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Miniature IR Sounder Constellation for Thermodynamic and Wind Vertical Profiles

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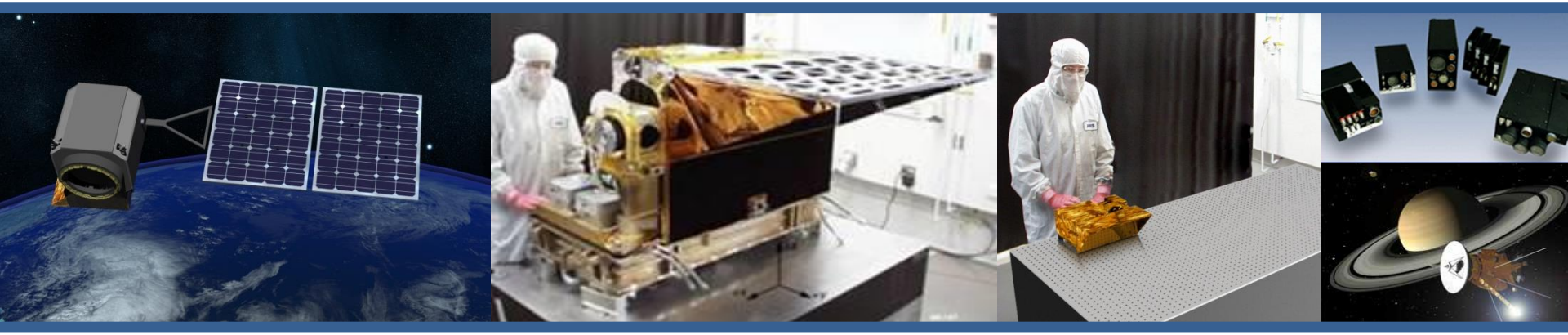

Cost and Concept Study Builds on BAE's MISTiC Winds Distributed Micro-Satellite Approach

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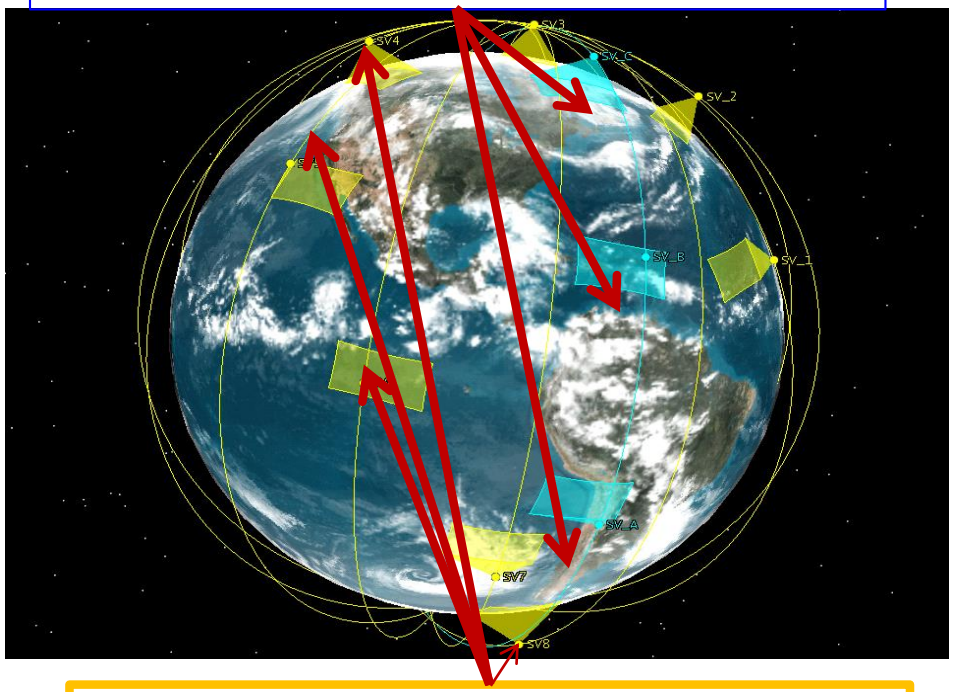
– MISTiC® Winds Temperature and Humidity Sounding Constellation Options.

