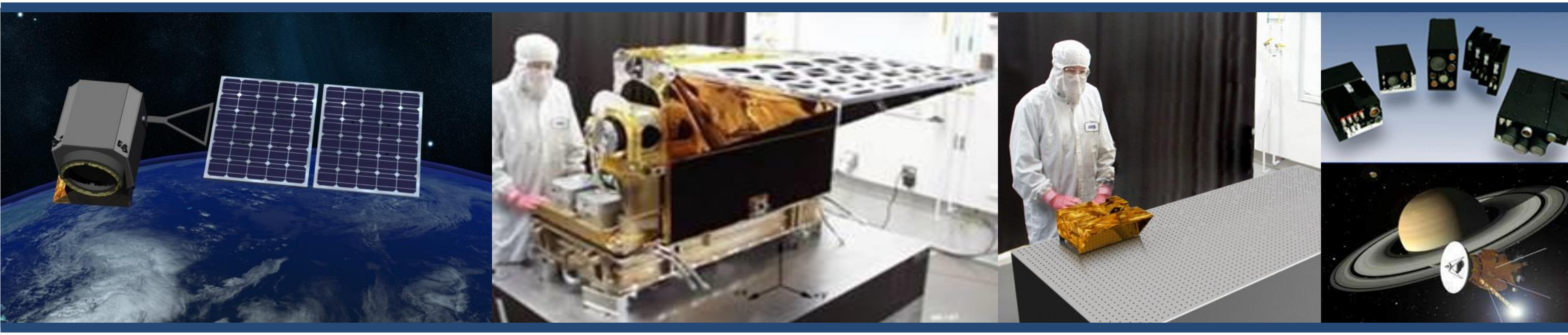
# NASA Instrument Incubator Program (IIP)
# MISTiC™ Winds

## Midwave Infrared Sounder for Temperature and humidity in a Constellation for Winds

## Earth Science Technology Forum

June 23, 2015

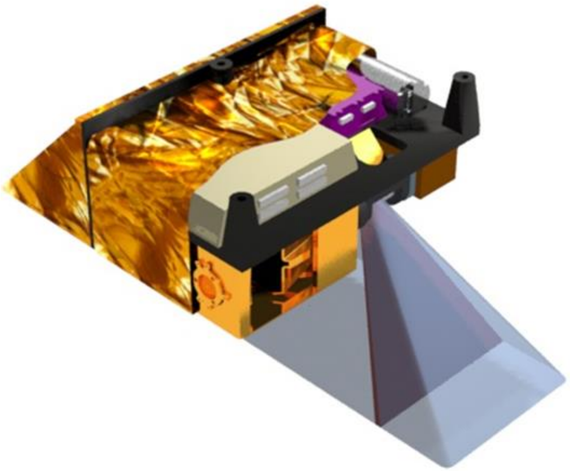
POC:kevin.maschhoff@baesystems.com

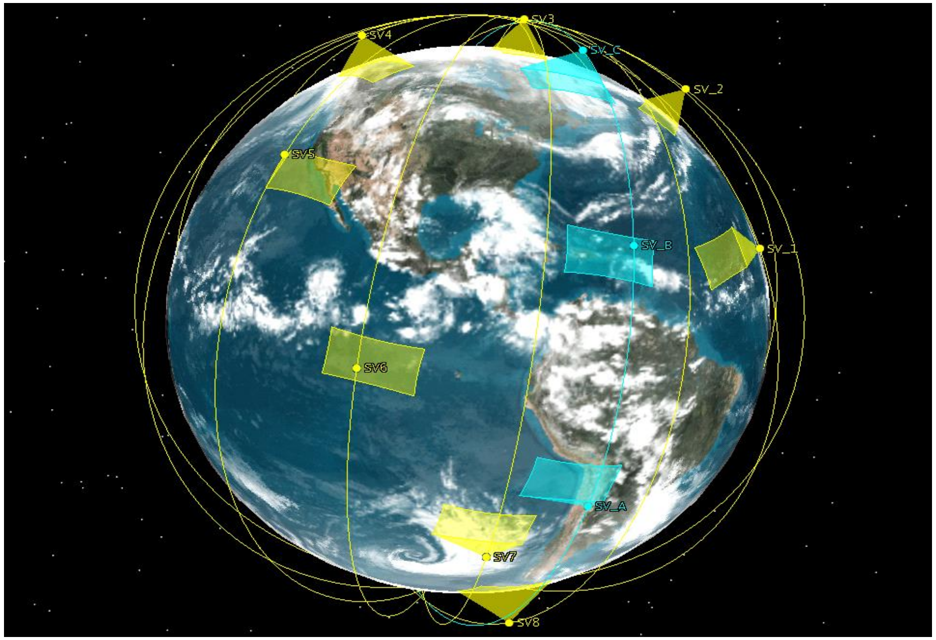


# MISTiC™ Winds

BAE SYSTEMS

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






NASA ESTO IIP PI: Kevin R. Maschhoff, BAE Systems

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
- <u>Enabled by</u>:
  - LEO Constellation Approach
  - Micro-Sat-Compatible Instrument
  - Low-Cost Micro-Sat Launch

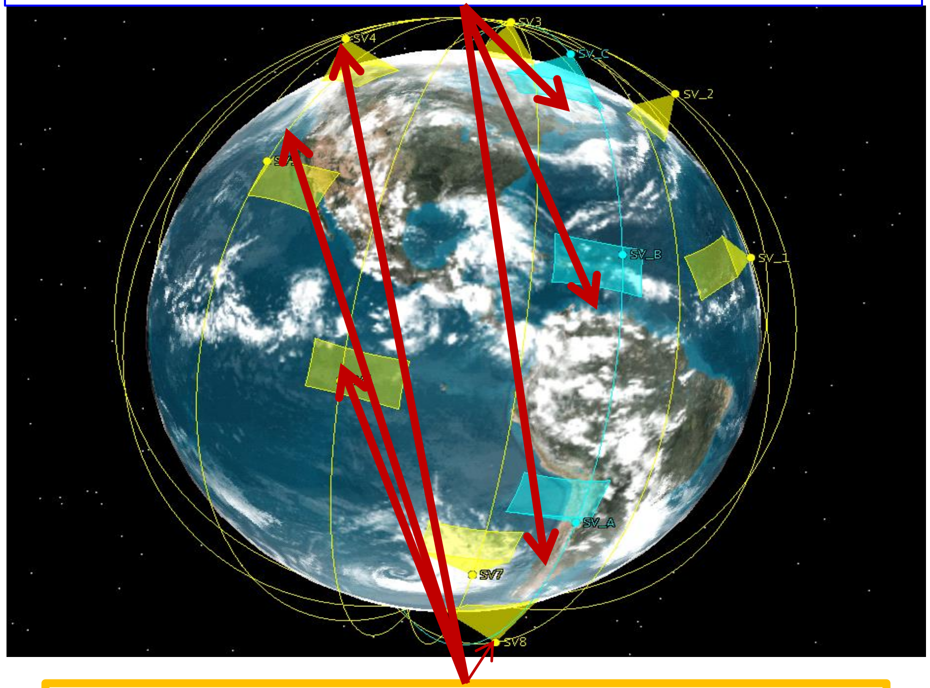
# MISTiC™ Winds- Two Affordable Measurement Concepts to Reduce Weather Forecasting Errors

