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

K. R. Maschhoff[1]
1) BAE Systems, P.O. Box 868, Nashua, NH 03061-0868 USA

Abstract

MISTiC® 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 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. Key technical risks have been reduced through laboratory and (NASA ER2) airborne testing under NASA's Instrument Incubator Program and BAE Systems IR&D, and through an OSSE performed by NASA GMAO. A summary of the airborne test results and the OSSE will be presented.

1. INTRODUCTION

The MISTiC® Winds concept for using a low-earth-orbiting constellation of microsatellite, each hosting miniature IR spectrometer for providing high-spatial resolution hyperspectral IR soundings and vertically resolved AMV winds in the troposphere has been presented previously[1,2]. The work presented here is an initial report of results from a set of airborne observations that have been performed as one component of an instrument technology and observation method risk reduction program that is preparing the way for a future mission employing microsatellites in constellation for hyperspectral AMV winds and IR sounding observations from space. The airborne component of this risk reduction program allows the demonstration of an IR spectrometer assembly-which is essentially identical to that planned for the space version of the MISTiC instrument- within a dynamic and thermal environment highly relevant to the future space mission. The flight plan for these airborne demonstration observations included repeat-pass observations of various scenes- with time-separations comparable to those used for space-based multispectral AMVs, providing an opportunity to observe the position change of cloud and atmospheric moisture tracer features in hyperspectral imagery. Together, the use of the flight-like IR spectrometer together with repeat-pass imagery from the ER2 provide an initial demonstration of the MISTiC Winds observations method planned for an eventual space mission, together with some initial spectral radiance data.

2. MISTIC AIRBORNE OBSERVATON INSTRUMENTATION AND APPROACH

Hyperspectral infrared sounding of the temperature and moisture vertical profiles have been performed from space since AIRS was launched aboard AQUA in 2002 (AIRS reference). Therefore, the focus of this airborne demonstration for MISTiC is on observations of the cloud and moisture fields using the MWIR portion of the MISTiC spectrum critical to enabling this new observation. One important aspect of the airborne demonstration is that the altitude of the observation should be sufficiently above the atmospheric moisture field so that the observed spectra are closely similar to those expected for a space mission. A second aspect is that the platform should allow repeat observations of the atmospheric field-within a relatively short

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delay of 10 to 20 minutes, so that the changes observed in the cloud and moisture fields are primarily introduced by the wind. Therefore, a near-space demonstration of the atmospheric observations planned for MISTiC Winds can be performed by flying an infrared imaging spectrometer with the appropriate optical characteristics on board a high-altitude air platform such as a high-altitude jet or a high-altitude balloon- and each of these platforms were considered. The NASA ER2 was selected as the platform for these MISTiC demonstration observations. The planned flight altitude of 65 kft above MSL is typically above 99% of the atmospheric moisture. The use of the ER2 allows a re-visit of the scene within the 10-20 minute time-frame. The high-altitude balloon platform is actually capable of much higher altitudes than the ER2, and under the appropriate stratospheric wind conditions, may actually provide enough hang-time for useful image revisit over at least a portion of the observing field. However, the relatively light stratospheric wind conditions needed to ensure a repeat at the desired interval are only available during the stratospheric wind “turn-around periods” in the spring and fall, and the number of launching sites in the US is quite limited. So, in practical terms, the ER2 provides more flexible and frequent for flight opportunities. One additional benefit of the use of a fixed-wing platform is that independent observations of the atmospheric conditions through radiosondes could be implemented using existing radiosonde launch capabilities.

2.1 Airborne Instrumentation

Figure 1 shows the space instrument concept together with the airborne payload implementation. In the airborne implementation, the instrument is hosted within fore-body section of the NASA ER2 Super-pod and is shown at right in Figure 2. The airborne instrument includes the IR spectrometer assembly, mechanical coolers for the spectrometer and IR focal plane array detector, detector array interface and control electronics, a scan mirror, two miniature IR calibration sources, a GPS/IMU, overall instrument telementry, command, and control electronics.