1. **Frequent-Sounding Constellation**
   – **e.g. 90 min refresh-globally (8)**
   – **e.g. 30 min refresh-globally (24)**
2. Wind-Vector Formations
   – e.g. 4 3-Satellite Formations for Cloud-Drift and Water Vapor Motion-Vector Winds

– **Both Provide More Frequent 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) (example)

A 24-Node SSO Constellations Provides 30-Minute Global Refresh of IR Sounding Observations

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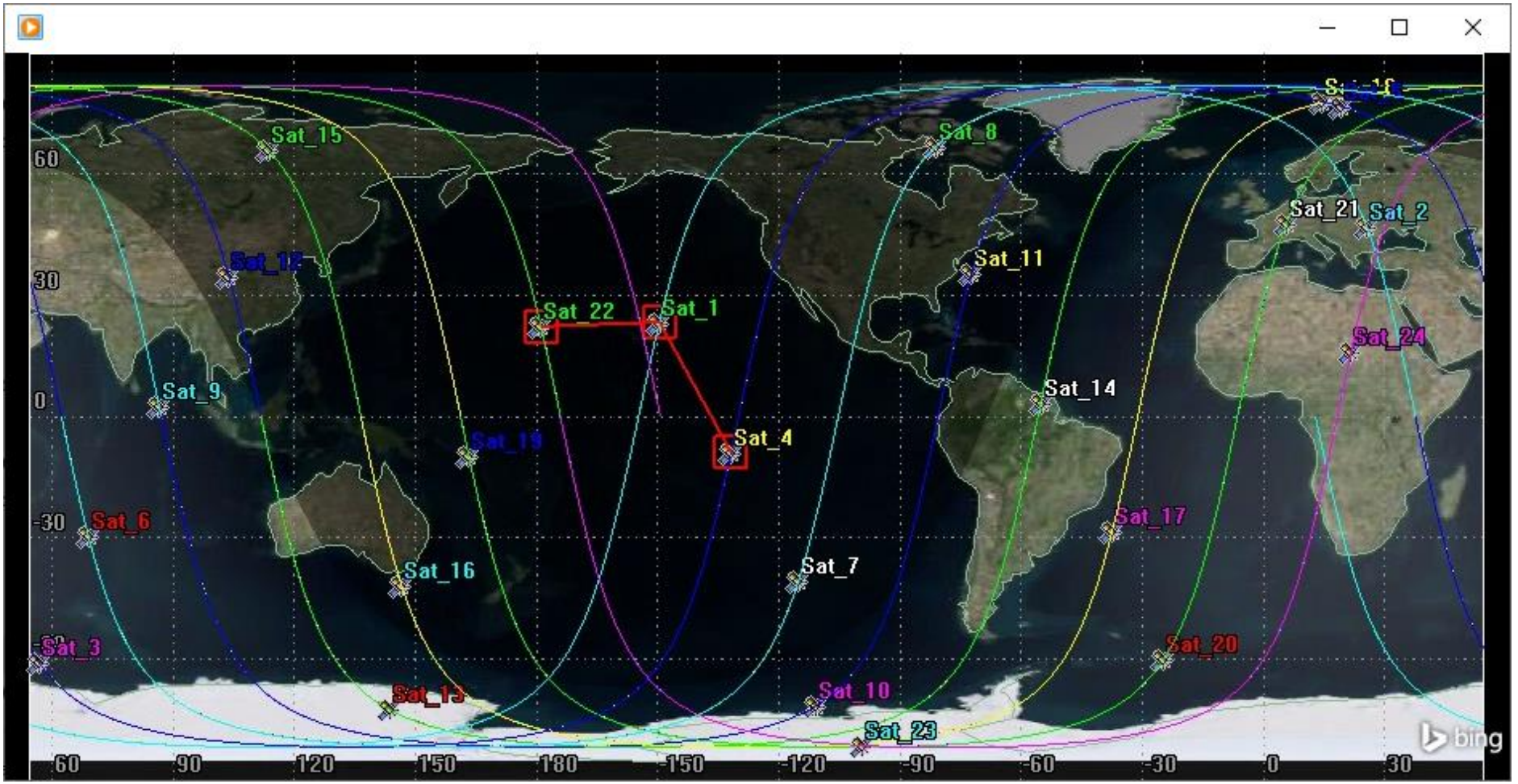