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

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

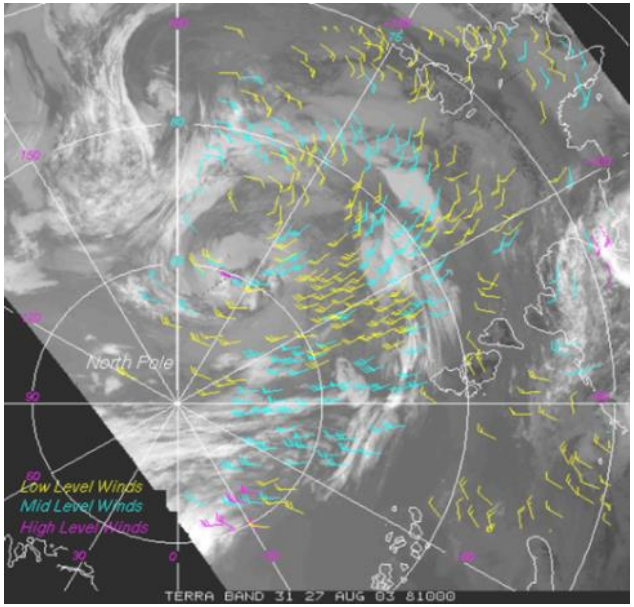
***Motion-Vector Winds Formation (blue)***




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

# 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

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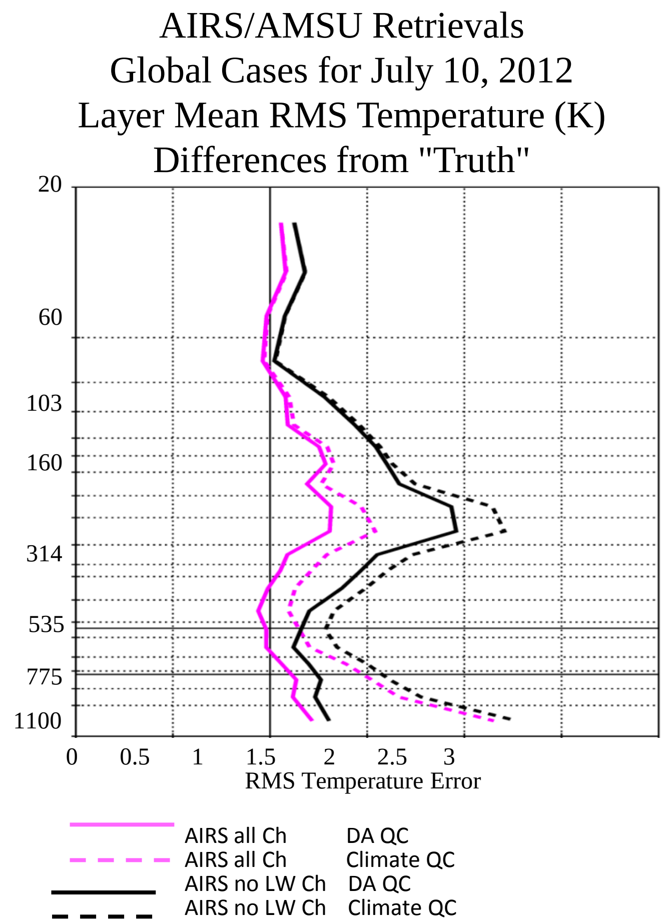
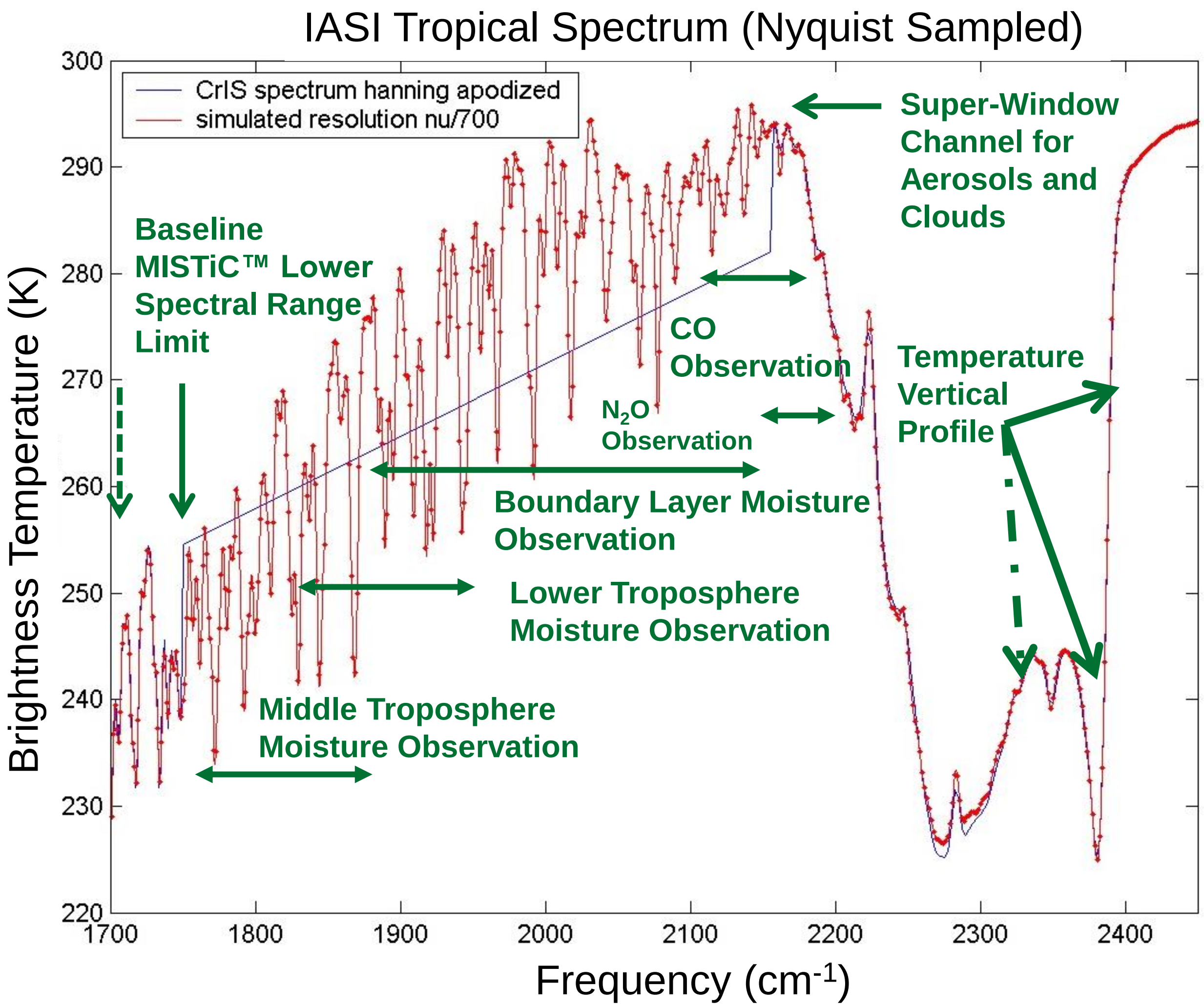
- MISTiC™ Winds' Vertical Temperature Profile Retrieval Comparable to AIRS & CrIS in Lower Troposphere
  - Vertical Temperature Profile Retrieval Accuracy for Two Different Quality Control Thresholds Shown
    - Using All AIRS Channels—solid curves
    - Using SWIR/MWIR-Only –dashed curves
- Additional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

