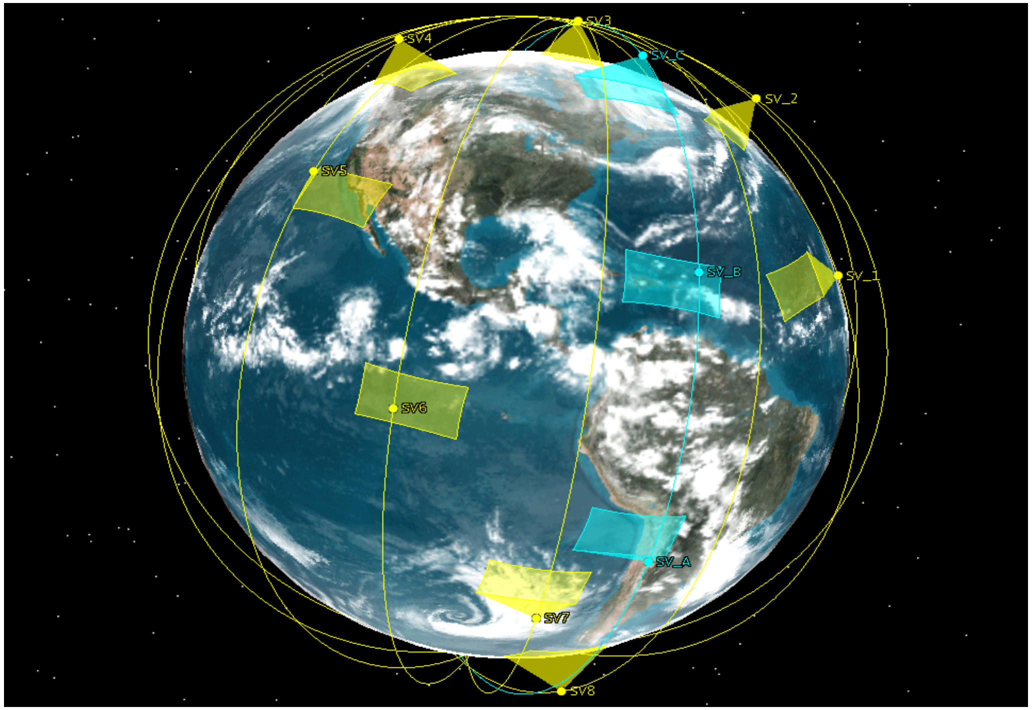
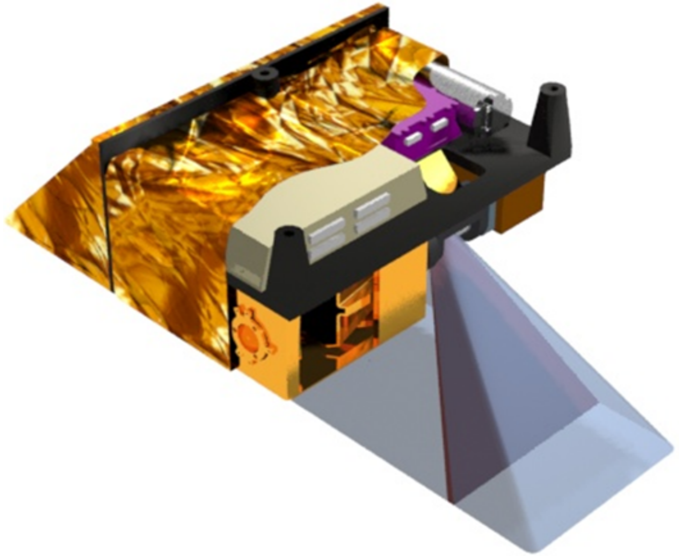
MISTiC™ Winds

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





NASA ESTO 2013 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
- Enabled by:
  - LEO Constellation Approach
  - Micro-Sat-Compatible Instrument
  - Low-Cost Micro-Sat Launch

BAE SYSTEMS

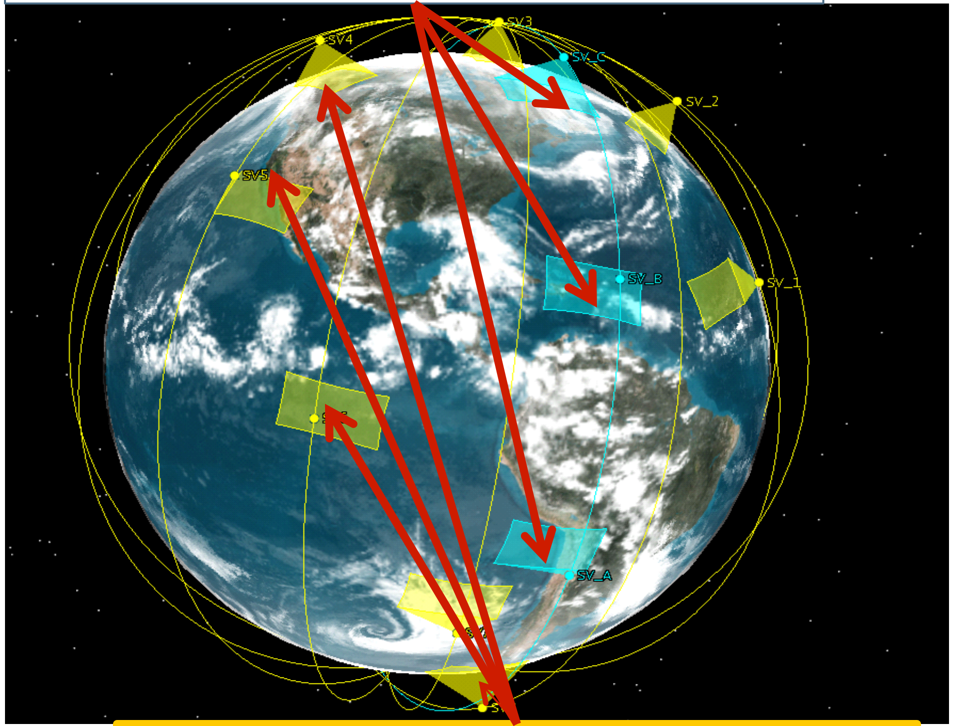
MISTiC™ Winds-An Affordable System of Systems Approach for the Observation of Atmospheric Dynamics

POC:kevin.maschhoff@baesystems.com

- 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
       - 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

