Vertically Resolved Wind Observation Method Comparison and Synergy Assessment

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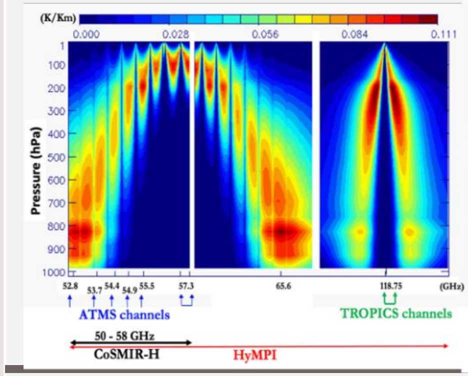
Study Objectives

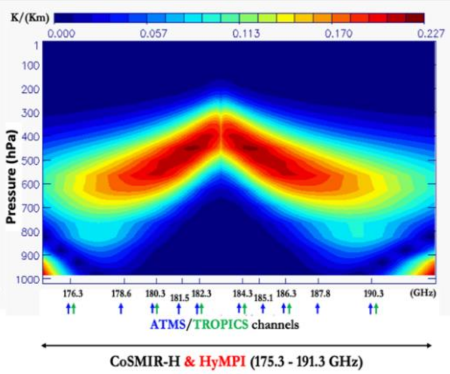
- Evaluate the Technical Capabilities of an on-orbit constellation of miniature infrared sounding instruments that work together to meet NOAA's Future 3D-Wind Observation requirements and Compare with Alternate Approaches:
- Compare IR Hyperspectral AMVs, Microwave hyperspectral AMVs, DWL, and Multi-Angle Stereo observation capabilities, in accuracy, spatial coverage, and atmospheric feature capture,
- Assess Potential Observation Synergies, Especially Synergies between Hyperspectral IR-AMVs and Stereo,
- Evaluate Options and Describe Recommended Optimum Observation Architecture.
- Provide sufficient observing system definition for each observation type compared (requirements and key design features) to support a balanced, informed comparison

Vertically Resolved Wind Observation Methods Evaluated Under This Study

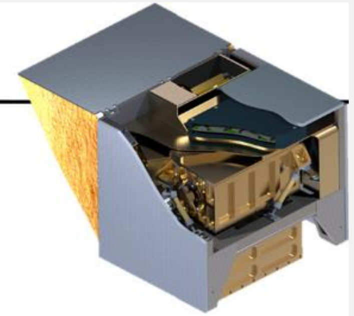
Hyperspectral Microwave Water Vapor AMVs

Potential future instrument (and AMV constellation) using photonic integrated circuit-enabled mapping instruments providing hyperspectral coverage of water vapor (near 183 GHz) and temperature (near 57 GHz) vertical profiles . Instrument is conical scanning—GSD scaled for winds





MISTiC Winds Hyperspectral IR AMVs

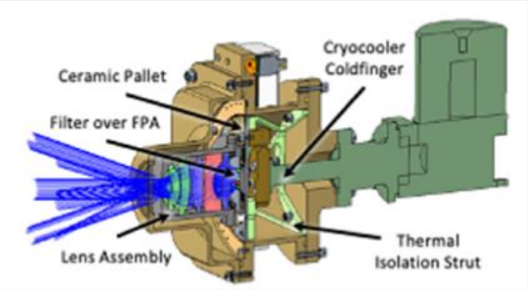


MISTiC Winds

3D Wind
Observations with Miniature IR sounders
on ESPA-Class Micro-Satellites via Hyper- spectral
Atmospheric Motion Vectors

CMIS AMV Wind Observation

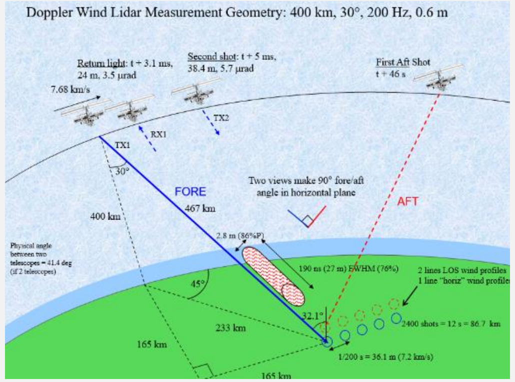
- Stereo AMVs observed with high resolution, 24/7 capability MWIR camera
- Newer FPA technology (Type II Super lattice) allows warmer detector operating temperature
- Multiple CMIS deployed in leader-follower formation for best coverage



CubeSat-compatible CMIS Multi-angle Imager

Aerosol Doppler Wind LIDAR

- Wind SP concept updates LARC 2 micron DWL Approach with:
- New 50 mJ 200 PPS laser transmitter
- New rapid-LOS switching
- Use of two receiver apertures to provide both horizontal wind components in one location within ~ 1 min
- Airborne demonstrations in progress



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NOAA 3D Wind BAA Requirements
(BAA Table 2)

Attribute	Minimum	Mid-Point	Maximum
Minimum Coverage Area	Close to Global if Possible, Regional Gaps Acceptable	Global	Global
Update Rate[1]	24 hours	6 hours	3 hours
Latency[2]	165min	60 min	30 min
Horizontal Resolution (nadir)	400 km @ nadir	40 km @ nadir	15 km @ nadir
Vertical Resolution	4 km	2 km	1 km
Uncertainty: Direction	± 15 °	± 10 °	± 5 °
Uncertainty: Speed	10 m/s	5 m/s	2 m/s or 10%
Vertical Extent	Mid-Troposphere to Just Above Tropopause	Surface to Just Above Tropopause	Surface to Stratopause

1. Update rate is the time interval between successive collections from the same geographic point on or above the surface of the earth.
2. Data latency is defined as the period from the time of observation of all of the requisite data by the satellite until the data product produced from those data is available to the users at the distribution system

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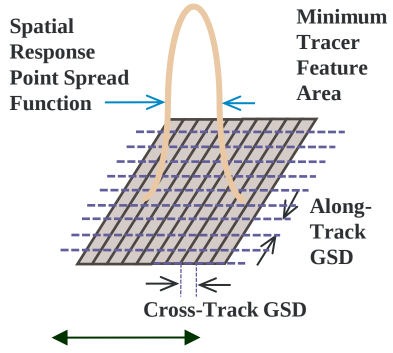
Candidate Horizontal Resolution
Formulation for Predicting Performance

- Horizontal Resolution can be considered as the inverse of a Horizontal Observation Density or Horizontal Rate
- The observed Horizontal Rate depends on geometric observation rates and meteorological condition probabilities for Layer L.

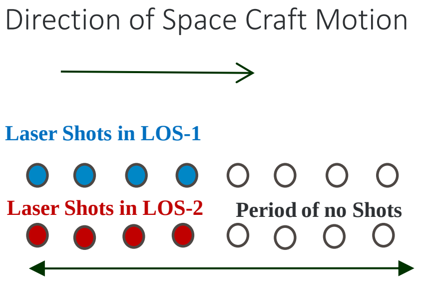
$$HR_L = HRgeomet_L \times Pmet_L$$

  - $HRgeomet$ approach is shown for AMV and DWL at Right
  - $Pmet$ is the probability of a wind observation is obtained in the geometric region
  - $Pmet_L$ is a product of probabilities that the the water vapor tracer, cloud fraction, or aerosol density support a wind observation for Layer L



1/RHgeomet for MISTiC AMV

Geometric Horizontal Rate for an AMV is given by the inverse of the number of samples needed to define the Tracer (e.g. 10 GSD x 10 GSD Area)



1/RHgeomet for Langley Wind SP

Geometric rate for an Doppler Wind LIDAR is the repeat period for the number of shots, followed by the duty cycle gap, for Langley's rapid-LOS-switching DWL

The multiple factors that determine horizontal resolution of an observation method can be evaluated separately

Wind Observation Methods Summary—Study Approach

- Assessments of the Vertically-Resolved Wind Observing Method Performance Against NOAA's BAA Wind Requirements were Performed for 4 Methods
  - Specific Key Observing System Parameters and Instrument SWAP available for MISTiC Winds and CMIS
  - Key parameters for Wind SP DWL and HyMPI-AMV identified through extensive dialog with observing method providers-and represent their choices-where defined.
  - Self-Consistent sets of key parameters identified for HyMPI AMV and Wind SP methods for wind assessment for this study