- Operational Constellation Can Be Built Up Incrementally-Providing Value at Each Stage
  - e.g. Initiated During LEO Sounder-Sat Demonstration Period
  - e.g.-Expanded together with Numerical Weather Prediction Refresh Rate Upgrades

Next-Gen IR Vertical Profiling Constellation Employs Suite of Miniature Hyperspectral Sounders

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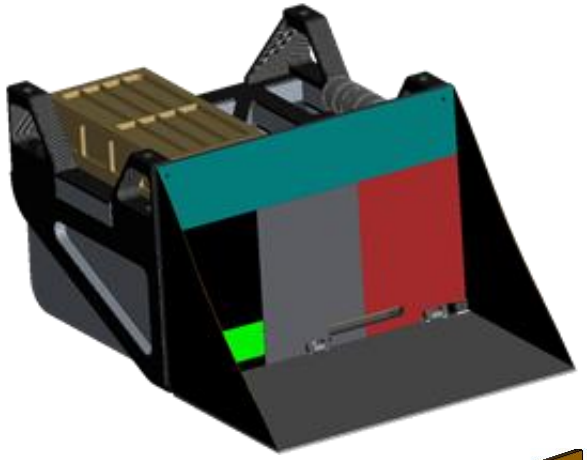
MISTiC Profiles Temperature and Water Vapor in the Troposphere

- Spectral Range: 1750-2450 cm^{-1}
- Spectral Resolving Power > 725:1
- NESR < .01 $mW/m^2/str/cm^{-1}$ @ 2393 cm^{-1}

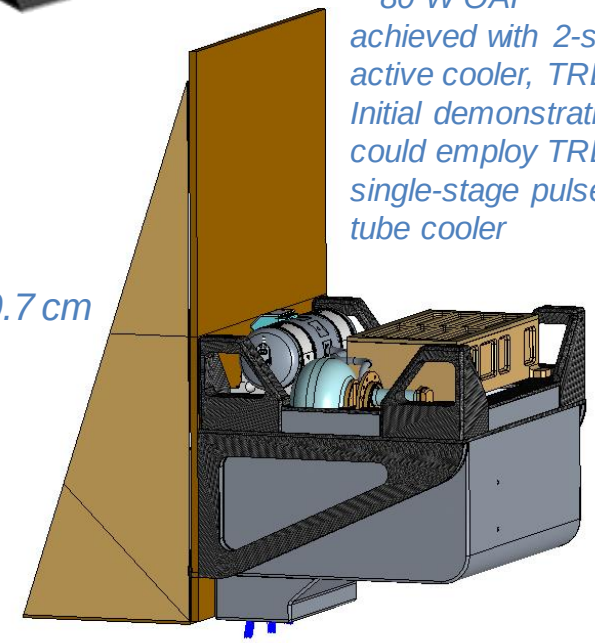


MISTiC®
Mass: 15 kg
Size (Stowed):
30.5 × 23.5 × 20.7 cm
OAP: 50 W
TRL-6

LISSTIC Profiles Temperature in the Troposphere and Stratosphere

- Spectral Range: 680-1050 cm^{-1}
- Spectral Resolving Power > 900:1
- NESR < 1.03 $mW/m^2/str/cm^{-1}$ @ 740 cm^{-1}

LISSTiC®
Mass: 20 kg
Size (Stowed):
30.5 × 23.5 × 20.7 cm
OAP: 80 W
*TRL-6**



** 80 W OAP achieved with 2-stage active cooler, TRL-4. Initial demonstration could employ TRL-6 single-stage pulse tube cooler*

For any Observing Node, the two instruments can operate together, or MISTiC can be used alone, providing flexibility on stratosphere refresh rate, deployment, and cost.

