MISTiC WINDS, A MICRO-SATELLITE CONSTELLATION APPROACH TO HIGH RESOLUTION OBSERVATIONS OF THE ATMOSPHERE USING INFRARED SOUNDING AND 3D WINDS MEASUREMENTS

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Abstract

MISTiC[TM] Winds is an approach to improve short-term weather forecasting based on a miniature high resolution, wide field, thermal emission spectrometry instrument that will provide global tropospheric vertical profiles of atmospheric temperature and humidity at high (3-4 km) horizontal and vertical (1 km) spatial resolution. MISTiC's extraordinarily small size, payload mass of less than 15 kg, and minimal cooling requirements can be accommodated aboard a 27U-class CubeSat or an ESPA-Class micro-satellite. Low fabrication and launch costs enable a LEO sun-synchronous sounding constellation that would collectively provide frequent IR vertical profiles and *vertically resolved* atmospheric motion vector wind observations in the troposphere. These observations are highly complementary to present and emerging environmental observing systems, and would provide a combination of high vertical and horizontal resolution not provided by any other environmental observing system currently in operation. The spectral measurements that would be provided by MISTiC Winds are similar to those of NASA's Atmospheric Infrared Sounder that was built by BAE Systems and operates aboard the AQUA satellite. These new observations, when assimilated into high resolution numerical weather models, would revolutionize short-term and severe weather forecasting, save lives, and support key economic decisions in the energy, air transport, and agriculture arenas–at much lower cost than providing these observations from geostationary orbit. In addition, this observation capability would be a critical tool for the study of transport processes for water vapor, clouds, pollution, and aerosols. Key technical risks are being reduced through laboratory and airborne testing under NASA's Instrument Incubator Program.

1. INTRODUCTION

The concept for using infrared radiance spectra to measure the vertical profile of atmospheric temperature and water vapor (infrared sounding) was first advanced by Kaplan et al[1] in 1959. NASA's AIRS instrument[2], launched into a low-altitude polar orbit 2002, provided the first on-orbit demonstration of this method implemented with hyperspectral radiances-in the case of AIRS, there are nearly 2400 spectral channels. Observations from AIRS and other LEO hyperspectral sounders have since become one of the most important inputs into national operational numerical weather models[3,4,5,6]. NOAA evaluated the possibility of including a hyperspectral IR sounder on the GOES-R series[7], but determined that the cost and risk was too high, in light of budget constraints (after a combined NASA and NOAA expenditure of nearly $400M). The indefinite deferral by NOAA's GOES program of this observation method-that has been shown to provide significant weather forecast impact -was one of the primary motivations for MISTiC[TM] Winds.
3D-Winds, or vertically-resolved atmospheric motion-vector winds (AMVs), was one of the planned observations from the GOES-R IR sounder series, in light of the frequent observation opportunities available from GEO. AMVs have been observed by GEO meteorological imaging instruments since the introduction of the geostationary weather satellite in the 1970's and '80s. While these Met-imager-based wind observations provide a benefit to the numerical weather prediction models (NWP), the RMS wind velocity error projected for the GOES-R series imager (the Advanced Baseline Imager), remains relatively large, near 5-6 m/s[8], roughly 3x higher than the velocity error needed by NWP models[9].

AMVs are determined from observing the horizontal displacement of a feature in either the 2D water vapor field, or the cloud field, over a known time interval. This feature velocity, identified with the wind velocity, must

then be assigned a height in the atmosphere. The two leading wind-velocity error terms for met-imagers are the errors in the vertical height assignment, and in the relative position change of the tracked feature. The GOES ABI improves the accuracy of the relative position term, by moving from the 4 km resolution of current GOES imagers to 2 km in ABI. The GOES-R IR Sounder would have addressed the height-assignment error by using an ensemble of high spectral-resolution channels from which a more accurate feature height can be determined.