- Challenges with this Study Approach
  - HyMPI-AMV and Wind SP DWL assessments preliminary -insufficient maturity/definition for space. Each await additional development (as do competing instrument team approaches)
  - There are other wind DWL LIDAR approaches and other teams pursuing Hyperspectral Microwave, with potentially different design points, and capabilities
    - HOWEVER, the differences noted between the various observing methods are significant and major conclusions are relatively insensitive to instrument design differences

3D Wind Observation Method Comparative Performance -Geometric Case for Horizontal Resolution

- Text Color-Code:
  - Blue—Meets NOAA Max. Performance
  - Green—Meets Mid-Range Performance
  - Red—Meets NOAA Min. Performance
  - Crimson-Bold-Shadow—Below NOAA Min Performance

Attribute	BAA Mid-Point Rqmt	Microwave 3D Constellation (Conical-Scan,1-m aperture)	MISTiC Winds SSO Constellation (700 km orbit height)	CMIS Constellation (700 km orbit height)	Wind SP DWL Geometric Observation Density
Min. Coverage Area	Global	Global (> 95% coverage)	>90% of Global	>90% coverage with two CMIS per SC, 2 SC/plane.	**Observation Lines every 2620 km cross-track (at equator)**
Horizontal Resolution	40 km @ nadir	Geometric Resolution ~64 km	Geometric Resolution: 12 km	Geometric Resolution: <12 km @ nadir (12x12 pix)	Geometric Resolution: 28 km (1-D only)
Vertical Resolution	2 km	~ 1.5 km (Upper Trop.) ~2 km (Mid-Trop. ~ 2.5 km (Lower Trop.)	1 km (mid trop.) ~ 1.5 km near trop & PBL	< 0.5 km (Cloud Geometrical Thickness)	2 km @ 500 hPa, <0.5 km in clear PBL
Uncertainty: Direction	± 10 °	12° rms at 10 m/s	6 ° rms at 10 m/s	5 ° rms @ 10 m/s	5 ° rms @ 10 m/s
Uncertainty: Speed	5 m/s	8.6 m/s	< 1.5 m/s @ nadir <2 .2 m/s @ 52 ° off-nad.	<0.5m/s @nadir, <2 m/s @ 50 ° off-nadir	<1.m/s @ in clear PBL < 2 m/s nominal
Vertical Extent	Surface to Just Above Tropopause	Surface to ~ 200 hPa	Surface to ~ 200 hPa	Not a vertical profile, Limited to Cloud Layers, Mostly Limited to Lower and Upper Troposphere	Surface to Lower Stratosphere

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3D Winds Observation Method Space Segment Implementation Comparison

Instrument Accommodation Attributes	MISTiC	CMIS	Study-Estimated Wind SP	Study-Estimated Hyperspectral Microwave
Instrument Power (oper)	51W	7.3W	550W	250W
Instrument Mass	19.6 kg (20% contingency)	5.2 kg (17% contingency)	350-450 kg (large uncertainty-design not done)	160 kg
Instrument Footprint Size	31.4 X 24. X 27.3 cm	29 X 27.8 X 21.6 cm	1x2m (x1.2 m)	1x1 (x1.5)
Data Rate (uses compression)	46 GiB/day	7.2 GiB/day	(much less than other methods)	0.5 GiB/day
Number of Instruments per Spacecraft	1	2	1	1
Number of Spacecraft per Wind Observation	3	2	1	3
Spacecraft Mass	70 kg	70 kg	1200-1500 kg	500 kg
Space Segment Mass Per Wind Observation Plane	<250 kg	<170 kg	1200-1500 kg	1500 kg
Orbit Height (used in study)	700 km	700 km	400-450 km	800 km

Wind Observation Accommodations Estimates per LEO orbital plane

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Wind Observation Methods Summary-Method Comparison

Wind Observation Method	Key Advantages	Key Disadvantages
IR Hyperspectral AMVs (Example:MISTiC Winds	AMV (Water Vapor) method meets nearly all NOAA Mid-point requirements	Horizontal Resolution Mid-point rqmt not met on average in lower troposphere -- due to higher cloud densities
Multi-Angle Stereo AMVs (Example: CMIS)	Would provide most accurate wind-speed/angle and vertical resolution --- for 1-2 cloud levels	Cannot profile wind through the column • Very few observations in mid-troposphere • No observation in cloud-free areas or below-dense-clouds
Aerosol DWL (est.) (Example—Study Estimate of Langley's Wind-SP Approach)	• Could meet Maximum wind speed/angle performance in cloud-free lower and under above-median aerosol loading, • Can profile the troposphere, with Mid-range wind speed/direction and vertical resolution performance.	• Area coverage very limited-to curtain, and to horizontal resolutions larger than 40 km along-track in most aerosol and cloud conditions • Substantial Instrument and Space Segment Size and Mass
Hyperspectral Microwave AMVs Example-Study Estimate of GSFC HyMPI AMV)	Concept could meet Minimum requirements, with vertical coverage through troposphere with instrument size comparable to current conical microwave instruments	• Substantial Space Segment Size and Mass • Mid-Point or better performance would require several large instrument payloads per plane

Wind Observation Method Synergy Summary-Significant Opportunities

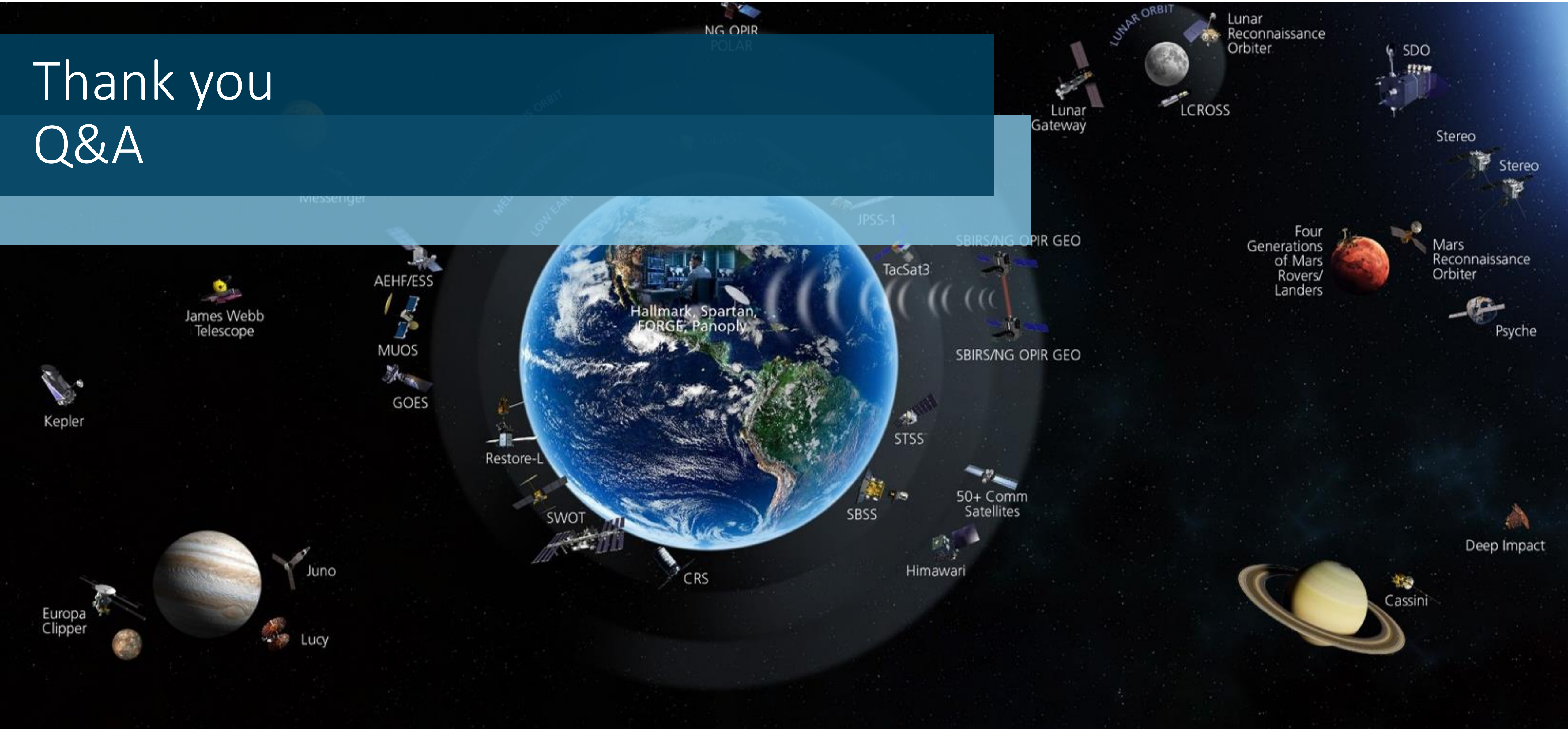
Synergistic Combination	Key Benefits of Combination	Comments
MISTiC + CMIS AMVs with GPS/R and RO	Wind and Thermodynamic Profiles from the Upper Troposphere to (ocean) Surface	Also co-located higher level products (Potential Vorticity, Moisture Flux, PBL Height)
MISTiC and HyMPI (ROI AMVs)	3D Winds in Clear and Cloudy Conditions	Possibly hosted on 3 mini-sats
DWL and CMIS AMVs	Cross-validation of DWL (Cloud) heights and wind vectors	Also, DWL Aerosol 3D Winds
MISTiC and GSX AMVs (cued)	Persistence of Wind Tracking within ROI	For higher-speed winds

