Satellite Infrared Radiance Validation Studies using a Multi-Sensor/Model Data Fusion Approach

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Topics

- Motivation
- Validation methodology
- Calibration validation examples using spacecraft- and aircraft-based sensors
  - Instrument systems & datasets
  - Spatial registration
  - Spectral fidelity
  - Radiometric accuracy
- Summary & Conclusions

Motivation for satellite sensor cal/val and benefit from using airborne sensors

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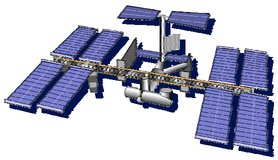
- ***Post-launch validation activities are critical to verify quality of satellite measurement system (i.e., sensor, algorithms, and direct/derived data products)***

- ***Resulting data contribute toward essential cal/val activities***
  - On-orbit sensor performance verification
  - On-orbit sensor calibration validation
  - Validate algorithms
  - Direct and derived data product validation
  - Long-term monitoring of sensor performance (radiance & geophysical)



- ***Aircraft underflights fundamental to space-based sensor validation***
  - High-altitude aircraft platforms (Proteus, ER-2, DC-8, WB-57, P-3, BAE-146-300, etc.) instrumented with validation sensors (NAST-I, S-HIS, ARIES, INTESA, NAST-M, LASE, MAS, etc.) provide validation data by obtaining spatially & temporally coincident observations with satellite platforms of interest (e.g. Terra (Modis), Aqua (Modis & AIRS), Aura (TES), and future Metop (IASI), NPP/NPOESS (CrIS), and ~~EO-3~~ (GIFTS).

Calibration Validation Approach*

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- **Spatial**
  - **Landmark navigation**
    - compare observations to databases for time invariant distinct features of known spatial characterization (e.g., coastlines)
  - **Comparison with coincident observations**
    - compare measurements with other temporally-coincident same-scene view observations containing spatial feature variability (coastlines, thermal gradients, clouds, hot lava, fires, etc.)
- **Spectral**
  - **Comparison with simulations**
    - compare clear sky measured radiance to LBL radiative transfer model calculations for spectral regions where FM parameters are well-known (e.g. spectroscopy, temperature and CO_2 profiles for 15 μ band); vary simulated instrument spectral response to minimize residuals (e.g., effective metrology laser wavenumber for FTS or channel SRFs for grating)
  - **Comparison with coincident observations**
    - compare measured radiance with other temporally-coincident same-scene view high-spectral resolution measurements (i.e., a/c- or s/c-based FTS)
- **Radiometric**
  - **Comparison with other coincident observations and simulations**
    - compare measured radiances in window and opaque regions across spectral extent, for varying uniform clear sky over ocean and overcast scene temperatures, with other observations/calculations
      - High-spectral resolution measurements (aircraft, e.g. NAST-I & SHIS; s/c, e.g. AIRS, IASI, CrIS)
      - Broadband radiance measurements (e.g., GOES, SEVERI, MODIS, VIIRS)
      - Radiative transfer calculations (using, e.g., radiosondes, NWP analysis fields, e.g., ECMWF)

* ***Applied to each detector, i.e. FTS band, grating channel, etc.***

Characteristics of Remote Sensors Employed in Study

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Instrument system	Sensor type	Spectral extent	Spectral resolution	Nadir IFOV	Platform
NAST-I	Michelson interferometer	3.5 – 16 μ, continuous	0.25 cm^{-1}, υ/δυ > 2000	2.5 km (from ER-2)	ER-2 / Proteus
S-HIS	Michelson interferometer	3.0 – 17 μ, continuous	0.5 cm^{-1}, υ/δυ > 1000	2.0 km (from ER-2)	ER-2 / Proteus
AIRS	Grating spectrometer	3.8 – 15.4 μ, discrete channels	~0.4 – 2.2 cm^{-1}, υ/δυ ~ 1200	~ 13.5 km	AQUA
MODIS	Grating spectrometer	3.6 – 14.4 μ (IR bands 20 – 36) , discrete channels	~13 – 128 cm^{-1}, broadband filters	~ 1 km	AQUA

Case Study: *PTOST*

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- **PTOST (February 18 - March 13, 2003, HAFB, Hawaii).** The 2003 ***Pacific THORPEX Observing System Test (PTOST)*** was the first in a series of Pacific and Atlantic observation campaigns in support of the WWRP/USRP THORPEX Program. THORPEX - a Global Atmospheric Research Program aimed at improving short range (up to 3 days), medium range (3-7 days) and extended range (two week) weather predictions. Flights targeted frontal boundaries and storm systems, as well as satellite sensor validation underflights (TERRA, AQUA, and ICESat)

Aircraft Payload Included:

ER-2 (NAST-I, NAST-M, S-HIS, MAS, CPL); G-IV (Dropsondes, in-situ O_3)

Satellite Platforms Included:

Terra, Aqua, GOES

Case Study: *EAQUATE*

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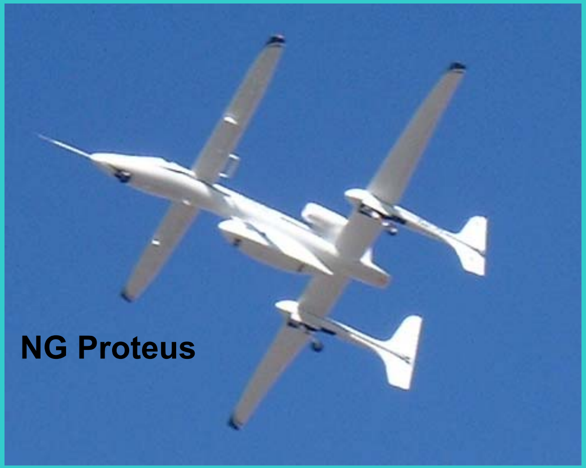
Continued NPP/NPOESS risk mitigation with pre-Metop (IASI , AMSU, MHS, HIRS) collaborations focusing on Aqua satellite cal/val and chemistry product validation

- **European AQUA Thermodynamic Experiment (EAQUATE)**
  - Naples, Italy; 3 – 11 Sep; Proteus, Potenza/Naples ground sites, AQUA
  - Cranfield, UK; 11 – 19 Sep; Proteus, BAE 146-300, & AQUA

Measurements Included:

NG Proteus (NAST-I, NAST-M, S-HIS, FIRSC, MicroMAPS)
UK BAE146-300 (ARIES, TAFTS, SWS, MARSS & Deimos; dropsondes; in-situ cloud phys. & trace species)
Ground sites: Potenza/Naples (lidar, radiosondes, aeri, m-wave)
Satellite: AQUA (AIRS & MODIS); MSG (Seviri)



Spatial Calibration Validation Example

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- Comparison of Aqua AIRS and MODIS relative spatial registration
  - AIRS spatially-convolved with MODIS B31 (11 μ) SRF
  - MODIS B31 integrated spatially over AIRS IFOVs
  - RSS differences calculated for varying relative offsets in spatial co-registration
  - Portions of granules examined for 7 recent NAST campaign flight days

Sample Spatial Registration Results

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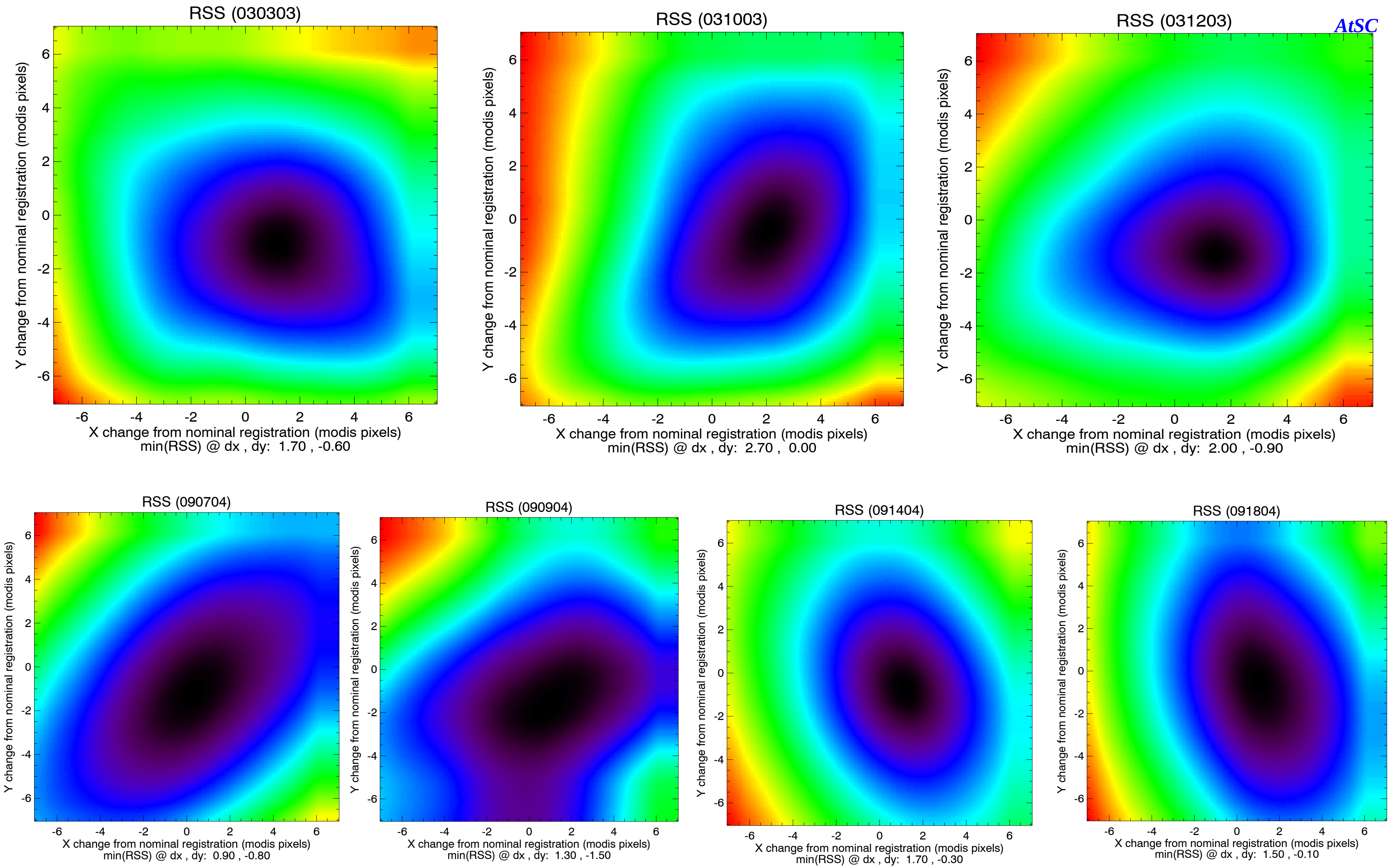

AIRS vs MODIS Co-registration Comparison Summary°

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DATE*	Δx#	Δy#
030303	1.70	-0.60
031003	2.70	0.00
031203	2.00	-0.90
090704	0.90	-0.80
090904	1.30	-1.50
091404	1.70	-0.30
091804	1.50	-0.10
Average	**1.69**	**-0.60**
Standard Deviation	**0.57**	**0.52**

° preliminary results; not necessarily representative of all spectral bands or spatial positions.