MISTiC[TM] Winds (Midwave Infrared Sounding of Temperature and humidity in a Constellation for Winds) addresses both of these AVM wind error terms, at a system cost much lower than that of a GOES-R class IR sounder. MISTiC™ does this while providing a measurement of the vertical temperature and moisture profile of the troposphere at unprecedented spatial resolution and refresh rate.
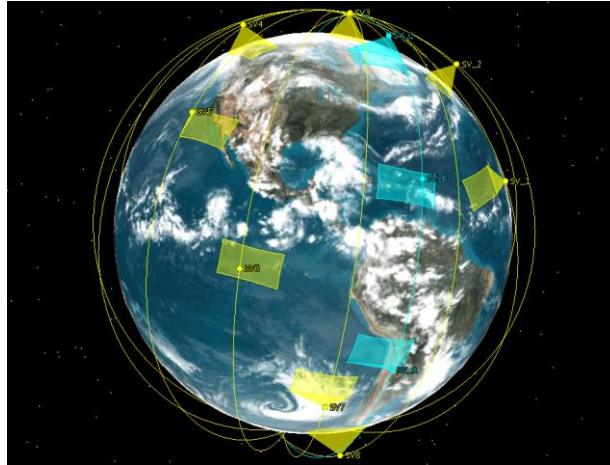
Figure 1: Two MISTiC[TM] Polar-Orbiting Constellations are Shown, One Group of Three in a Single Orbital Plane, that Observe a Wind Triplet Blue), Frequent IR Soundings from Separate Orbital Planes (Goldenrod)

A true 3-D Wind observation capability has been shown by observation system simulation experiments (OSSEs) to have greater impact on weather forecast accuracy improvement than provided by additional observations of the atmospheric mass fields[10]. While the approach to 3-D Winds has long been thought to be a Doppler wind LIDAR, MISTiC[TM] Winds AVMs may provide comparable 3D-Wind measurements at substantially lower cost, for observations in the middle and upper troposphere.

The key technical risks in meeting mission objectives relate to providing accurate, precise hyper-spectral radiometry within the limited accommodations of a micro-satellite. Recently completed design studies continue to show the practicality of this approach. Remaining technical risks will be reduced through laboratory, airborne, and radiation-tolerance testing of an advanced-technology infrared focal plane array, under NASA's Instrument Incubator Program.

This innovative approach, utilizing state-of-the-art sensor technology in a novel architecture, will make critical new atmospheric state and transport observations affordable to the nation.

2. MISTIC[TM] WINDS WEATHER OBSERVING SYSTEM CONCEPTS

One of the central ideas behind MISTiC[TM] Winds is the use of a constellation of small satellites, each hosting a miniature infrared spectral sounding instrument, to enable much more frequent observations of the three-dimensional atmosphere than a single instrument in LEO could provide. Two separate observing concepts, each using the same spectrometer implementation, are illustrated in Figure 1. The first of these provides infrared soundings of the atmosphere at regular, evenly spaced intervals. For example, 12 satellites in sun-synchronous orbit with regularly spaced orbital planes provide an IR atmospheric sounding observation refresh-rate of 1 hour, globally. A second constellation concept employs groups of three satellites in an

orbital plane, with nodal crossing times separated by a short interval, nominally 10 minutes. One such wind-triplet group is shown, in blue, in Figure 1. Each group of three observes a motion-vector wind triplet, analogous to three sequential views of a region by a GEO met-imager, or, for polar regions, by the NASA MODIS instrument, which scans over the polar regions each 112 minutes. AMV winds, such as that shown in Figure 2, are a derived product, with wind velocity being determined from three radiance images. Twelve MISTiC™ satellites in this constellation type would provide vertically-resolved wind velocity measurement, globally, with a re-fresh rate of 3 hours, together with vertical temperature and moisture soundings of the troposphere with the same 3-hour refresh rate.
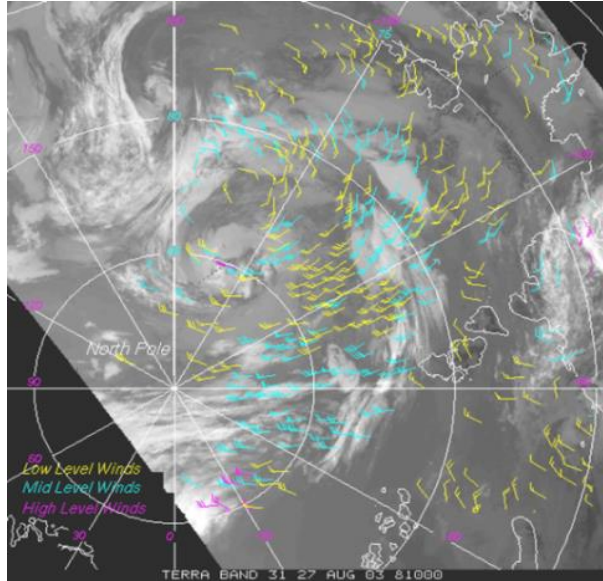

