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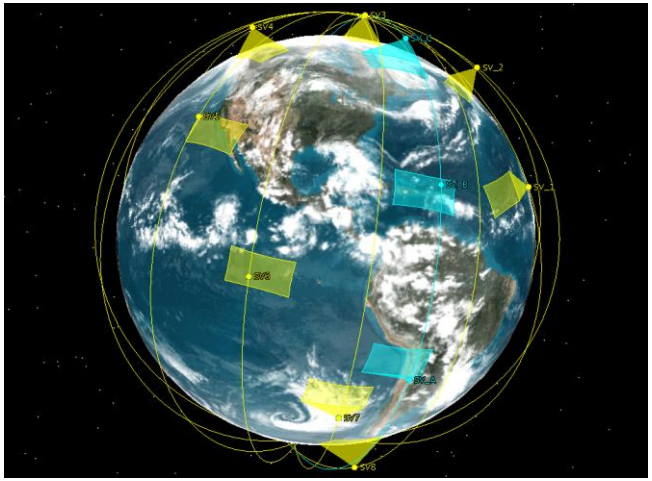
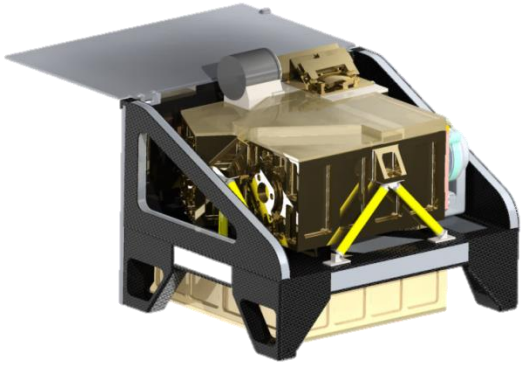
MISTiC™ Winds

A NASA Instrument Incubator Program

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

April, 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**
  - **Laboratory Assessment of Spectral Resolving Power**
- IIP Accomplishments Summary

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

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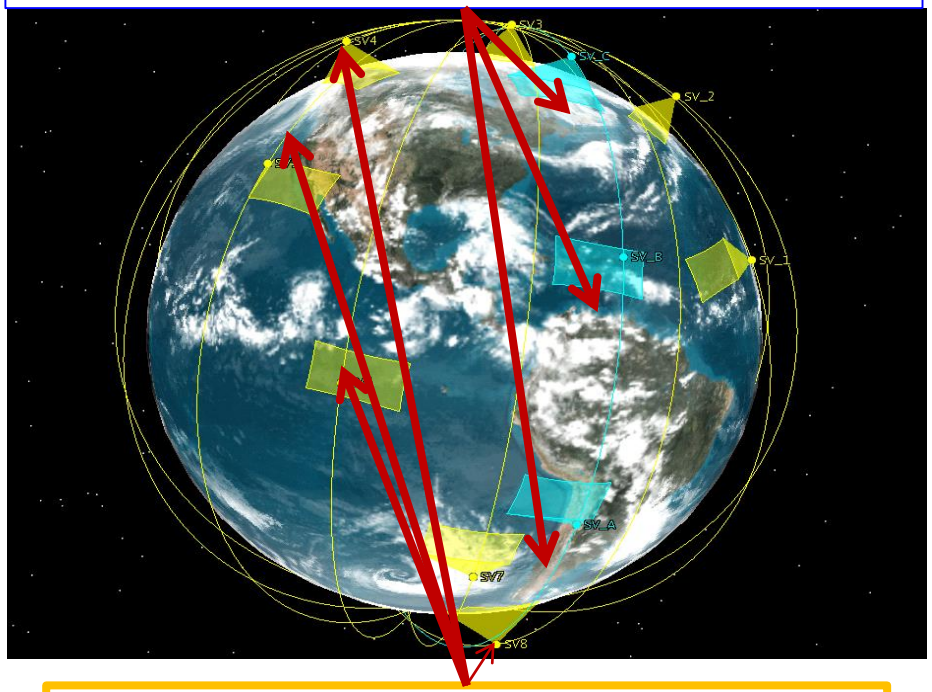
- MISTiC™ Winds Temperature and Humidity Sounding Constellation Options.
  1. Frequent-Sounding Constellation
     - e.g. 90 min refresh-globally.
  2. **Wind-Vector Formations**
     - **e.g. 4 3-Satellite Formations for Cloud-Drift and Water Vapor Motion-Vector Winds**
       - **Provide 3-Hr Refresh 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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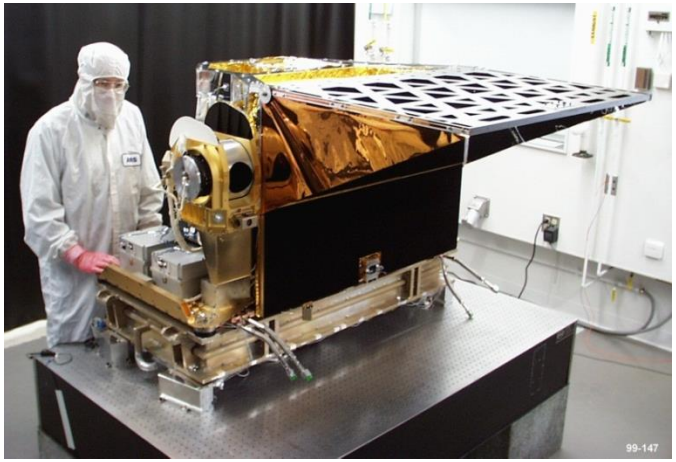
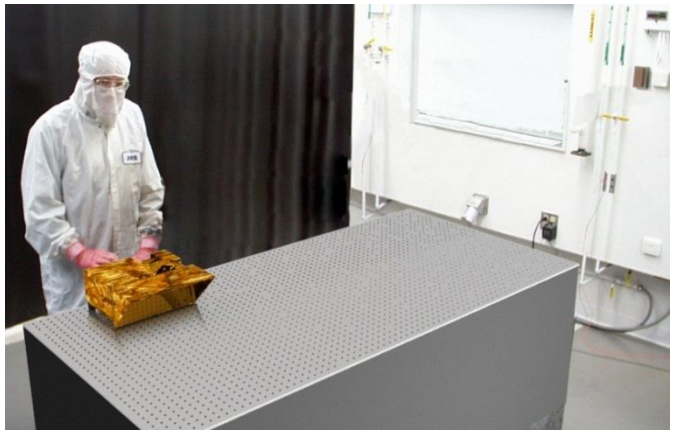
- Size Drivers
  - Geo-Stationary Imagers /Sounders Driven by Orbit Radius
  - IR Sounders Driven by # of Channels and LWIR Band Cooling
- **Moving MISTiC™ to a LEO orbit and eliminating LWIR channels enables massive reduction in SWaP**
  - Current concept is 60-125X less volume than Sounders proposed 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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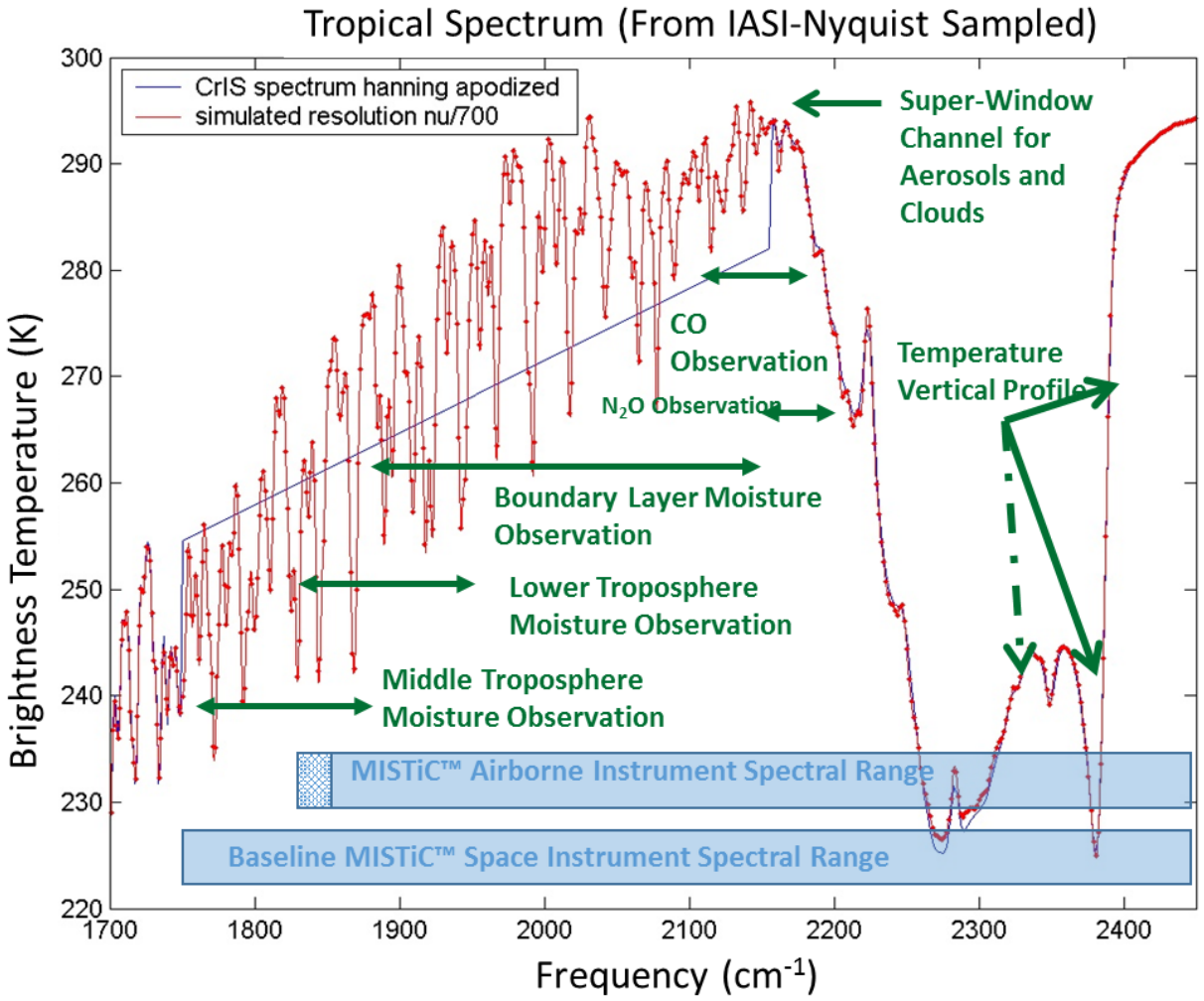

- SWIR Coverage at NEΔT and $\Delta\nu$ Sufficient for CO_2 R-Branch Temperature Sounding of Surface to Upper Troposphere
  - Sharper Vertical Resolution using Line Wings
  - Spectral Resolution > 700:1 is Sufficient
- Mid-Trop. CO
- Mid-Trop. N_2O
- Moisture in Planetary Boundary Layer
- Moisture Profile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