* Select flight days during recent NAST field campaigns

units of modis pixels

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Example spectral impact of spatial mis-registration for neighboring channels

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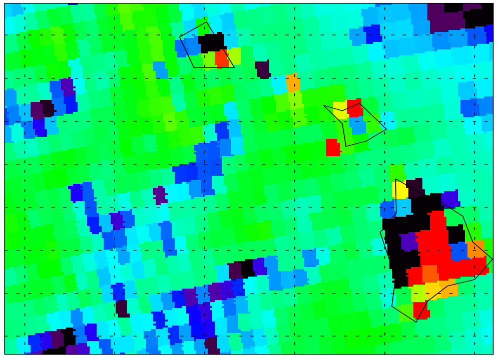
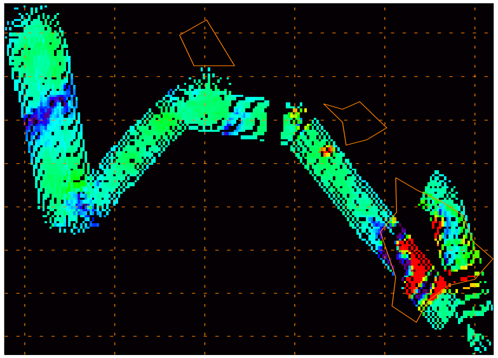
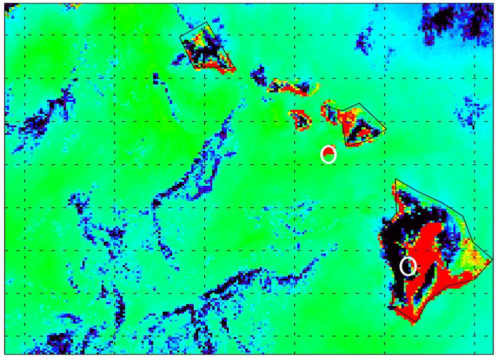
AIRS MB32



NAST MB32

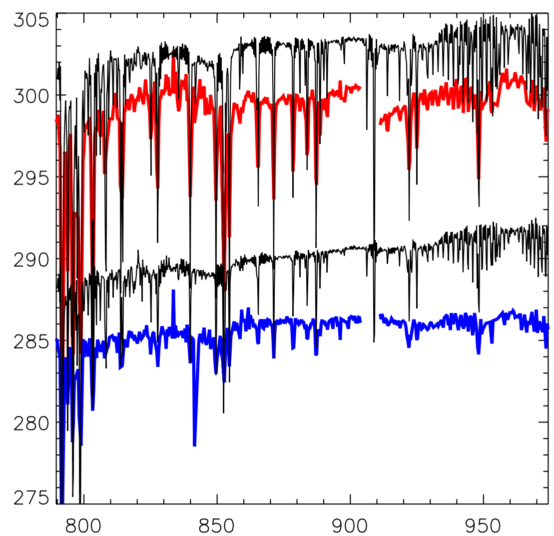


MB32

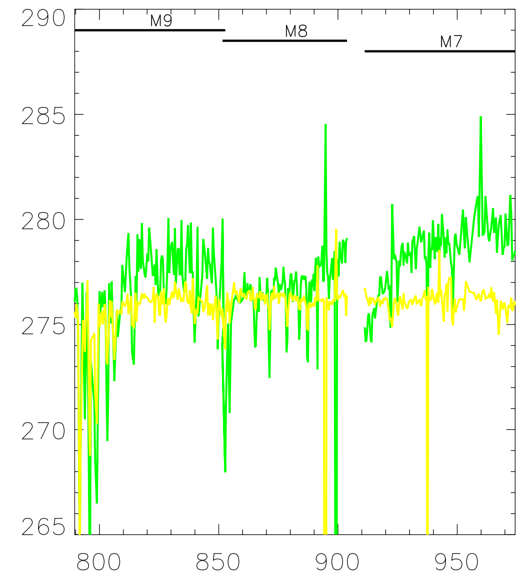


- ➢Spectra for uniform & non-uniform scenes shown for two days
- ➢NAST-I in black; AIRS in colors
- ➢Spectral extent of 3 AIRS detector modules also shown

030303



091404



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Spectral Calibration Validation Example

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- NAST-I laser cm^{-1} stability study
  - Spectral calibration fidelity assessed by varying laser wavenumber in simulations to best match measured (calibrated) radiance spectra (i.e. minimizing RSS of obs-calc residual)
- Select days examined from most campaigns
  - CAMEX3 (13 Sep 98); Wallops99 (23 Aug 99); AFWEX (29 Nov, 4 Dec 00); CLAMS (10 Jul 01); IHOP (11 Jun 02); CF (26 Jul 02); PTOST (3, 10, & 12 Mar 03); ATOST (19 Nov, 3 & 8 Dec 03); INTEX (22 Jul 04); EAQUATE (9 &18 Sep 04)
- Simulation assumptions
  - υ_0=15799.d0 cm^{-1} (~.633 micron) used as baseline for sims
  - Atmospheric state from PTOST 030303

Laser wavenumber offsets vs time

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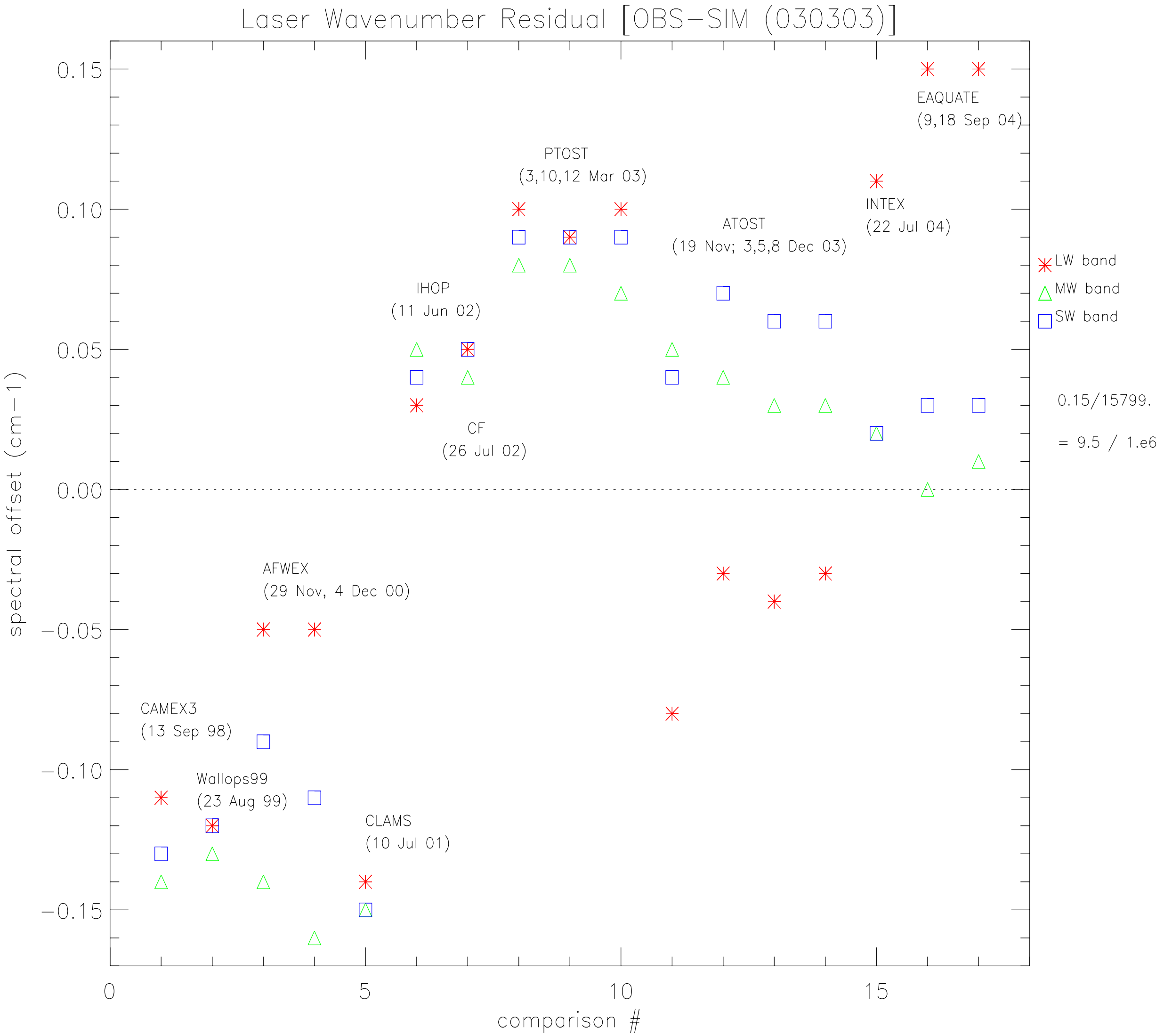
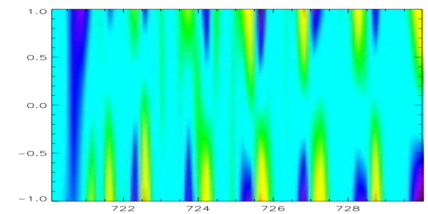
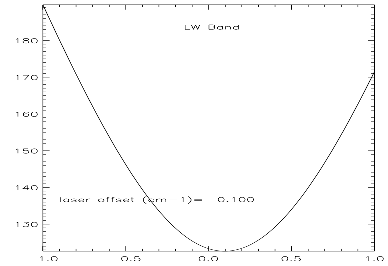
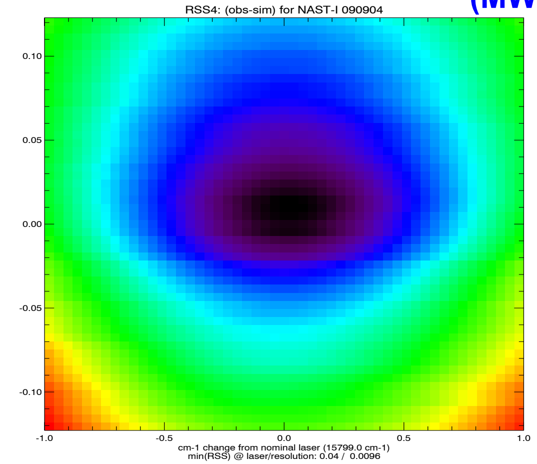