Acknowledgements

- 3D Winds Study Final Report
- Vertically Resolved Wind Observation Method Comparison and Synergy Assessment
- Prepared for NOAA, NESDIS Office of Systems Architecture and Engineering (SAE), Joint Venture Partnerships under
- Contract 1332KP22CNEEP0006_3D Winds_BAE_SF33
- NOAA POC: Aydin Sadeqi (aydin.sadeqi@noaa.gov)

- Multiple informative conversations with members of teams for HyMPI, Wind SP, and CMIS:
- Dr Michael Kavaya, Dr Antonia Gambicorta, Dr Jeffery Piepmeier, and Dr Mike Kelly

Thank you
Q&A



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Supplementary Material

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Comparison of Estimated MISTiC Wind Performance to BAA Mid-Point Requirements

Comparison of BAA Mid-Point Requirements to Projected Performance of MISTiC Winds:

- Two orbital planes, each with 3 spacecraft
- Spacecraft separation: 15 min
- Orbital Altitude: 700 km
- Assessed for Water Vapor Motion-Vector Winds

3D Wind Attribute	BAA Mid-Point Requirement	MISTiC Winds SSO Constellation	Comments
Min. Coverage Area	Global	>95% of Global	Using ± 52 degree scan angle
Update Rate	6 hours	6 hours	For 2-orbital plane system
Latency	60 min	30-60 min	Obtained via LEO com-sat constellations
Horizontal Resolution	40 km @ nadir	Geometric Resolution: 12 km Res. For Average Atmosphere: 500 mb P_{Met}= 0.27-0.5: 20 -40 km 850mB P_{Met} = .1: 120 km	• 700 km orbital altitude, • 20 min LTAN separation • Assumes 10-GSD Region for Water Vapor Tracer Tracking (cloud-free) • AIRS Clear/Cloud Fraction
Vertical Resolution	2 km	1 km (lower /mid trop.)	< 1.5 km in upper trop.
Uncertainty: Direction	± 10 °	<6 ° rms at 10 m/s	Varies as 1/ Wind Speed
Uncertainty: Speed	5 m/s	< 2.2 m/s RMS nominal	For 90^{th} Percentile Wind-shear
Vertical Extent	Surface to Just Above Tropopause	Surface to ~ 100 hPa	Just above Tropopause

- Strong 3D Wind Performance Through Most of Column vs Mid-Point Requirements.
- Clouds limit number of water vapor AMV observations below PBL

Horizontal Feature Tracking Error Contributions AMV Wind Speed Error

- Observing the displacement of a feature in the cloud or water vapor fields between two observations of the feature, at times T_1 and T_2, provide ideal estimate of wind speed at that level:

$$V=\frac{|\vec{D}|}{T_2-T_1}=\frac{|\overrightarrow{P_2-P_1}|}{T_2-T_1}\ .$$

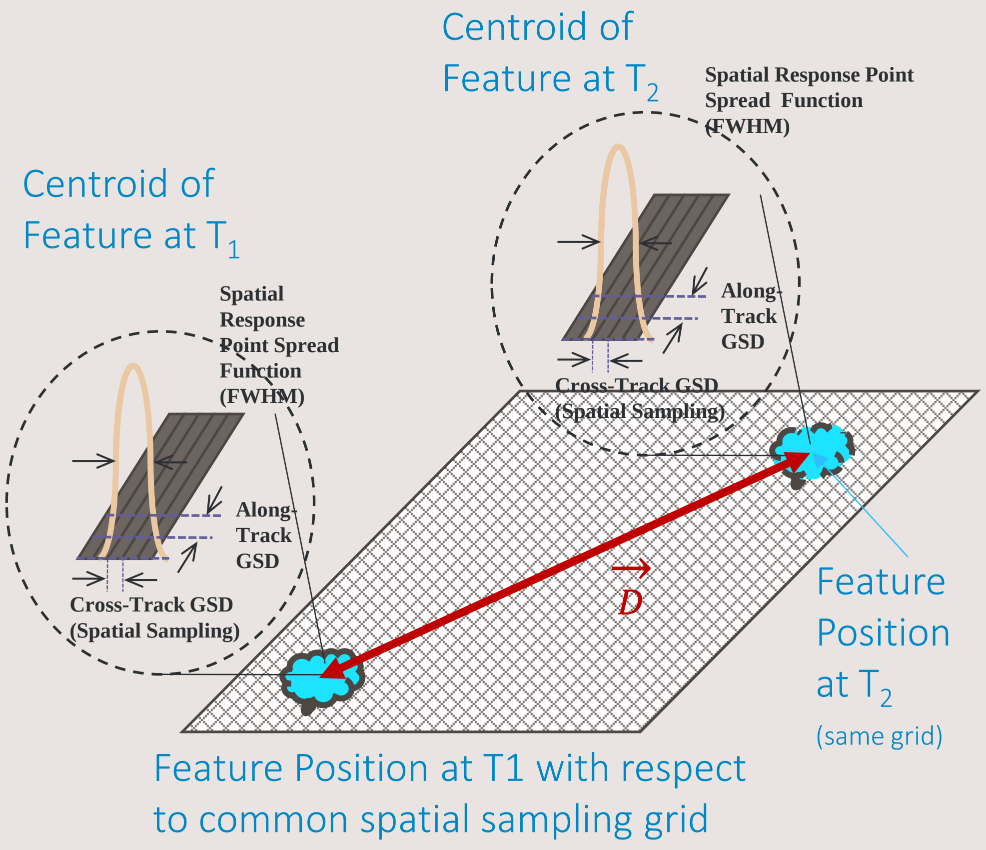
  - But, the feature position observations have uncertainties.

- The Tracking-Error-Lower-Limit (TELL) for wind speed error includes the effects of uncertainties in feature centroid position-- for each of the two observations

$$TELL=\frac{|\overrightarrow{\Delta D}|}{T_2-T_1}=\frac{|\overrightarrow{\Delta P_2-\Delta P_1}|}{T_2-T_1}\cong\frac{\sqrt{2}/_2\cdot\delta S_{eff}}{T_2-T_1}$$

where δS_{eff} is the effective horizontal sample (pixel) spacing, _provided_ that the observing system Point Spread Function (PSF) FWHM is constrained, e.g.

$PSF\ FWHM=\frac{2\cdot Wavelength}{Aperture\ (proj.)}\cdot Range\lesssim 2\cdot\delta S_{eff}$ for diffraction-limited sys.



