Update on The Integrated Upper Air Water Vapor System

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1. INTRODUCTION

This extended abstract provides an update for the meteorological community on this new concept of providing water vapor measurements from the surface to various points aloft throughout the troposphere using different sensors all integrated into one system. 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 was described at last year's AMS under a Phase 1 Small Business Innovation Research initiative:

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

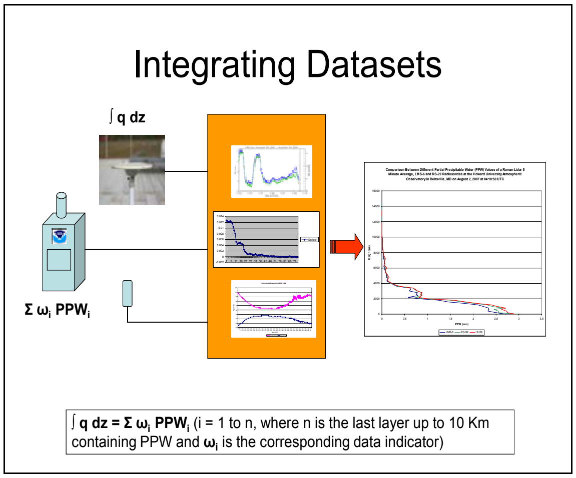
A Phase 2 SBIR was awarded to Bennett Aerospace of Cary, North Carolina this past summer and is currently underway. No details from their designs will be divulged in this abstract; rather it will provide an overview of how the pieces will be integrated into a new composite real-time water vapor system. The interested reader may contact this company directly for additional information about its involvement with this SBIR.

One challenge will be how to maximize the **Li**ght **D**etection **a**nd **R**anging **(**lidar) data when certain weather conditions exist and a description of a possible technique for mitigating this issue will be discussed in this extended abstract. Preliminary thoughts on a potential network configuration will also be outlined as it pertains to this concept

2. IUAWVS OVERVIEW

The particulars of this subtopic were discussed in last year's extended abstract on this topic. In general, data are brought in from the three independent sensors, synchronized and quality-controlled (QC) before being integrated into a new *integrated water vapor* product as shown in Figure 1. For example, the real-time surface data would be used to interpolate water vapor to the first "height gate" in the lidar measurements, thus filling in this gap. The GPS-MET data would be used to possibly fill in the top part of the water vapor profile – this and a future extended abstract – and also serve to QC the output lidar data for IPW consistency. The author has also described a technique (see references) whereby differences in IPW between the GPS-MET and a lidar could be re-distributed to correct for biases.

Therefore, the purpose of the subtopic is to develop a prototype "operational" lidar for test and evaluation of these concepts. An eventual later goal is to "operationalize" the system as a step towards a national IUAWVS network.



Integrating Datasets

$\int q\,dz = \Sigma\,\omega_i\,PPW_i$ (i = 1 to n, where n is the last layer up to 10 Km containing PPW and ω_i is the corresponding data indicator)

FFigure 1. Overview of the major components of the IUAWVS.

A fundamental feature of this system will be the calculation of Partial Precipitable Water (PPW – see references for further details on this concept) for each layer of the lidar measurements, which has been well described by the author in recent extended abstracts. Another critical feature of the data base is time synchronization (Figure 2) of the different components to ensure the data are being integrated, correctly.

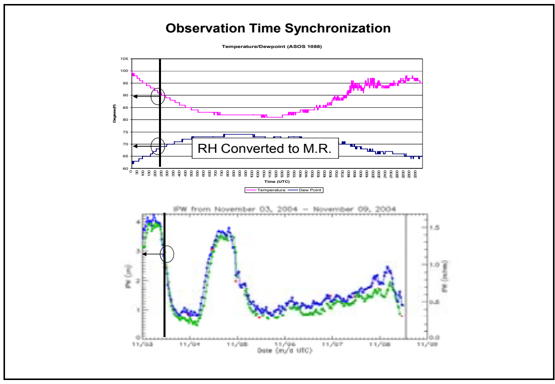


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Figure 2. Example of time synchronization of the Surface and GPS-MET Components.

Last year's extended abstract also discussed in detail the limitations of the lidar component of the system due to attenuation of the laser signal with the surrounding environment. Figure 3 illustrates types of limitations possibly occurring during a lidar sounding profile.