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



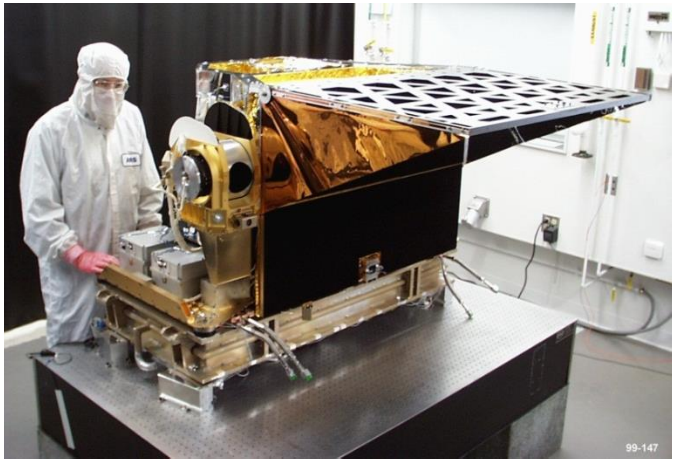

- SWIR Coverage at NE$\Delta$T and $\Delta\nu$ Sufficient for $CO_2$ R-Branch Temperature Sounding of Surface to Upper Troposphere
  - Sharper Vertical Resolution using Line Wings
  - Spectral Resolution > 700:1 is Sufficient
- Mid-Trop. CO
- Mid-Trop. $N_2O$
- Moisture in Planetary Boundary Layer
-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

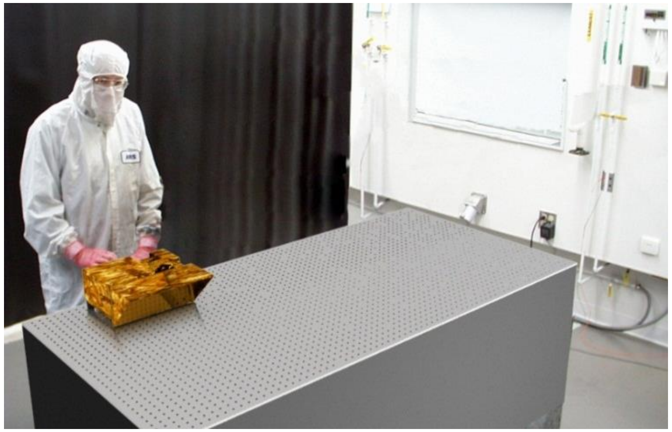
Channels Below 1750 $cm^{-1}$ Needed to Observ in for Upper Troposphere—*but*, *UT is Observ Sufficient Frequency by CrIS/IASI and ATMS*

# 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 in-Progress
  - 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

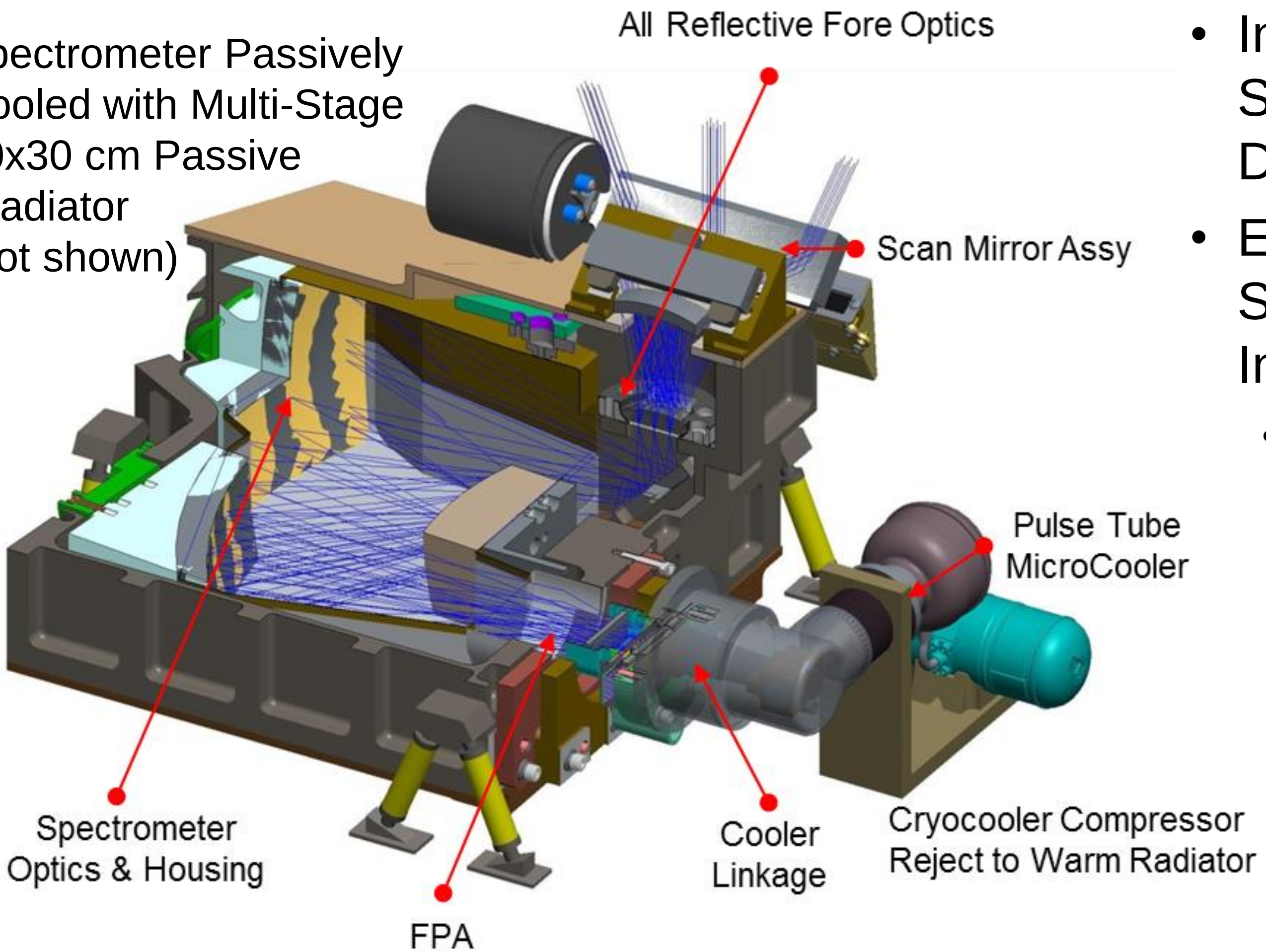




Artist's Rendering Depicts a MISTiC™ Instrument, for Comparison to AIRS

# MISTiC IR Spectrometer Detailed Physical Concept

Spectrometer Passively Cooled with Multi-Stage 30x30 cm Passive Radiator (not shown)

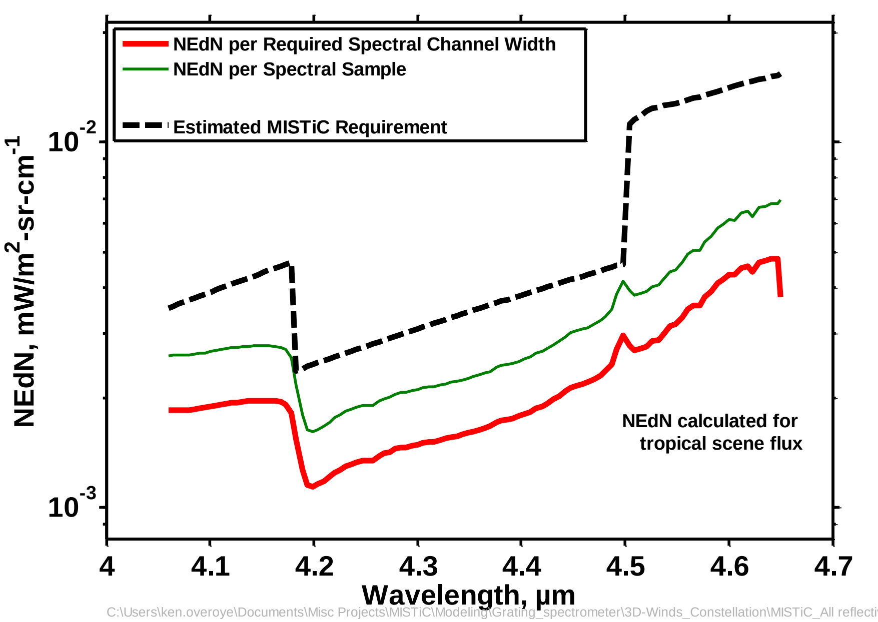



- Infrared Sounder Spectrometer Major Dimension ~ 20 cm
- Envelope Studies Show 30x30x20 cm Instrument (Stowed)
  - Compatible with:
    - 27U Cube-Sat
    - ESPA-Class MicroSat

