8.6 The Integrated Upper Air Water Vapor System

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1. INTRODUCTION

This extended abstract will describe a new concept of providing and integrating water vapor measurements from the surface to various points aloft throughout the troposphere using different sensors all situated together. One day this approach to sensing the atmosphere for this critical atmospheric parameter could become a continuous and near real-time method unlike today where it is sporadic and requires expendables to be used up. The composite system will be described in general terms and its integration delineated so one can perceive how a continuous monitoring of water vapor aloft could be obtained sometime in the future. A Small Business Innovation Research (SBIR) initiative has been approved for two vendors to develop portions of the composite system. No details from their designs will be divulged in this abstract; rather it will provide an overview of the overall concept and how the pieces could be integrated into a new composite real-time water vapor monitoring system. Other aspects of the system already exist and could be integrated easily into the overall architecture of the composite system. One challenge will be the use of commercial-off-the-shelf data basing products for integrating and time-syncing the different datasets, thus providing users and numerical weather prediction models a consistent and highly temporal set of water vapor observations.

2. SBIR SUMMARY

SUBTOPIC: *Compact, Eye-Safe, All-Weather Ground-Based Water Vapor Profiling Lidar*

Water vapor profiles were first measured by **Li**ght **D**etection **a**nd **R**anging **(**lidar) in 1966, shortly after the invention of the laser. Since that time, lidar technology has advanced greatly, with large advances in the various component technologies that make up a lidar, not least of which are the lasers. Progress in optical filters, digital electronic data systems, and low-noise optical detectors have all matured to the point that reliable, automated lidar systems have recently become reality. Small elastic backscatter lidar systems are offered commercially for cloud and aerosol profiling research applications, topographic mapping, and wind profiling. Water vapor lidar technology is now at a point that an inexpensive, compact eye-safe system could be commercialized for operational applications. This is due mainly to the availability of reliable, inexpensive tunable lasers with wavelengths able to access the near infrared water vapor absorption bands.

The widespread use of such systems operating 24/7 would go a long way to adding substantially to the data base of water vapor measurements, filling in the many gaps in coverage that existing instruments do not cover, particularly in the time domain. Routine water vapor profiles are mainly acquired using humidity sensitive capacitor instruments lofted using radiosonde/balloons twice a day over mostly the developed regions of the world. Small lidars would supplement, and then begin to replace these instruments while collecting data, continuously.

The lifetime of the lidar should be at least 10 years, with service intervals of 1-3 years. They should be self-contained, automated, and have their data networked via hard wire or wireless interface to the Internet for real-time transfer of the data to end users. On-board data processing to level 1, and in some cases, to level 2 processing is feasible given the enormous leaps in digital electronics capabilities in recent years.

Preliminary measurement requirements are as follows:

1. Absolute water vapor profiles from near the surface (<100 m AGL desired) to the tropopause. Lower stratosphere is a desired goal.
2. Accuracy and precision of 5% in relative humidity (RH)
3. Vertical resolution: ~100-200 m through the tropopheric layer.
4. Temporal resolution: 10 minutes in the Planetary Boundary Layer, 60 min. above.
5. Continuous autonomous operation in all weather conditions.
6. Periodic automatic or semi-automatic calibration on site
7. Mean Time Between Failures > 1yr.
8. Service/maintenance intervals > 1 yr.

9. Service life > 10 yr.
10. System cost < $100K/system

Possible system architecture includes:

1. Two possible approaches may be possible: Differential Absorption Lidar (DIAL) system architectures, one based on the direct transmission of a diode laser output in the 1.4-1.5 micron wavelength bands, using Pulse Code Modulation or short pulse operation.
2. The second is a diode pumped pulsed laser operating on a water vapor absorption line near 1.44 microns and seeded by a small DFB diode laser.

Both of these architectures should be compared with other existing lidar architectures (e.g. Raman backscatter and other DIAL systems) to weigh costs and risks vs. performance as a first step toward selecting the most cost effective system for commercialization.

Two companies have been issued Phase 1 contracts for conducting this preliminary work:

- Bennett Aerospace, LLC
  2054 Kildaire Farm Road #181
  Cary, NC 27518
- Physical Sciences Inc.
  20 New England Business Center
  Andover, MA 01810

The interested reader may contact these companies directly for additional information about their efforts with this SBIR.

