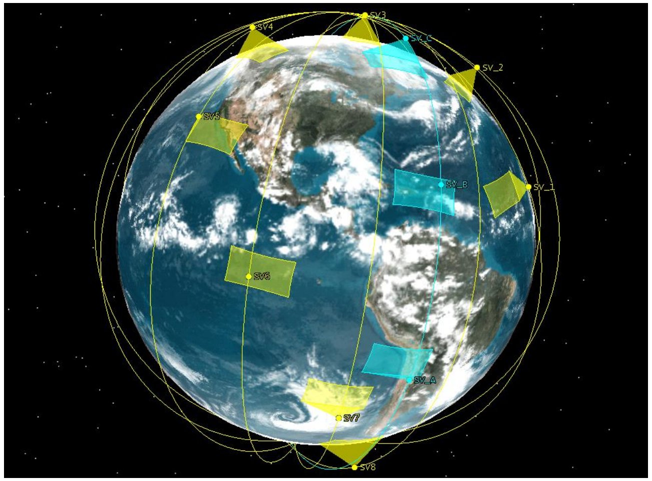
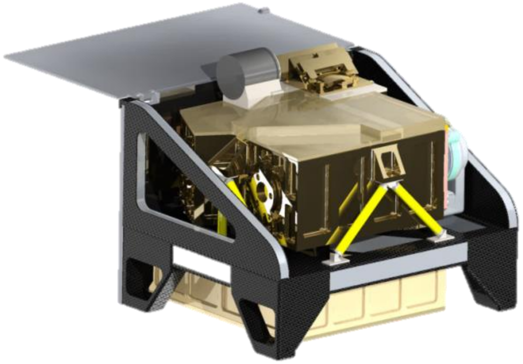
MISTiC™ Winds

A NASA Instrument Incubator Program

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

December13, 2017





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Science Team:
H. H. Aumann JPL
J. Susskind NASA GSFC

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

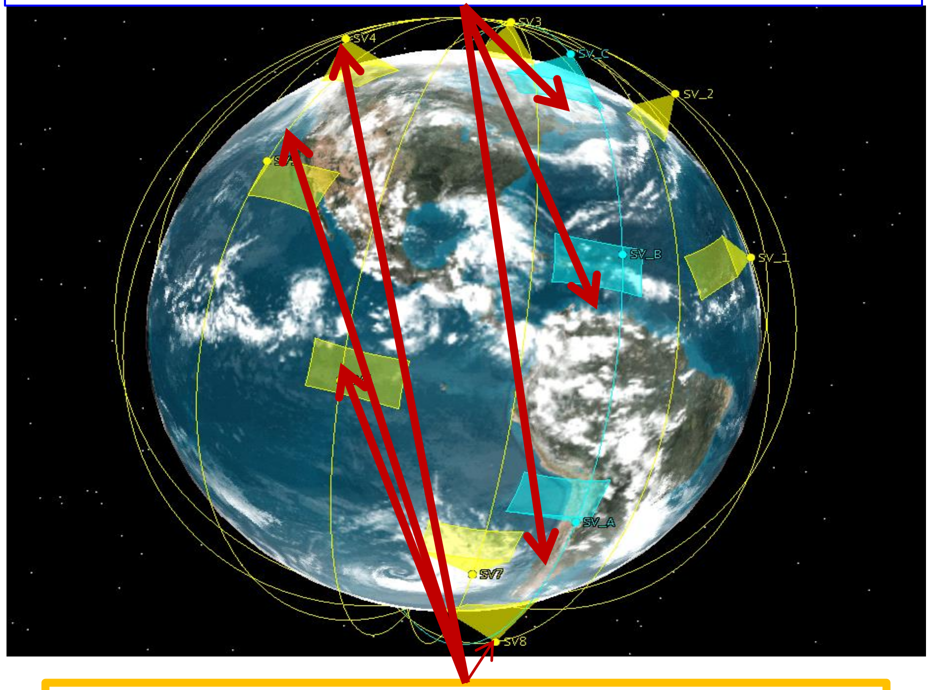
- Instrument Concept and Mission Concept Summary
- Instrument Physical Concept Update
- Risks Reduction Progress
  - FPA Radiation Test Summary
  - Spectrometer and Airborne Instrument Build
  - **Airborne HSI AMV Winds Observation Demonstration**
  - Next Steps
- IIP Summary

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

BAE SYSTEMS

- 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)**

Motion-Vector Winds Formation (blue)



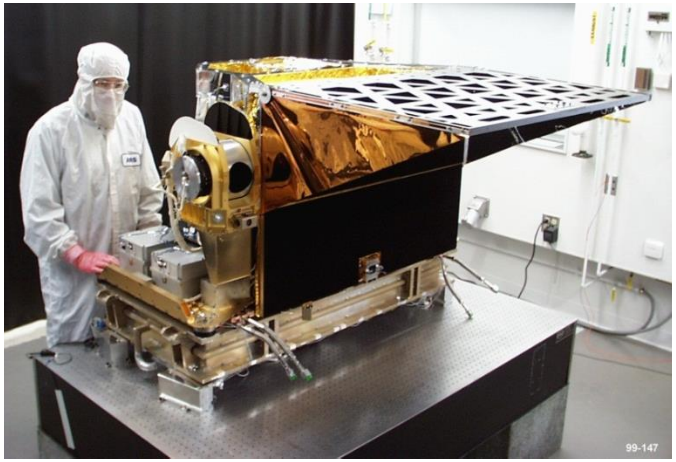
90 min Refresh of IR Soundings Provided by Spectrometers in 8 Orbital Planes (gold)

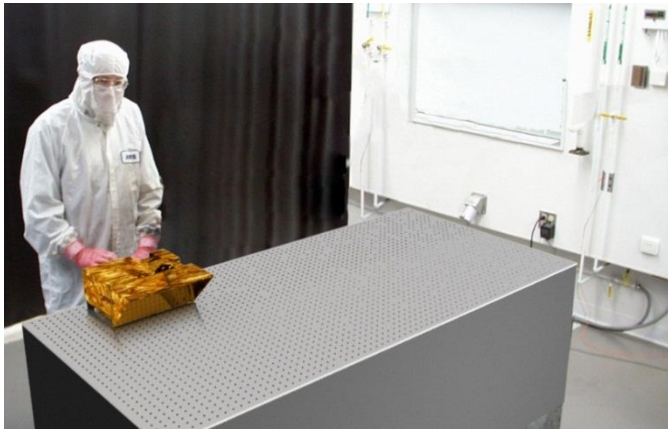
Miniature Spectrometers Operated in Constellations Offer Lower Cost /Lower Risk Approach than GEO for Frequent-Refresh IR Soundings & 3-D Winds