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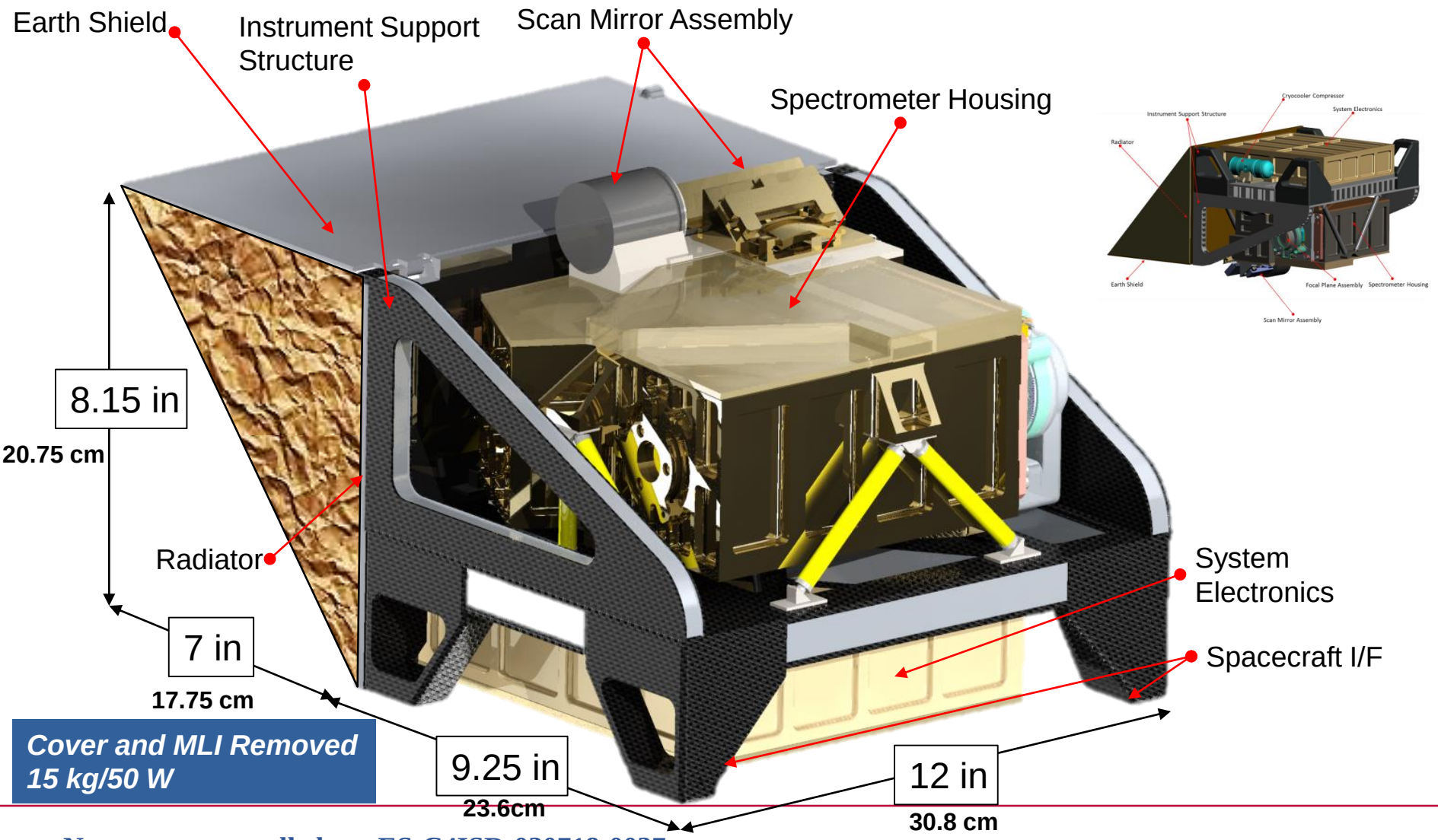

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Primary Efforts under NASA IIP Address Instrument Concept, Technology and Measurement Challenges (Continued)

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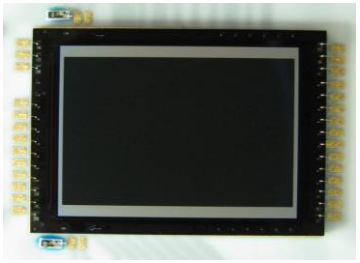
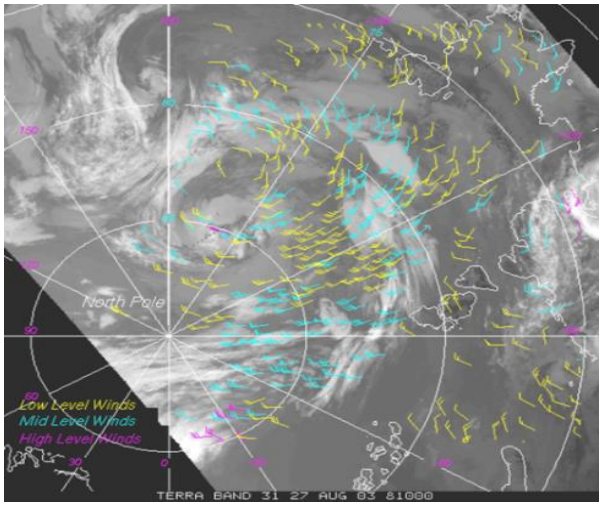
- ✓ Space Mission concept development
- ✓ Technology Risk Reduction
  - Challenge: Get a higher operating temperature FPA in order to reduce cooler power
    - Benefit: Large reduction in SWAP
  - Approach: Use of new APD-Class MWIR FPA
    - Risk: APD Array Not Yet Tested in Space Radiation Environment
    - Mitigation: Radiation Testing on IIP *(by 9/15)*
- Observation Method Risk Reduction (*IN PROGRESS*)
  - 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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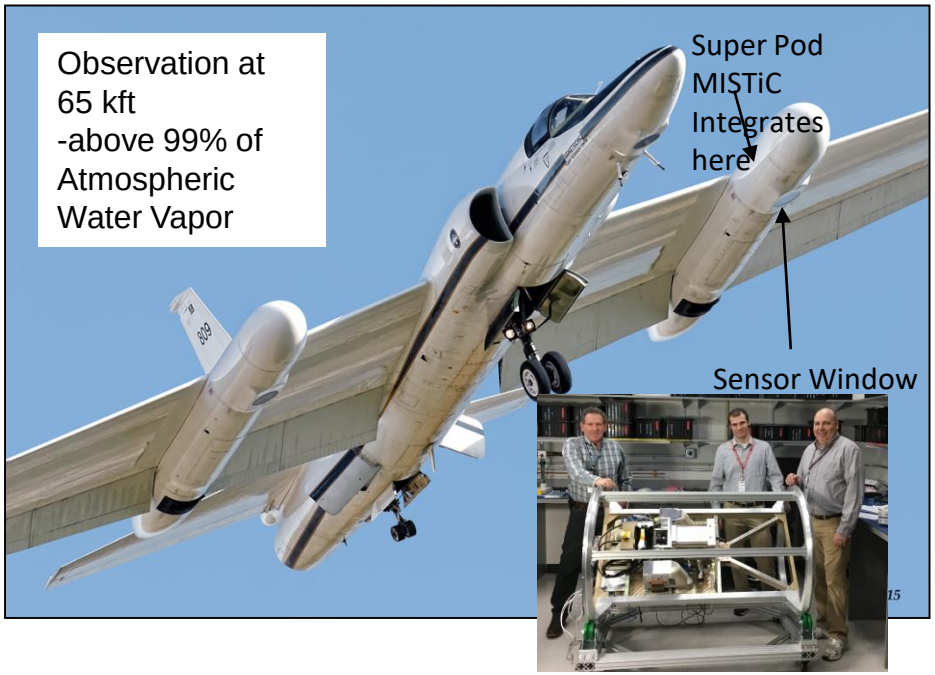

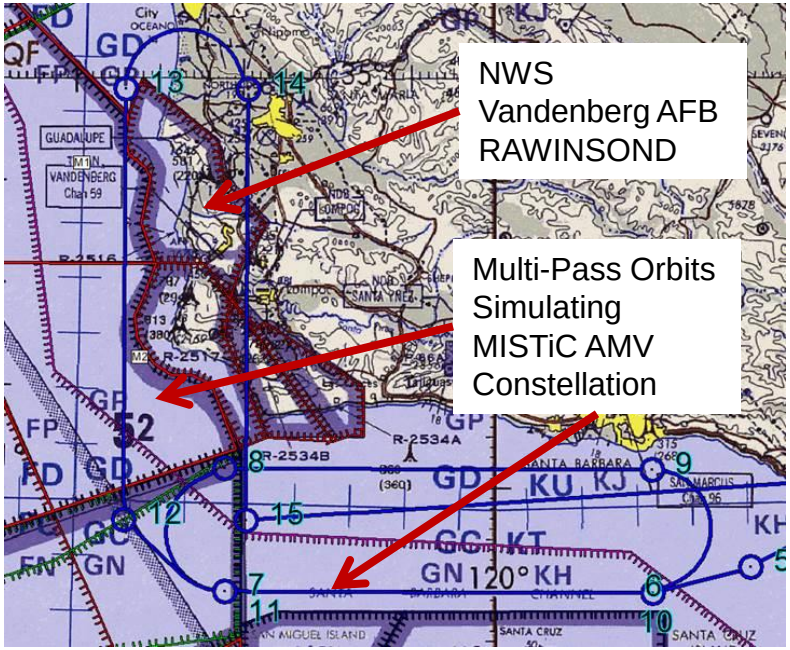

Airborne Spectrometer Very Similar to Space Instrument--with these differences:

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

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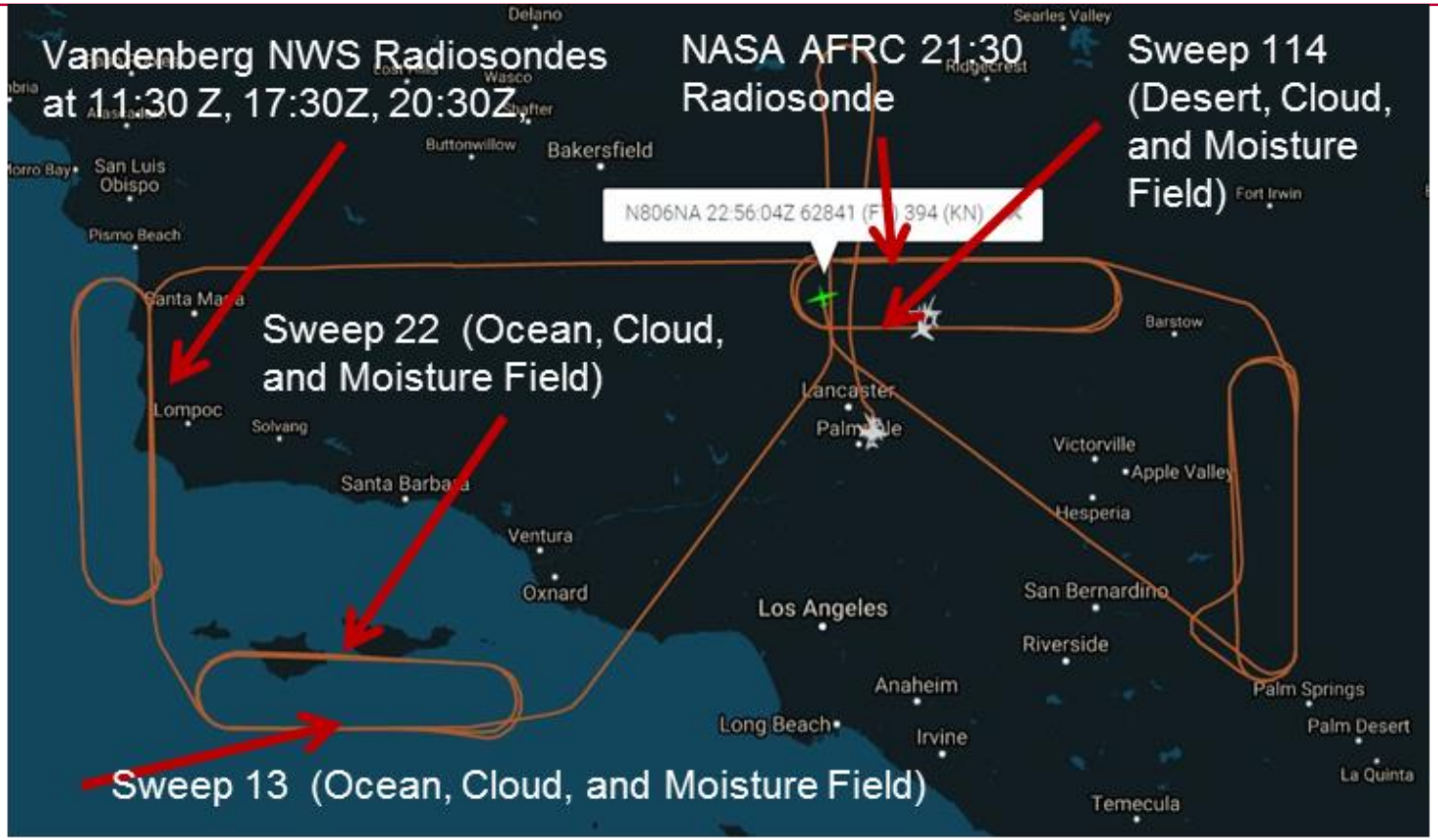
Flight Path for NASA ER2 (Carrying MISTiC Airborne Instrument) on 4 December 2017



MISTiC Airborne Instrument on NASA ER2 Observed Wind, Temperature, and Water Vapor over the Channel Islands and Nearby Ocean, and Over Edwards AFB

Example Observation: Hyperspectral Cloud Motion Vector Wind over Edwards Air Force Base

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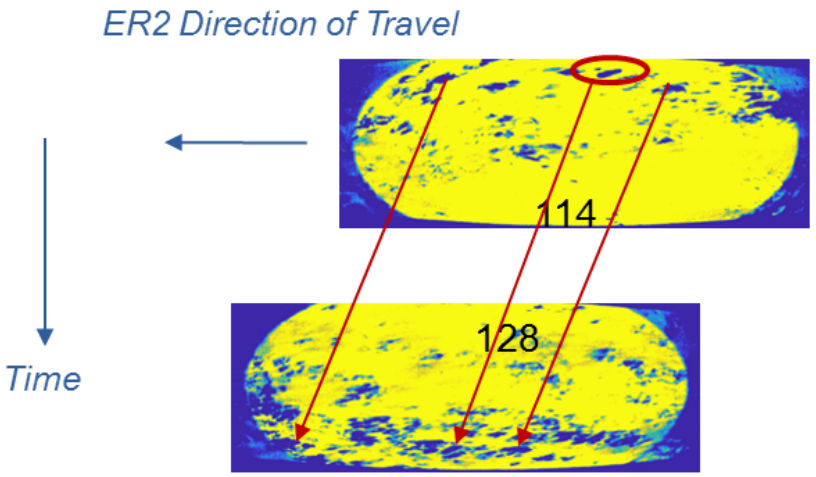
- Cloud Tracer Position from Sweep 114:
  - Nadir Pt: 35.10606 deg N 117.9255 W
  - Pixel 328, 427 (1.5 mr along tr, 2.5 mr across track)
  - ER2 Heading 89.16 deg @222.46 m/s
  - Altitude=19.8 km (above sea lev)
  - T_{114}=xx7523.5 sec
- Cloud Tracer Position from Sweep 128:
  - Nadir Pt: 35.1096 deg N 117.9766 W
  - Pixel 49, 550 (1.5 mr along tr, 2.5 mr across track)
  - ER2 Heading 90.2 deg @219.9.46 m/s
  - Altitude=19.7 km (above sea lev)
  - T_{128}=xx8609.9 sec
- Velocity Determination:
  - Est. Cloud Height 2.7 km, Land Elev. = .7 km
  - ΔX=(4.9+2.6-1.08) km West = 6.5 km West
  - ΔY=(12.4) km South→ 1 km/1086 sec = 13.2 m/s out of NNE (CMV wind at angle of 30 degrees from North)



Hyperspectral images from Sweeps 114 and 128 capture the positions of a cloud tracer in the MWIR channel group (Ch 1-27, or 4.7-4.8 μm)

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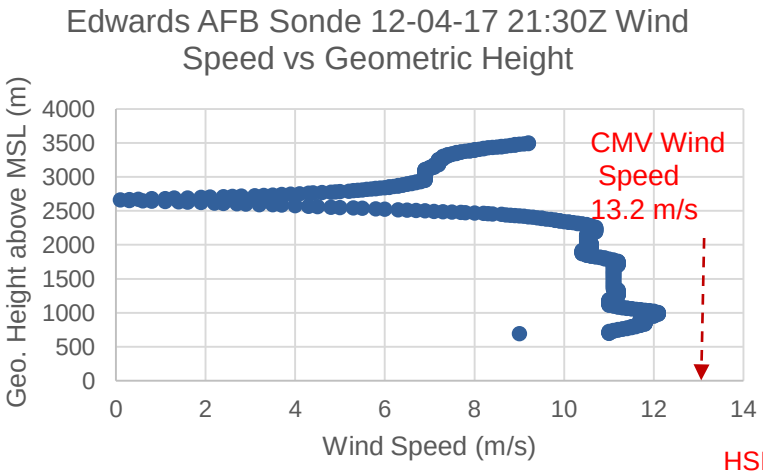
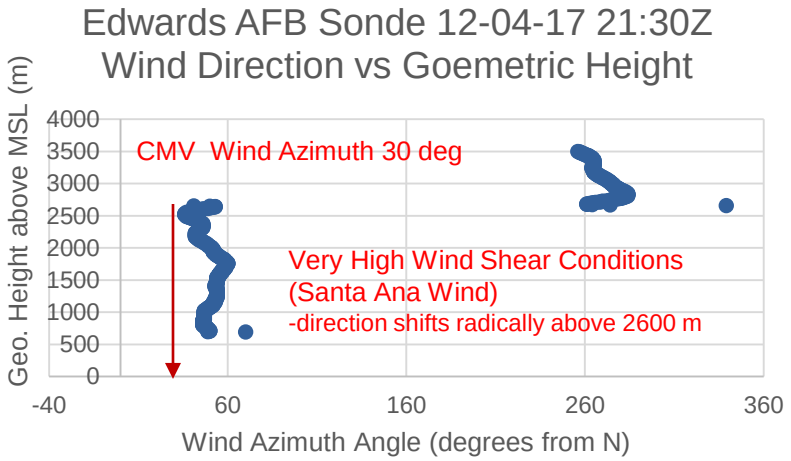
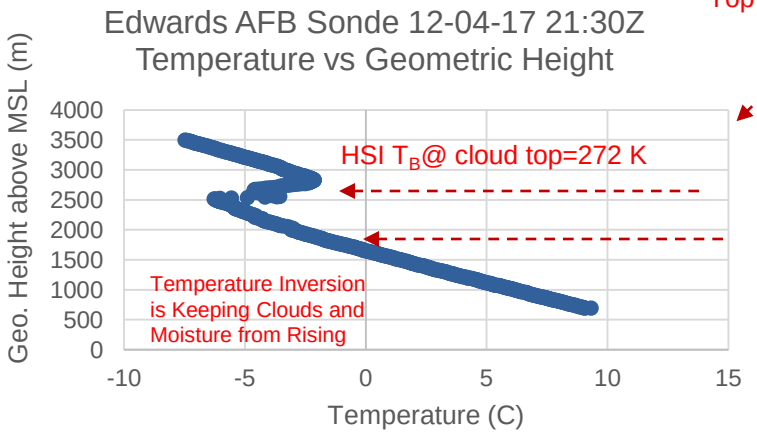
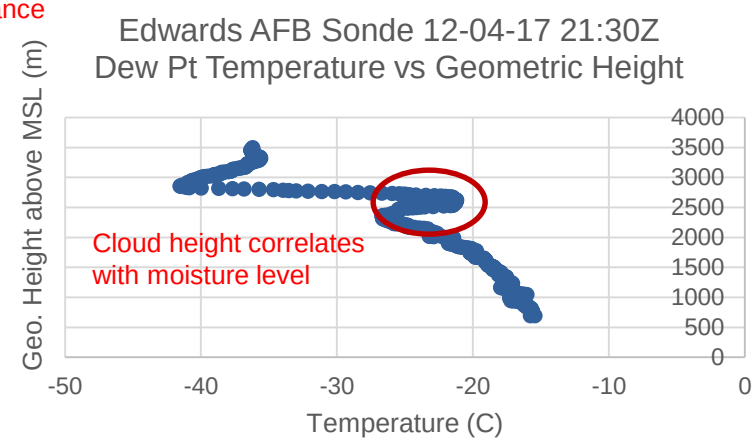
4 Dec. 2017 21:30Z Sonde Observation over Edwards AFB and Related MISTiC Airborne Observations





HSI T_B@ cloud top=276 K
Prior to Correction for Cloud Top Solar Reflectance





MISTiC Cloud Motion Vector Wind Observation and Sonde Observation Agree on Wind Speed to < 2 m/s and Wind Direction < 10 degrees. Weather Scenario Physically Sensible

