2.3 Update on the Consensus Reference Concept for Testing Radiosondes

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1. INTRODUCTION

The U. S. has been testing radiosonde manufacturer's radiosondes for many decades at test facilities around the country and has developed a number of test techniques for verifying performance. Recent advances in measuring the upper air atmosphere utilizing state-of-the-art referencing technologies and the development of new test techniques within the U.S. are now available for evaluating radiosonde performance to meet the more stringent climate monitoring requirements. Examples of these reference technologies include: NASA's Advanced Temperature Measuring system, Howard University Atmospheric Observatory (HUAO) LIDARs for measuring the mid-to-upper tropospheric moisture, Snow White, high-precision GPS measurements of height, the Integrated Precipitable Water sensor using GPS techniques, various radiometers, and ground-based surface instrumentation to measure clouds and weather. Each reference technology can play an important role in the *Consensus Reference Concept;* whereby, data are integrated into information bases from which statistical techniques would be applied to the time-based and pressure/height candidate instrument measurements of say, temperature, moisture variables, cloud bases, and winds as compared to the references in use.

This extended abstract covers one aspect of the Consensus Reference Concept; namely, using the Integrated Precipitable Water and *Partial Precipitable Water* to develop consensus between different observing moisture platforms. This work is a result of data collected during early phases of the Water Vapor Variability – Satellite/Sondes (WAVES) Project held at Howard University in Beltsville, MD. Previous extended abstracts covered other aspects of this concept which should better help the reader understand the development of these processes.

2. HOWARD UNIVERSITY TEST FACILITY

Figure 1 is a Google Earth® image of the HUAO test facility used during the WAVES project operational phase. Systems configured at the facilities for this study included upper air systems, surface systems, a RAMAN LIDAR, and a GPS Integrated Precipitable Water sensor. These were all within close proximity of each other at the test facility.

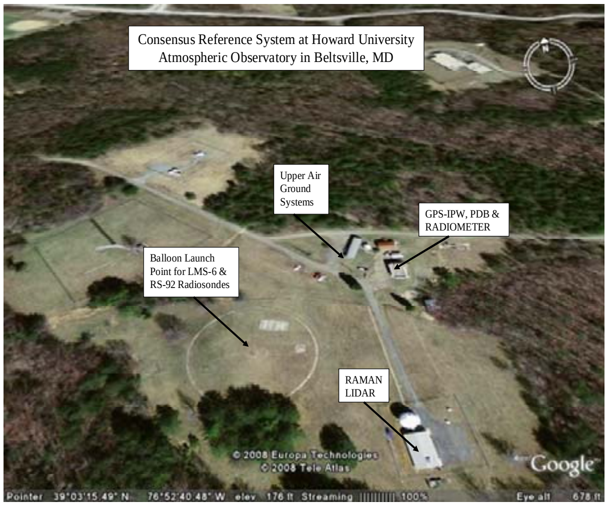


Figure 1. System configuration at Howard University during WAVES.

2.1 Consensus Reference System

The Consensus Reference System consists of the following components:

- One or more ground systems for tracking radiosondes and reference instruments
- HUAO 30-meter tower for low-level measurements
- Surface systems
- Remote systems including GPS-IPW, Wind profiler, and radiometers
- Precision Digital Barometer
- Data Base Management System/Display

An *In-Situ GPS Reference* is also being pursued for independent measurements/calculations of geometric heights, geo-potential heights, derived-pressures, and the u- and v-components for calculating winds aloft. See accompanying paper for further details on this topic.

Refer to Figure 1 for a visual description of the systems used during the CRS evaluation at Howard University. The real challenge with CRS is integrating datasets from the diversity of technologies and synchronizing them within the frames-of-reference as discussed in previous extended abstracts.

2.3 Moisture Referencing

Moisture referencing is the most challenging of the measurements since water vapor is very variable. As Figure 2 illustrates, one method is to utilize the all-weather aspects of the GPS-IPW derived measurements as a reference. Other technologies, e.g., LIDAR, also provide excellent reference measurements, but are limited in one way or another and thus can only be used in a limited fashion within the consensus referencing concept.