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

BAE SYSTEMS

- 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**

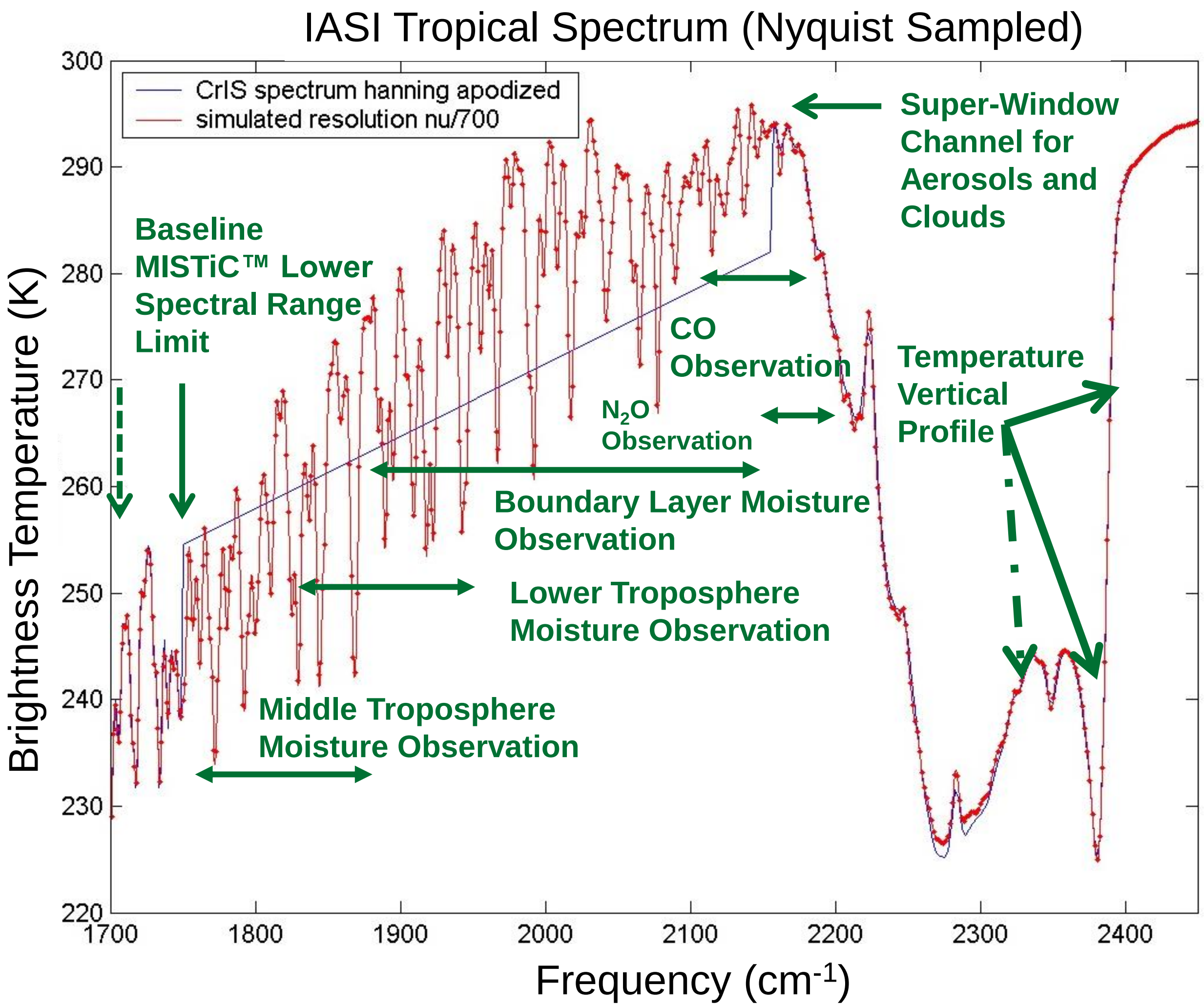




Artist's Rendering Depicts a MISTiC™ Instrument, for Comparison to AIRS

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

BAE SYSTEMS



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

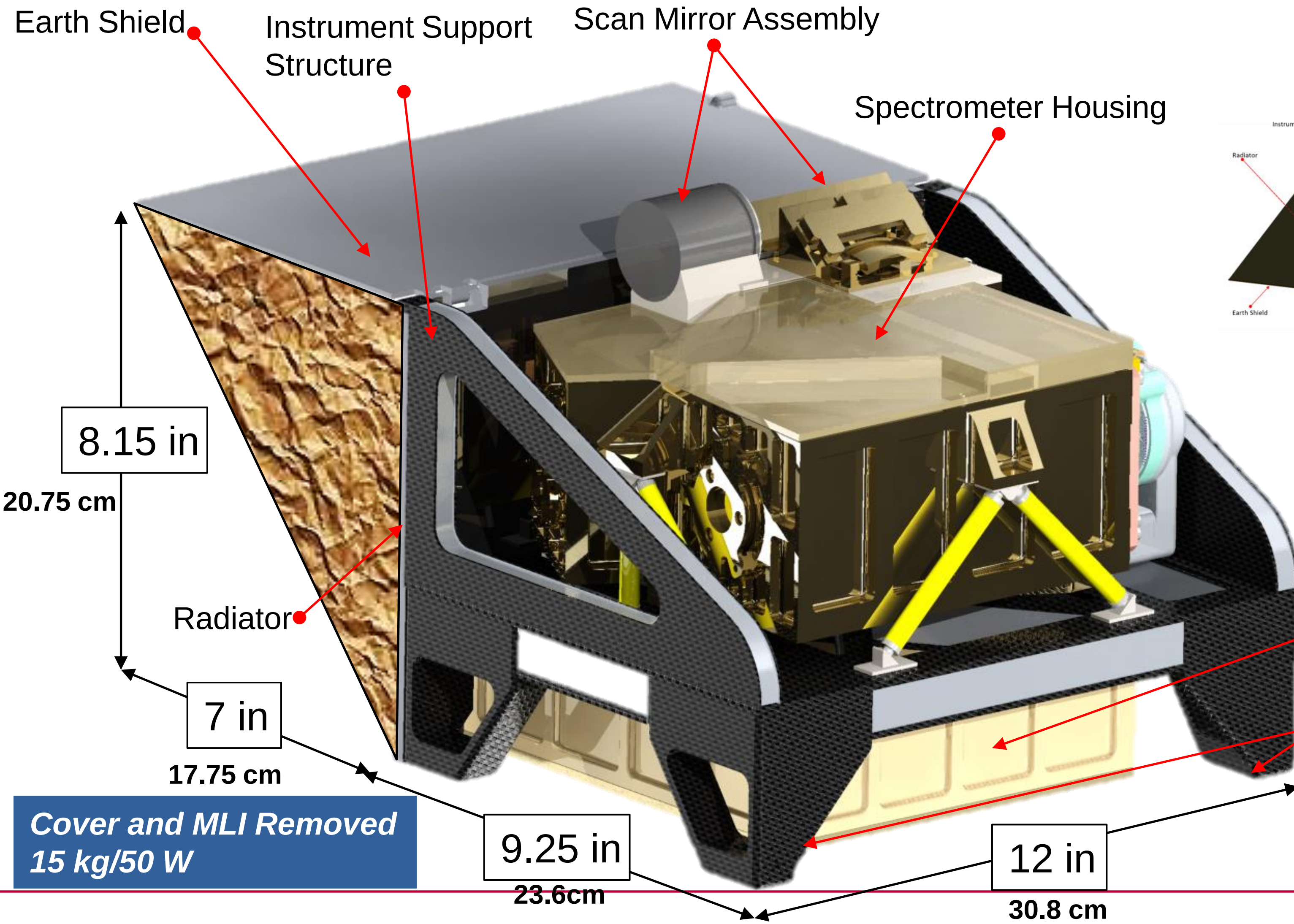
BAE SYSTEMS

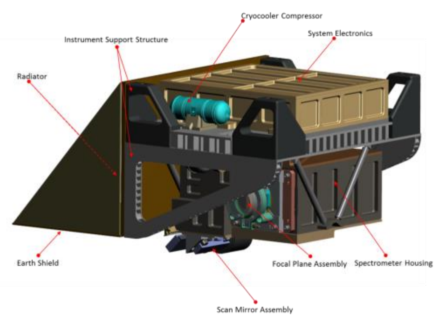
MISTiC™ Key Instrument Performance Characteristics		
Characteristic	Value	Comments
Minimum Spectral Frequency	1750 cm^{-1}	5.72 μm
Maximum Spectral Frequency	2450 cm^{-1}	4.082 μm
Spectral Sampling	~ 2:1	<590 spectral samples
Spectral Resolution @ minimum	>700 :1	$\nu/\delta\nu$ ((comparable to CrIS-Apodized)
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