2.1 System Components

The *Base Unit* of the IUAWVS consists of the following key components:

- An operational (vs. research-grade) lidar meeting the requirements of the SBIR effort
- A well-performing moisture sensor capable of measuring real-time RH
- A GPS-MET system capable of reporting the integrated precipitable water throughout the column
- Possibly a data logger for providing data sets easily via interfaces to a local office

The *Monitoring and Control* portion of the future system might be integrated into, or be separate from, the Base Unit and serves several functions as described in Section 2.2. Figure 1 provides an overview of how might each IUAWVS interface with a weather unit, i.e., any agency or company wishing to have one or more of these units connected to their office of operations.

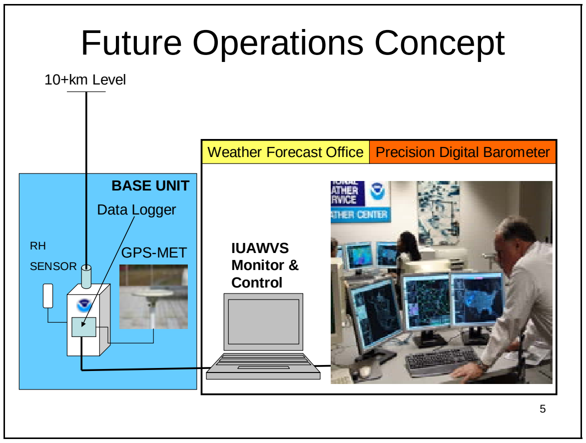
Future Operations Concept

Figure 1. Possible office configuration with a local weather unit

2.1.1 Precision Digital Barometer (PDB)

The weather office environment should have a PDB as a surface-based tie point for determining the pressure profile as a function of the "gate-heights," i.e., heights above the lidar, used to acquire the water vapor measurements. An example of what this profile might look like is shown in Figure 2.

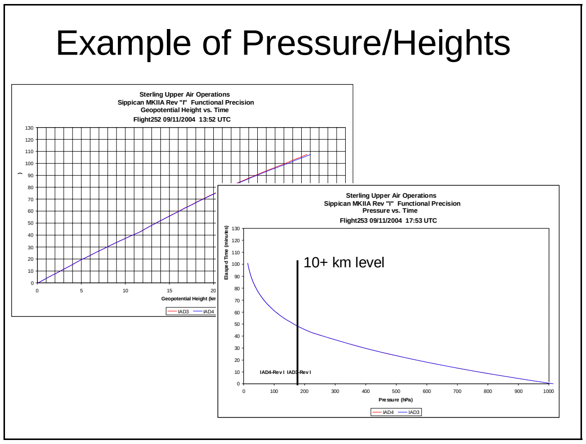
Example of Pressure/Heights

Figure 2. Example of pressure/height profiles

2.1.2 Temperature/Dew Point Sensor

Having a co-located commercially-available temperature/dew point sensor capable of providing high-quality, real-time measurements of temperature and dew point/relative humidity interfaced into a local data logger have excellent possibilities for improving the total measurements from the IUAWVS. Mixing ratio values (Figure 3) can be computed in real-time and meshed with the lidar measurements serving as a surface tie-point for the observation. This also provides another dimension of quality control to the total data set.

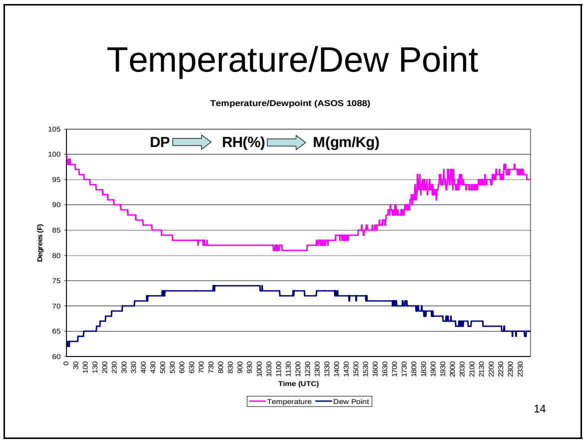

Figure 3. Example of real-time surface temperature and moisture profiles.

2.1.2 GPS-MET Sensor

Previous references provided by the author and Seth Gutman from NOAA's Office of Atmospheric Research are available on this topic. The interested reader is referred to them for further details on this excellent technology. An example of a continuous set of GPS-MET measurements is shown in Figure 4 and could be used for quality control as well as serve as a data gap-filler.

