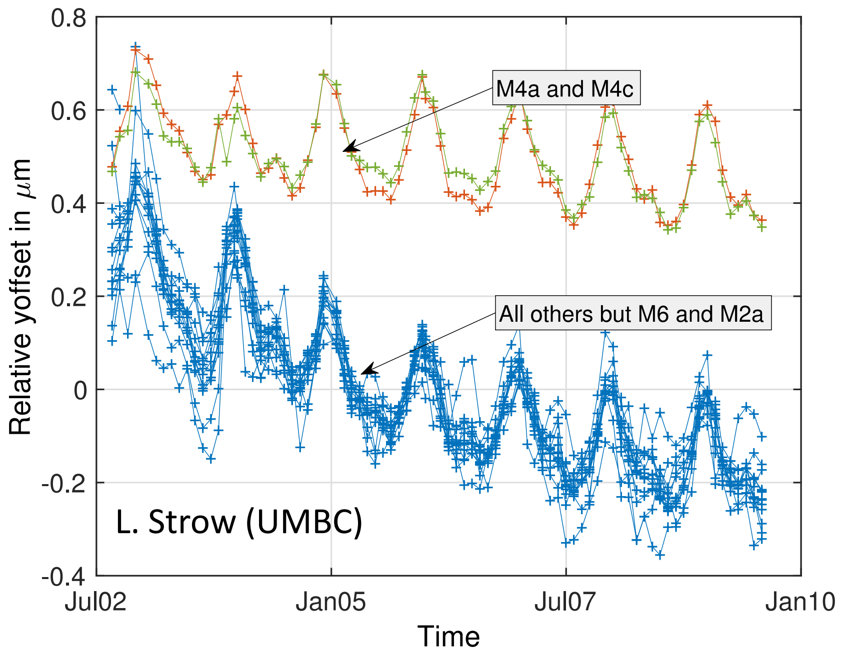
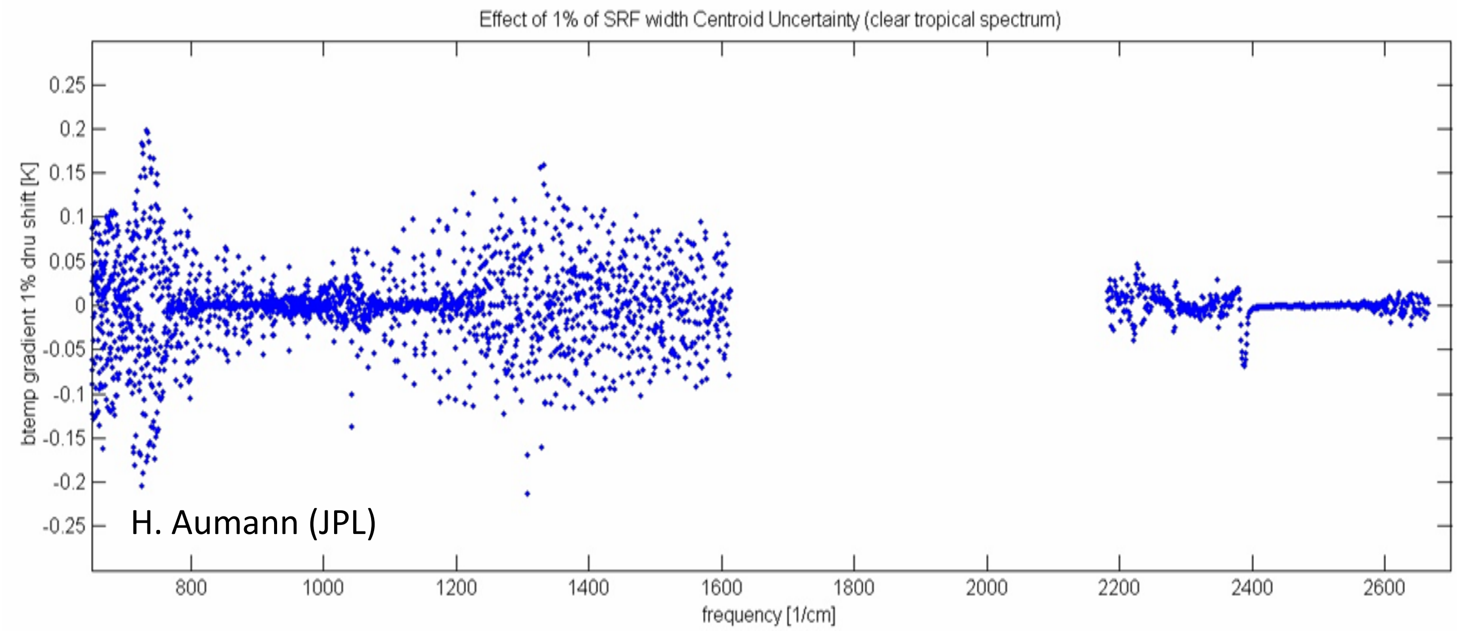
AIRS shows excellent spectral stability



