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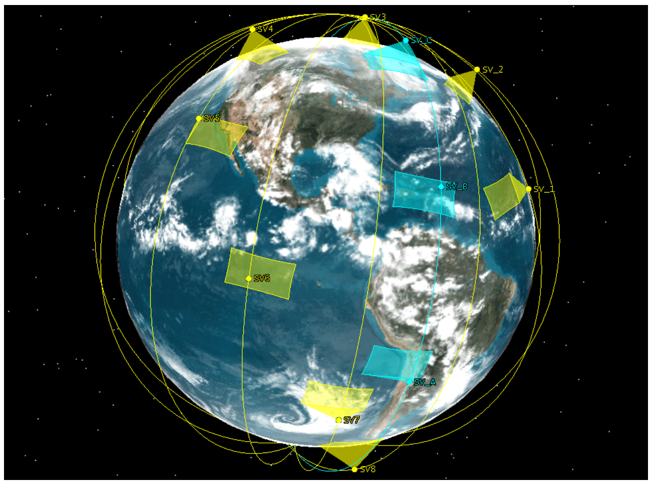
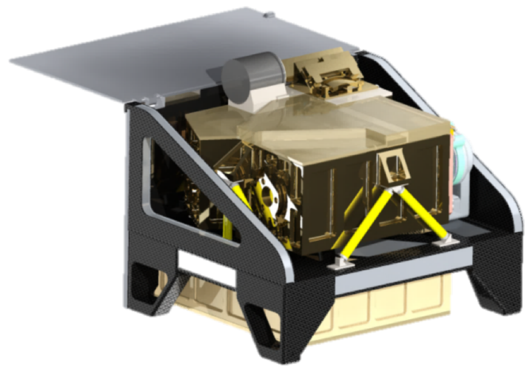
MISTiC™ Winds

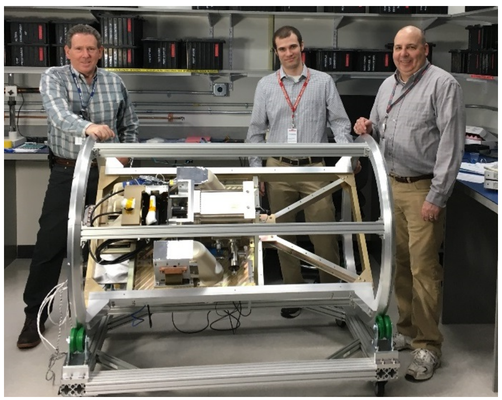
A NASA Instrument Incubator Program

An Affordable System of Systems Approach for the Observation of Atmospheric Dynamics

October, 2018







MISTiC™ Winds

- Provides High Spatial/Temporal Resolution Temperature and Humidity Soundings of the Troposphere
    - Atmospheric State and Motion
    - Improved short term weather forecasting
- Enabled by:
    - LEO Constellation Approach
    - Micro-Sat-Compatible Instrument
    - Low-Cost Micro-Sat Launch

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Topics

- Instrument Concept and Mission Concept Summary
- Instrument Physical Concept Update
- Risks Reduction Progress
  - FPA Radiation Test Summary
  - Spectrometer and Airborne Instrument Build
  - **Airborne HSI AMV Winds Observation Demonstration –Initial Observations**
- Next Steps
- IIP Summary

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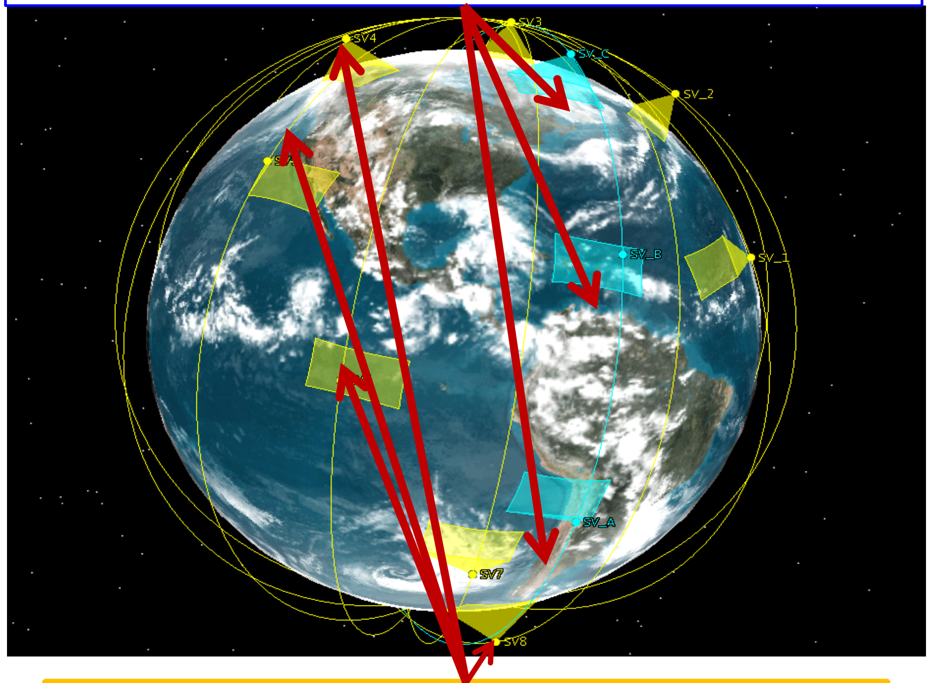
MISTiC™ Winds- Two Affordable Measurement Concepts to Reduce Weather Forecasting Errors

- MISTiC™ Winds Temperature and Humidity Sounding Constellation Options.
  1. Frequent-Sounding Constellation
     - e.g. 90 min refresh-globally.
  2. **Wind-Vector Formations**
     - **e.g. 4 3-Satellite Formations for Cloud-Drift and Water Vapor Motion-Vector Winds**
       - **Provide 3-Hr Refresh for 3D Winds *and* Atmospheric Soundings (T, H_2O)**

Miniature Spectrometers Operated in Constellations Offer Lower Cost /Lower Risk Approach than GEO for Frequent-Refresh IR Soundings & 3-D Winds

Motion-Vector Winds Formation (blue)



90 min Refresh of IR Soundings Provided by Spectrometers in 8 Orbital Planes (gold)

LEO orbit and SWIR/MWIR-only Spectra Enables MISTiC™ Instrument SWaP Reduction of 1-2 Orders of Magnitude

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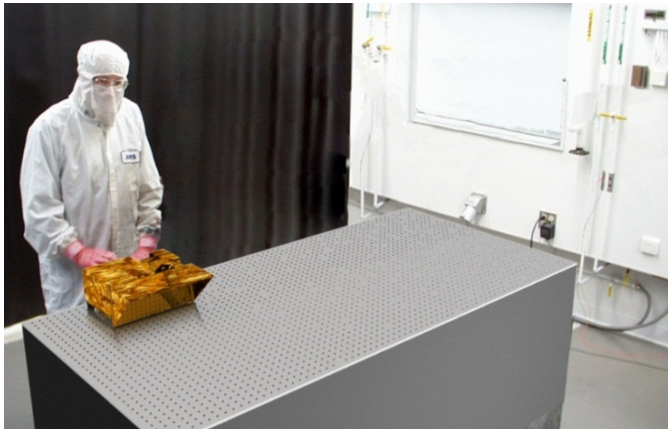
- Size Drivers
  - Geo-Stationary Imagers /Sounders Driven by Orbit Radius
  - IR Sounders Driven by # of Channels and LWIR Band Cooling
- **Moving MISTiC™ to a LEO orbit and eliminating LWIR channels enables massive reduction in SWaP**
  - Current concept is 60-125X less volume than Sounders proposed for GOES-R
  - Reduce power demand with an advanced FPA technology that won't require as much cooling
- IIP Instrument Concept Design
- Baseline envelope consistent with hosting on a 50 kg ESPA-Class Microsatellite
  - "Objective" Envelope consistent with 27U Cube sat Envelope (about 1 cubic foot of spacecraft volume)
- **Small instrument size depicted continues to be feasible as instrument concept fidelity increases**



Artist's Rendering Depicts a MISTiC™ Instrument, for Comparison to AIRS

Achieve Reduced SWaP by Reducing Number of Spectral Channels to the Mid IR only-*Sufficient to Sound the Dynamic Portion of the Atmosphere*

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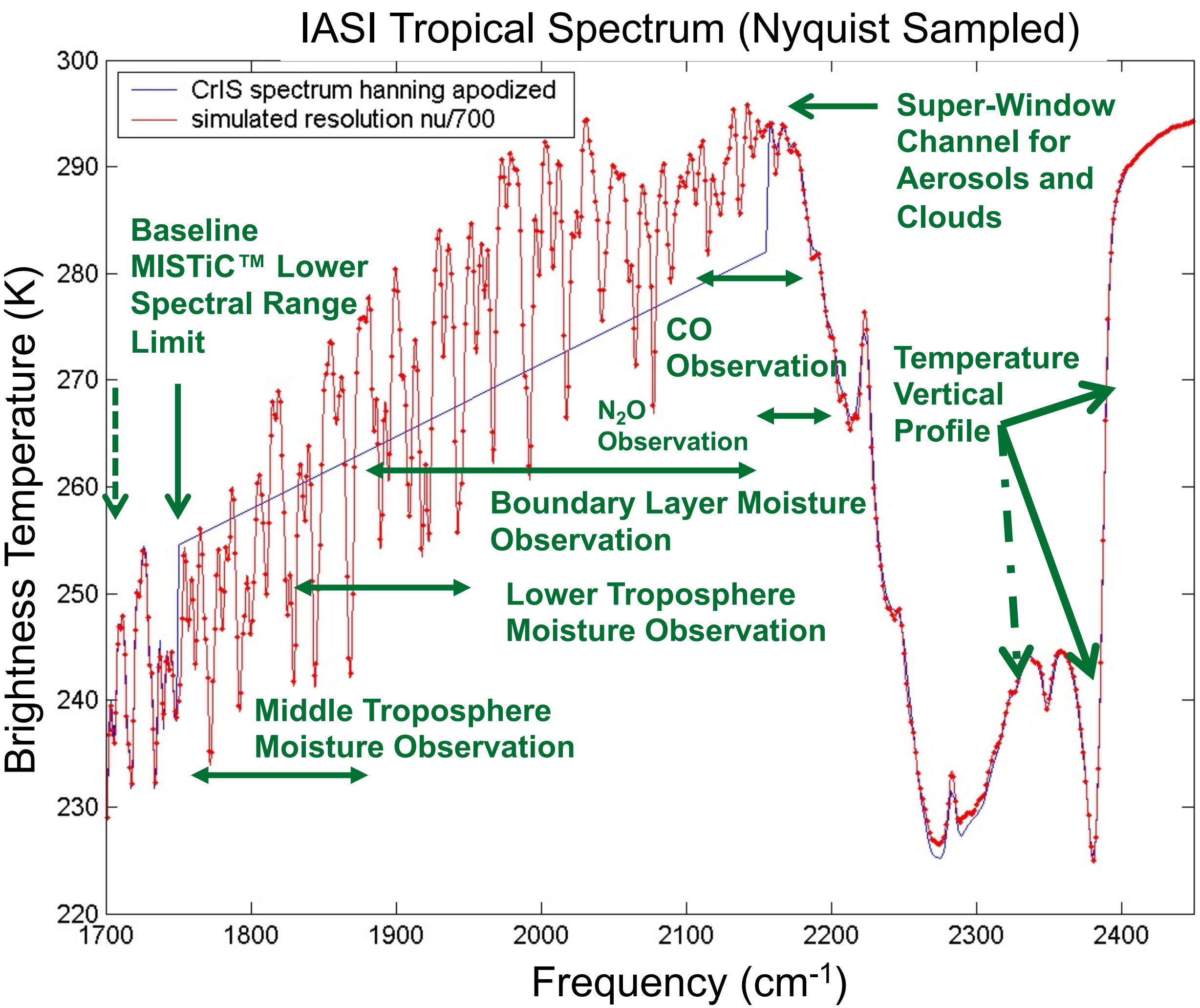
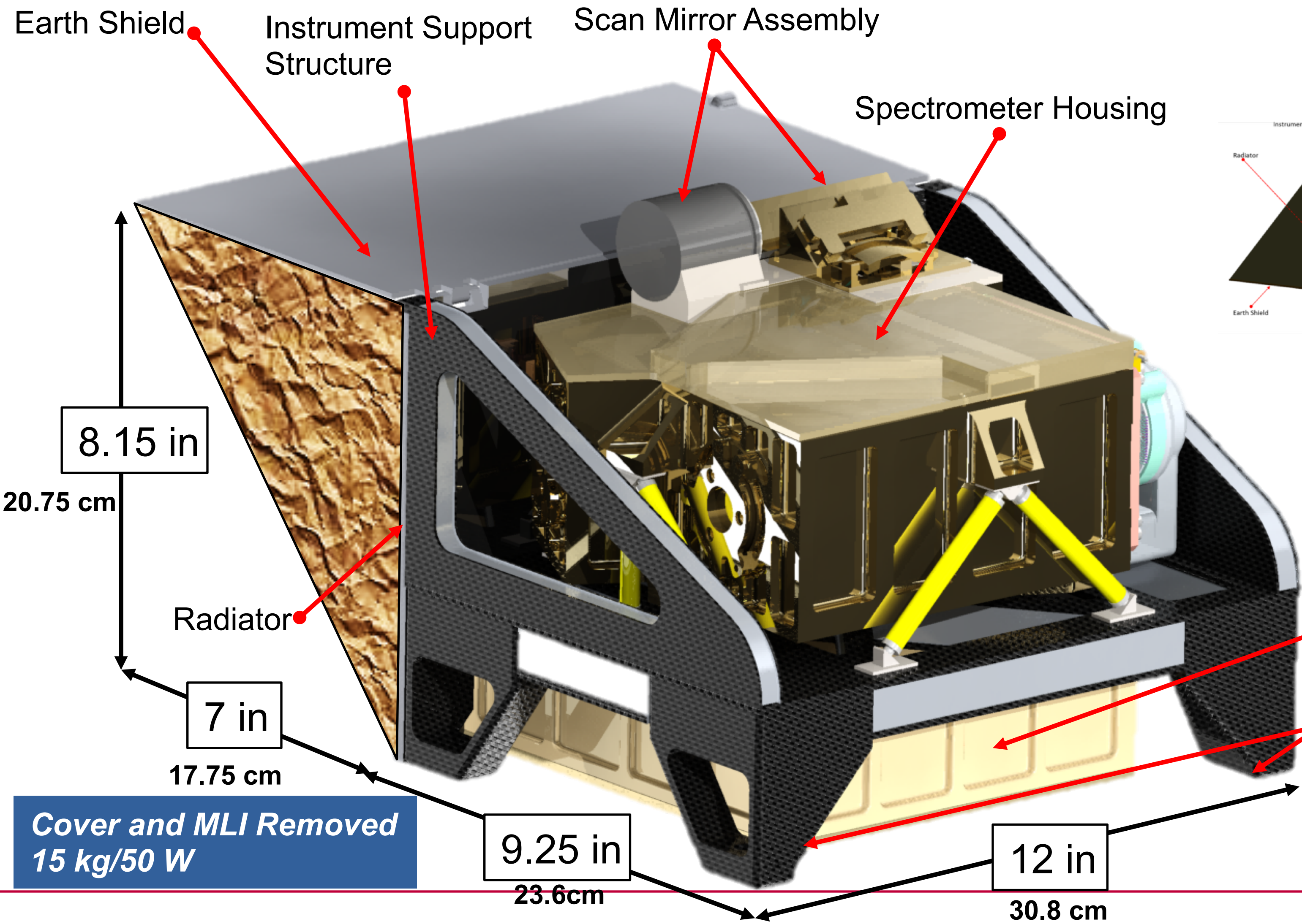
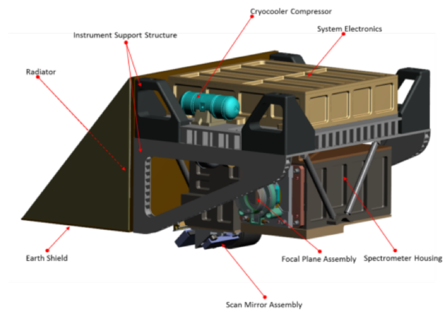