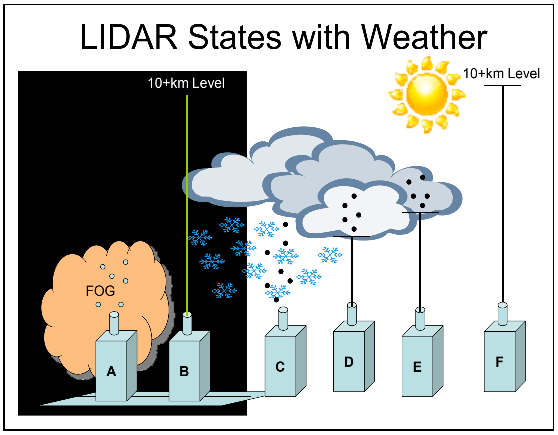


Figure 3. Lidar Limitations.

2.1 Types of Operational LIDAR Soundings

The general concept for a future operational IUAWVS centers on composite observations falling into two basic classes:

1. Measured lidar observations for the system to the 10-km level.
2. Interrupted observations, impacting the measurements to the 10-km level.

Those falling into Class 2 can be "blended" or "synthesized" depending on the amount and length of time missing data was encountered. Because the different components of the system all need to be in balance with each other, a mathematical technique can be applied to reconstruct the moisture lidar sounding (L_m-Sounding) back to the 10-km level. See Section 3 for further details on the technique.

Regardless of the class, the L_m-Sounding can be further categorized as either a *Timed* or *Hourly* observation. A Timed L_m-Sounding signifies one that is time-stamped as soon as the lidar observation is completed, while an Hourly L_m-Sounding is synchronized to be within 5-minutes of the hour. Note, other time stamps, e.g., 15-minute L_m-Soundings, could be categorized as well.

Additionally, Figure 4 illustrates types of L_m-Sounding as follows:

1. Prime
2. Blended
3. Synthetic
4. No-OBS
5. Blended/No-OBS

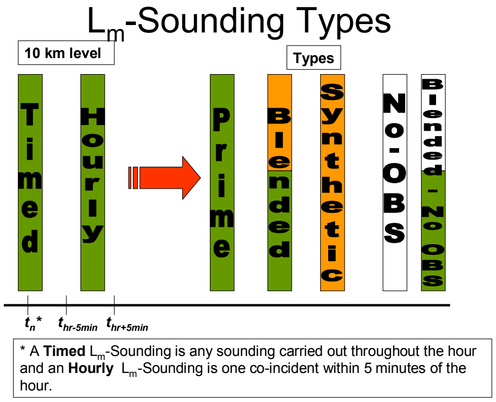


Figure 4. Relationship between types and categories of L_m-Soundings.

2.2 Definitions

Below are the definitions for each type of L_m-Sounding above.

Definition: A **Prime** L_m-Sounding is taken by the lidar system to the 10-Km level and corrected for IPW differences. A **Prime** L_m-Sounding always replaces all previous **Prime/Blended/Synthetic** Observations as the latest observation in the data base and has the highest quality flags (see Section 4) assigned to it. Data from a **Prime** L_m-Sounding can be used to create a **Blended** and/or **Synthetic** observation as described below.

Definition: A **Blended** observation is a combination of both real L_m-Sounding data taken by the system to some point below the 10-Km level combined with data from a previous **Prime** L_m-Sounding adjusted for the GPS-MET IPW differences (refer to Figure 5). A **Blended** L_m-Sounding always replaces all previous **Blended/Synthetic** Observations as the latest observation and has the quality flags assigned to it based on the amount of real L_m- Sounding data used. Data from the last **Prime** L_m-Sounding is used to create a **Blended** observation, provided it is less than 6 hours old; otherwise it defaults to a **No-OBS** for that portion of the sounding.

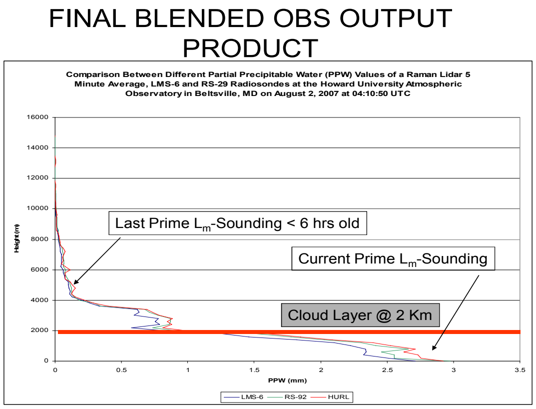

FINAL BLENDED OBS OUTPUT PRODUCT

Figure 5. Cloud impacting L_m-Sounding forcing a Blended Observation.