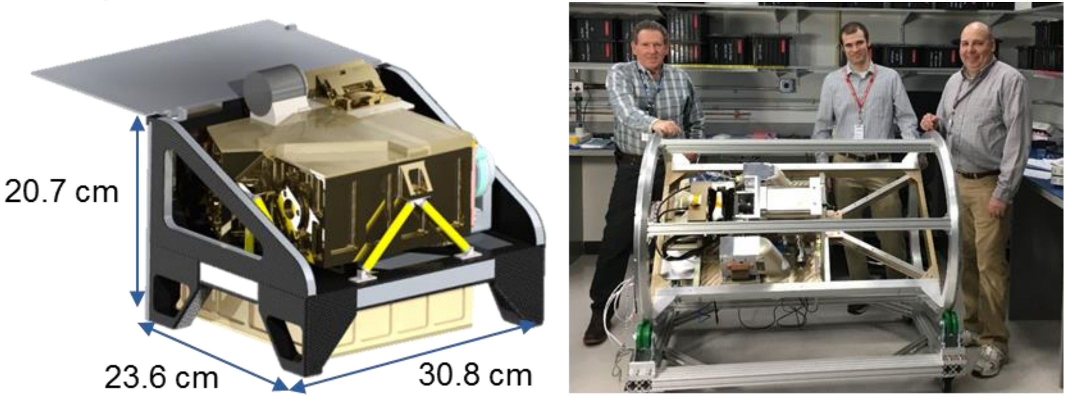
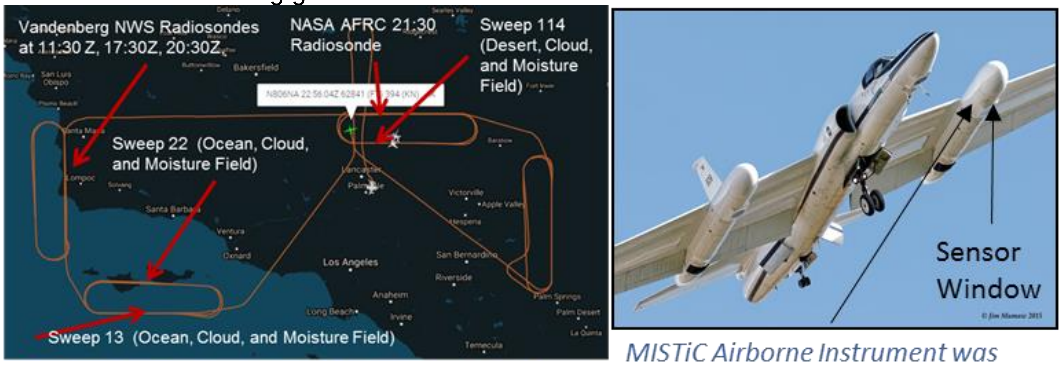


Figure 1: The MISTiC spectrometer, integrated in payload for an ESPA-class microsatellite -on the left, and included in an airborne payload configured to fly in a super-pod on the NASA ER2 -on the right (with team).

The spectrometer optical design covers the spectral range shown in Figure 3, and this build represents a high-fidelity brass-board implementation of the spectrometer assembly for the space instrument. In order to minimize cost for the airborne instrument, an off-the-shelf version of the IR FPA was included. The infrared detector array on this off-the-shelf FPA has useful spectral response over much-but not all- of the range shown in Figure 3. The airborne instrument also includes rugged commercial grade electronics rather than space-grade electronics, and other steps to minimize cost. In some ways, it requires more resources to accommodate the cooled IR spectrometer in an airborne payload than it does in space. The airborne instrument houses the cooled spectrometer within a vacuum vessel, and employs a tactical military-grade cryo-cooler to cool the spectrometer-features unneeded in the space instrument. The optics preceding the spectrometer have a different focal length than that used for the space instrument-to accommodate the difference in altitude between the space and airborne observations. The spectrometer, scan mirror, and radiometric calibration sources are inside of a sealed ZnSe window (not shown in Figure 1) that is required to keep the Super-pod pressurized (at 4 psi) even while the ER2 is flying in the stratosphere. The raw scene data are radio-metrically calibrated by using a two-point method employing radiance from black-body cavity sources at two temperatures to develop correction coefficients for the raw scene data. One complication introduced into the radiometric calibration of the airborne hyperspectral image data is that the Super-pod window is not inside the calibration loop. The effects on the scene radiance-- through window attenuation and window self-emission are addressed through the use of in-flight window temperature data and spectral transmission data obtained during ground tests.



