NASA Instrument Incubator Program (IIP) MISTiC™ Winds

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

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MISTiC™ Winds

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

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

NASA ESTO IIP PI: Kevin R. Maschhoff, BAE Systems
Science Team: H. H. Aumann JPL, J. Susskind NASA GSFC
MISTiC™ Winds- Two Affordable Measurement Concepts to Reduce Weather Forecasting Errors

- MISTS™ 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

- **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**
  - $\leq 0.1 \text{K Added Error in Lower Troposphere}$
  - NOTE-AIRS Version 6 Algorithm Primarily uses /SWIR MWIR Channels for Sounding, using LWIR Channels only for Cloud-Clearing
- **Fine spatial resolution ($\sim 3 \text{ km @ nadir}$) 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

- SWIR Coverage at NEΔT and Δν Sufficient for CO₂ 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. N₂O
- 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 Observe Moisture in for Upper Troposphere—but, UT is Observed with 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

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

- 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
- 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)

→ 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

- **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)
- **Measurement Risk Reduction**
- 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 (by 10/16)
MISTiC Winds Airborne Test CONOPS

• **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 Jet Stream (300mB) "Steering" Winds (500mB)
  - Cloud-Drift and Lower-Level Moisture Field Motion (750 mB)
  - OSSEs by NASA and NOAA Show 500 mb Wind Assimilation has Greatest Weather Forecast Impact

Platform Drift (GPS-Tracking)

IASA-A on METOP-A
ΔT = 45 min

IASA-B on METOP-B

H_{ob} > 30 km (>98,500 ft AGL)

H_{Cld} ~ 3 km

H_{WV} ~ 10 km

H_{Ground} Level

RAWINDSONDE Reference

Nominal Vertical Wind Field

Jet Stream (300mB)

"Steering" Winds (500mB)

Cloud-Drift and Lower-Level Moisture Field Motion (750 mB)
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

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

- 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
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).

- 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).

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

PI: Kevin R. Maschhoff, BAE Systems

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

IIP-13-0004

**TRL_{in} = 4**

**TRL_{current} = 4**
GOES-R Sounder (HES) after Formulation Phase
(Geo Hyperspectral Sounding Feasible)

GOES-R Sounder

- 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 μm (1689-2400 cm⁻¹)
  - 9.65-14.7 μm (680-1036 cm⁻¹)
- Spectral Resolution: λ/Δλ > 1000
- NEΔT: 0.2K
- Spectral Stability: <0.01 Δλ

HES

- Mass: 214 kg
- Power: 326 W
- Data Rate: 7.3 Mbps
- CONUS Sounding Coverage Rate:
  - CONUS/hr @ 5 km GSD
- SW/M Coverage Rate:
  - 62 Deg. Disk/hr @ 10 km GSD
- Disk Sounding Coverage Rate:
  - 62 Deg. Disk/hr @ 20 km GSD
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

Modeled Brightness Temperature Change Due to Increase in Boundary Layer Moisture

- Red 5 cm H$_2$O
- Blue 6 cm H$_2$O

(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

\[ \vec{V}_g \approx \frac{1}{f} \vec{k} \times \nabla \Phi = \frac{R}{f} \ln \left( \frac{p_0}{p_1} \right) \vec{k} \times \nabla p T(\vec{x}) \]

\[ \frac{D\vec{V}}{Dt} = -f \times \vec{V}_a \]

Ageostrophic Wind → Indicative of Weather Pattern Change

- Acceleration-Related to Ageostrophic Wind

\[ \vec{V}_{gr} = \frac{2 \vec{V}_g}{1 + \left( 1 + 4 \frac{\vec{V}_g}{fR_T} \right)^{1/2}} \]

\( \Phi \) = 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

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

<table>
<thead>
<tr>
<th>KPP</th>
<th>KPP Attribute</th>
<th>Requirement</th>
</tr>
</thead>
<tbody>
<tr>
<td>3D Motion Vector Winds</td>
<td>Layer Wind Speed Uncertainty</td>
<td>&lt; 2 m/s rms</td>
</tr>
<tr>
<td>(Moisture and Cloud Motion</td>
<td>Layer Wind Direction Uncertainty (above 10 m/s)</td>
<td>&lt; 10 degrees rms</td>
</tr>
<tr>
<td>Vectors)</td>
<td>Layer Height Pressure Height Assignment Error</td>
<td>&lt;30 mB</td>
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<tr>
<td></td>
<td>Layer Effective Vertical Thickness</td>
<td>&lt;100 mB</td>
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<tr>
<td></td>
<td>Minimum Pressure of Highest Pressure-Level</td>
<td>&lt;350 mB (MMV)</td>
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<tr>
<td></td>
<td></td>
<td>&lt;500 mB (CMMV)</td>
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<tr>
<td></td>
<td>Tracer Potential Density (Cloud-Free Conditions for MMV, Cloud Contrast for CMV)</td>
<td>&gt;1 per 6 km sq per vertical layer:</td>
</tr>
<tr>
<td>Temperature Vertical Profile</td>
<td>Layer Effective Vertical Thickness</td>
<td>&gt;100 mB (~ 1 km)</td>
</tr>
<tr>
<td></td>
<td>Layer Temperature Accuracy</td>
<td>&gt;1 K</td>
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<tr>
<td></td>
<td>Sounding Measurement Potential Density</td>
<td>&gt; 1 per 6 km sq</td>
</tr>
<tr>
<td>ObsFrequency</td>
<td>Observation Refresh Period</td>
<td>&lt;3 hours (4 planes)</td>
</tr>
</tbody>
</table>

MISTiC Winds Observes both Total Wind Velocity Vector and the (via IR Sounding) the Geostrophic/Gradient Wind Vector Component in ≥ 6 Layers