Wind Speed TELL places constraints on observing system horizontal sampling density and aperture size

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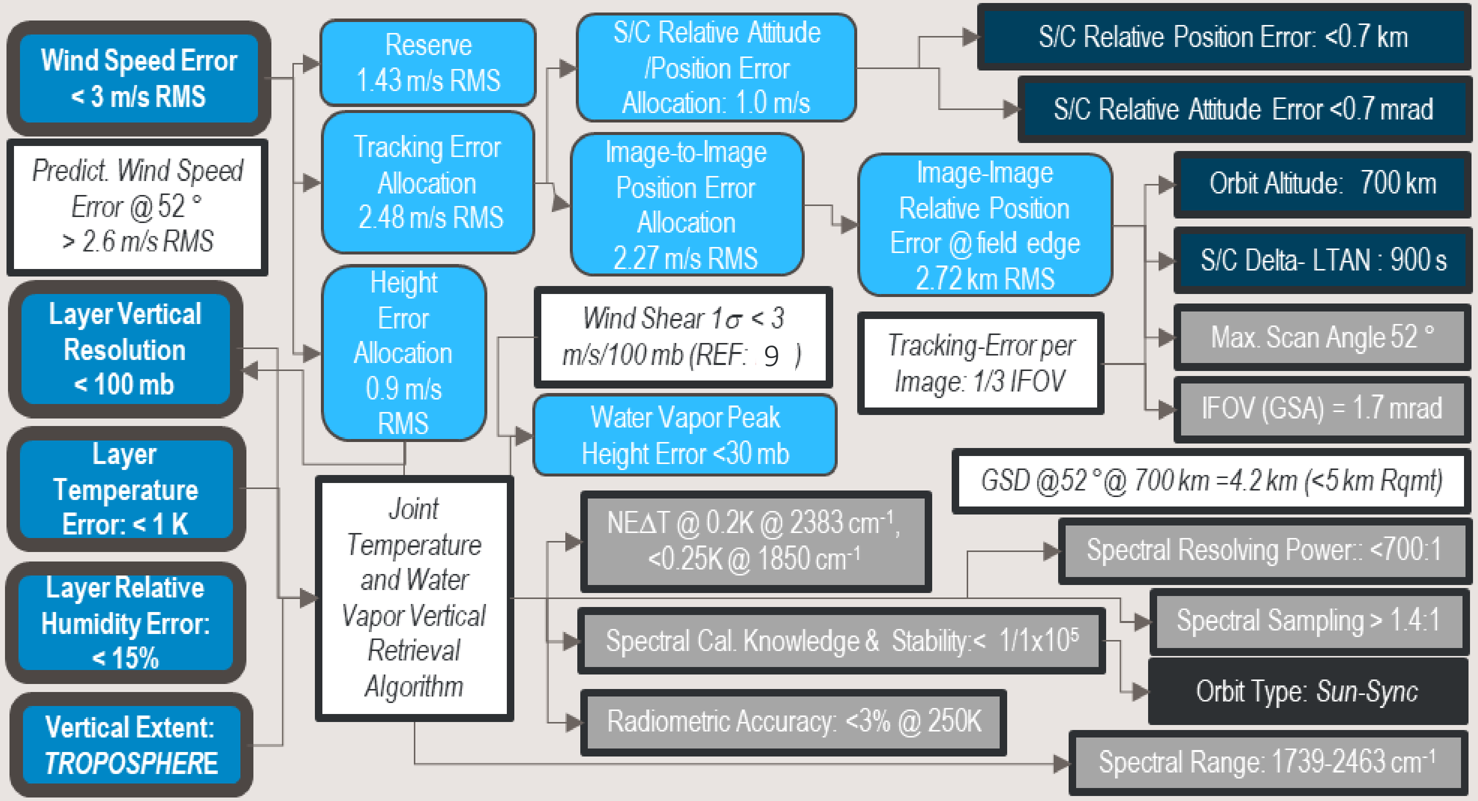
Wind Speed Error Decomposition for MISTiC Winds, for the 3 m/s Requirement Identified by NRC/ESAS Decadal Survey (2017).



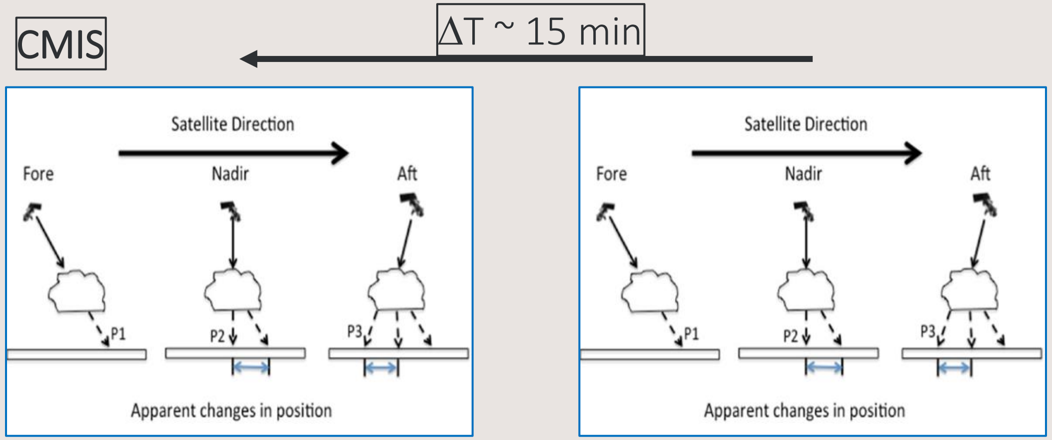
MISTiC Winds Observation Method Designed to Meet ESAS 3D Wind Requirements

- Over full Field of Regard (± 52°)
- For 90th Percentile Wind-Shear Conditions

(Dark blue/Bold outline are Level-2 requirements. Light-blue are intermediate flow-down requirements for wind speed, grey/bold outline are instrument requirements, and black are spacecraft or mission requirements.)

Detailed Requirements Decomposition for Observing Method that Exceeds NOAA Mid-Point Requirements

CMIS


CMIS
ΔT ~ 15 min
Satellite Direction
Fore
Nadir
Aft
P1
P2
P3
Apparent changes in position
Satellite Direction
Fore
Nadir
Aft
P1
P2
P3
Apparent changes in position

Comparison of CMIS Wind Observation with Mid-Point Requirement

Predicted Performance Characteristics for CMIS 3D Wind Observations vs Mid-Point Requirements

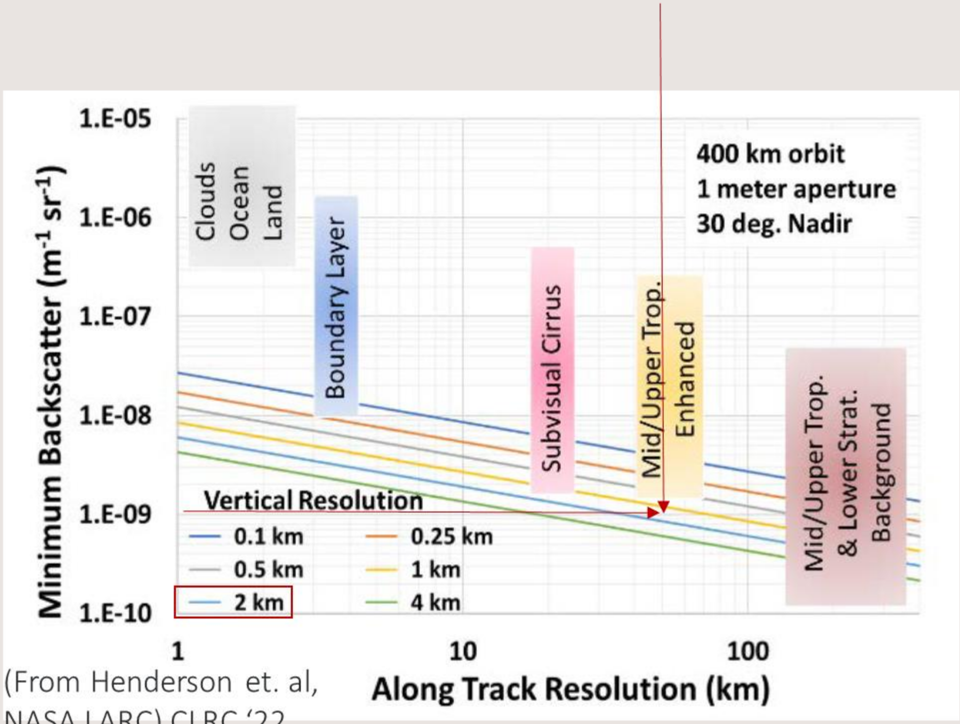
Attribute	BAA Mid-Point Requirement	CMIS Constellation Performance (700 km orbit, 2 instr/S/C, two S/C per Orbital Plane, 2 Planes)	Comments
Min. Coverage Area	Global	>90% with two CMIS per SC	Current Cross-Track FOV ~ 50 °
Update Rate	6 hours	6 hours	For 2-orbital plane system
Latency	60 min	30-60 min	Obtained via LEO com-sat constellations
Horizontal Resolution	40 km @ nadir	Geometric Resolution: <12 km @ nadir (12×12 pix) Resolution for Average Atmosphere: 500 mb P_{Met}= 0.125 — 120 km 850 mb P_{Met}= 0.33 — 40 km	Horizontal Wind Observation Rate Depends on both Wind Observing Method and Sensor Design, and Cloud Frequency at that Height
Vertical Resolution	2 km	< 0.5 km (Maximum Performance (Limit-Typical Cloud Geometrical Thickness)	• Cloud defines volume of air participating in tracked feature •20 meter knowledge for cloud-top height
Uncertainty: Direction (RMS)	± 10 °	<3 ° rms at 10 m/s @ nadir <12 ° rms at 10 m/s @ 50 °	Varies as 1/ Wind Speed
Uncertainty: Speed (RMS)	5 m/s	<0.55m/s @ nadir, <2 m/s @ 50 ° off-nadir	Tracking Error for 5-min LTAN difference between leader and follower satellites
Vertical Extent	Surface to Just Above Tropopause	Note: can typically only measure 1-2 cloud top layers within the atmospheric column	Limited to Cloudy Layers visible from above, primarily in Lower Troposphere (for water clouds) , and cirrus clouds in the upper troposphere /stratosphere