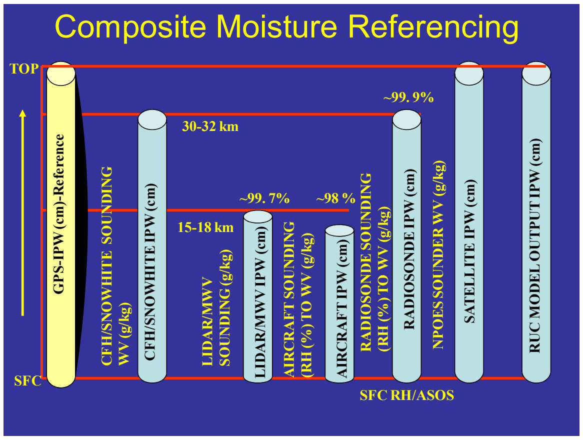
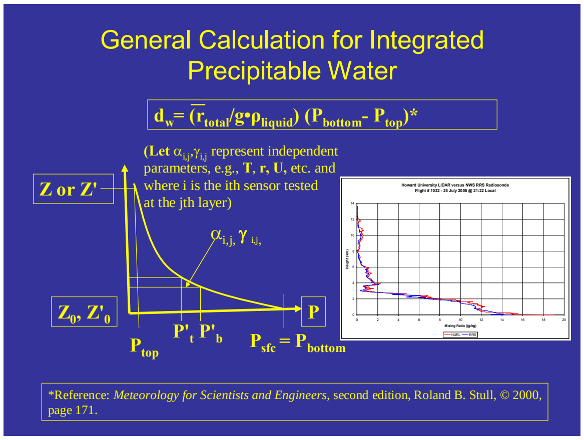

Composite Moisture Referencing

Figure 2. Moisture Referencing System and candidate test systems.

2.2 PARTIAL PRECIPITABLE WATER

Although many forms of the Integrated Precipitable Water (IPW) equation exist, the one used for this work is shown in Figure 3.* As stated in a previous extended abstract on this subject, Consensus Referencing is based on a frames-of-reference concept whereby different systems would be providing their sounding data with respect to height, pressure, or time. So translations between these different references can transform say heights associated with a RAMAN LIDAR into equivalent pressures to be used within the equation shown in Figure 3.


General Calculation for Integrated Precipitable Water

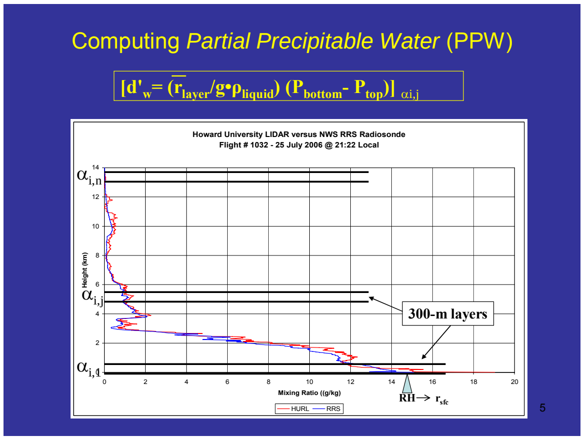
$d_w = (\overline{r}_{total}/g \bullet \rho_{liquid})\,(P_{bottom} - P_{top})^*$

(Let $\alpha_{i,j}, \gamma_{i,j}$ represent independent parameters, e.g., **T**, **r**, **U**, etc. and where i is the ith sensor tested at the jth layer)

*Reference: *Meteorology for Scientists and Engineers*, second edition, Roland B. Stull, © 2000, page 171.

Figure 3. Reference and candidate test systems converted to similar frames-of - references.

Figure 4 illustrates how moisture soundings from different technologies can be converted to *partial precipitable water* (PPW) measurements thus allowing candidate test systems to be compared directly with a reference using this concept.


Computing *Partial Precipitable Water* (PPW)

$[d'_w = (\overline{r}_{layer}/g \bullet \rho_{liquid})\,(P_{bottom} - P_{top})]_{\alpha i,j}$

Figure 4. Generating $\alpha_{i,j}$ layers for different technologies.