PTOST
030303
(LW)



EAQUATE
090904
(MW)



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Radiometric Calibration Validation Examples

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- **Incorporate multiple, independent, temporally- & spatially-coincident data from recent NAST field campaigns (PTOST & EAQUATE)**
  - Satellite:
    - **AQUA (AIRS & MODIS)**
  - Aircraft:
    - **ER-2/Proteus (NAST-I & S-HIS)**
  - Ground:
    - **Potenza** (**lidar & radiosondes**)
- **Verify spatial co-registration by comparing geo-referenced images at select λ**
- **LBL-based calculations for simulated observations**
  - Using best combination of "truth" data for sfc & atm state
- **Compare view-angle-coincident observations with broadband SRFs applied (i.e. Modis)**
- **For clear, uniform regions, compare high resolution spectra (i.e. NAST-I, S-HIS, & AIRS)**

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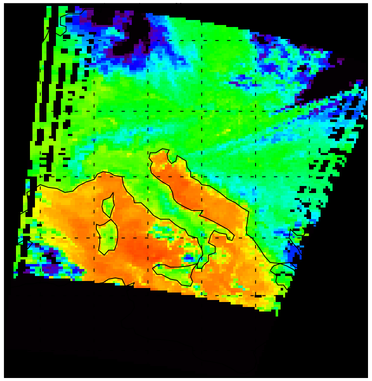
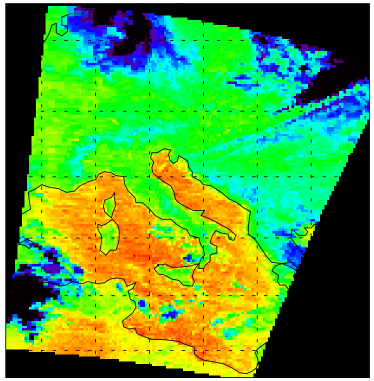
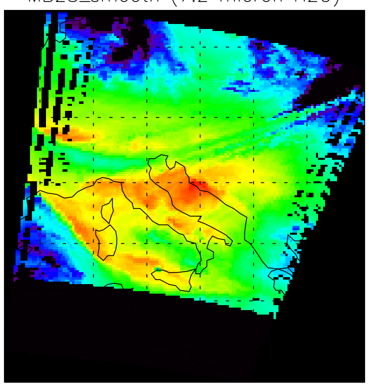
MB31_smooth (11 micron LW Win)



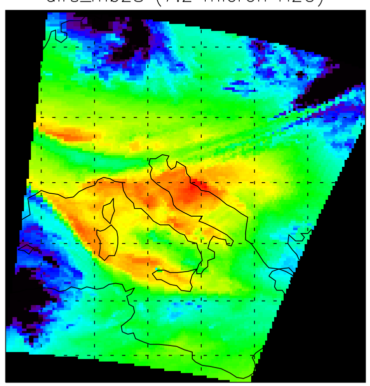
airs_mb31 (11 micron LW Win)



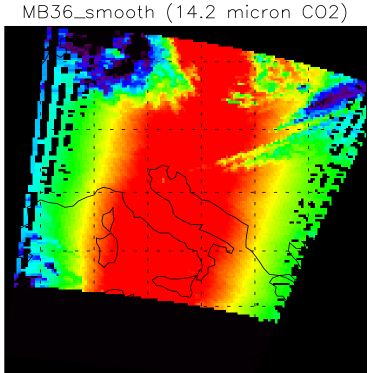
MB28_smooth (7.2 micron H2O)



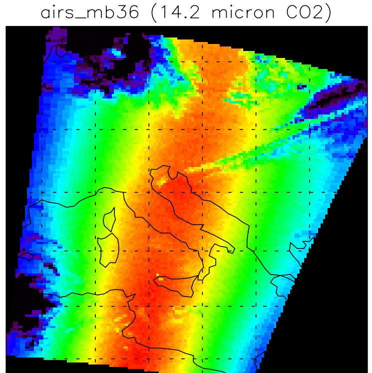
airs_mb28 (7.2 micron H2O)



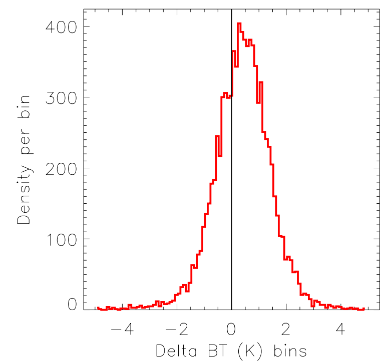
MB36_smooth (14.2 micron CO2)

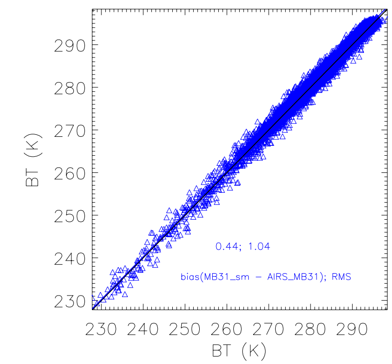


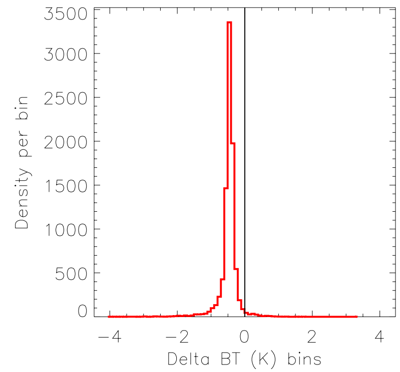
airs_mb36 (14.2 micron CO2)