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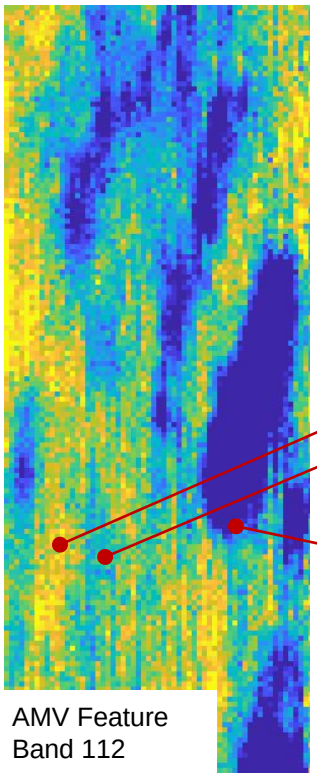
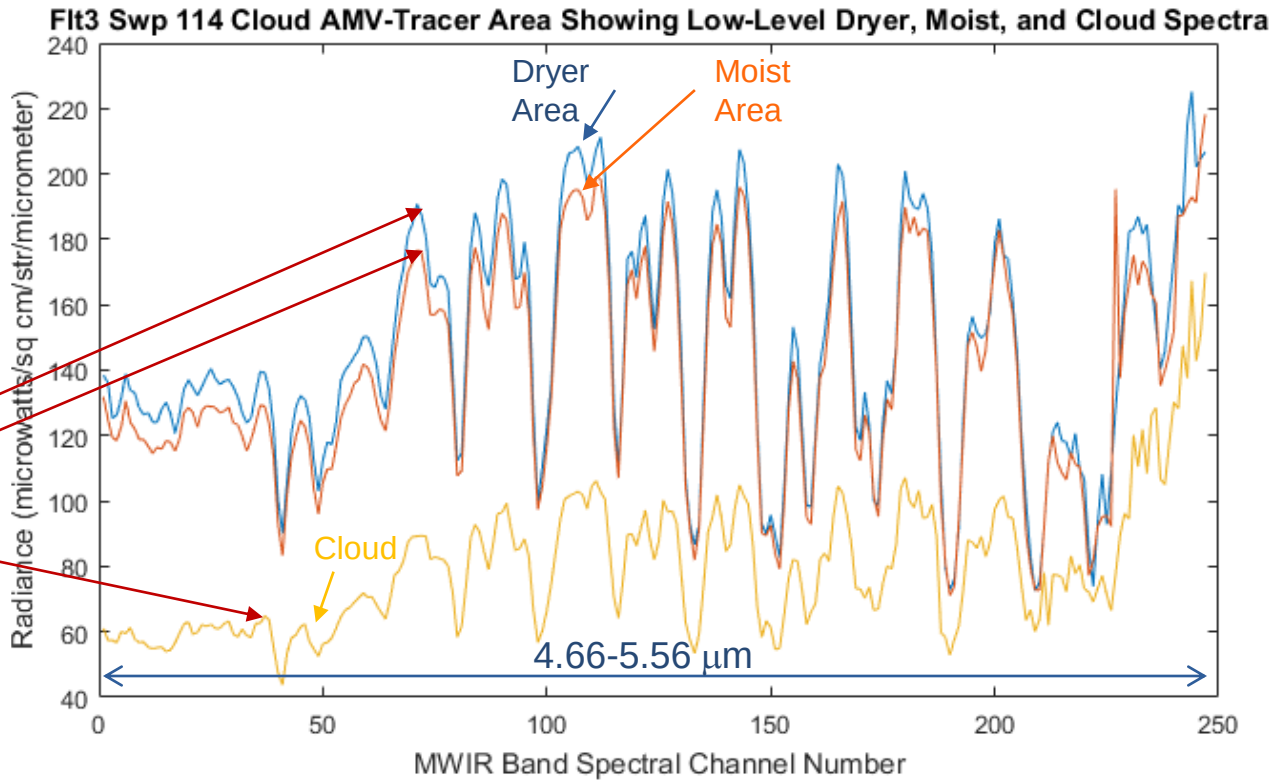
Areas of Reduced or Greater Low-Level Moisture Can Seen Near A Low-Level Cloud, and Distinguished from High-Level Moisture Field



AMV Feature
Band 112



Low Level Moisture Observed Surrounding Low Altitude Clouds

Flt 3 Swp 114 for a Window Channel (72) and Channels With Decreasing Transmission due to Increasing Water Vapor Absorption

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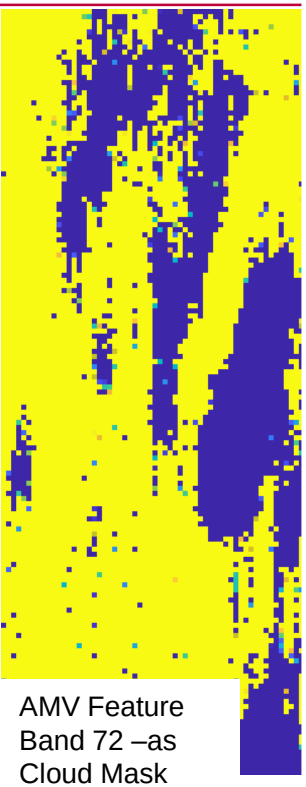
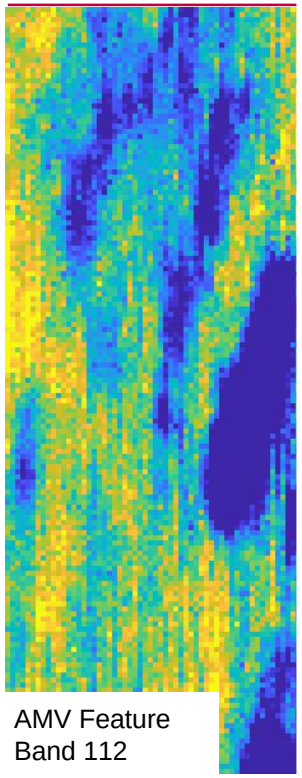
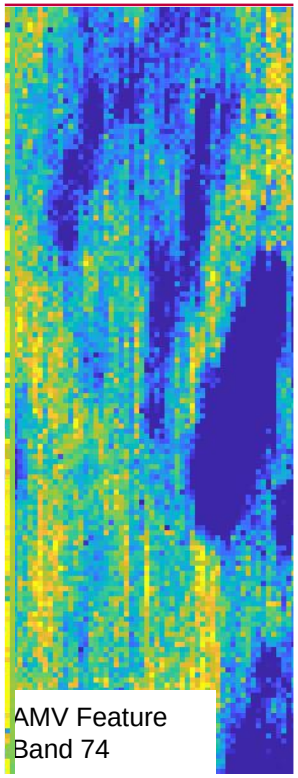