A Motion-Vector Winds Formation



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

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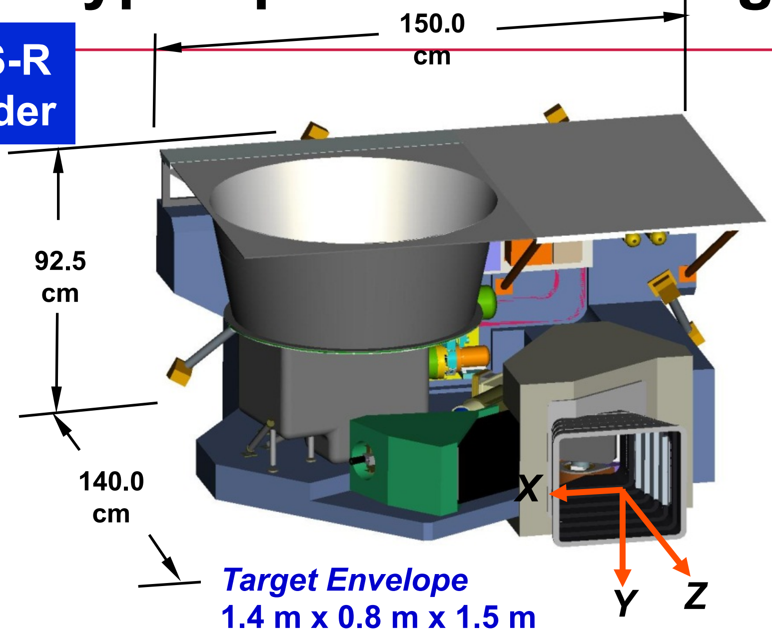
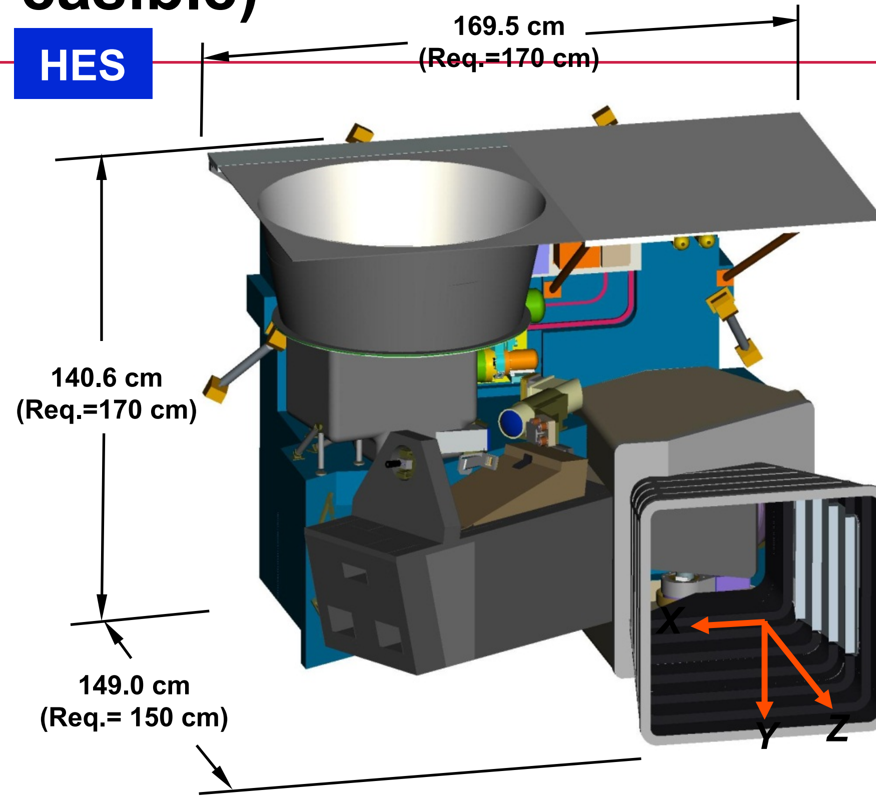
GOES-R Sounder (HES) after Formulation Phase (Geo Hyperspectral Sounding Feasible)

GOES-R Sounder



HES

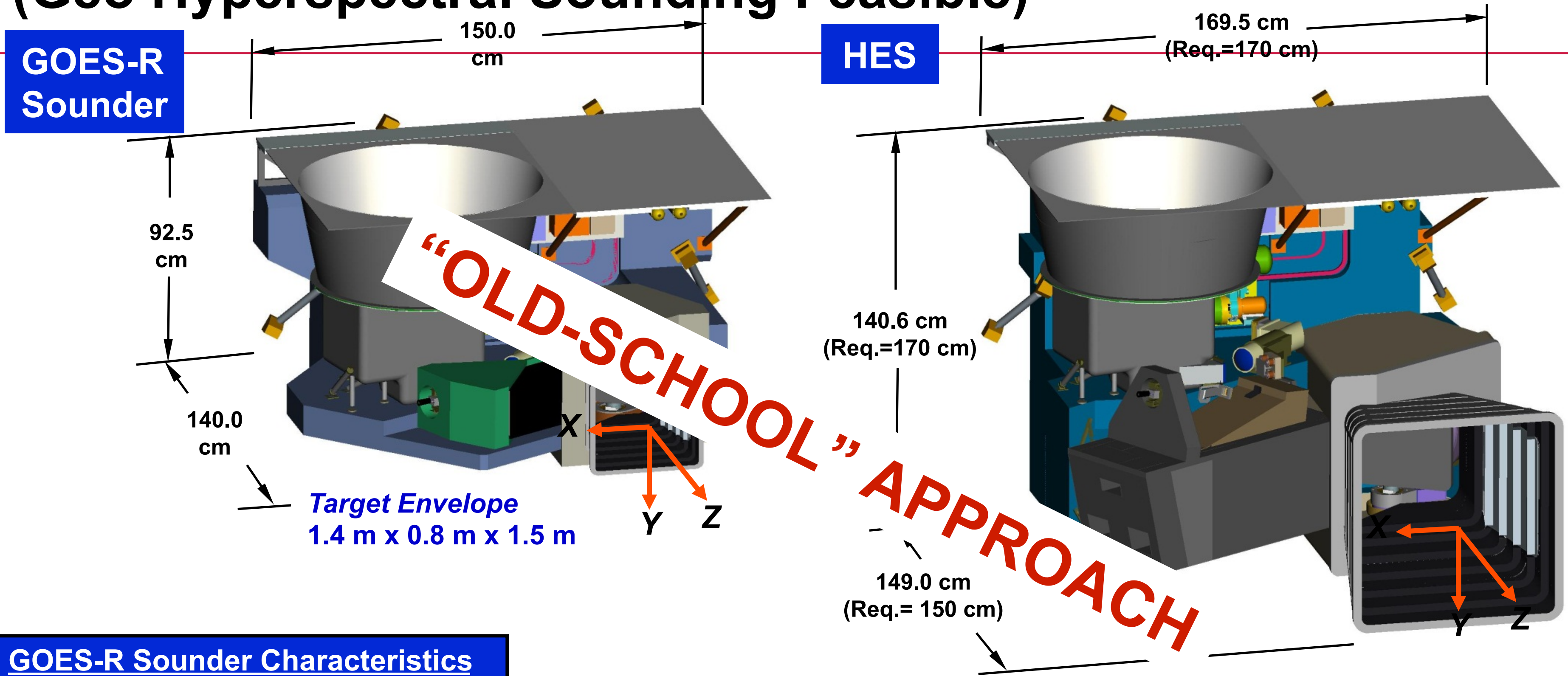


GOES-R Sounder Characteristics
- Mass: 169 kg
- Power: 223 W
- Data Rate: 1.8 Mbps
- CONUS Sounding Coverage Rate:
  - CONUS/hr @ 10 km GSD (Can Provide 2x CONUS/Hr also)
- Disk Sounding Coverage Rate:
  - 62 Deg. Disk/hr @ 20 km GSD
- Meso-scale Demonstration @ 5 km

Shared Characteristics
- Spectral Coverage:
  - 4.165-5.92 mm (1689-2400 cm^{-1})
  - 9.65-14.7 mm (680-1036 cm^{-1})
- Spectral Resolution: l/dl>1000
- NEDT: 0.2K
- Spectral Stability: <0.01 dl

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

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



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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