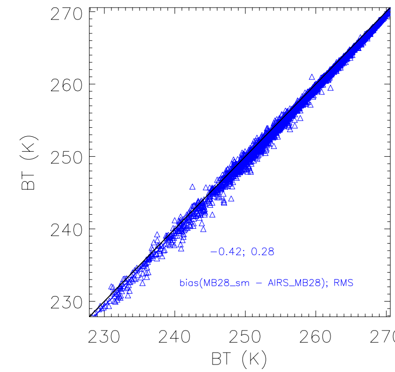


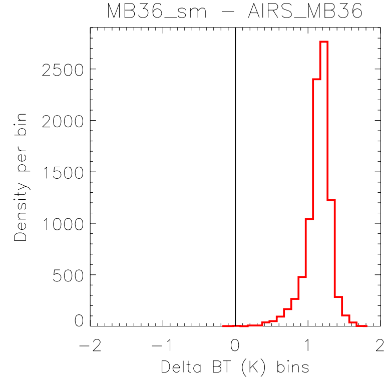
MODIS vs AIRS

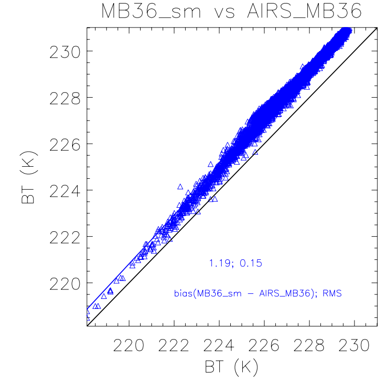












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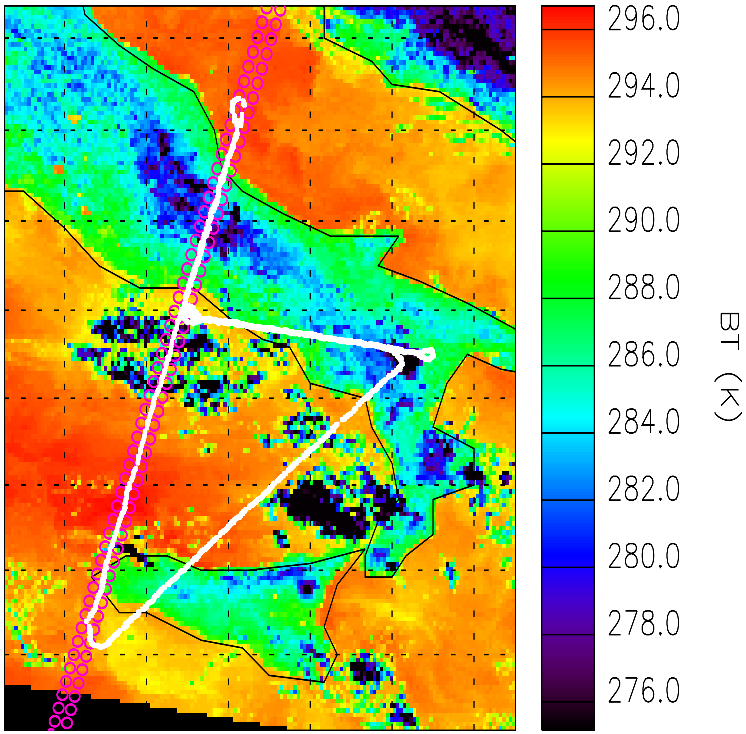
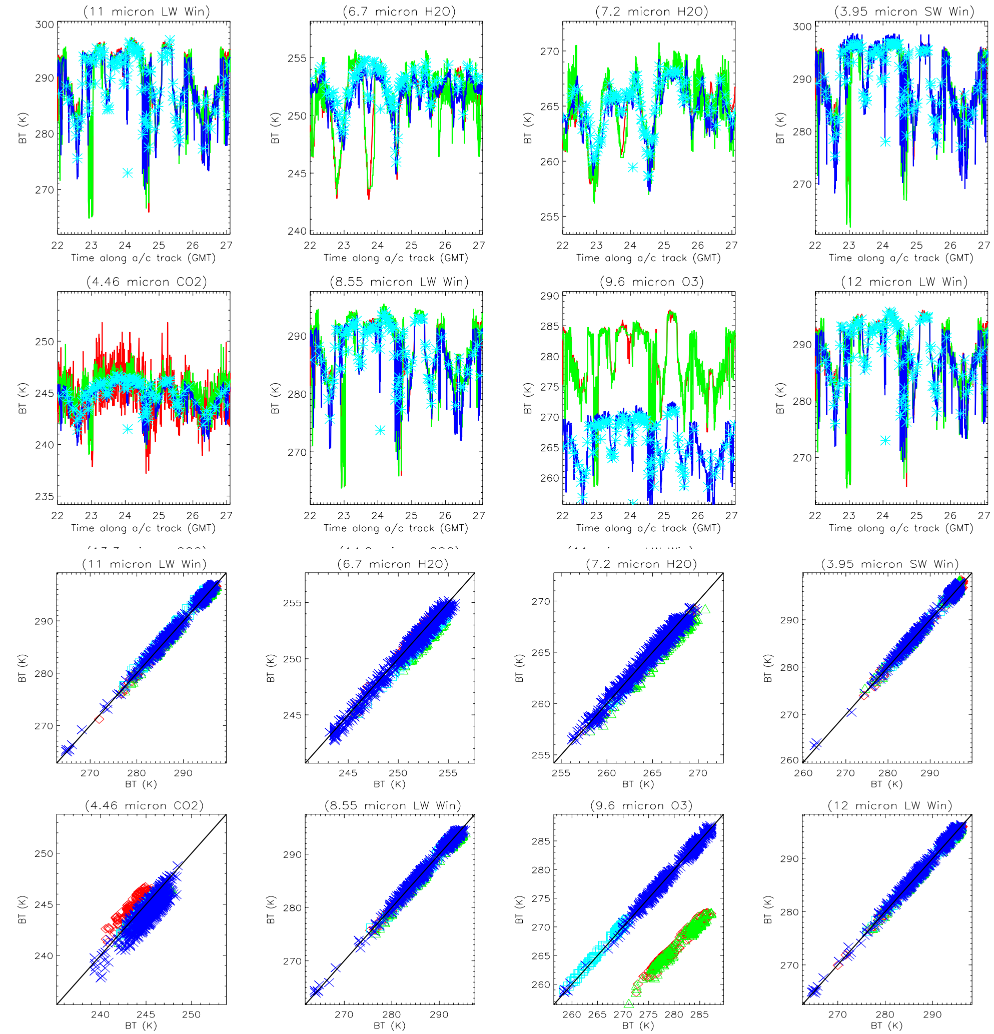
MODIS vs NAST-I, S-HIS, AIRS

MB31 (11 micron LW Win)





NAST-I
S-HIS
AIRS
MODIS

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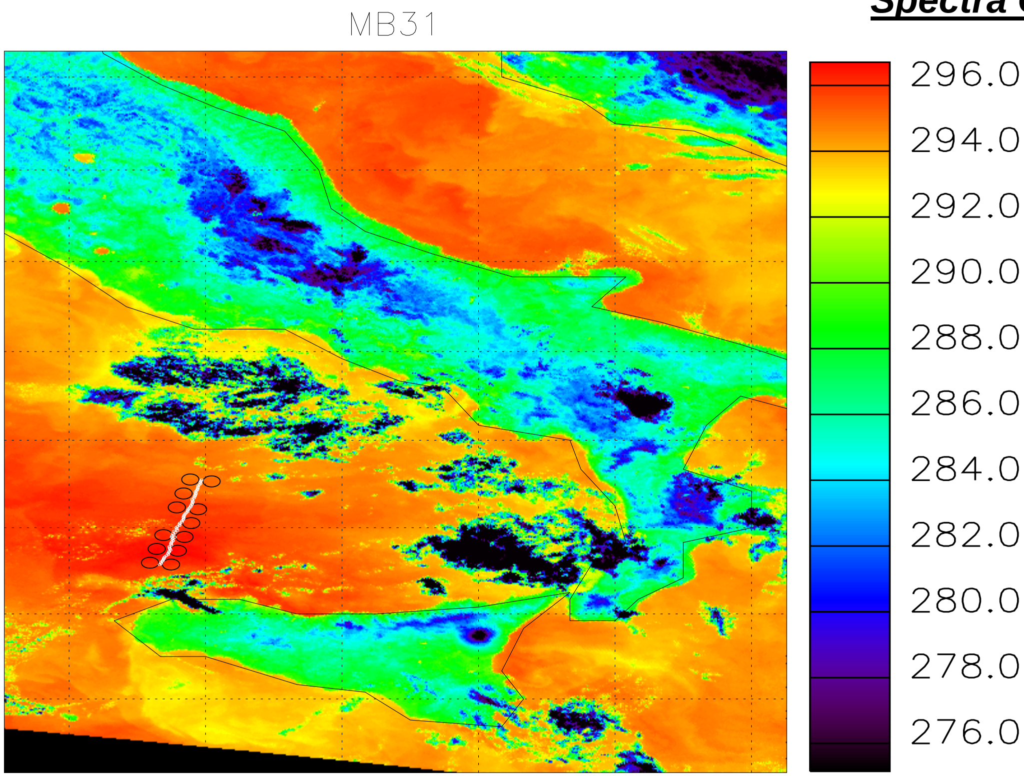
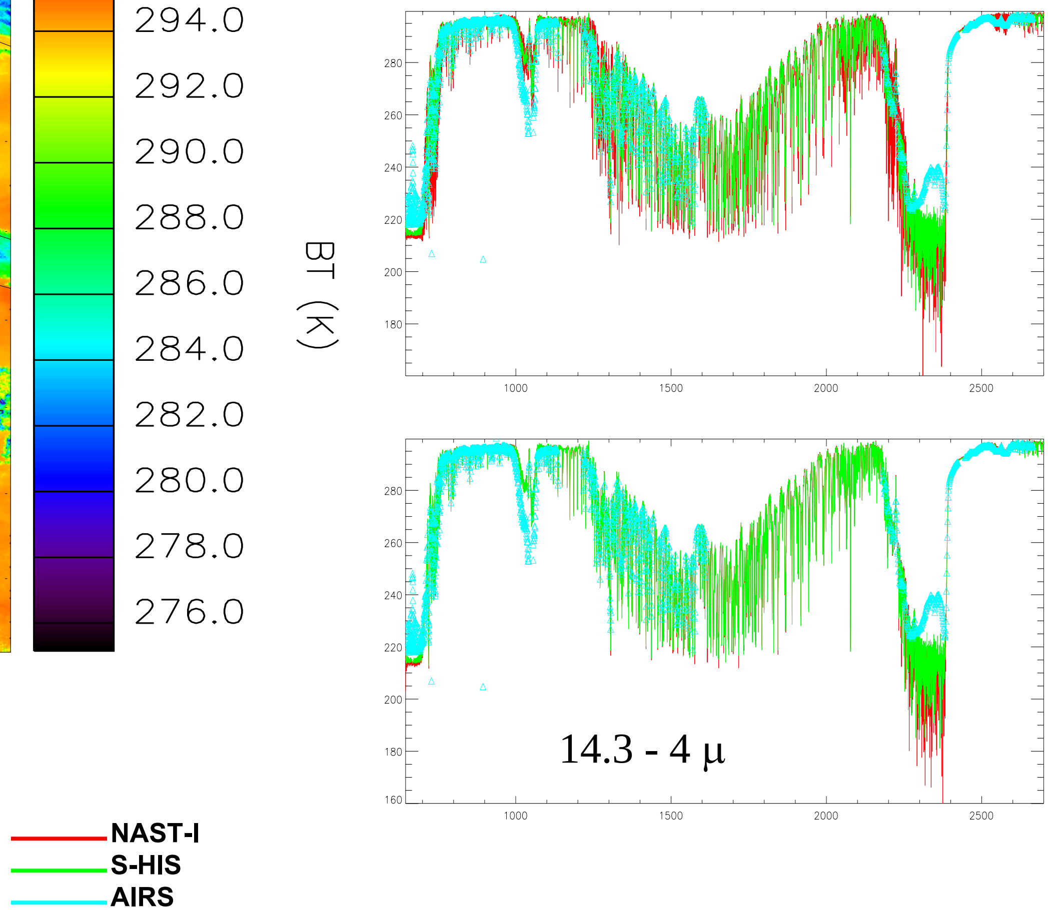
Spectra Comparison: NAST-I, S-HIS, AIRS