MISTiC Airborne Instrument on NASA ER2 Observed Wind, Temperature, and Water Vapor over the Channel Islands and Nearby Ocean, and Over Edwards AFB

MISTiC Airborne Instrument was Carried within ER2 Super-Pod

Figure 2: ER2 Flight Path on 4 December 2017 on the left and NASA ER2 Showing the Super-pod location for the MISTiC Airborne instrument on the right

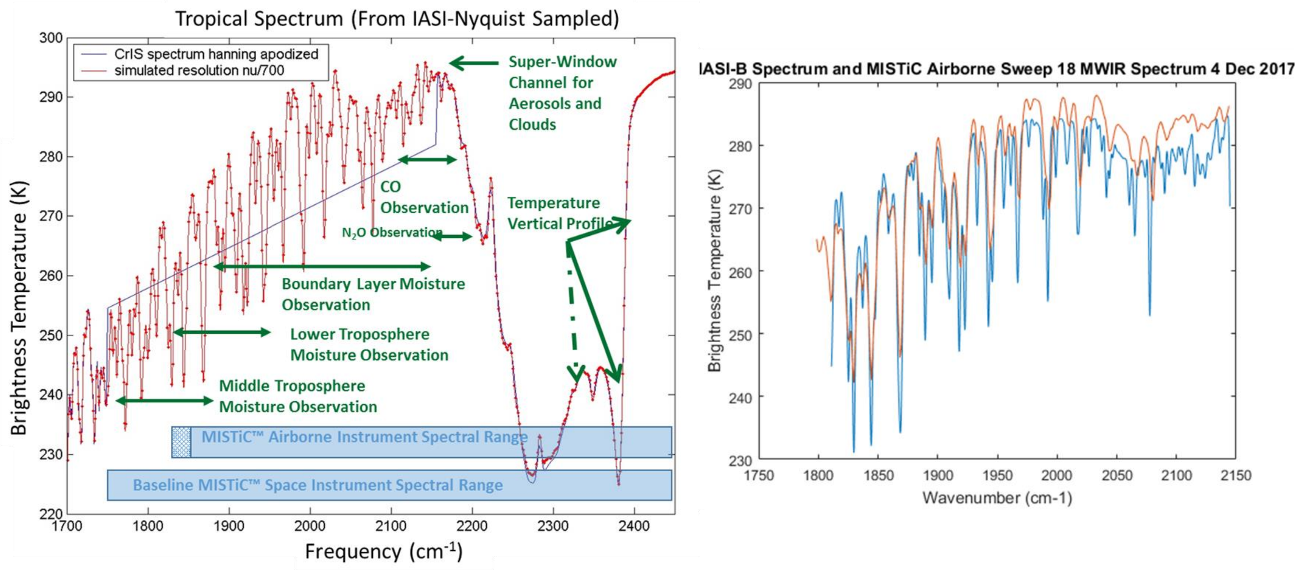


Figure 3: (left) Example IASI spectrum over a tropical ocean scene is used to illustrate the atmospheric information expected from the MISTiC Winds, and (right) IASI-B and MISTiC Airborne observations on 4 December 2017 south of the Channel Islands. IASI-B overflew the area about 1 hour prior to MISTiC.

Figure 3 shows an example IASI spectrum over a tropical ocean scene (and apodized to achieve a spectral resolving power of 700:1) is used to illustrate the atmospheric information content expected from the MISTiC Winds spectral observations. In addition to gas species indicated, the hyperspectral observations will include cloud radiances across much of the spectral range. The planned spectral coverage range for the MISTiC space instrument as well as the more restricted range provided by the airborne demonstration instrument are indicated in the figure. The spectral range obtainable from the off-the-shelf infrared detector array is less than that planned for the space instrument.