MISTiC Winds IR Spectral Sounding Instrument Concept

BAE SYSTEMS





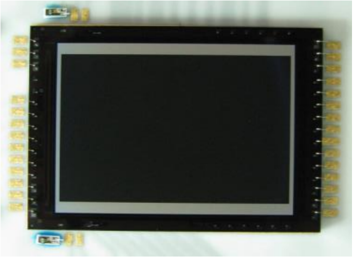
Cover and MLI Removed
15 kg/50 W

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

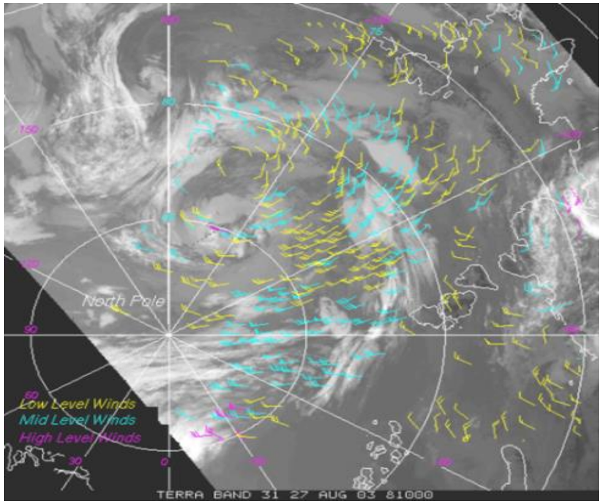
BAE SYSTEMS

- ✓ 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

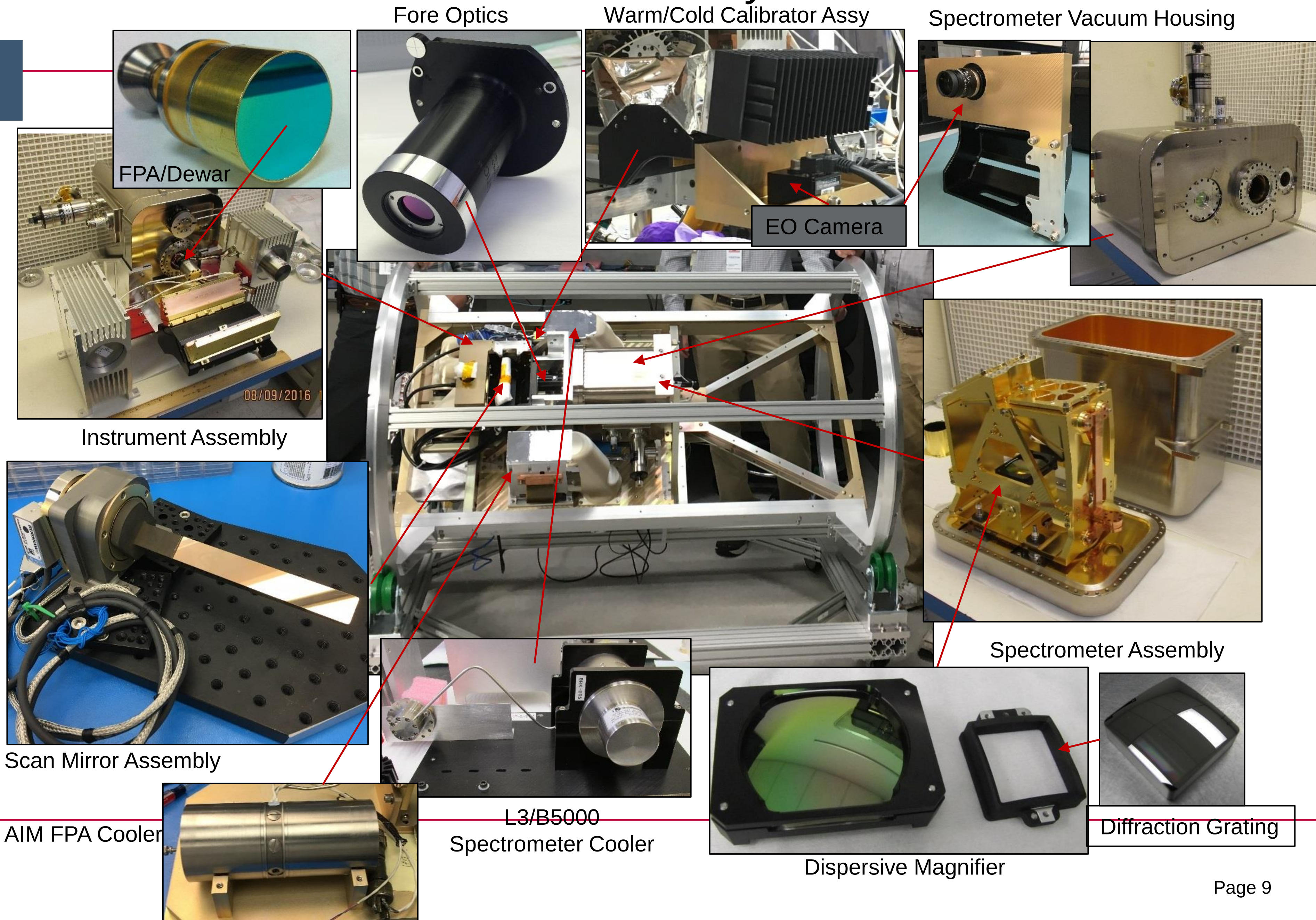


The MWIR HgCdTe Avalanche Photodiode-based IR Focal Plane Array Detector selected for MISTiC allows high-sensitivity hyperspectral measurements at 85K



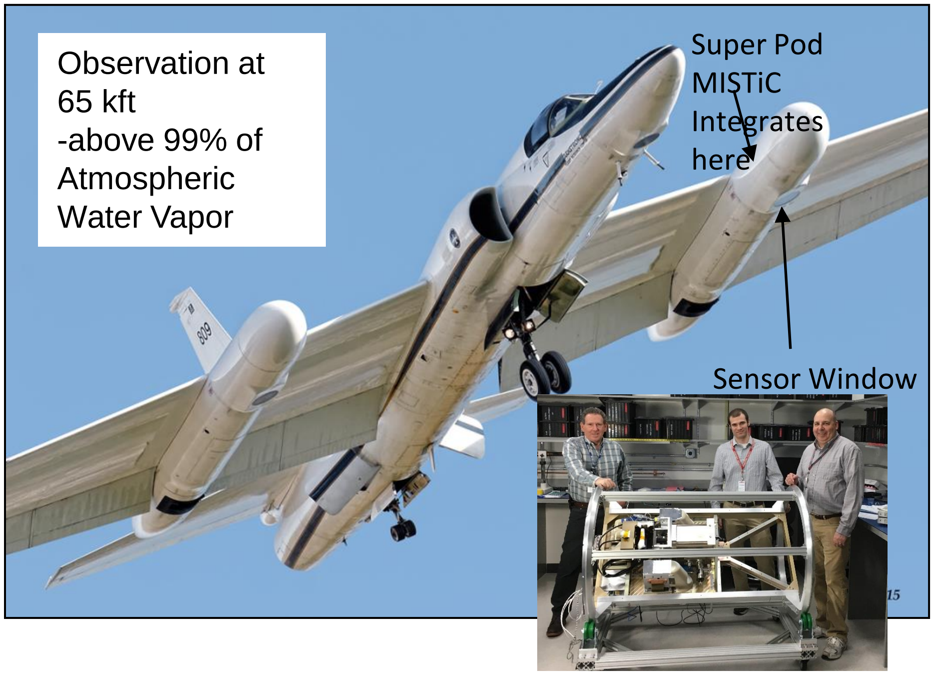
MISTIC™ Winds Tracers Features Would Have Better Vertical Resolution Than MODIS Winds

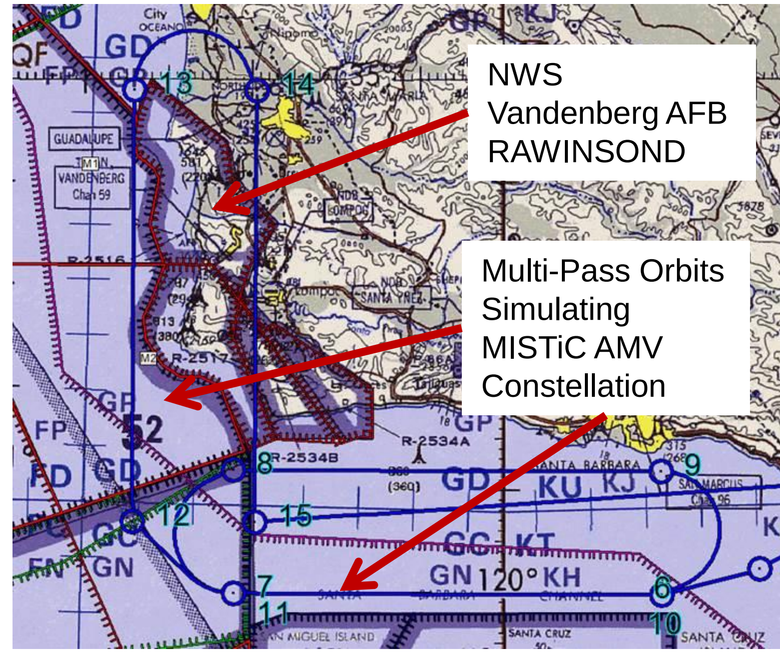
MISTiC Airborne Instrument Summary



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

BAE SYSTEMS





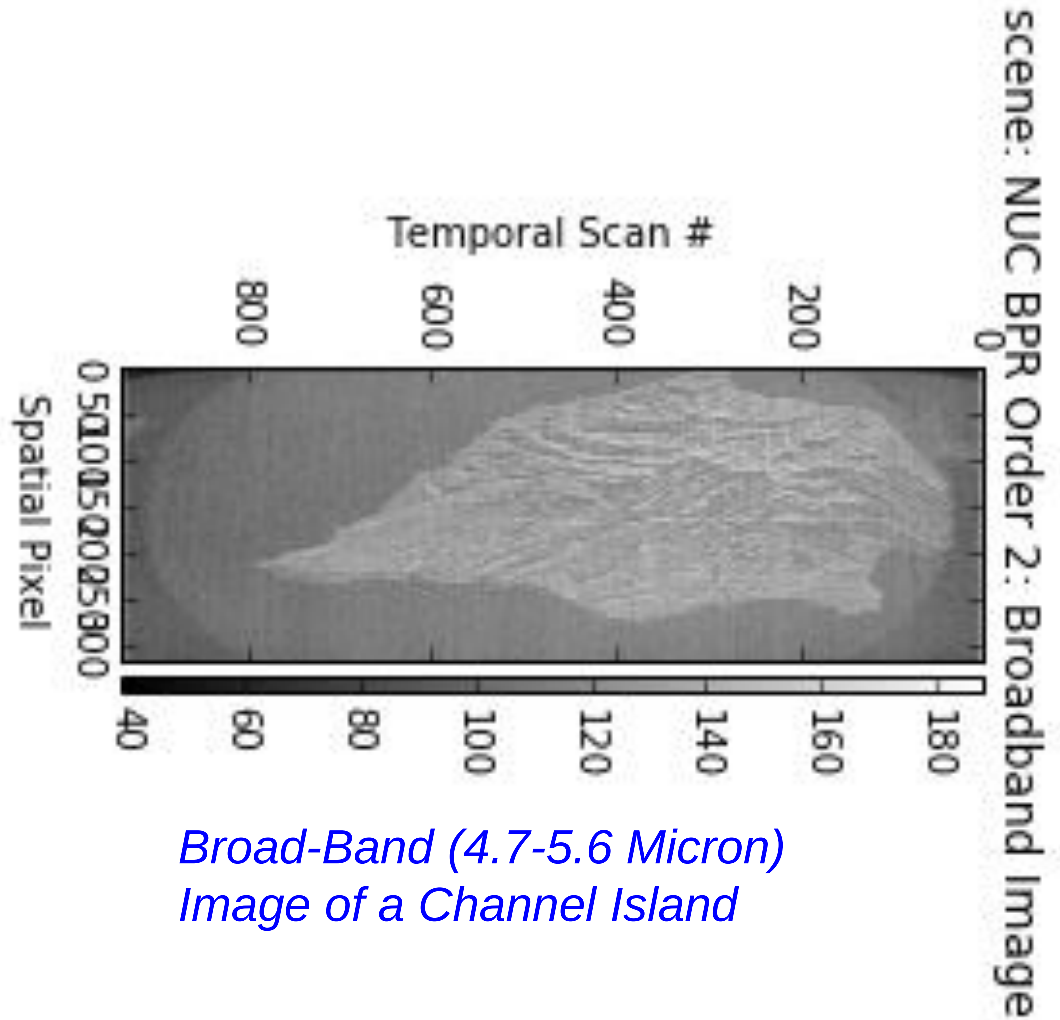
Airborne Spectrometer Very Similar to Space Instrument--with these differences:

- 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?)