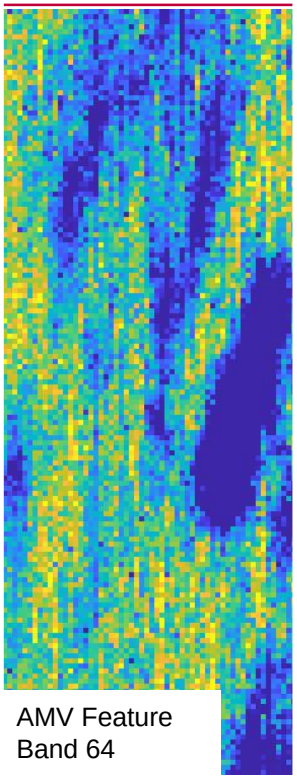
AMV Feature Band 72 –as Cloud Mask



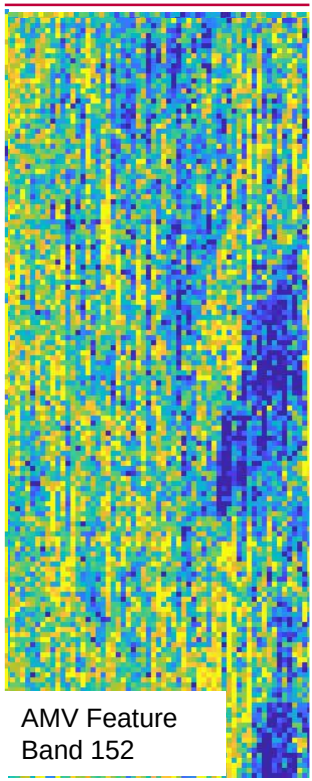
AMV Feature Band 112



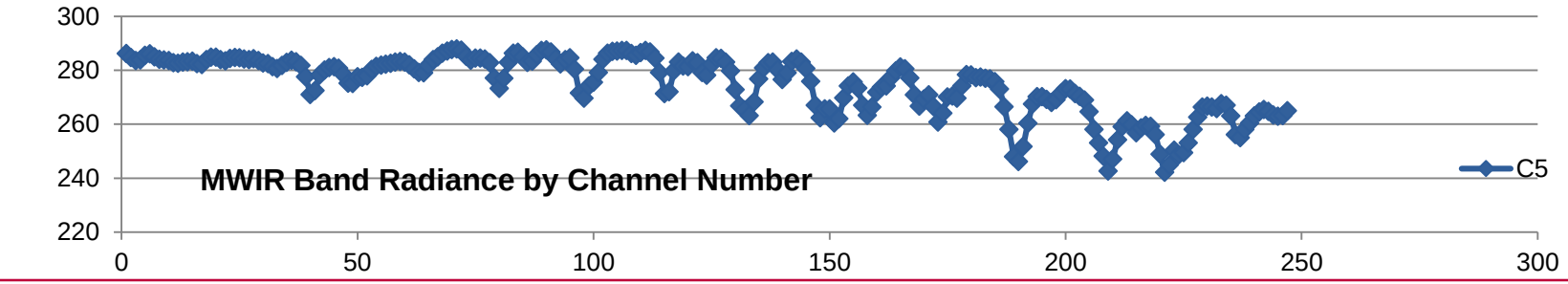
AMV Feature Band 74



AMV Feature Band 64



AMV Feature Band 152



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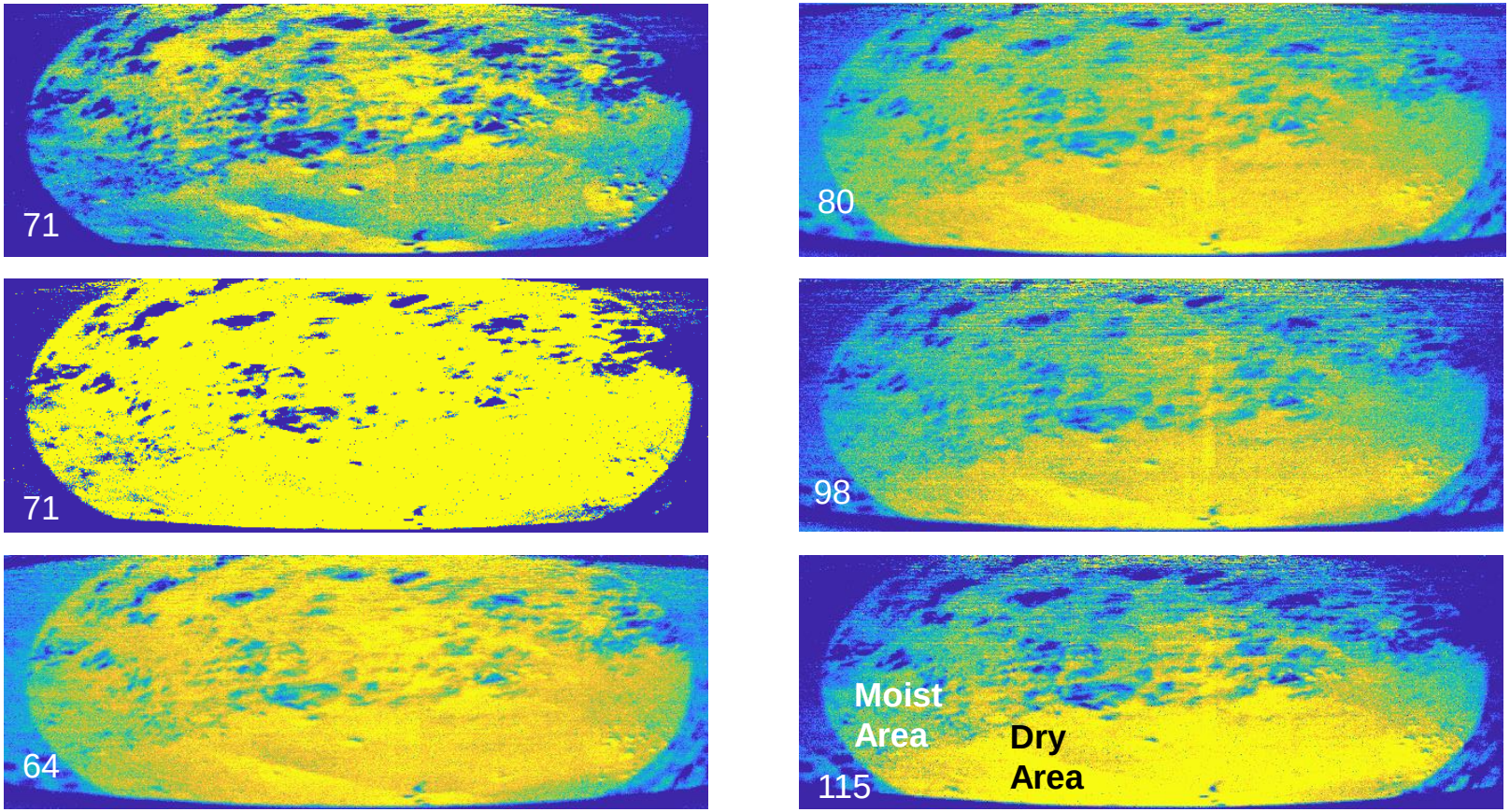
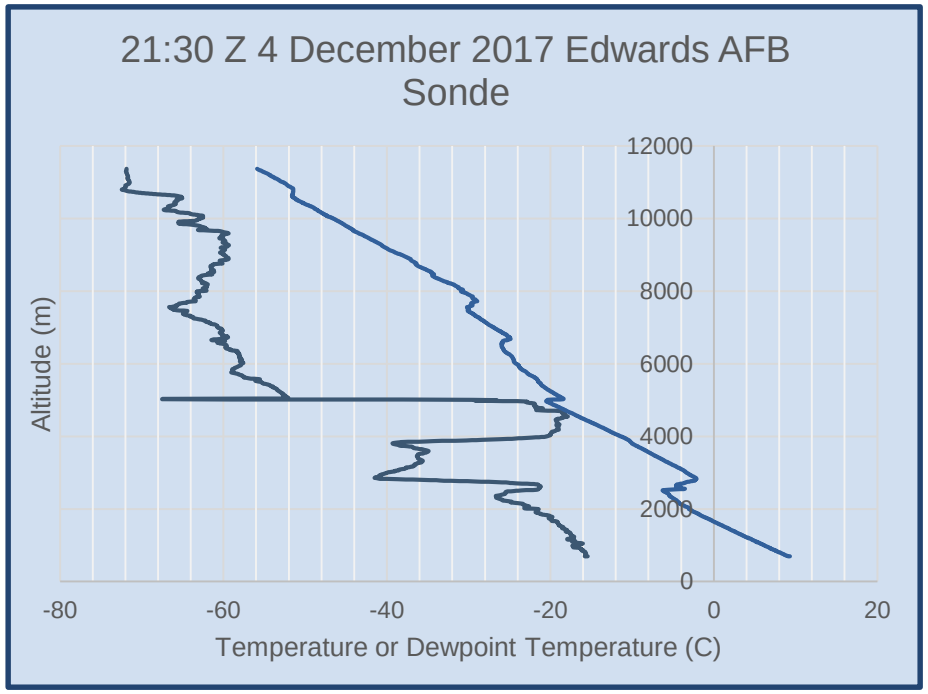
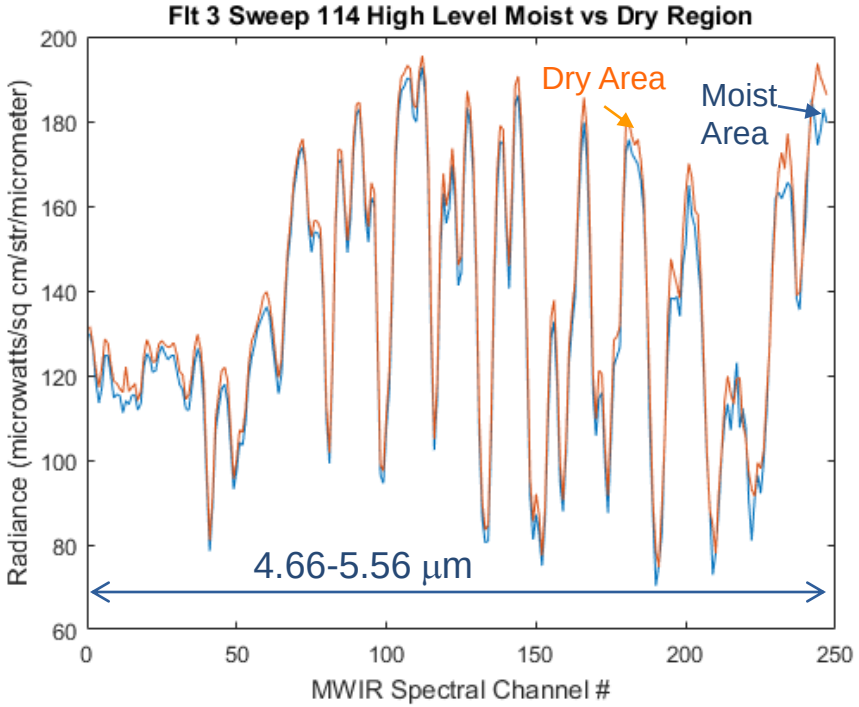
Flt 3 Swp 114 for a Window Channel (71) and Channels With Decreasing Transmission due to Increasing Water Vapor Absorption



Low-Level Clouds and Moisture Field Under a Higher-Level Moisture Field Near Edwards Air Force Base. Channels shown are a window channel (71) and channels with increasing water vapor absorption (64→98→115)

Radiosonde Data During MISTiC Flt 3 Edwards Over-Flight And MISTiC Airborne MWIR Spectra for Areas of Dry Air and Moist Air in Sweep 114



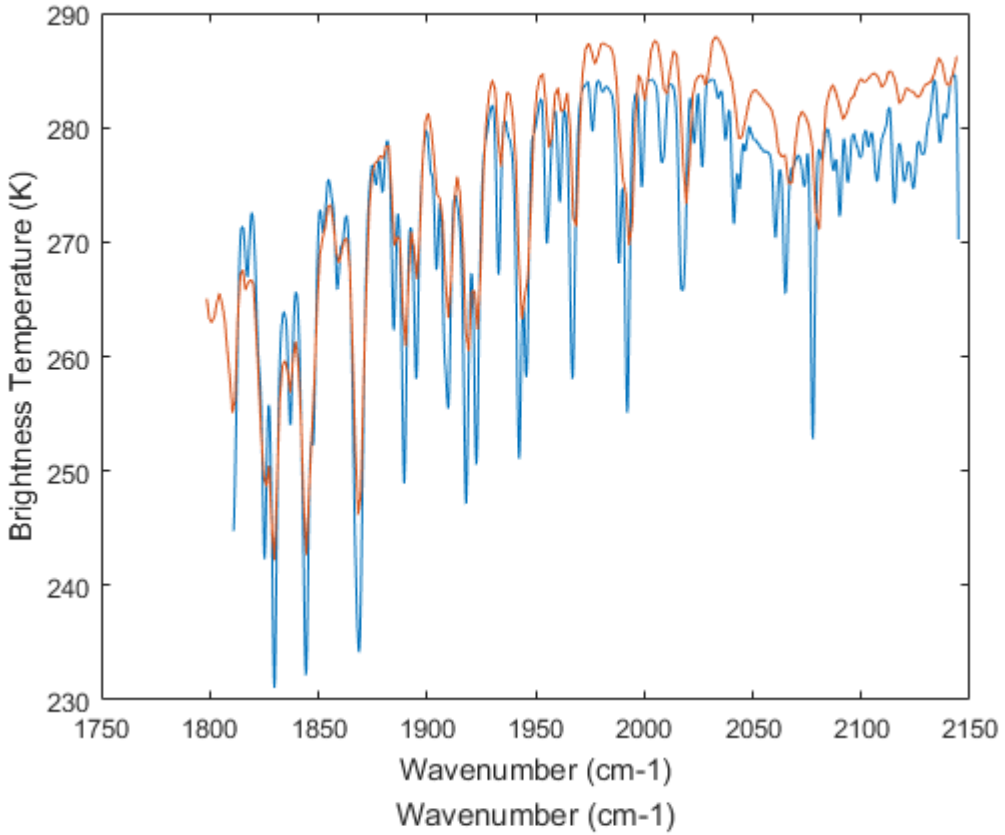


Radiosonde Data Shows with High Water Vapor Band Aloft and Limited Moisture-Trapped by Strong Inversion at Lower Altitude

MWIR Band Spectra for Dry and Moist Regions – Largest Radiance Impacts for Spectral Channels Most Sensitive to Higher Altitudes

4 December 2017 Comparison between IASI-B and MISTiC

- Dr Aumann provided nearest (reasonably cloud-clear) IASI-B observations within ~ 0.1 deg Lat/Lon of the MISTiC overflight
  - Clearest one shown (3 K of cloud contamination)
- IASI-B Spectrum Convolved to Resolving Power of ~ 500:1
  - Apparent MISTiC resolving power a bit less-due to Fore (or Aft)-Optics Defocus
- Low Level Warm Santa Ana Wind Probably Warmed Lowest Layers of Atmosphere during time between IASI-B and MISTiC ER2 overpasses
- Corrections for ER2 Window May Contribute to MISTiC Radiance Error



MWIR Brightness Temperature Observed on 4 December over the Cloud-Clear Ocean by the MISTiC Airborne (red) Instrument on the ER2 south of the Channel Islands, and the closest IASI-B (blue) (relatively) cloud-clear field observed from space approximately an hour earlier