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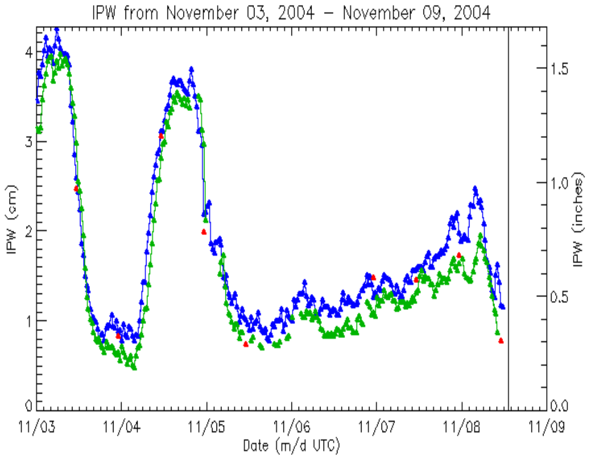

Figure 4. Example of "GPS-MET" 30-min data and radiosonde IPWs every 12 hours.

2.2 Monitoring and Control (M&C)

The M&C function would provide the following functions either independent of the Base Unit or as part of an integrated, total package under one system design:

- Data basing and further data integration from the individual sensors
- Applying further QC algorithms to improve the quality of the final product
- Generating one or more products from the combined data in established formats.

Data brought in from the three independent sensors could be integrated and synchronized into a new *integrated water vapor* product. For example, the real-time surface data could be used to interpolate water vapor to the first "height gate" in the lidar measurements, thus filling in this gap. The GPS-MET data could be used to possibly fill in the top part of the water vapor profile – a future extended abstract – and also serve to QC the output lidar data for IPW consistency. The author has also demonstrated a technique (see references) whereby differences in IPW between the GPS-MET and a lidar could be re-distributed to correct for biases.

Products would be generated on several levels to meet a wide range of applications:

1. Data streamed locally into the office could be displayed on local applications computers and processed to meet immediate use of the data. For example, high resolution of water vapor distribution in the atmosphere would meet many requirements such as identifying the amount of available water vapor for wild fires.
2. Hourly or more frequent profiles of RH or mixing ratios, even Partial Precipitable Water (see references for details), could be generated and encoded for long-line transmission. These could be transmitted over a wide range of product formats such as BUFR, NetCDF, and XML, to name a few.
3. A high resolution data set would also need to be captured for either local storage or long-term archive that might have a wider range of engineering parameters in addition to the meteorological data.

Note the Phase 1 SBIR currently has the Base Unit and M&C functions set apart in order to focus more on the required new lidar technology and not the back-end functions as described above, which can be produced at a later time after the technology is perfected.

2.3 Operations Features

One of the key elements of the real time water vapor system will be its ability to measure under most non-precipitating weather conditions, both daylight and at night, and operate in an unattended, reliable, mode. Operational features of the system under varying weather and sunlight conditions are shown in Figure 5.

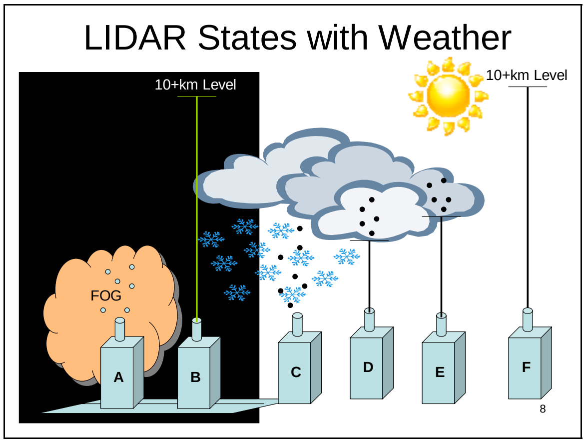

Figure 5. Weather states for an operational lidar.

Clearly, the lidar is not expected to work well under Condition A, i.e., a significant fog event, although the other two sensor components should work just fine under all conditions above. If Condition A is a light fog, the lidar might be able to function and provide a good water vapor sounding. Condition B suggests that the lidar should punch through a thin cloud layer to its expected 10-kilometer range with minimal loss of data in night time operations. Once precipitation is occurring as shown in Condition C, the attenuation of the lidar signals will invariably cause poor quality data. Fortunately, the recovery time should be quick once precipitation ceases or there is a break in the weather condition impeding full performance.

Conditions D and E represent one of the most common situations in the atmosphere; namely, measuring water vapor up to the base of varying non-precipitating cloud types and amounts. It is understood that the lidar should function nominally up to the cloud base. Then, depending on the thickness of the cloud deck, either continue reporting reasonably good data if the cloud is thin or as the signal becomes too attenuated for good data to be produced as a result of a thick cloud deck, it fails quality control and is tagged, accordingly. The final condition (F) will be the nominal day-time clear weather case reaching up to 10 kilometers in height. The challenge for the lidar technology will be to demonstrate its ability to withstand much of the sunlight intrusion impeding many lidars today when the solar effect is near its maximum.