2.2 MISTiC Airborne Instrument Flights on NASA ER2

Airborne versions hyperspectral IR sounding instruments have been used many times as part of validation campaigns for AIRS(ref), CrIS(ref), and more recently the GOES 16 ABI(ref). However, the specific use of repeat-pass flight trajectories with an air platform to simulate space-borne acquisition of a sequence of images from which to derive AMVs- with image repeat periods of 10-20 minutes- does not appear to have been reported previously. A key benefit of repeat-pass imagery on this time scale is that the primary changes between images are due to the translational motion of clouds and moisture features as they move with the wind (advection), rather than due to changes in the spatial distribution (shape) of the features themselves. A second practical benefit is that the probability of observing an atmospheric feature on multiple passes from the relatively low vantage point of an aircraft platform is much higher if the time-separations used are not too large.

Flight Path for a MISTiC Observation Demonstration Flight on 4 December 2017

The path of this flight is shown on the left in in Figure 2, and closely followed the plan developed with the pilot and flight planning support at NASA Armstrong. Following launch from Palmdale (approximately 10:30 AM PST), and ascent-stage maneuvers, the ER2 climbed above 60kft above MSL, and MISTiC hypercube collection was initiated while flying to the southwest to the east of Oxnard. (There is evidence of one of the many fires in the region in one portion of the first hypercube of this flight.) After leveling off at the observation altitude of 65kft, the ER2 executed 2 ½ passes around the orbit- following a "racetrack" pattern, for the first Orbit, just south of the Channel Islands. The ER2 then proceeded to a second Orbit (2 ½), which included both land and open-ocean features near Vandenberg AFB. The third Orbit location (2 ½) is over Edwards AFB, and the fourth Orbit location is to the east, over the Twenty-nine Palms region. The fourth Orbit was followed by return-to-base. These Orbit locations were chosen in part to support independent observations of the weather features for comparison to the MISTiC observations. The first two Orbits are close to the Vandenberg AFB National Weather Service RAWINSONDE launch site, which provided measurements of wind velocity and the atmospheric thermodynamic properties. Two additional sondes were launched from Vandenberg on 4 December, supplementing the standard ~ 0Z and 12Z launches. The first Orbit is over the open ocean—just following the IASI-B overpass—providing the simplest situation for comparing MISTiC and IASI-B spectra, and refining MISTiC spectral calibration. The first Orbit also over-flew departure pathway of commercial airliners flying out of LAX, potentially allowing comparisons with ACARS data. The third Orbit was executed over Edwards AFB, when a special RAWINSONDE was launched for MISTiC by the Armstrong weather support staff. Finally, the Twenty-nine Palms Orbit is over the departure and arrival pathway to LAX from the east, providing another opportunity for comparison with ACARS data. AQUA, with AIRS over-flew the area during the third Orbit, as did Soumi NPP and JPSS-1, each hosting a CrIS instrument.

The "Orbit"-the Approach to Repeat-Pass Imaging

The purpose of the Orbit is to enable repeat-pass observations of the scene in order to observe how atmospheric features are translated (the process as "advection") by the wind between observations. The orbit straight and level sections are flown in approximately 6 min., and were chosen to allow 2 or three hypercube collections –referred to as "sweeps" --while the ER2 was in level flight. The individual orbit period was approximately 1000 seconds, and was selected to balance the needs for infrared radiance data SNR (the longer the viewing, the better), and to reduce the likely-hood of the clouds and moisture patterns from either moving out of the field of repeat-observation, or undergoing excess shape or feature change between observations. (A motion-vector wind observation employs multiple observations of the scene, and observes where features (clouds or distinctive features in the moisture field) have moved between observations to compute the wind velocity.)

Notes on the Weather for 4 December '17 Flight

The weather over the region during the 4 December flight was characterized by two phenomena characteristic of the Southern California winter. At low altitudes, the conditions for the famed Santa Ana winds had arisen a few days prior, and a strong low-level easterly wind was flowing throughout the LA region through much of the week. The air was quite dry and relatively warm for December, and contributed to an outbreak and rapid spread of more than a dozen wild-land fires in the LA region. These conditions interrupted the more typical December conditions in which a strong temperature inversion forms over the eastern Pacific, forming and trapping a low-lying marine cloud layer. At higher levels, a strong NW flow from the eastern Pacific spreads over the region. These low-altitude and higher-altitude patterns combine to produce conditions of particularly high wind-shear. From a weather remote sensing perspective, these conditions represent one of the most complex and error-prone situations for traditional motion-vector winds observations, which use images from multi-spectral imagers in GEO.