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

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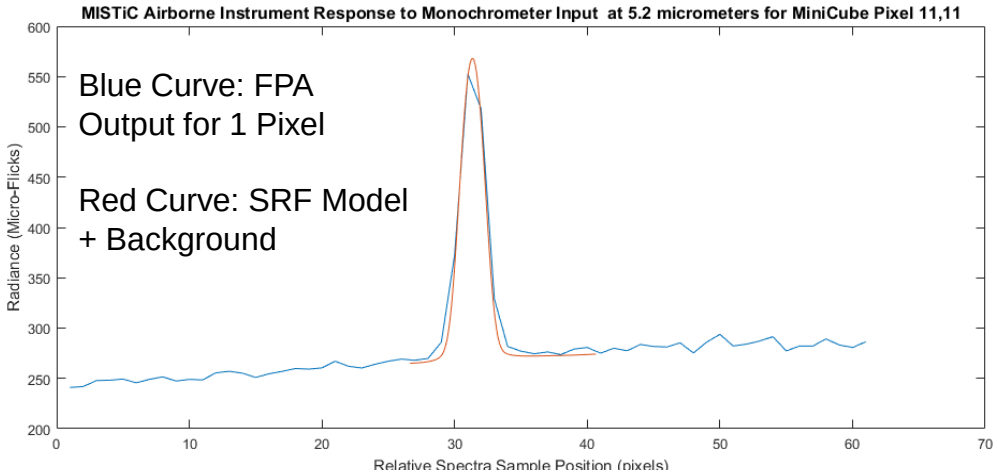
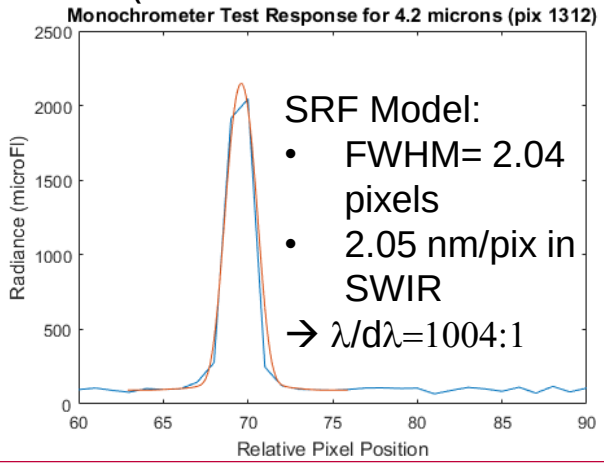
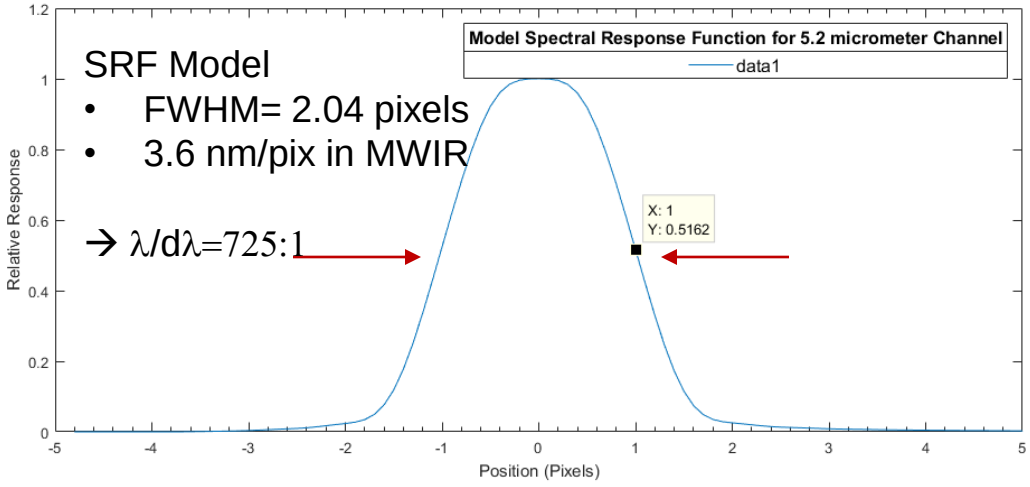
- Monochrometer Test Background
  - f/5 6” C-T instr. with Hot ceramic source
  - Entrance and exit slits 1 pixel wide
  - > 3 mrad beam projected onto MISTiC scan mirror (fills slit) as mirror scans scene
- SRF Model Elements:
  - Detector SRF (top-hat)
  - Spectrometer Optics Diffraction
  - DC Meas.-Lab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







Accomplishments of the NASA IIP MISTiC Winds Risk Reduction Program

- Developed key instrument and mission requirements, Observing System architecture and instrument detailed concept design- tailored to focus on dynamic weather characterization in the Troposphere-- with miniature instruments in a constellation
  - Cloud and water vapor motion vector winds with rms wind-speed errors < 2 m/s at 6+ levels in the troposphere
  - High resolution IR soundings of temperature and vertically resolved moisture gradients in the troposphere
  - 15 kg/50 W Instrument is 60x smaller in volume, 10x lower mass, and 4x lower power demand than NASA's AIRS instrument
- Performed critical technology risk reduction through laboratory and airborne testing:
  - APD-mode 640x480 IRFPA with Proton total dose tolerance for 4-year LEO mission life demonstrated
  - Ultra-Low distortion brassboard IR spectrometer assembly demonstrates >700:1 spectral resolving power and high spectral calibration temperature-stability ($d\lambda/dT$ < 2.5% of spectral response function FWHM per 100 mK)
- Conducted several flights on ER2 (~30 hours) multi-pass observations over land sites in southern California, and over the nearby ocean
- Analyzed the airborne data to show vertically resolved moisture gradients, and hyperspectral cloud AMVs- matching Radiosonde wind speed observations to < 2 m/s -- under challenging high wind-shear conditions

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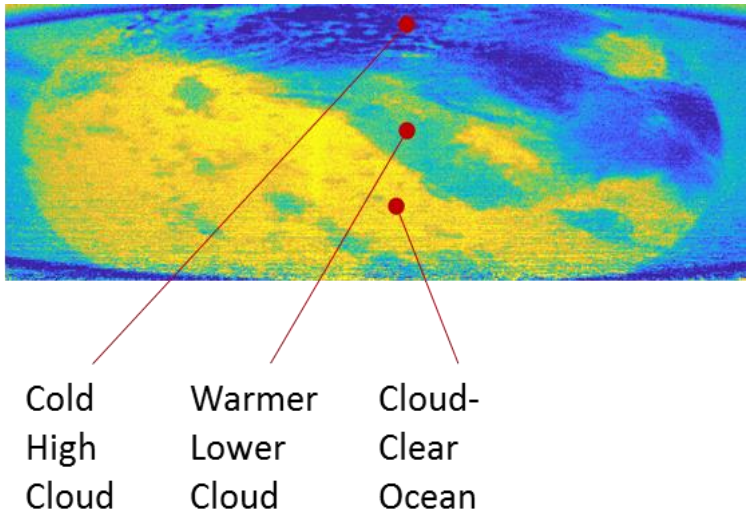
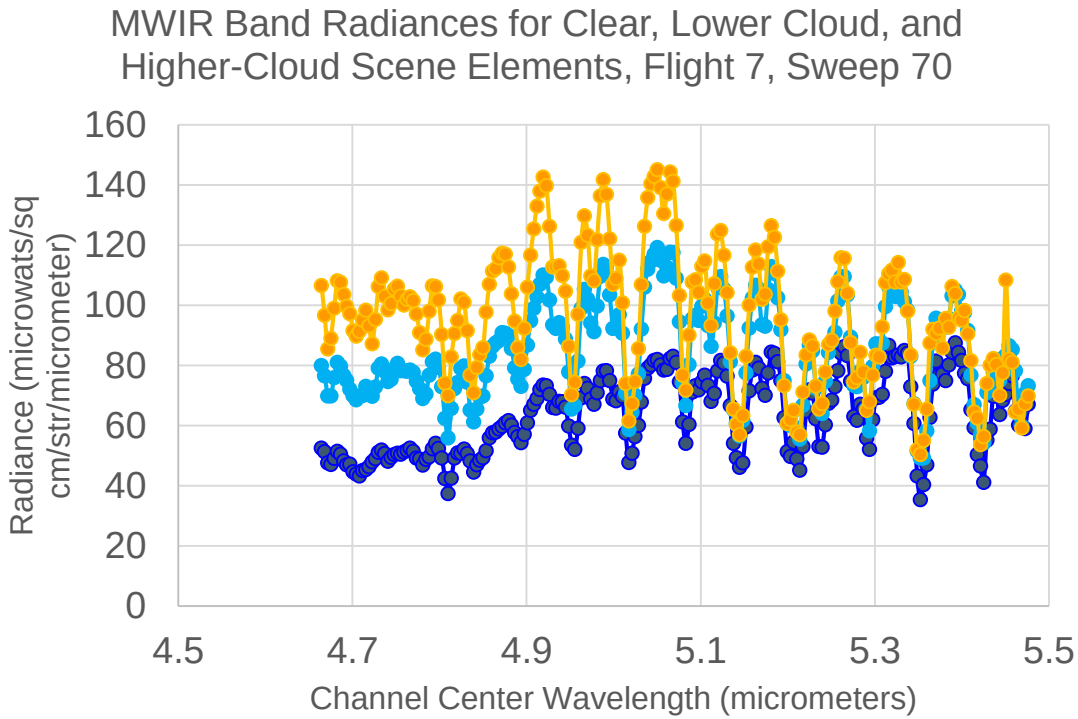
Supplementary Material

Example Observation of a “Wind Tracer” in MISTiC Airborne

- 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

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

Sw 13 and Sw 28 Band 80—showing Banded Mid-Level "Cloud Tracer"

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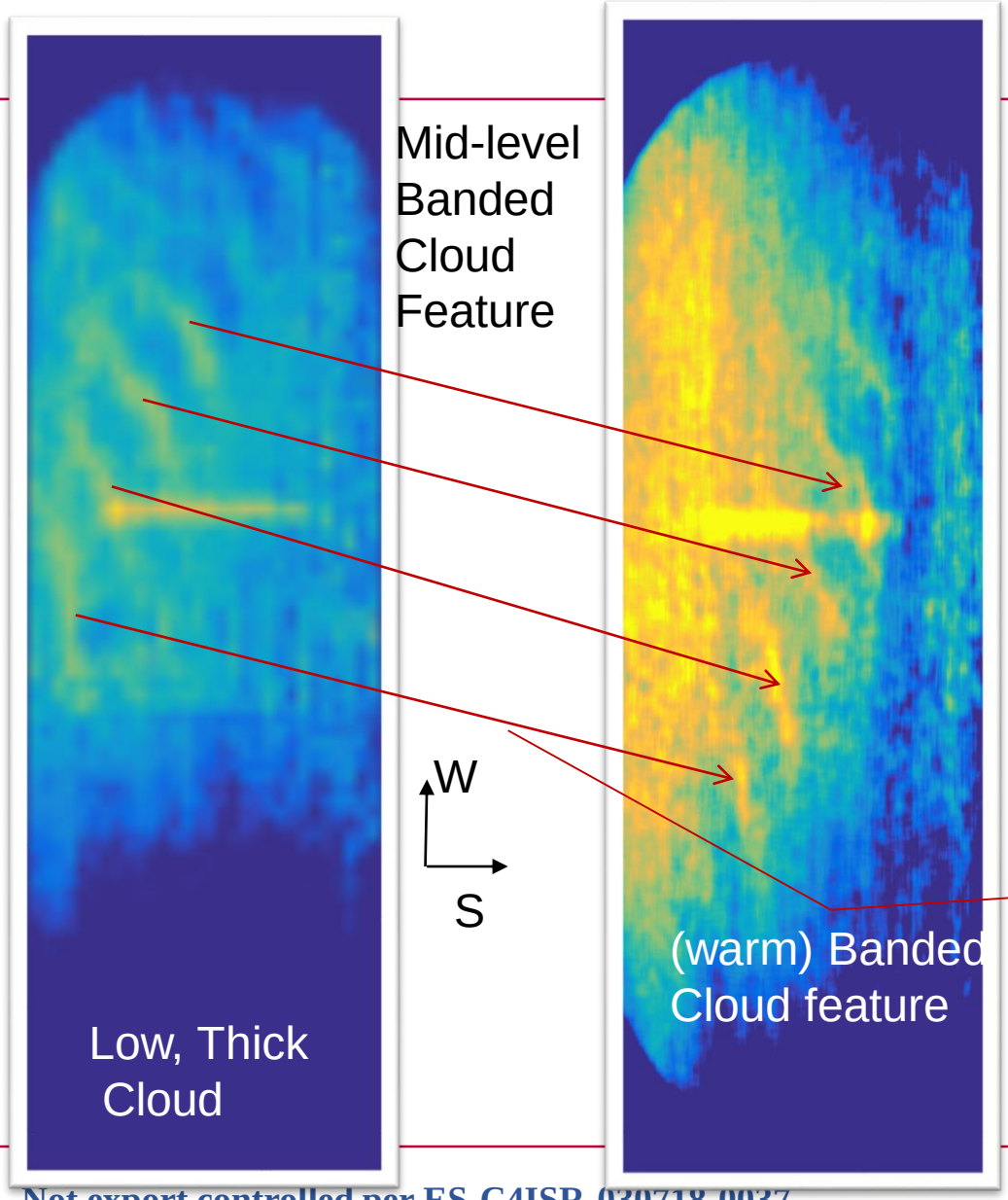
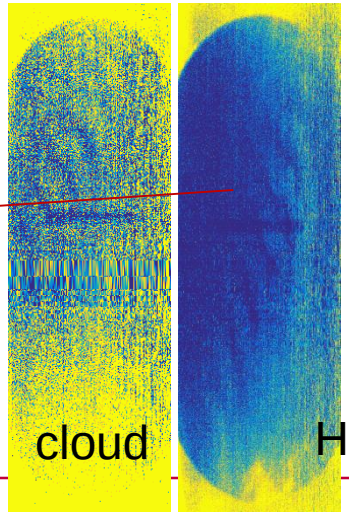


