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An Integrated Wind and Thermodynamic Profiling Instrumentation and Decision Support System:

Concepts for the UAV Superhighways

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Table of Contents

1. Introduction

Timely and accurate micro-weather information is required for safe and effective Unmanned Aircraft Systems (UAS) operations. Radiometrics Corporation (RDX) of Boulder, Colorado and Weather Decision Technologies International (WDSS) of Norman, Oklahoma have built an instrumentation and integration system that provides high-resolution measurements of atmospheric boundary layer winds and thermodynamics in real-time. The system, termed the Wind and Thermodynamic Profiling System (WTPS), can provide valuable data across many applications including those important in the UAS space regarding weather related hazards. WTPS applications include air quality monitoring, emergency management support, mesonet monitoring solutions, airport operations, and space launch support.

Data from WTPS can be used as part of an integrated sensor/software suite to help UAS operators make go/no-go decisions with respect to flights. These data can also be included in the initialization and data assimilation of high-resolution Numerical Weather Prediction (NWP) models, thereby providing improved short-term forecasts. In turn, WTPS data can also be used for NWP model verification and improvement purposes.

The WTPS instrumentation suite consists of:

- A Boundary Layer Radar Wind Profiler (RWP) which retrieves wind velocity in the vertical through about 3km Above Ground Level (AGL).
- A Microwave Profiling Radiometer (MWR) which retrieves thermodynamic variables such as temperature, humidity, and liquid water content in the vertical through 10km AGL.
- An Acoustic Wind Profiler (sodar) which retrieves very high-resolution winds in the vertical from the surface to about 200m AGL.
- An Automated Weather Station (AWS) that records surface weather conditions.

Data from the instrumentation are updated, integrated, and new products produced every 5 minutes. The data, algorithms, and products are used to monitor and detect boundary layer hazards to UAS operations including:

- the presence of wind shear and it's magnitude
- the presence of turbulence and it's magnitude
- temperature inversions and their strength, depth, and estimated dissipation times
- low-level jets and their strength and depth
- atmospheric stability
- the presence of fog, it's depth and estimated burn off time
- the presence, location, and depth of icing conditions

Figure 1 below shows the WTPS instrumentation. The figure shows the instrumentation are connected to a central processing shelter which contains all necessary hardware for ingest, integration and processing. Data and products are sent to Web based displays that can be customized for requirements by various users.

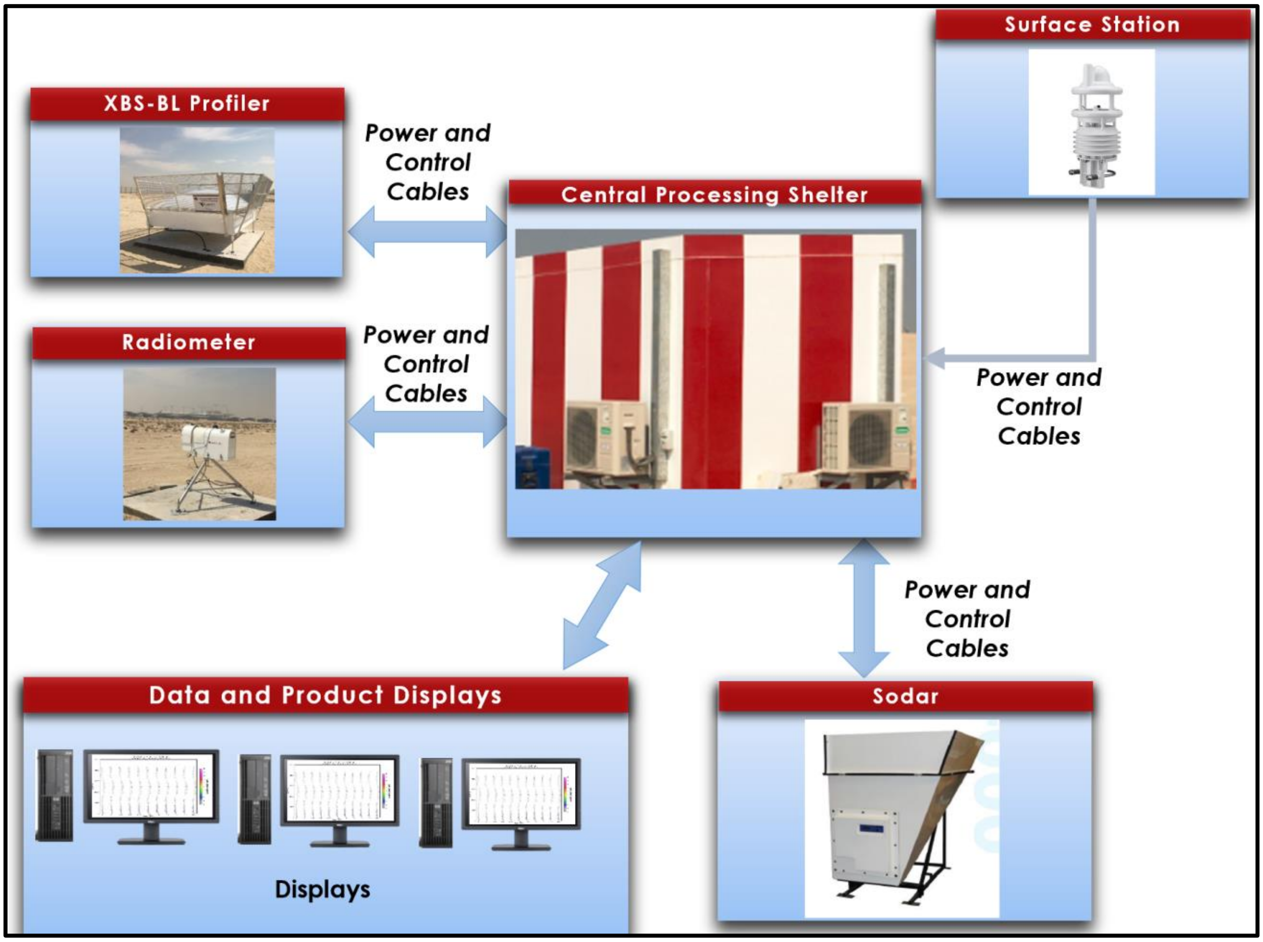

Figure 1. Schematic of WTPS instrumentation and connections.

Data from the system are also provided in various formats that can be used by downstream applications including atmospheric sounding displays used by the US National Weather Service and the FAA Central Weather Service Units. Data are also available in formats that be used for NWP model initialization and assimilation.

Figure 1 is used to show the overall instrumentation system using a fixed site. The system is also available in a trailer configuration as shown in Figure 2 below.

Figure 2. Mobile RWP and MWR system.

2. Boundary Layer Observations

Current high-resolution modeling and forecasting accuracy is fundamentally limited by inadequate boundary layer humidity, wind and temperature information. It is widely recognized that continuous thermodynamic and wind soundings in the boundary layer are required for accurate monitoring of atmospheric conditions in addition to providing improvements in NWP modeling and forecasts. It is also known that UAS operations are vulnerable to micro-weather hazards including convection, thermals, fog, icing, and frontal passages. Yet, boundary layer observations are significantly lacking in both coverage and timing. Localized weather risks to UAV operations typically arise and dissipate on time scales for which no data radiosonde data are available.

Figure 3 below illustrates the gap in boundary layer data collection through a comparison of data between the twice daily radiosonde launches and the continuous data from a MWR. The top 2 panels in the figure are temperature and humidity collected from the MWR while the bottom two are the same fields from the radiosondes. The figure clearly shows the significant gap in boundary layer measurements between the two radiosonde launch times and the ability to fill this gap using WTPS instrumentation.