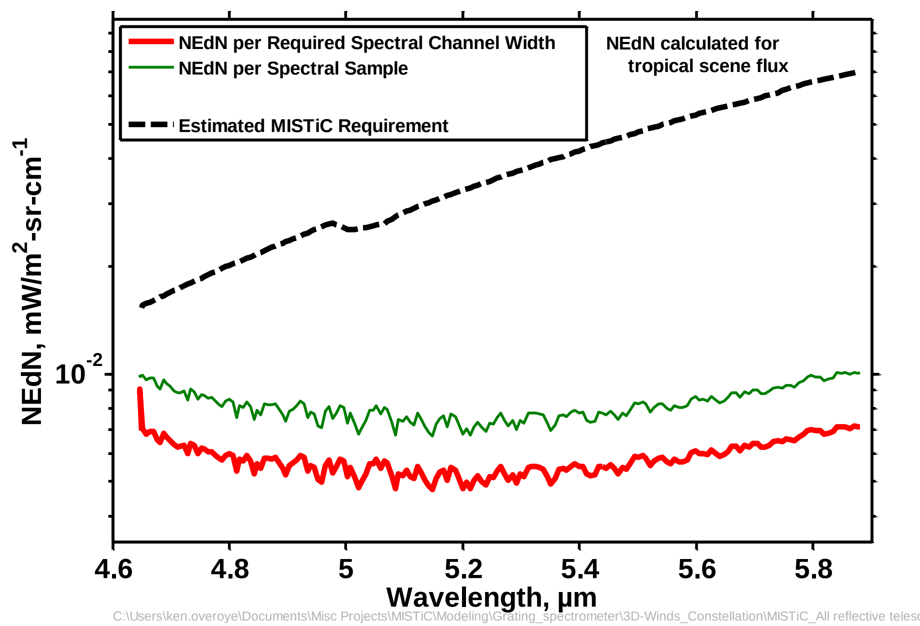
BAE SYSTEMS

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

**Sounding NEdN vs Wavelength:**

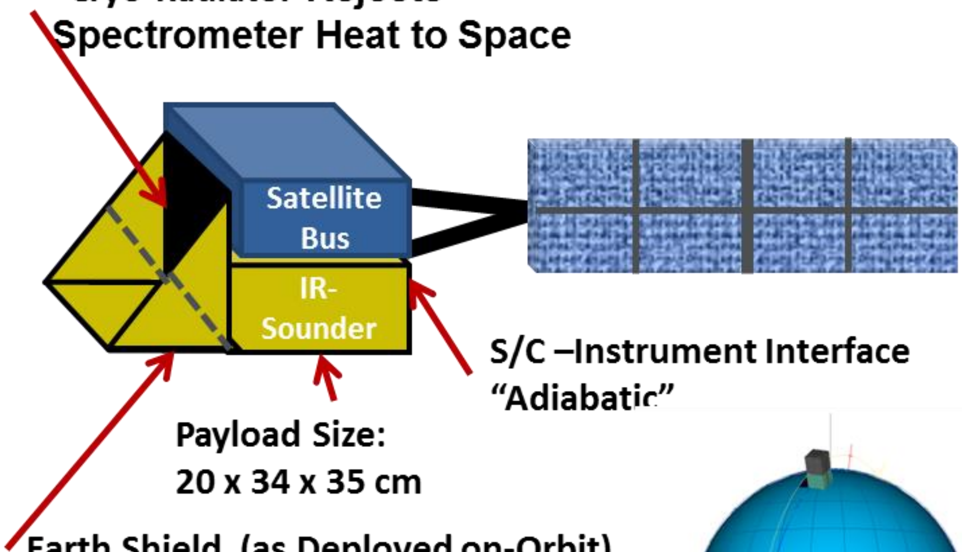



**Sounding NEdN vs Wavelength:**

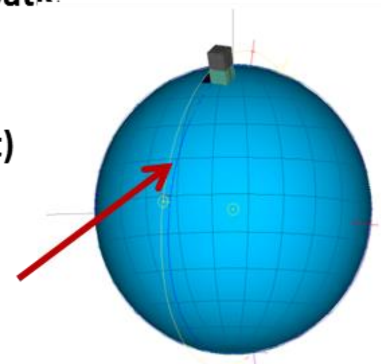


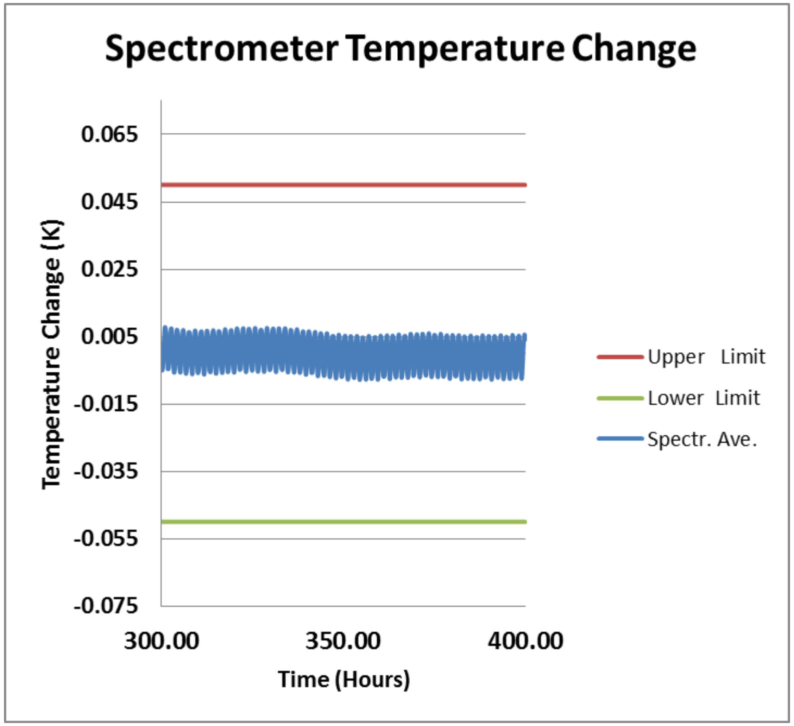

- Spectrometer Radiometric Modeling Methods Developed for AIRS, GOES-R HES, etc  used to Estimate MISTiC™ Winds Instrument Sensitivity
- Sensitivity Similar to AIRS (<200 mK @ 250K Scene) for low brightness temperature regions near 4.2 µm
- Updated APD detector noise modeling still be included in system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