Figure 2: MODIS Winds (from H. H. Aumann, JPL)

The MISTiC™ Winds combination of observations is expected to be particularly advantageous for NWP. The differential equations solved numerically to provide a weather forecast constitute an initial-value problem, which requires initial conditions provided by weather observation for solution. MISTiC™ Winds observations would provide information on both the initial atmospheric state, and its first time-derivative, as initial conditions for NWP. One major advantage of LEO vs GEO hyperspectral sounding observations is that it is much easier to provide high spatial resolution, comparable to that of the GOES-R ABI, with a LEO sounder than with a GEO sounder. The required instrumentation is much smaller and much lower in mass and cost. The combination of high vertical and horizontal resolution and refresh rates allow the short-term three-dimensional behavior of the atmosphere to be observed.

3. MISTIC™ INSTRUMENT CONCEPT

The MISTiC™ instrument is a dispersive imaging spectrometer, which combines features of BAE Systems' airborne and ground-based hyperspectral imaging systems developed for the Department of Defense with spectral resolution, range, and spectral calibration stability and knowledge requirements derived from the NASA AIRS instrument requirements.   A conceptual view of this instrument in operation is shown in Figure 3. The instrument will be carried aboard a small satellite in polar sun-synchronous orbit. An internal scan mirror scans the slit-image field of view across the surface of the earth from east to west as the satellite progresses through the orbit. Like AIRS, the instrument will periodically observe both deep space, and an on-board blackbody source to provide the data to adjust the raw radiances to correct for detector non-uniformity effects. Sensitive spectrometers operating in this portion of the infrared require cooling for both the spectrometer optics and the detector array. The spectrometer is cooled by using radiator panels that reject its heat to space. The detector is actively cooled.
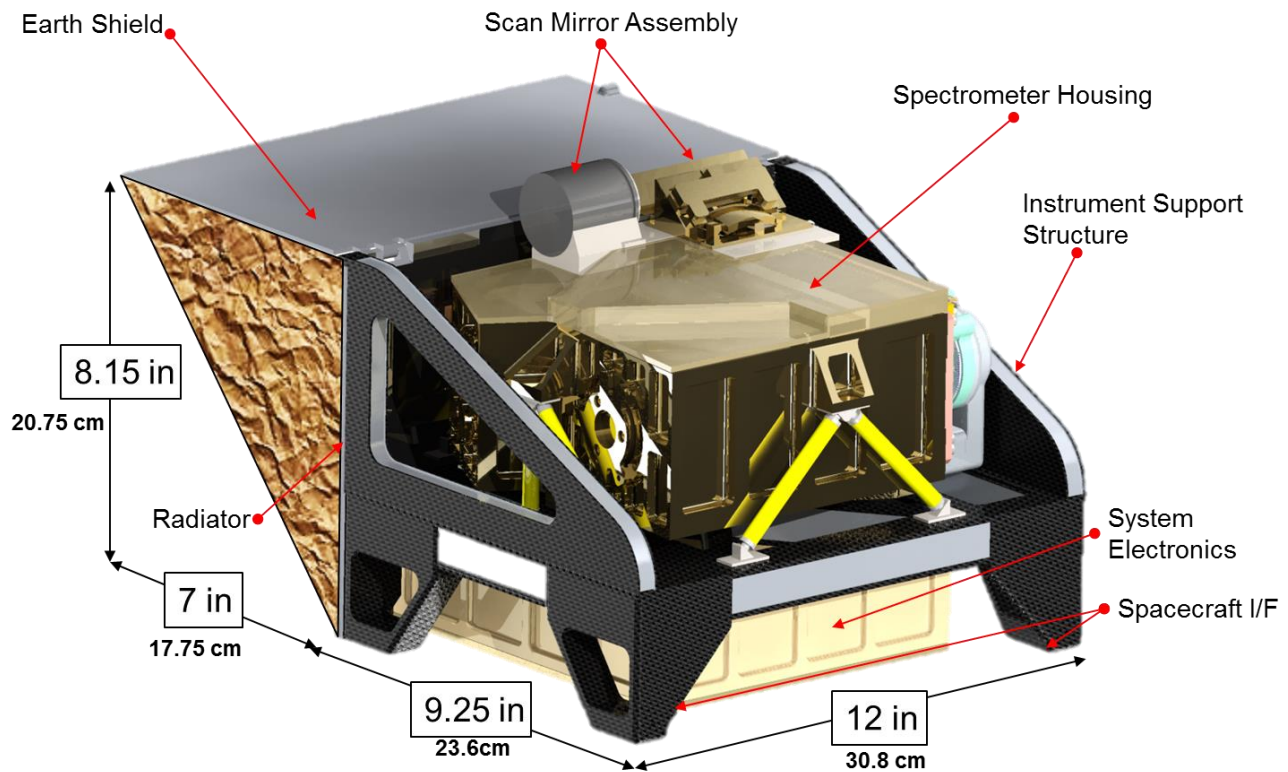
Figure 3: MISTiC™ Instrument Concept, Earth-Shield Deployed, but with Outer Panels Removed