- SWIR Coverage at NEΔT and $\Delta\nu$ Sufficient for CO_2 R-Branch Temperature Sounding of Surface to Upper Troposphere
  - Sharper Vertical Resolution using Line Wings
  - Spectral Resolution > 700:1 is Sufficient
- Mid-Trop. CO
- Mid-Trop. N_2O
- Moisture in Planetary Boundary Layer
- Moisture Profile in Lower and Middle Troposphere
  - WV Motion Vector Winds
- Clouds
  - Cloud MV Winds

Channels Below 1750 cm^{-1} Needed to Observ
in for Upper Troposphere—*but, UT is Observ*
Sufficient Frequency by CrIS/IASI and ATMS

MISTiC Winds IR Spectral Sounding Instrument Concept





Cover and MLI Removed
15 kg/50 W

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Primary Efforts under NASA IIP Address Instrument Concept, Technology and Measurement Challenges (Continued)

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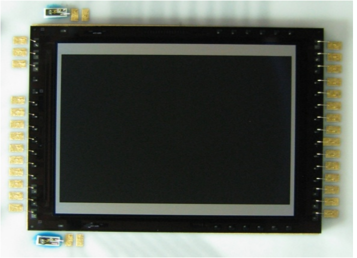
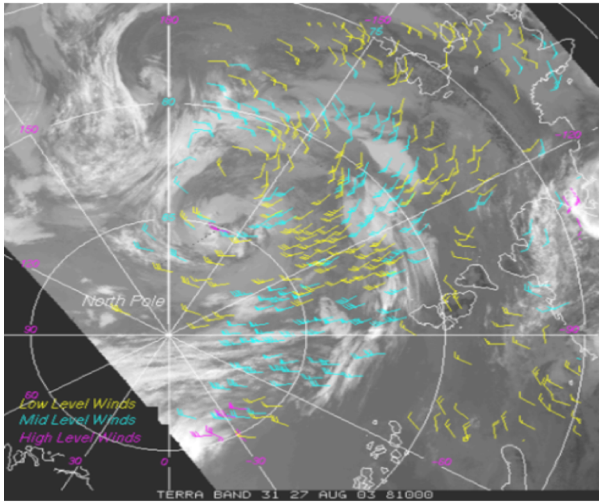
- ✓ Space Mission concept development
- ✓ Technology Risk Reduction

  Challenge: Get a higher operating temperature FPA in order to reduce cooler power
    - Benefit: Large reduction in SWAP
  - Approach: Use of new APD-Class MWIR FPA
    - Risk: APD Array Not Yet Tested in Space Radiation Environment
    - Mitigation: Radiation Testing on IIP *(by 9/15)*
- Observation Method Risk Reduction
  - Challenge: Application to Highly Vertically Resolved (3D) MV Winds is highly plausible-but not demonstrated
    - Benefit: MV Winds at Low Cost -> Better weather forecasting
    - Risk: Tracer De-correlation Behavior at finer vertical resolution unknown in detail
    - Mitigation: Airborne observations of Tracer De-Correlation Times & Behavior



The MWIR HgCdTe Avalanche Photodiode-based IR Focal Plane Array Detector selected for MISTiC allows high-sensitivity hyperspectral measurements at 85K



MISTIC™ Winds Tracers Features Would Have Better Vertical Resolution Than MODIS Winds

Airborne Testing of MISTiC Spectrometer on the NASA ER2 Platform Reduces Observing Method Risks

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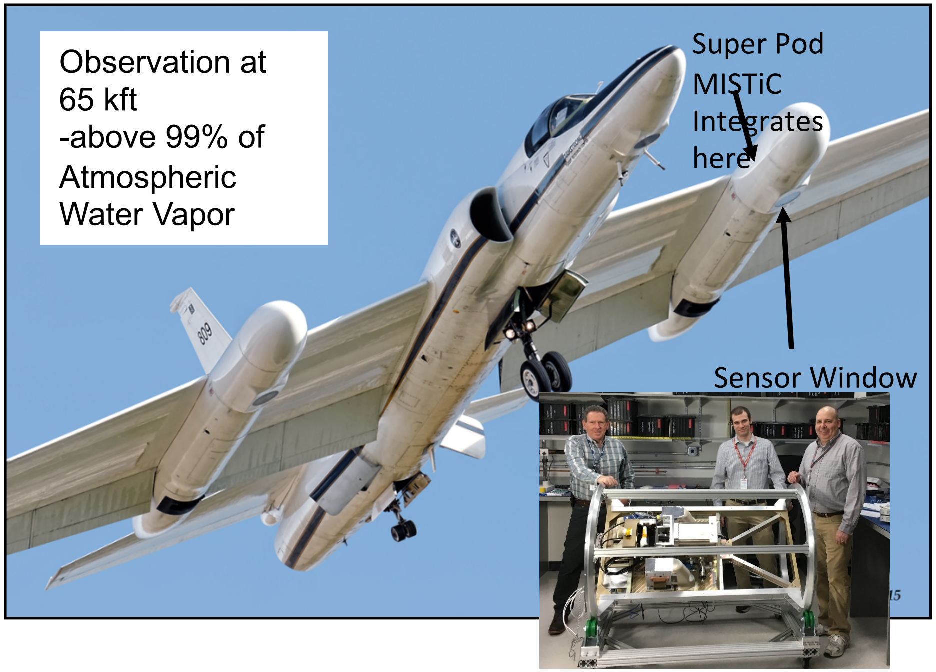
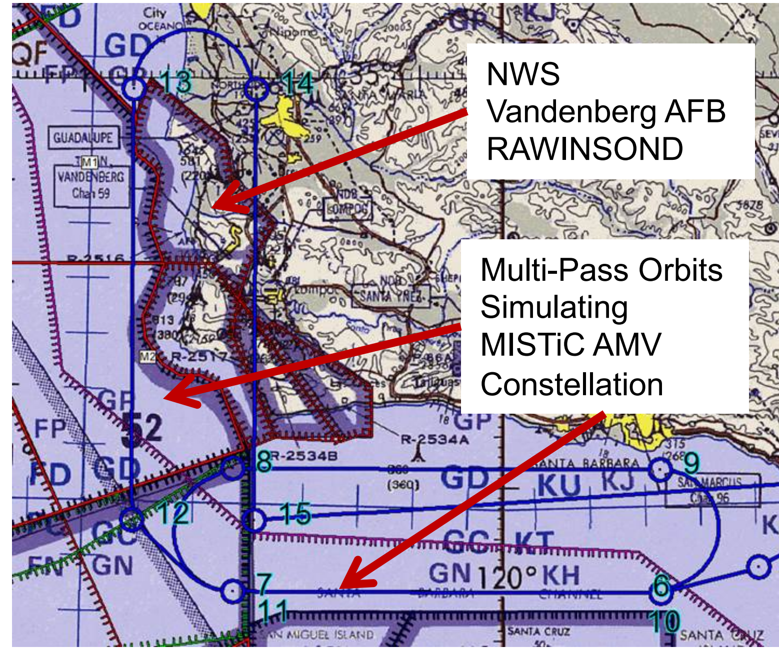




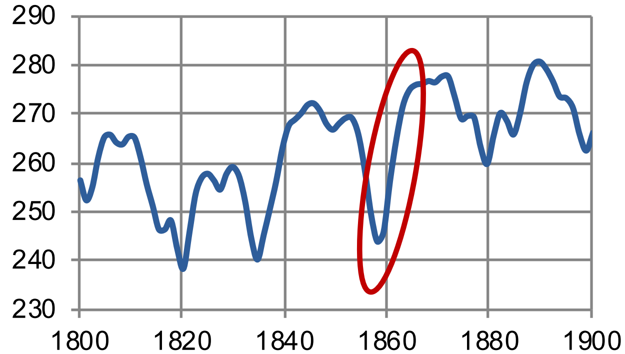
Airborne Spectrometer Very Similar to Space Instrument—but with these differences:

- Off-the shelf APD FPA, Filter (λ_{co} ~ 5.4μm vs 6)
- Active Cooling of Spectrometer- (in Vacuum Vessel)
- Pod Window (outside rad. cal. loop)
- (rugged) COTS electronics, cryo-coolers, etc

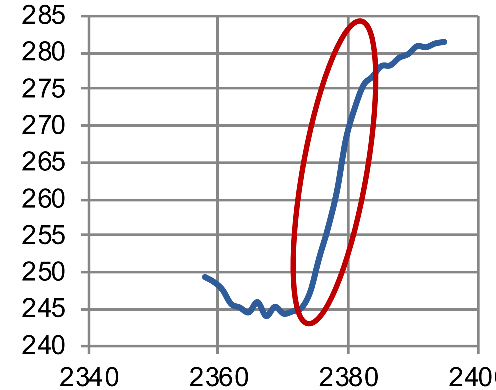
MISTiC and Independent Observations

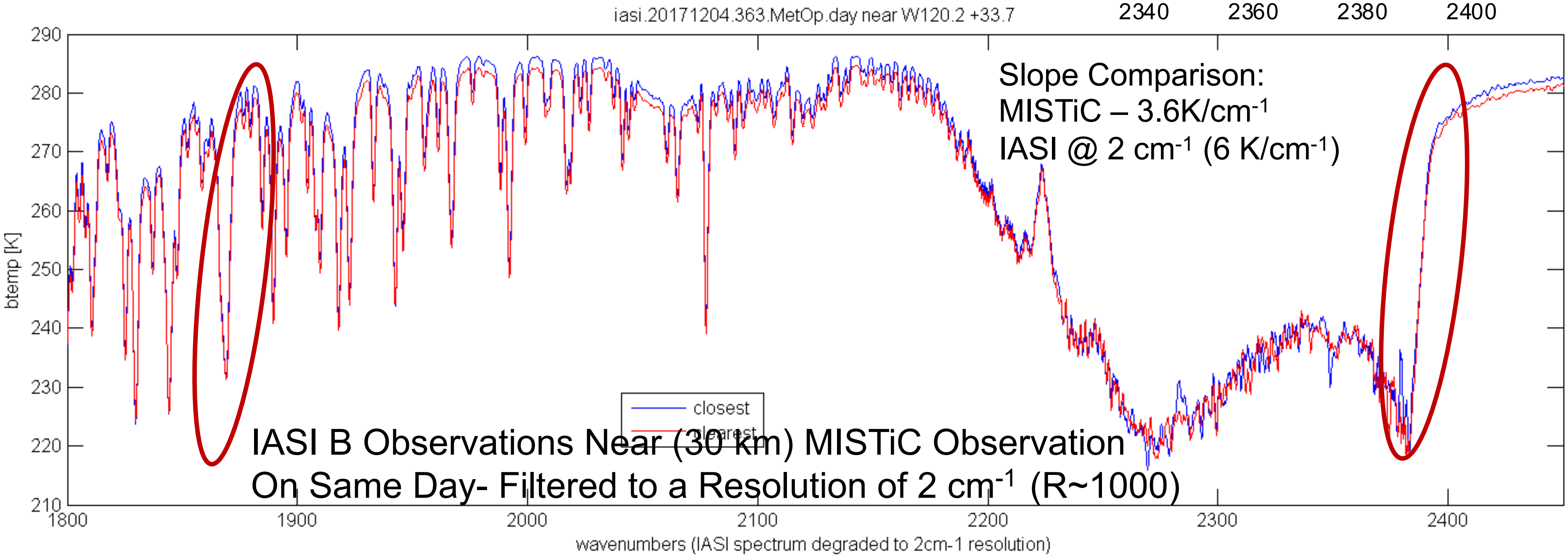
- IR Imaging/Sounding Spectroscopy
- Visible Context Images
- NWS RAWINSONDEs
- METSAT Obs (IASI A,B, AIRS, GOES West (?GOES 16?)