Identified and Adopted Key DWL LIDAR Design and Mission Parameters-for Study

Langley Wind SP: Single DWL Platform Assumed @ 400 km Orbit Height

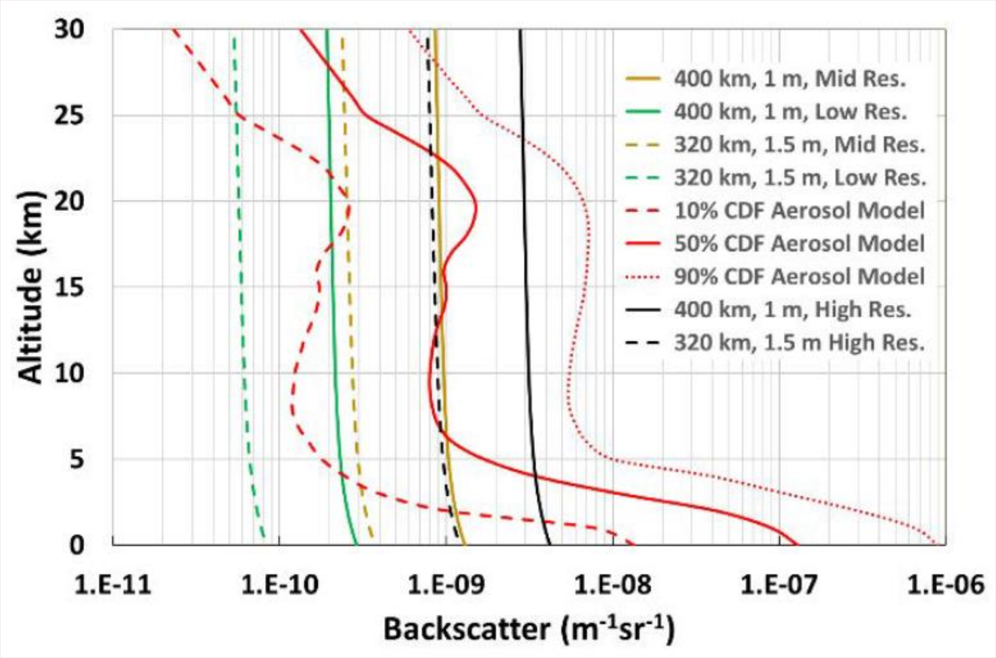
- Assumed Aerosol Backscatter at:
- ~PBL Top: $\sigma > 3x10^{-8}$ /m/str
  - 500 hPa Height: $\sigma > 1x10^{-9}$ /m/str
  - σ = Global Median Backscatter
  - Cloud Fraction ~ 0.6
- Payload Key Parameter Assumptions for this Study:
  - Pulse Power= 50 mJ, PRF=200 Hz, 2 Sec min Aggregation Period
  - Receiver Apertures(2) = 80 cm , 30° Off-Nadir,

Aerosol Doppler Wind LIDAR Performance Models from LARC used for 3D Wind Horizontal Resolution Estimates in Real Atmosphere-Median Aerosol σ



(From Henderson et. al, NASA LARC) CLRC '22

LIDAR Minimum Back-Scatter Cross Section vs Along-track (or Horizontal) Resolution (per LOS assumed), with Vertical Resolution as a Parameter

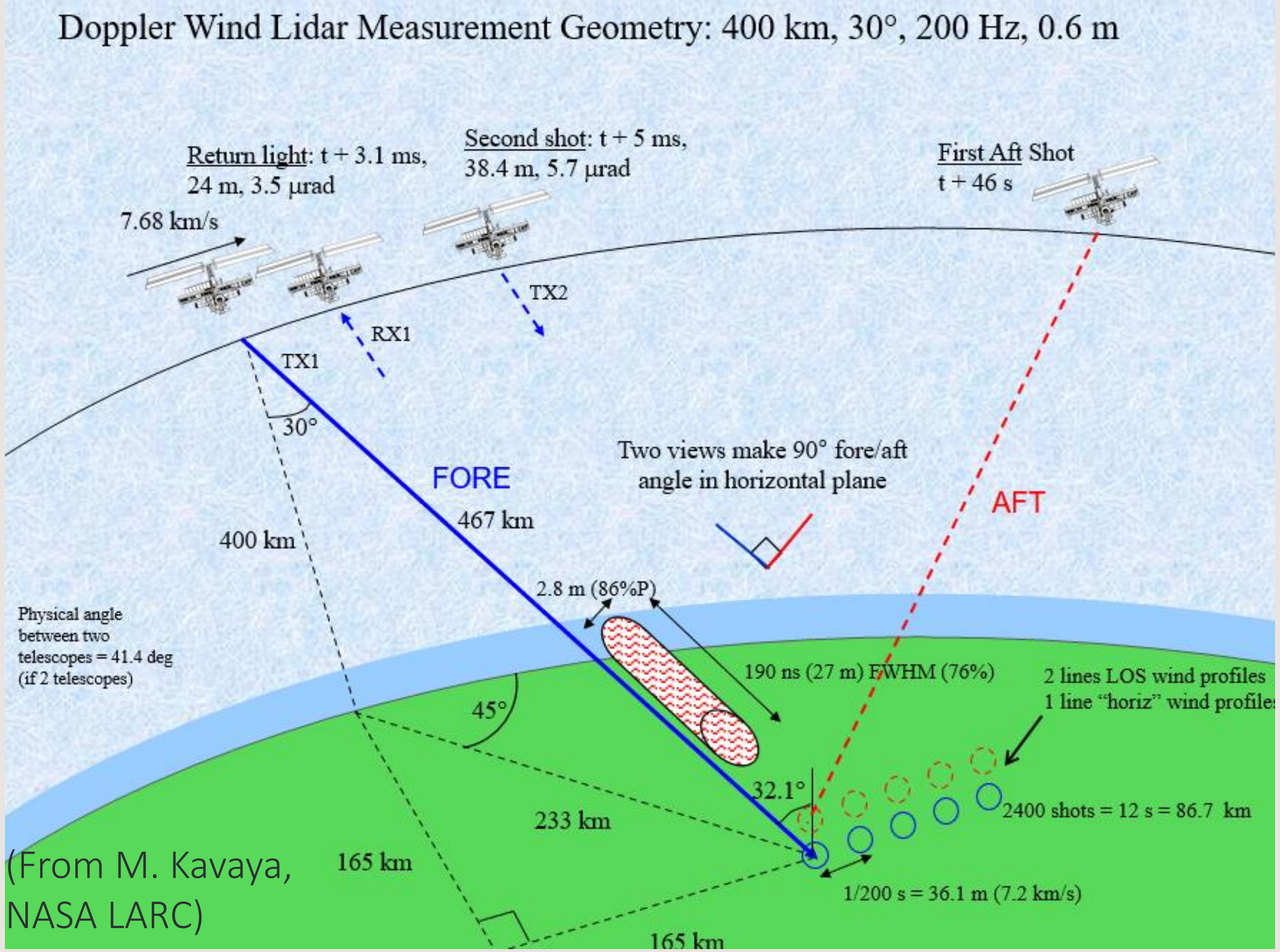


Aerosol Back-scatter Cross-section for 2 micron radiation,(From CLRC '22 Henderson et. Al. Figure 5)