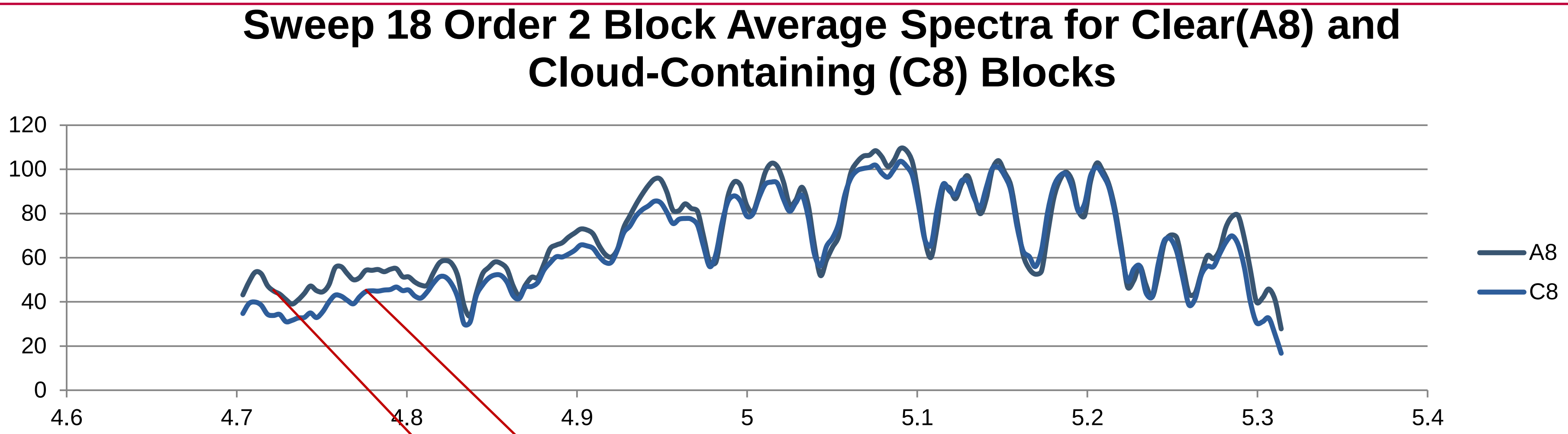
Airborne MISTiC Instrument Acquires Hyperspectral Imageryto Capture Atmospheric Motion Vectors