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

# Primary Efforts under NASA IIP Address Instrument Concept, Technology and Measurement Challenges

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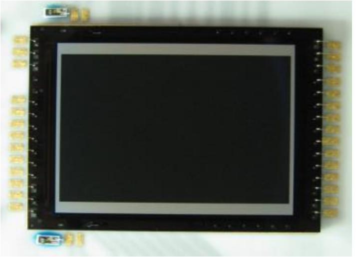
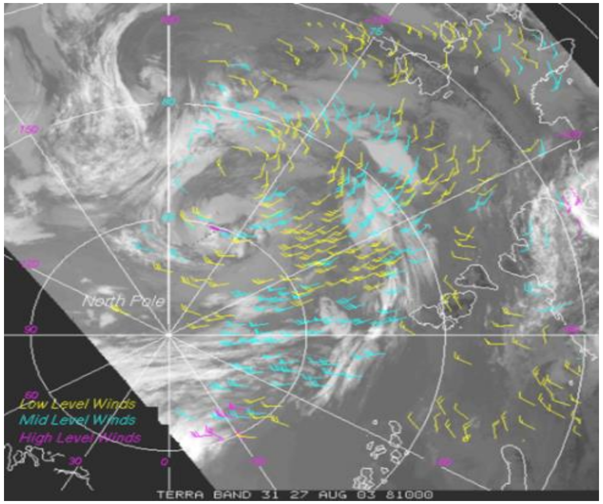
- Space Mission concept development
- <u>Technology Risk Reduction</u>
- Challenge: Get a higher operating temperature FPA in order to reduce cooler power
    - <u>Benefit</u>: Large reduction in SWAP
  - Approach: Use of new APD-Class MWIR FPA
    - <u>Risk</u>: APD Array Not Yet Tested in Space Radiation Environment
    - <u>Mitigation</u>: Radiation Testing on IIP *(by 9/15)*
- <u>Measurement Risk Reduction</u>
  - Challenge: Application to Highly Vertically Resolved (3D) MV Winds is highly plausible-but not demonstrated
    - <u>Benefit</u>: MV Winds at Low Cost -> Better weather forecasting
    - <u>Risk</u>: Tracer De-correlation Behavior at finer vertical resolution unknown in detail
    - <u>Mitigation</u>: Airborne observations of Tracer De-Correlation Times & Behavior *(by 10/16)*



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



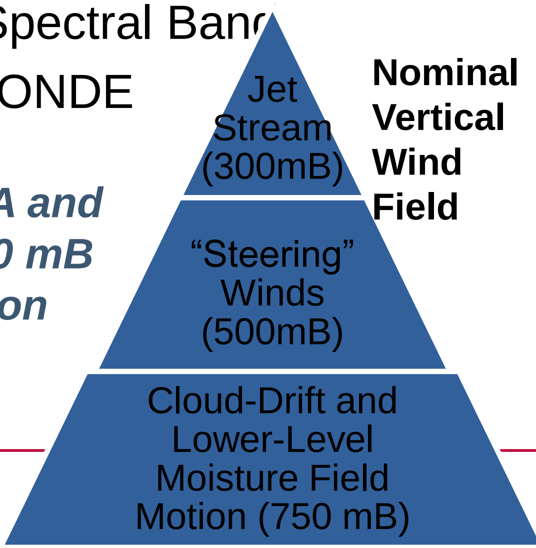

MISTIC™ Winds Tracers Features Would Have Better Vertical Resolution Than MODIS Winds

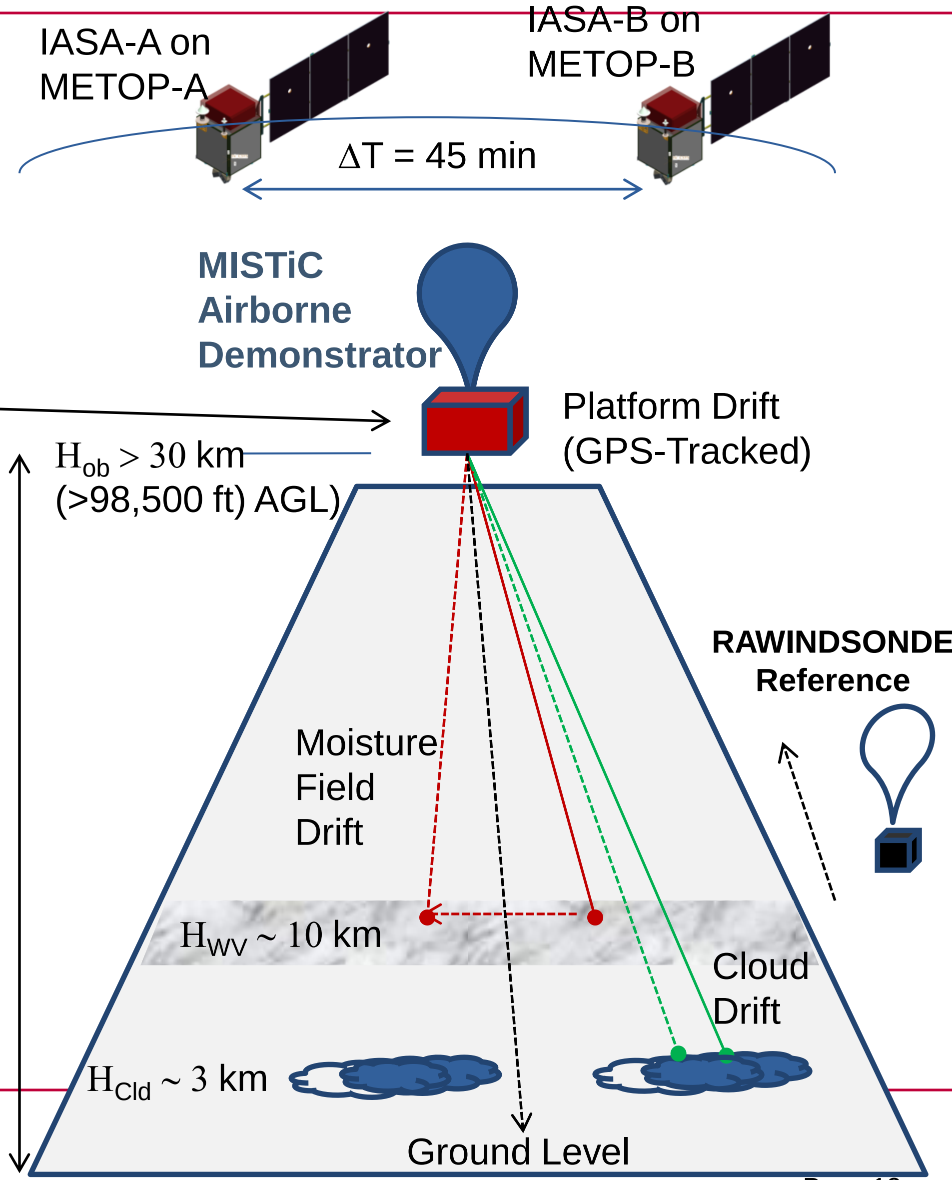
# MISTiC Winds Airborne Test CONOPS

BAE SYSTEMS

- *Test Objective*: Demonstrate Vertically-Resolved Moisture-Feature Tracking by an MWIR HSI Instrument for 500mB -Level Winds
- *Test Approach*:
  - Observe with Airborne MWIR HSI Instrument (MISTiC Airborne Moisture Tracking Demonstrator)
  - Under-fly METOP A and B to Correlate IASI Observations in MISTiC's Spectral Band
  - RAWINDSONDE Reference