To determine PPW the atmosphere, is segmented into 300-meter layers ($\alpha_{i,j}$, where i is the ith sensor under test and j is the jth PPW layer within the sounding)and a (d´ for determining the amount of PPW within the layer) is calculated. The advantage of PPW over mixing ratio or relative humidity is that it can be easily linked to IPW, i.e., the sum of the PPWs is approximately equal to the IPW. Note 300-m layers were selected because they approximate

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[*] Reference: *Meteorology for Scientists and Engineers*, second edition, Roland B. Stull, © 2000, page 171.

the 1000 feet/minute rise rate of the balloon. Thus, an independent reference like a GPS-IPW sensor situated within the same test bed as illustrated in Figure 1 can provide this linkage. A microwave radiometer could also serve this purpose, if available.

3. Linking the IPW with PPW

For the example in this study, two different radiosondes, a Lockheed Martin/Sippican LMS-6® and a Vaisala RS-92®, and the HU RAMAN LIDAR were used to measure similar summer night-time atmospheres, each providing information on their respective moisture contents. The technique of converting this data into PPW in millimeters for the 300-m ($\alpha_{i,j}$), increments allows all three sensors to provide equivalent moisture measurements. Then five 300-m sub-layers (S_n) are grouped into macro-layers designated by A_k (see Figures 5a & 5b).

The goal here is to adjust each of the three PPW profiles independently through the use of an independent reference -- in this case the GPS-IPW sensor -- such that each of the three is potentially in consensus with each other along with the reference. The technique that follows illustrates one method for performing this work.

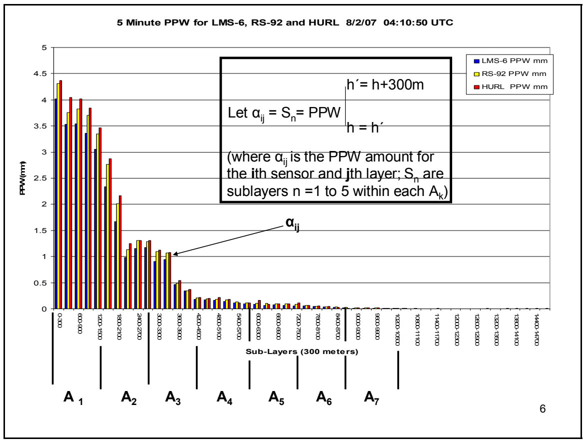
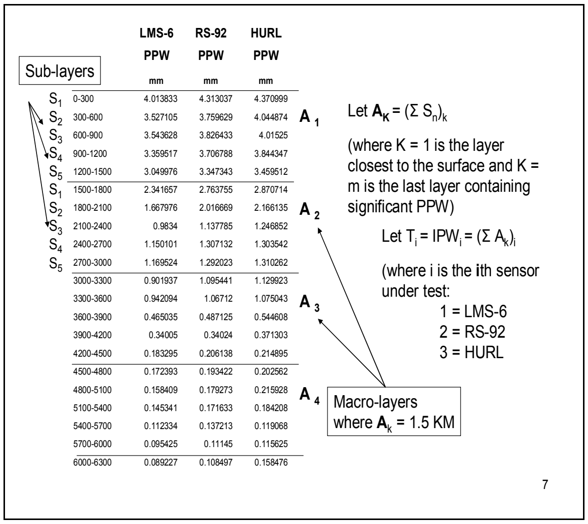


Figure 5a. PPW calculated for each sub-layer within every macro-layer.

3.1 Segmented Layers

Figure 5b provides actual data for a segment of the soundings shown in Figure 5a with the 300-m sub-layers and 1.5 km macro-layers also delineated. Sub-layers, S_n, are accumulated within each macro-layer, A_k, and the IPW for each candidate sensor is computed and denoted by T_i in Figure 6.