MB31 stddev
(AIRS IFOVs)

max = 0.22 K

min = 0.05 K

mean = 0.11 K

stdev = 0.05 K

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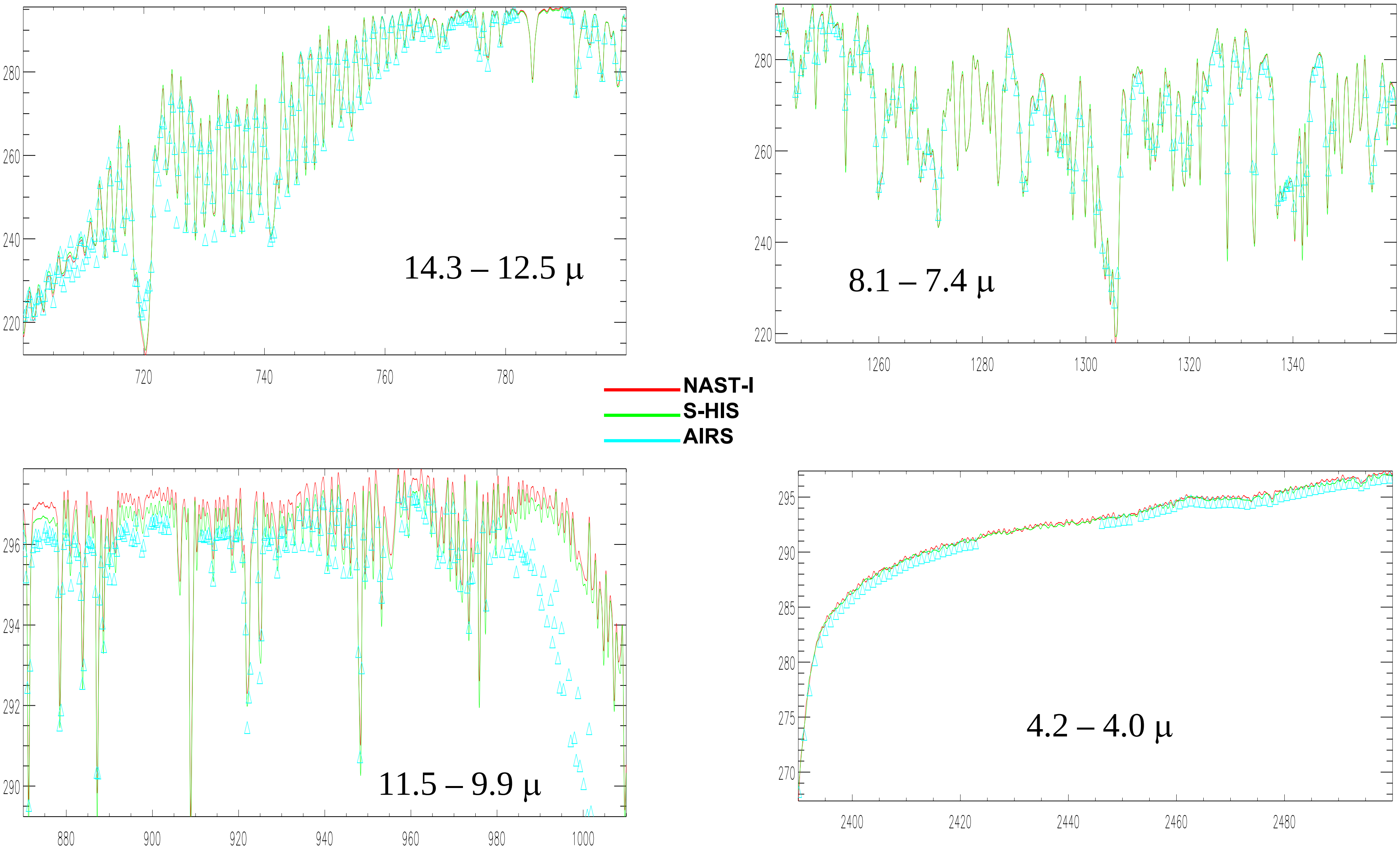
Spectra Comparison: NAST-I, S-HIS, AIRS



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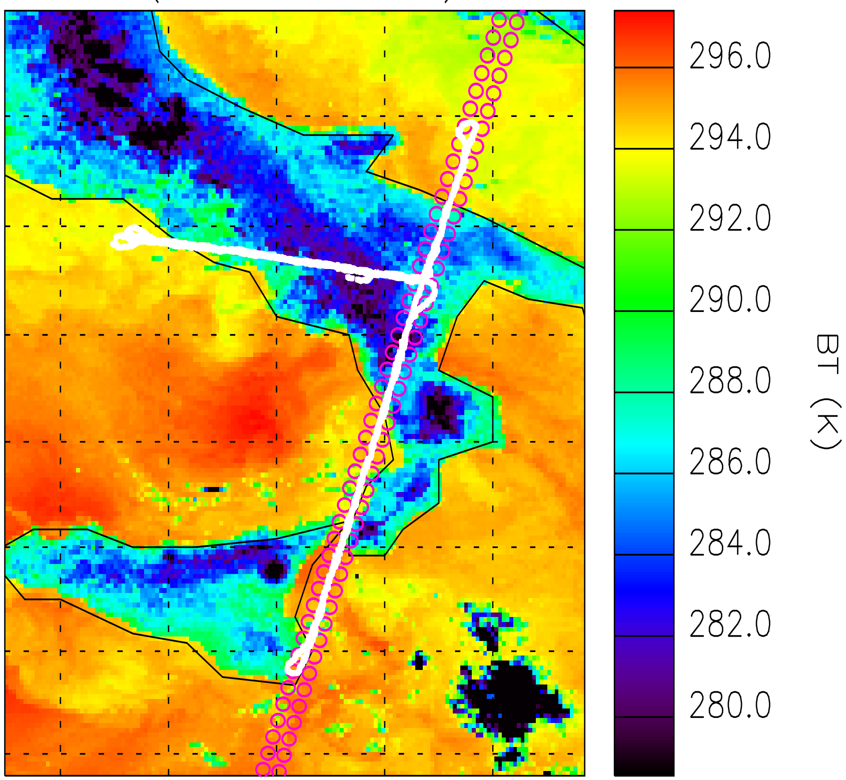
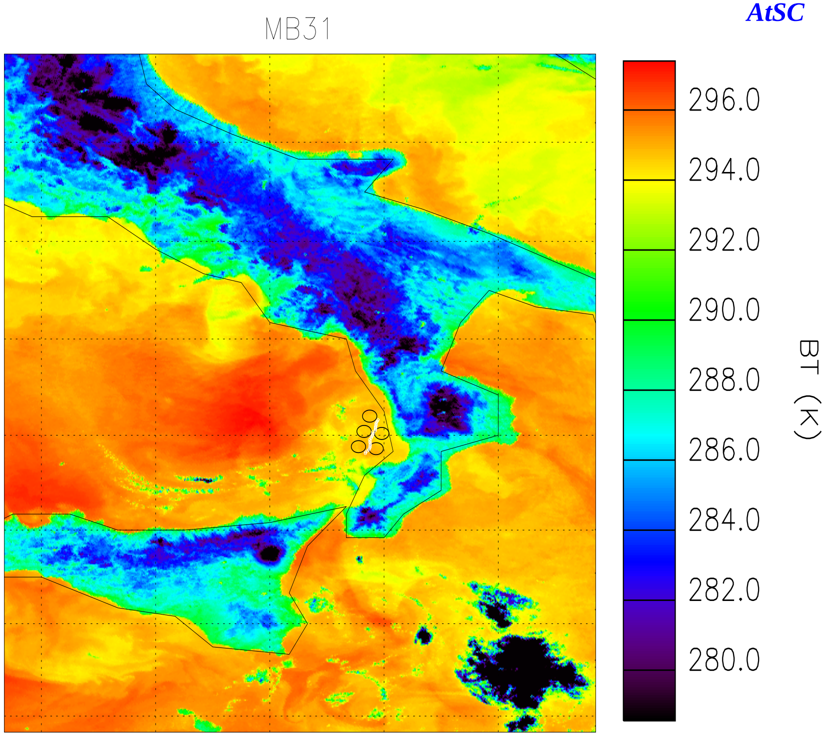
Spectra Comparison: NAST-I, S-HIS, AIRS

MB31

(11 micron LW Win)





MB31 stddev (AIRS IFOVs)