Definition: A **Synthetic** observation (Figure 6) is derived solely from the last **Prime/Blended** L_m-Sounding data taken by the system within the previous 6 hours up to the 10-Km level adjusted with data computed from the GPS-MET IPW differences. A **Synthetic** L_m-Sounding never replaces previous **Prime** or **Blended** Observations as the latest observation; rather it serves as a place holder in the data base until the next **Prime** or **Blended** observation is created. It has the lowest quality flags assigned to it based on the fact no real L_m-Sounding data is derived and the flag is lowered even further as time elongates from the last **Prime** or **Blended** L_m-Sounding. Figure 6 illustrates the concept of a Synthetic observation.

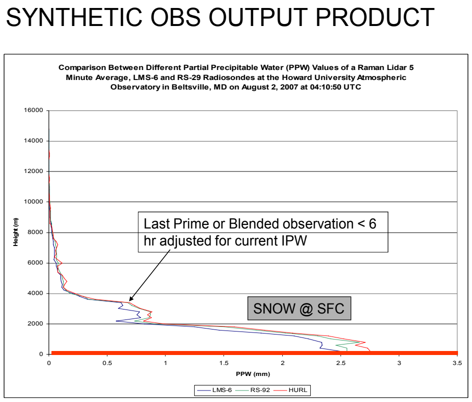
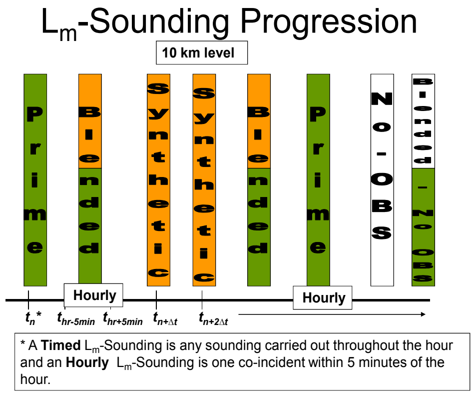

SYNTHETIC OBS OUTPUT PRODUCT

Figure 6. An example of a Synthetic Observation.

Definition: A **No-OBS** observation means no data is being reported by the lidar system. A **No-OBS** L_m-Sounding may exist when the system has failed or is inoperative.

Definition: A **Blended** - **No-OBS** observation is a combination of both real L_m-Sounding data taken by the system to some level below the 10 KM mark and then no data above that level. This type occurs when a system is just being activated and clear weather conditions to acquire a **Prime** observation have not yet transpired. A **Blended - No-OBS** L_m-Sounding always replaces all previous Blended/Synthetic

This means that during, say a several hour cycle, the L_m-Soundings could be categorized as illustrated in Figure 7 as conditions change. It should be noted the key here if that L_m-Soundings are still reported to the 10-km level no matter which type is being reported.


L_m-Sounding Progression

* A **Timed** L_m-Sounding is any sounding carried out throughout the hour and an **Hourly** L_m-Sounding is one co-incident within 5 minutes of the hour.

Figure 7. Progression of L_m-Soundings through several hours of operation.

3. MATHEMATICAL TECHNIQUE

The underlying premise of the technique is centered on a balance equation between the integration of PPWs computed from the lidar (**$\Sigma\ \omega_i$ PPW$_i$**) and IPW derived from the GPS-MET (**$\int q\, dz$**) component of the system synchronized for time (t_n):

(1) **$\int q\, dz|_{tn} = [\Sigma\ \omega_i\ PPW_i]_{tn} = \omega_1\ PPW_1 + \omega_2\ PPW_2 + \ldots + \omega_n\ PPW_n$**

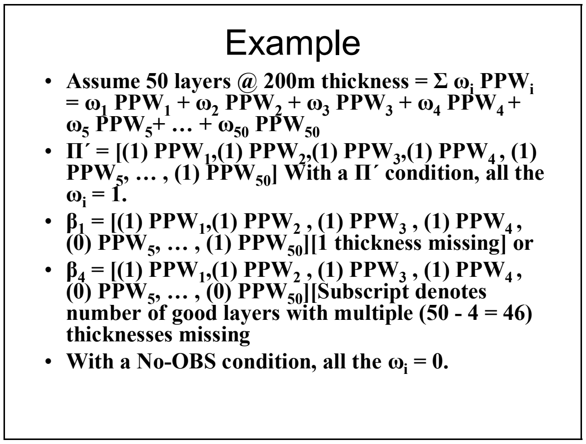
Note, while PPW is a function of Δ**p** it can also be expressed as a function of Δ**Z.** The parameter **ω_i** signifies whether the L_m – Sounding data for a particular layer has been actually observed (i.e., **ω_i** = 1) or rejected (**ω_i** = 0) for some reason. When data is collected up to the 10-km level (all **ω_i** = 1), it will be designated as **Π'** identifying it as a **Prime** L_m-Sounding.