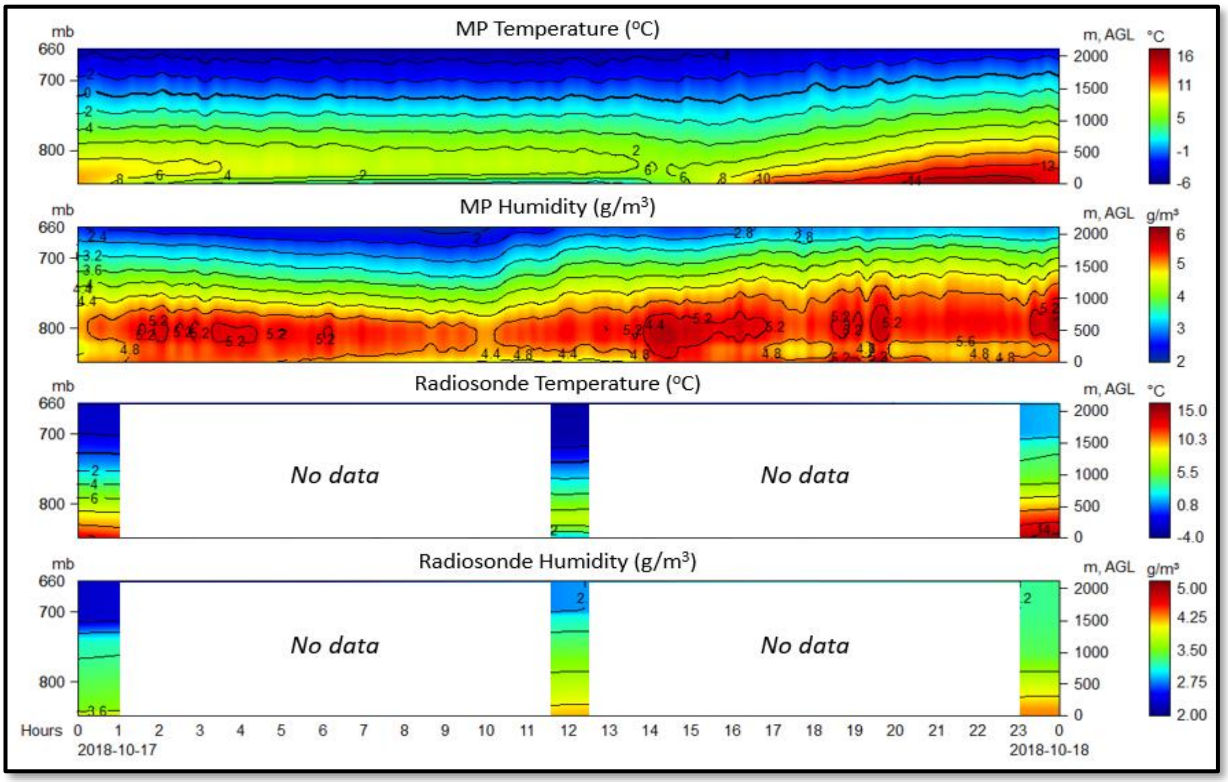

Figure 3. Data showing continuous MWR temperature and humidity collection (top 2 panels) and twice daily radiosonde launches (bottom 2 panels).

3. WTPS Applications

3.1. Wind Measurements

WTPS provides the ability to constantly monitor low-level wind field characteristics along with any associated wind shear, low-level jets, turbulence, headwinds, tailwinds, and crosswinds. Wind retrievals are processed through various algorithms which are compared to user-defined magnitude and depth characteristics and provide automated alerts for conditions exceeding thresholds.

An example of a wind display and shear alert page configured for the Denver International Airport is shown in Figure 4 below. Wind shear that exceeds user defined thresholds are automatically alerted for and shown in the table on the right side of the figure. All wind barb profiles and shear calculations are updated every 5 minutes.

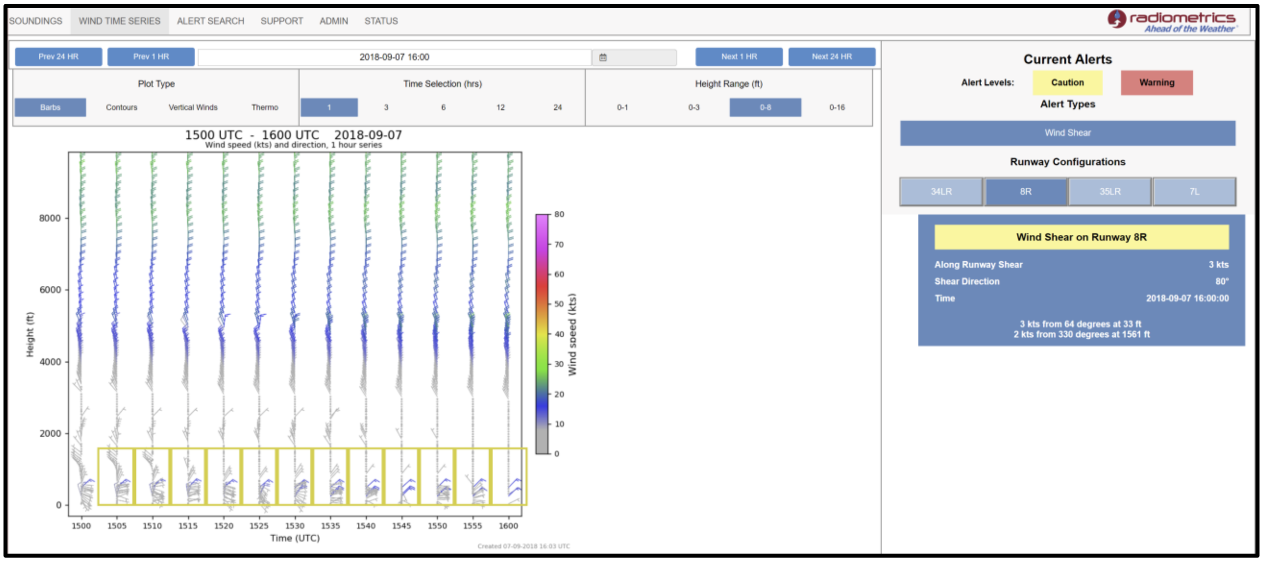

Figure 4. Wind barb plot showing areas of detected wind shear through the lowest 1600 ft. Yellow/red polygons depict “caution” and ”warning” thresholds. Mouse-over of wind barbs allows “pop up” information boxes as also shown in the figure.

The low-level jet (LLJ) is a mainly nocturnal phenomenon. Monitoring the strength and depth of such jets is very important in aviation operations. The WTPS allows monitoring of these jets and their characteristics in real-time.

Mechanical processes often drive mixing of the high velocity winds aloft down to the surface, resulting in unforeseen changes in surface and boundary layer wind speeds. Atmospheric stability dictates the extent of the downward mixing, which can be evaluated using radiometer retrievals to determine mixing depth prior to the mixing occurring.

Figure 5 below shows a 24 hr time series of wind barbs and wind shear warnings (vertical boxes) from the WTPS installed at the Abu Dhabi International Airport. Note the development of a strong LLJ (max winds > 45kts) just above the surface at approximately 2205 UTC. Note also the shallow depth of maximum speeds of the LLJ – less than 2000 ft. These measurements would not be possible without the installation of the WTPS.