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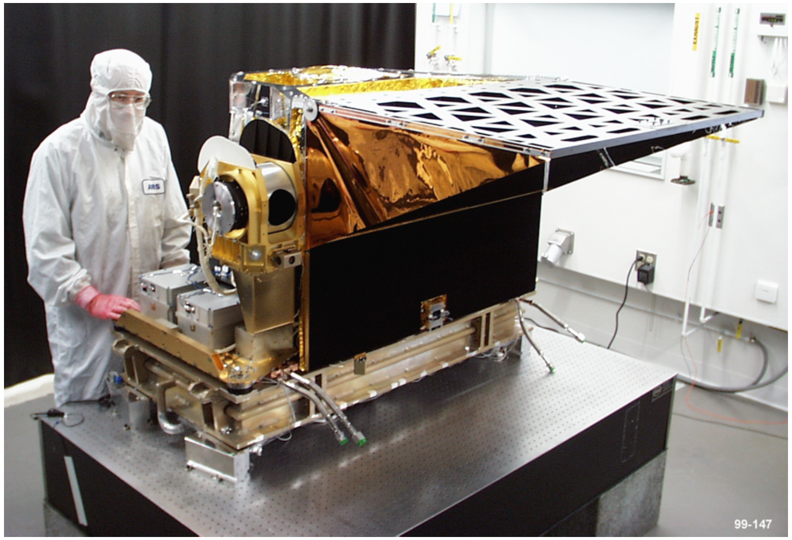
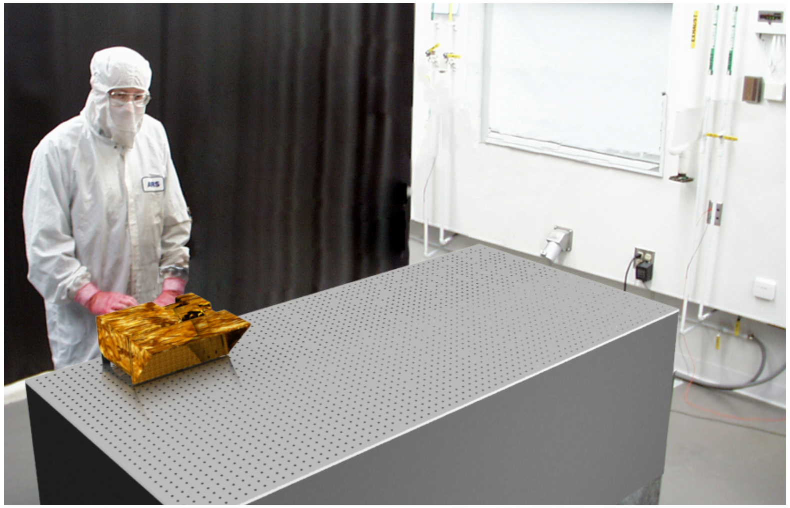
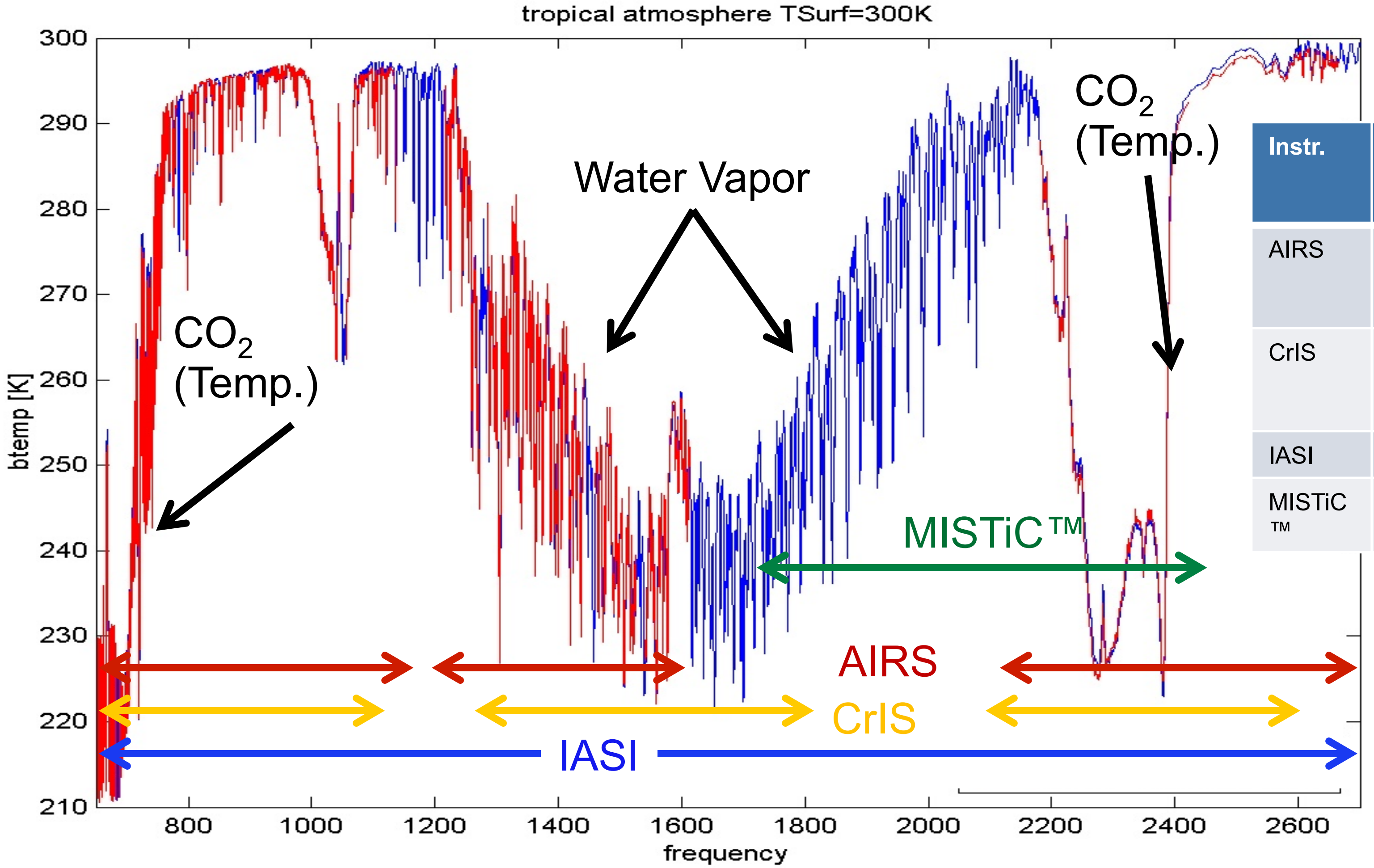
MISTiC™ Instrument Would be Much Smaller than AIRS

- Artist's Rendering Depicts a MISTiC™ Instrument, for Comparison to AIRS
- Instrument Concept Design in-Progress
  - Baseline envelope consistent with hosting on a 50 kg ESPA-Class Microsatellite
  - "Objective" Envelope consistent with 27U Cubesat Envelope
- Small instrument size depicted continues to appear feasible





Spectral Coverage for MISTiC™, AIRS, CrIS, and IASI



Instr.	Spectral Coverage (cm^{-1})
AIRS	650-1150, 1200-1600, 2180-2650
CrIS	650-1100, 1200-1750, 2150-2550
IASI	650-2750
MISTiC ™	1750-2450