Primary Critical Atmospheric Emission Spectral Features Observed in MISTiC Winds Airborne Observation



Spectral Edge Response Consistent with Resolution ~600 in Key Mid-Trop WV and Temp Sounding Regions –close to 700 design goal

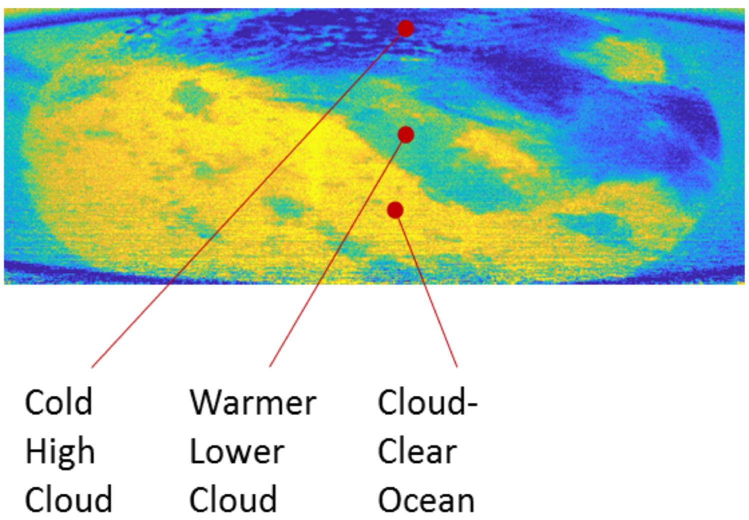


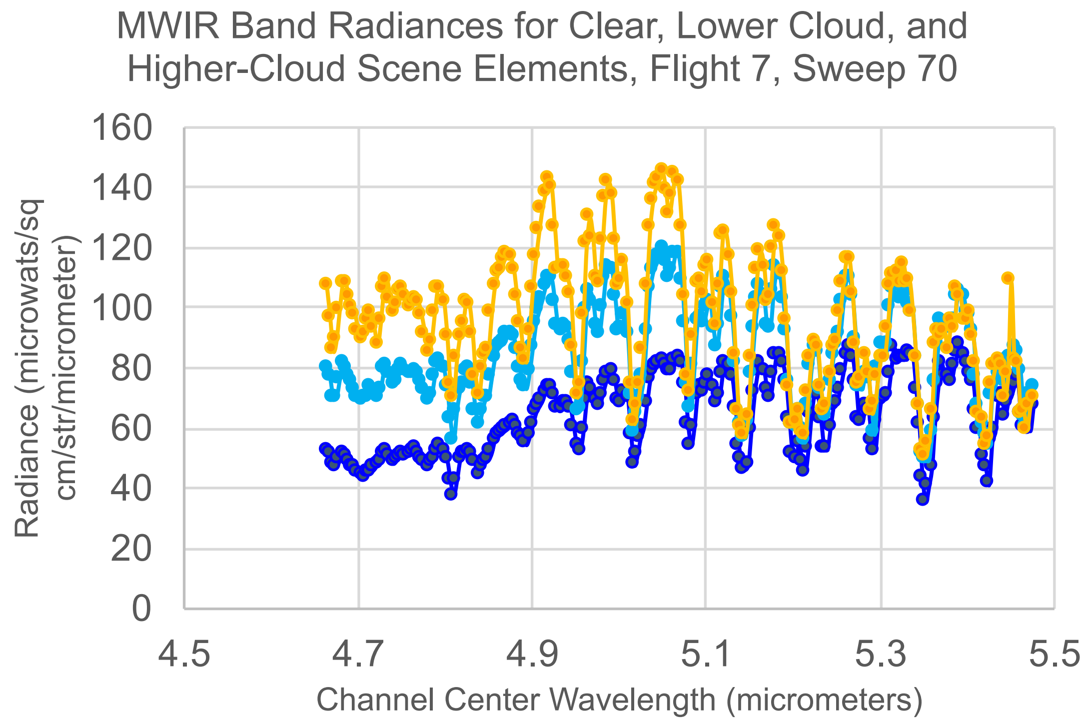


Slope Comparison:
MISTiC – 3.6K/cm^{-1}
IASI @ 2 cm^{-1} (6 K/cm^{-1})

IASI B Observations Near (30 km) MISTiC Observation On Same Day- Filtered to a Resolution of 2 cm^{-1} (R~1000)

MISTiC ER2 Flight 7 Targeted Cloud Motion Vectors Arising from a Low Pressure System Moving Through SF Bay Area





- A High-Transmission (window) Channel near 5 μm for an Ocean Scene with Clouds at Two Levels (Flt 7/Sweep 70)
  - Spectra are shown for radiance averages for 1km x 0.5 km regions within the indicated areas of the image
  - High Spectral Contrast Indicates Substantial Difference in Cloud Top Height

For Preliminary Estimates of Cloud Height, MODTRAN 6 is Used to Related Radiances to Atmospheric Model

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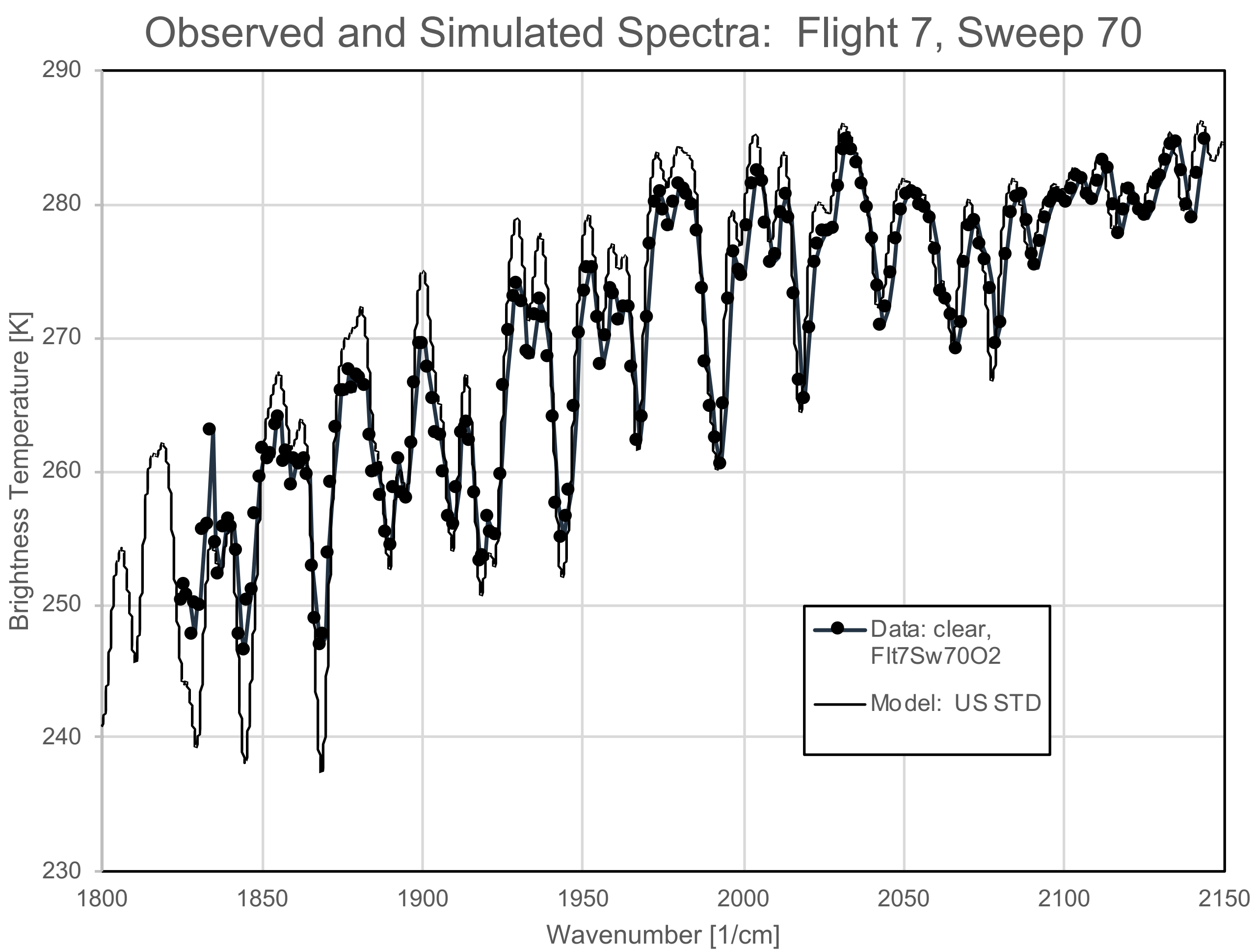
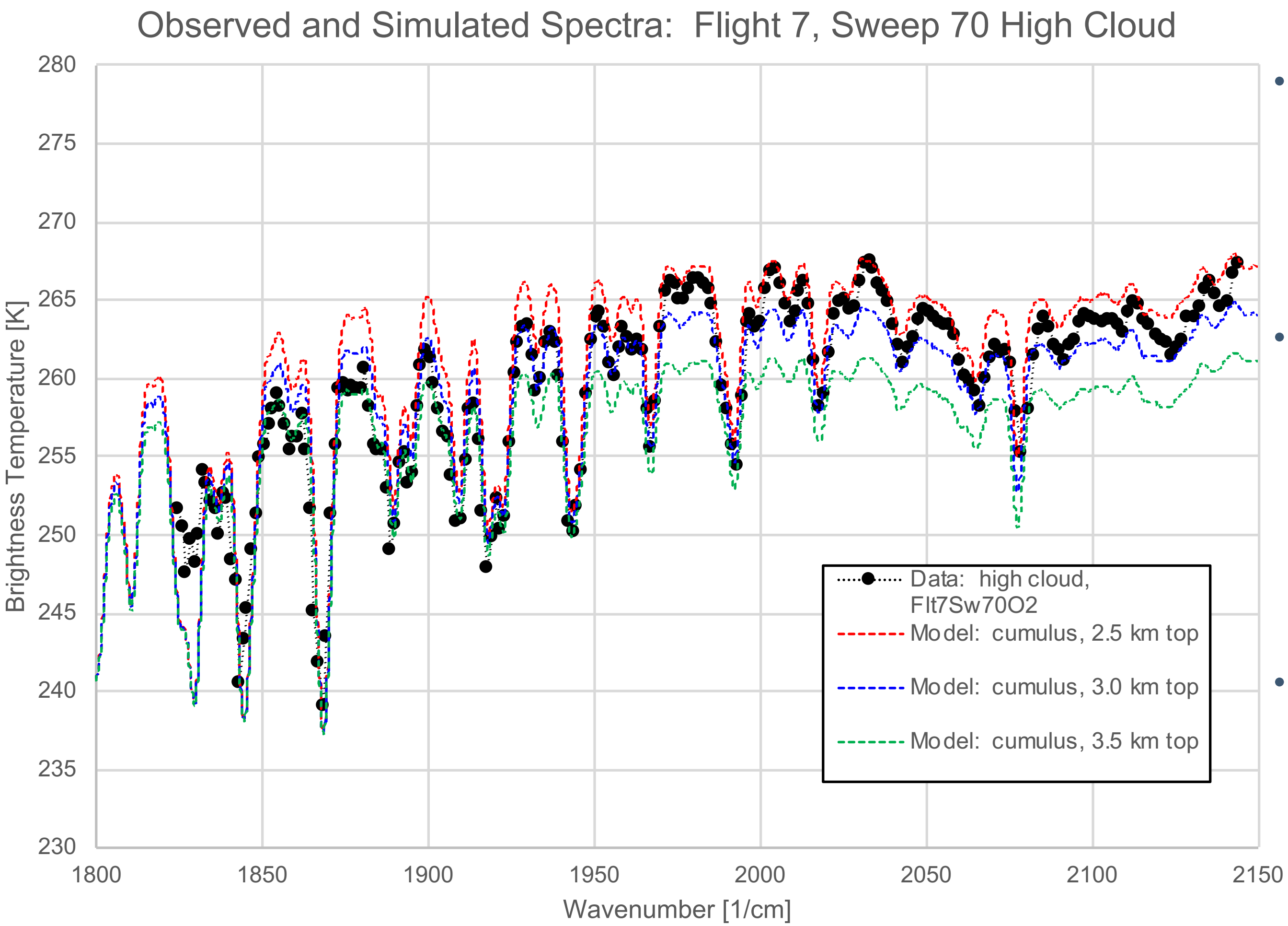


- No Radiosonde Observation for Comparison at this Pacific Location
  - 35N, 125.5W
- MODTRAN 6 Data Fits are with:
  - US Standard Atmosphere
  - 3.5 cm-1 Resolving Power
- US STD ATM
- -close-but not quite right (actual atmosphere has more moisture)

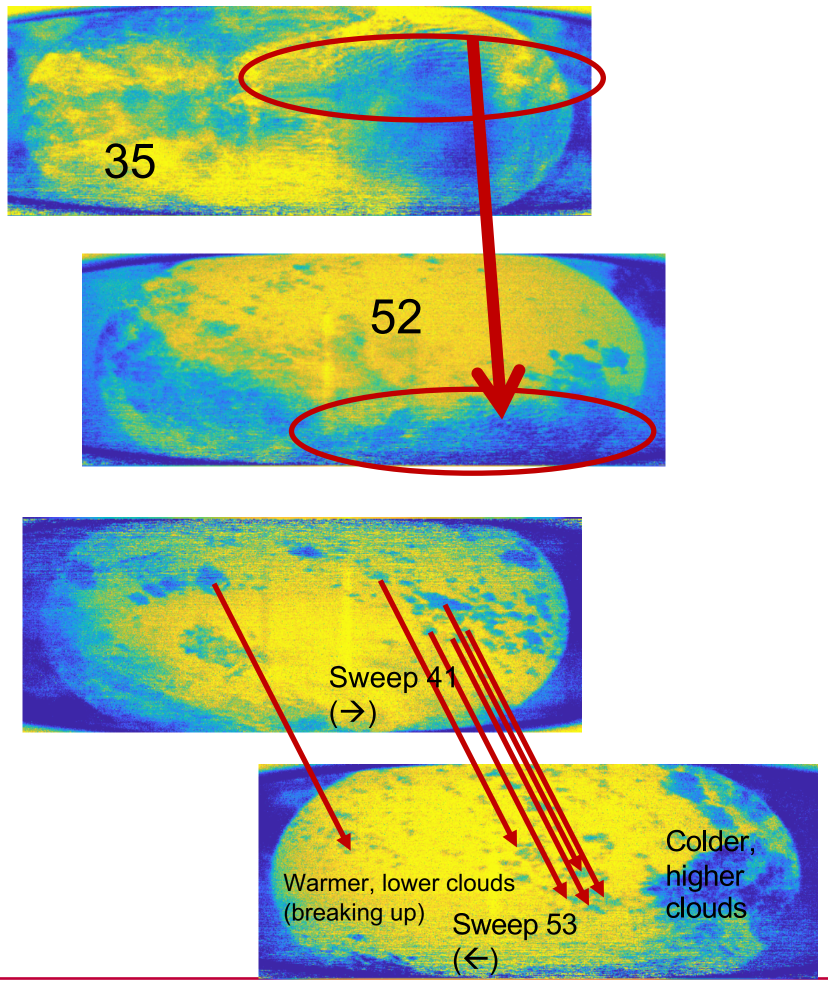
Spectral Data "Fitting" with MODTRAN 6 Cloud Model Demonstrates MISTiC Data Allow Discrimination on Cloud Height



- Hyperspectral Spectral Radiance Data for Cloudy Pixels Allow Retrieval of Cloud Top Height
- MODTRAN-6 Cumulus Model (in US STD ATM) With Different Cloud Heights Indicate Height Sensitivity to ~ 0.5 km (~ 50 mB)
- Better fit to actual atmosphere, higher fidelity cloud radiative model, and better SRF Model will improve spectral fit