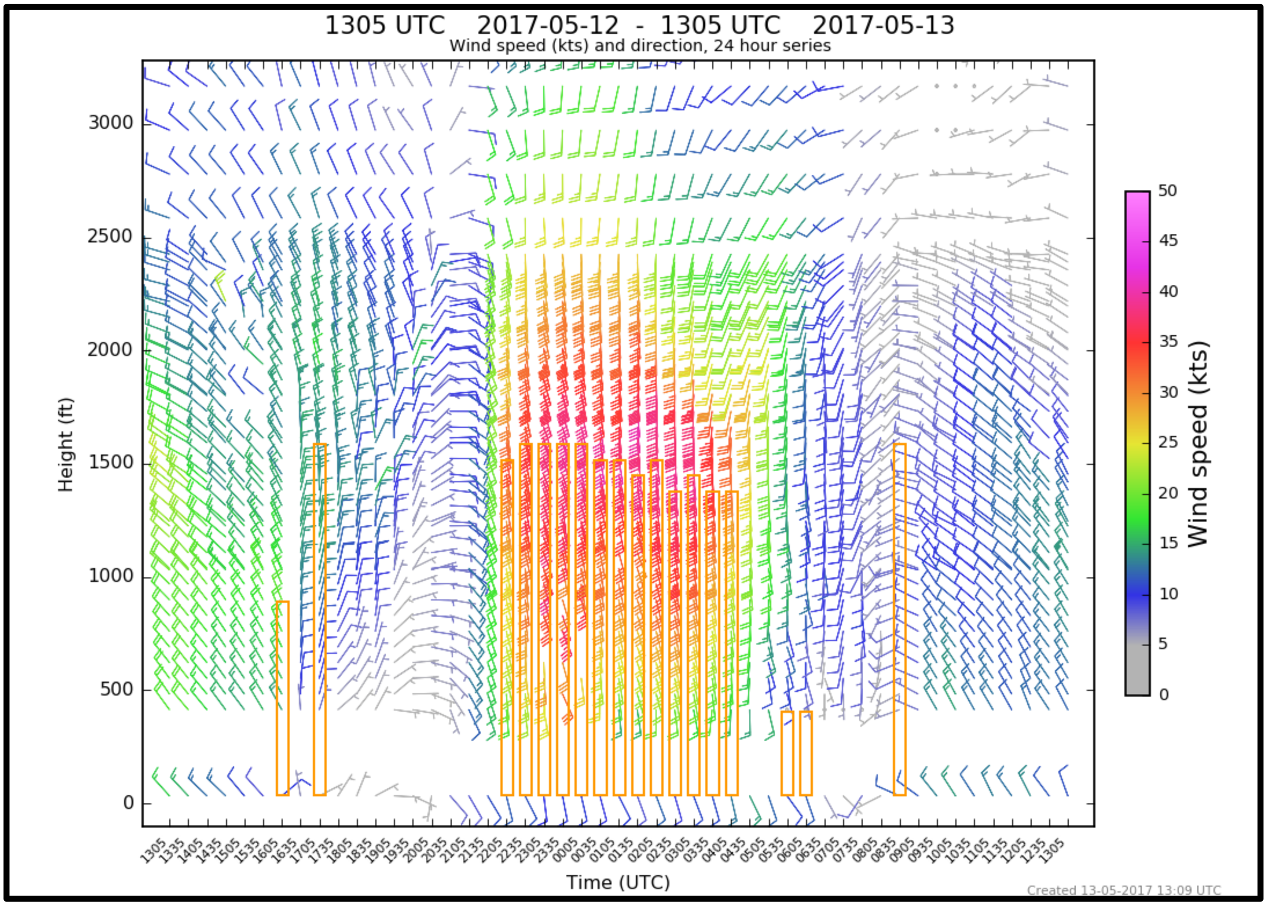

Figure 5. Wind speed, cross-wind, wind shear and low-level wind shear with wind barb overlays.

Knowledge of these conditions prior to flight operations provides decision makers with the necessary awareness to make go/no-go decisions regarding UAS operations.

In addition to deriving vertical profiles of horizontal winds, the vertical wind fields are also calculated. A one-hour time series of vertical winds is shown as a contour plot in Figure 6 below. These profiles are calculated in both clear air and non-clear air conditions. These types of vertical wind profiles updated every 5 minutes are likely crucial to UAS operations and may provide information on thermal structure and strength.

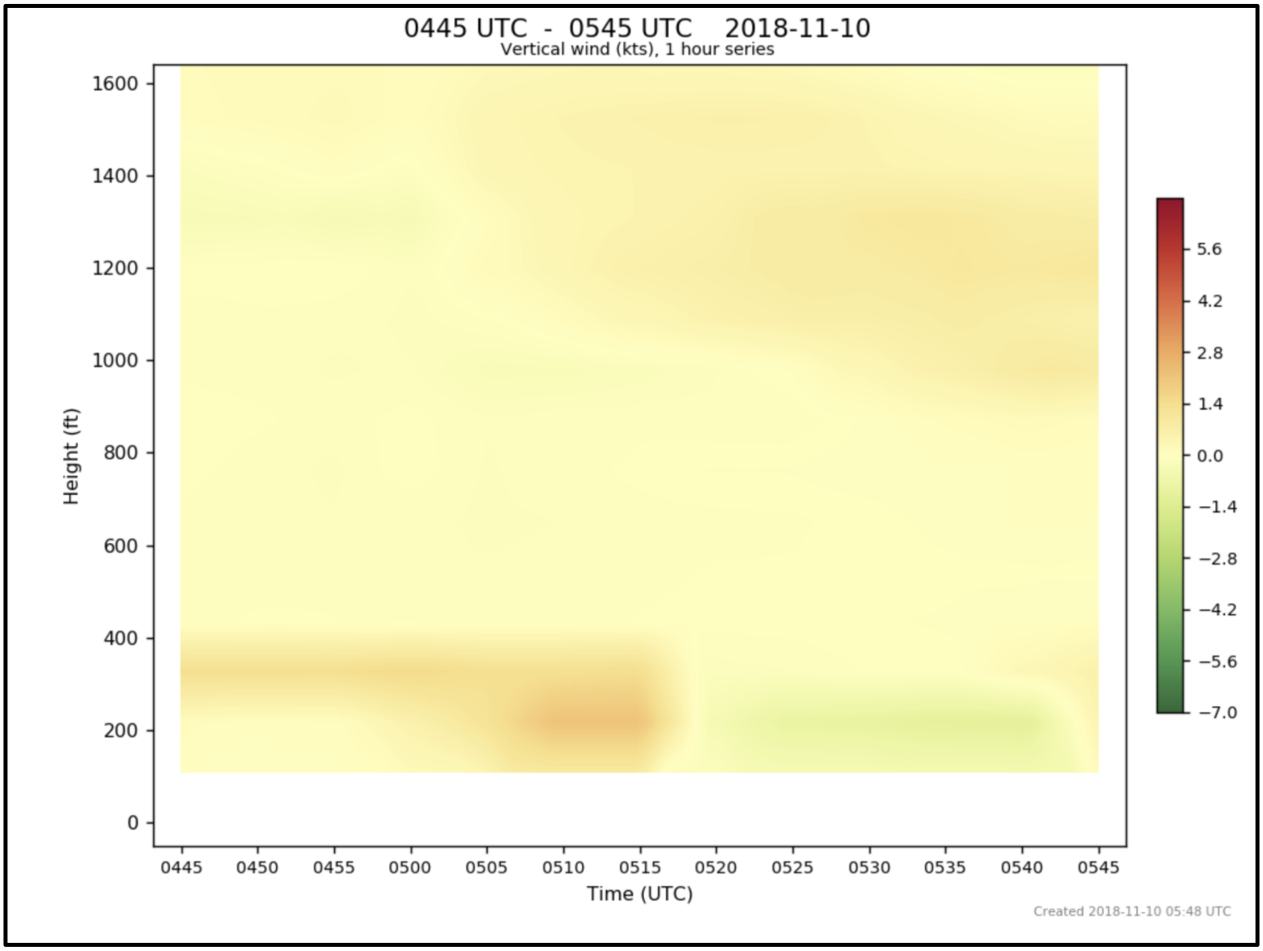

Figure 6. Contour plot of vertical wind speeds derived from profiler measurements.

3.2 Temperature Inversions

WTPS thermodynamic retrievals provide the ability to monitor low-level temperature inversions (LLTI) that effectively change the atmospheric profiles in the boundary layer due to temperature increasing with height. LLTIs occur frequently and have significant effects on aircraft approach and departure. Aircraft encountering a LLTI will notice changes in performance including a decrease in climb rate for the same thrust rate when compared to a take-off where a LLTI is not present. The LLTI strength and depth characteristics provided by WTPS, along with the vertical wind fields as shown in Figure 6 above, are likely important to UAS operations as well since their presence represents stability regimes that affect thermal production hazardous to UAS operations.

A WPTS thermodynamic and wind analysis is shown in Figure 7 below. The figure shows a 6-hour time period in which an inversion of approximately 7 °C is centered at about 2000 ft AGL. Note the significant increase in low-level humidity and liquid water content during the inversion period.