(MISTiC = Midwave Infrared Sounding of Temperature and humidity in a Constellation)

Elements of a New Paradigm for Weather Observation in a Distributed Architecture

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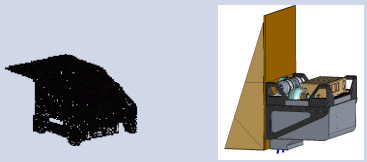
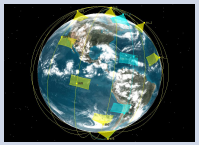
Element	Benefit for NOAA	Example
Miniature Robust but Single-String IR Sounding Instruments –5 yr life plan	Leveraging NASA Investment and Moore's Law to Lower Cost	
Standard Micro-Satellite Hosts—Selected for DoD Constellations	Multiple Sources, Leveraging NASA and DoD Investments and Need for Large Numbers	
Sun-Synchronous Low Earth Orbit Selection	• More Stable for Calibration • Lower-Cost Access than GEO • 50 x closer—Small Optics	
Commercial Small-LV – Based Services	Multiple Sources- Driven by DoD and Commercial Space Market	
Low Impact SSO Plane Change Capability (SSO_A→Polar→SSO_B)	Enables Multiple Observing Nodes per Launch, Reducing Cost and Deployment Period	

Distributed Architecture of Small Instruments

- *Increases Resilience and Fault Tolerance*
- *Reduces and Spreads Cost*
- *Increases Flexibility and Technology Infusion Potential*

Global Observations Provided by 24-Node SSO IR Sounding Constellation

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Observation Product (Baseline)	Refresh Rate	(N) Spatial Sampling	Comments
LEO IR Vertical Profiles of Temperature and Water Vapor and Radiances (two CO_2 Bands)	12 hours	9 km (6x6 sub-sampling)	• For Each Plane Added • Cloud-Cleared Radiances
Rapid Refresh IR Vertical Profiles of T and WV --and Radiances	30 min	3 km	HES PORD Spectral Quality
Vertically Resolved Water Vapor Motion-Vector Winds (assuming wind triplet observation)	90 min	15 km (5x5 sample tracer)	Also Improves and Height Assignment for GEO Cloud AMVs
High Latitude Multi-Spectral Meterological Imaging	5 min;>80° 10min;>70°	1.5 km	Similar to an ABI in Tundra Orbit
Low-Impact Options			
Day/Night Band (visible)	30 min	0.5 km	0.5 kg Add to MISTiC
Host for T and WV μWave Sound	30 min	e.g. 30 km	e.g 4 kg Add to S/C

LEO SSO Constellation Provides Substantial Observation Value In Addition to Temperature and Water Vapor Vertical Profiles -With Potential for More

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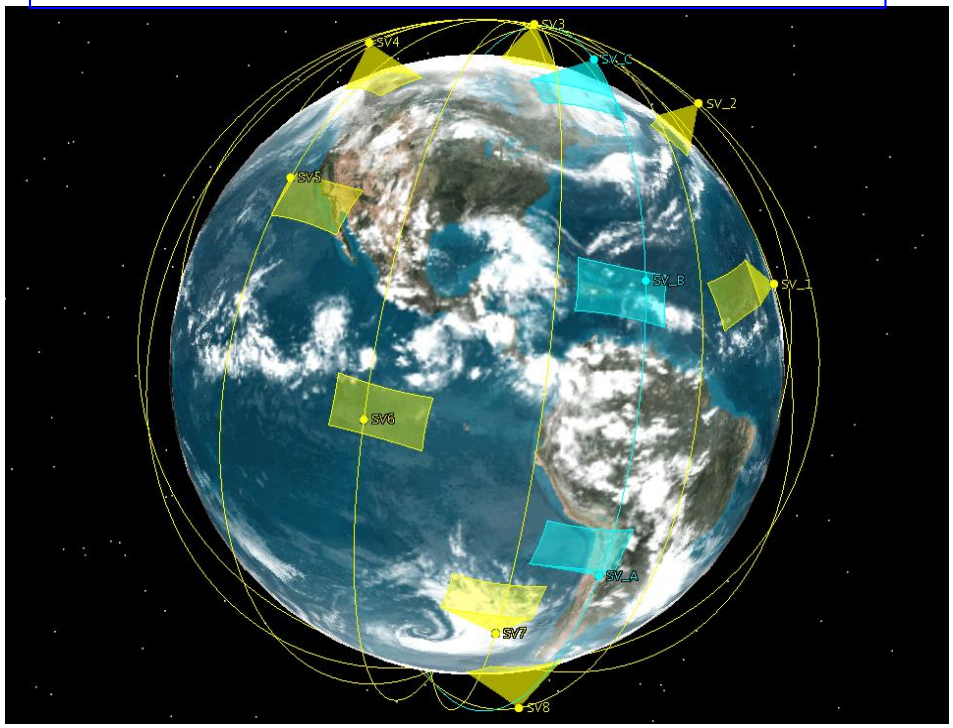
Additional Notes on Hyperspectral AMVs