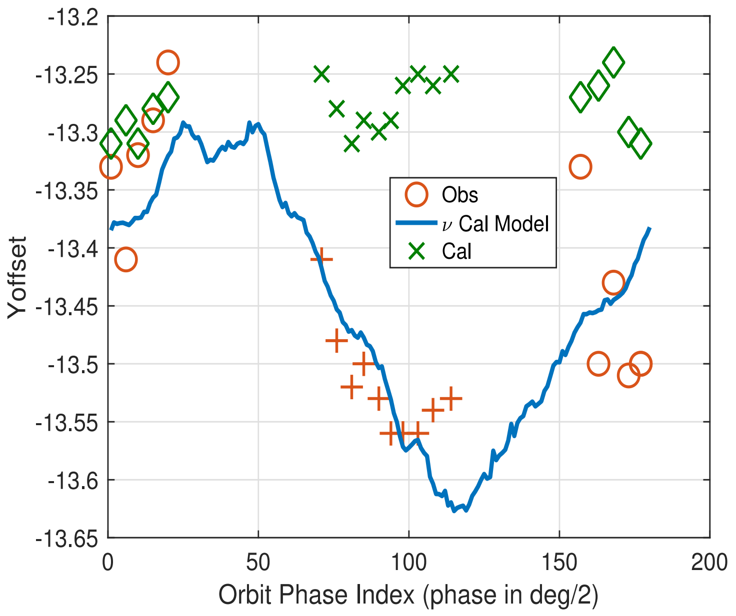


- Changes in 5 years of AIRS data in terms of y_0 as a function of time
- 0.1 µm in focal plane dimensions is 0.1% of channel spacing (1ppm)
- The long-term component:
  - An annual trend of -0.07 µm per year early in the mission
  - Leveling off around 2008
- Worst case peak-to-peak orbital cycle + seasonal + long term is ~1 µm or ~8 ppm.

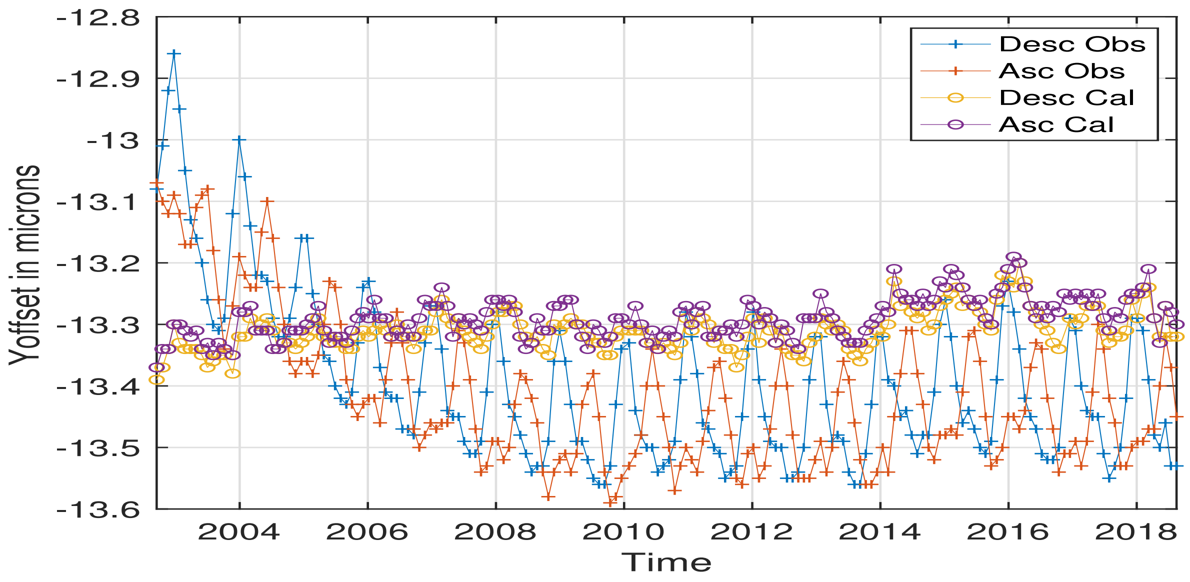
- The frequency grid of AIRS varies with orbital, seasonal, and long-term components, but only by 0.5% of width of the SRF.
- AIRS requirement is knowledge within 1%. **Actual is about 0.2%**
- The effect is much less than the instrument noise, i.e. for most applications it can safely be ignored.
- This effect becomes significant only when many spectra are analyzed together, as in the evaluation of long-term climate trends, or comparing day vs. night characteristics, where the random noise in each measurement becomes insignificant.