Approach to 2D Wind Vector Identification for MISTiC Airborne Observations

The basic approach to observing the wind employed for MISTiC is the geometrical method first developed for Motion Vector Winds following the introduction of GEO multispectral imagers. The image field is examined for features in the cloud or moisture field that have been moved from one location to another during the time interval, and identifies track-points on these features to allow a quantitative measure of the change. This vector position difference is computed using image data, together with attitude and ephemeris data. In MISTiC Airborne, a feature position is determined from the GPS coordinates of the sweep nadir point, that angular position within the image field, GPS altitude, optics focal length, and FPA pixel size. The wind speed observed is just the magnitude of this vector difference. For the operational GEO AMVs, where thousands of AMVs are derived from a sequence of full-disk images, the manual identification of track-points procedure is too time-intensive, has been replaced by a spatial correlation computation method –but that is not needed, given the relatively much smaller number of image-pairs observed in a MISTiC airborne flight. Also, the image pixel-level spatial resolution available from MISTiC airborne is very high (50 m at nadir)-compared to that available to GEO met imagers, simplifying the correct identification of a geometric feature-a wind tracer in multiple positions. Finally, the low altitude of the MISTiC observations and wide angular field introduce substantial geometric distortion of the shape of tracer features as well as a truncation of the feature by the very limited spatial field of view. These are aspects of the images that a human image interpreter can reasonably overcome, but which would pose great difficulties to an automated cross-correlation algorithm. The other critical aspect of the AMV observation is the accurate assignment of height.

3. INITIAL DECEMBER 4 2017 WIND VECTOR IDENTIFICATION FOR MISTIC AIRBORNE

The unusual weather conditions encountered on 4 December informed the choice of which hypercube data sets to examine initially, with an objective of identifying wind-tracking features. First, MISTiC Airborne is most sensitive to low-level observations, given the observation geometry and spectral coverage in the MWIR band. Second, the very dry low-level layer introduced by the Santa Ana winds suggested that there was very limited low-level moisture spatial contrast in the scene. Third, the usually dense marine stratus layer over the adjacent ocean layer was substantially broken up by the Santa Ana. So the initial search for wind tracers was confined to hypercube scenes with broken clouds fields, and focused on cloud motion vectors.

Before considering the wind observations from MISTiC, it is useful to note the character of spectral observations obtained from the MISTiC Airborne instrument, and how these compare to other observations. On 4 December, MISTiC Airborne overflew California's Channel Islands area beginning at approximately 11:30 Pacific time. Approximately 1 hour earlier, the IASI-B instrument overflew and observed approximately the same region. The right side of Figure 3 shows the spectrum observed by IASI-B (convolved to a resolving power of 514:1), and that observed by MISTiC Airborne. There are clear points of correlation, but also some important differences. The MISTiC observation footprint is clear of cloud contamination. The IASI-B observation was the geographically closest (within 0.1 degrees) of the MISTiC observation that was judged sufficiently cloud clear for comparison purposes. It was not entirely cloud-clear though: diagnostics indicated approximately 3K of cloud impact on brightness temperature remaining. Another difference is that the MISTiC Airborne instrument appears to have a spectral resolving power somewhat lower than the resolving power than the 514:1 used for IASI-B. Other laboratory tests have shown that this reduced resolving power is caused by optical elements other than the spectrometer itself. Never the less-they impact the resolving power for the airborne observations. Finally, even with this relatively close spatial match--these instruments have rather substantial differences in spatial attributes. IASI-B observation was made at an angle of approximately 50 degrees off-nadir, so its footprint is approximately 30 km wide, whereas the MISTiC observation, taken also off-axis (at approximately 30 degrees) have been averaged over a 5km footprint. Given all of these differences, the agreement is sufficiently encouraging. The spectral calibration of MISTiC Airborne was intended to be adjusted and aligned with IASI-by the experimental design.