***OSSEs by NASA and NOAA Show 500 mB Wind Assimilation has Greatest Weather Forecast Impact***

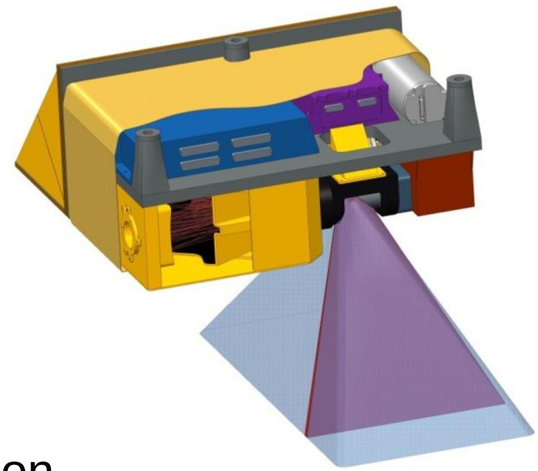


# Objective: Affordable Means To Improve Fine-Scale Weather Forecasts

- Short Term Weather Benefits Multiple Users
  - Examples include
    - Airlines and air traffic control having greater knowledge of weather 3 hours out to reduce flight delays
    - Improved Power Grid Load Forecasts
  - MISTiC™ constellation can also be configured to do pollution tracking
- Near term tasks to Operational System
  - OSSE modeling to predict forecast error improvement
  - IIP mitigates technology risks
    - Radiation testing of FPA
    - Flight demonstration of concept via aircraft or balloon
  - Full Mission Development

***MISTiC™ Miniature IR Sounder***



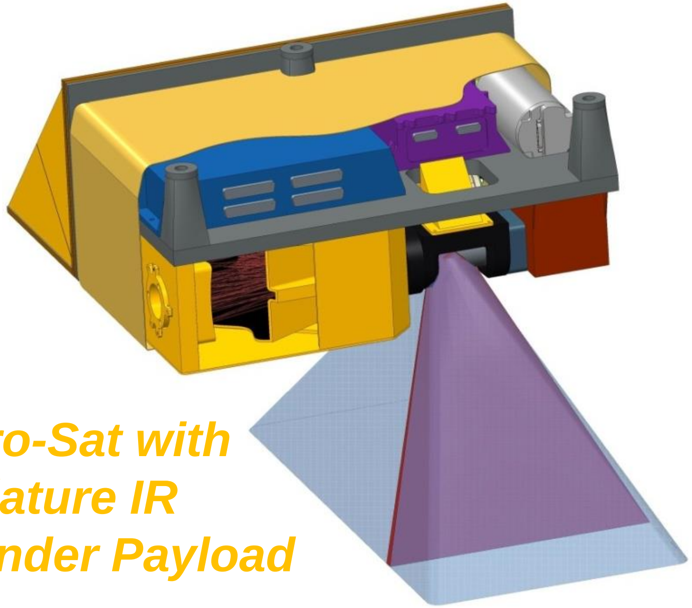
**Miniature Spectrometers Operated in LEO Constellations Offer Affordable/Lower Risk Approach for Improved Short Term/Fine Scale Weather Forecasting**

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

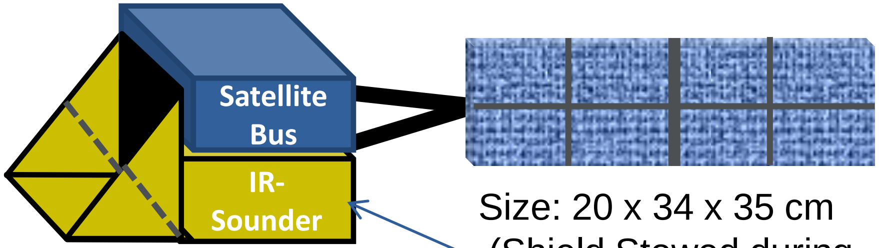
BAE SYSTEMS

- 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
- 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

***MISTiC™ Miniature IR Sounder***



***Micro-Sat with Miniature IR Sounder Payload***




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

## Supplemental Material

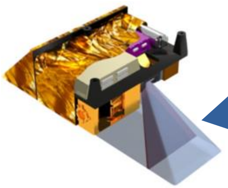
# MISTiC Winds: Midwave Infrared Sounding of Temperature and humidity in a Constellation for Winds

PI: Kevin R. Maschhoff, BAE Systems

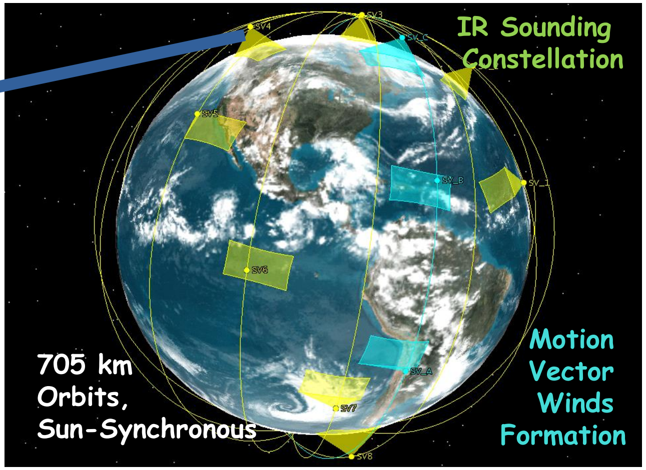
BAE SYSTEMS

Advance the readiness of a miniature, high resolution, wide field, thermal emission imaging spectrometer to measure vertically resolved tropospheric profiles of temperature and humidity for deriving global 3-D wind measurements.

- Provide ~ 2-3 km spatial resolution temperature and humidity soundings of the troposphere using an AIRS-like (Atmospheric Infra-red Sounding) method.
- Enable a LEO constellation approach that provides 3-D Wind field measurements and atmospheric state and transport observations at low system cost.
- Reduce technology risks with the Infrared Focal Plane Array (IRFPA) and spectrometer technologies critical for significant instrument size, weight and power reduction (20 x 30 x 30 cm, 15 kg, 50 W).