3.1 Achieving High-Quality Instrument Performance within the Resource Constraints of a Small Satellite

The objective adopted for MISTiC™ Winds is to provide high-quality observations of proven scientific and meteorological value, while making dramatic reductions in size, mass, power and cost.   This objective is pursued in a comprehensive way that includes:

- Adopting Spectral Channel and Orbit Altitude Requirements Optimized for the Mission,

- Using Innovative Instrument Opto-Mechanical and Thermal Design to Minimize Resources,

- Leveraging Advanced Instrument Technology and the Rapidly Developing and Increasingly Capable Nano-Satellite Technology Base.

3.2 Requirements Tailoring for the 3D Winds and Short-Range Weather Forecasting Mission

As mentioned above, re-locating hyperspectral IR observations envisioned for GEO to a LEO constellation that can provide comparable refresh rates would provide a major reduction in required resources. A second critical requirements adjustment is to focus spectral coverage range and resolution on the troposphere, and to leverage scientific and algorithmic advances of the AIRS Science Team. Figure 4 shows the planned spectral range for MISTiC™ observations. It includes spectral radiances strongly influenced by CO_2 emission in the troposphere (near 2385 cm^{-1}) -from which the vertical temperature profile is extracted,   and radiances strongly influenced by atmospheric moisture fields (between 1700 and 2000 cm^{-1}), that, together with the temperature profile, can be used to extract vertical moisture profile. This range also includes channels strongly influenced by clouds, by aerosols, and by CO and N_2O in the free troposphere.
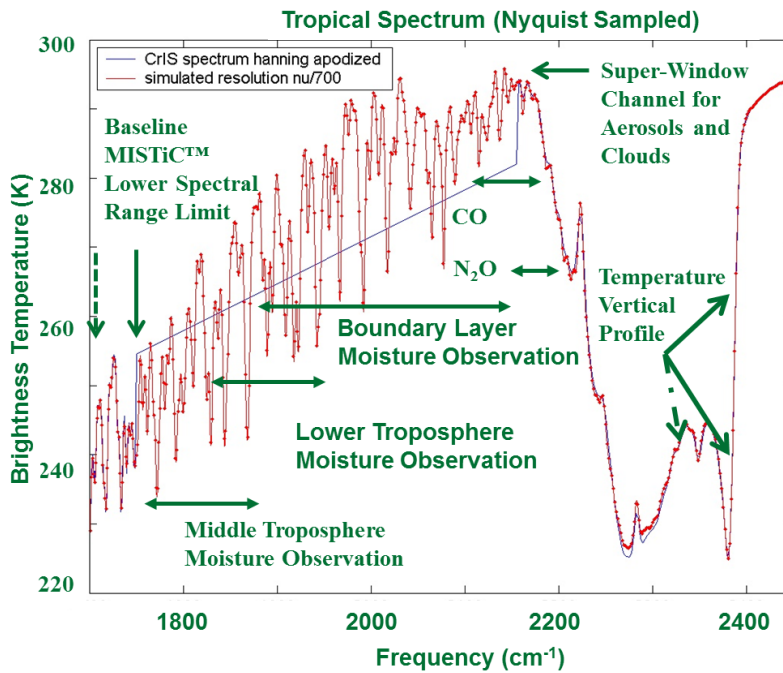
Figure 4: Infrared Emission Spectrum, Highlighting Spectral Regions with Critical Atmospheric Information Content