Critical Spectral Channels to Monitor Troposphere Selected for MISTiC™

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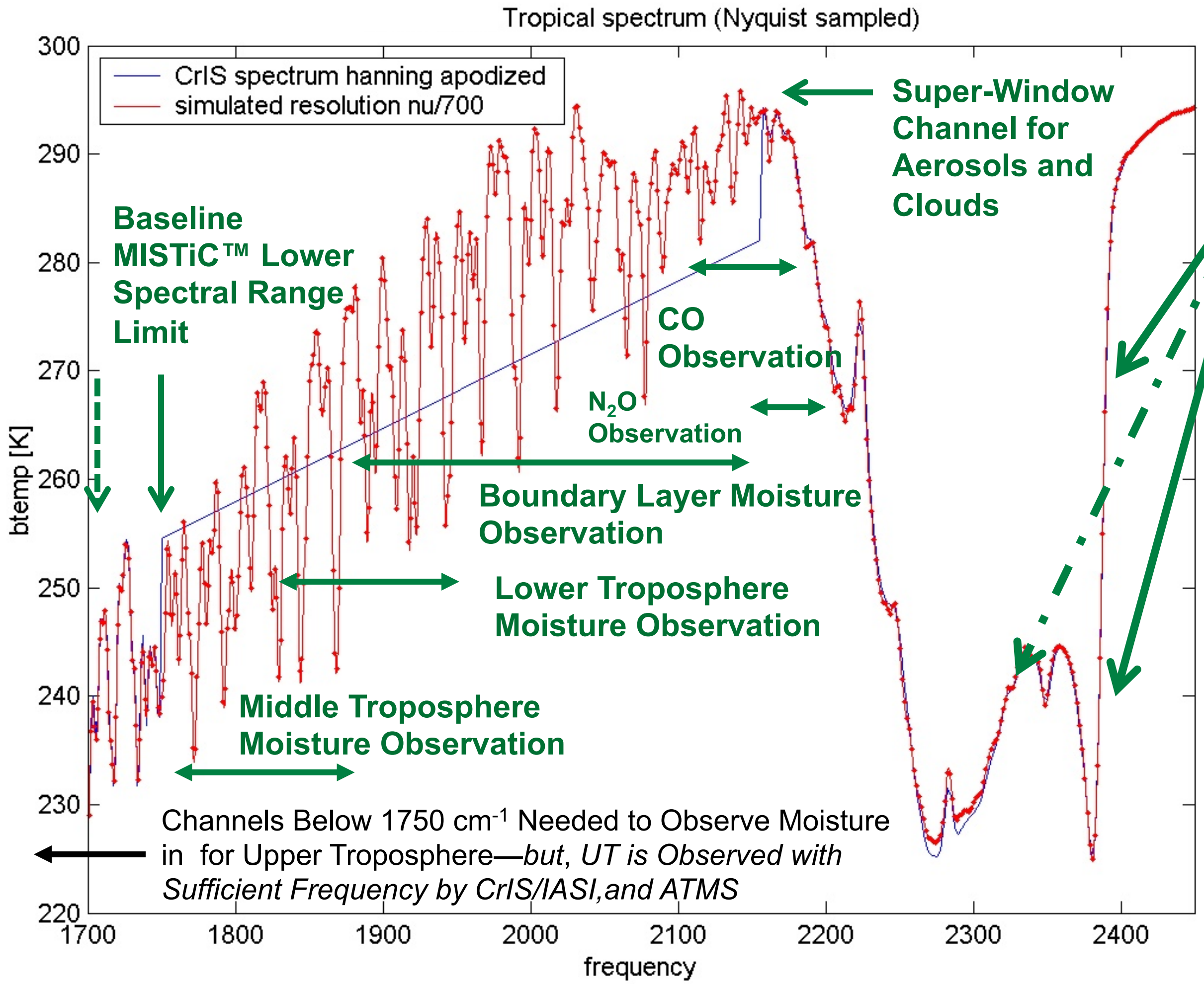
For MISTiC™, we Select ~ 600 Spectral Channels in the Mid IR-*Sufficient to Sound the Dynamic Portion of the Atmosphere*



- SWIR Coverage at NEDT and Dn Sufficient for CO_2 R-Branch Temperature Sounding of Surface to Upper Troposphere
  - Sharper vertical resolution using 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

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

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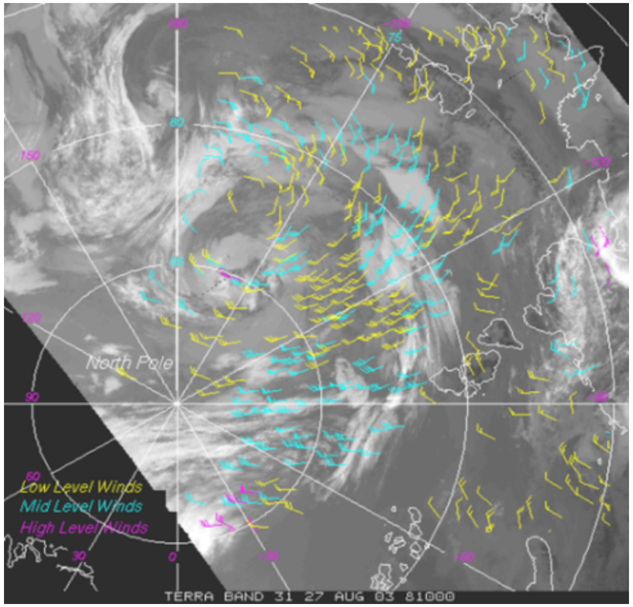
MISTiC™ Key Instrument Performance Characteristics		
Characteristic	Value	Comments
Minimum Spectral Frequency	1750 cm^{-1}	5.72 mm
Maximum Spectral Frequency	2450 cm^{-1}	4.082 mm
Spectral Sampling	~ 2:1	<590 spectral samples
Spectral Resolution @ minimum	>700 :1	n/dn ((comparable to CrIS-Apodized)
Spectral Calibration Knowledge	1/100,000	dl/l
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
- Spatial Resolution Notably Finer than AIRS Resolution (13 km @Nadir for AIRS)
  - 3.0km @ Nadir
- Reduced Spectral Range Enables Major SWAP Reduction

MISTiC Winds Observes the 3D Vector Wind Profile

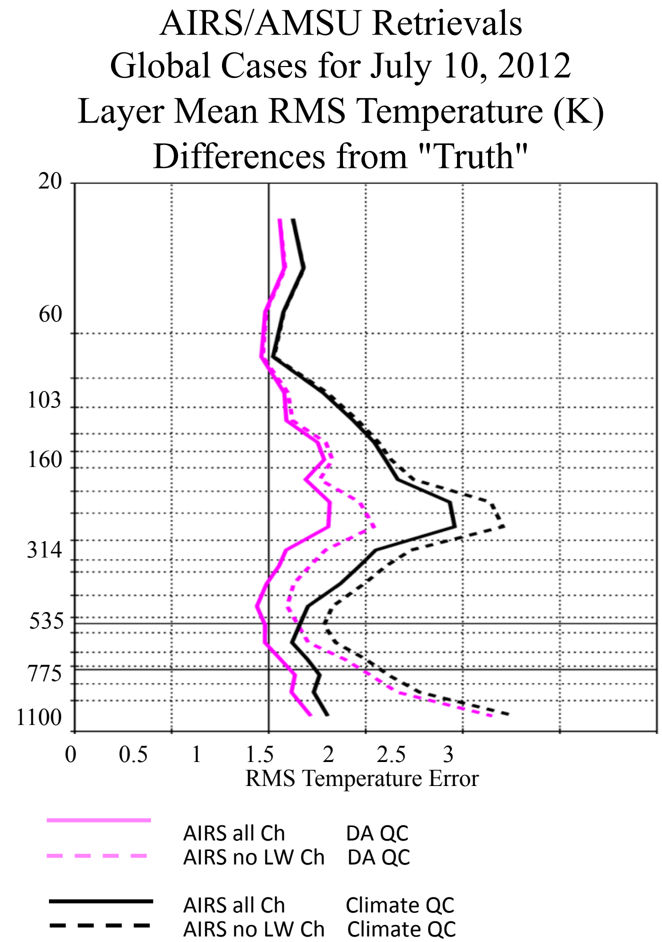
- MISTiC Winds Observes 3D Atmosphere at 3 closely spaced times to Produce Multi-Altitude Motion-Vector Winds
  - Projected Wind Speed Error ~ 2 m/s rms
    - ~3x better than projected for GOES-R
  - SWIR/MWIR Imaging/Sounding Provides Much Better Tracer Height Assignment than GOES
    - 1K/1 km Temperature 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