Cloud Motion Vectors Observed During Flight 7

- Higher/Colder Cloud
  - Cloud Feature Motion (together with GPS data and other telemetry) Indicate a Wind Speed of 7 m/s blowing from direction of 349 degrees (11 degrees west of north)
  - Altitude of the Cloud Top (Derived from IR Radiances) is Estimated at 2.7 km
- Warmer/Lower Cloud
  - Lower, warmer cloud motion indicates higher wind speed, and different direction-- more out of NW, but also with cloud shape changing (evaporating)
  - Altitude of the Cloud Top (Derived from IR Radiances) is Estimated at 0.7 km



Example Observation of a “Wind Tracer” in MISTiC Airborne and Radiosonde Comparison

- MISTiC observes the wind by observing the shift in location of features in the cloud and moisture fields
  - MISTiC’s innovation is to do this with a hyper-spectral instrument, and the different spectral channels see the scene in different ways—depending on the details of moisture and carbon dioxide emission for that spectral channel.
  - These differences, ultimately, relate to height assignment for the feature
  - Initial Observations identify a cloud with unique spatial features—and observed it at different locations during different observation periods from the ER2
    - ~ 1000 seconds elapse between observations, allowing wind to move the feature
- A unique bar-pattern cloud feature (group) was observed multiple times during the recent MISTiC flight—over a sight just south of the Channel Islands-west of LA
  - After accounting for changes in plane position and image scan start/stop times, the features have shifted ~ 4 km to the east, and ~ 4.5 km to the south from one observation pass to the next
  - Feature velocity reasonably matches that of wind at ~ 9000 ft from the Northwest-as indicated by radiosondes launched from near-by Vandenberg AFB—ΔV~ 2 m/s

4 December MISTiC (Airborne) Flight on NASA ER2 Over Southern California and Adjacent Coastal Waters

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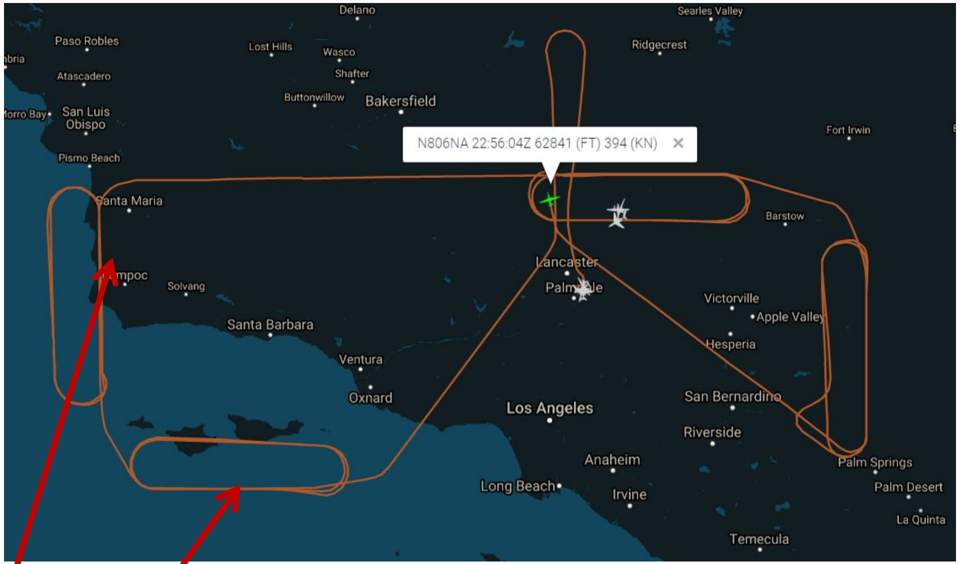
orbit 1:
- south edge: 11-17,26-32,41-46
- north edge: 19-24,34-39

orbit 2:
- east edge: 50-55,65-70,80-85
- west edge: 57-63,72-77

orbit 3:
- north edge: 97-103,112-117,127-131
- south edge: 104-110,119-125

orbit 4:
- east edge:137-142,152-157,166-171
- west edge: 146-150,159-164



Sweep 13 (Ocean, Cloud, and Moisture Field)

Infrared Hyperspectral (and Visible Broad-band) Observations near Eastern-most Channel Island and Nearby Ocean

Vandenberg Radiosondes at 11:30 Z, 17:30Z, 20:30Z

Sw 13 and Sw 28 Band 80—showing Banded Mid-Level “Cloud Tracer” Shift in Location

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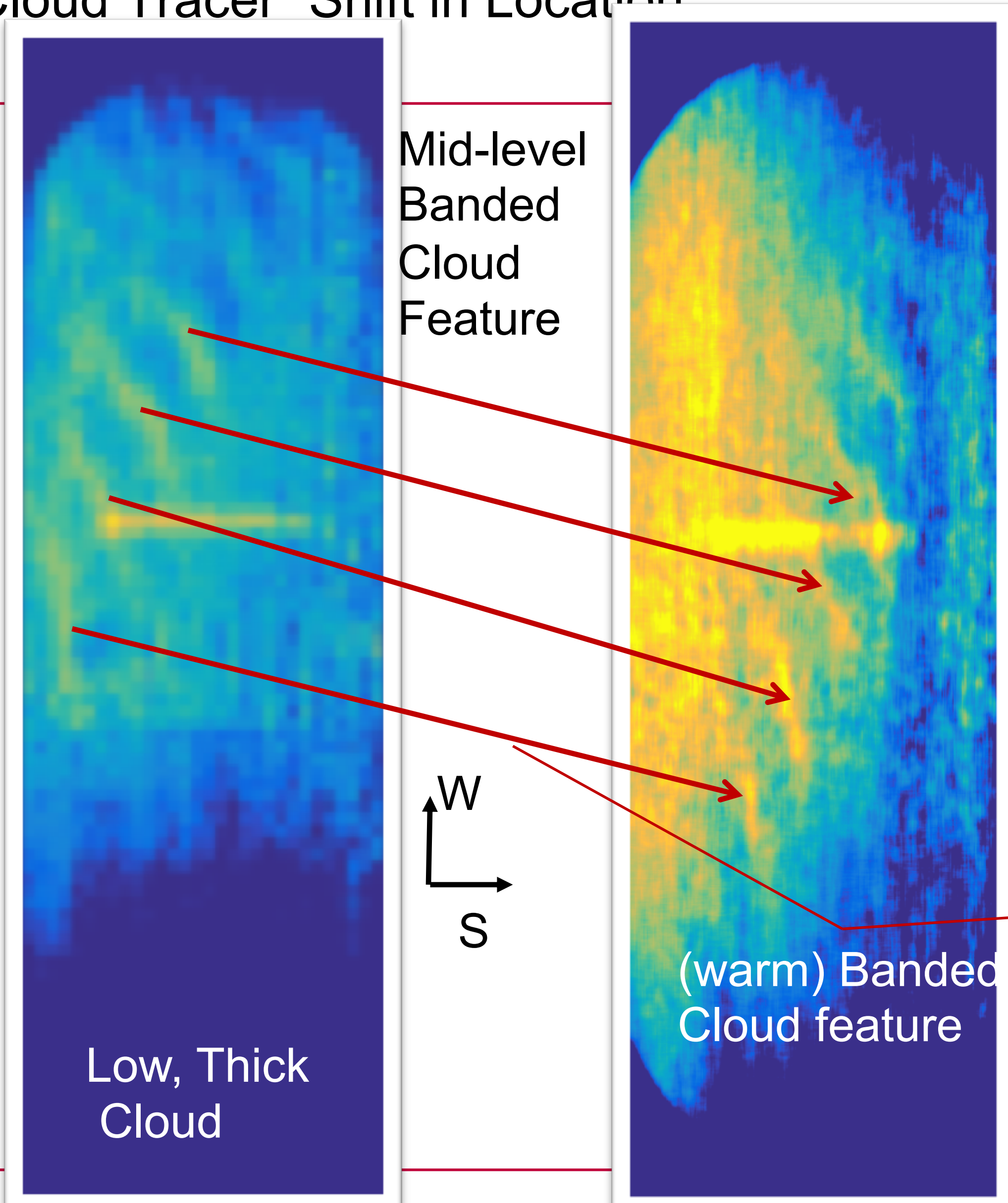
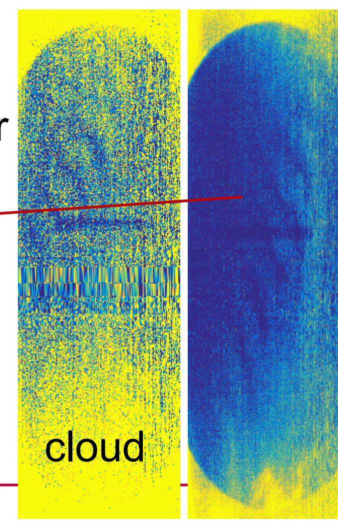


Sweep 13 Pixel		Sweep 28 Pixel	
X-tr	Al-tr	X-tr	Al-tr
57	363	145	604
95	316	183	511
145	262	224	454
200	206	220	305

Feature pixel (angle) position within Sweep, GPS position/velocity for the Sweep, and estimated feature height used to compute (feature) wind velocity

Higher cloud



Sw13 (l) and Sw 28 (r)-Band 80 Neg Cont

Not export controlled per ES-C4ISR-030718-0037

Sw13 (l) and Sw 28 (r)-Band 80 Positive Contrast

Rawinsondes Launched from Nearby Vandenberg AFB Show Both the NW Wind Driving Higher Cloud Motion and East Wind Driving Lower Cloud Motion

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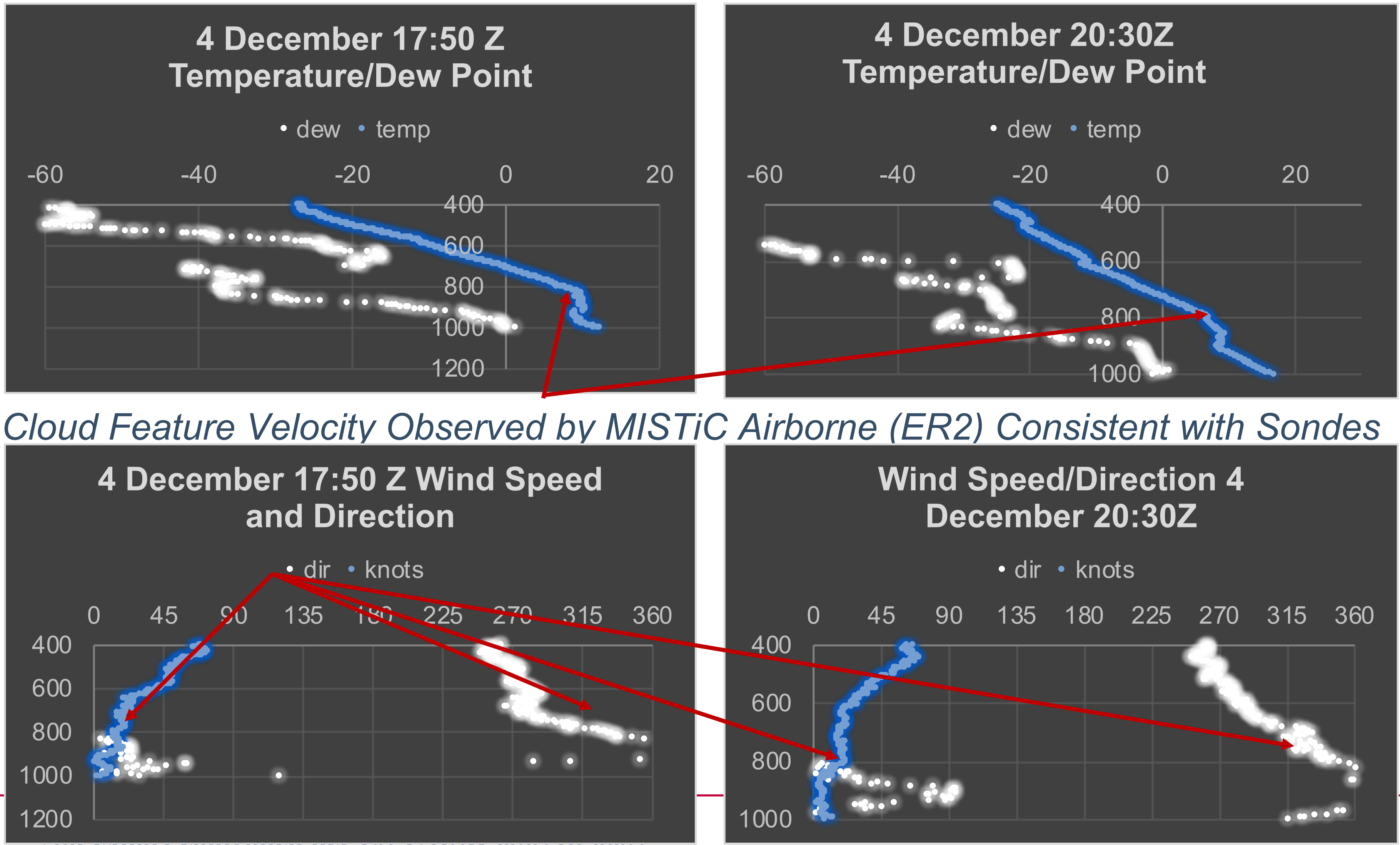
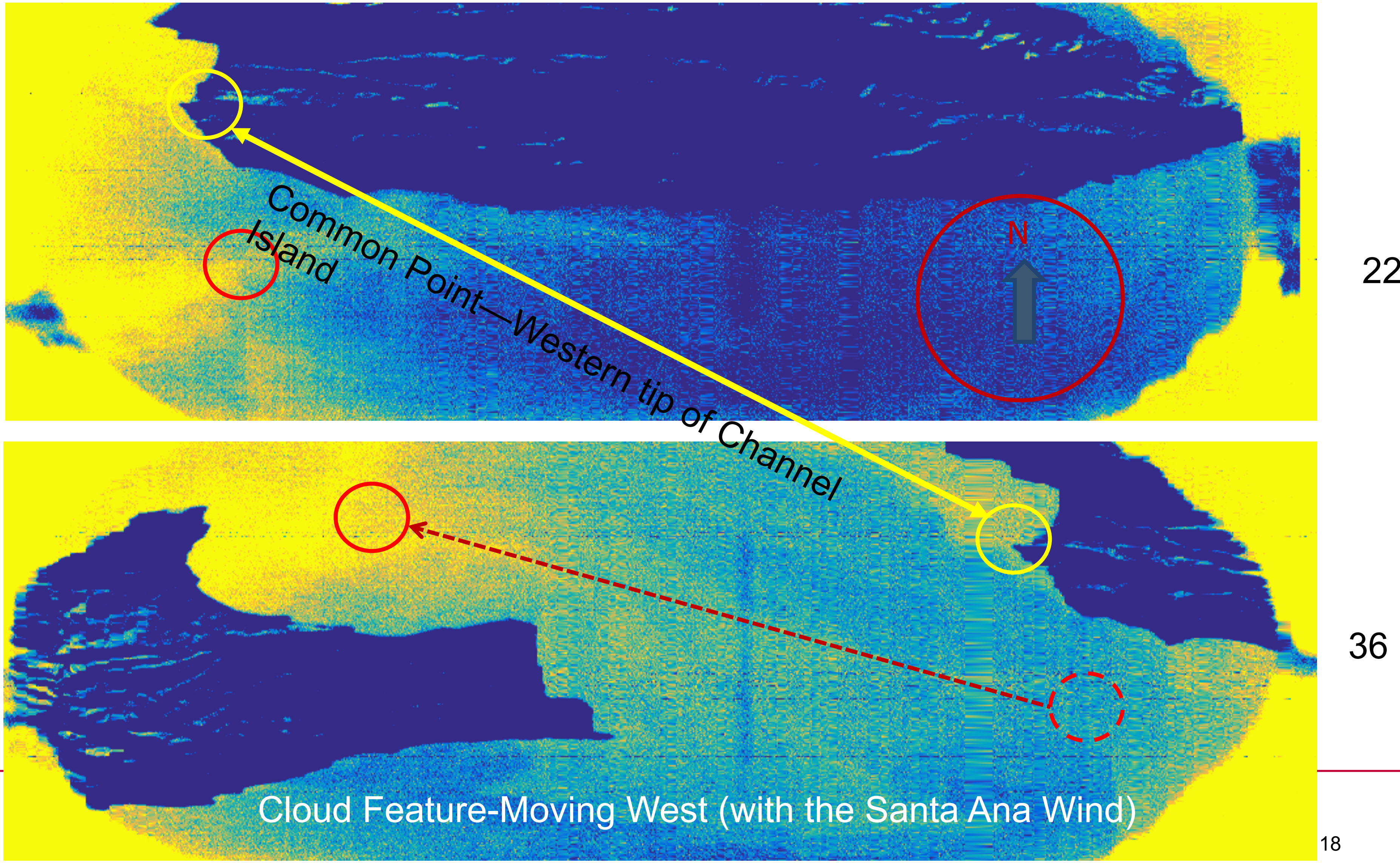