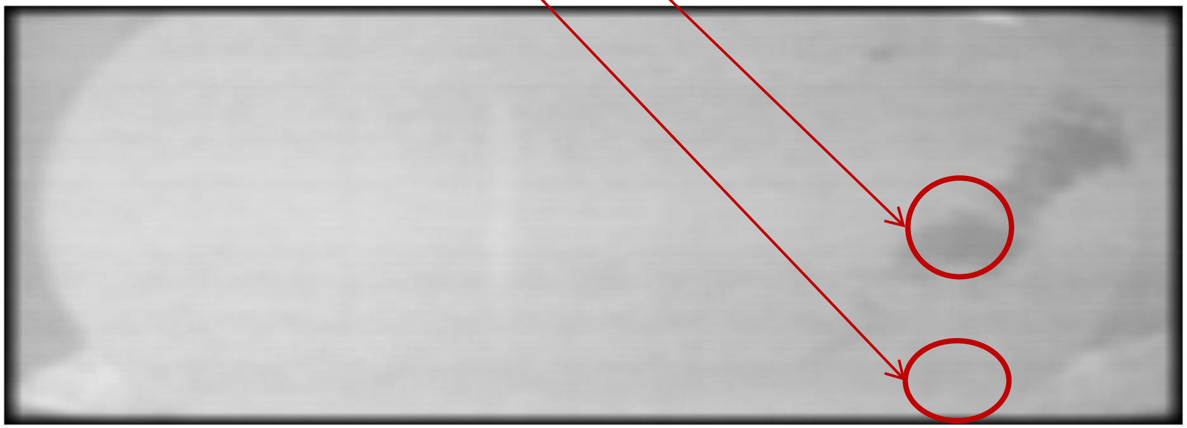


Broad-Band (4.7-5.6 Micron) Image of a Channel Island

- 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

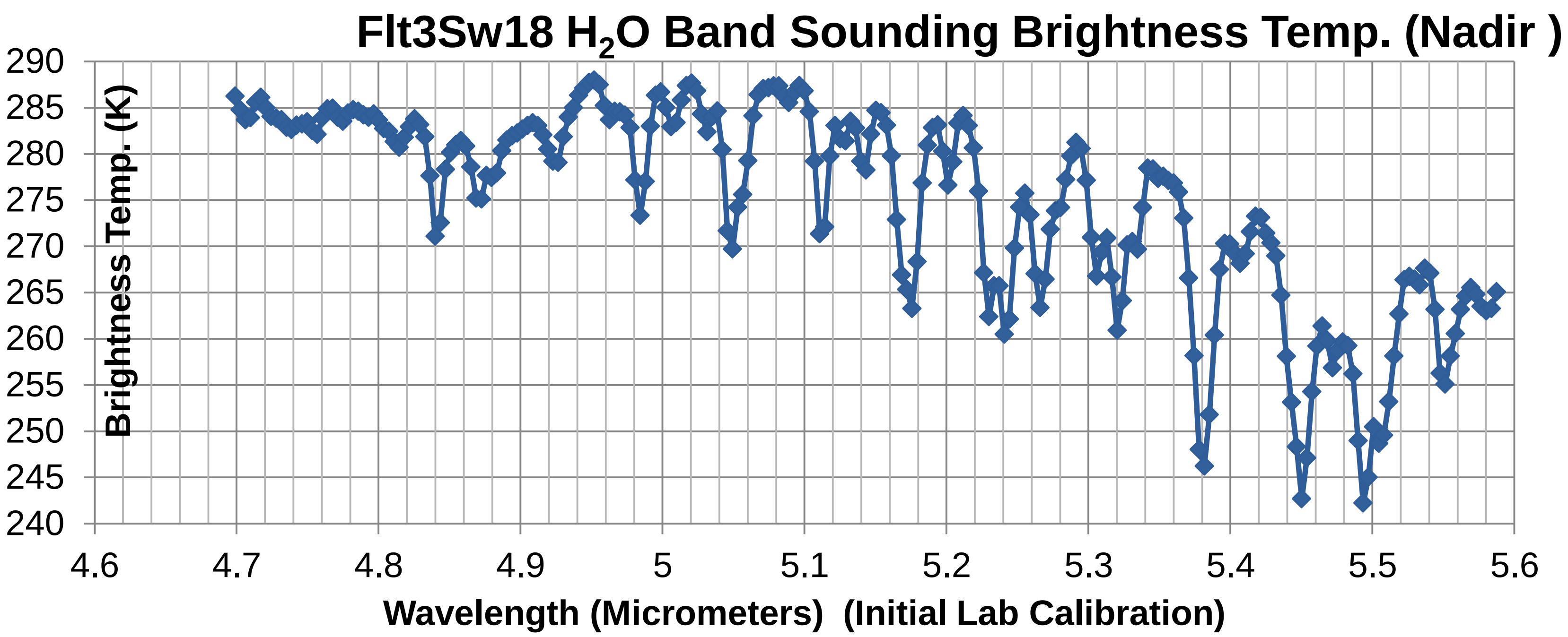




5.01 µm Spectral Channel Image

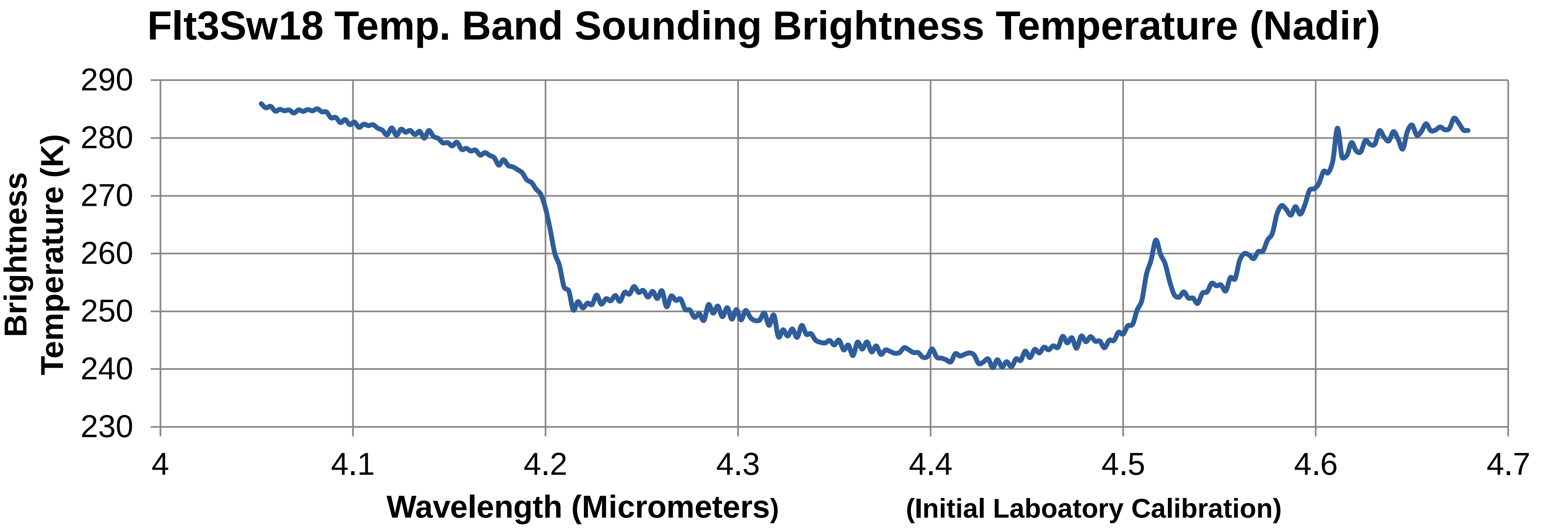
- Cloud tops are colder than ocean surface
  - Lower Radiance
- Low cloud temperature close to surface temperature (low thermal contrast)

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



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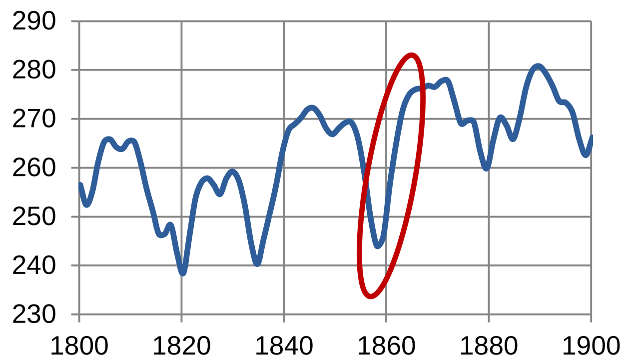
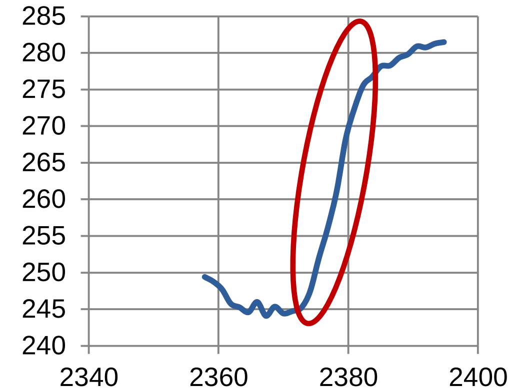
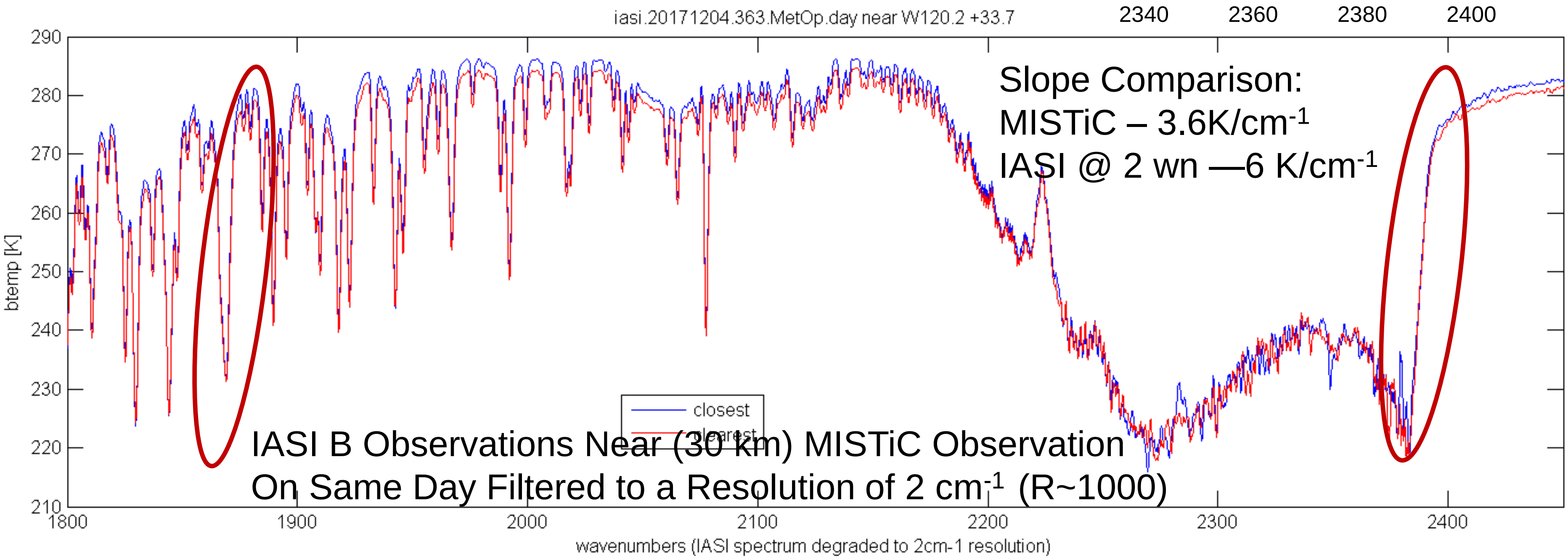
Primary Critical Atmospheric Emission Spectral Features Observed in MISTiC Winds Airborne Observation



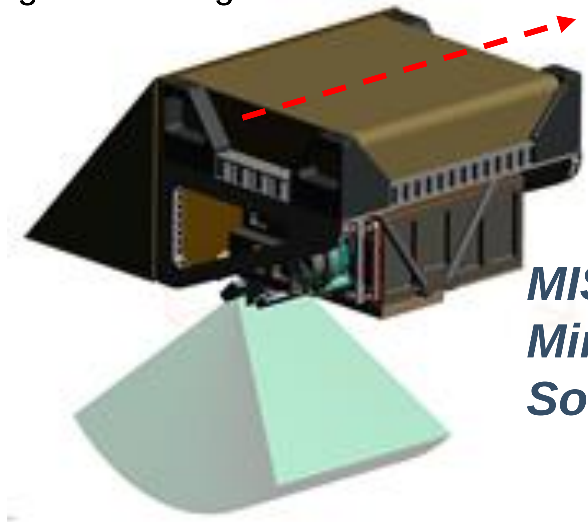
Spectral Edge Response Consistent with Resolution ~600 in Key Mid-Trop WV and Temp Sounding Regions –close to 700 design goal



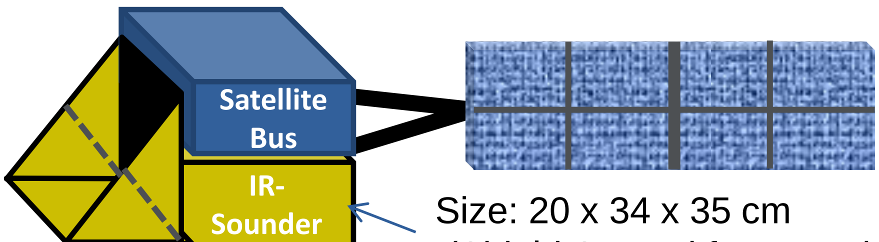


MISTiC™ Winds-A Miniature High Vertical Resolution Infrared Sounder for 3D Winds and Frequent IR Soundings

- 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



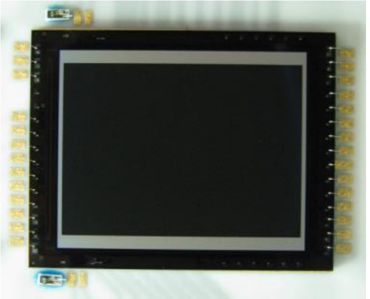
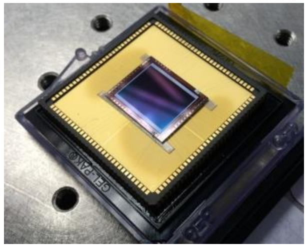
Micro-Sat with Miniature IR Sounder Payload