The first wind tracer identified (by its unique banded pattern) is shown in Figure 5. This figure shows images of spectral band 80 in the MWIR group, which represents a local spectral brightness temperature minimum, and is near 2007 cm^{-1}. Images of other spectral channels with similar brightness temperatures appear similar. (Portions of this tracer image are also seen in window channels—those with the highest brightness temperatures--, but in these, it competes with brighter near-surface features.) The specific images coordinates if the feature in each image are used together with the GPS positon and velocity data, instrument scan mirror angle data, and time difference to compute the apparent speed of 6 m/s, or approximately 11.6 knots.

The flight pattern intentionally included portions close to and over the Vandenberg AFB, which hosts a RAWINSONDE launch site that is part of the National Weather Service operational network, launching sondes at nominally at 0Z and 12Z (noon and midnight, Greenwich Time). It was learned that the NWS was also planning supplemental launches from Vandenberg on 4 December, at 17:30Z and 20:30Z, bracketing the timeframe in which MISTiC would be flying over or near Vandenberg. The RAWINSONDE data collected from these mid-period launches are shown in Figure 6, and indicate a speed of 7.3 m/s, or 15 knots for the altitude at which the brightness temperature of the feature matches the temperature-- at 9000ft. The radiosonde data also include a wind direction observation. The difference between the sonde-observed wind direction that indicated by MISTiC observations was approximately 3 degrees.

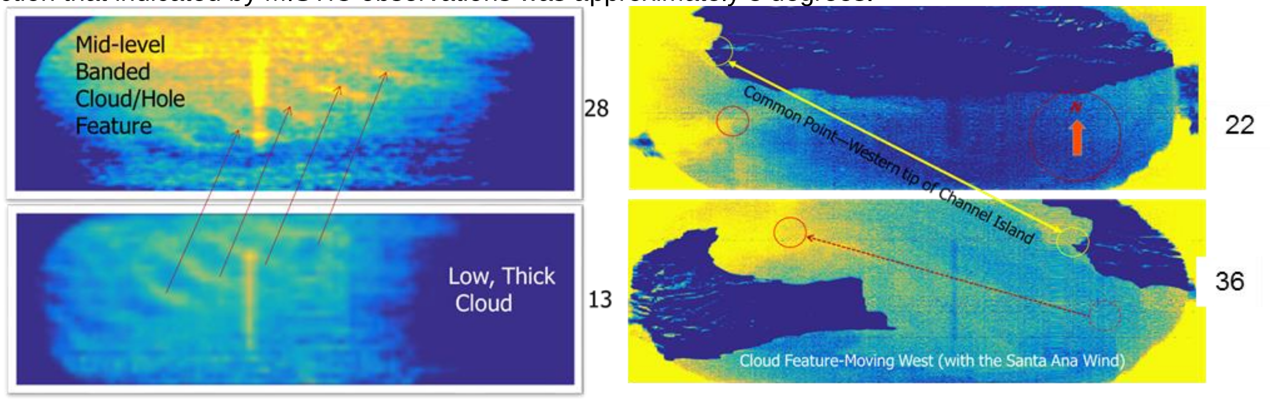


Figure 5: (Left) A unique banded cloud/hole feature was observed in a spectral channel near 2000 cm^{-1} in sweep 13 and later in Sweep 28, allowing a cloud motion wind vector to be derived. (Right) A cloud feature in low-lying broken marine stratus is observed first in Sweep 22 and approximately 1000 seconds later in Sweep 36 near the Channel Islands. These images are averages of 27 spectral channels spanning 2100.5-2144.8 cm^{-1}, and are shown in reverse contrast (yellow-coldest).

The right side of Figure 5 shows two images used to identify a wind tracer feature. The images are averages of 27 spectral channels in the range 2100.5-2144.8 cm^{-1} (window channels). The two hypercubes (sweeps 22, and 36,) were taken at a time separation of approximately 1080 seconds. They were taken at different spatial positions along a nearly east/west track, although they share Channel Island geometric features that allow a visual double-check on position, and position change. This cloud feature-while recognizable, was also undergoing a process of deformation, changing its shape with time. The wind calculated from the observed cloud position change is 24 m/s. The wind direction observed was 199.4 degrees, primarily out of the east, and consistent with the high-speed low-level Santa Ana winds blowing through Los Angeles—just to the east of this observation position. This cloud feature lies close enough to the surface that a comparison between this wind velocity that that of the radiosonde at that level is not expected to be valid, since a strong low-level east-wind east of Vandenberg would be blocked, or at least orographically modified by the coastal mountain range that lies between the Vandenberg area and inland southern California (including Palmdale).