Additional criteria and operational goals for the lidar portion of the system can be found in Table A.

SBIR Operational Goals

Goal	Minimum	Maximum	Remarks
First Gate Last Gate	100 m 10 km	500 m 15 km	Data can be interpolated from surface to 1st Gate
Data Availability	1/hr	12/hr	Proc. Time < 5min
Sunshine	No data rejected	Few data rejected	Bright or hazy; birds or aircraft impacting
Cloud Contamination	No data rejected	Few data rejected	Thin or translucent
Cloud Contamination	Some data rejected after cloud base	Most data rejected after cloud base	Thick or opaque
Fog, obscurations	Some data rejected	Most data rejected	
Liquid Precipitation	Some data rejected	Most data rejected	
Frozen Precipitation	Some data rejected	Most data rejected	9

Table A. Additional operational features of the lidar.

2.4 Maintenance Features

Another key element of an operational lidar is to meet the SBIR criteria for its maintainability. This means certain features will need to be incorporated into the design to ensure it can meet the SBIR criteria as follows:

- Maximize use of COTS components meeting operational goal while attempting to reduce the overall number
- Ruggedized to meet harsh environments, e.g., Alaska to Puerto Rico to desert conditions
- Remote diagnostics leading to “modern” methods for maintenance
- Performs maintenance checks and issues status messages on the current state of the system

These maintenance criteria as well as many more will have to be demonstrated during Phase 2 testing of the candidate systems.

3. APPLICATIONS

The real question then becomes, what applications could benefit from this advanced technology? The answer should become clear with the following sections below. Applications for the IUAWVS fall into several categories including:

- Local Applications
- Numerical Weather Prediction Model Impacts
- Satellite and In Situ Calibrations

Each of these is described in more detail below.

3.1 Local Operational Impacts

One of the most direct impacts this technology would have on a local operational environment would be the ability to monitor changes in the moisture field in near-real-time. Understanding how the moisture field is changing both locally and upstream from the weather unit provides great insight in how automated weather forecasts will be generated in the future. For example, Figure 6 illustrates a typical upper air radiosonde sounding taken every 12 hours -- courtesy of the University of Wyoming Atmospheric Sciences web site. With the IUAWVS in place, the moisture sounding would update each hour or faster up to the red bar indicating the potential maximum altitude of the system. Note, it is understand that thick clouds and precipitation will impair the number and quality of soundings; nevertheless, the number available will still be much larger than the 2/day as is the case today.

Especially important will be the calculation of many indices each hour at a minimum which can provide a new level of awareness to the forecast staff in seeing significant weather changes associated with these forecast parameters. When combined with satellite-derived moisture soundings for the stratosphere, an entire sounding to the 30-35 km level would be possible.

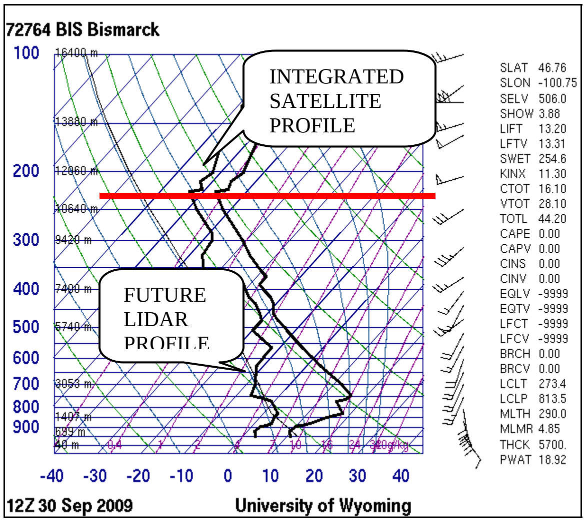

Figure 6. Hourly lidar/satellite composite profiles.

3.2 Model Output Applications

One of the key areas of improvement to be expected from a network of these systems would be in the arena of numerical weather prediction and modeling. Because several models now function on hourly updates with products generated every 3 hours, having reliable, high resolution water vapor data on this time scale could have a significant impact on such features as the generation and strength of a wide range of storms.