max = 0.16 K

min = 0.10 K

mean = 0.14 K

stdev = 0.02 K

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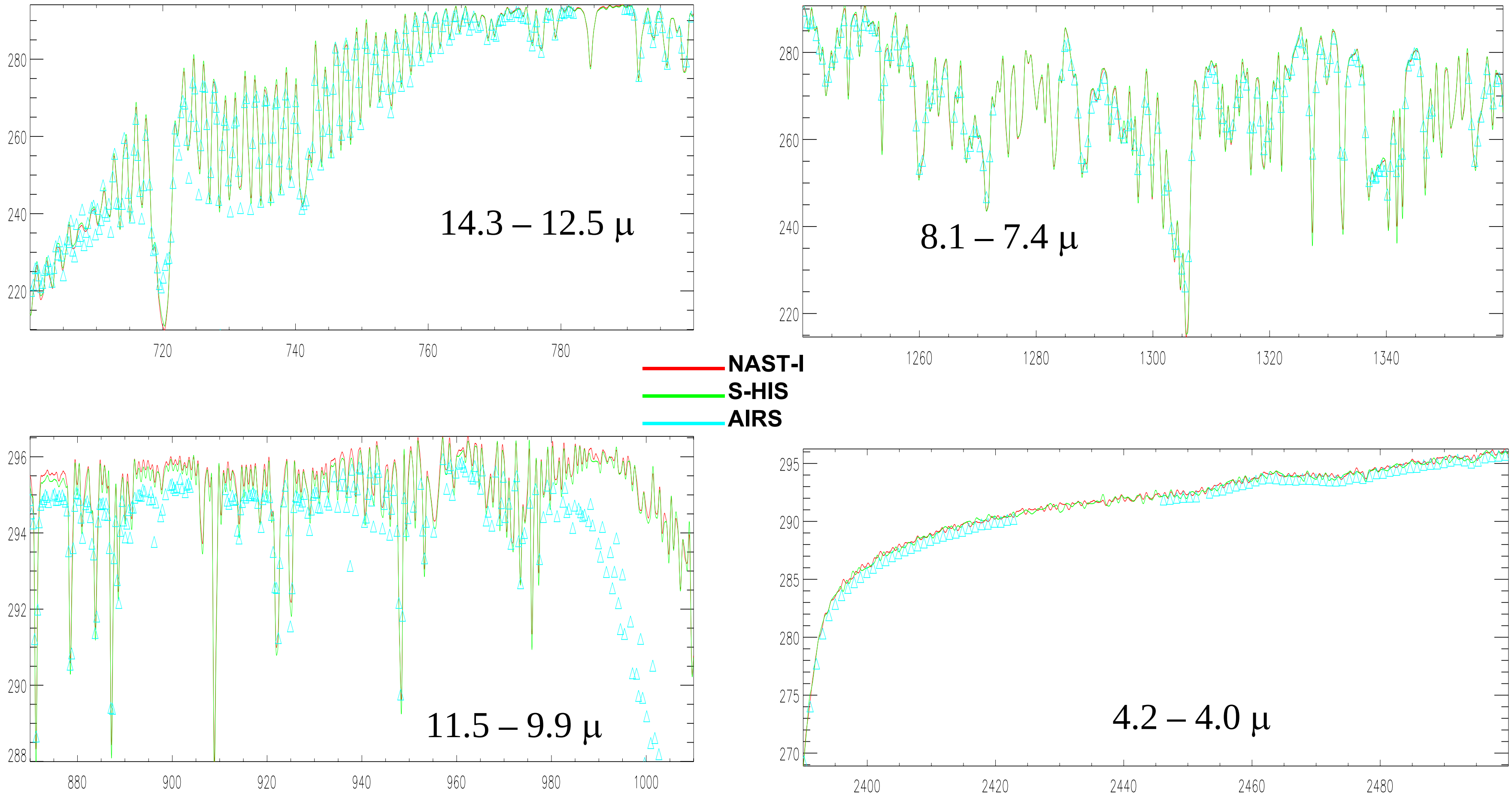
Spectra Comparison: NAST-I, S-HIS, AIRS



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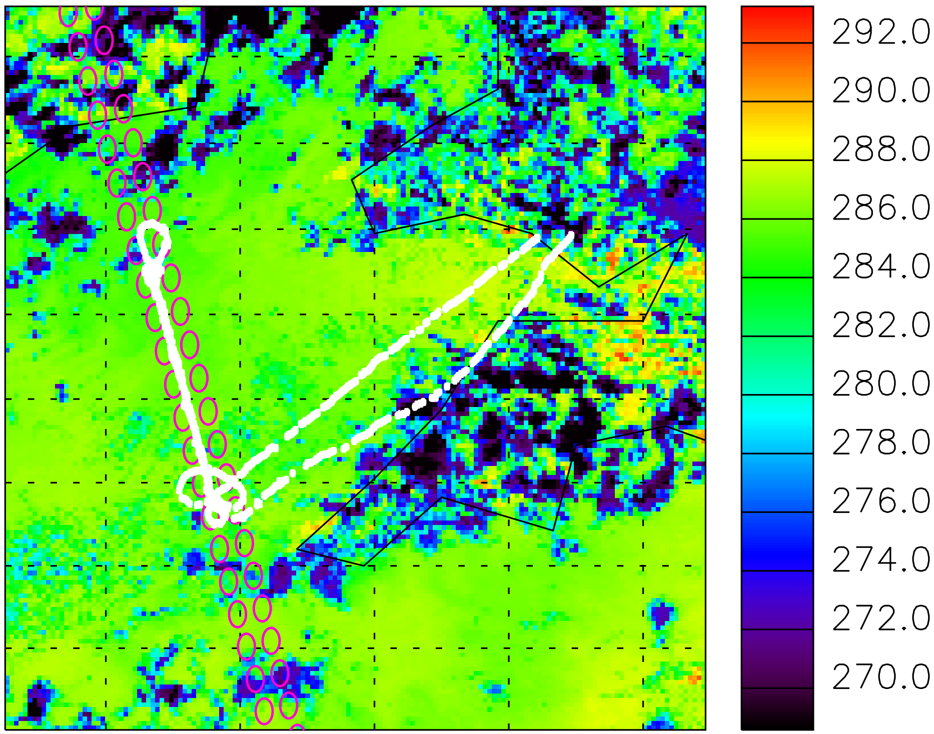
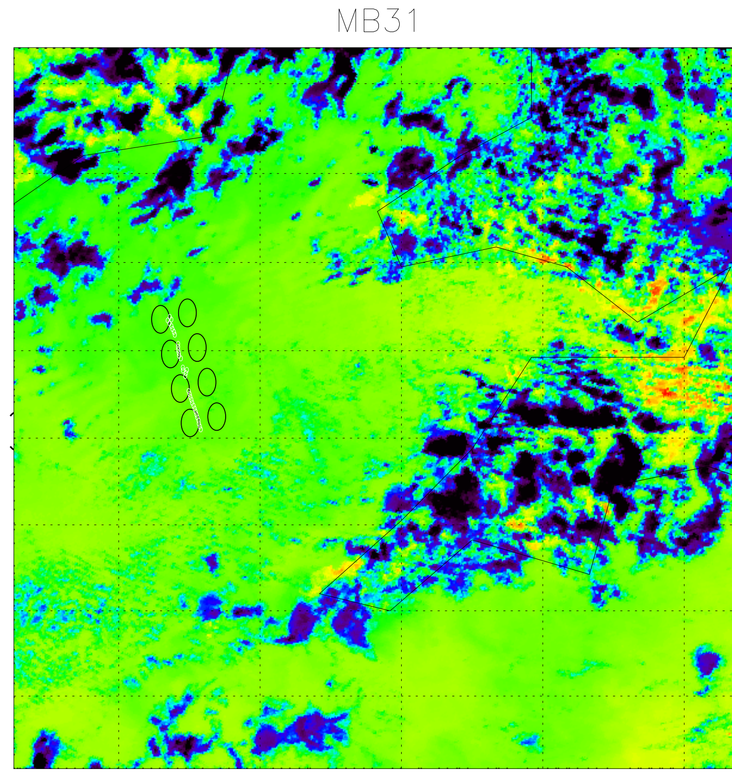
Spectra Comparison: NAST-I, S-HIS, AIRS

MB31 (11 micron LW Win)





MB31 stddev (AIRS IFOVs)

max = 0.23 K

min = 0.07 K

mean = 0.16 K

stdev = 0.05 K

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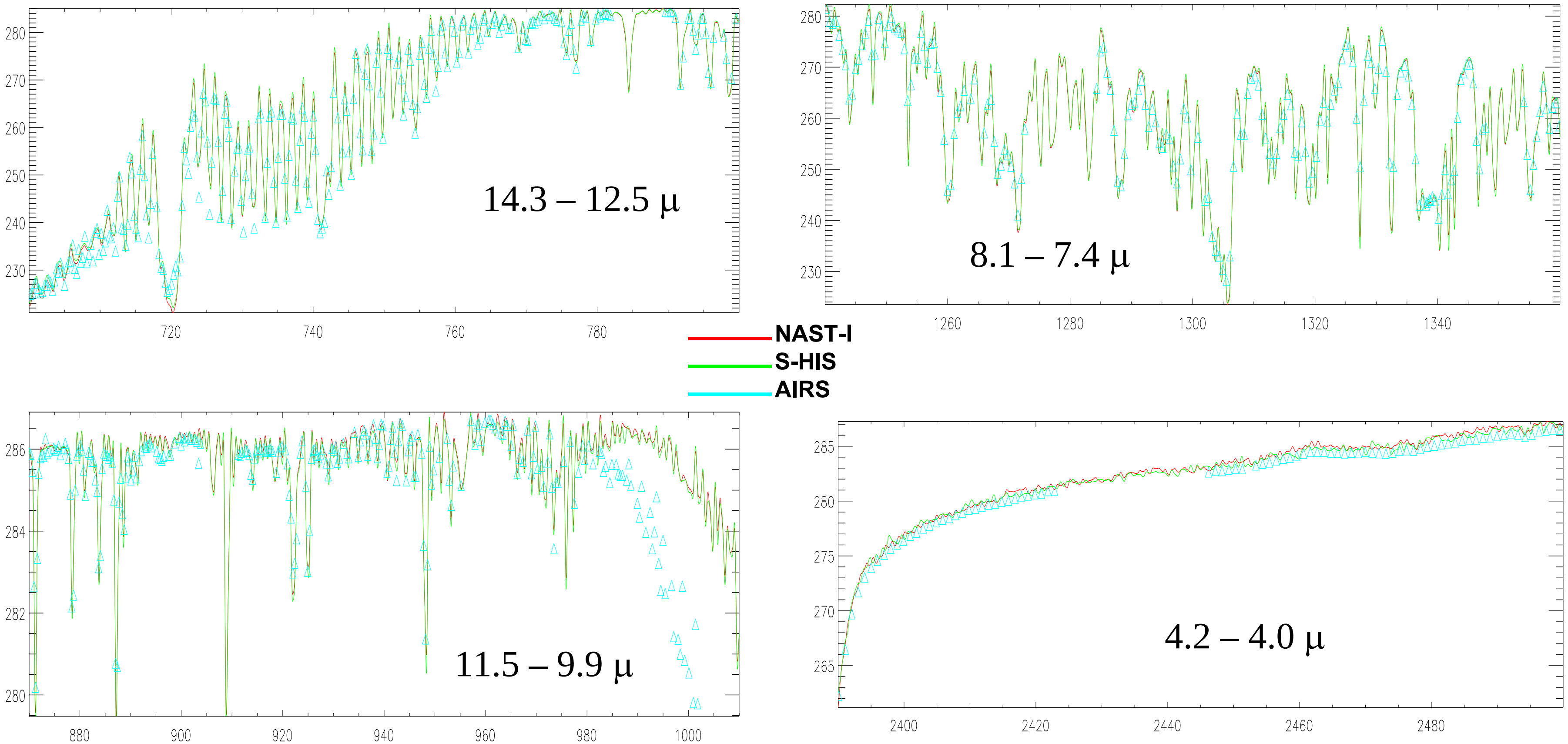
EAQUATE 091404