*MISTiC Instrument will fit on a 27U CubeSat or a ESPA-Class Micro-Sat*



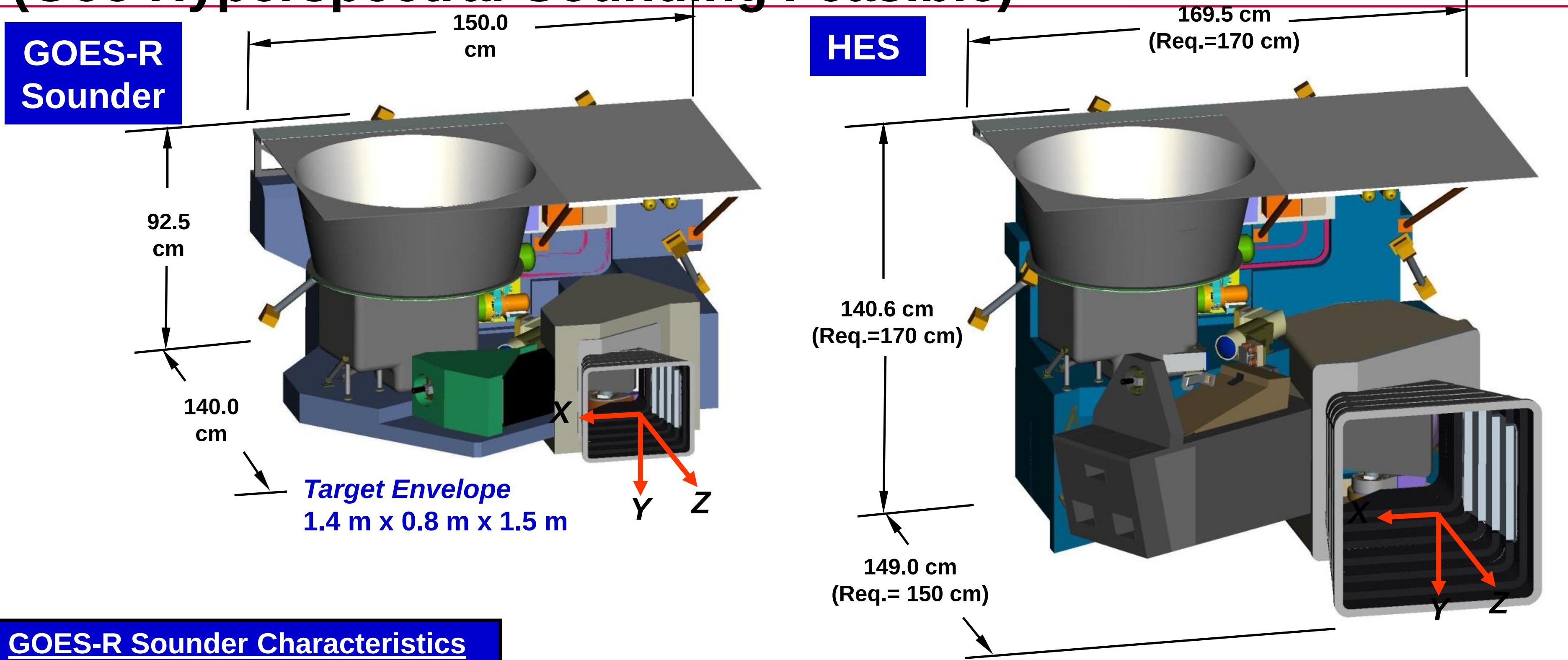

- Optimize and refine space-based measurement approach based on experience with AIRS, AIRS-Light and small satellite provider experiences.
- Demonstrate calibration stability of miniature MWIR spectrometer (4.08 - 5.8 um) in ground testing.
- Demonstrate robustness of spectrometer by performing space level thermal fluctuation testing and vibration testing to launch levels.
- Verify instrument measurement capability of 3-D cloud-drift and water vapor motion vector winds on high altitude balloon or high-altitude fixed-wing platform.
- Demonstrate IRFPA space radiation tolerance (> 25 krad).

| | |
|---|---|
| • Instrument science and payload requirements review | 10/14 |
| • Instrument science and payload concept review | 12/14 |
| • Airborne demonstration plan review | 06/15 |
| • Detector/ROIC radiation test/analysis complete | 09/15 |
| • Calibration stability test complete | 03/16 |
| • Airborne instrument design/build complete | 05/16 |
| • Airborne demonstration complete | 10/16 |
| • Airborne demonstration data analysis complete | 12/16 |

**Co-Is/Partners:** J. Susskind, NASA GSFC; H. Aumann, JPL

**$TRL_{in}$ = 4    $TRL_{current}$ = 4**

# GOES-R Sounder (HES) after Formulation Phase (Geo Hyperspectral Sounding Feasible)




**GOES-R Sounder Characteristics**
- Mass: 169 kg
- Power: 223 W
- Data Rate: 1.8 Mbps
- CONUS Sounding Coverage Rate:
  - CONUS/hr @ 10 km GSD (Can Provide 2x CONUS/Hr also)
- Disk Sounding Coverage Rate:
  - 62 Deg. Disk/hr @ 20 km GSD
- Meso-scale Demonstration @ 5 km

**Shared Characteristics**
- Spectral Coverage:
  - 4.165-5.92 $\mu$m (1689-2400 cm$^{-1}$)
  - 9.65-14.7 $\mu$m (680-1036 cm$^{-1}$)
- Spectral Resolution: $\lambda/\delta\lambda$>1000
- NE$\Delta$T: 0.2K
- Spectral Stability: <0.01 $\delta\lambda$

**HES Characteristics**
- Mass: 214 kg
- Power: 326 W
- Data Rate: 7.3 Mbps
- SW/M Coverage Rate:
  - CONUS/hr @ 5 km GSD
- Disk Sounding Coverage Rate:
  - 62 Deg. Disk/hr @ 10 km GSD

BAE SYSTEMS

# 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

# Observing Water Vapor in the Boundary Layer within the MISTiC Spectral Range

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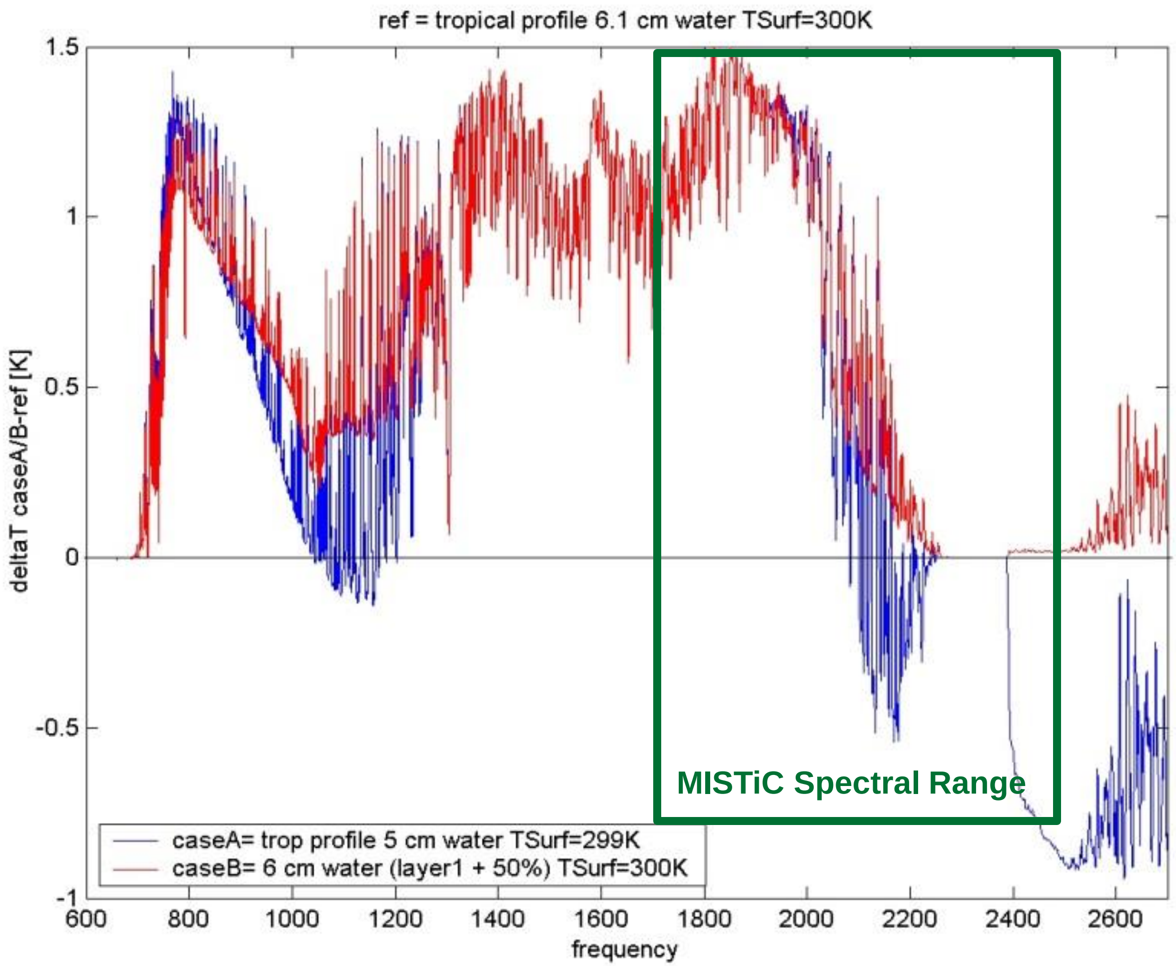
Modeled Brightness Temperature Change Due to Increase in Boundary LayerMoisture

