11.1 **EVALUATION OF IN SITU SENSORS: HOW THE NWS HAS MOVED FORWARD**

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1.0 INTRODUCTION

The National Weather Service has evaluated in-situ sensors for many decades using various measurement techniques. These techniques are continuously validated and updated to take into consideration advances in observing and measurement technology. Recent improvements to in-situ atmospheric measurements and environmental simulation capabilities (to replicate extremes or particular conditions) allow for improved assessments of sensor changes in the observing network. The NWS continues to utilize standard test techniques, such as evaluating sensor precision, but the evolving test capabilities greatly reduce risk and increase insight during the transition to an operational product.

For NWS's upper air and surface observing systems, the past testing methodologies consisted of chamber simulations and real-environment testing. No matter the type of instrument, the challenges are to make laboratory simulations more like the real environment and have traceable references in the real environment that are as accurate as laboratory-grade references. When specifically pursuing new capabilities for radiosonde test and evaluation, the result included a reference-quality humidity radiosonde measurement, a method to simulate and validate GPS wind calculations, and a capability to directly compare satellite sounding measurements to a specific radiosonde type measurement anywhere in the world. In addition to these independent comparisons, five radiosondes may be placed onto a single balloon for a greater number of comparisons per payload (compared to two).

2.0 PURPOSE

The NWS's Sterling Field Support Center (SFSC) is a facility which tests and evaluates in-situ sensors to ensure the highest level of data quality within NWS products. This paper will provide insight into some of the NWS test processes and capabilities of in-situ sensors using radiosonde testing as an example and how testing as a whole has evolved through the years.

3.0 DATA AND METHODOLOGY

In order to properly test the validity of a vendor's radiosonde and associated hardware, a large number of tests need to be accomplished. This involves utilizing the chamber capabilities (with associated instrumentation) available at the SFSC while also performing live flight tests.

3.1. Chamber Tests

In the past evaluations of radiosondes, the NWS has had limited capabilities of simulating various conditions for radiosondes in a laboratory environment. NWS has relied significantly on a radiosonde's in-flight precision to determine the repeatability of a measurement, but sought methods to have a better understanding of the sensor's accuracy. NWS's SFSC is working on updating testing procedures and equipment for evaluating all parameters utilizing reference quality instrumentations in conjunction with environmental chambers.

Radiosondes are now thoroughly tested for accuracy and precision over a wide range of temperature and humidity between the maximum and minimum ranges outlined in requirements. These parameters can be tested by placing the radiosonde into an environmental chamber and then precisely controlling the temperature and/or humidity within that chamber. Each profile is conducted with multiple radiosondes to ensure precision of the sensor suite at those particular environmental conditions. The sensors are compared to an array of calibrated references within the chamber for a complete characterization of the radiosonde performance.

Not only will the radiosonde be evaluated under steady state temperature conditions, but it will also be subjected to realistic pressure and temperature profiles using a newly acquired flight similitude chamber available at SFSC. During this test, the radiosondes are tested for accuracy and precision throughout the profile. The tests comprise of multiple unique profiles (utilizing a new radiosonde each time) that encompass conditions seen throughout the NWS domain. Each profile is conducted with multiple radiosondes to ensure precision of the sensor suite at those particular environmental conditions. Similar to the other chamber testing, this test also uses calibrated reference sensors for comparison to characterize the radiosonde.

As an added resource for within the flight similitude chamber, SFSC has acquired a GPS simulator for evaluating a radiosonde's GPS data output. Real life datasets were converted from multiple locations across the US to develop reference datasets which the simulator utilizes as the reference latitude, longitude, and height information. The GPS simulator outputs two signals; one that is emitted via an antenna inside of an enclosed area (ideally the Flight simulator) and one that is sent directly to the ground station for differential GPS calculations. The radiosonde will transmit all data as normal to a tracking system for processing. The output file of the software is then compared to that of the original data set to establish the GPS accuracy. As with all tests at SFSC, each profile is conducted with multiple radiosondes to ensure precision of the sensor suite.

While the NWS does possess reference quality humidity sensors for in-flight comparisons, there are limitations to what those sensors are capable of (i.e. unreliability within high moisture (heavy cloud decks and precipitation)). To better understand a radiosondes durability and data quality, a spray test was developed where all of these parameters could be evaluated. The spray tests include a variety of different realistic precipitation types and temperatures within the chambers in order to fully test the operational capabilities under these conditions. While the spray tests are occurring, calibrated reference instruments in the chamber will be used to monitor conditions. The data from these units will also be used to evaluate the operational status of the temperature sensor during the test. Radiosondes are fully examined afterword to look for potential non-conforming workmanship, e.g. improperly sealed joints.