Spectra Comparison: NAST-I, S-HIS, AIRS



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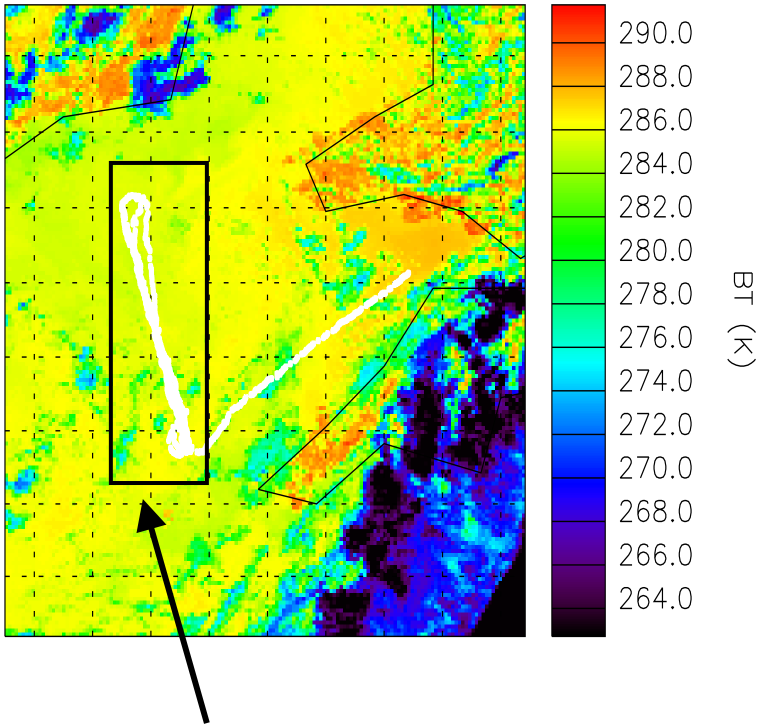
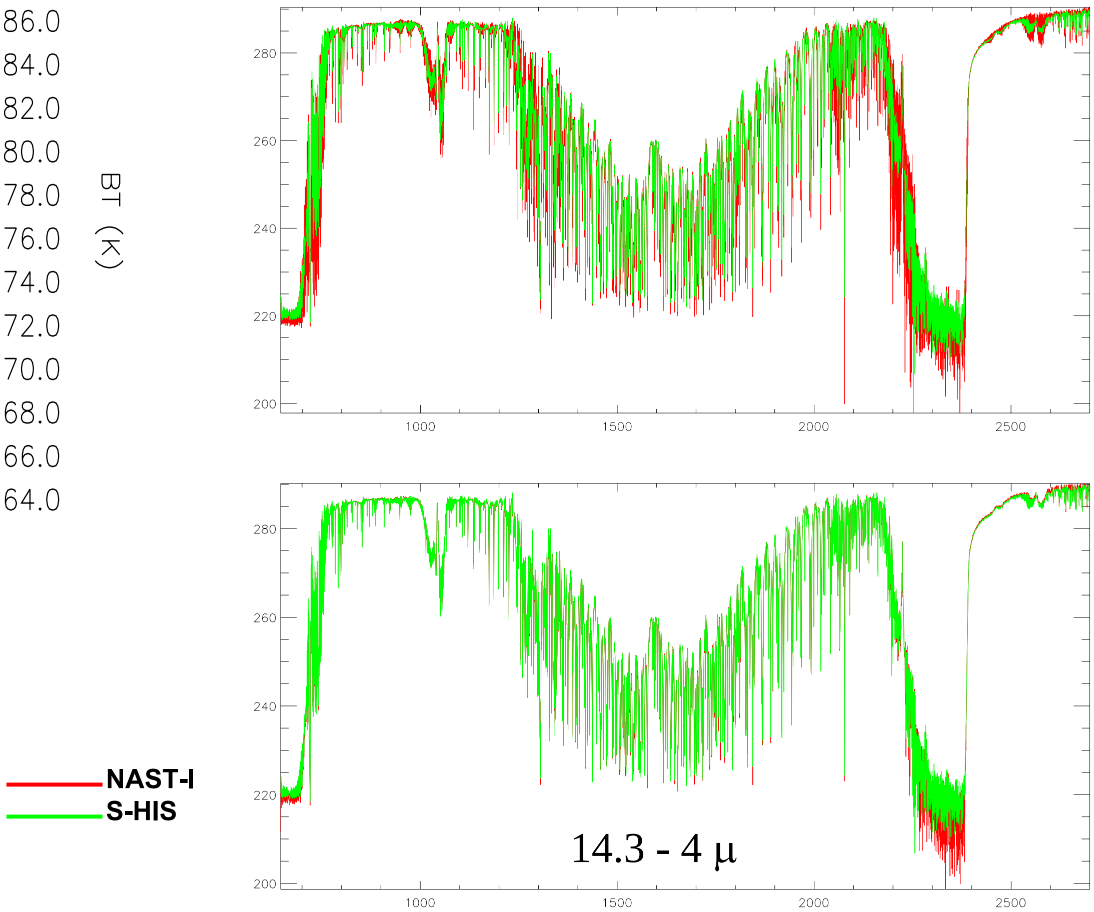
MB31 (11 micron LW Win)



Selected nadir IFOVs (NAST-I & S-HIS)

Spectra Comparison: NAST-I, S-HIS



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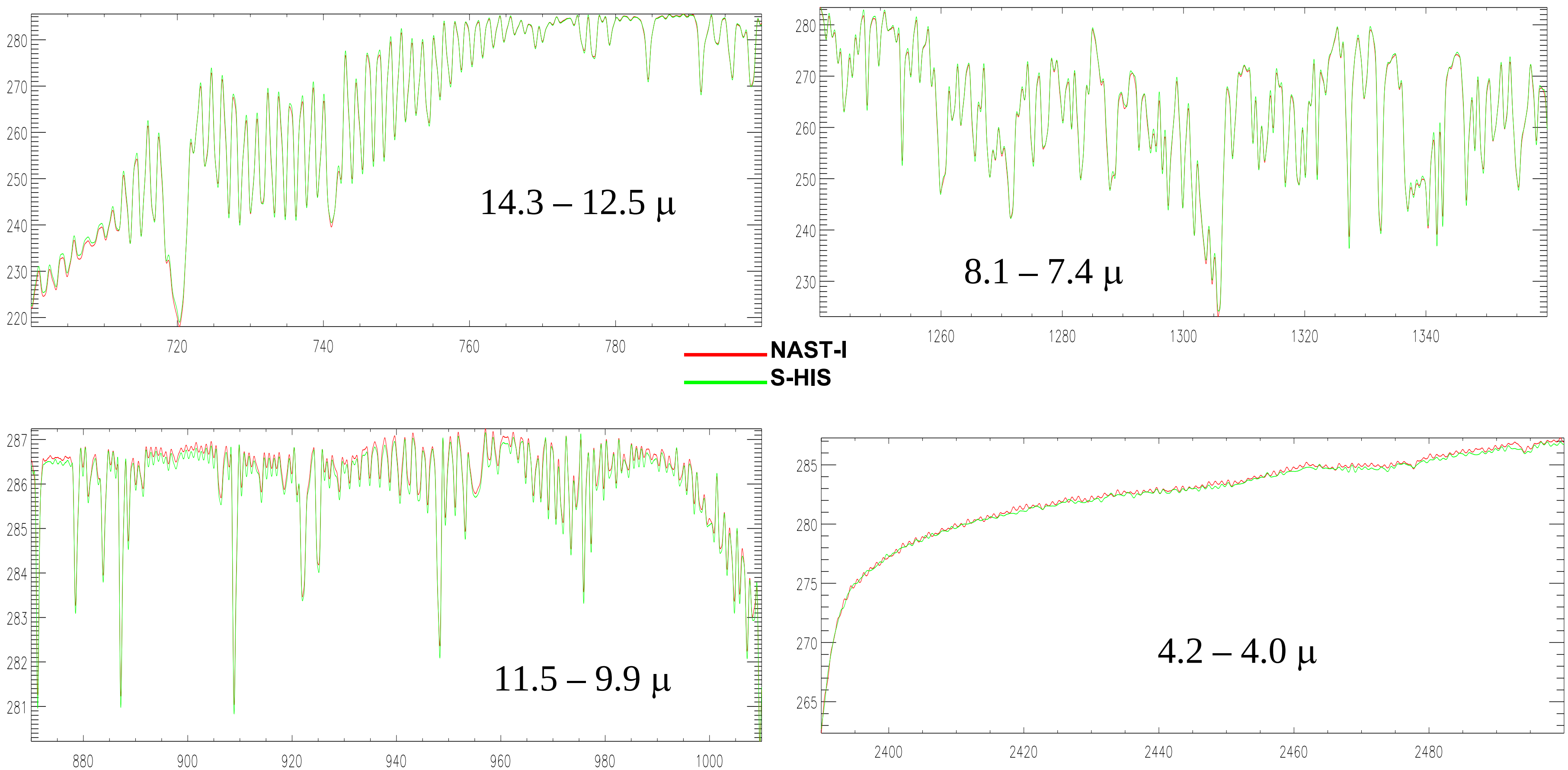
Spectra Comparison: NAST-I, S-HIS



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MODIS – AIRS (all overlapping IFOVs)