To generate a **Blended** Observation (β) assume a Π' exists for up to 6 hours (t_n – 6) prior to the current time. For each thickness with ω_i = 0 resulting in a **No-OBS** condition, take each corresponding layer ($\Pi'_{\Delta p}$), insert it into the profile, and then interpolate the tie points. Afterwards, adjust the total profile using the amount of difference in IPW measurements from Equation (1).

Conceivably, one 200m-thickness with **ω_i** = 0 interlaced between two layers with **ω_i** = 1, can be resolved simply with any interpolation scheme. More than 1 consecutive thickness with **ω_i** = 0 results in a **No-OBS** condition. Interpolation is also required between the surface RH converted to mixing ratio and the first L_m-Sounding height gate.

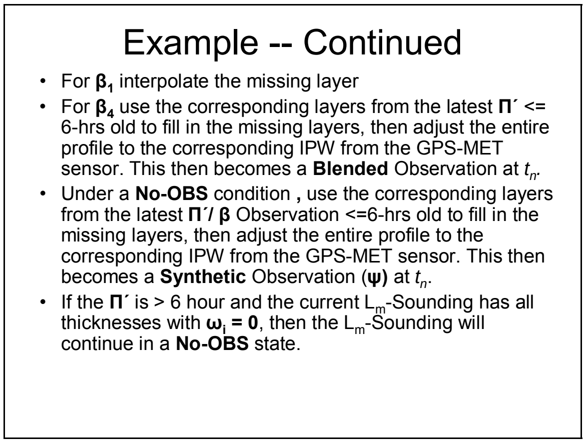
To generate a **Synthetic** Observation (ψ) assume a Π' or β exists for up to 6 hours (t_n – 6) prior to the current observation time. Since all thicknesses will have **ω_i** = 0 resulting in a **No-OBS** condition, take all corresponding layers ($\Pi'_{\Delta p}$ or $\beta_{\Delta p}$), and insert them into the profile. Afterwards, adjust the total profile for the amount of difference in IPW measurements between the two as above.

Exhibits Ia and b illustrate examples for each type of observation and how to apply adjustments to the profiles. Note, more details will be forthcoming concerning actual examples with real data.



Example

- **Assume 50 layers @ 200m thickness = $\Sigma\ \omega_i$ PPW$_i$ = ω_1 PPW$_1$ + ω_2 PPW$_2$ + ω_3 PPW$_3$ + ω_4 PPW$_4$ + ω_5 PPW$_5$+ … + ω_{50} PPW$_{50}$**
- **Π' = [(1) PPW$_1$,(1) PPW$_2$,(1) PPW$_3$,(1) PPW$_4$, (1) PPW$_5$, … , (1) PPW$_{50}$] With a Π' condition, all the ω_i = 1.**
- **β_1 = [(1) PPW$_1$,(1) PPW$_2$, (1) PPW$_3$, (1) PPW$_4$, (0) PPW$_5$, … , (1) PPW$_{50}$][1 thickness missing] or**
- **β_4 = [(1) PPW$_1$,(1) PPW$_2$, (1) PPW$_3$, (1) PPW$_4$, (0) PPW$_5$, … , (0) PPW$_{50}$][Subscript denotes number of good layers with multiple (50 - 4 = 46) thicknesses missing**
- **With a No-OBS condition, all the ω_i = 0.**