The adopted spectral range specifically excludes the very long-wave spectral channels also dominated by CO_2 emission, for to include these would dramatically increase the required electrical power, instrument size and cost. AIRS algorithms have advanced to the point where the temperature profile retrieval employs the short-wave channels to retrieve troposphere temperature, with the long-wave channels supporting cloud-clearing and the retrieval of stratospheric temperature[11]. By mission design, observation of stratospheric temperature is not essential for MISTiC[TM], since these will be well-observed by the NASA/NOAA JPSS for decades to come.

An important design consideration for MISTiC is the selection of the lower frequency limit (upper wavelength limit) of the spectral band. This design parameter strongly influences the retrievable information content and data quality for the moisture profile in the upper troposphere, and also strongly influences the size, and power demands of the instrument, due to the exponential dependencies of detector characteristics on band gap and temperature. Under the IIP, the impact on retrieved layer RMS error for both the temperature and moisture were evaluated for different values of the lower-frequency band limit, ranging from 1950 cm^{-1} down to 1650 cm^{-1}. For this study, truth was selected to be the AIRS instrument retrieved temperature and moisture profiles collected for cloud-free footprints over the Pacific Ocean.

The key results of this study are shown Figure 5.   One conclusion is that reasonably accurate temperature vertical profiles can be provided up to a pressure-height of 200 mB, using just the CO_2 emission band centered on 4.3 μm (2383 cm^{-1}). A second key result is that a lower-limit of 1750 cm^{-1} is sufficient to provide a moisture retrieval of sufficient accuracy. While a lower-limit of 1650 cm^{-1} would provide somewhat better retrievals, it would also drive out the lower-frequency detector spectral cutoff, and drive up the required instrument cooling power.   Overall, the major benefit is a reduction in spectral channel count by a factor of 3 for MISTiC Winds relative to current hyperspectral sounders, and the exclusion of the most resource-intensive channels. It has also since been recognized that the temperature vertical profile can be accurately retrieved with somewhat coarser spectral resolution than used for AIRS, (matching the effective spectral resolution of CrIS), and this fact has been taken into account in the selection of MISTiC Winds spectral resolution and sampling requirements.