Sweep 13 Pixel		Sweep 28 Pixel	
X-tr	Al-tr	X-tr	Al-tr
57	363	145	604
95	316	183	511
145	262	224	454
200	206	220	305



Higher cloud

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

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

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

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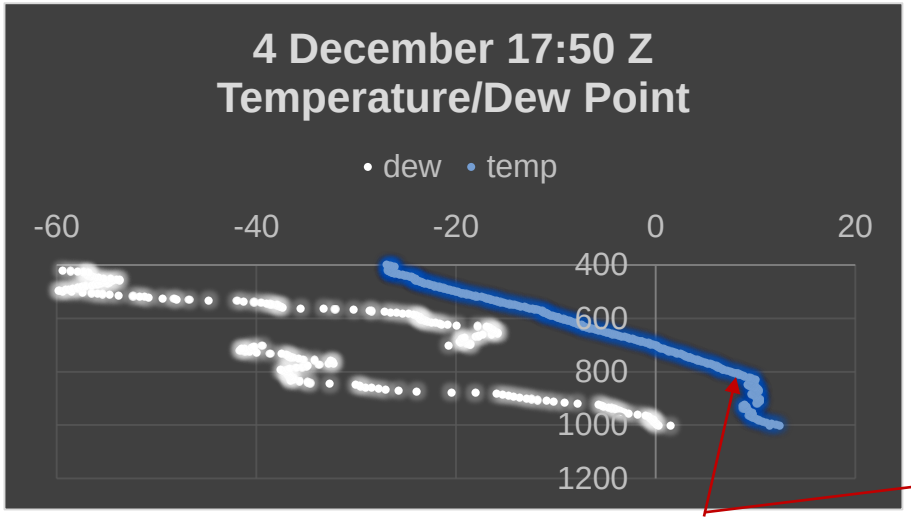
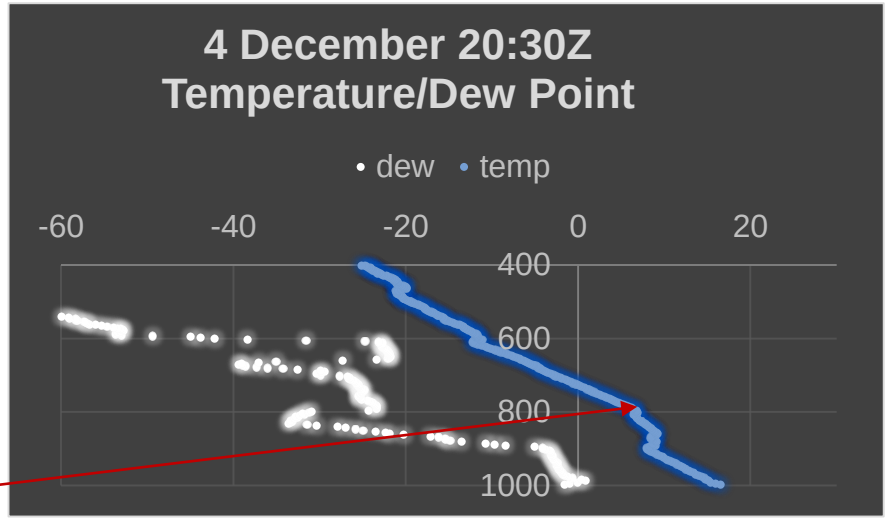
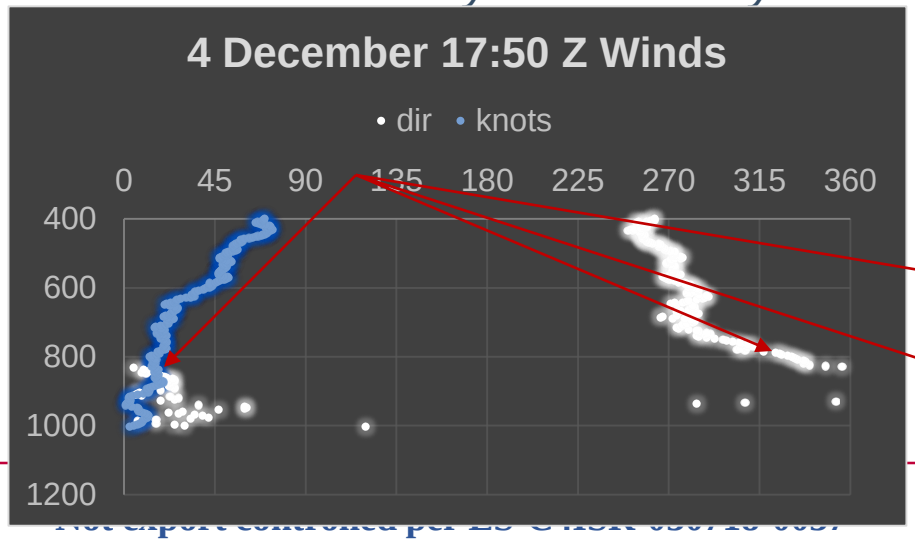
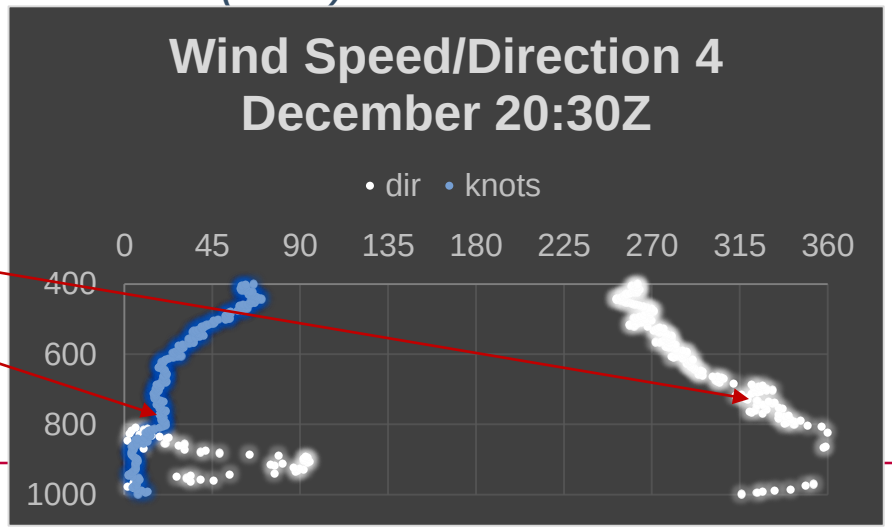


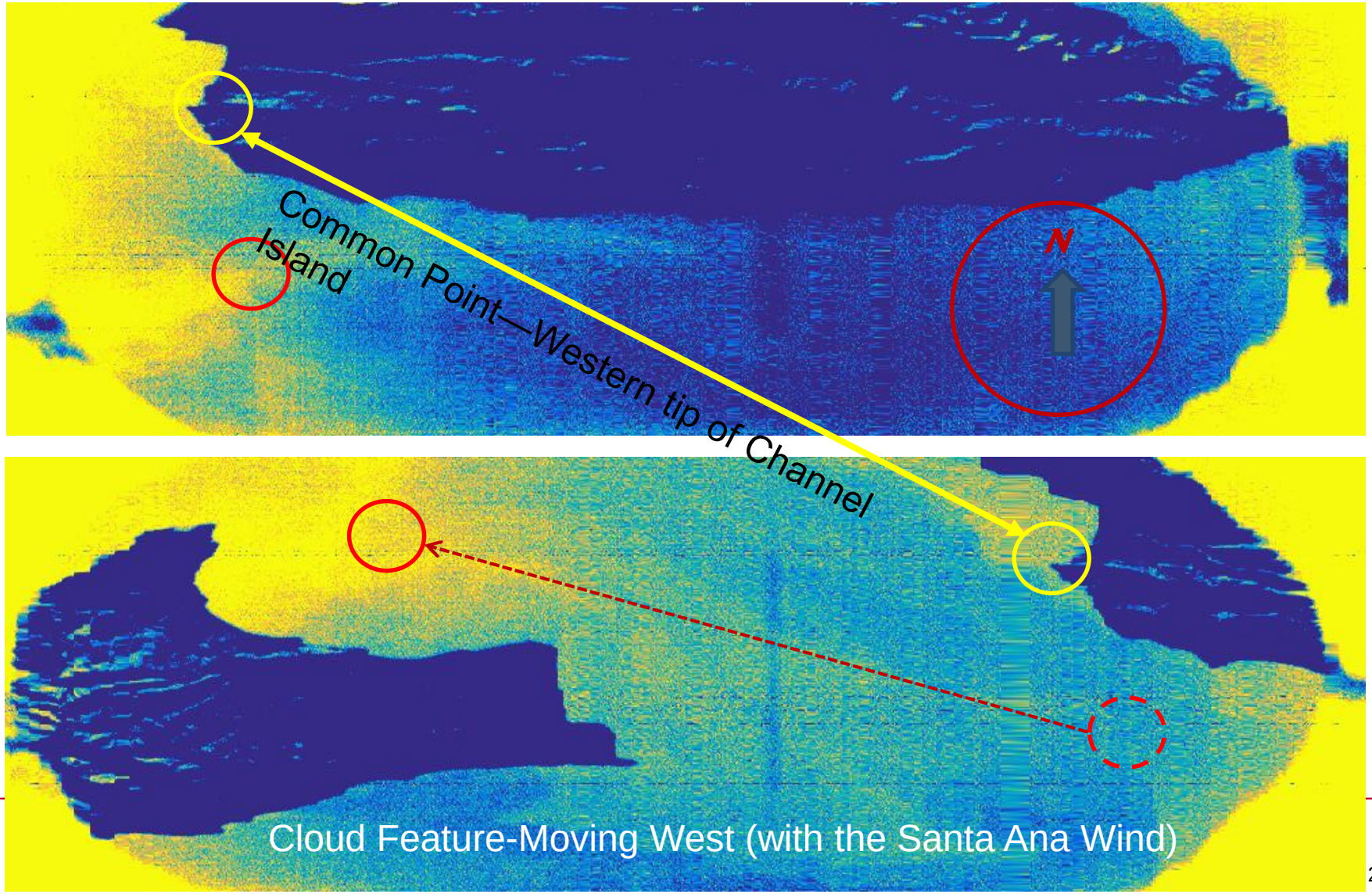


Cloud Feature Velocity Observed by MISTiC Airborne (ER2) Consistent with Sondes





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)