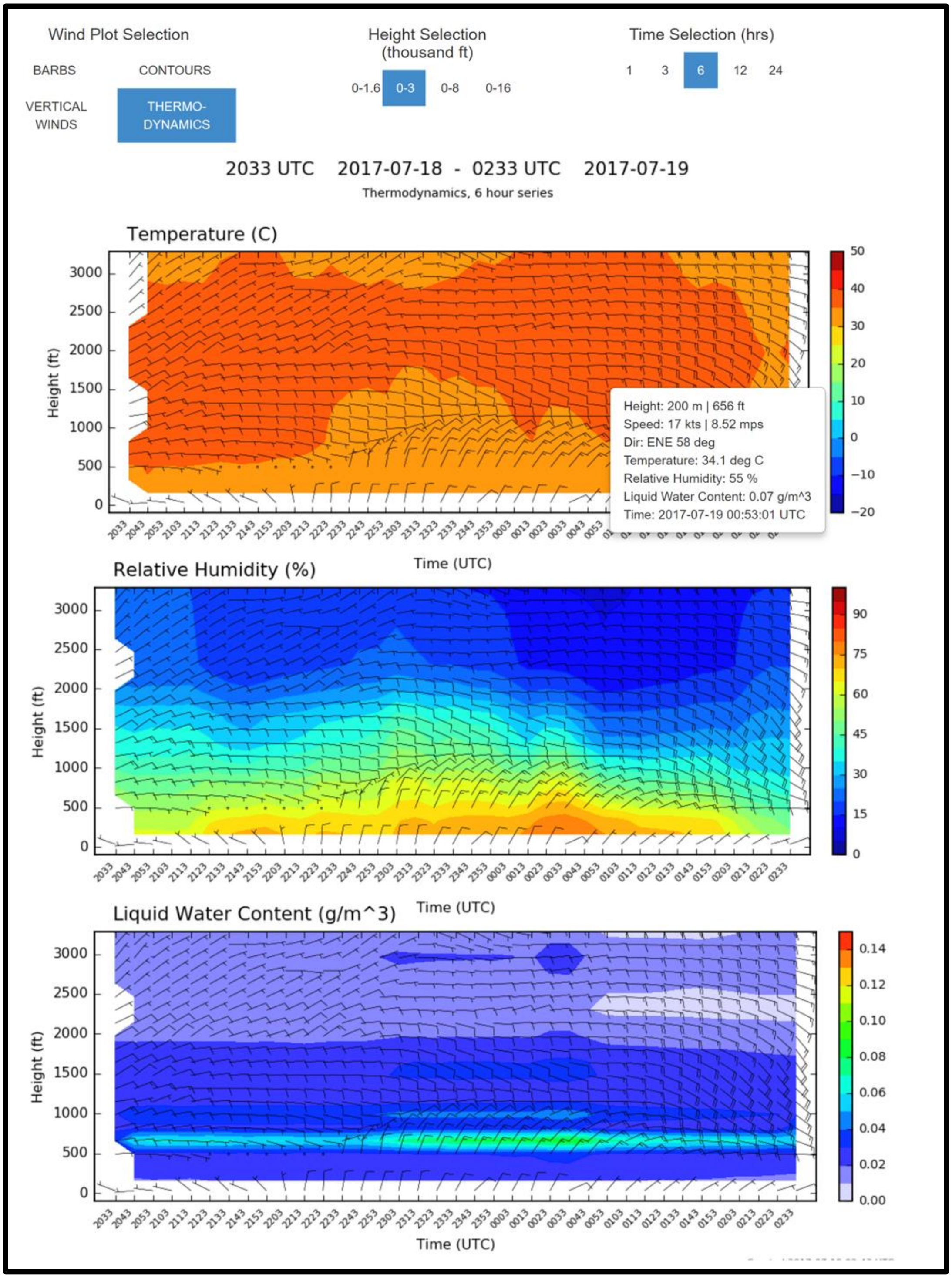

Figure 7. Time series (6 hrs) showing temperature inversion, RH and LWC overlain with wind barbs.

3.3 Fog Conditions

WTPS water vapor and liquid water measurements provide information on the amount and depth of liquid and vapor present in the boundary layer. This information, combined with temperature, dewpoint, and relative humidity characteristics, forms the basis for reliable detection and characterization of fog, a major hazard for all aviation operations. Studies using WTPS instrumentation have demonstrated that conditions associated with the evolution of fog events are dependent on the type of fog as well as mesoscale and geographic features specific to the location. As such, formation and dissipation characteristics need to be analyzed at the installation site in an effort to adapt algorithms for the nuances specific to the location.

WTPS data are important for not only detecting fog and its characteristics but are also useful in forecast operations. As an example, forecasters using data from the WTPS installation at the Dubai International Airport (DXB) have successfully shown that the additional information gained from in-situ observations significantly increases the understanding of the local boundary layer structure during fog events, and as a result, the predictability of such occurrences. For example, DXB meteorologists used WTPS observations to verify that high humidity in the boundary layer in excess of 1,000 feet deep inhibits fog formation.

Under these conditions radiative cooling cannot provide enough heat loss to cool the atmosphere sufficiently to reach saturation during the overnight hours. Additionally, cooling at the top of the boundary layer often leads to stratus cloud development, further limiting the amount of longwave radiation that can escape. Although this scenario is contrary to general fog formation characteristics, local forecasters are now able to recognize when these conditions are present and successfully provide a confident ‘no fog’ forecast, even though the numerical weather prediction models suggest fog formation in the terminal area. Figure 8 below shows a 2-week period of WTPS data collected at the San Francisco International Airport, clearly showing the timing of formation and dissipation of the fog layer.

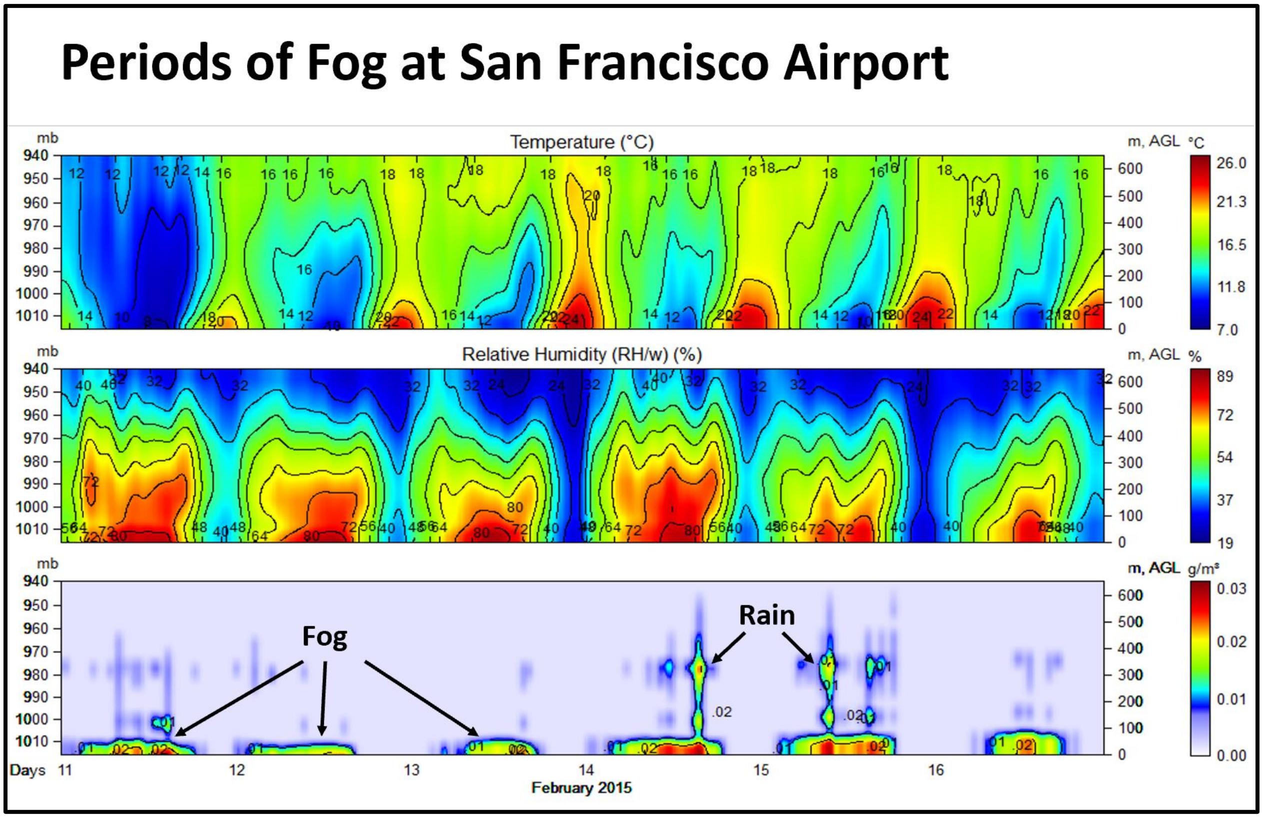

Figure 8. Temperature, relative humidity, vapor density, liquid water (fog) and winds at LAX.

3.4 Frost, Freezing Rain, and Icing Conditions

WTPS provides measurements of integrated vapor and integrated liquid throughout the atmosphere. These measurements, when combined with the retrieved temperature profiles, allow for the monitoring of potentially hazardous phenomena including frost, freezing rain potential, and boundary layer icing potential. Algorithms can be applied to these retrievals to provide end-users with decision support regarding icing timing, depth, and amount.

WTPS data can provide vital information regarding precipitation type and amount at the surface and can help discriminate between rain, freezing rain, ice pellets, and snow. The real-time temperature profiles can also assist in forecasting the timing of any precipitation phase changes as well. Figure 9 below shows a time series of WTPS data during icing conditions at Denver International Airport.