Vertical Temperature Profile Retrieval with SWIR/MWIR Sounder Comparable to AIRS & CrIS in Lower Troposphere

- Vertical Temperature Profile Retrieval Accuracy for Two Different Quality Control Thresholds are Shown
  - Using All AIRS Channels—red curves
  - Using SWIR/MWIR-Only –black curves
- Modest Additional Error Experienced when 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
- Additional Benefit from MISTiC™ Express- <u>*fine spatial resolution*</u> (~ 3 km @ nadir)
  - 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)

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Comparative System of Systems Estimates for Instruments for Tropospheric Wind Profile Measurement

Instrument	Power	Size (cm)	Mass (kg)	# of Levels*	** State Measured	Orbit and # Platforms
MISTiC™	<60 W***	20x34x35***	15	~10	YES	LEO (12)
HES	550 W	170x170x 150	315	~10	YES	GEO (6)
Hybrid Wind LIDAR (est)	750 W	150x150x 100	400	10-15	NO	LEO (4)

* Number of wind levels in the troposphere

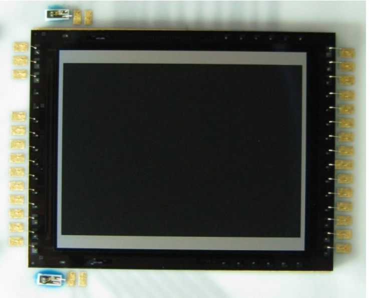
** Atmospheric State Measurement (Vertical & Spatial Temperature and Moisture Fields etc)

***Updated (based on small satellite provider discussions

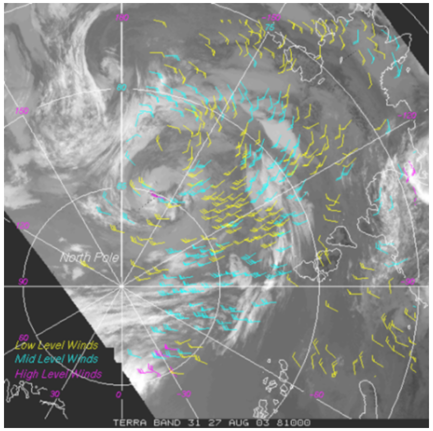
Miniature Spectrometers Operated in Constellations Offer Lower Cost /Lower Risk Approach than GEO for Frequent-Refresh IR Soundings & Winds

Risk Areas and Risk Reduction Under NASA IIP

- Use of new APD-Class MWIR FPA Allows its Operation at Much Higher Temperature → Low Cooler Power
  - Benefit: Reduced SWAP
  - Risk: APD Array Not Yet Tested in Space Radiation Environment
  - Mitigation: Radiation Testing
- Application to Highly Vertically Resolved (3D) MV Winds is highly Plausible-but Not Demonstrated
  - Benefit: MV Winds at Low Cost
  - Risk: Unknown (detailed) Tracer De-correlation Behavior
  - 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 100K



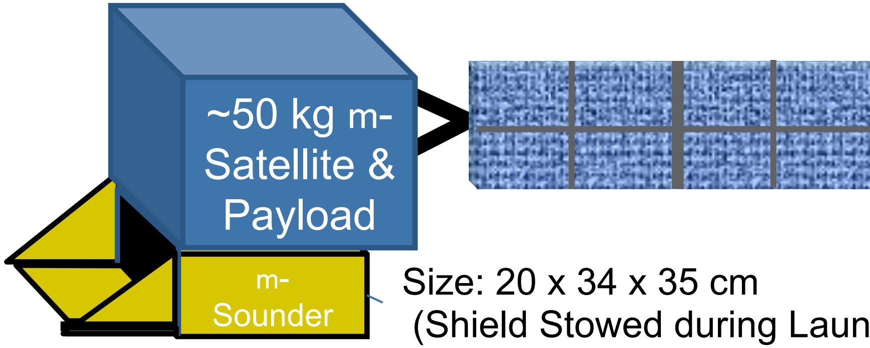
MISTiC™ Winds Tracers Features Would Have Better Vertical Resolution Than MODIS Winds (shown)

BAE SYSTEMS

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
- 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



Supplemental Material

- MISTiC™ Mission Concepts
- Application of MISTiC™ Approach to the JPSS Gap Mitigation Mission
- Data Down-Link Options
- Constellation Launch Options
- Distributed Architecture Benefits for an Observing System

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

Industry Trend	Public Examples	Benefit to MISTiC™ Winds
Launch Becomes an Affordable Service	● SpaceX Lands its Falcon-9 Booster—Reusable S/C ● F15-Launched Booster ● Rail-Gun Launched Rocket Booster (Super STRYPI)	● Multiple Routes to LEO Space for ~ $1M-$3M per 50 kg Spacecraft ● Launch Opportunities
MicroSats Becomes a High-Tech Semi-Custom Commodities	● 3-d Printed 27U Spacecraft Demo. (Millennium Space) ● Multiple MicroSat Vendors Offer 50 kg bus	● 27-U CubeSat ($1M-$3M) ● 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 ● Low-cost Arc-Sec class ACS
Communications and Ground Stations Become Affordable Standard Services	Standard Ground Stations with X-Band (Space Flt Networks) ● $50k/mo (dedicated) or ● $20/minute (shared)	● Affordable Polar and Selected Mid-Latitude x-Band Coms and Ground Stations for MISTiC™

Miniaturization of IR and m−Wave Sounders Allows Migration Toward a Distributed LEO Architecture