1 Km Layer Temperature (K) RMS Differences from Truth

1 Km Layer Precipitable Water RMS % Differences from Truth
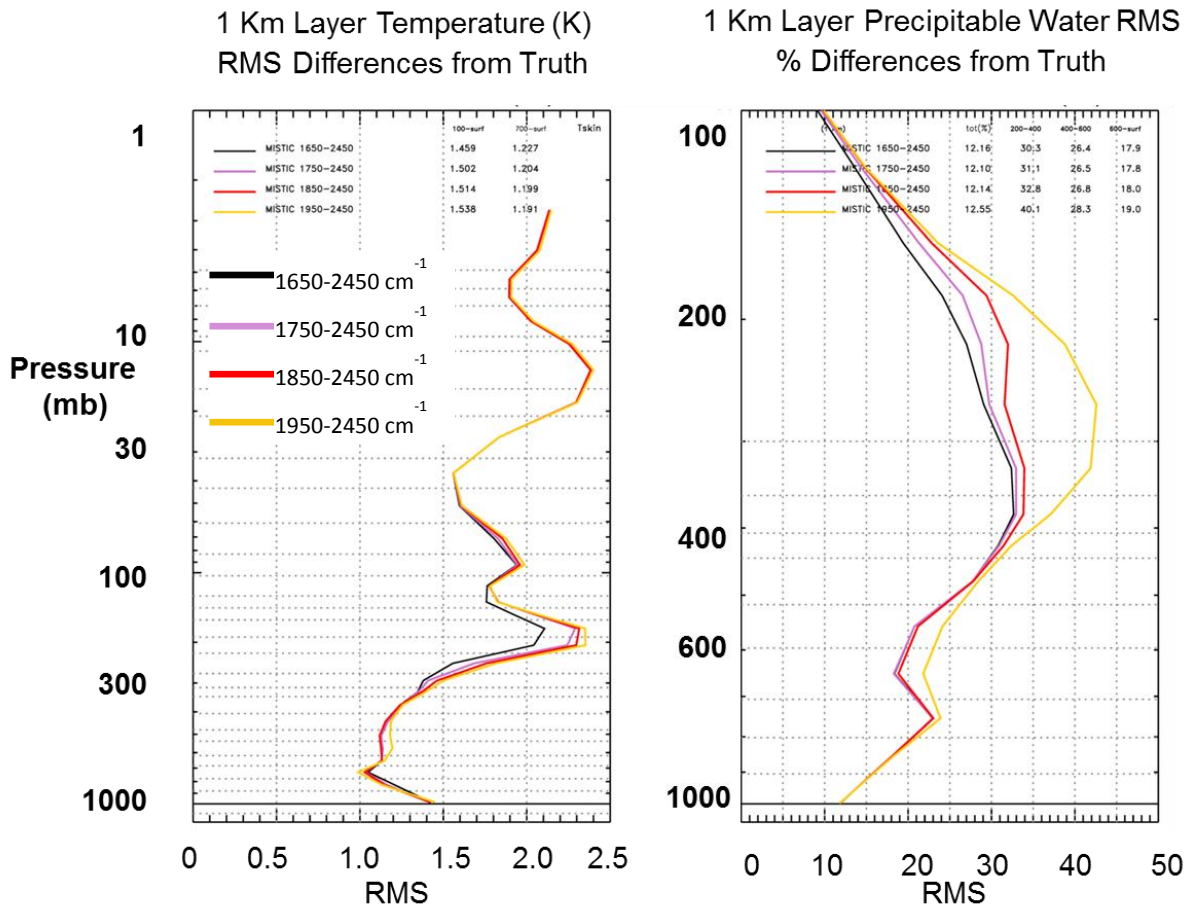

Figure 5: Vertical Atmospheric Temperature and Moisture Profile RMS Error Dependence on Lower Frequency Band-limit for MISTiC Winds (From J. Susskind, NASA GSFC Sounder Research Team)

The combination of requirements choices, design, and the use of contemporary technology used in MISTiC Winds allow tremendous reductions in instrument size. Figure 6 shows the NASA AIRS instrument, together with the MISTiC™ instrument concept at the same scale. Also, GOES-R Formulation-Phase studies yielded a GEO Sounder instrument size much larger than AIRS, and very much larger than a MISTiC™ instrument.

The AIRS and MISTiC™ mission and requirements, while similar, are not identical. The difference in vertical coverage was addressed above. An area where MISTiC™ provides considerably higher performance is in the area of spatial resolution and sampling density. MISTiC™ is optimized to provide accurate 3D Winds observations, which require both high spectral resolution and high spatial resolution. Key MISTiC™ instrument requirements are summarized in Table 1.

The 3D Winds observation uses a constellation approach, and therefore requires a system-of-systems requirements framework, involving instrument requirements, space craft requirements, and ground-processing requirements. MISTiC™ Winds targets both cloud and moisture-field AVMs. Key requirements that relate to the 3D Wind observations are shown in Table 2.