Spectral Calibration Enables Correction to Constant Frequencies

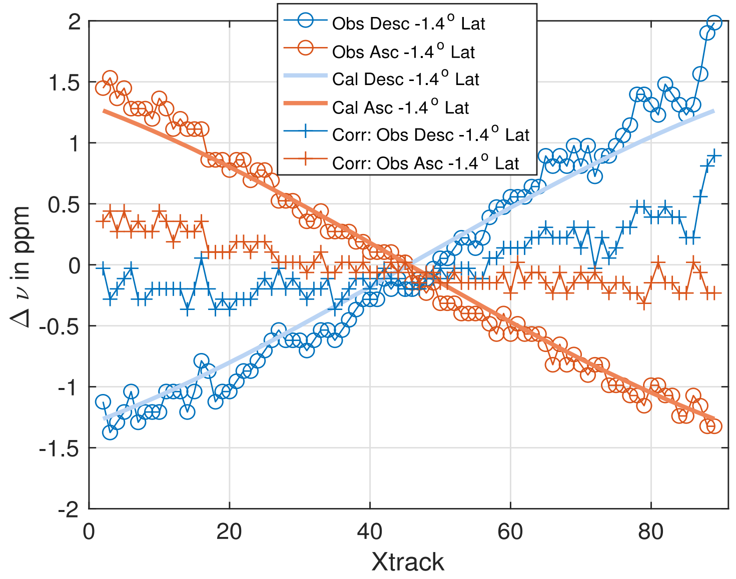
Improved Correction for Orbital Variations



Resulting calibration good to <0.2 micron



Improved Correction for Doppler Effects



We use this information in L1C V6.6 to resample the entire mission to a common frequency set.