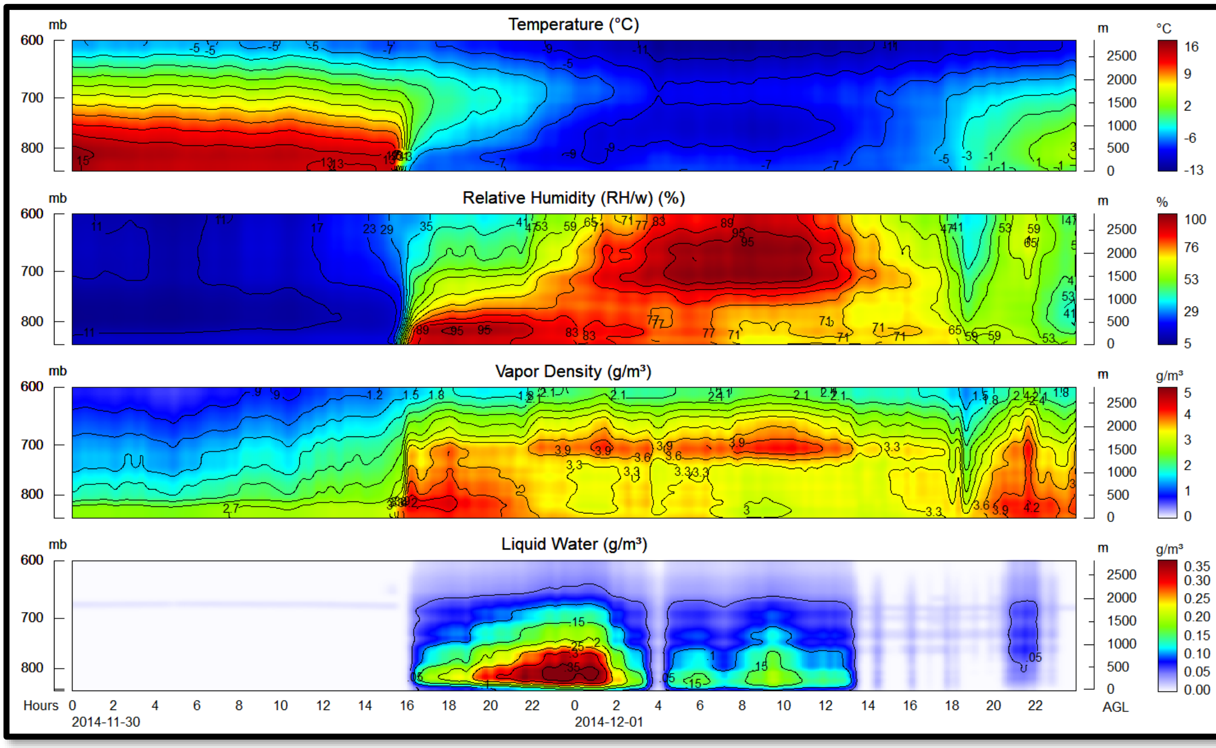

Figure 9. Dense supercooled drizzle and fog during a late fall upslope storm presented severe icing hazard at Denver International Airport (DIA).

3.5 Atmospheric Stability, Forecast Indices, and Convection

WTPS provides real-time monitoring of atmospheric thermodynamic and wind conditions which can be used to derive stability parameters along with traditional sounding forecast indices, which allow for the monitoring of atmospheric stability. By tracking the dynamic conditions in real-time, forecasters are provided with more information with respect to the potential storm type and severity characteristics, as well as the timing of convective initiation. In general, radiosondes are launched from select sites globally two times per day at 00 UT and 12 UT to monitor atmospheric conditions. Unfortunately, very few boundary layer observations exist between the two launch times, when much of the dynamic weather occurs. WTPS data are combined into sounding formats every 5 minutes. A WTPS sounding analysis and display including forecast indices and thermodynamics is shown in Figure 10.

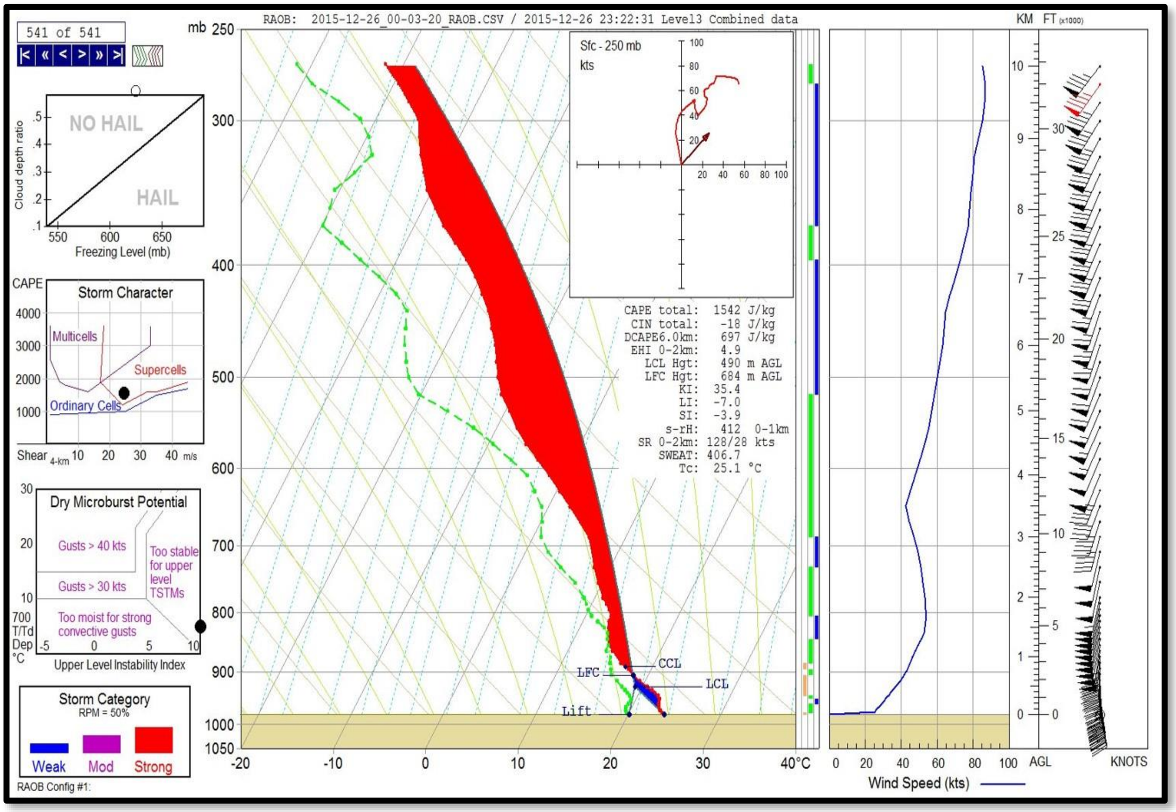

Figure 10. WTPS sounding with indices, thermodynamic and storm characteristics.

4. WTPS Instrumentation and Display System

This section describes the instrumentation suite and display components of the WTPS.

4.1 Radiometrics RAPTOR Radar Wind Profiler

Radiometrics RAPTOR RWP systems are available in two boundary – the RAPTOR VAD-BL or the RAPTOR XBS-BL as shown in Figure 11 below. The VAD-BL provides data collection to a higher altitude AGL, however for the UAS project the XBS-BL provides excellent boundary layer observations. Both systems require minimal maintenance.

Figure 11. RAPTOR XBS-BL RWP phased array antenna (left) and VAD-BL (right).

The RAPTOR data acquisition systems utilize a digital transceiver design, that uses a single non-proprietary COTS software defined radio (SDR) card. The SDR card employs high speed analog-to-digital converters and digital-to-analog converters to enable signal processing to occur at the Intermediate Frequency (IF) level rather than solely at base band frequencies. This digital IF receiver decreases the cost and parts count, increases reliability, reduces receiver signal imbalances, and aids the signal detection and processing algorithms. RWP processing hardware is shown in Figure 112 below. The hardware including the processing system CPU, motherboard, and memory are designed to allow for the ability to be upgraded over time to match new technology without modifying secondary hardware components such as the chassis, cooling fans, and bus. Figure 13 below shows time-height vertical wind profiles observed with the RAPTOR RWP installation in Bangkok International Airport.

Figure 12. RAPTOR RWP control and data acquisition hardware.