Updated Concept for Two-LOS Doppler Wind LIDAR Observation for Wind SP

- Concept employs two telescopes together with rapid LOS switching to interrogate both horizontal wind vector components
  - ~45 second time-difference between horizontal wind component observations
  - Small cross-track spatial difference between components, depending on time-sampling of different LOS components
- Space Segment Concept updates (planned by LARC to follow January 2023 Airborne Demonstration)
  - Current best aperture estimate—80 cm

Minimum horizontal (along-track) resolution 30 km (50% duty cycle). This is the Geometrically Defined Horizontal Resolution



(From M. Kavaya, NASA LARC)

Comparison of Estimated Doppler Wind LIDAR Performance to BAA Mid-Point Requirements

<table>
<tr><th>Attribute</th><th>BAA Mid-Point Requirement</th><th colspan="3">Estimated Wind SP DWL Observation Performance</th><th colspan="2">Comments</th></tr>
<tr><td>Min. Coverage Area</td><td>Global</td><td colspan="3">~ 0.05% of Globe (Observation Curtains every 2620 km cross-track -at equator)</td><td colspan="2">Observations along track parallel to SSP only</td></tr>
<tr><td>Update Rate</td><td>6 hours</td><td colspan="2">12 hours</td><td>6 hrs</td><td>1 DWL in SSO</td><td>2 DWL in SSO</td></tr>
<tr><td>Latency</td><td>60 min</td><td colspan="3">30-60 min</td><td colspan="2">via LEO constellations</td></tr>
<tr><td rowspan="4">Horizontal Resolution</td><td rowspan="4">40 km @ nadir</td><td rowspan="4">Geometric Resolution: 14 km

(Along-Track only)</td><td colspan="2">Resolution for Average Atmosphere</td><td colspan="2" rowspan="4">• 50% Duty Cycle per LOS
(e.g. (7 km fore, 7 aft),
• Mid-trop Limiting Factor: Aerosol Density

• At PBL Top, Back-Scatter from Cloud and Aerosol
• Below PBL Top Limiting Factor: Cloud Masking</td></tr>
<tr><td>500 mB: P_{Met}= 0.27</td><td>103 km</td></tr>
<tr><td>PBL Top P_{Met} ≈1
($P_{Met\text{-}Cld}$+$P_{Met\text{-}Aer}$)</td><td>14 km</td></tr>
<tr><td>Below PBL P_{Met} = 0.4</td><td>35 km</td></tr>
<tr><td>Vertical Resolution</td><td>2 km</td><td colspan="3"><2 km @ 500 mB,
<0.5 km in clear PBL & PBL Top</td><td colspan="2">Aggregation Choice to Minimize Horizontal Res.</td></tr>
<tr><td>Uncertainty: Direction</td><td>± 10 °</td><td colspan="3"><12 ° rms at 10 m/s @ 500 mb
<3 ° rms at 10 m/s in PBL</td><td colspan="2">Depends on LOS Wind Speed for each LOS</td></tr>
<tr><td>Uncertainty: Speed</td><td>5 m/s</td><td colspan="3">< 2 m/s nominal</td><td colspan="2">Single-LOS Uncertainties combine in quadrature</td></tr>
<tr><td>Vertical Extent</td><td>Surface to just above T'pause</td><td colspan="3">Surface to ~ 20 km</td><td colspan="2">Varies with Regional Aerosol Density</td></tr>
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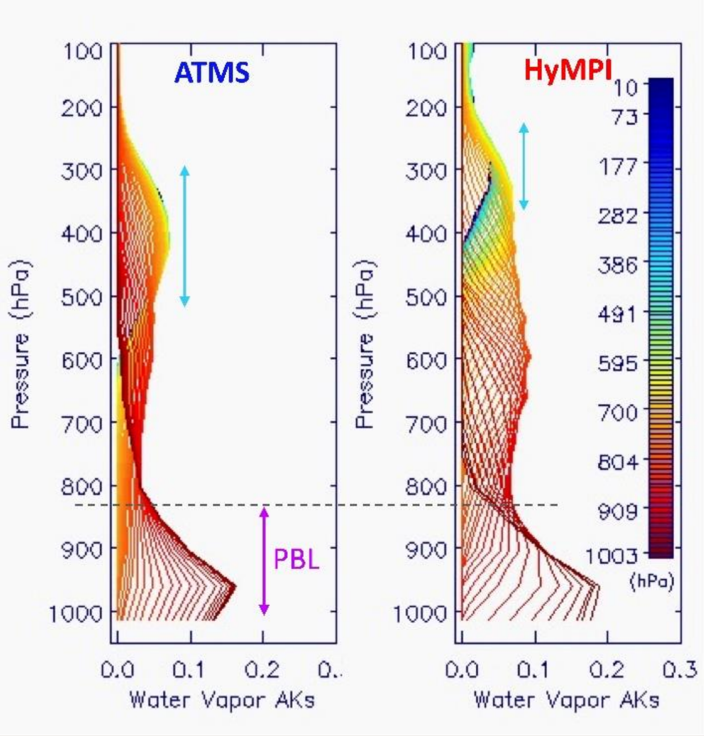
Hyperspectral Microwave Provides Some Improvement in Vertical Resolution relative to ATMS



- This lead to somewhat higher vertical resolution for the hyperspectral implementation as well as some improvement in sensitivity (due to the more complete spectral coverage)
- FWHM of the water vapor averaging kernel is less than ~1.5 km (150 hPa) in the upper troposphere and ~ 2.5 km near the PBL (850 hPa). Pressure-broadening degrades the resolution in the lower troposphere)

From Gambacorta et al, NASA GSFC)

Hyperspectral Microwave AMV Wind Observing System Key Design Parameter Set Used in Example Assessment BAA Minimum Speed Error

Parameter	Value	Notes
Orbit Height	800 km	For 90% coverage
Orbit Type	Sun Sync.	12 hr refresh
Number of Sat	3	AMV Wind Triplet for QC
Satellite Separation	30 min	For multiple spatial samples
Scan Geometry	Conical	For multiple beams in each Band
Scan Angle	52 °	For 95% coverage
Horizontal Resolution	13.2 km	Aperture: 1.1 m (radial) x .67 m (azimuthal)

Parameter	Value	Notes
GSD	6.7 km	Nyquist Sampling
Sample Period	0.03125 sec	Follows ATMS
Microwave Band 1	57 GHz,	• Temp. Profile • Drives aperture
Microwave Band 2	183 GHz	• W Vapor Profile • Under-Illumin.
Number of Spatial Channels per Band	40/40	allows for high- eff- iciency waveguides
Conical Scan Rate	1.66 rpm	Constant rate
Conical Scan Range	180 °	50% duty cycle

Instrument and Mission Design Concept Considerations for Microwave AMVs

- Instrument Payload Size, Mass, and Power Strongly Driven by Microwave Aperture Diameter and Number of Simultaneous IFOVs per Major Band
- Signal collection (integration) periods similar to ATMS needed to support temperature/water vapor vertical profiles for AMVs (~ 30 ms/sample)
- The significant reductions in IFOV needed for even NOAA's minimum 3D Wind requirement (Wind Speed)
  - → Multiple simultaneous microwave channels needed for each major band
- Axial Scan Mode of Spatial Coverage Used in ATMS, AMSU does support multiple simultaneous channels per major band (space between horns)
- Conical – Scan Can Meet spatial image sampling for winds
  - 800 km alt., 110 m aperture, 52°, 15 rpm, 40 ch/major band (57 GHz)

photo: AMSR-E instrument
(160 cm aperture, 7 Ch)
120-cm GPM-GMI also conical)