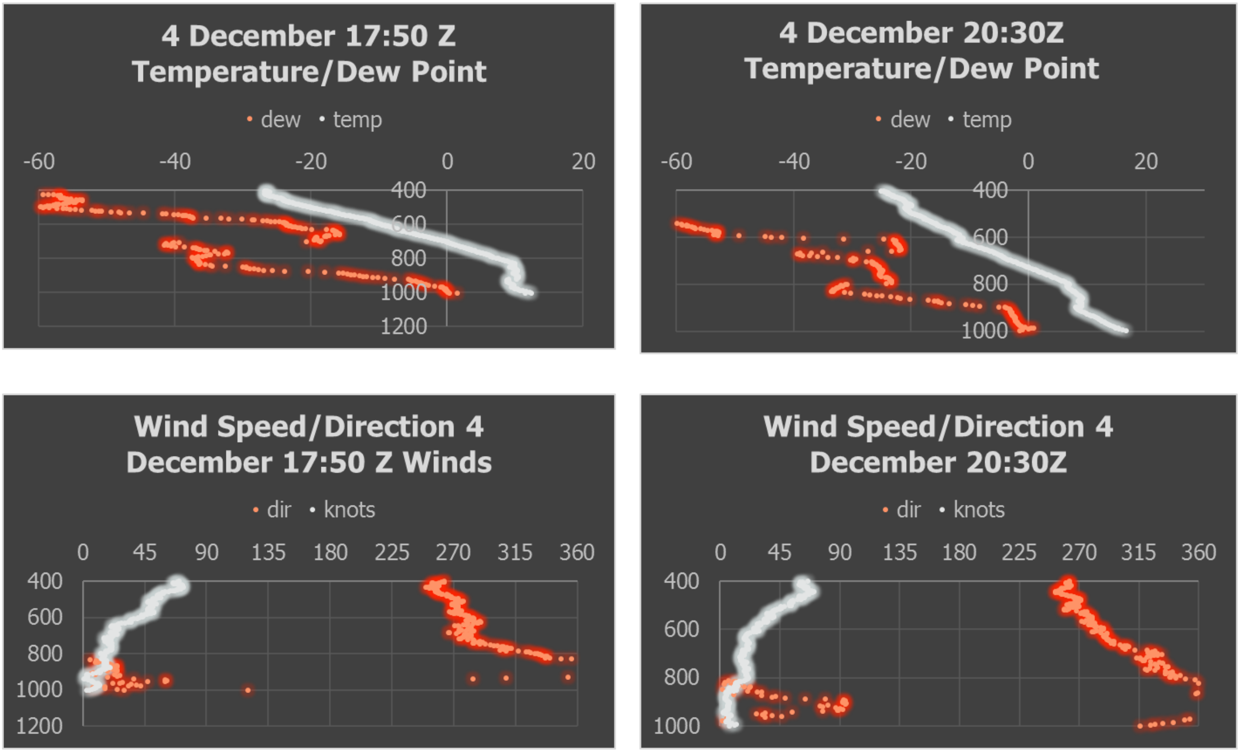


Figure 6: RAWINSONDE Data from RAWINSONDE launched from Vandenberg on 4 December. Data include Temperature, Dew Point Temperature (C), Wind Speed (Knots), Wind Direction (Degrees) vs Pressure Height (mB)

One of the striking and unexpected observations was that the colder (over-ocean) clouds observed during this flight were actually those at lower altitude. The cause of this, the presence of a strong marine inversion layer over the ocean, is part of the typical weather pattern of the region, and was only partly disrupted by the Santa Ana wind event. NWS Vandenberg RAWINSONDE data from 11:30Z on 4 December features a temperature vertical profile shows a very strong inversion of nearly 8K. At that local time in California, the sun had not yet risen. This temperature inversion condition is common over the eastern pacific, and fosters the formation of low-level stratus cloud layer, which are then trapped (prevented from rising) by the inversion cap. The colder low clouds observed by MISTiC (in Figure 5-Right) are consistent with this cloud type and vertical temperature profile condition. At the Vandenberg sonde-launching site (on land of course), solar radiation progressively warms the land surface, reducing the temperature difference between the surface and the top—of the boundary layer - weakening the inversion The sonde data in Figure 6 show this progressive weakening of the inversion layer. However, the much larger heat capacity of the ocean should keep surface layer temperatures low, and allow a much slower rate of rise, and maintain the inversion layer structure through the morning—consistent with the MISTiC observations over the ocean-near the Channel Islands.