- Vertically Resolved Wind Observations are Provided by the IR Sounding Constellation at Rates Typical of GOES-R Water-Vapor Wind Observations
  - 30-minute image refresh
  - 90 minute wind-triplet refresh
  - or 60-minute refresh, using "Optical Flow" methods
- LEO Hyperspectral Constellation Offers Improved Height Assignment for GEO Meteorological Imager Cloud AMVs
  - IR Sounding Retrieval Identification of Cloud-Top Pressure for Wind-Tracer Clouds
  - Cross-correlation between GEO Imager and LEO Sounder Features Facilitated by Common Band Coverage and Comparable Spatial Resolution

Motion-Vector Winds Formation (blue)



MISTiC Winds Initial Demonstration Configuration

- Three Hyperspectral Sounders in a Wind-Triplet Configuration
  - 10-15 minute Time Separation
- Possible Implementation of NOAA's SounderSAT (Distributed Architecture)

GOES-R Sounder (HES) after Formulation Phase Forms Basis of a Cost Model Comparison for Next-Gen Sounder

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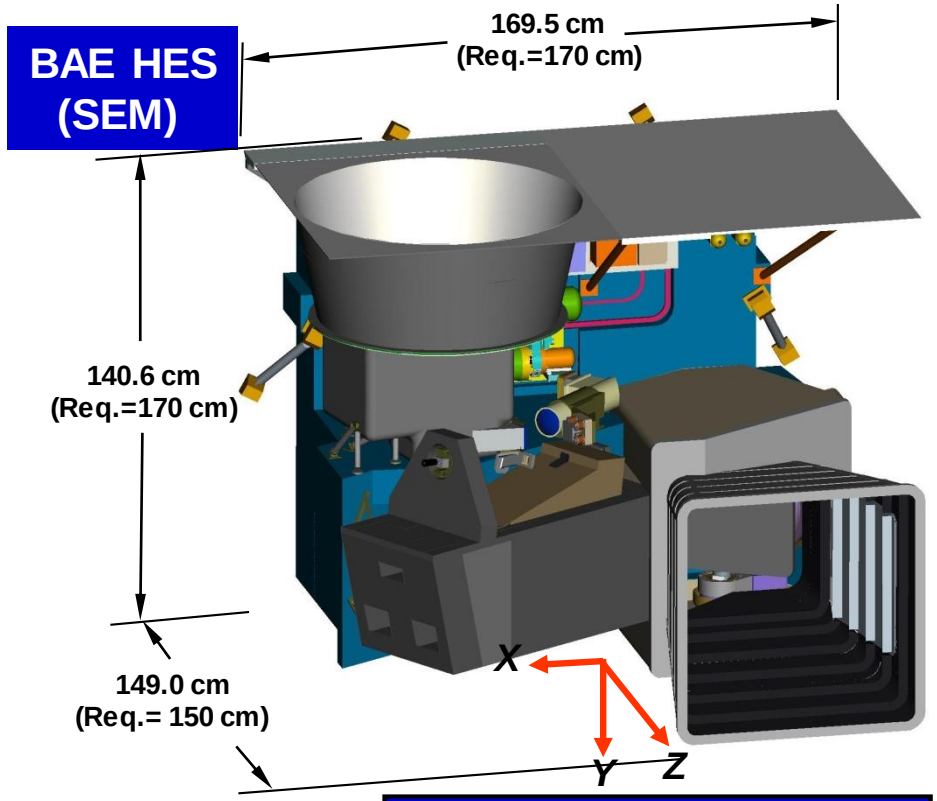
- BAE Systems Led One of Three Contractor Teams in HES Formulation Phase
  - Dilts Associates Provided Model Cost Estimates for GOES-R HES Instrument Program
- HES PORD Requirements Similar, but Not Identical to GEO BAA
  - FPA Size and Optics Aperture (and mass) Would Increase to Meet GEO BAA Rates
- Some Technology Advances since 2007 Could Allow Reduced Cost (Additive Manufacturing, FPA Technology, Elect.)
- → Cost Impacts Assumed to Counter-Balance