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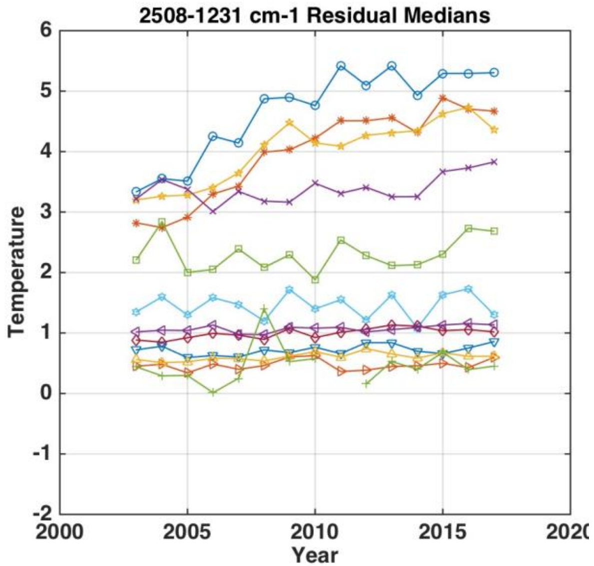
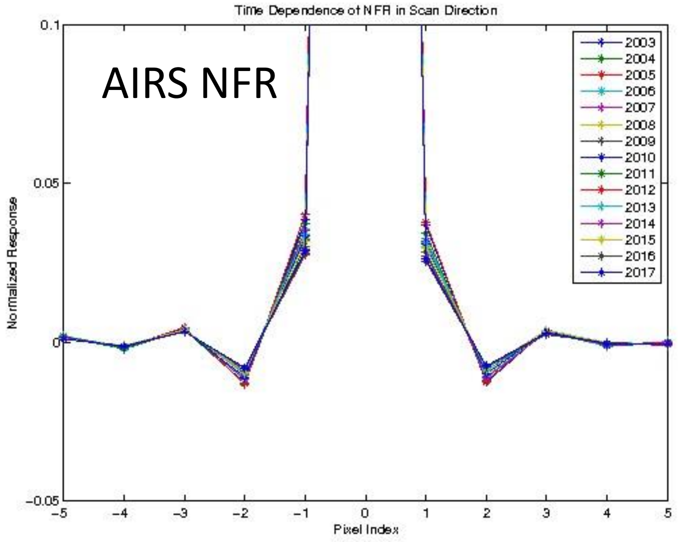
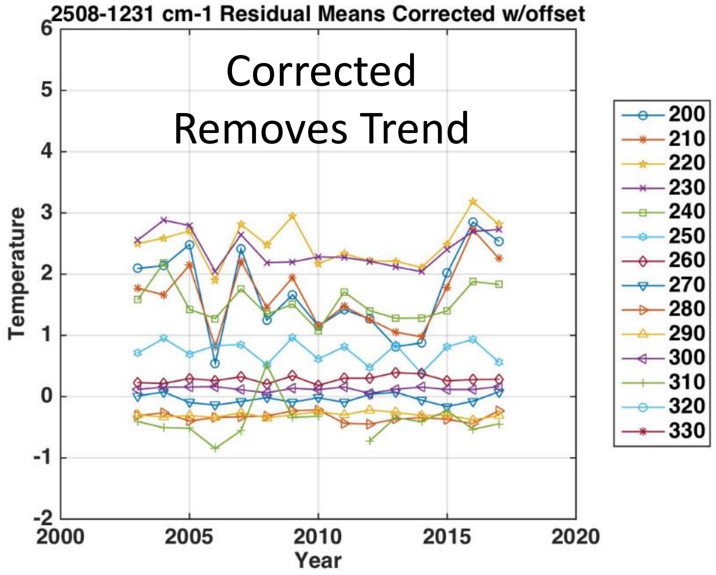
Spatial Response Impacts Radiometric Trend and Bias