4. SUMMARY AND NEXT STEPS

The MISTiC® Winds concept for using a low-earth-orbiting constellation of microsatellite, each hosting miniature IR spectrometer for providing high-spatial resolution hyperspectral IR soundings and vertically resolved AMV winds in the troposphere has been presented previously[1,2]. The work presented here is an initial report of results from a set of airborne observations that have been performed as one component of an instrument technology and observation method risk reduction program that is preparing the way for a future mission employing microsatellites in constellation for hyperspectral AMV winds and IR sounding observations from space.

Following two Engineering Check-out flights in May of 2017, an Observation Demonstration Flight of the MISTiC airborne instrument took place aboard a NASA ER2 on 4 December of 2017. Hyperspectral Imaging/Sounding observations, including some repeat-pass observations were taken over several area in southern California and the adjacent eastern Pacific. Initial analysis of the observation data focused on the ocean-scene cases, which generally are more easily interpreted due to the uniform surface emissivity conditions. The MISTiC ER2 flight was complemented by RAWINSONDE launches close to the MISTiC over-flight locations and times, two conveniently but independently launched from the NWS site on the Vandenberg Air Force Base, and one launched from Edwards Air Force Base by the NASA Armstrong weather support team. These provide an independent observation of the local thermodynamic and wind vertical profile conditions that MISTiC observations can be compared with. Satellite observations, including those from several hyperspectral sounders are also available for comparison. The near-surface weather conditions were somewhat extreme, with the strong, relatively dry Santa Ana wind conditions prevailing for the MISTiC flight period.

A comparison of MISTiC Airborne observations with an IASI-B observation in an adjacent spatial location, and approximately 1 hour earlier indicates reasonable correlation of the MISTiC airborne observations with IASI. Initial analysis of repeat-pass hyperspectral imaging/sounding observations over the ocean near the Channel Islands yielded two cloud motion-vector wind observations. For one of these, there is also a corresponding radiosonde launched from the NWS site at Vandenberg, within 50 km of the MISTiC observation and just 30 minutes earlier. The MISTiC Cloud Motion Vector and the radiosonde observations of wind speed and direction are within 2 m/s of each other, and 3 degrees azimuth respectively, for wind flowing off the eastern Pacific at approximately the 9000 ft level, (out of the NW). A second cloud motion vector was also observed, indicating a strong easterly wind at quite a low level and high wind speed, consistent with the Santa Ana wind flowing through the LA basin on that day. These results are limited, but encouraging for the MISTiC method, especially since the high wind shear conditions under which these observations were made are among the most challenging conditions for AMVs. There is quite a bit more MISTiC ER2 data from this first observation demonstration flight that still needs to be analyzed. Next steps include AMV analysis of flight segments over the other three regions covered by this flight, and potential use of the SWIR band radiance data for AMV height assignment.

5. ACKNOWLEDGEMENTS

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6. REFERENCES

1. K. R. Maschhoff, J. J. Polizotti, H. H. Aumann, and J. Susskind, “MISTiC Winds: A micro-satellite constellation approach to high resolution observations of the atmosphere using infrared sounding and 3D winds measurements," Proc.SPIE 9978, CubeSats and NanoSats for Remote Sensing, 997804 (19 September 2016); doi: 10.1117/12.2239272

2. “MISTiC Winds, a micro-satellite constellation approach to high resolution observations of the atmosphere using infrard sounding and 3D wind measurements”, K. R. Maschhoff, J. J. Polizotti, H. H. Aumann, and J. Susskind, http://cimss.ssec.wisc.edu/iwwg/iww13/proceedings_iww13/index.html