- Red 5 cm $H_2O$
- Blue 6 cm $H_2O$

*(Provided by:*

*H. H. Aumann, JPL)*



# MISTiC™ Winds Observes the Atmospheric State (p(x), T(x), q(x)) and Wind Field- *Simultaneously*

- Mass-Field Motion-Vector Methods Measure the Total Wind Field (geostrophic and ageostrophic components)

$$\vec{V} = \vec{V_g} + \vec{V_a}$$

- IR Sounders Measure Atmospheric State Variables that Enable Computation of the Steady State Wind Components
  - Geostrophic Wind → Steady Horizontal Flow
  - Gradient Wind→ Steady Curved Flow

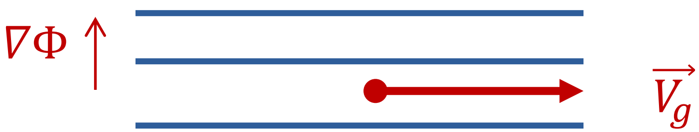
Acceleration-Related to Ageostrophic Wind

$$\frac{D\vec{V}}{Dt} = -f \times \vec{V_a}$$

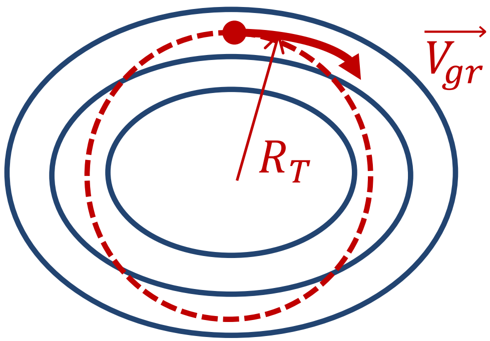
Ageostrophic Wind→Indicative of Weather Pattern Change

$$\vec{V_g} \cong \frac{1}{f}\vec{k} \times \nabla\Phi = \frac{R}{f} ln\left(\frac{p_0}{p_1}\right)\vec{k} \times \nabla_p T(\vec{x})$$

$$V_{gr} = \frac{2V_g}{1+\left(1+4\frac{V_g}{fR_T}\right)^{1/2}}$$



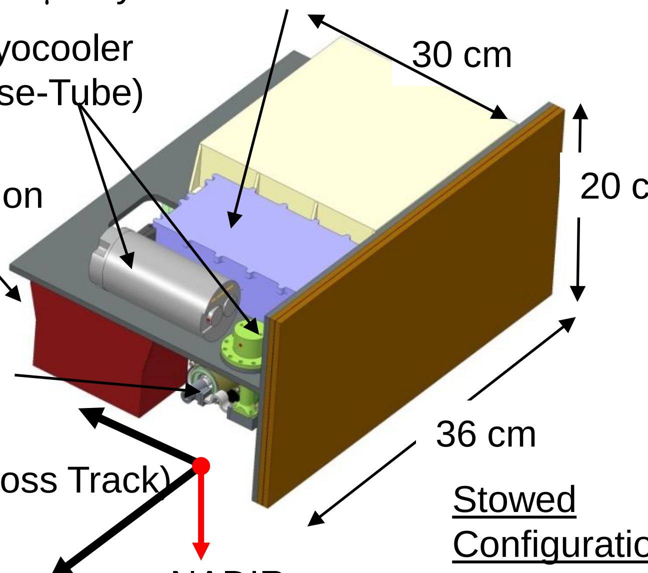

Geostrophic Wind

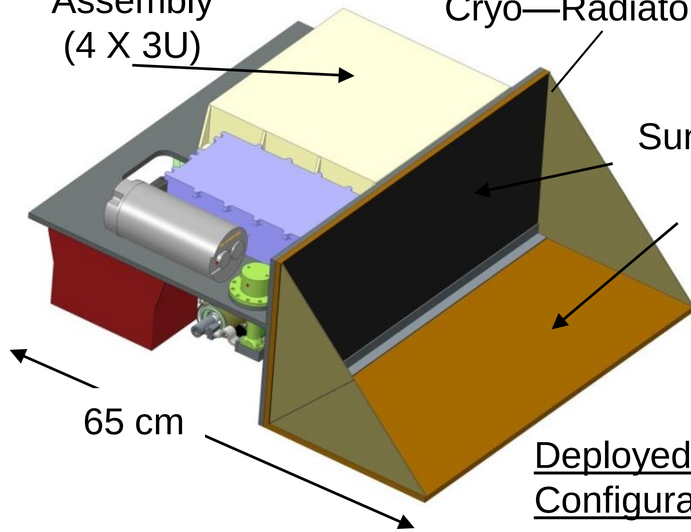


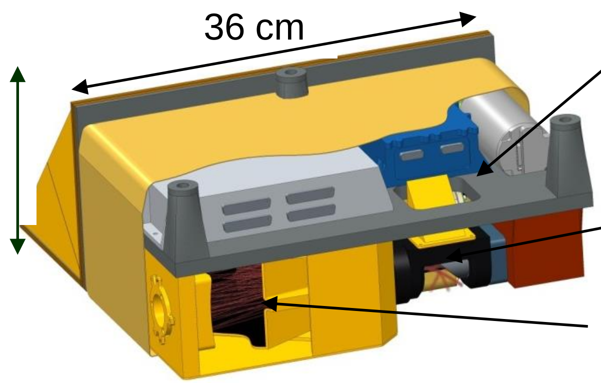

Gradient Wind

Φ=Geopotential
p's are pressure
V's are wind velocity
f=Coriolis Factor

# MISTiC™ Integrates Miniaturized Versions of Standard IR Sounder Functional Elements into a Flight Proven Architecture




Includes all Elements Needed to Produce Well-Calibrated Infrared Radiances

**Example Instrument Configuration Shown**
**-Instrument Configuration Study In-Progress**

# MISTiC™ Winds is Well-Positioned to Leverage Key Trends in Microsatellites --in the Age of "Agile" Space

BAE SYSTEMS

| Industry Trend | Public Examples | Benefit to MISTiC™ Winds |
|---|---|---|
| ***Launch Becomes an Affordable Service*** | ● SpaceX Lands its Falcon-9 Booster—Reusable S/C<br>● F15-Launched Booster<br>● Rail-Gun Launched Rocket Booster (Super STRYPI) | ● Multiple Routes to LEO Space for ~ \$1M-\$3M per 50 kg Spacecraft<br>● Launch Opportunities |
| ***MicroSats Becomes a High-Tech Semi-Custom Commodities*** | ● 3-d Printed 27U Spacecraft Demo. (Millennium Space)<br>● Multiple MicroSat Vendors Offer 50 kg bus | ● 27-U CubeSat (\$1M-\$3M)<br>● Competitive Pressure to Maintain Low Costs and Availability-for MISTiC™ Host |
| ***S/C Component Evolution -Follow Moore's Law-Like Improvement Path*** | ● Active Market Place for Standard S/C subsystems (Reaction Wheels, Solar Panels, Batteries, Coms, etc) | ● Majority of S/C Resources Available for Payload<br>● Low-cost Arc-Sec class ACS |
| ***Communications and Ground Stations Become Affordable Standard Services*** | Standard Ground Stations with X-Band (Space Flt Networks)<br>● \$50k/mo (dedicated) or<br>● \$20/minute (shared) | ● Affordable Polar and Selected Mid-Latitude x-Band Coms and Ground Stations for MISTiC™ |

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

| KPP | KPP Attribute | Requirement |
|---|---|---|
| 3D Motion Vector Winds<br><br>(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)<br><500 mB (CMMV) |
| | Tracer Potential Density (Cloud-Free Conditions for MMV, Cloud Contrast for CMV) | >1 per 6 km sq<br>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