Mirror degradation likely culprit for SW trends in non-uniform scenes





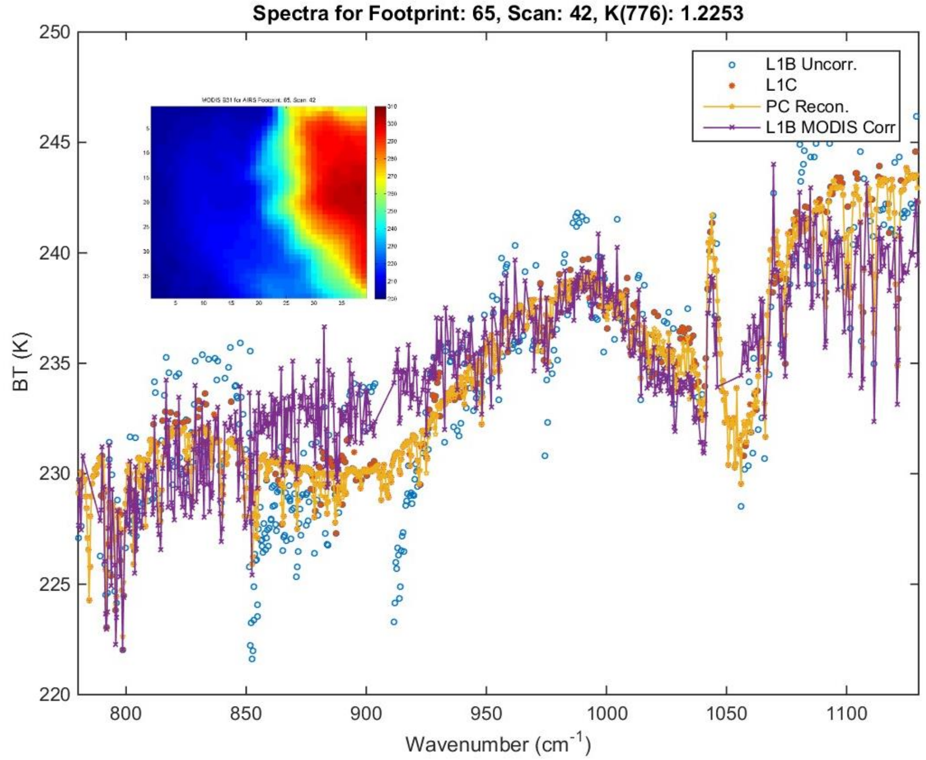


- Trend seen in AIRS 2508 cm^{-1} – 1231 cm^{-1} when viewing DCCs
- Trend not seen on Dome C
- Regression of PSF on the difference with 1231 cm^{-1} reveals changing PSF
- Correction of PSF removes trend
- >6x6 uniformity should be used to evaluate geophysical trends

T. Pagano, “AIRS In-Flight Near Field Response and Observed Shortwave Drift”, ADF 930, Sept 16, 2018
C. Wilson, “Radiometric Calibration of AIRS and Possible contamination ofScan Mirror”, AGU, December 2018

Non-uniform Scenes Impact Spectrum

Differing point spread functions can cause breaks in AIRS spectra in Non-uniform scenes



- AIRS Level 1C can reconstruct bad channels
- Using an imager (MODIS) can correct effect

T.S. Pagano, H. Aumann, D. Elliott,, E. Manning, “Improving AIRS radiance spectra in high contrast scenes using MODIS’, Proc. SPIE 9607-19, San Diego, CA (2015)

L1C Cleans-up AIRS Spectra

<u>Version 6.0</u>

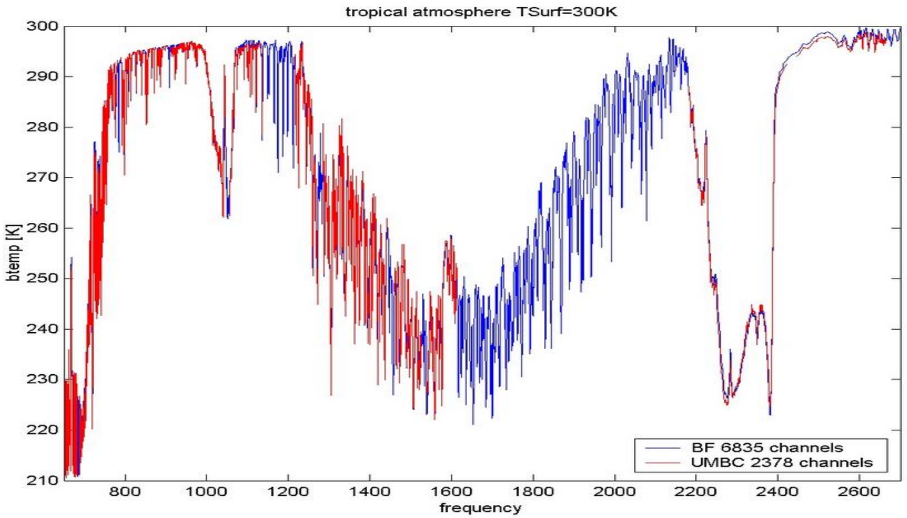
- Designed to facilitate use of AIRS Level 1 radiances
  - For Comparison to other Hyperspectral IR
  - For Comparison to Broadband Imagers
  - For Ingest by L2 Retrievals
- Version 5 L1B for all “good” channels
- Fills Dead Channels with PC Reconstruction (PCR)
- Fills bad Cij (Co-registration) Pixels with PCR
- Fills Gap with PCR
- Fills Very High Noise Pixels with PCR
- All filled channels are flagged