Cloud Feature Velocity Observed by MISTiC Airborne (ER2) Consistent with Sondes

Temperature and Dew Point (C), Wind Speed (deg) and Wind Direction vs Pressure Height (mB)

Sweeps 22 and 36, which contain a cloud tracer that moved ~ up(north) and left (west) Window Band Group (Ch 1-27, or ~4.7-4.8 μm)



Modeled (MODTRAN6) Spectra Using Colocated Sonde over Edwards AFB Compare Well with Observed MWIR Radiance Spectra

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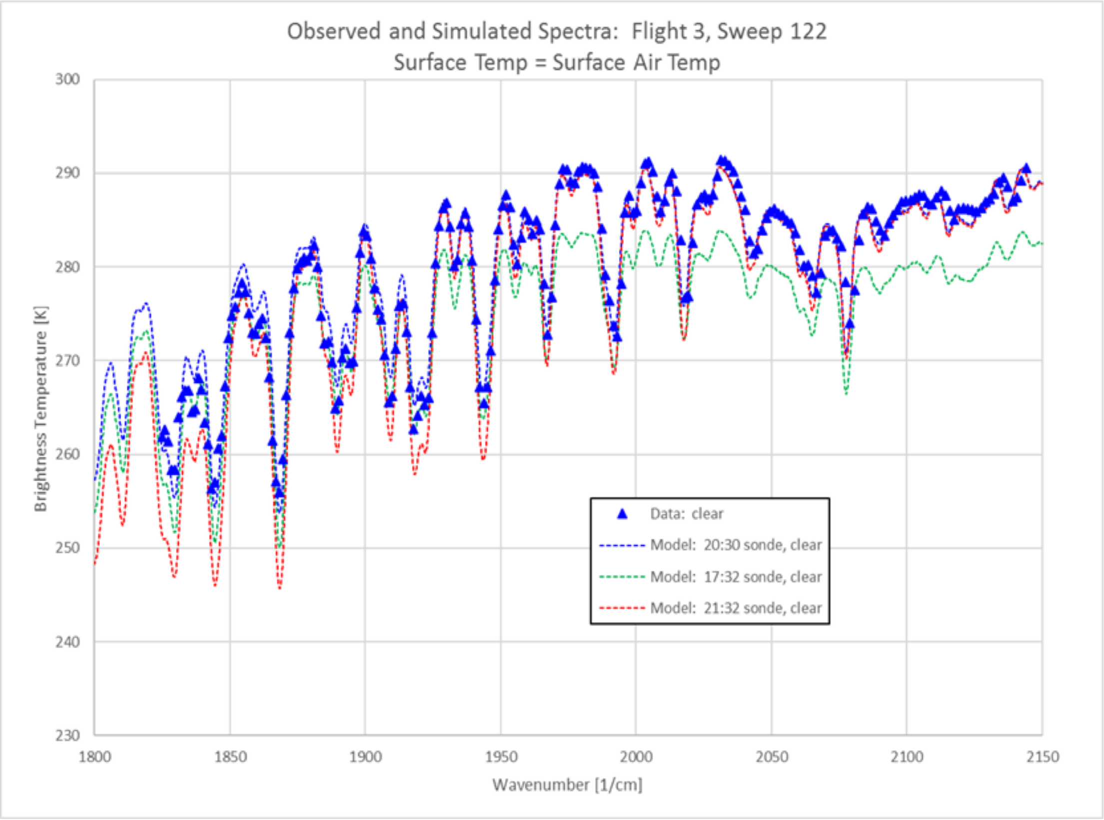

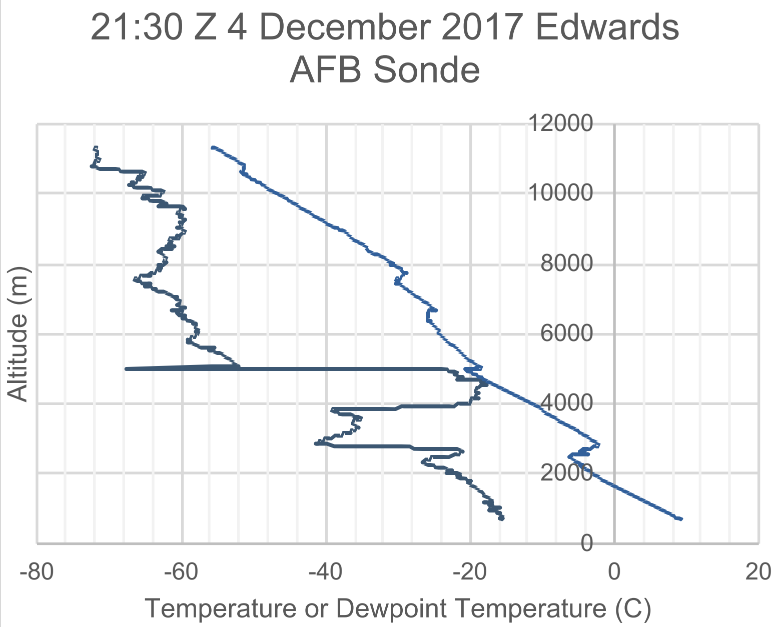

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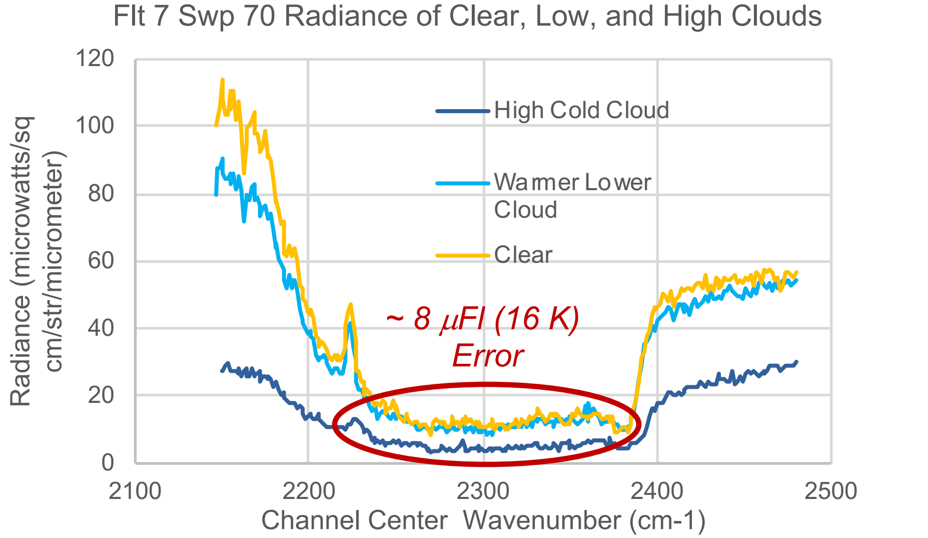
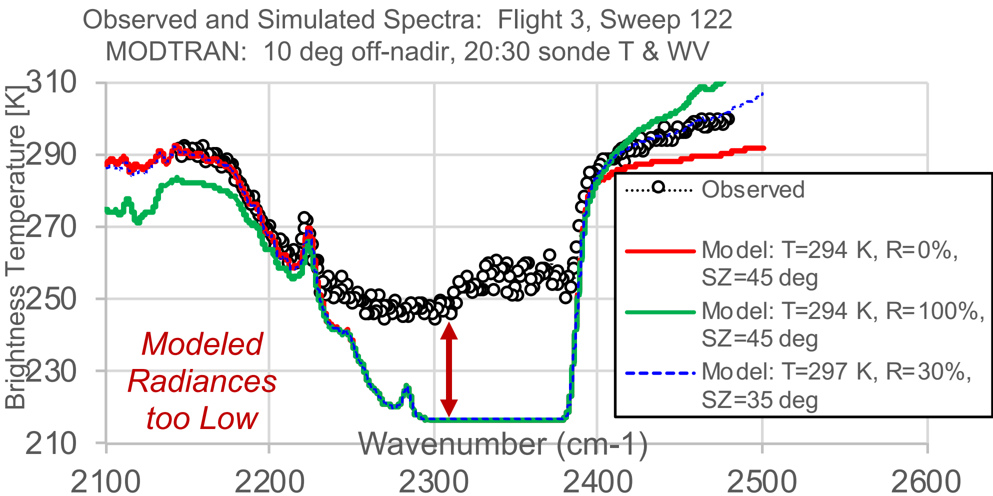
Some Remaining Issues and Challenges

- Radiometric Calibration in SWIR Band Needs Improvement-in Airborne Instr.
  - Cold Cloud “Radiance” is Lower in Region of Very High CO_2 Absorption—*not physical*
    - Probable Cause—uncorrected window or (reflected instrument) self-radiance
- No Water Vapor AMV Wind yet Measured during ER 2 flights (Some Observation of Water Vapor Gradients)
- Radiance Forward Modelling and Retrieval to Date is Insufficient—or Absent
  - Radiance Modeling in 2200-2400 range is not yet employing enough of the correct physics
  - MODTRAN 6 cloud radiance models too simple to use for cloud height estimates
    - Need CRTM or SARTA
  - No actual temperature/moisture retrievals yet demonstrated for MISTiC
    - (GSFC Sounding Research Team Overall Team Funding Issues)





Lab Measurements of MISTiC SRF using Mono-chrometer Input Meet Resolving Power: λ/dλ>700:1 at key λs

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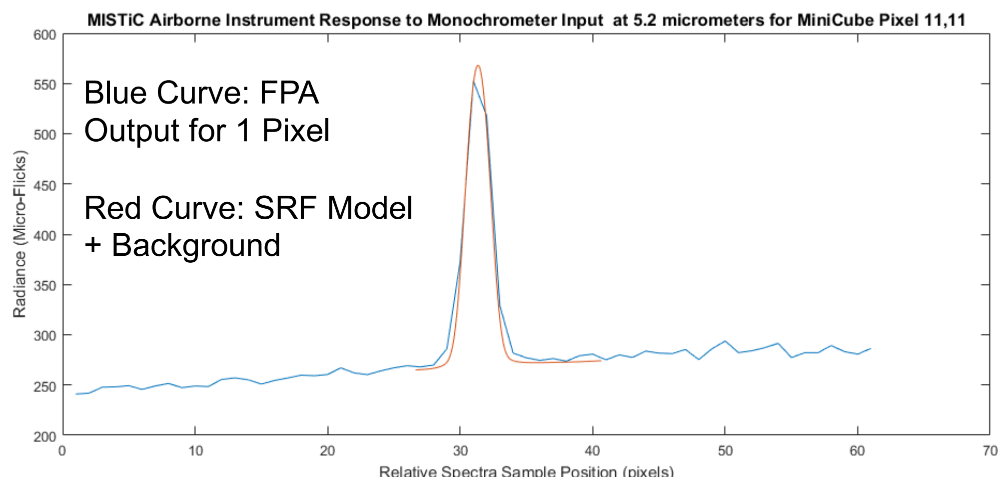
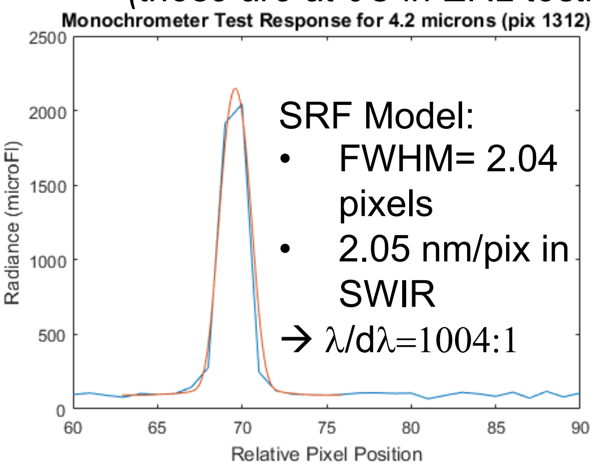
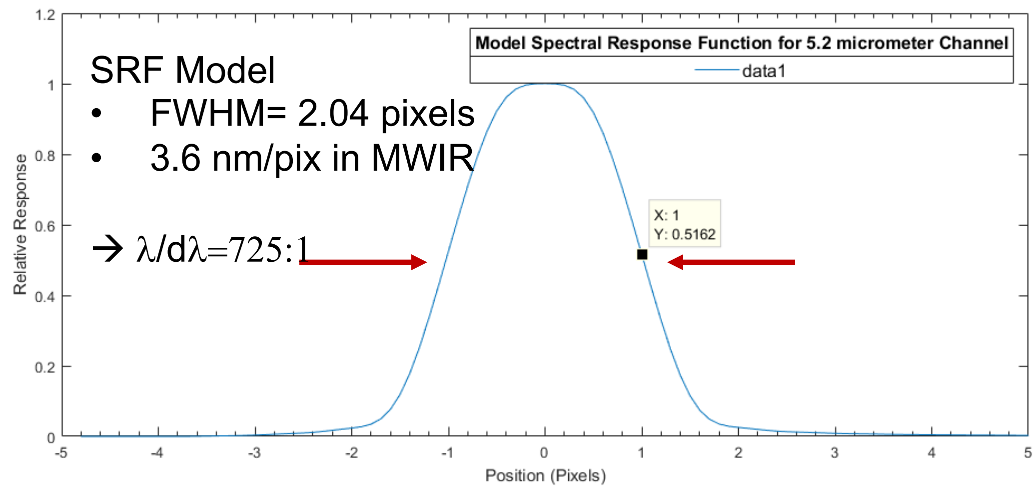
- Monochrometer Test Background
  - f/5 6" C-T instr. with Hot ceramic source
  - Entrance and exit slits 1 pixel wide
  - > 3 mrad beam projected onto MISTiC scan mirror (fills slit) as mirror scans scene
- SRF Model Elements:
  - Detector SRF (top-hat)
  - Spectrometer Optics Diffraction
  - DC Meas.-Lab Background Removed (linear)
- Spect. At Flight (Cryo) Temp, Fore-optics and Dewar (exterior walls) at ~295K
  - *(these are at 0C in ER2 testing)*