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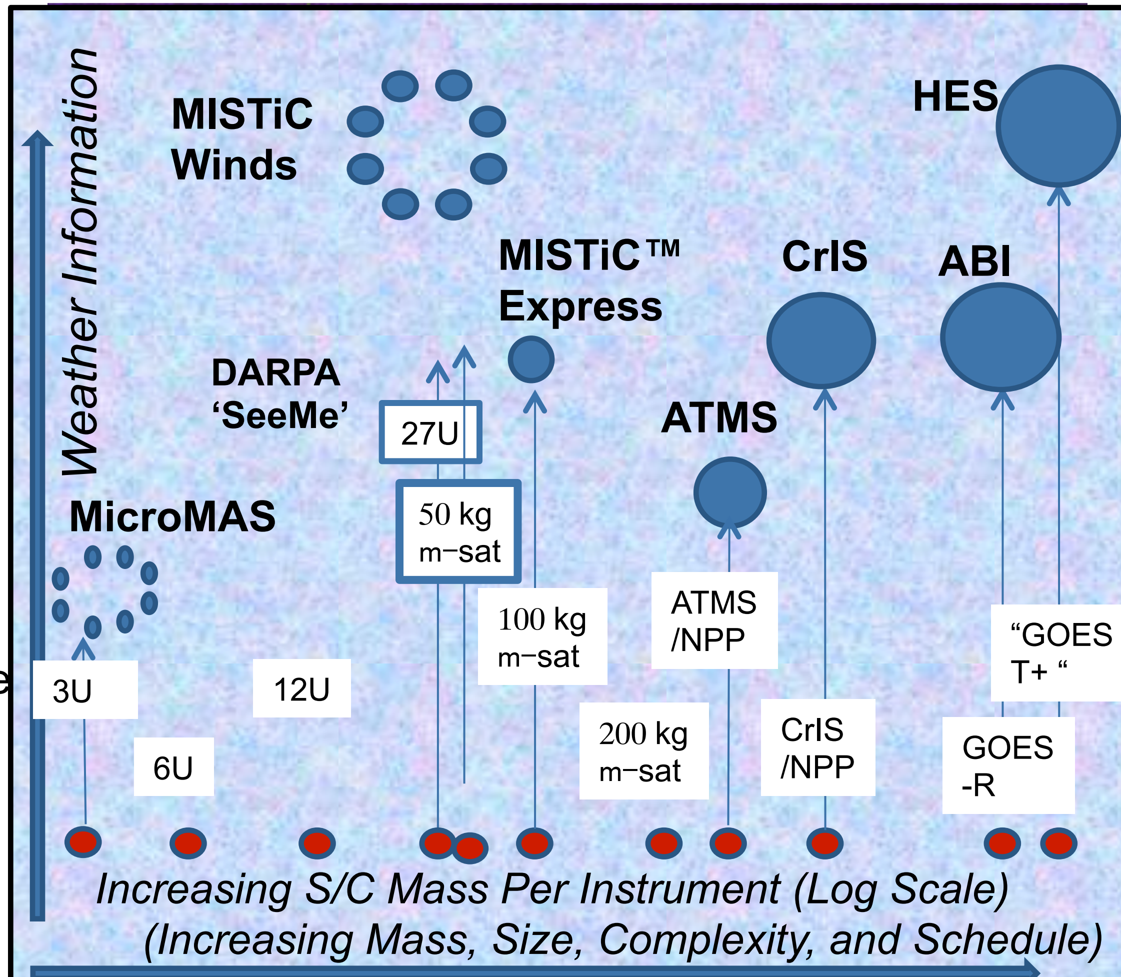
- **NASA and DoD are Moving to Distributed Architectures for Weather Observations**
  - COSMIC 1 & 2
  - MicroMAS/MiRaTA
  - CYGNSS
  - (Defense Weather Follow-on)
- **Distributed Architectures Offer NOAA Key Advantages**
  - Resiliancy Through Multiple Low-Cost Independent Systems
  - Multiple Low-Cost Paths to Space (m-Sats, Hosted Payloads, Small Aircraft-Assisted Launchers etc)
  - Faster Infusion of Technology Advances (3-5 yrs vs 25 yrs)
  - Coordinated Sensor-Web Obs.



Migration of Weather-Observation Systems to Micro-Weather Satellites in a Distributed Architecture in LEO Improves System Resiliency, Performance, and Reduces Cost

MISTiC™ Science Data Down-Link Requirements-- and Implementation Options

Key Derived Requirements :

Key Attribute	Requirement	Comments
Reference Orbit Type	Polar Sun/Sync	Altitude 704-833 km
Instrument Data Rate	<5 Mbits/sec	After lossless data compression (on-board)
Maximum Data Latency	30 min.	Frequent-Sounding Const.
	60 min.	3D-Winds Constellation Type

Approach Options:

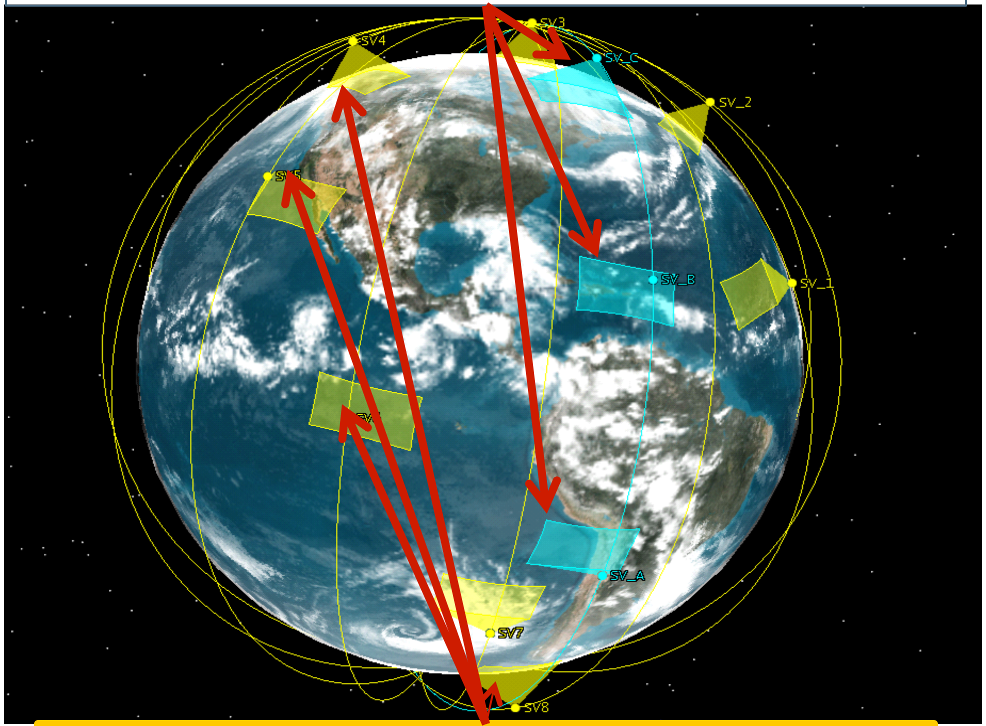
Approach Option	Capability	Comments
X-Band Link at Poles	< 60 min. Latency	>80 Mbits/Sec Links
Mid-Latitude Ground Stations (Commercial)	~30 min. Latency	Land-based Gnd Stations (Commercial Service Coming).
Up-Link to TDRSS	<30 min	>300 Mbits/Sec in Ku and Ka
(Future) Laser-Comm.	<10 min	LEO Sat-Sat Link+ Gnd Link

Options for Deploying a MISTiC™ Winds Constellation

- Key Challenge—Insertion of MISTiC™ S/C into Multiple Orbital Planes (“*the Large Dv Problem*”)
  - The entire constellation might be launched at once-but in one plane
    - Small Dv allows spread in-plane
- Multi-Plane Distribution Examples:
  - Exploit Orbital Precession
    - ~6 months for 22.5 deg. change
  - Multiple (2-4) ride-share launches
  - Dedicated Small Launch Vehicles
    - e.g. DARPA ALASA,

Multiple Options for Deploying Elements, or the Entire Constellation Exist, with More Options Emerging in Next Few Years

A Motion-Vector Winds Formation:
Groups of 2-3 satellites view scene 2-3 times



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

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Options for Operational MISTiC™ Winds Operational Concept-- Presented to NASA in IIP

Mission Objective	Data Product Objective	Constellation Approach	Number of m-Sats
Tropospheric Winds Observation (Prototype Operational Vertically Resolved Winds and Atmospheric State Observation	Fine Vertical Resolution 3-d Winds Products (Cloud and Moisture Motion Vector Winds) with Sounding Products	Observations by each of 2-3 instruments spaced by ~ 5 min. (same orbital plane	9-12
Rapid Refresh Temperature/Humidity Profile Observation (Prototype Operational Weather Observation)	Separately Acquired Infrared Spectral Radiances, for Assimilation into Regional Weather Models	Independent observations by platforms in sun-synchronous orbits with nodal crossing times spaced by 90 minutes	8
Secondary Transport Observation (e.g. supporting a GACM or PACE Primary NASA Mission)	Multi-level wind vector data co-incidentally collected with primary mission/trace chemical total column observations	Observations by each of 3 instruments spaced by ~ 5 min (same orbital plane as primary payload)	3

Comparative Estimates for Instruments for LEO Infrared Temperature and Humidity Sounding Measurements *(JPSS Gap Mitigation-Another Application of MISTiC™)*

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Instrument	Power	Size (cm) (Earth-Shield Stowed)	Mass (kg)
MISTiC™	60 W	20x34x35*	15
CrIS	124 W	71x88x94	165
MISTiC™ with Space-Qualified FPA Technology	75 W	17x34x50*	30

* Engineering Estimates for Size—Detailed Instrument Lay-out being Developed During 1st Phase of NASA IIP

- MISTiC™ Instruments (and Small S/C) are Single-String to keep SWAP-C Low

but….