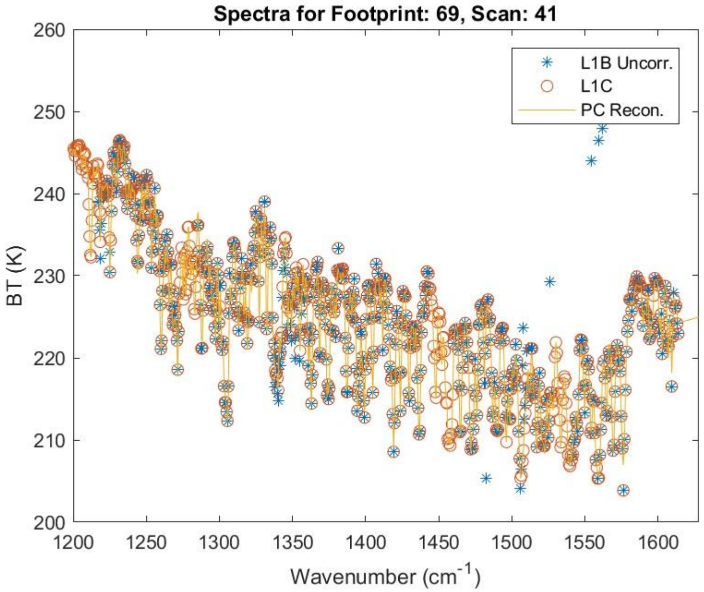
<u>Version 6.6</u>

- Same as Version 6.0 but with…
- Constant Frequency Grid (does not change with time)
- V6.6 L1C will be used to support LLS’s CHIRP product

<u>Version 7.0</u>

- Updated filling algorithms
- Version 7k Radiometric and Polarization Coefficients
- netCDF Output





- L1C V6.0 available on a 1-mo rolling basis. V6.6 & V7 Available in 2020

Lessons Learned for a Future IR Climate Observing System

- Hyperspectral Infrared Instruments Calibration
  - Instrument artifacts will impact radiometric accuracy of the system. Even with a perfect blackbody. At the 100 mK Level, everything shows up
  - Artifacts to watch for: Nonlinearity, Polarization, Non-Gaussian Noise, Ghosting, Out-of-Band, Channel Spectra, Gain Drift (Not all of these are a problem for AIRS)
  - Test conditions (viewing geometry, source drift) will impact ability to characterize the instrument
  - Comprehensive pre-flight testing with full documentation will allow you to go back and re-analyze the data if needed
  - Nonlinearity characterization on-orbit is essential.
  - Nonlinearity can change from ground to orbit as gain changes
  - Deep Space Look enables characterization of mirror emission properties
- Radiance Trending for Climate
  - Use large uniform scenes
  - Use spectral windows to avoid spectral shifts or use L1C
  - Know the stability of your target: E.g. SST, CO_2 Trends
  - Multiple Satellites (AIRS, CrIS, IASI) allow bridging operational gaps in data
- IR Sounders are remarkably well calibrated and at the threshold of establishing climate trends with statistical significance and well defined uncertainties.

Summary and Conclusions

- NASA AIRS on Aqua in excellent shape through 2022
  - Over 1000 Peer Reviewed Publications using AIRS data
- The AIRS instrument is remarkably stable
  - AIRS 17-year record is an important baseline for climate studies.
  - Validation of stability shows window channels < 10 mK/year
  - Stability across the spectrum complicated due to changing CO_2 and climate
- Radiometric Calibration Coefficients Updated for V7
  - Improves absolute accuracy, L/R Assymetry, agreement with CrIS
- New coefficients and stability validated in-orbit
- Spatial and spectral response impact stability
- Lessons learned highlight the complexity of the problem
- Expect a 40+ year IR sounder Climate Data Record
  - AIRS, CrIS and IASI agree to ~100 mK enables inter-satellite radiance climate data records to be developed
  - e.g. Strow's Climate Hyperspectral InfraRed Product (CHIRP) under development