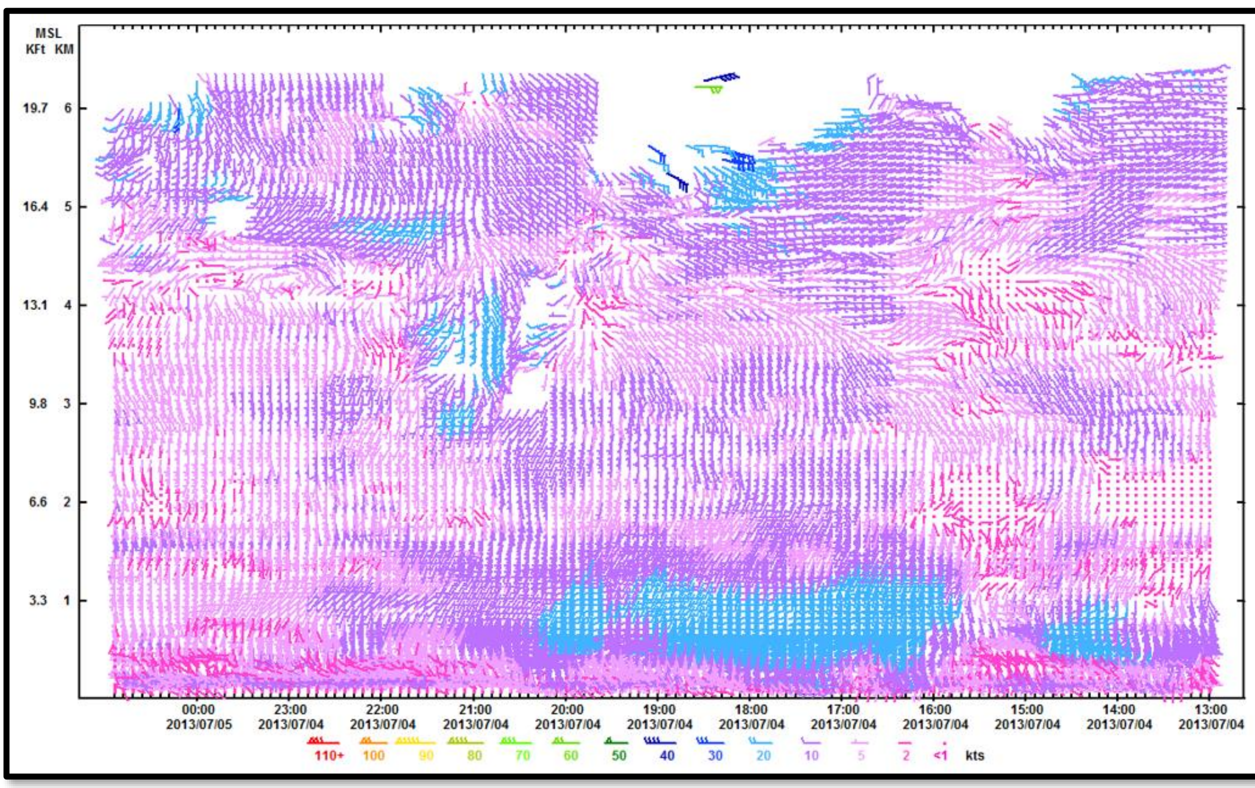

Figure 13. Example time-height product displaying vertical wind profiles observed with the RAPTOR RWP installation in Bangkok International Airport.

Figure 14 below shows a time series of power returned to the RWP in a daytime clear air situation over a 7 minute period. As can be seen in the figure power is returned by a number of phenomena and shows a chaotic boundary layer including clear air turbulence and the top of the mixed layer which changes significantly over a short period of time. Although chaotic there is likely significant information that can be extrated and related to UAS flight conditions.

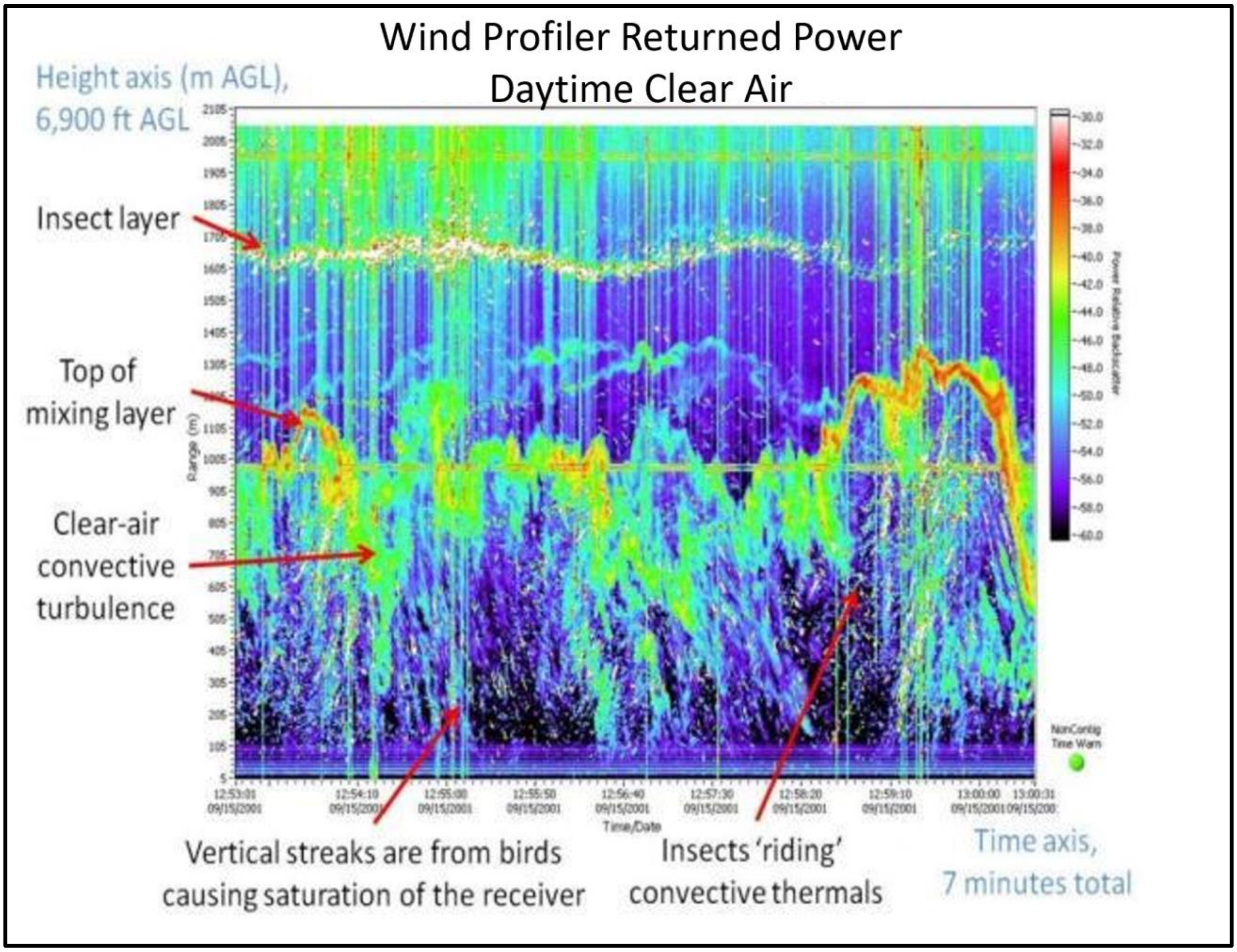

Figure 14. Time series of wind profiler returned power for a period of 7 minutes.

4.2 Radiometrics MP-3000A Thermodynamic Profiling Radiometer

Radiometrics utilizes proprietary state-of-the-art microwave and radiometer technology to ensure optimum performance, portability, flexibility and cost-effective operations at any location in nearly all-weather conditions including polar, mid-latitude, desert and tropical climates.

Figure 15. MP-3000A Microwave Profiler at Toronto Pearson International Airport (YYZ).

The MP-3000A (MWR), as shown in Figure 15 above, is a passive all-weather atmospheric monitoring system designed to provide continuous real-time retrievals of thermodynamic and liquid properties from the surface to 10 km. The radiometer provides direct measurements in the boundary layer and uses various processes to retrieve measurements to 10 km AGL. The instrument incorporates two passive microwave receivers to observe molecular emissions from the atmosphere. The K-Band receiver includes 21 channels ranging in frequency from 22-30 GHz which focus on emissions from the atmospheric water vapor, while the V-Band receiver includes 14 channels ranging from 51-59 GHz that target the oxygen emissions. The instrument also includes collocated surface meteorology sensors to observe temperature, relative humidity, and pressure along with a vertically pointing infrared thermometer for cloud base characteristics. An onboard rain sensor is used to activate the Superblower during precipitation events in order to keep the radome free of hydrometeors, allowing for continuous all-weather operations.

The microwave brightness temperature and surface sensor observations are used to derive radiosonde-like profiles of temperature, relative humidity, water vapor, and liquid water along with integrated vapor, integrated liquid, cloud base height, and cloud base temperature, which are updated every few minutes and provide critical data for short-term numerical forecasting and nowcasting of local high-impact weather events that otherwise could not be obtained by other practical means.