Sub-layers		LMS-6 PPW mm	RS-92 PPW mm	HURL PPW mm	
S_1	0-300	4.013833	4.313037	4.370999	
S_2	300-600	3.527105	3.759629	4.044874	A_1
S_3	600-900	3.543628	3.826433	4.01525	
S_4	900-1200	3.359517	3.706788	3.844347	
S_5	1200-1500	3.049976	3.347343	3.459512	
S_1	1500-1800	2.341657	2.763755	2.870714	
S_2	1800-2100	1.667976	2.016669	2.166135	A_2
S_3	2100-2400	0.9834	1.137785	1.246852	
S_4	2400-2700	1.150101	1.307132	1.303542	
S_5	2700-3000	1.169524	1.292023	1.310262	
	3000-3300	0.901937	1.095441	1.129923	
	3300-3600	0.942094	1.06712	1.075043	A_3
	3600-3900	0.465035	0.487125	0.544608	
	3900-4200	0.34005	0.34024	0.371303	
	4200-4500	0.183295	0.206138	0.214895	
	4500-4800	0.172393	0.193422	0.202562	
	4800-5100	0.158409	0.179273	0.215928	A_4
	5100-5400	0.145341	0.171633	0.184208	
	5400-5700	0.112334	0.137213	0.119068	
	5700-6000	0.095425	0.11145	0.115625	
	6000-6300	0.089227	0.108497	0.158476	

Let $\mathbf{A_K} = (\Sigma\ S_n)_k$

(where K = 1 is the layer closest to the surface and K = m is the last layer containing significant PPW)

Let $T_i = IPW_i = (\Sigma\ A_k)_i$

(where i is the ith sensor under test:
1 = LMS-6
2 = RS-92
3 = HURL

Macro-layers where $\mathbf{A_k}$ = 1.5 KM

7

Figure 5b. Actual data (PPW) calculated for each sub-layer within the macro-layers.

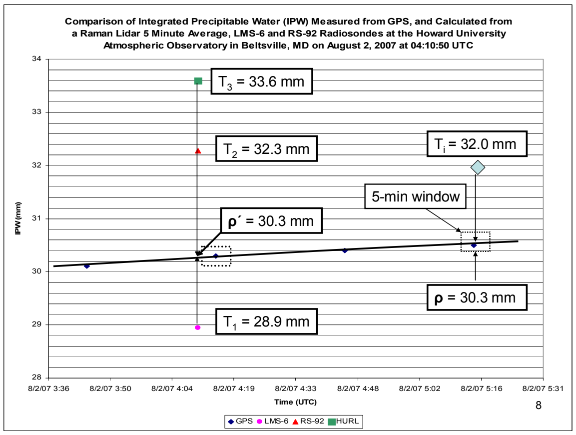
3.2 Consensus Reference Value

The next step in the process is to compute the Consensus Reference Value (CRV) for each sensor as follows:

1. Since the reference is a continuous measuring system, many more IPW measurements will have been taken than the three sensors under test. Note for the purposes of this study only one LIDAR profile was used, although there could have been several to many profiles available for the intercomparisons. As a result, use a curve fitting program to best fit the IPW data for the reference **ρ**.

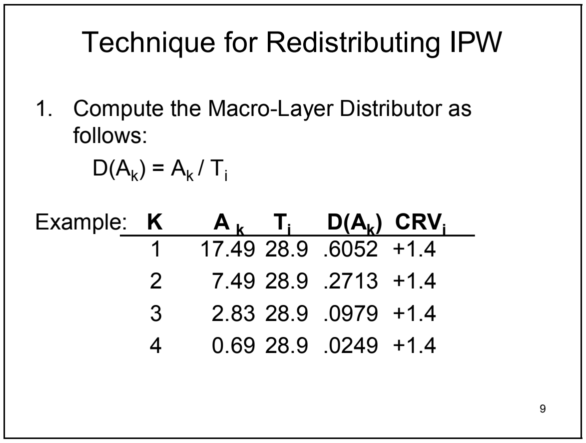
2. Set a window of 5-minutes before and after each measurement of **ρ**. Subtract the T_i from **ρ** if it is within the window or estimate **ρ** from the curve fit if it is outside the window, denoted as **ρ´**. Examples of this are shown in Figure 6.

Figure 6. IPW calculated for each sensor and the reference.



3. Compute either **ρ** – T_i or **ρ´** – T_i (where the sign indicates whether to distribute an excess (**ρ** < T_i) or deficit (**ρ** > T_i) of IPW. This is called the Consensus Reference Value (CRV_i). Note, if **ρ** is within +/- 0.5 mm of T_i, then the two are already considered "in consensus."

4. Next, compute the Macro-Layer Distributor as shown in the box below. The ratio here prevents the technique from over-correcting the PPW within any A_k.