Performance Characteristics
- Spectral Coverage:
  - 4.165-5.92 μm (1689-2400 cm^{-1})
  - 9.65-14.7 μm (680-1036 cm^{-1})
- Spectral Resolution: $\lambda/\delta\lambda$>1000
- NEΔT: 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

IR Sounding Requirement Summary (Level 2)

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Attributes	LEO Target (Baseline) Source: NOAA LEO BAA	GEO/XO Target Source: NOAA GEO BAA	Current Program of Record (CrIS/N-20) Source: JPSS Level 1 Requirements Document	MISTiC + LW/VLW Instrument Suite Constellation Pro-jected Capability
Update Rate				
Full Disk (62 deg LZA)	(12 Hours Assumed)	30 min	12 Hours	30 min for Surf to 30 mb, 90 min for 30 mb-0.5 mb
CONUS		30 min		
MESO		5 min		
A. Horizontal Resolution (Horizontal Cell Size or Spatial Resolution)	10 km(at nadir)	3 km(at nadir)	14 km	3 km –CF, S-30 mb 6 km –PC, S-30 mb 9 km-PC, 30-0.5mb
B1. Temperature Measurement Precision Expressed as an error in layer average temperature				
1. Cloud-Free (CF) to Partly Cloudy (PC), Surface (S) to 850 mb over ocean	1.6 K per 1 km Layer	0.75 K (Accuracy) per 2 km layer (Vertical Coverage Range Not Specified)	1.6 K per 1 km Layer	1.6 K per 1 km Layer
2. Cloud-Free to Partly Cloudy, 850 to 300 mb over ocean	1.6 K per 1 km Layer		1.6 K per 1 km Layer	1.6 K per 1 km Layer
3. Cloud-Free to Partly Cloudy, 300 mb to 30 mb	1.5 K per 3 km layer		1.5 K per 3 km Layer	1.5 K per 3 km layer
4. Cloud-Free to Partly Cloudy, 30 mb to 1 mb	1.5 K per 5 km layer		1.5 K per 5 km Layer	1.5 K per 5 km layer
5. Cloud-Free to Partly Cloudy, 1 mb to 0.5 mb	3.5 K per 5 km layer		3.5 K per 5 km Layer	3.5 K per 5 km layer
B2. Moisture Measurement Precision (expressed as a percent of average mixing ratio in 2 km layers)				
1. Cloud-Free to Partly Cloudy, Surface to 600 mb	Greater of 20 % or 0.2 g kg^{-1}	10% (Accuracy) per 2 km layer (Vertical Coverage Range Not Specified)	Greater of 20% or 0.2 g/ kg	Greater of 20 % or 0.2 g kg^{-1}
2. Cloud-Free to Partly Cloudy, 600 mb to 300 mb	Greater of 35 % or 0.1 g kg^{-1}		Greater of 35% or 0.1 g/ kg	Greater of 35 % or 0.1 g kg^{-1}
3. Cloud-Free to Partly Cloudy, 300 mb to 100 mb	Greater of 35 % or 0.1 g kg^{-1}		Greater of 35% or 0.1 g/ kg	Greater of 35 % or 0.1 g kg^{-1}
Latency	-	10 min	-	10 min
C. Horizontal coverage from 832 km orbit	2000 km	NA	2200 km	2000 km
D. Lifetime of the Sensor (in years)	5	5	7	5 (With partial constellation refresh)