Plan to refine/update major parameters in consultation with Observation Method Developers

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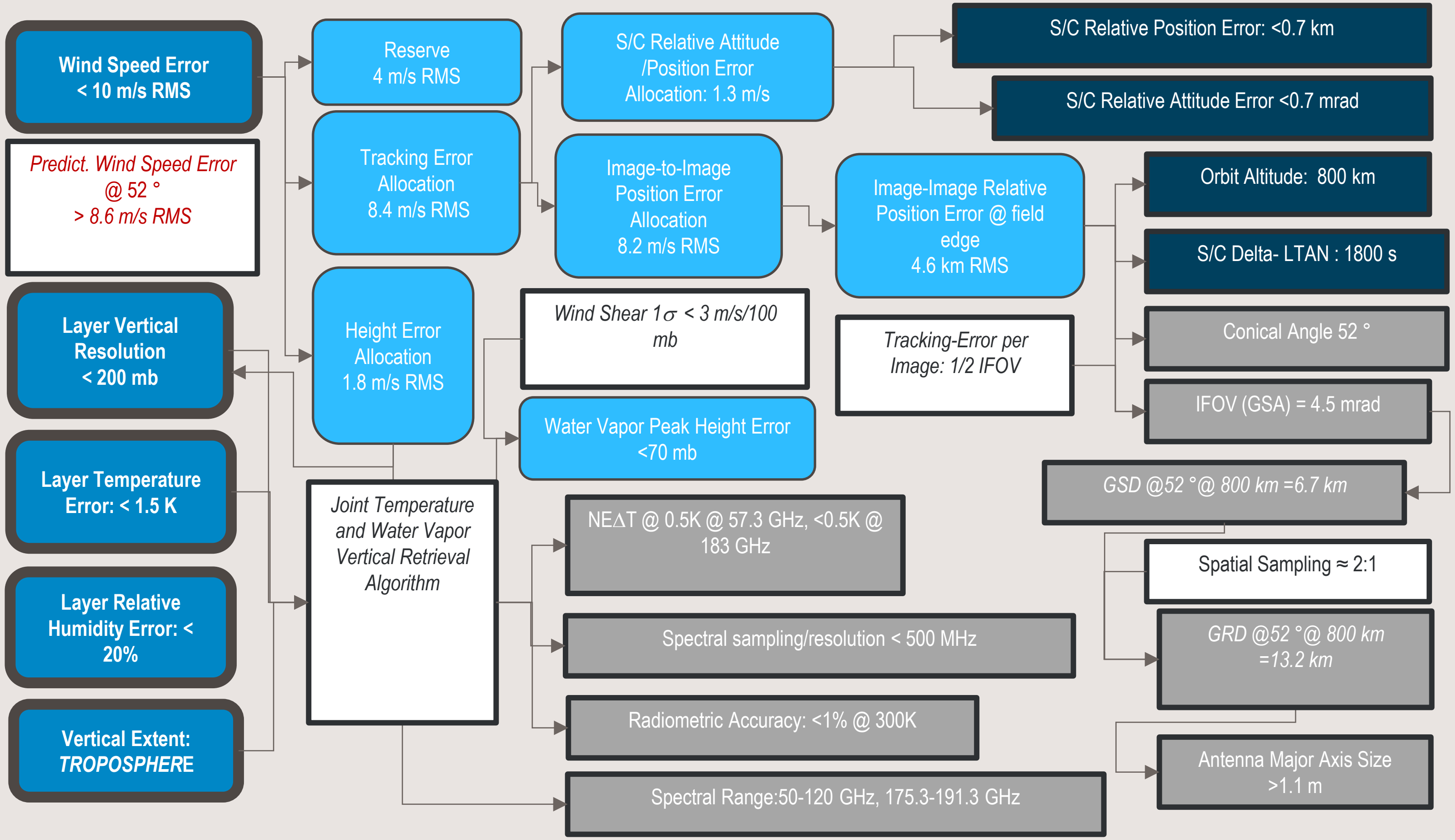
Microwave Band 1	57 GHz,	• Temp. Profile • Drives aperture
Microwave Band 2	183 GHz	• W Vapor Profile • Under-Illumin.
Number of Spatial Channels per Band	40/40	allows for high- eff-iciency waveguides
Conical Scan Rate	1.66 rpm	Constant rate
Conical Scan Range	180 °	50% duty cycle

Allocation of NOAA Threshold Wind Speed Error Requirement Example for Hyperspectral Microwave AMV Observation Method—Including Vertical Error and Horizontal Error Terms

- As for the IR Hyperspectral, the Wind Speed Error Depends on both Instrument Horizontal Resolution/Sampling and Vertical (Retrieval) Resolution
  - Parameters chosen to meet Minimum Wind Speed Requirement-with Margin
- Finer Wind Speed Performance Possible - but with
  - 3 very large instruments providing AMVs
  - Innovative approaches needed to provide simultaneous observation with hundreds of beams



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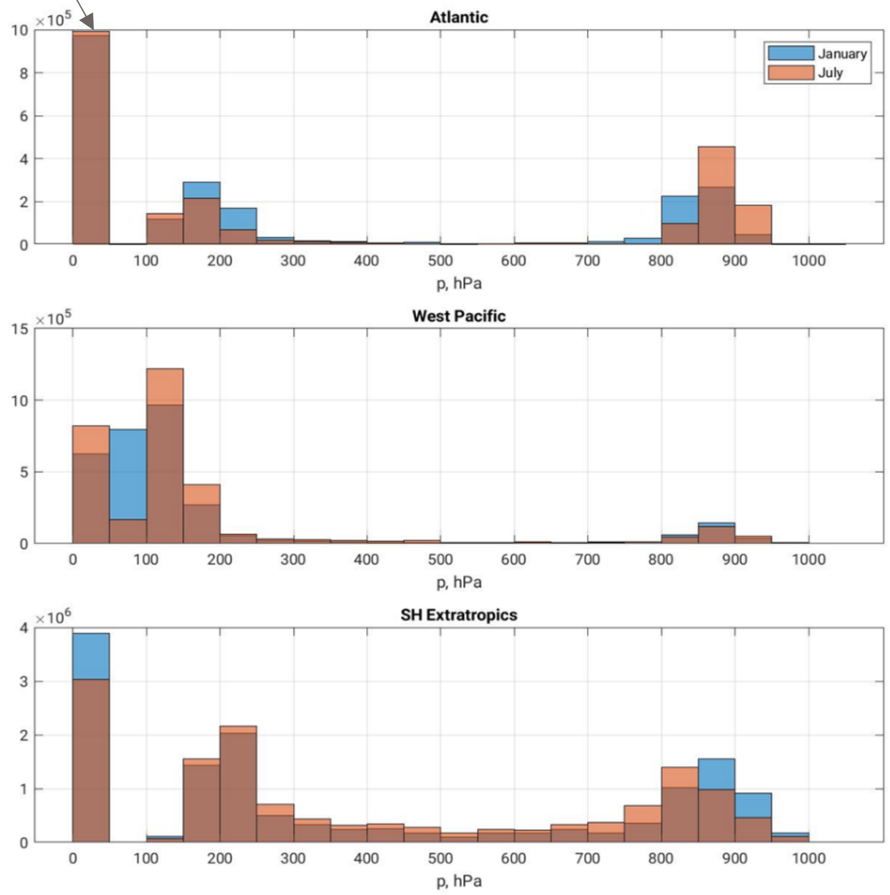
Performance of Hyperspectral Microwave AMVs vs NOAA Minimum Requirements

Attribute	BAA Minimum Requirement	Microwave 3D Constellation Example	Comments
Min. Coverage Area	Close to Global if Possible, Regional Gaps Acceptable	Global (> 95% coverage)	Modest gaps at lower latitudes
Update Rate	24 hours	12 hours per Wind Triplet	Assuming Sun-Synchronous Orbit
Latency	165min	102 min	Presumes single down-link during Svalbard near-polar crossing
Horizontal Resolution	400 km @ nadir	Geometric Resolution ~64 km Meteorological Probability TBD	~ 10x GSD image pixel sampling of Water Vapor Tracers for Geometric Resolution.
Vertical Resolution	4 km	~ 1.5 km @ 200 mb ~ 2 km @ 500 mb ~ 2 km @ 850 mb	Spectral Vertical Retrieval
Uncertainty: Direction	± 15 °	<12 ° rms at 10 m/s	Varies as 1/ Wind Speed
Uncertainty: Speed	10 m/s	< 8.5 m/s	This is based on an estimate with a 110 cm conical scanner with 52° off-nadir angle.
Vertical Extent	Mid-Troposphere to Just Above Tropopause	Surface to 200 mb	Matches ATMS Water Vapor Vertical Coverage (and HyMPI).