Figure 16 below shows a time series of MWR temperature, relative humidity, and liquid water content over a 24-hour time period as recorded at the Jordan NY Mesonet station during a frontal passage. These continuous wind and thermodynamic (including liquid) observations identify micro-weather parameters crucial to safe and effective UAS operations, including convection, precipitation, turbulence, up and down-drafts, lightning and supercooled liquid (icing hazard).

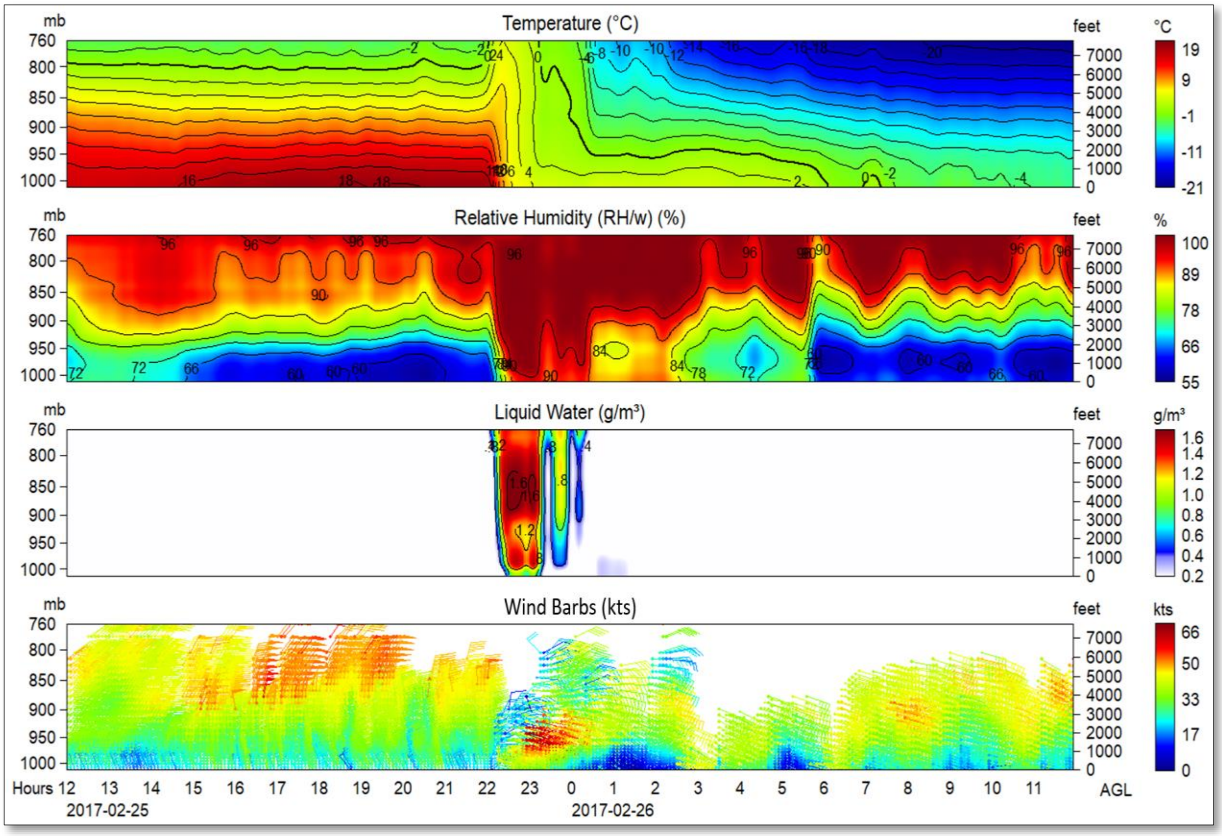

Figure 16. Time series of MP-3000A thermodynamic retrievals from location at Jordan NY Mesonet site.

It is widely recognized that three-dimensional (3D) humidity and liquid information is essential for accurate estimations of convective initiation, precipitation, and icing hazard modeling and forecasting. Accurate forecasting is in turn required for safe and effective UAS operations.

MWR observations at low-elevation angles in the cardinal (north, south, east and west) directions are able to provide 3D moisture (humidity and liquid) information. Figure 17 below shows a 24-hour time series of brightness temperature (Tb) observations measured by an MWR. These observations which are sensitive to changes in the boundary layer humidity and liquid show a significant increase in humidity starting at 9 UT. The spikes later in the time series show liquid water in the form of clouds that are not quantitatively derived through other methods. These data can be considered one type of observation that can be assimilated into NWP modeling efforts.

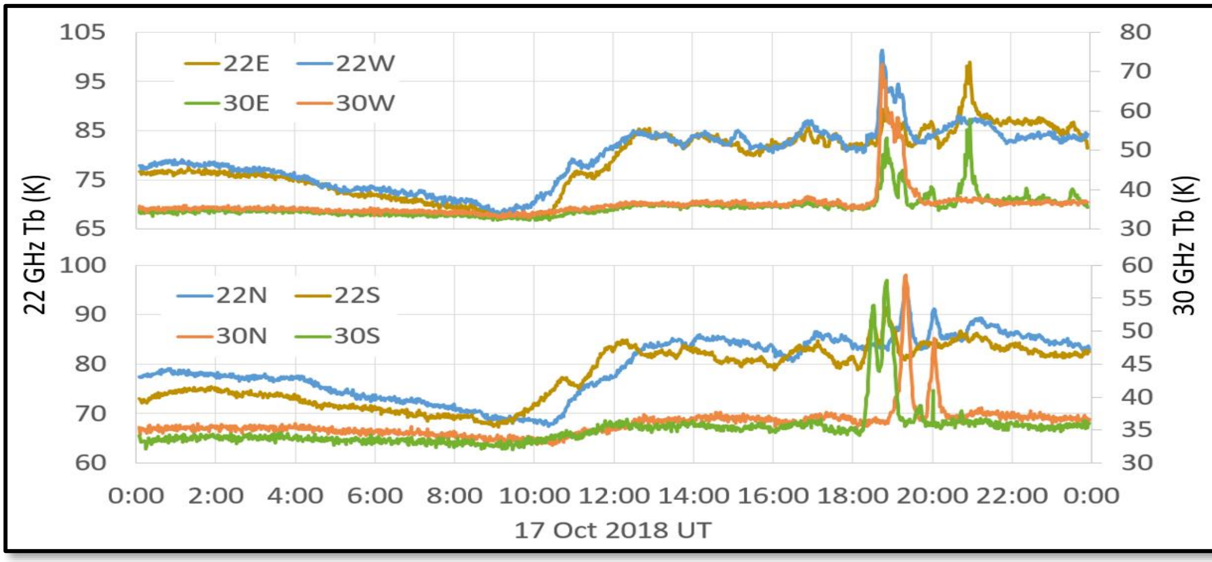

Figure 17. MWR observations at 15° elevation angle north, south, east and west.

The MWR thermodynamic retrievals are then combined with the RWP and sodar vertical wind profiles to create real-time radiosonde-like soundings and derive essential forecast indices and alerts. The integrated data allow for increased accuracy in short-term forecasting and nowcasting in support of aviation operations through continuous monitoring and evaluation of rapidly changing weather conditions.

4.3 Radiometrics AWP-4000 Acoustic Wind Profiler

The AWP-4000 acoustic wind profiler (sodar) provides a cost-effective solution to acquire accurate low-level boundary layer winds to fill the gap between surface observations and the first gate of the RWP. The sodar utilizes acoustic propagation and Doppler shift principles to retrieve high-resolution vertical wind profiles from near-surface to 200 m AGL. The sodar operates at a pulse frequency near 4500 Hz to derive wind measurements at a height resolution of approximately 5 m for wind speeds up to 45 m s^{-1}. The AWP wind data are then integrated with local surface observations, and boundary layer RWP retrievals to provide a complete vertical wind profile throughout the boundary layer. Figure18 below shows an AWP-4000 used for launch support operations at Kennedy Space Center at Cape Canaveral, Florida.

Figure 18. AWP-4000 used for launch support operations at Kennedy Space Center, Cape Canaveral FL USA.

4.4 Data Integration, Processing, and Visualization

The front page of the WTPS display system is shown in Figure 19 below. The display is Web based and can be viewed by any user that has access to the WTPS URL. Composite soundings accessed through the WTPS Web page provide forecasters and other users with an integrated display of the most recent thermodynamic and wind profiles as well as the ability to inspect all current automated alerts including those for fog, low ceilings, inversions, and wind shear. Users also have the capability to go back in time to analyze archived profiles and alerts as well as overlay previous soundings for comparison.

It should be noted that although this version of the display is configured specifically for an airport, the display can be customized for various user needs.