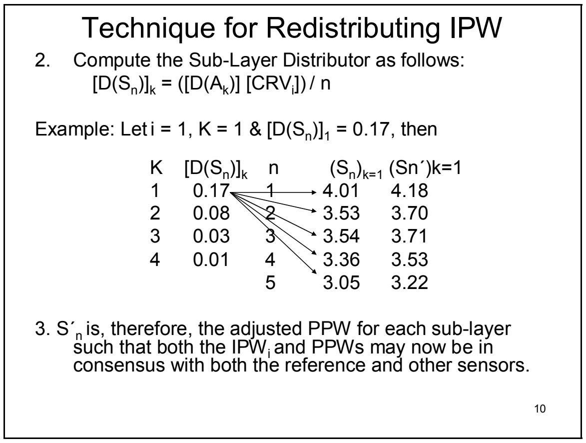
Technique for Redistributing IPW

1. Compute the Macro-Layer Distributor as follows:
   $D(A_k) = A_k / T_i$

Example:

K	A_k	T_i	$D(A_k)$	CRV_i
1	17.49	28.9	.6052	+1.4
2	7.49	28.9	.2713	+1.4
3	2.83	28.9	.0979	+1.4
4	0.69	28.9	.0249	+1.4

5. The next step in the process is to compute the sub-layer distributor by distributing an equal amount across the 5 sub-layers as shown in the following box. The sub-layers are then denoted by (S_n´) for the adjusted PPW values, in this case, the LMS-6 radiosonde. The technique would be applied across all macro-layers for each candidate sensor under test.



Technique for Redistributing IPW

2. Compute the Sub-Layer Distributor as follows:
   $[D(S_n)]_k = ([D(A_k)]\ [CRV_i]) / n$

Example: Let i = 1, K = 1 & $[D(S_n)]_1 = 0.17$, then

K	$[D(S_n)]_k$	n	$(S_n)_{k=1}$	(Sn´)k=1
1	0.17	1	4.01	4.18
2	0.08	2	3.53	3.70
3	0.03	3	3.54	3.71
4	0.01	4	3.36	3.53
		5	3.05	3.22

3. $S´_n$ is, therefore, the adjusted PPW for each sub-layer such that both the IPW_i and PPWs may now be in consensus with both the reference and other sensors.

4. POSSIBLE OUTCOMES

There are three potential outcomes from this technique after all the data are processed in this manner:

- **All sensors under test are now in consensus with the reference (ρ) and each other.**
- **At least one of the test sensors is still not in consensus with the reference and the other sensors, and is possibly in error.**
- **Most or all test sensors are in error with the reference, but not with each other; therefore, the reference is possibly in error.**

This could have benefit for long term studies as would be required for climate monitoring of the upper atmosphere or for adjusting different data sets from different sensor platforms within numerical weather prediction models.

5. CONCLUSIONS

The purpose of this paper is to inform the meteorological and climate communities about the potential for a consensus reference concept, whereby an ensemble of tests are conducted and the results standardized to formulate a consistent pattern for evaluating upper air instrumentation and systems.

The concept of PPW has important attributes for assessing the atmospheric moisture distribution:

- PPW is a "conserved" value, meaning it is constant within the layer and can be

derived from any in situ/remote sensor measuring water vapor aloft
- Can be linked directly with a reference and any residual can be re-distributed over the PPWs; thus "matched" soundings from a wide range of in situ and remote instruments can be obtained
- Could be of great benefit to NWP and climate modeling since the distribution of precipitable water in the atmosphere can be monitored more consistently than with RH or mixing ratio values

Once the method discussed in this paper is further developed and proven, the plan is to document it into a catalogue for use by the wider community. Other techniques can also be developed by others who wish to contribute their knowledge and expertise to this concept.

5. Acknowledgements

The NWS wishes to acknowledge the efforts of those involved with the HUAO WAVES 2007/2008 project. Special appreciation goes to Dr. Everett Joseph and Demetrius Venable along with Michael Hicks is in order. Within NWS, the SAIC support contractor, especially Ryan Brown deserves special attention. Finally, special thanks are in order for Seth Gutman from NOAA/OAR, and Belay B. Demoz (NASA/Goddard) who have provided inspiration and a deeper understanding towards developing these concepts.

6. References

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