Considerations for Complementary DWL and IR Hyperspectral Wind Observations

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- Both DWL and IR Hyperspectral AMVs Should Each Provide Valuable Constraints on Numerical Weather Models
  - OSSEs for Each show Forecast Accuracy Improvements
  - AEOLUS Demonstration Encouraging
- However, a Dedicated US Demonstration Mission Would Face Substantial Barriers
  - Aggregate Cost would Exceed NASA Earth Venture Budget Cap
  - Preferred Orbit Conditions for Hyperspectral AMVS and DWL are Not Compatible
    - HSI AMV (MISTiC): LEO SSO, 650-850 km altitude
      - Multi-Platform Observation--Micro-Sat Hostable
    - DWL: LEO 300-400 km, can be SSO, but not required
      - Medium-Sized (or Larger) Satellite with High-Power -Demand Payload

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Notes on Use of Simultaneous Nadir Overpasses for Cross-Calibration and Observation Comparison

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- Cross-Calibration of IR Sounders is a Long-Standing Priority of the Science Operational Weather Communities—and Could be used for Comparison of 3D Wind Observations
  - Most-Valued Approach: Observation Comparison at Simultaneous Nadir Overpasses
  - In the Case of Two Observatories in SSOs…
    - SNOs occur at high latitudes (70-80 Deg.)
    - Rate of SNOs Proportional to Orbit Period *Difference*
    - *SNOs Available for any LTAN and Height, but only observe polar zone conditions*
    - *AEOLUS is in a 300 km SSO with 1-week repeat*

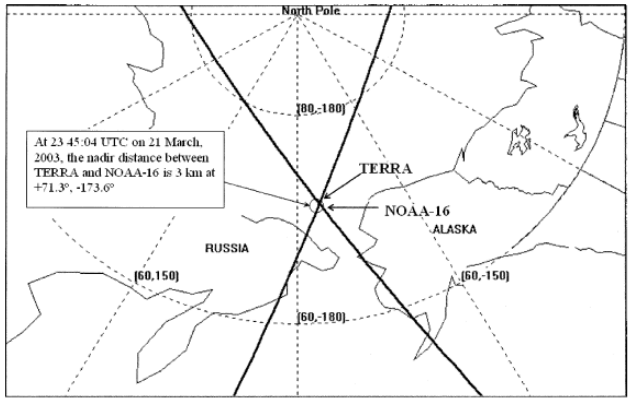

FIG. 1. Simultaneous (1 s) nadir overpass (SNO) between *NOAA-16* and *Terra*.

  - While MISTiC Winds is Designed to be in SSO, a DWL may not require this orbit type—changing the SNO Opportunities in frequency and latitude

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Summary

- NOAA is Studying Options for its Next Generation Observing System
  - LEO-Focused initially on Vertical Thermodynamic Profiling "SounderSAT"
  - GEO/XO---Including Interest BAE's LEO Sounding Constellation
    - Vertically Resolved Atmospheric Motion-Vector Wind Observations Enabled
  - NOAA has Included Interest in the Vertical Wind Profile In This Planning
- BAE Systems LEO IR Sounding Constellation Study Shows that Observations of the Needed Science Data Quality are Achievable and Affordable, and Lower Cost than GEO Implementation
  - Including Vertically Resolved AMVs
- Comparisons of Hyperspectral AMVs with DWL More Likely Through Cross-Platform Comparisons Rather than a Joint, Co-manifested Mission
  - Both Observation Types Would Add Significant Value for NOAA