MISTiC™ Winds-A Miniature High Vertical Resolution Infrared Sounder for 3D Winds and Frequent IR Soundings

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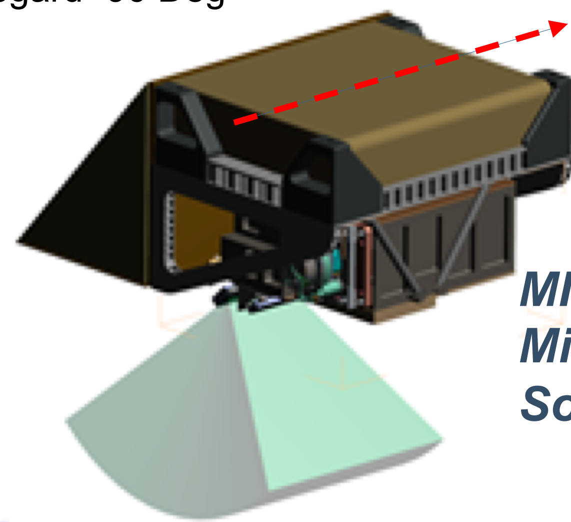
- Miniature Spectrometers Enabled by:
  - Optimized Low-Impact Spectral Channel Selection Proven through a Decade of NASA's AIRS Experience
  - Innovative Opto-Mechanical/Thermal Design Minimizes S/C Resources Needed to Cool IR Spectrometer
  - Advanced Large-Format IRFPA, Miniature Cryocooler, and Electronics
    - *All Technologies TRL-5 or Higher*
- Compact IR Sounder Design, Mature Algorithms and Technologies Enable:
  - Payload Hosting on a Micro-Satellite for a Low-Cost Total IR Sounding Mission
  - ~1 km Vertical & ~3 km Horizontal Resolution (@Nadir) in the Troposphere
    - Temperature, Moisture, Wind Profile

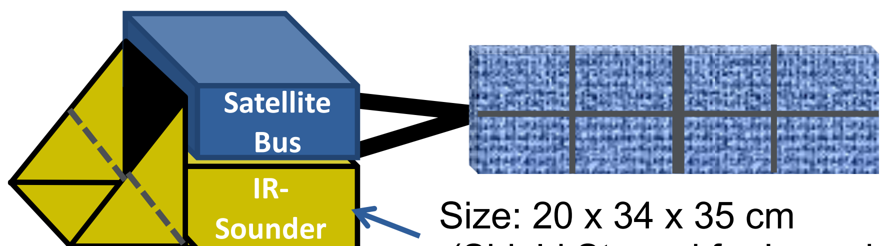
X-Track Field of Regard- 90 Deg

Flight Path



MISTiC™ Miniature IR Sounder

Micro-Sat with Miniature IR Sounder Payload

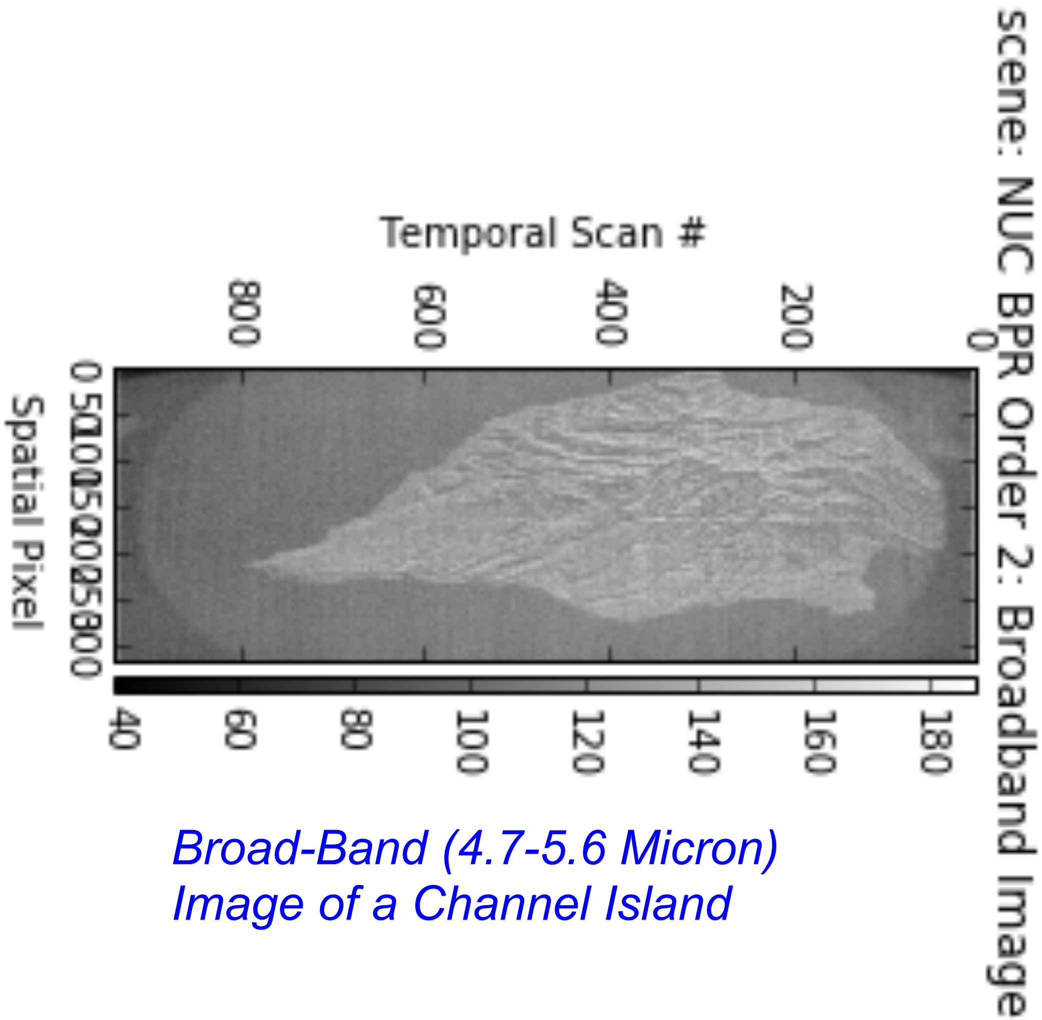


Size: 20 x 34 x 35 cm
(Shield Stowed for Launch)

Not export controlled per ES-C4ISR-030718-0037

Supplemental Material

Airborne MISTiC Instrument Acquires Hyperspectral Imagery to Capture Atmospheric Motion Vectors

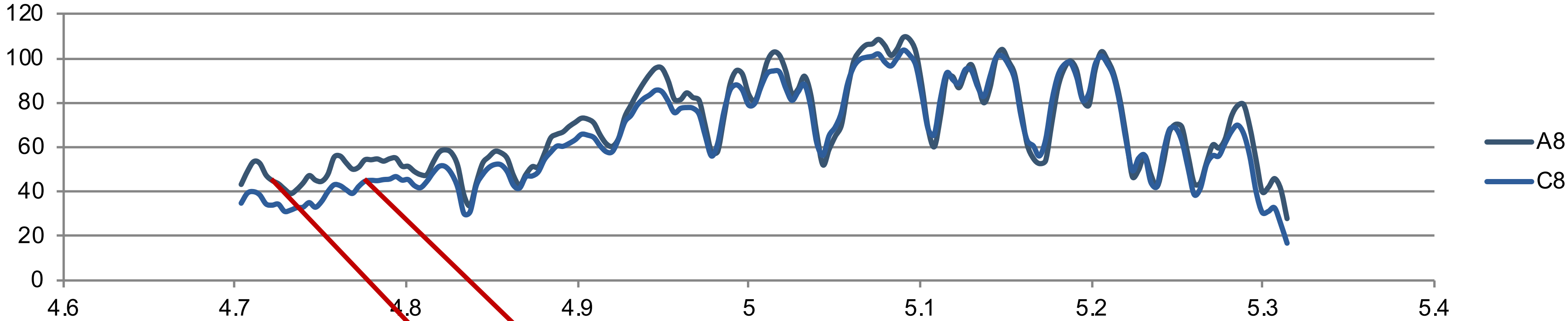


Broad-Band (4.7-5.6 Micron) Image of a Channel Island

- Observations of a Constellation Simulated by Repeat-Looks from ER2
  - 15-20 min Orbits
    - 6 min Straight Segments
  - 65 kft Altitude Above 95+% of Atmospheric Moisture
  - 50-m GSD Pixels Aggregated to MISTiC Wind Space GSD (1.3 km @ nadir)
    - Slit Scanned Along Direction of Travel

Low-Lying Cloud Decreases IR Radiance –Selectively

Sweep 18 Order 2 Block Average Spectra for Clear(A8) and Cloud-Containing (C8) Blocks



5.01 µm Spectral Channel Image

- Cloud tops are colder than ocean surface
  - Lower Radiance
- Low cloud temperature close to surface temperature (low thermal contrast)

Spectrum for a 3 km Footprint over Ocean Near Channel Islands for MISTiC Winds Moisture-Band

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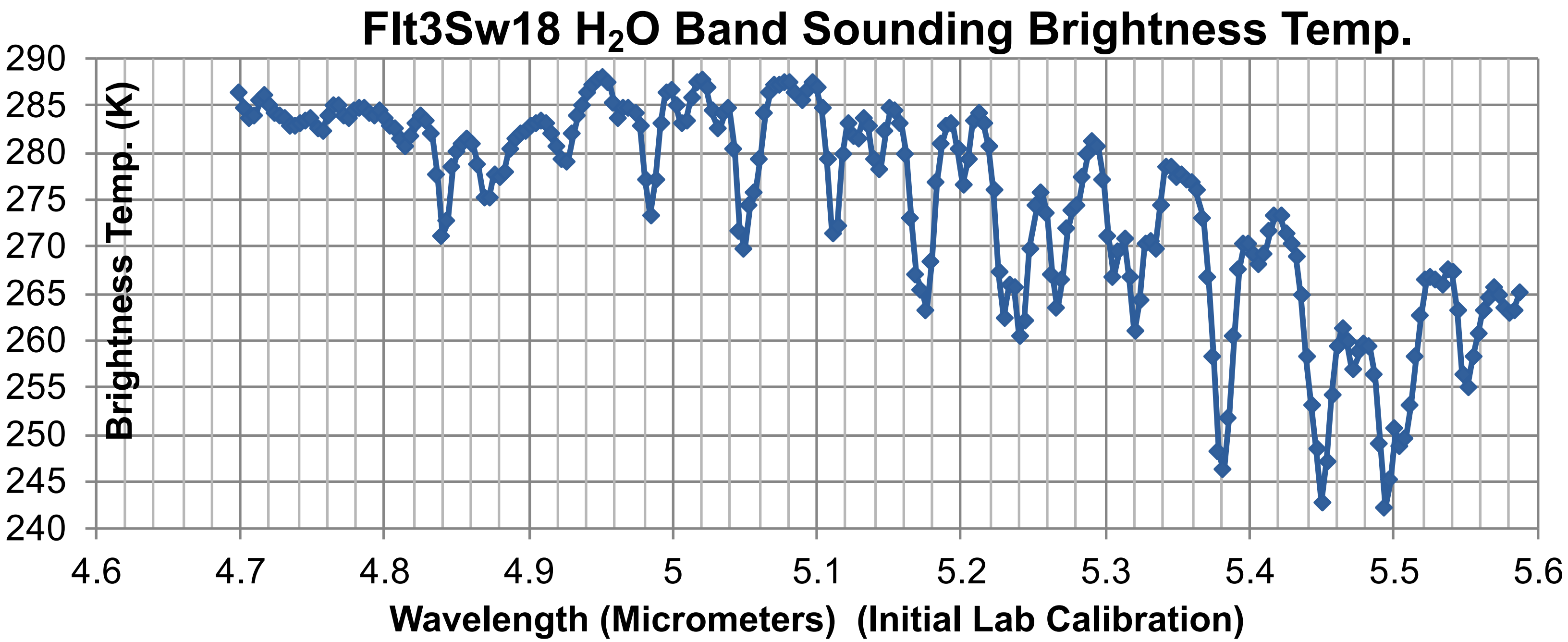

- Initial Radiometric Calibration:
  - 2-Point (-10C and 25C Blackbodies)
  - Calculated Transmission Correction for ER2 SuperPod Window
  - Window Emission—temperature-monitored, (but not yet included)
- Initial Spectral Calibration—Monochrometer at Room Temperature

Spectrum for a 3 km Footprint over Ocean Near Channel Islands for MISTiC Winds Temp.-Band