- Two MISTiC™'s Could Be Launched at Once into 1:30 PM Orbital Plane- for Redundancy

A Distributed – Architecture Approach to System Resiliency

A Miniature Sounding Spectrometer Incorporating Current Technology Would Operate with Lower FPA Temperature (more cooler power) but with an FPA at TRL-6 would Support a Schedule that Provides JPSS-1 Launch-Failure Risk

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

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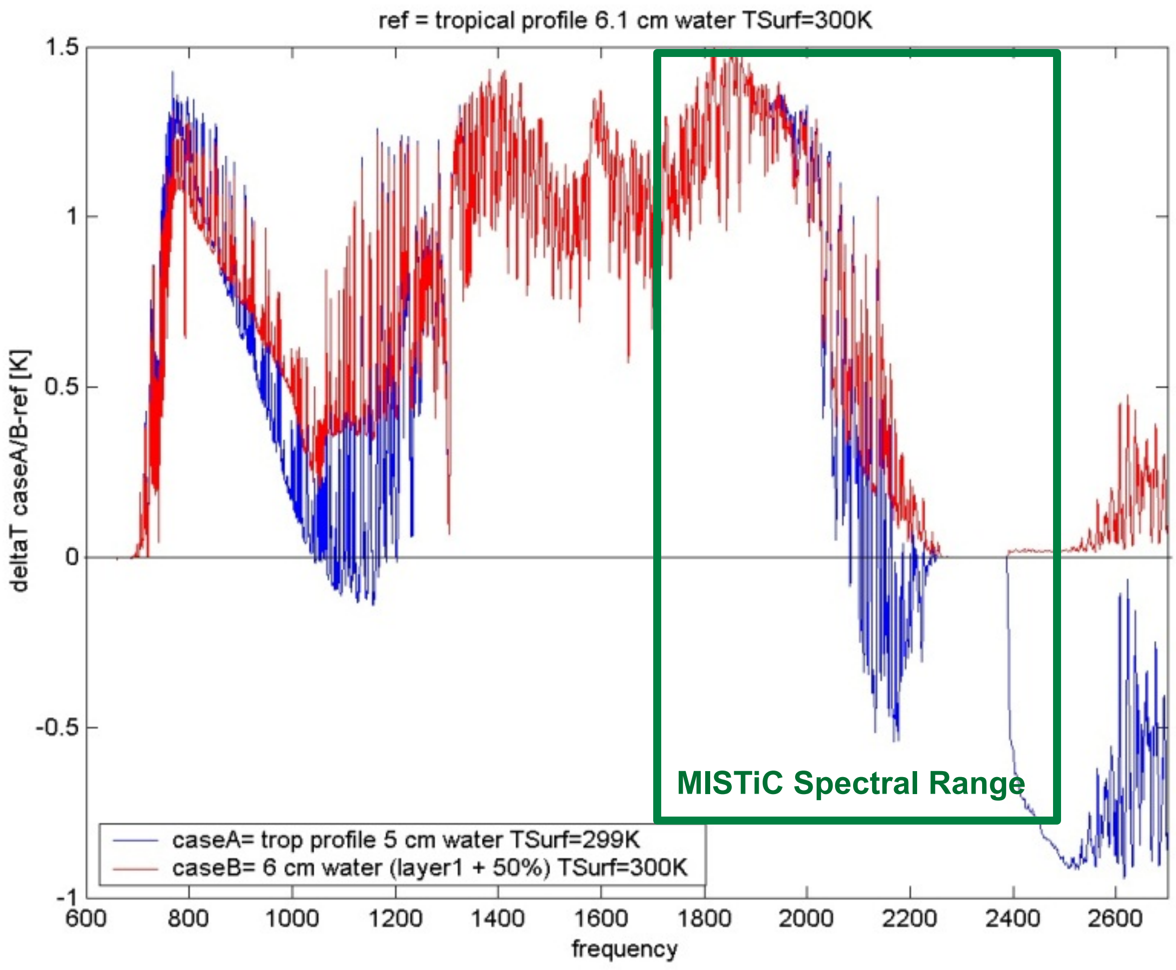
- Model Brightness Temperature Change Due to Increase in BL Moisture
  - Red 5 cm
  - Blue 6 cm