Supplemental Material

FPA Radiation Tolerance Risk and Risk Reduction Plan

- <u>APD-Class SWIR/MWIR FPA Ionizing Radiation Tolerance Risk</u>
  - High Sensitivity APD-Mode IRPFA Enables Higher Operating Temperature—Reducing Power Demand
  - Selected FPA Successfully Used Operationally in Airborne Hyperspectral Mission
  - ***Remaining Risk***: APD Array Not Yet Tested for Key MISTiC™ Conditions in Space Radiation Environment
    - Radiation Under Operating Bias
    - Evaluated for Low Frequency Operation (1/f knee <10 mHz)

The MWIR HgCdTe Avalanche Photodiode-based IR Focal Plane Array Detector selected for MISTiC™ allows high-sensitivity hyperspectral measurements at 90K

- <u>Risk Reduction Plan</u>
  - Proton Total Dose Testing of Engineering-Grade APDIS FPA (s)
    - Dose Applied Under Sufficient Bias for Gain > 100
      - λ_{co} similar to that needed for Temperature-Band
    - Includes Testing at Frequencies down to 10 mHz

Projected APD Detector Characteristics Meet MISTiC Updated Sensitivity(Dark Current) Requirements at 90K

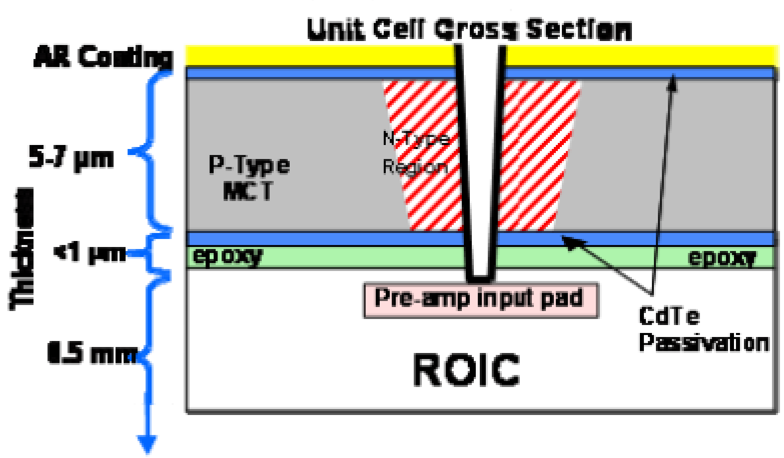
BAE SYSTEMS

Updated Minimum Scene –Generated Photo-Current Density

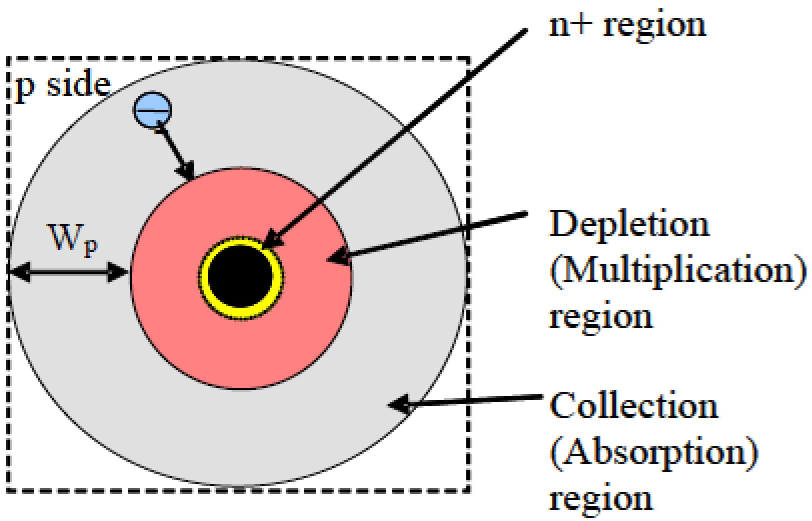
- $8x10^{-10}$ A/cm^2 (Temperature Band)
- $2x10^{-8}$ A/cm^2 (Water Vapor Band)

DRS HDVIP Dark Current Density Model Estimates

Temp.	J_{dark} @ λ_{co}= 5.1 µm	J_{dark} @ λ_{co}= 6.4µm
85 K	$1x10^{-11}$ A/cm^2	$5x10^{-9}$
90 K	$4x10^{-11}$ A/cm^2 √	$1x10^{-8}$ √
95 K	$1x10^{-10}$ A/cm^2	$5x10^{-8}$



(a)



(b)

HDVIP® e-APD architecture.(a) Cross section of the HDVIP process. (b) Top-Side view

Ionizing Radiation Tests of HgCdTe APD FPA Demonstrate its Compatibility with Space Environment

BAE SYSTEMS

Ionizing Radiation Test Background:

- Test Performed by AFRL Infrared Radiation Effects Laboratory
- Test Type: Total Dose-Proton
  - 68 MeV Proton Energy
  - FPA Cooled/Under Operating Bias Voltages During Proton Irradiation
- FPA Radiometric Characterization Pre-Radiation and at 6 Dose Steps

Key Test Results:

- ROIC Essentially Unchanged to 70 krad
- Detector dark current (and noise) increase with dose, but acceptable rate
  - FPA Noise < Requirement at 20 krads Proton Dose\
  - Modest 1/f noise increase, at high APD gain at higher proton doses

Total Ionizing Dose (krad(Si))	Median Pixel Dark Current (A) (zero bias reference)
Pre-Rad	1.3x 10^{-15}
1	1.26x 10^{-15}
5	1.82x 10^{-15}
15	3.5x 10^{-15}
25	6.3x 10^{-15}
35	8.0x 10^{-15}
70	16.0x 10^{-15}

Allocated Dark Current Rqmt. < 5 fA/Pix

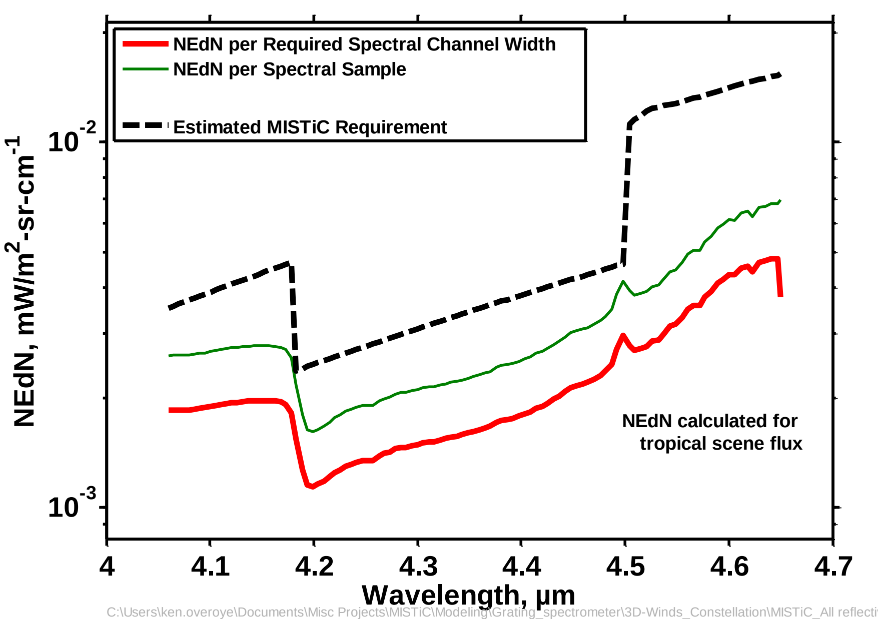
HgCdTe 640x480-Format APD-Mode IR FPA Technology Readiness Level Advanced to 5

GOES-R Advanced Baseline Imager, AIRS, and CrIS

- Size of Geo-Stationary Imagers/Sounders Driven by Orbit Radius
- Size of IR Sounders Driven by # of Channels and LWIR Band Cooling

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

Sounding NEdN vs Wavelength:



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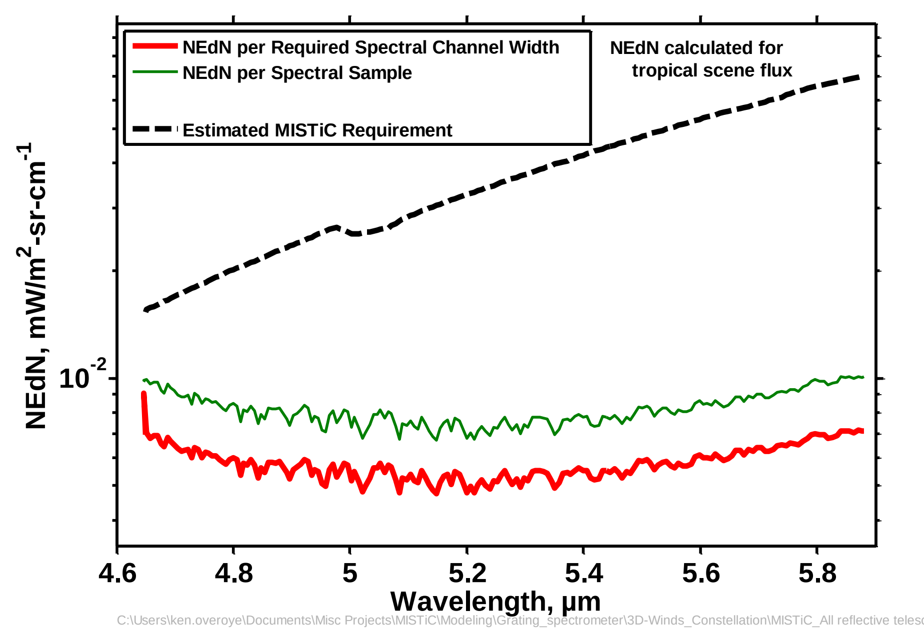
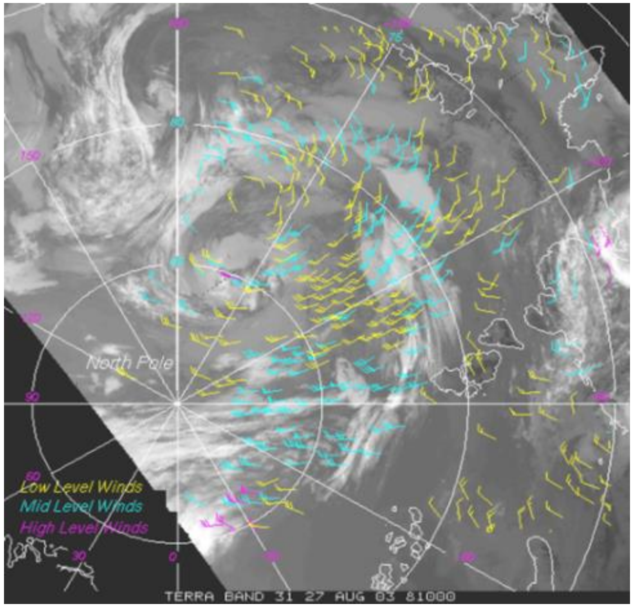


- Spectrometer Radiometric Modeling Methods Developed for AIRS, GOES-R HES, etc used to Estimate MISTiC™ Winds Instrument Sensitivity
- Sensitivity Similar to AIRS (<200 mK @ 250K Scene) for low brightness temperature regions near 4.2 μm
- Updated APD detector noise modeling still be included in system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

MISTiC Winds Observes the 3D Vector Wind Profile

- MISTiC Winds Observes 3D Atmosphere at 3 closely spaced times to Produce Multi-Altitude Motion-Vector Winds
  - Projected Wind Speed Error ~ 2 m/s rms
    - ~3x better than projected for GOES-R
  - SWIR/MWIR Imaging/Sounding Provides Much Better Tracer Height Assignment than GOES
    - 1K/1 km Temperature Sounding Enables Separation of Temperature and Moisture Concentration Contributions to Radiance
  - Both Moisture and Cloud Motion Vector Winds Observed by MISTiC
- OSSE's Show that 3D-Winds Observations Would Have the Largest Impact on Short Term Weather Forecast of Any New Observation
  - MISTiC Observes Thermodynamic State *and* Mass-Field Motion

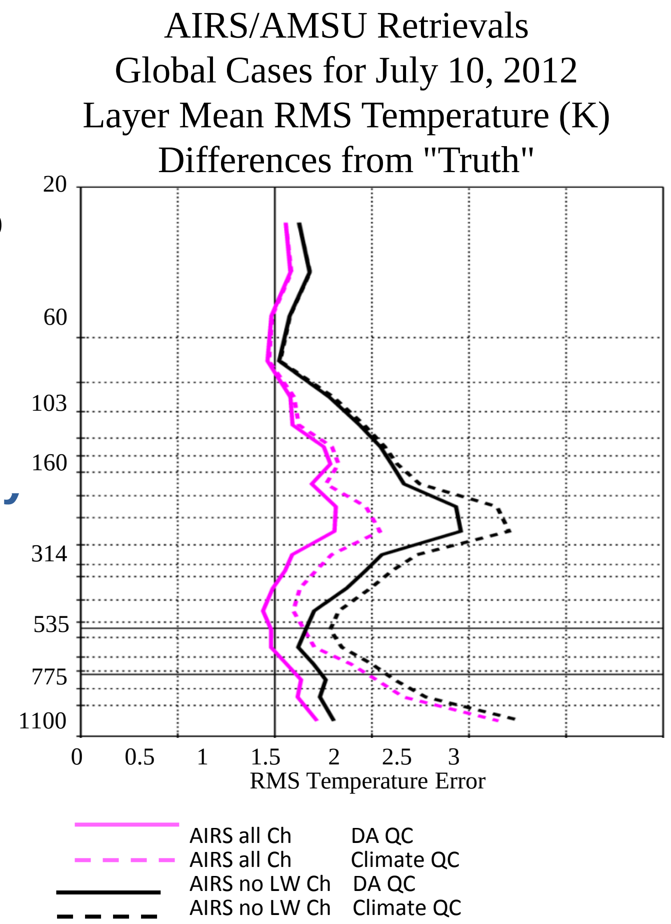


MISTIC Winds' Tracers Features Would Have Better Vertical Resolution Than MODIS Winds (shown) and GOES Imagers

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

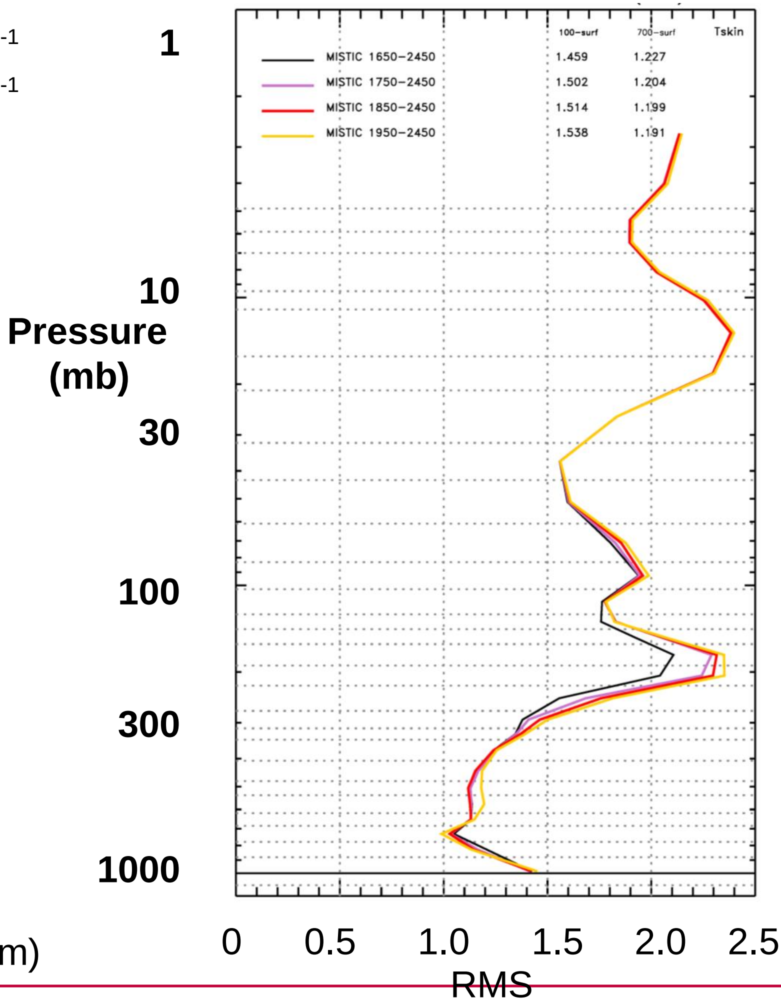
BAE SYSTEMS

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

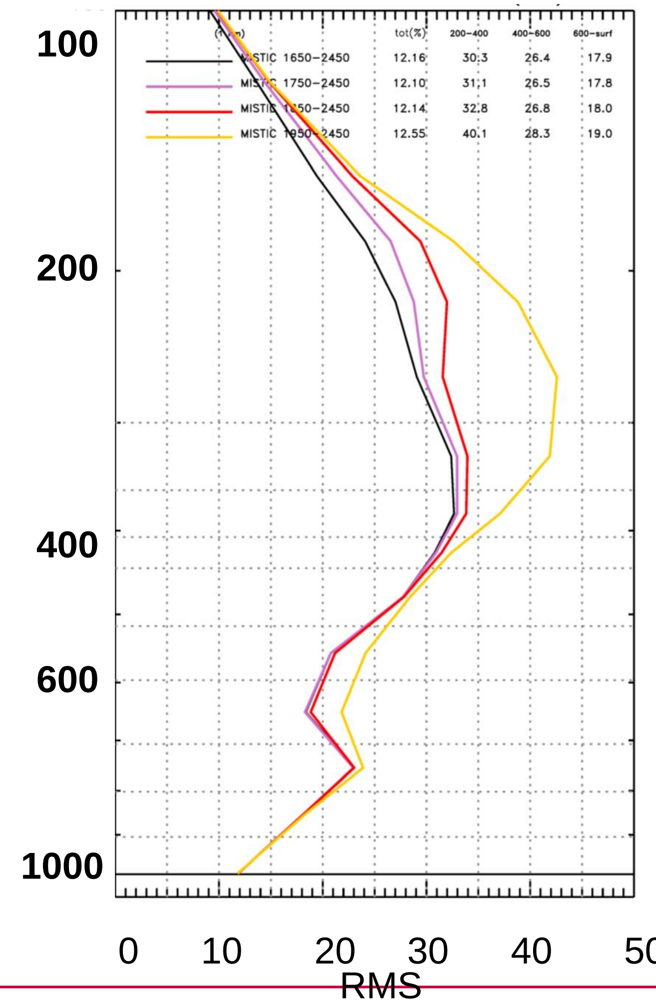
- Reasonably accurate temperature sounding can be done, using just the 4.2 micron band of CO_2, up to about 200 mb
- Water vapor retrieval accuracy best at1650 cm-1 but good enough at 1750 cm-1 spectral cut-off validating MISTiC™ Winds spectral range selection