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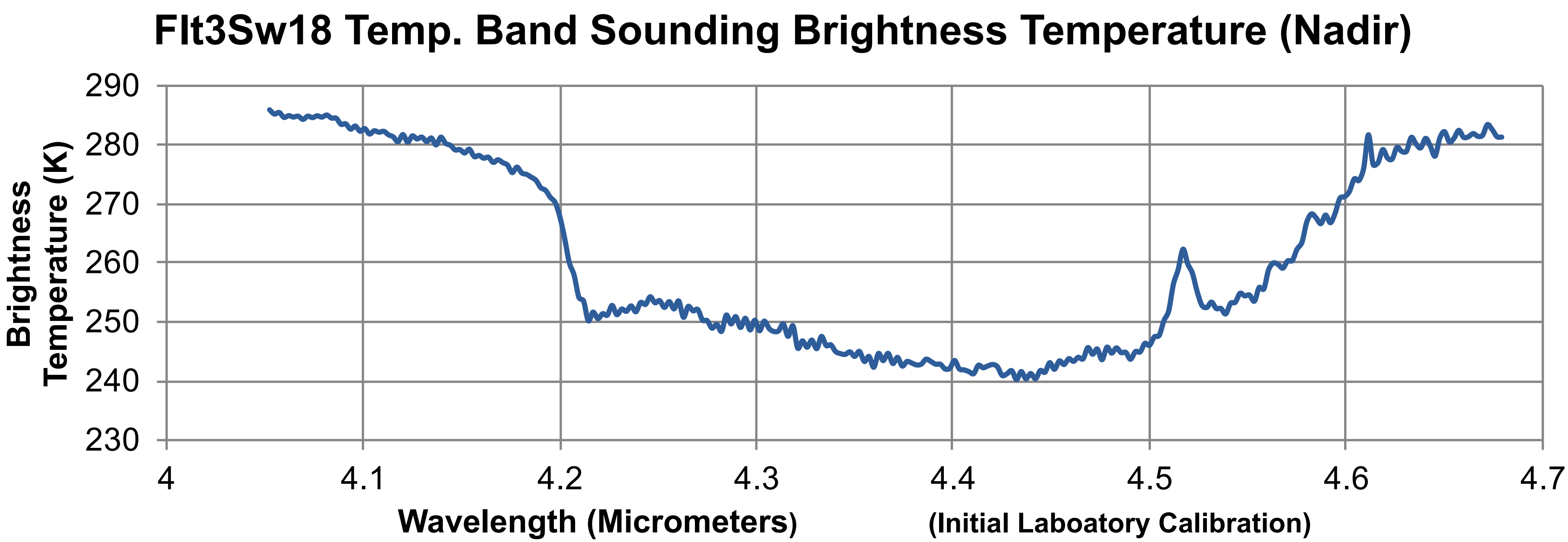

- Initial Radiometric Calibration:
  - 2-Point (-10C and 25C Blackbodies)
  - Calculated Transmission Correction for ER2 SuperPod Window
  - Window Emission—temperature-monitored, (but not yet included)
- Initial Spectral Calibration—Monochrometer at Room Temperature

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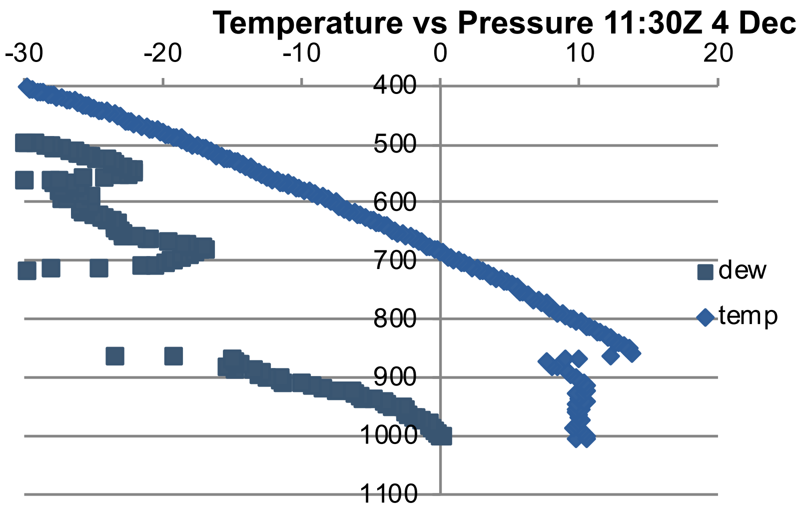

Not export controlled per ES-C4ISR-030718-0037

Tracer Example Observation Location (Observation Nadir Point)
Time of Observation: ~ 11:30, 11:30 + 1083 sec Pacific Time

Orbit 1 –West-bound	Longitude (deg)	Latitude (deg)	Heading (deg)
• Sw13 (pass 1)	-119.670779	33.757959	-88.59
• Sw28 (pass 2)	-119.705720	33.755339	-88.84

Sweep 22 Selected Water Vapor-Band Images-Show Differences Vertical Information Content

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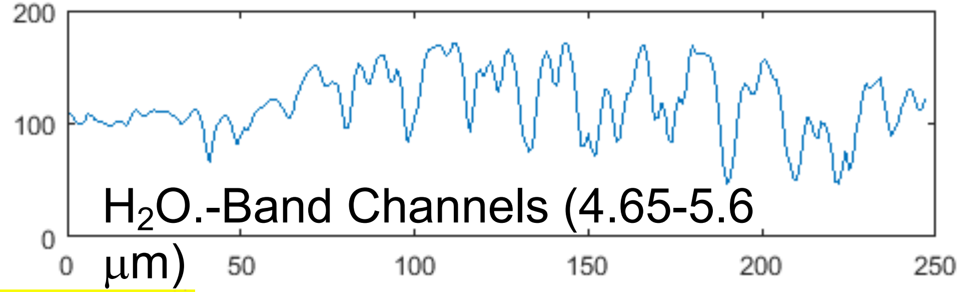
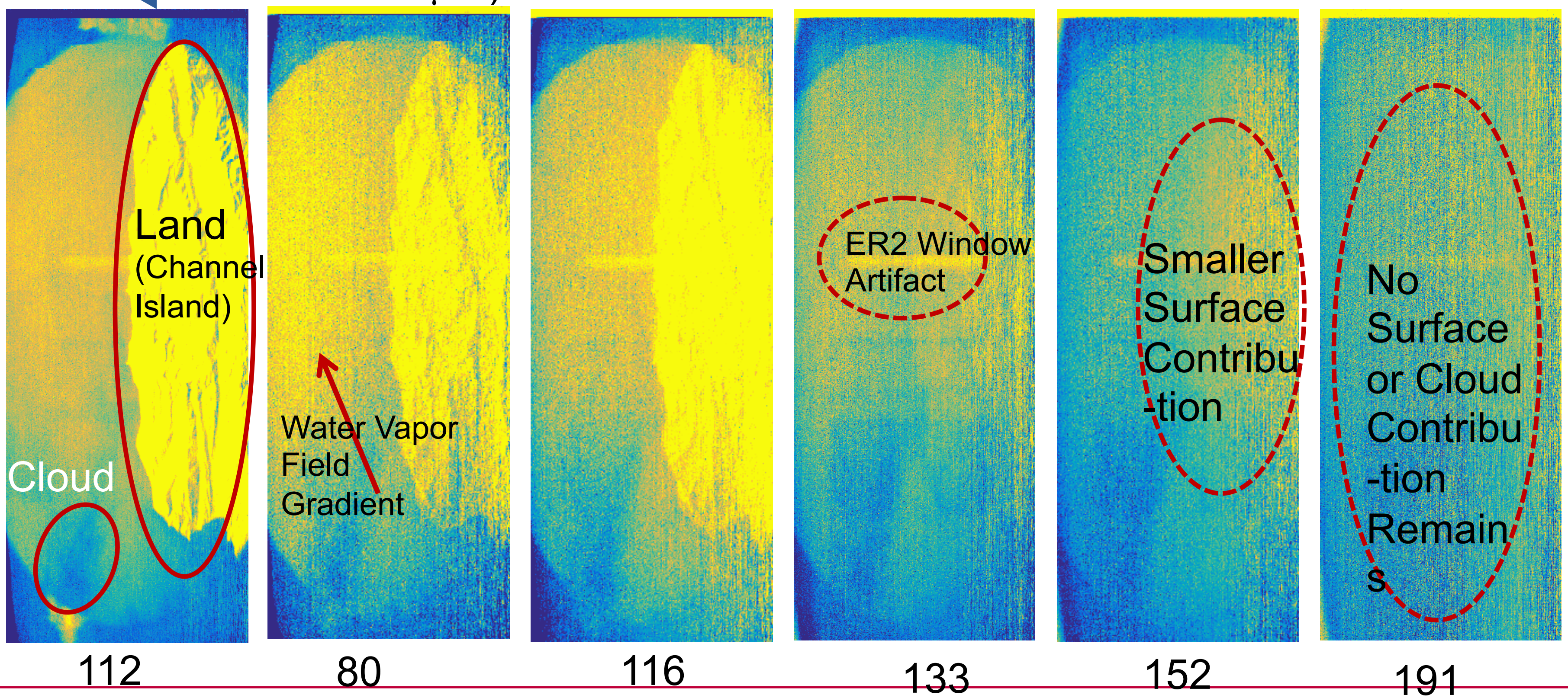
Surface-Dominated (High Brightness Temp.) Band



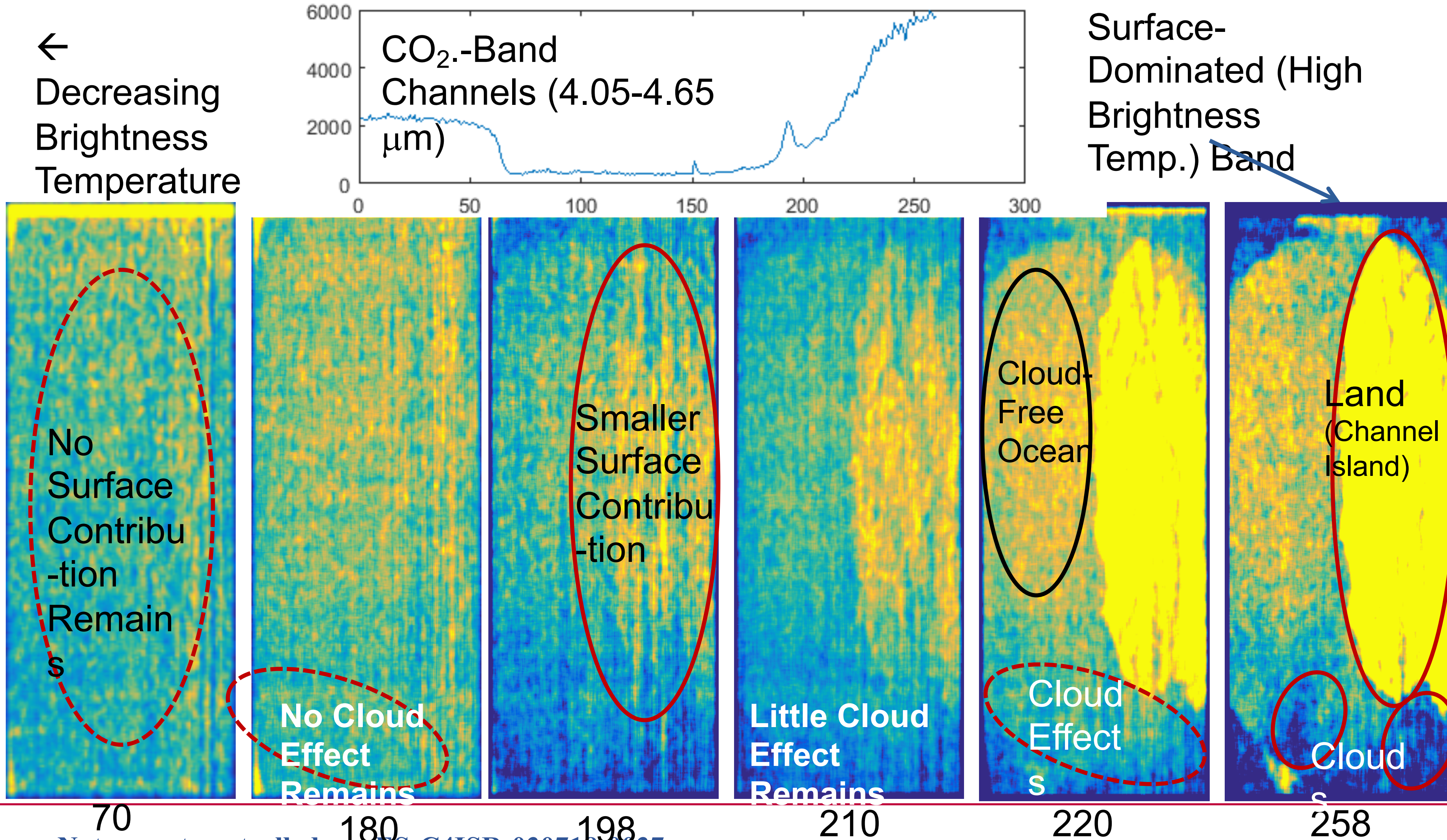
H_2O.-Band Channels (4.65-5.6 µm)

→ Decreasing Brightness Temperature



Selected H_2O (Water Vapor)-Band Channels

Sweep 22 Selected "Temperature"-Band Images- Show Differences in Vertical Information Content with Band



Selected CO_2 (Temperature)-Band Channels

MISTiC™ Winds Level 1 Instrument Performance Characteristics and Level-2 Sounding Data Quality (updated)

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MISTiC™ Key Instrument Performance Characteristics		
Characteristic	Value	Comments
Minimum Spectral Frequency	1750 cm^{-1}	5.72 μm
Maximum Spectral Frequency	2450 cm^{-1}	4.082 μm
Spectral Sampling	~ 2:1	<590 spectral samples
Spectral Resolution @ minimum	>700 :1	$\nu/\delta\nu$ ((comparable to CrIS-Apodized)
Spectral Calibration Knowledge	1/100,000	$\delta\lambda/\lambda$
Angular Sampling	1.6 mr (cross-dispersed)	1.38 km (@ Nadir)
Orbital Altitude and Orbit	705.3 km	Polar/Sun-Synchronous
Angular Range (cross-track)	1570 radians	90 Degrees—Same as AIRS
Spatial Resolution	<3.0 km (geometric mean)	@ Nadir
Radiometric Sensitivity	<200 mK (max)	(<150 mK @ 2380 cm^{-1})
Radiometric Accuracy	<1%	@ 300K Scene Background
Key Sounding Data Product Characteristics,		
Vertical Resolution—Temperature	~ 1 km	In Lower Troposphere
Layer Accuracy	~ 1.25 K	In Lower Troposphere
Vertical Resolution—Humidity	~ 2 km	In Lower Troposphere
Layer Accuracy—Humidity	~ 15 %	In Lower Troposphere