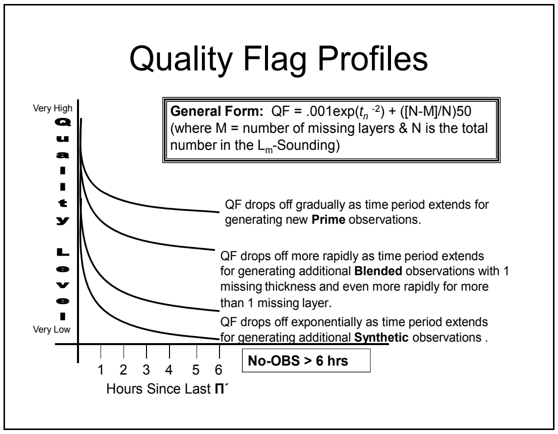
Example -- Continued

- For **β_1** interpolate the missing layer
- For **β_4** use the corresponding layers from the latest **Π'** <= 6-hrs old to fill in the missing layers, then adjust the entire profile to the corresponding IPW from the GPS-MET sensor. This then becomes a **Blended** Observation at t_n.
- Under a **No-OBS** condition **,** use the corresponding layers from the latest **Π'/ β** Observation <=6-hrs old to fill in the missing layers, then adjust the entire profile to the corresponding IPW from the GPS-MET sensor. This then becomes a **Synthetic** Observation (**ψ**) at t_n.
- If the **Π'** is > 6 hour and the current L_m-Sounding has all thicknesses with **ω_i = 0**, then the L_m-Sounding will continue in a **No-OBS** state.

Exhibits Ia and b. Examples of how L_m-Soundings are determined.

4. QUALITY CONTROL

After the observation has been constructed for either Class – Timed or Hourly – the next step is to apply a Quality Control Flag (QCF) to it as part of the meta-data. In this way, users of the output can determine which are real, which are blended, and which are synthetic observations. A possible scheme can be applied as shown in Figure 8 whereby each type of observation has a QCF index that declines over time up to 6-hrs. After this time, further L_m-Soundings observations made fall into a **NO-OBS** state until either a **Prime** or **Blended** observation next occurs.



Quality Flag Profiles

General Form: QF = .001exp(t_n $^{-2}$) + ([N-M]/N)50 (where M = number of missing layers & N is the total number in the L_m-Sounding)

Figure 8. QCF scheme for assessing the quality of the observation.

Products would then be generated including the QCFs on several levels to meet a 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.
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.

5. FUTURE OPERATIONAL FEATURES

The widespread use of such systems operating 24/7 later this century would move the field of meteorology, substantially, toward real-time measurements of water vapor filling in the many gaps in coverage that existing instruments do not cover, particularly in the time domain. Small lidars could be deployed in various network configurations like other technologies, e.g., GPS-MET, with a consortium of communities purchasing units and then networking them into a continuous observational suite.

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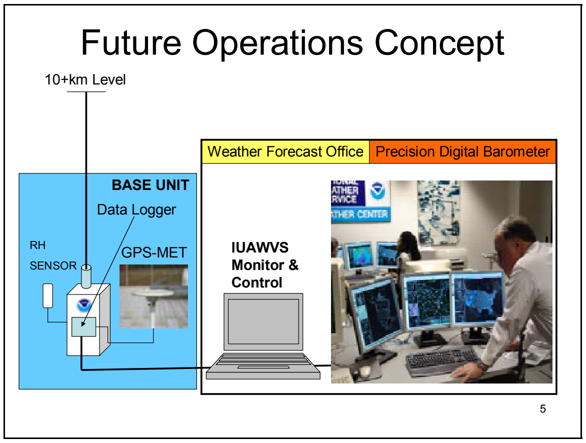
One of the key elements of the real time water vapor system will be its ability to measure under most non-precipitating weather conditions, both in daylight and at night, operating in an unattended, reliable, mode. Operational features of the system under varying weather and sunlight conditions are shown in Figure 9. Applications for the IUAWVS fall into several categories including:

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

These were discussed in last year's extended abstract in some detail.



Future Operations Concept

Figure 9. Weather states for an operational lidar.

With the implementation of an IUAWVS-type system, one can see the future possibility to one day have an operational temperature lidars 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 (Figure 10). Although others have also discussed this concept in the past, this author believes the technology to make this into a reality is at our door step given the lidar breakthroughs coming about over the next decade or two.

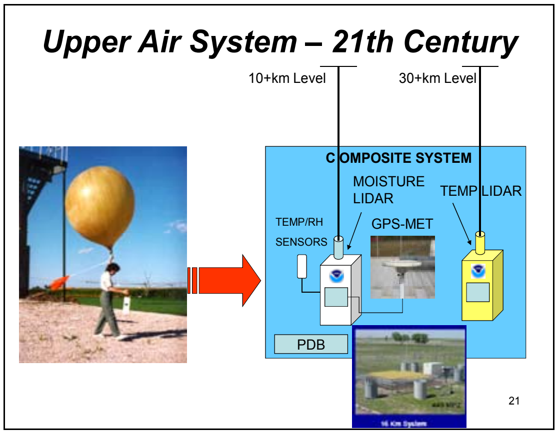


Figure 10. What the future holds!

6. 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 with the integration of other technologies to ultimately replace radiosondes around the world.

7. ACKNOWLEDGEMENTS

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