(from NASA GSFC Sounder Research Team)

1 Km Layer Temperature (K) RMS Differences from Truth



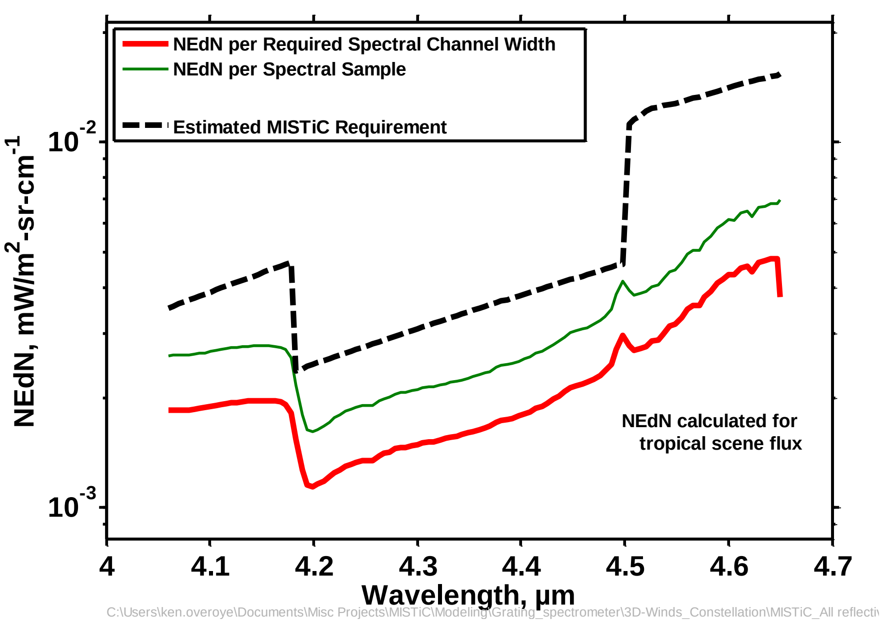
1 Km Layer Precipitable Water RMS % Differences from Truth



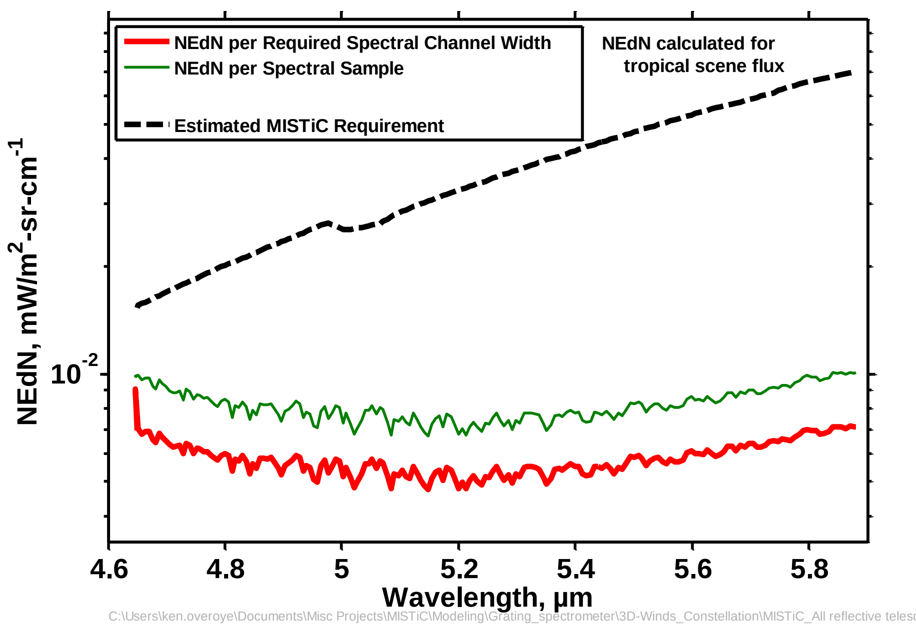
Truth = AIRS Retrievals version 6 - Ocean 50°N to 50°S December 4, 2013

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

Sounding NEdN vs Wavelength:



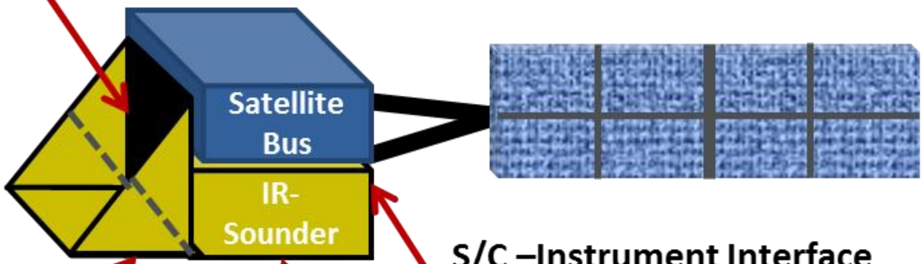
Sounding NEdN vs Wavelength:



- 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

Spectrometer Temp. Variation in Worst-Case Orbit is Small

Cryo-Radiator Rejects Spectrometer Heat to Space

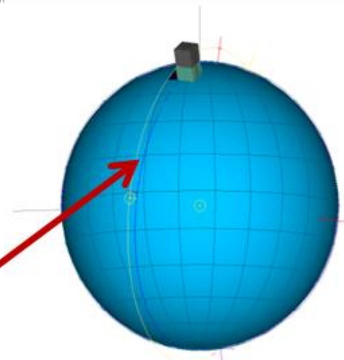


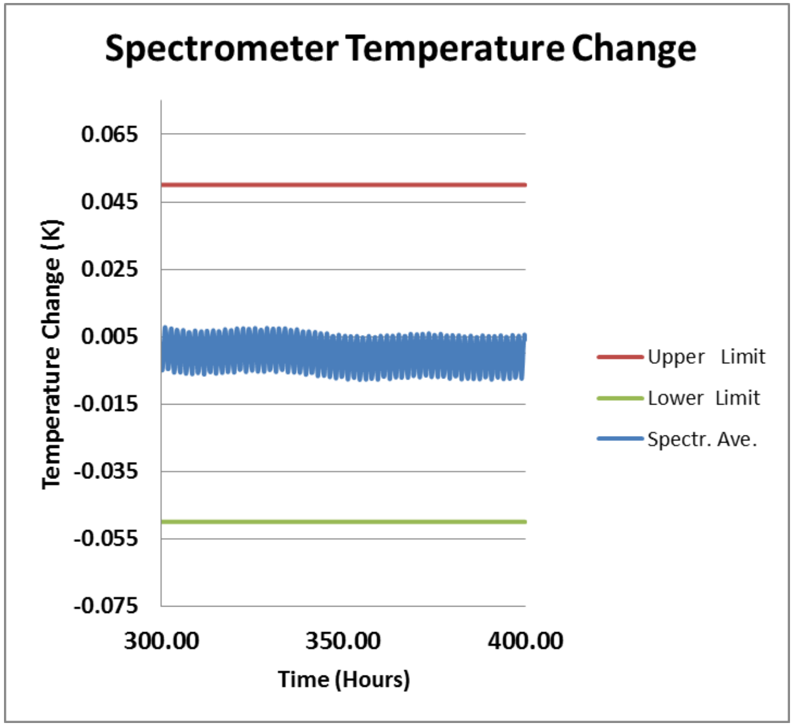
S/C –Instrument Interface "Adiabatic"

Payload Size:
20 x 34 x 35 cm

Earth Shield, (as Deployed on-Orbit)

Earth Shield Blocks some, but Not All Solar Illumination of Cryo-Radiator in 1:30 PM Orbit (Worst Case Orbit)





1000+-node Thermal Model Assessment

→MISTiC Meets Stringent IR Sounder Spectral Calibration Stability Requirements Within Envelope/Mass Limits of a Small Micro-Satellite

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