- MISTiC™ Data Quality Requirements Similar to those Demonstra-ted by NASA's Successful AIRS Instrument
  - Spectral Resolution
  - Spectral Calibration Stability
  - Radiometric Sensitivity/Accuracy
  - Reduces Spectral Resolution (rel to AIRS) Consistent with CrIS Info. Content
- Spatial Resolution Notably Finer than AIRS Resolution (13 km @Nadir for AIRS)
  - 3.0km @ Nadir
- Reduced Spectral Range Enables Major SWAP Reduction

Not export controlled per ES-C4ISR-030718-0037

Key MISTiC 3D Winds System (of Systems) - Level Performance Requirements (draft)

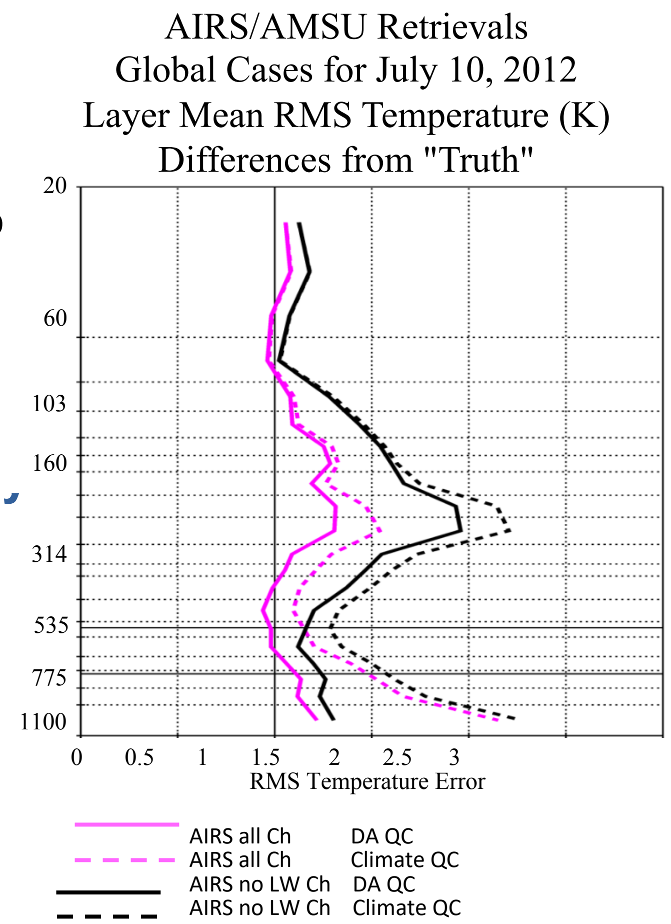
KPP	KPP Attribute	Requirement
3D Motion Vector Winds (Moisture and Cloud Motion Vectors)	Layer Wind Speed Uncertainty	< 2 m/s rms
	Layer Wind Direction Uncertainty (above 10 m/s)	< 10 degrees rms
	Layer Height Pressure Height Assignment Error	<30 mB
	Layer Effective Vertical Thickness	<100 mB
	Minimum Pressure of Highest Pressure-Level	<350 mB (MMV) <500 mB (CMMV)
	Tracer Potential Density (Cloud-Free Conditions for MMV, Cloud Contrast for CMV)	>1 per 6 km sq per vertical layer :
Temperature Vertical Profile	Layer Effective Vertical Thickness	>100 mB (~ 1 km)
	Layer Temperature Accuracy	>1 K
	Sounding Measurement Potential Density	> 1 per 6 km sq
ObsFrequency	Observation Refresh Period	<3 hours (4 planes)

MISTiC Winds Observes both Total Wind Velocity Vector and the (via IR Sounding) the Geostrophic/Gradient Wind Vector Component in ≥ 6 Layers

MISTiC™ Winds' Concept Based on Proven Science From Current Flight Instruments

BAE SYSTEMS

- **MISTiC™ Winds' Vertical Temperature Profile Retrieval Comparable to AIRS & CrIS in Lower Troposphere**
  - Vertical Temperature Profile Retrieval Accuracy for Two Different Quality Control Thresholds Shown
    - Using All AIRS Channels—solid curves
    - Using SWIR/MWIR-Only –dashed curves
- **Additional Error experienced is modest using only SWIR/MWIR Channels**
  - ≤ 0.1K Added Error in Lower Troposphere
  - NOTE-AIRS Version 6 Algorithm Primarily uses /SWIR MWIR Channels for Sounding, using LWIR Channels **only for Cloud-Clearing**
- **<u>Fine spatial resolution</u> (~ 3 km @ nadir)a new benefit**
  - Yield of Cloud-Clear Observations much higher for MISTiC than for CrIS, IASI, and AIRS
  - Increased Cloud Contrast in Partly Cloudy Scenes

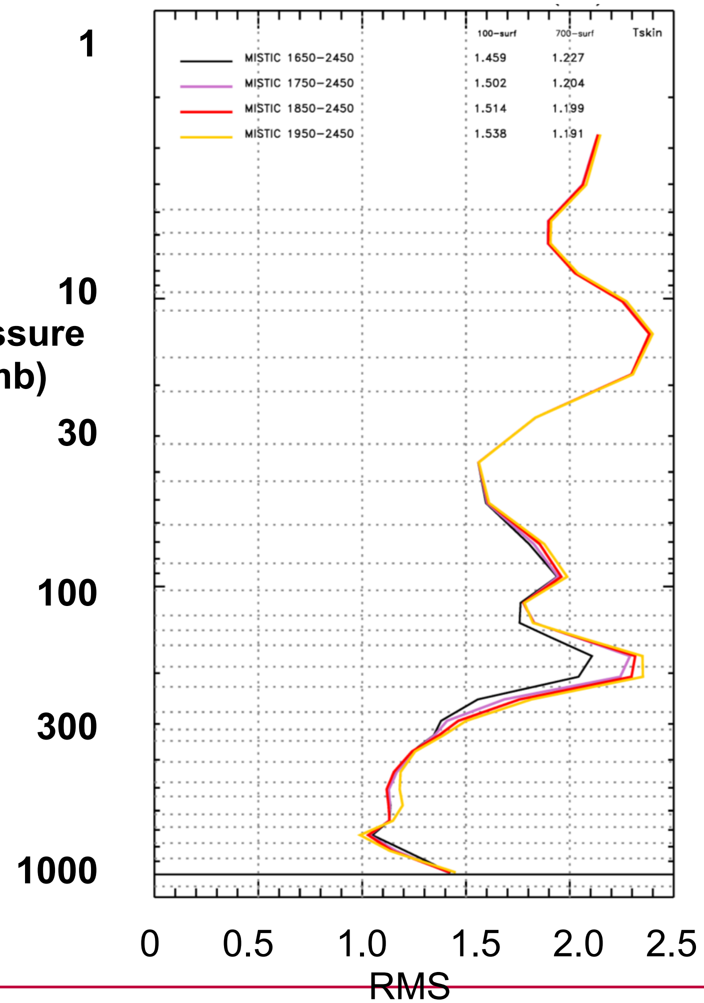


(from Joel Susskind NASA GSFC)

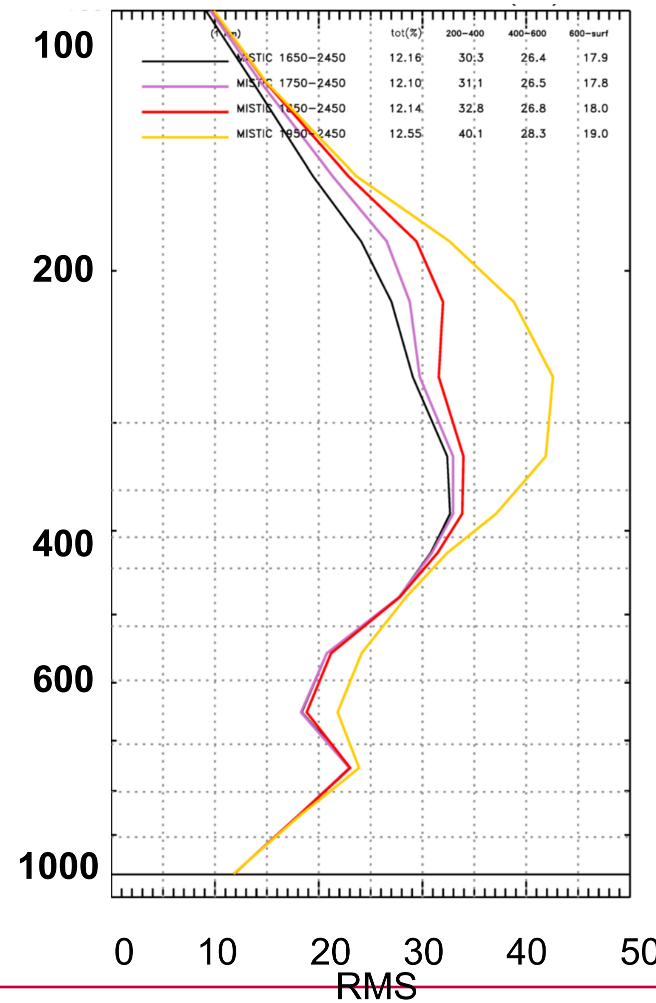
MISTiC™ Winds Retrieval Simulation Validates Chosen Spectral Range

1650-2450 cm-1
1750-2450 cm-1
1850-2450 cm-1
1950-2450 cm-1

1 Km Layer Temperature (K) RMS Differences from Truth



1 Km Layer Precipitable Water RMS % Differences from Truth



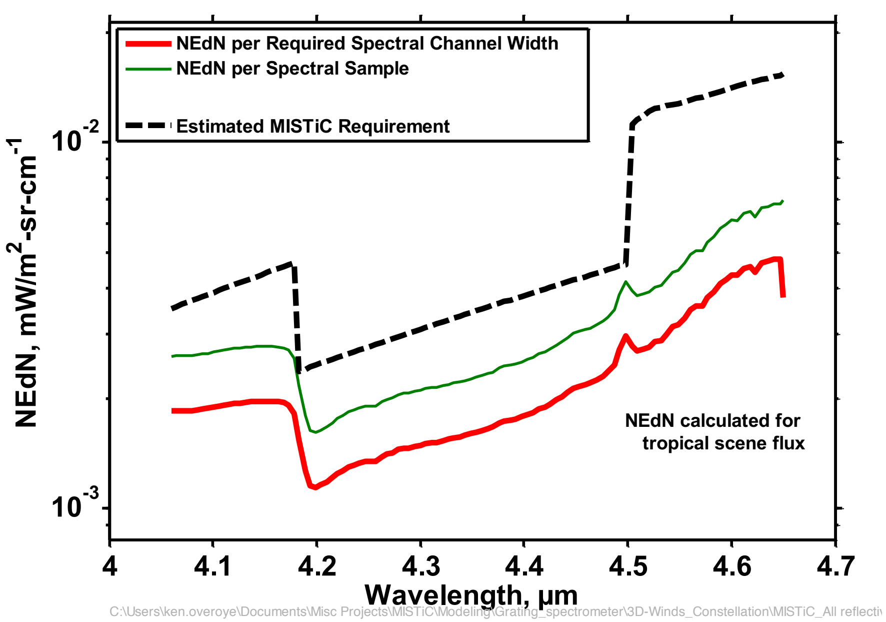
- Reasonably accurate temperature sounding can be done, using just the 4.2 micron band of CO_2, up to about 200 mb
- Water vapor retrieval accuracy best at1650 cm-1 but good enough at 1750 cm-1 spectral cut-off validating MISTiC™ Winds spectral range selection

(from NASA GSFC Sounder Research Team)

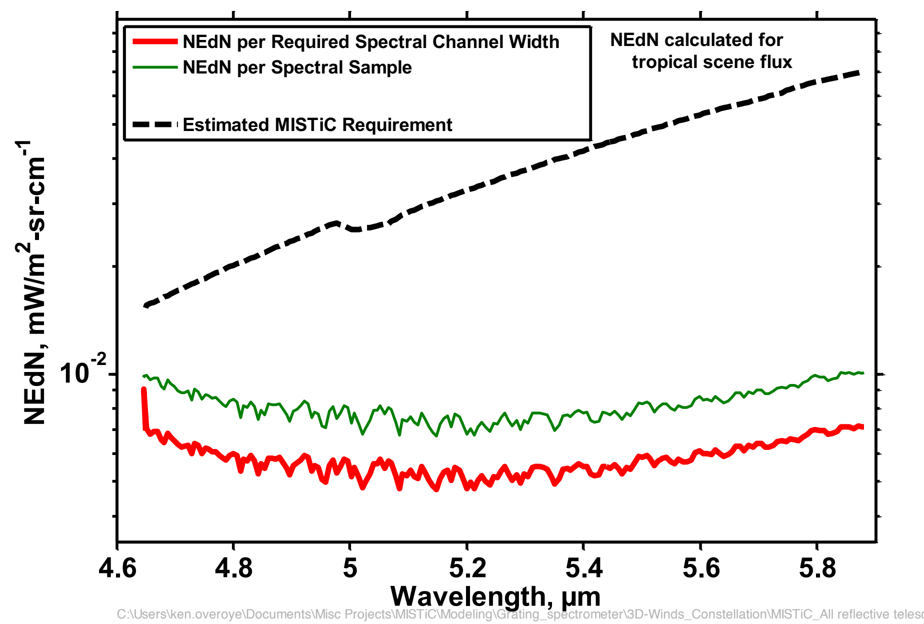
Truth = AIRS Retrievals version 6 - Ocean 50°N to 50°S December 4, 2013

MISTiC™ Winds Instrument Radiometric Sensitivity Performance Estimates Show Solid Margin Against Requirements

Sounding NEdN vs Wavelength:



Sounding NEdN vs Wavelength:



- Spectrometer Radiometric Modeling Methods Developed for AIRS, GOES-R HES, etc used to Estimate MISTiC™ Winds Instrument Sensitivity
- Sensitivity Similar to AIRS (<200 mK @ 250K Scene) for low brightness temperature regions near 4.2 µm
- Updated APD detector noise modeling still be included in system model
  - APD FPA Vendor-modeled dark current and noise are in acceptable range for MISTiC™ at 90K