Clouds are Not Uniformly Distributed Vertically Through Troposphere

- Cloud levels are predominantly located in the upper troposphere, or lower troposphere (near PBL)
  - Mid-troposphere cloud density is very low, except
    - High Latitudes (± 50-60 degrees and above)
- Bi-Modal Distribution in Cloud-Top Pressure Consistent with Geostationary Imager Cloud AMV observations
- Limits CMIS (and MISTiC Cloud AMVs) wind observation density in mid-troposphere
- The G5NR somewhat over-emphasizes this effect. Real atmosphere has somewhat higher mid-level cloud density

Cases with no cloud obscuration fall in the "0" bin .



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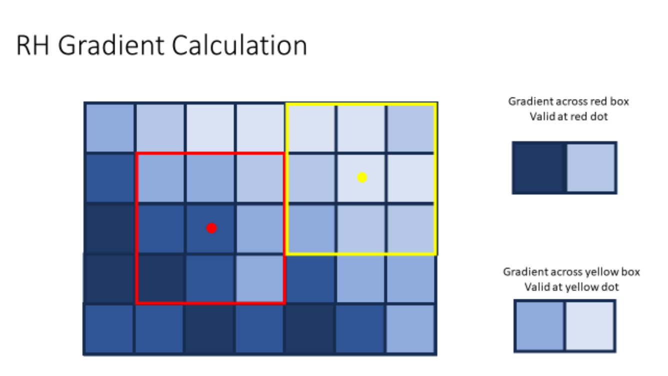
Water Vapor AMV Probability Estimated Using GMAO's Relative Humidity Gradient Method

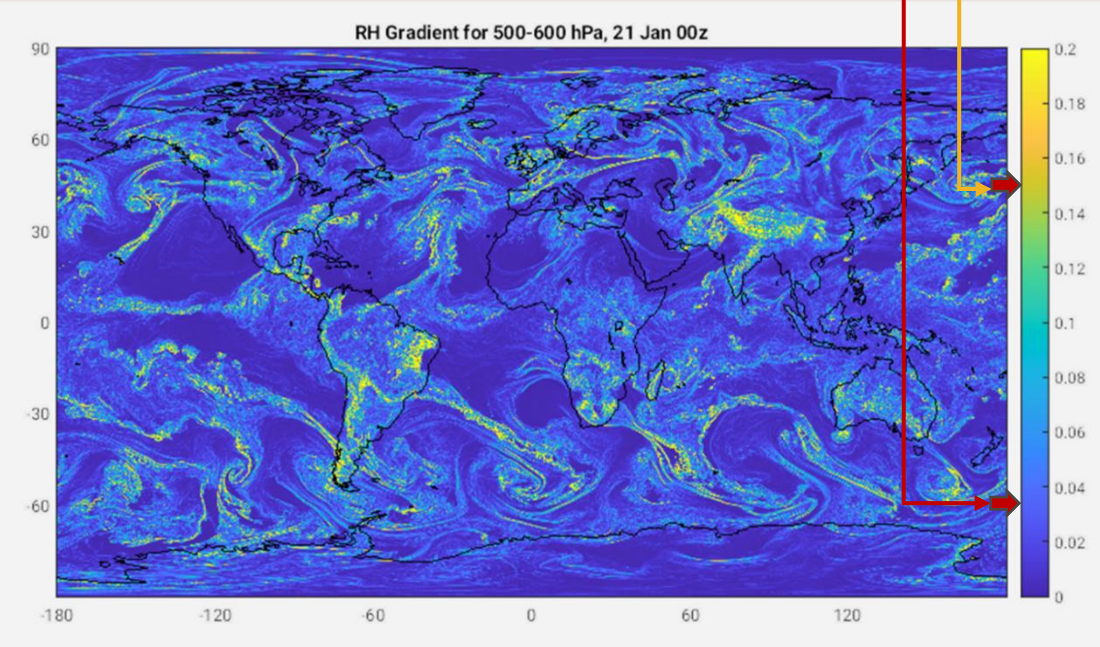
- Model fields smother than MISTiC Sensor would resolve
  - < 2.5 km RH vs 30 km model field
- OSSEs (and this study) use GMAO's Gradient Method
- Not all higher-gradient regions yield good (2D) wind vectors



- Regions with moderate gradients are very widely distributed across the globe, over both land and ocean, and at all latitudes. (*MISTiC AMV Cap.*)
- Regions with the highest gradients are also widely distributed-but less-so. (Hyperspectral Microwave AMV Capability)
- Never-the-less, there are regions, some spanning hundreds of kilometers, where the gradients are very low, and give few AMV wind observations.

Hyperspectral Microwave Mapper RH Difference Capability (NOAA Minimum)

MISTiC RH Difference Capability (averaged over 20 km)

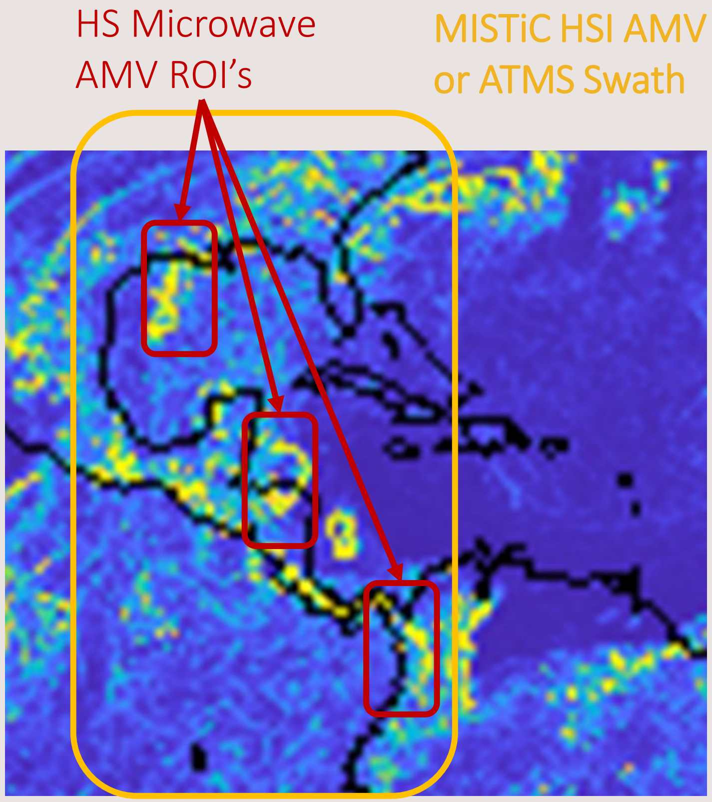


Model Relative Humidity Gradients Indicate Significant Hyperspectral AMV Density for Mid-Troposphere

Example: Cueing a Narrow-Field Hyperspectral Microwave AMV via IR Hyperspectral AMVs , ATMS, and GOES

- Global HS Microwave AMV observing requires significant space segment resources (several Large Multi-beam Conical Scanners)
- Significant SWAP-C reductions possible for a Region-of-Interest HS Microwave AMV observing
  - Significant power/size reduction if just a handful of RF beams needed
  - Region—of-interest scanning might use cross-track scan methods
  - Potential for advanced tech. electronically-scanned approach (e.g. Blackwell et al)
- Data from other sensors (distributed architecture) or NWP could cue this HS Microwave AMV ROI sensor where to look
  - IR HS AMVs (zones of convergence), ATMS (high q), or GOES (high cloud tops)

A cued Hyperspectral Microwave AMV approach could be tailored to observe the winds-just below thick clouds-where no other method can.



Example G5NR Model Field Relative Humidity Gradients for 500-600 hPa Layer