Supplemental Material

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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

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

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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

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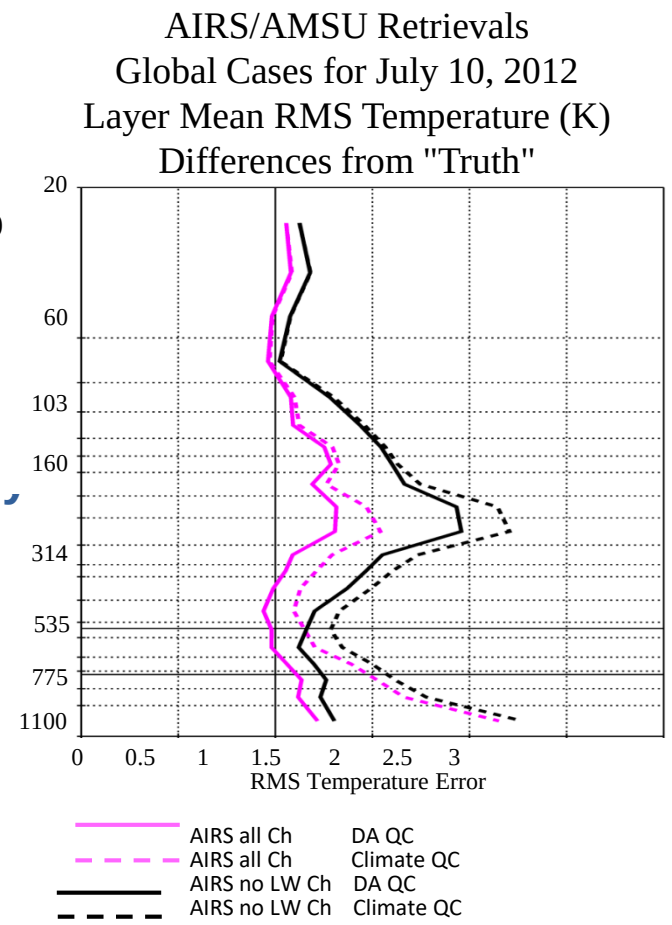
- **MISTiC™ Winds' Vertical Temperature Profile Retrieval Comparable to AIRS & CrIS in Lower Troposphere**
  - Vertical Temperature Profile Retrieval Accuracy for Two Different Quality Control Thresholds Shown
    - Using All AIRS Channels—solid curves
    - Using SWIR/MWIR-Only –dashed curves
- **Additional 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**
- **Fine spatial resolution (~ 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

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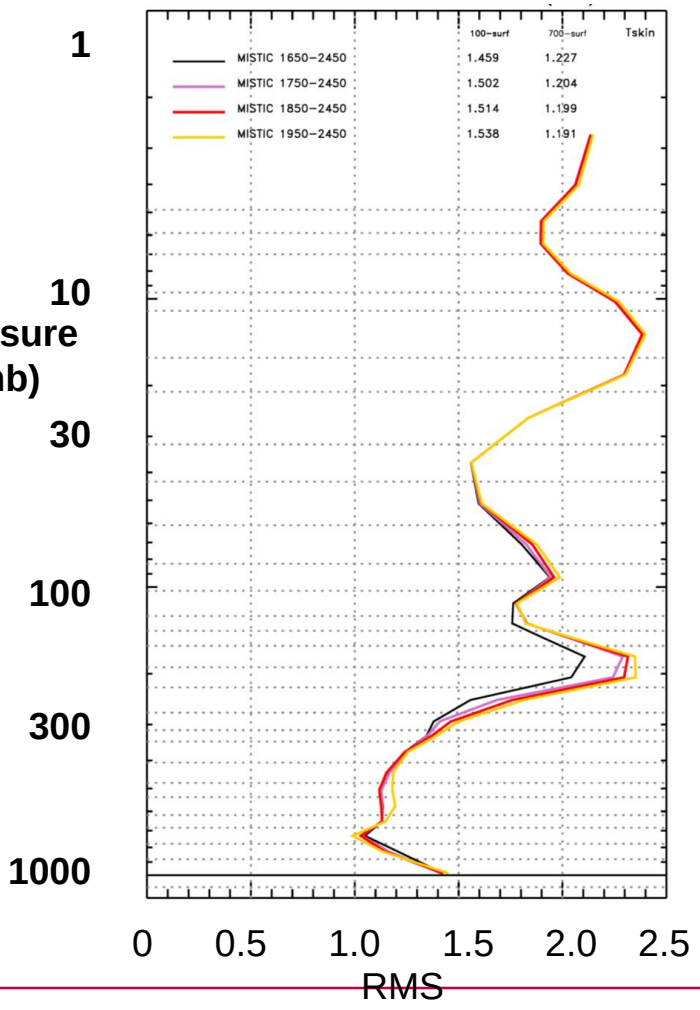
1650-2450 cm^{-1}
1750-2450 cm^{-1}
1850-2450 cm^{-1}
1950-2450 cm^{-1}

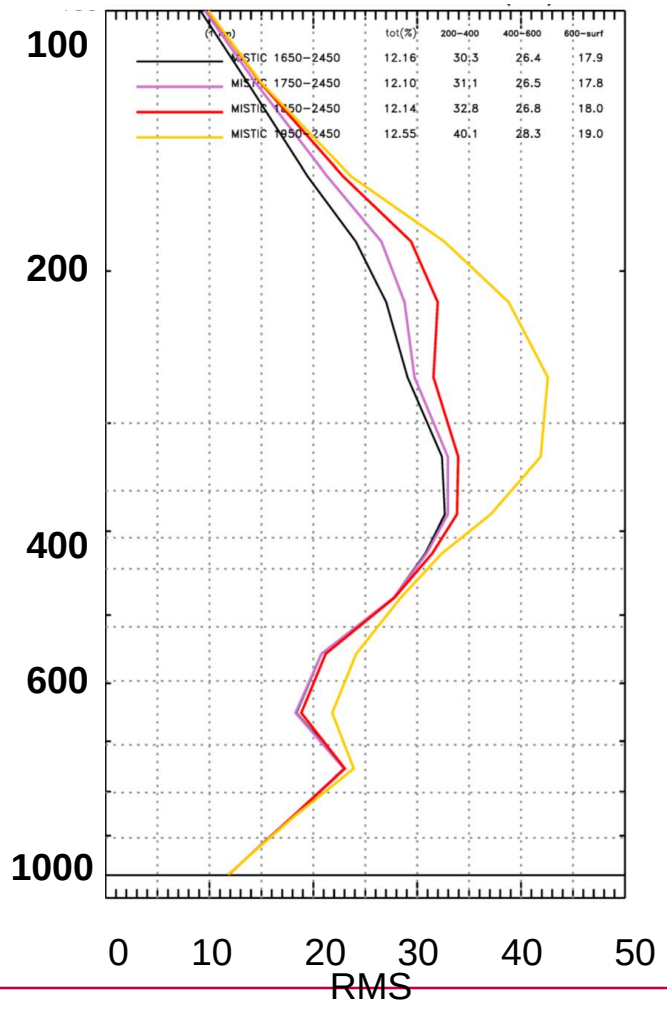
- Reasonably accurate temperature sounding can be done, using just the 4.2 micron band of CO2, up to about 200 mb
- Water vapor retrieval accuracy best at1650 cm-1 but good enough at 1750 cm-1 spectral cut-off validating MISTiC™ Winds spectral range selection

(from NASA GSFC Sounder Research Team)

1 Km Layer Temperature (K)
RMS Differences from Truth



1 Km Layer Precipitable Water RMS
% Differences from Truth



Not export controlled per ES-C4ISR-030718-0037

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

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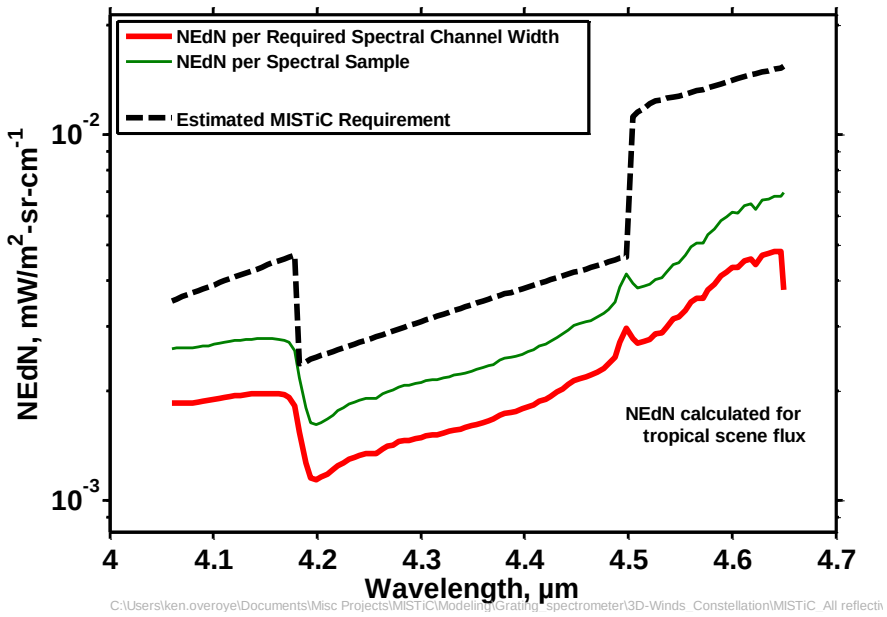
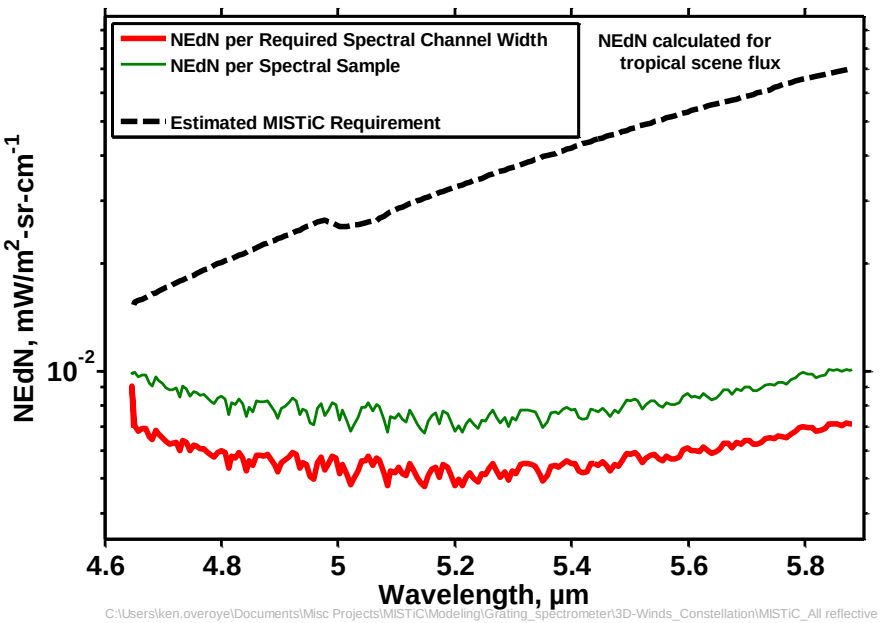
Sounding NEdN vs Wavelength:



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