3.1.1. Reference Instrumentation

A variety of reference instrumentation are utilized within all of the chamber tests at the SFSC. Once integrated, the reference instrumentation will serve as a metric which all sensor data will be compared to. This comparison will provide the accuracy data on the instruments and allow for comparison against specification accuracy values. All references used will be traceable to the National Institute of Standards and Technology (NIST) and will be within calibration as monitored by SFSC staff. All components of the sensors will have undergone valid calibrations, this includes any data loggers used in the test. The exact configurations of these reference instrumentation is still under development, however some initial tests to find out which sensors would work best for each type of chamber is currently underway. Due to the nature of some tests (specifically flight similitude and spray tests) not all sensors can be utilized due to either their inability to be saturated, or not being able to withstand low pressures. Table 1 and Table 2 provides a breakdown of the laboratory capabilities used at SFSC.

3.2. Flight Tests

In addition to laboratory testing with controlled conditions, the NWS significantly relies on in-situ measurements in the real-life environment. This is done through a few different flight configurations.

Functional precision tests are conducted to determine the amount of measurement variability existing between two identical instruments exposed to the same environment. For a series of test flights, two candidate radiosondes will be flown on the same balloon. To determine the functional precision, the mean and root mean square of the differences (RMSD) is calculated for each parameter over a range of pressures or heights. Requirements for what the sensor's precision must be are normally outlined within NWS specifications. For the functional precision test, two tracking systems will simultaneously track two radiosondes of the same type attached to one balloon. This series of flights is conducted at multiple locations over a variety of weather conditions to obtain as much information about the radiosondes as possible.

Functional repeatability tests the repeatability of one radiosonde tracked by two separate tracking systems. This flight series is utilized to understand the error, if any, when repeating the same measurement. Point-by-point comparisons are completed to look for any variation between ground stations tracking the same radiosonde.

While many reference comparisons are completed within the chambers, the NWS still likes to perform some series of flights while comparing the radiosonde under test to reference instrumentation. The Relative Humidity Reference flights using the Cryogenic Frost-point Hygrometer (CFH) are conducted in specific weather and sky conditions to allow for the best data collection; this includes clearer sky conditions, with broken or little cloud cover and no precipitation or thick cloud levels.

Also, not only have the types of flights changed, but the capacity of radiosondes of which the NWS can fly at a time has been increased. In years past, a standard comparison would only entail two sensors at a time being flown on one balloon (either radiosonde under test vs reference, or functional precision of radiosonde under test). Now the NWS has developed procedures in which up to 5 sensors could be flown at a time. This is useful as it provides better insight when comparing sensors to a reference as multiple of the same or 4 different sensors could be compared at a time. In the effort of functional precision tests, multiple precision tests could be conducted on one balloon which in turn would save a large amount of resources.

3.2.1. In-Flight reference sensors

One of the internationally accepted Relative Humidity radiosonde references is the Cryogenic Frost point Hygrometer (CFH). The instrument uses a chilled-mirror principle utilizing cryogenic liquid to cool the mirror below ambient frost point temperature. The mirror temperature is heated or cooled based on the relative difference against the cryogenic liquid. The CFH is calibrated to a NIST traceable standard and is flown married to a radiosonde for transmission purposes.

To calculate the water vapor mixing ratio and relative humidity the CFH-measured mirror temperature will be used in the vapor pressure equation. The phase of the condensation is taken into consideration using Goff and Gratch equation (Goff and Gratch, 1946) for ice condensate (Vömel et al. 2007). The CFH natively measures and outputs frost point temperature in degrees Celsius, which will be converted into RH for comparison purposes during this evaluation.

Another asset utilized in evaluating the humidity sensors is the GPS Integrated Precipitable Water (IPW) measurement. The GPS-MET sensor developed by the NOAA Office of Atmospheric Research is an accepted application for remote referencing. These data have shown excellent correlations with precipitable water calculations from radiosonde flights. This remote sensing technology estimates IPW by measuring the, "GPS signal time delays caused by the wet and dry refractivity of the electrically neutral (i.e., nondispersive) atmosphere" (Smith et al., 2007) with an uncertainty of about 2mm of water. The data from the IPW sites are available several times each hour.