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Band	090704	090904	091404	091804	030303	031003	031203
MB21 (3.95 micron SW Win)	-0.13	-0.04	0.02	-0.20	0.15	0.21	0.44
MB24 (4.46 micron CO2)	-0.16	-0.17	0.34	0.59	0.30	0.46	0.19
MB27 (6.7 micron H2O)	-0.99	-0.92	-0.64	-0.80	-0.55	-0.63	-0.65
MB28 (7.2 micron H2O)	-0.42	-0.41	-0.38	-0.47	-0.32	-0.36	-0.33
MB29 (8.55 micron LW Win)	-0.47	-0.37	-0.20	-0.47	-0.16	-0.10	-0.21
MB30 (9.6 micron O3)	0.36	0.35	0.50	0.45	0.59	0.67	0.63
MB31 (11 micron LW Win)	0.44	0.55	0.16	0.37	-0.05	-0.03	0.02
MB32 (12 micron LW Win)	-0.04	-0.00	-0.14	-0.17	-0.07	-0.06	-0.00
MB33 (13.3 micron CO2)	-0.42	-0.45	-0.45	-0.39	-0.50	-0.43	-0.42
MB36 (14.2 micron CO2)	1.19	1.29	1.03	0.92	1.23	1.14	1.24

← **EAQUATE** → ← **PTOST** →

- MODIS band SRFs applied to AIRS
- MODIS integrated over AIRS IFOVs
- "bias" values (K) of linear fits to scatter plots shown

Select Sensor Offsets Observed during EAQUATE* Flight Days

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* PTOST data shown in green

MB31 (11.0 μ)	MODIS - NASTI	MODIS – S-HIS	MODIS_sm - AIRS	NAST-I – S-HIS
090704	-0.43	-0.28	0.61	0.18
090904	-0.68	-0.43	0.64	0.14
091404	-0.56	-0.31	0.48	0.07
091804	N/A	N/A	0.61	0.11
030303	-0.35	-0.09	0.04	0.21
031003	-0.27	0.05	-0.04	0.29
031203	-0.33	0.05	0.02	0.23

- MODIS band SRFs applied to HSR sensor data
- View-angle-coincident data along nast nadir track compared
- MODIS integrated over AIRS IFOVs = MODIS_sm; others are single IFOVs
- “bias” values (K) of linear fits to histogram-filtered scatter plots shown

MB28 (7.2 μ)	MODIS - NASTI	MODIS – S-HIS	MODIS_sm -AIRS	NAST-I – S-HIS
090704	-0.44	-0.83	-0.44	-0.17
090904	-0.35	-0.56	-0.41	-0.27
091404	-0.32	-0.57	-0.36	-0.18
091804	N/A	N/A	-0.36	-0.12
030303	-0.09	0.38	-0.25	0.36
031003	0.09	0.45	-0.38	0.30
031203	N/A	N/A	-0.35	0.29

MB32 (12 μ)	MODIS - NASTI	MODIS – S-HIS	MODIS_sm -AIRS	NAST-I – S-HIS
090704	-0.31	-0.20	0.02	0.14
090904	-0.55	-0.28	0.03	0.17
091404	-0.39	-0.23	-0.03	0.04
091804	N/A	N/A	-0.02	0.12
030303	-0.31	0.03	0.02	0.22
031003	-0.17	0.14	-0.07	0.26
031203	-0.21	0.08	0.01	0.20

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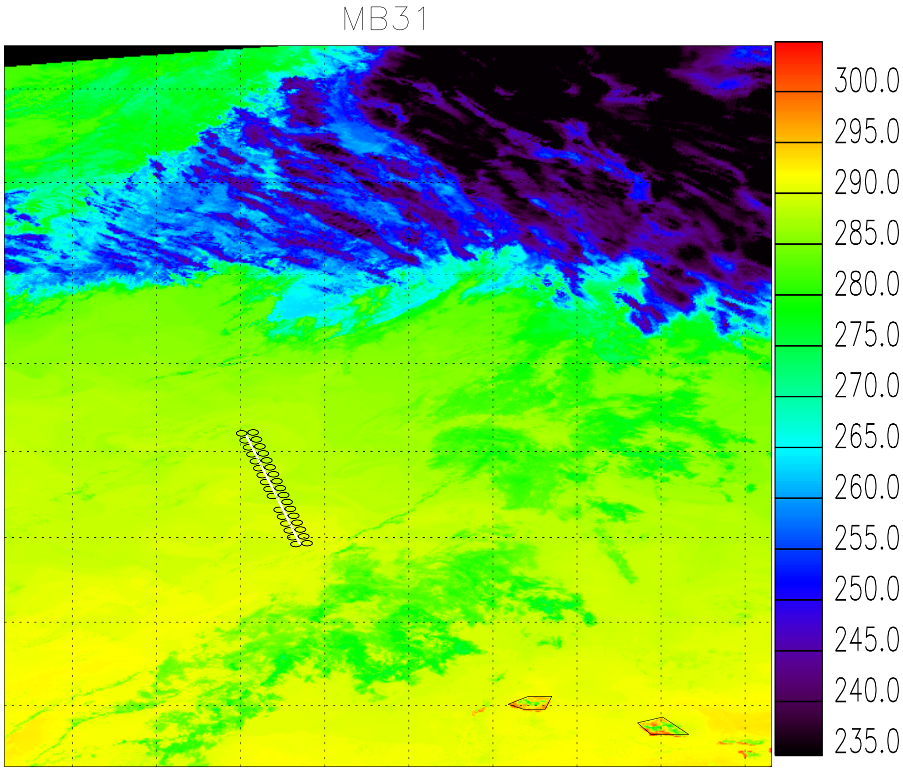
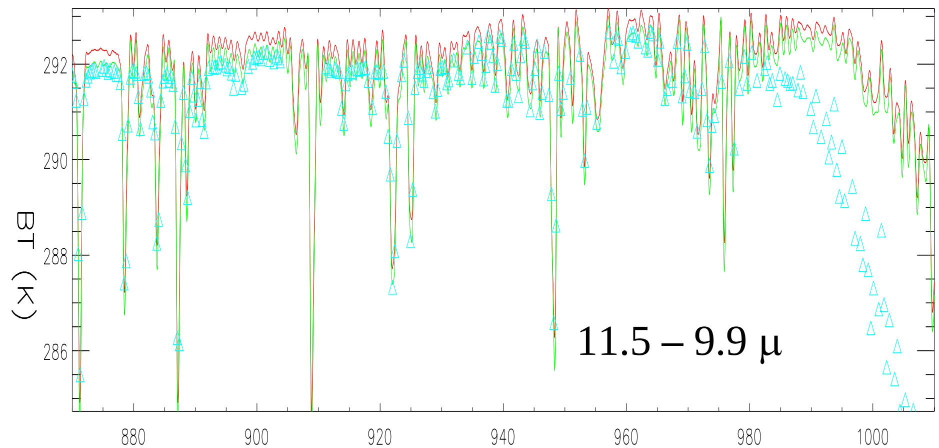
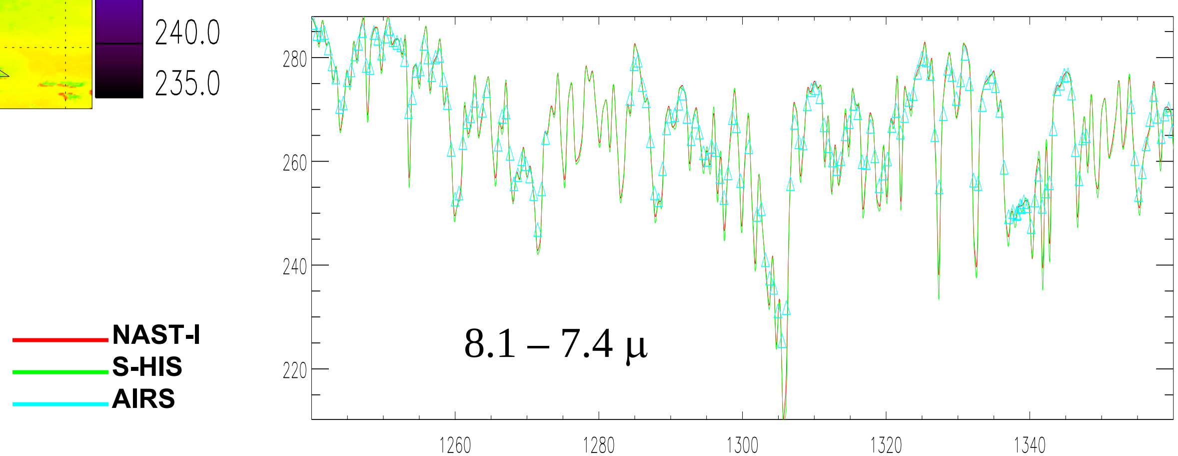
Spectra Comparison: NAST-I, S-HIS, AIRS







MB31 stddev (AIRS IFOVs)

max = 0.27 K

min = 0.04 K

mean = 0.10 K

stdev = 0.05 K

Satellite Infrared Radiance Validation Studies using a Multi-Sensor/Model Data Fusion Approach, Larar et al., ITSC-14, Beijing, China, 25-31 May, 2005.

Summary & Conclusions

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- Post-launch validation activities are critical to verify quality of satellite measurement system (i.e., sensor, algorithms, and direct/derived data products)
- Absolute and relative spatial registration can be validated using ground truth and simultaneous observations, respectively
- Spectral fidelity easily verified via simulations, but corresponding radiometric accuracy verification from simulation is limited by vertical accuracy of ancillary data and absolute accuracy of spectroscopic parameters
- Aside from collocated sensor(s) on same platform, space-based sensor radiometric validation best achieved using high-altitude aircraft based sensors; can eliminate errors from spatial and temporal mismatches and spectroscopic data uncertainties, and allows viewing most of atmospheric column; enables extrapolation of calibration reference through underflight/characterization of other (e.g. broadband) systems
- High resolution FTS systems (e.g., NAST-I & S-HIS) provide continuous spectra of high radiometric and spectral fidelity enabling emulation of other high-resolution or broadband instrument systems
- Spatial and temporal coincidence between observing systems crucial to differentiate between measurement uncertainty and geophysical variability