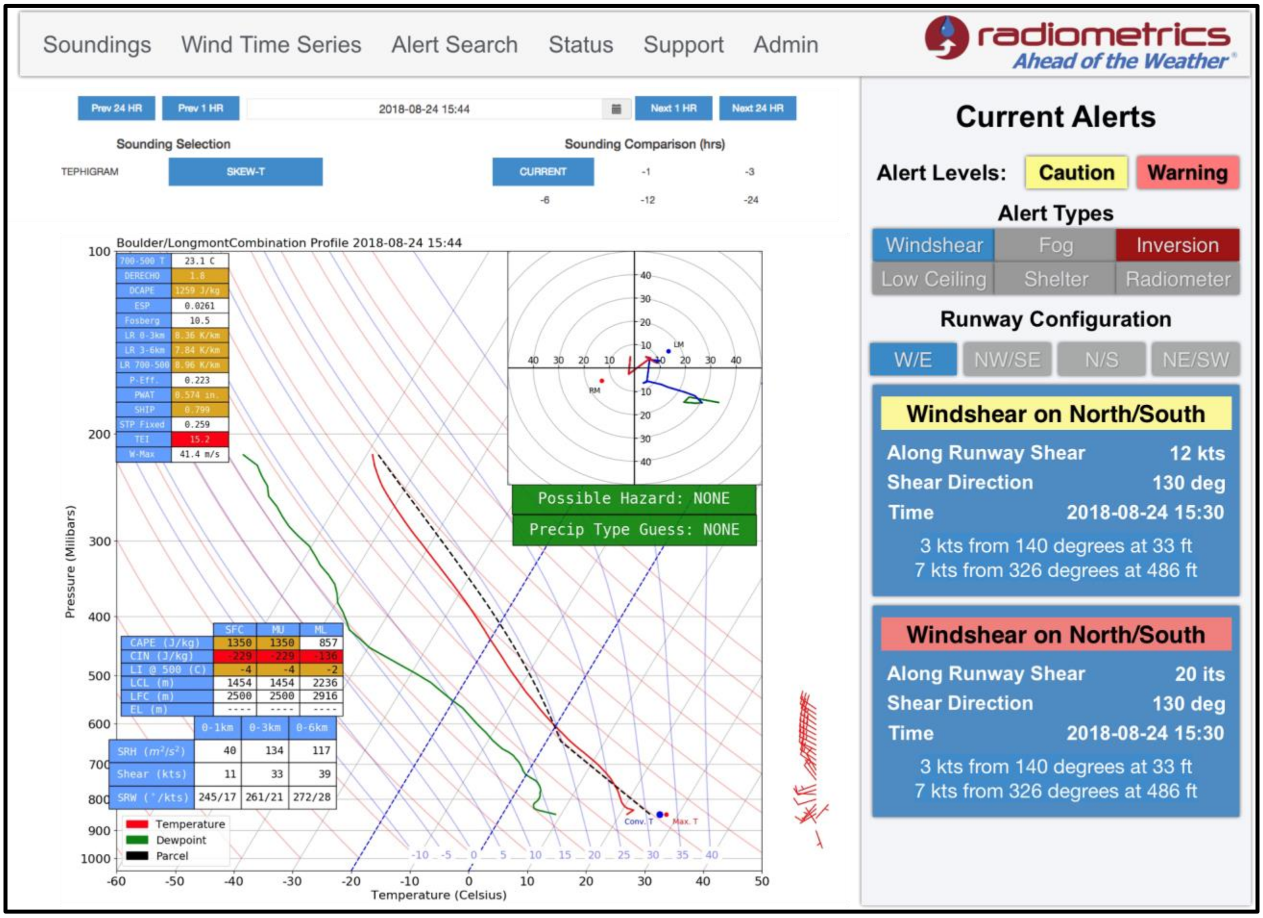

Figure 19. WTPS Main Page showing thermodynamic and wind profiles with current alerts including type and details.

Figure 19 above shows various capabilities available to the user include the ability to look at archived data in sounding or winds format along with the ability to search the database for any previously created alerts.

Figure 20 below shows the overall configuration of the WTPS processing and outputs. The figure shows data and products are stored in a central database and distributable to various customers in various formats. These formats include graphical, text, NWS/CWSU compatible, along with a number of standard FAA formatted messages.

Displays are customized for various users including meteorological users and non-meteorological decision makers.

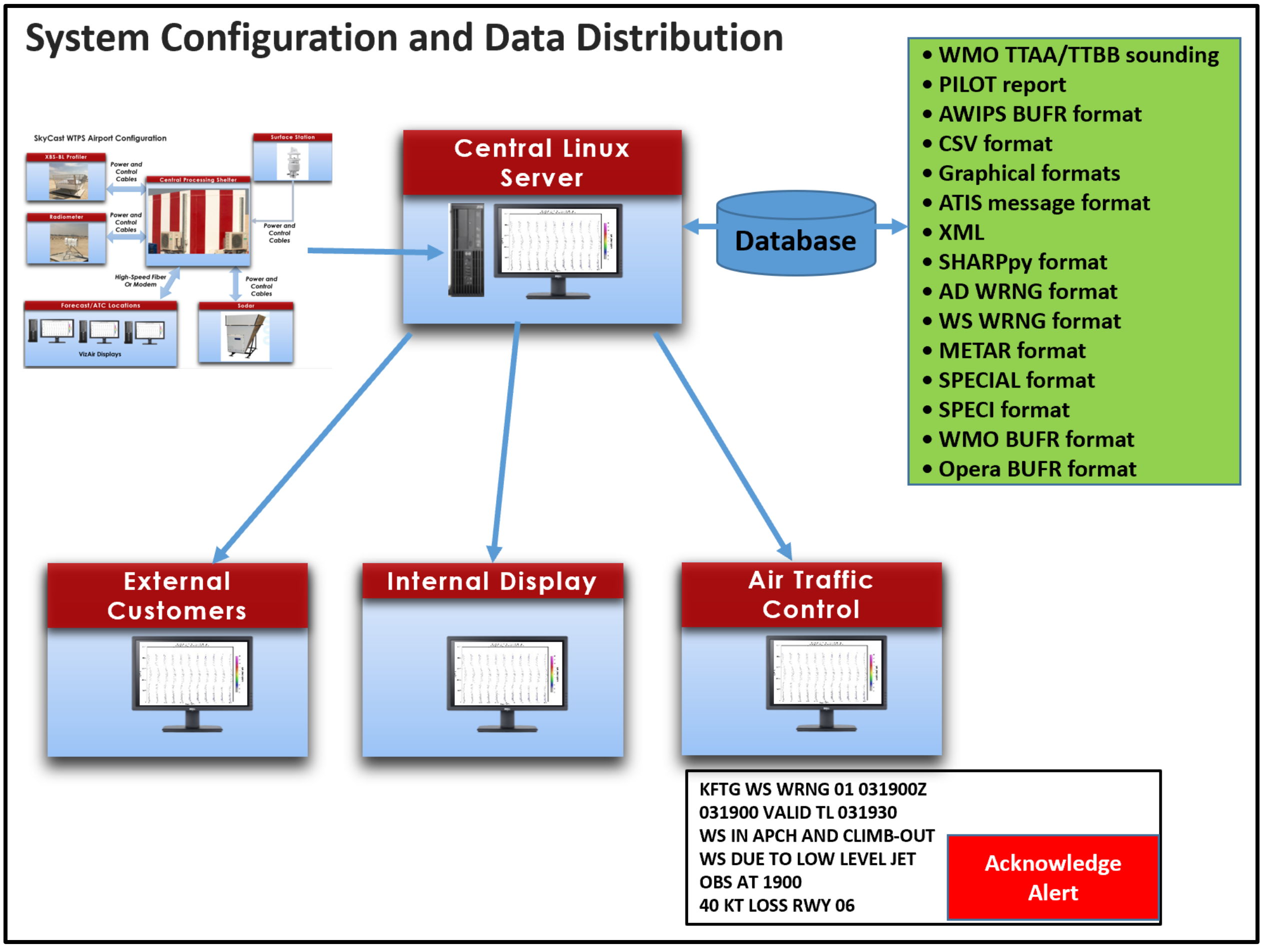

Figure 20. WTPS configuration and data distribution.

5. Conclusions

The Wind and Thermodynamic Profiling System described herein provides unique boundary layer measurements, data integration, processing, display, and distribution that cannot be realized from other instrument combinations. The systems is used to provide boundary layer information and also to develop algorithms, products, displays, and decision support tools specific to the interests of UAS stakeholders.

The WTPS instrumentation and processing is currently in use at several international airport locations, along with multiple instrumentation installations at various US locations.