Observing System Simulation Experiments are essential to evaluate the weather forecast impact of new observing strategies such as MISTiC Winds. An OSSE to evaluate the impact of MISTiC Winds was initiated by NASA GSFC GMAO in April of 2016, with results anticipated in the first quarter of 2017. This OSSE will use the GEOS-5 7- km Nature Run as the truth, and evaluate the impact on both short-term and longer-term forecasts.
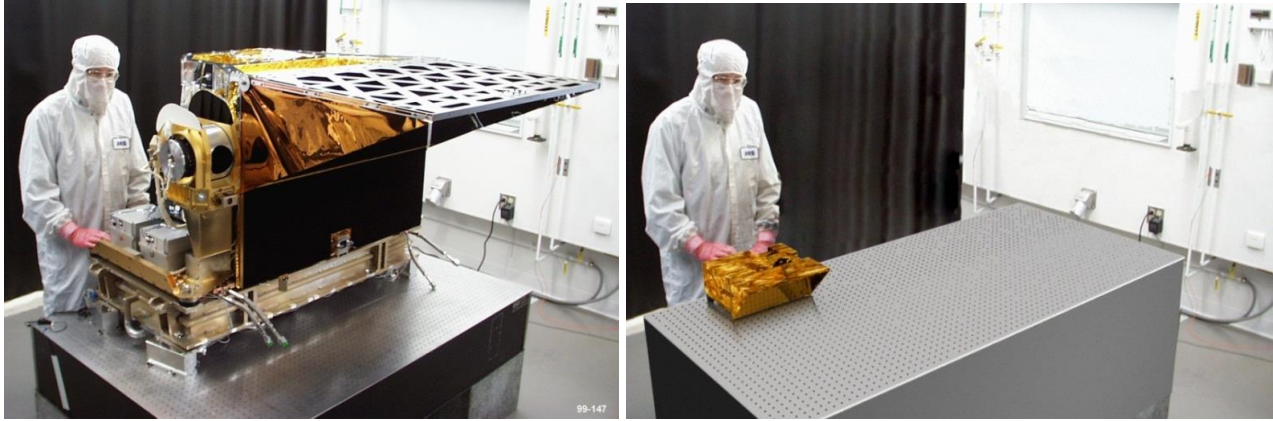
Figure 6: AIRS (above, with Earth Shield Deployed**) and MISTiC™ Instrument Artists Concept (below,** Earth Shield/ Radiator Not Shown for MISTiC[TM]**)**

MISTiC™ Key Instrument Performance Characteristics		
Instrument Characteristic	Value	Comments
Minimum Spectral Frequency	1750 cm^{-1}	5.72 μm
Maximum Spectral Frequency	2450 cm^{-1}	4.082 μm
Spectral Sampling	~ 2:1	<590 spectral samples
Spectral Resolution @ minimum	>700 :1	$\nu/\delta\nu$ (similar to CrIS-Apodized)
Spectral Calibration Knowledge	1/100,000	$\delta\lambda/\lambda$
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	~ 1-2 km	In Lower Troposphere
Layer Accuracy—Humidity	~ 15 %	In Lower Troposphere

Table 1: Key MISTiC™ Instrument Requirements, and Related Atmospheric Sounding Requirements

KPP	KPP Attribute	Requirement
3D Motion Vector Winds (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 Accuracy	<30 mB
	Layer Effective Vertical Thickness	<100 mB
	Minimum Pressure Height of Highest Level	<350 mB (MMV) <500 mB (CMMV)
	Tracer Potential Density (Cloud-Free Conditions for MMV, Cloud Contrast for CMV)	>1 per 6 km[2] 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[2]
Observation Frequency	Observation Refresh Period	<3 hours (satellites in 4 planes)

Table 2: Key 3D Winds Observation Requirements

4. SUMMARY

MISTiC[TM] Winds will provide an affordable path to high vertical and horizontal resolution infrared soundings, and these can be used in an atmospheric motion-vector winds product to provide a 3D-Wind profile in the troposphere, with the < 2 m/s rms wind speed error needed by NWP for significant weather forecast impact. NASA and NOAA studies have shown that 3D Winds Observations at the quality level expected for MISTiC Winds are the observation that will provide the most significant improvement in weather forecast skill. This advanced weather remote sensing capability is enabled by a very efficient spectrometer design that leverages sounding spectroscopy insights gained over the last decade by NASA's AIRS Science Team, and through many years of operational airborne hyperspectral sensor operation. Power demand for the space mission is minimized by introducing an advanced FPA technology (proven in airborne hyperspectral systems) that won't require as much cooling. This technology is being tested for its suitability in the space environment. The combination of efficient design, careful requirements selection, and advanced technology allow us to fit this instrument into tiny, affordable space craft, for launch on small, affordable launch vehicles or in groups of secondary payloads carried into LEO at low-cost. This is an affordable way to build a new weather remote sensing capability to improve operational short-term forecasts for the nation, and provide better observations of dynamic weather systems for both research and operations. The distributed LEO architecture approach to weather observations provides for a resilient system, with low-cost opportunities for the infusion of new observation technologies as they become available.

5. ACKNOWLEDGEMENTS

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