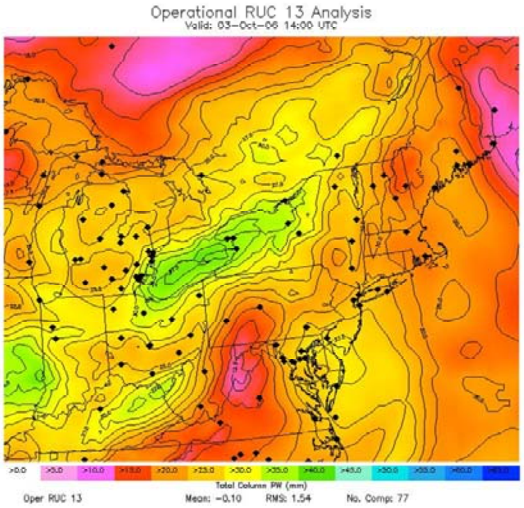

Figure 7. Rapid Update Cycle model output.

3.2 Satellite Calibrations

One of the biggest advantages this technology offers the meteorological community is with respect to calibrating space-borne instruments, i.e., satellite sensors. Today, satellite retrievals of temperature and water vapor depend heavily on ground-based systems to help calibrate their measurements. With the advent of the IUAWVS, it would be possible to synchronize satellite overpasses with the ground-based measurements, especially over open ocean areas where independent surface data is sparse at best. Figure 8 illustrates the linkage of satellite overpass with IUAWVS direct measurements. A reasonable world-wide network could have an immeasurable positive impact on the satellite-based soundings.

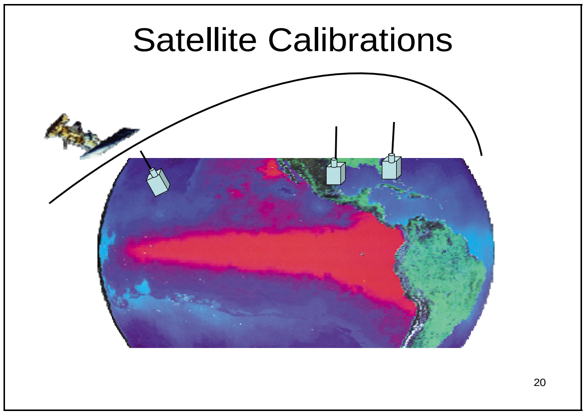

Figure 7. Network of satellite water vapor calibration sites.

3.3 Network Moisture Calibrations

Another potential application of the IUAWVS is with respect to serving as a reliable referencing system for other technologies in use as illustrated in Figure 8. Because the system will have two major referencing capabilities incorporated into the design, it would be possible to inter-compare measurements and make periodic adjustments to these other technologies, accordingly.

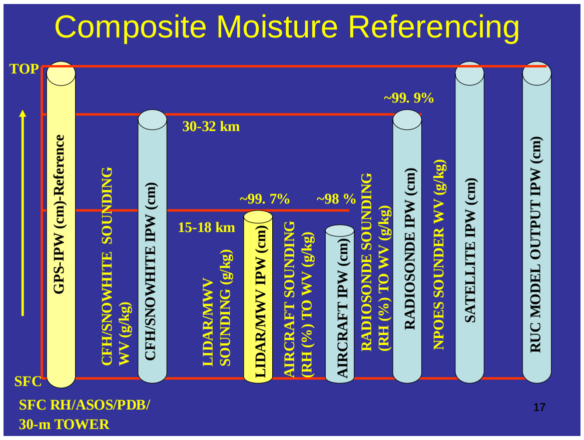

Figure 8. Moisture Referencing for other technologies in use.

4. WHAT THE FUTURE HOLDS

With the implementation of an IUAWVS-type system, one can see the future possibility to one day have a temperature lidar reaching the upper atmosphere in a similar manner. When combined with a wind-finding profiler technology, which can easily reach through the troposphere, the pieces could be in place to begin eliminating radiosonde networks around the world. Although others have discussed this concept in the past, this author believes the technology to make it this a reality given the lidar breakthroughs coming about allows these old concepts to be revisited.

5. CONCLUSIONS

The purpose of this paper is to inform the meteorological and aviation communities about the possibility for a *future integrated water vapor system* based on new lidar technology and interfaced with two other well known subsystems, a surface moisture sensor and a GPS-MET sensor.

Once the technology discussed in this paper is further developed and proven, it can be implemented for use by the wider community rather quickly. The techniques can then be refined and the process for ultimately replacing radiosondes can begin in earnest.

6. ACKNOWLEDGEMENTS

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Geary Schwemmer, Director, Research and Development, Science and Engineering Services, Inc.

7. REFERENCES

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