3.2.2. NESDIS Collaboration

As part of an ongoing collaboration with the Center for Satellite Applications and Research (STAR) a unique perspective on the radiosonde under test's data quality is conducted. This will take the form of utilizing a satellite or Numerical Weather Prediction (NWP) models as a transfer baseline which to compare the radiosonde under test. Members of the STAR team assist in providing in-depth analysis of the satellite and NWP data.

Prior to flights being completed, a schedule of satellite overpasses is evaluated in order to take advantage of satellite comparison data. Based on the release location and the path of the satellite, satellite angles greater than 70° are ideal for comparison, but angles less than that are not to be ruled out.

4.0 DISCUSSION

The updated approach to evaluating the in-situ instrumentation provides the NWS a much broader picture or a sensor's performance. Specifically, in the case of radiosonde releases, the improved capacity of 2 to 5 radiosondes on a balloon allows for some unique comparisons to take place while also saving time, resources and funding. One particular example of that was a flight campaign which had previously taken place where 4 radiosondes were flown on the same balloon as the CFH humidity reference instrument. All five of the sensors produced quality data and we able to be compared against the calculated relative humidity data of the CFH (Figure 1). Further breakdown also allows data analysis to take place in a direct comparison with each instrument which is graphically shown in Figure 2. In addition to the graphical representation, full descriptive statistical analysis (Table 3) can be conducted between a test radiosonde and the CFH to obtain even further information, which may include the amount of data (represented as a percentage) out of specification.

Similar to the CFH graphical analysis, the comparisons to the satellite data and NWP models can show representation of multiple sensors at a time when flown on the same balloon. This provides great insight into comparing radiosondes to each other, specifically current operational radiosondes to newer radiosondes to be installed within the network. By utilizing this method, a full data continuity study could be completed by utilizing a back log of radiosonde vs. satellite data to compare the old radiosondes to newer ones without the need to conduct any extra soundings. This data comparison also is of great use as the satellite data for the upper atmosphere becomes more accurate which could serve as an additional reference to compare radiosondes to in live flight operations.

5.0 TO THE FUTURE

The NWS SFSC is continuing to evolve the evaluation process of all in-situ instrumentation utilized within its networks. The SFSC is constantly working to update all testing procedures and develop better evaluations for all instrumentation. With this combined approach of evaluating radiosondes, observers can obtain a complete understanding of how well and how accurate a radiosonde's values are As the techniques to evaluate instruments evolve, the NWS's observations networks will become more accurate as better technology is implemented in the field.

6.0 REFERENCES

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7.0 TABLES and FIGURES

Chamber		Range	Capabilities
	Temperature/ Humidity	-62 to +66 °C 20% to 95% 234 cubic feet	Equipped with spray nozzle for ice accretion and frozen precipitation
	Temperature/ Humidity	-62 to +66 °C 20% to 95% 328 cubic feet	Intent to outfit chamber with radiation measurement system
	Temperature/ Altitude	-75 to +177 °C Ambient pressure to 10hPa 64 cubic feet	Equipped with GPS simulator to simulate differential GPS calculations
	Salt Fog	Set to 35 °C 80 cubic feet	Typical run is for 30 days

Table 1 - Laboratory Capabilities: Environmental Chambers

Lab		Standard	Range	Uncertainty
	Temperature	Platinum Resistance Thermometer	(-80 to +55 °C)	± 0.002 °C
		Thermometry Bridge		
		Calibration Bath		
	Humidity	Humidity Generator	10 to 95%	RH: ± 0.5%
		Low Humidity Generator (TS 4500)	-95 to +20°C	± 0.1 °C
		Low Humidity Generator (TS 3900)		± 0.2 °C
		Chilled Mirror	-70°C to +30°C	± 0.1 °C
	Pressure	Piston Cylinder Gauge DH type PPC4	500 to 1100 hPa	0.002%
		Cistern-Siphon type Standard Barometer	0 to 1075 hPa	0.006%
	Wind	MKS 698A	Diff Press	0.08%
		Mensor	Diff Press.	0.03%
		Paroscientific	800 – 1100 hPa	0.07%
		Omega	Diff Press	0.08 %