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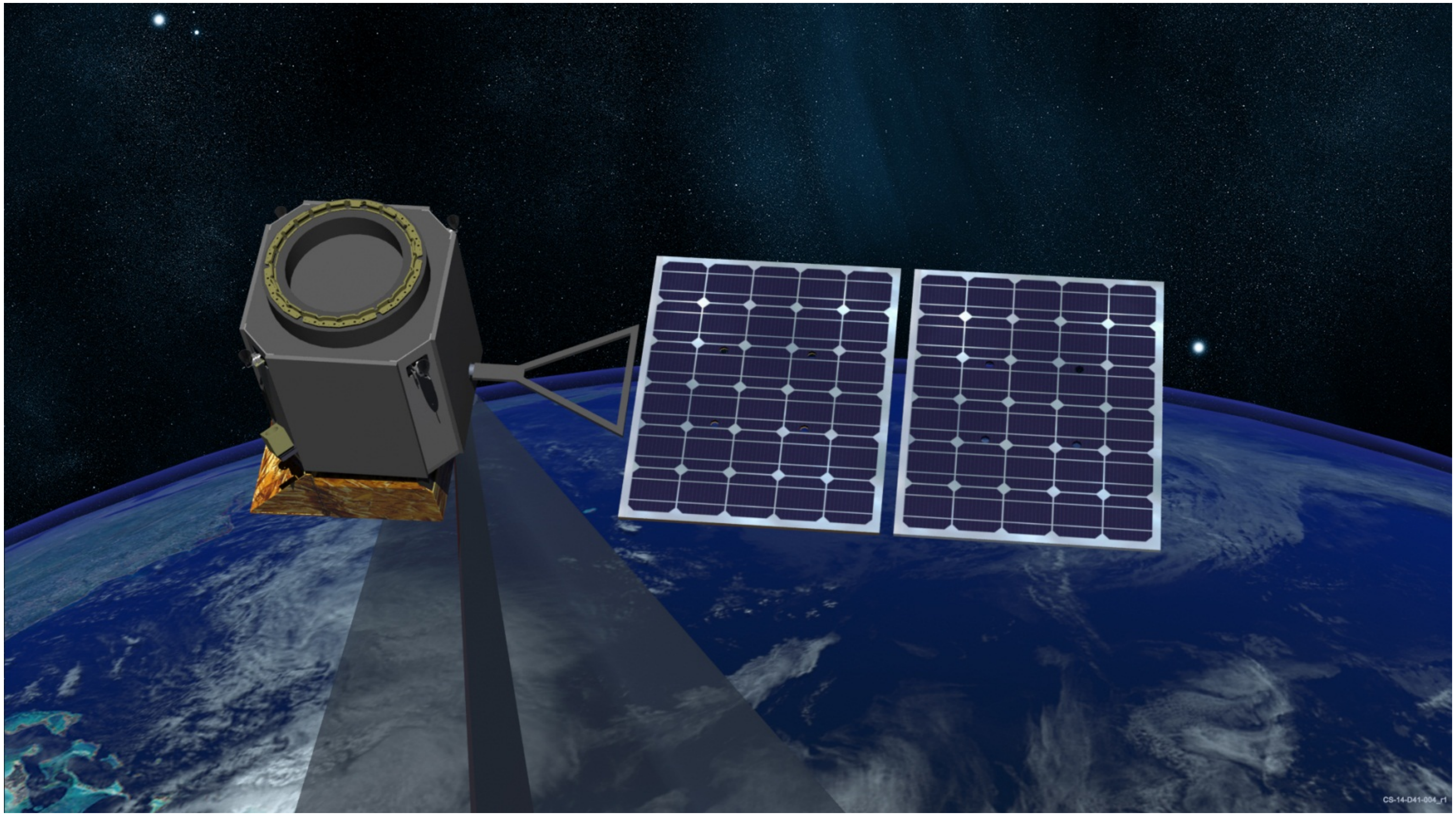
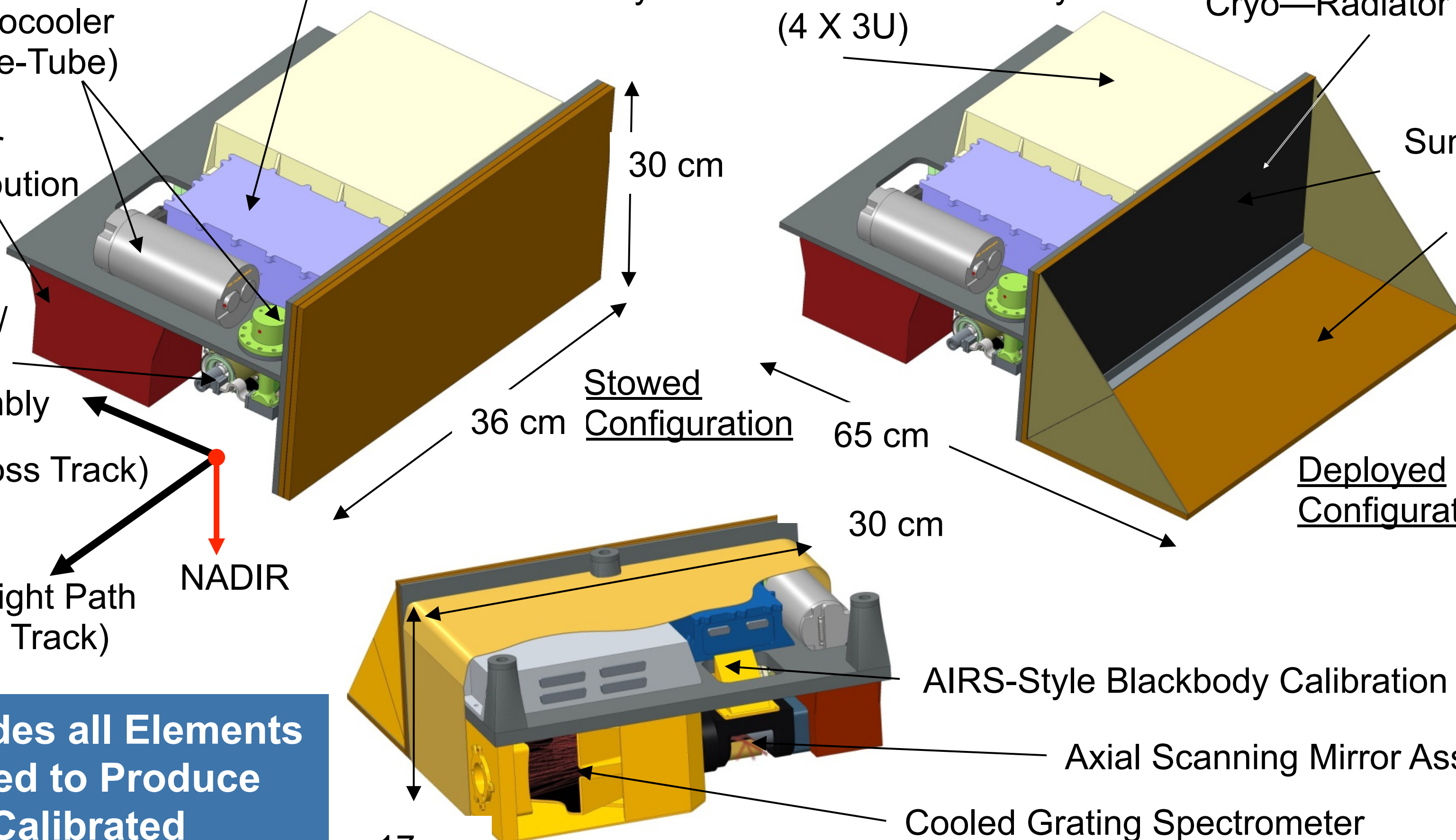
MISTiC Instrument Hosted by an ESPA-Class Micro-Satellite--Example



MISTiC Instrument Concept
Shown Hosted by ATK 150 Series
Micro-satellite

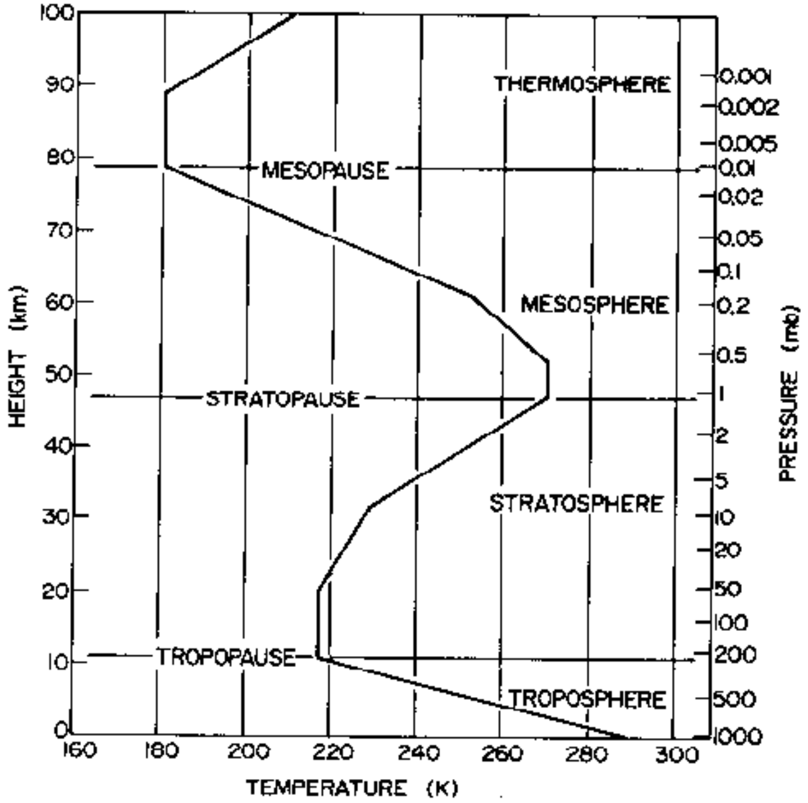
MISTiC™ Integrates Miniature Versions of Standard IR Sounder Functional Elements into a Proven Architecture



Includes all Elements Needed to Produce Well-Calibrated Infrared Radiances

Example Instrument Configuration Shown
-Instrument Configuration Study In-Progress

US Standard Atmosphere



- US Standard Atmosphere
- Temperature Profile