Table 2 - Laboratory Capabilities: Standards Labs

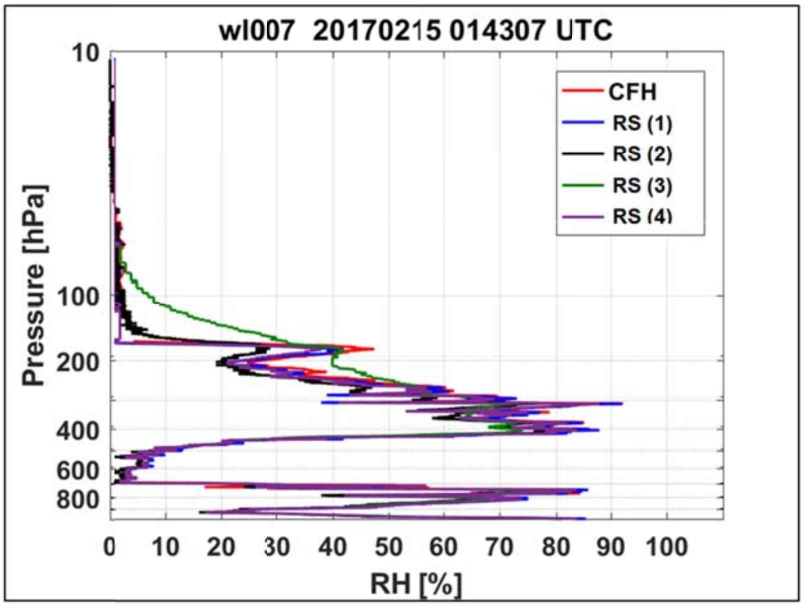

Figure 1 – CFH inter-comparison versus 4 radiosondes under test on a 5-sensor balloon configuration

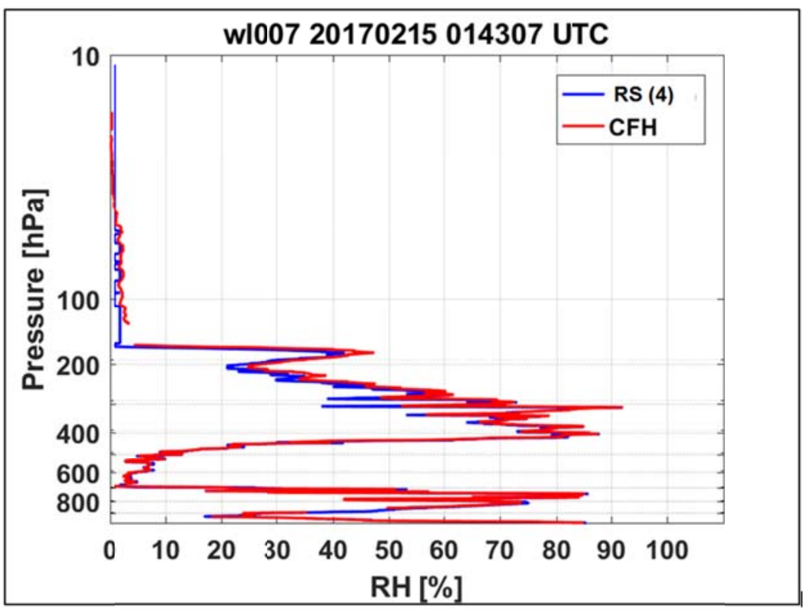

Figure 2 – CFH inter-comparison versus one of the radiosondes under test from a 5-sensor balloon configuration

Pressure Intervals (hPa)	N	Minimum	Maximum	Mean	Std. Deviation	RMSD	% Out of Spec
19 to 0	5169	-1.20	0.90	0.75	0.78	0.08	0.00%
49 to 20	6894	-1.10	1.50	0.44	0.49	0.11	0.00%
99 to 50	5612	-2.60	0.90	-0.39	-0.41	0.07	0.00%
199 to 100	5896	-25.90	13.80	-1.28	-0.73	1.44	0.91%
299 to 200	3242	-20.40	26.90	-1.31	-1.37	1.84	1.26%
499 to 300	4670	-24.30	33.60	-0.21	0.19	1.13	0.95%
849 to 500	5692	-35.60	17.50	0.59	0.63	0.82	0.64%
1070 to 850	2011	-16.90	5.50	0.80	0.94	0.67	0.06%
ALL	39905	-35.60	33.60	-0.15	0.04	0.66	3.86%
400 to 4	30075	-25.90	26.90	-0.42	-0.17	0.85	2.86%
SFC to 400	9830	-35.60	33.60	0.58	0.66	0.59	0.99%

Table 3 - Comparative statistical summary the relative humidity differences between the RS (4) and the CFH for different pressure levels between the surface and 0 hPa for seven separate soundings