RETEST AND EVALUATION REPORT

For the

SpectraSensors Water Vapor Sensing System II (WVSS-II)

October, 2009

U.S. DEPARTMENT OF COMMERCE
National Oceanic and Atmospheric Administration
National Weather Service/Office of Operational Systems
Field Systems Operations Center/Observing Systems Branch

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EXECUTIVE SUMMARY

Background

The U.S. Aircraft Meteorological Data Reporting (AMDAR) Program has been collecting wind and temperature observations from commercial aircraft since the early 1980's with dramatic increases after 1991 (See: David R. Helms. Suitability of Water Vapor Sensors for the AMDAR Fleet, June 27, 2008).

In January of 2009 the Sterling Field Support Center (SFSC) of the National Weather Service (NWS) received and was asked to evaluate a commercial off-the-shelf (COTS) water vapor sensing systems (WVSS) manufactured by SpectraSensors, Inc. of Rancho Cucamonga, CA. The results of these early tests can be found in "TEST AND EVALUATION REPORT For the SpectraSensors Water Vapor Sensing System II (WVSS-II) May, 2009." In general, the results of those tests were disappointing because of the large measurement uncertainty associated with the test methodology and equipment setup. This report describes the results of new tests performed in September and October of 2009.

Sensor and Test System Description

The Water Vapor Sensing System II (WVSS-II) manufactured by SpectraSensors, Inc. (SSI) is an aircraft-based laser absorption spectrometer instrument that uses a near-infrared diode-based sensor to provide measurements of atmosphere's water vapor volume mixing ratio, or humidity expressed in parts per million by volume (PPMv) in the atmosphere at different altitudes and locations.

The purpose of this experiment was to retest the WVSS-II sensor using an improved system setup and techniques and to confirm that WVSS-II is functional and that its performance specifications are fully verified under all environmental conditions, such as temperature, humidity and pressure that a sensor may encounter during a flight aboard an aircraft. To perform this investigation highly accurate and unique instrumentation was employed. A Thunder Scientific model 4500 generator was used to generate known temperature, humidity and pressure. To verify its performance independent primary chilled mirror hygrometer and a pressure standards were also used.

This test evaluated performance of a sensor at various static input conditions specified in Table 1, while the System Electronics Box (SEB) was at ambient laboratory conditions. The flow rate generated by TS4500 varied from four to six liters per minute.

Results

In the new configuration of the test system and using different techniques the sensor performed very well and was within specifications at all test points when the flow rate was five liters per minute. (See Graph 2). Even at four and six liters per minute the results are similar and repeatable except the first test point at 200 hPa.

Conclusions

Overall, the WVSS-II sensor performed well under most of the test conditions. With increase of altitude uncertainty of their measurements may be expected to rise. Its pressure calibration was off by one to four hPa. But the pressure differences are taken into account during factory calibration. Output of the sensors was not very steady (See Graph 1) and took long time to stabilize when exposed to constant humidity, generated by laboratory instruments, especially at four and six liters per minute flow rates. (See Graph 3 and 4). It may be explained by very fast response of the laser of WVSS-II. One could expect that the instrument performance characteristics should be stable.

INTRODUCTION

Purpose

The purpose of this calibration test was to retest the WVSS-II sensor using improved setup and techniques after a long period of experimentation and tests.

The performance of the sensor was evaluated at various static temperatures, humidity and pressure inputs as specified in Table 1, while the System Electronics Box (SEB) was maintained at ambient laboratory conditions.

Performance Requirements

Paragraph 5.2.6, Sensor performance objective of the NWS specification DG133W-08-RP-0141, dated March 2000 defines accuracy in term of “Threshold” and “Objective.”

Threshold Performance Level is the minimal performance level that is acceptable for Government applications associated with the detection, collection and distribution of the water vapor observations and shall be within 8.0 % from the reference measured and reported as Mixing Ratio (g/kg).

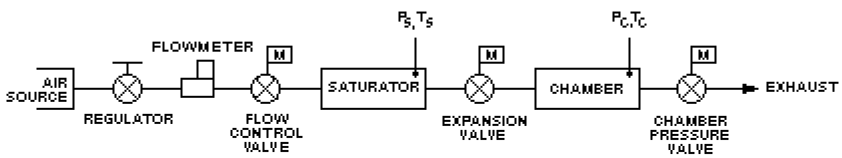
Objective Performance Level is the maximum performance level that is useful for most Government applications associated with the detection, collection and distribution of the water vapor observations and shall be within 5.0 % from the reference measured and reported as Mixing Ratio (g/kg).

Spectra Sensors, Inc. specification is: ±50 PPMv or ±5% of reading, whichever is larger.

Phase I of Water Vapor Sensing System II Instruments Test

1. Test approach

The Model 4500 automated humidity generation system is based on the fundamental, NIST proven, "two temperature-two pressure" principles. This process involves saturating air with water vapor at known temperature and pressure. The saturated high pressure gas flows from the saturator, through a pressure reducing valve where the gas pressure is reduced to test pressure, at the desired humidity and temperature conditions. Humidity generated by the 4500 does not depend upon measuring the amount of water vapor in the gas, but rather is dependent on the measurements of temperature and pressure alone.



Elemental Schematic of the 4500 generator.

The precision of the system is determined by the accuracy of the temperature and pressure measurements and on the consistency of them throughout. When set point equilibrium has been reached, the indication of saturation temperature and pressure as well as test temperature and pressure may be used in the determination of all hygrometric parameters. Some simplified common formulas are given below:

% Relative Humidity = $e_{sf} / e_{st} \times 100\%$
Parts Per Million by Volume (PPMv) = $e_{sf} / (P_s - e_{sf}) \times 10^6$

Where: e_{sf} = Saturation vapor pressure at the frost point temperature Tf
e_{st} = Saturation vapor pressure at the test temperature Tt with respect to water
P_s = Absolute saturator pressure in the same units as e_{sf}

In practice sophisticated enhancement factors are used to correct non-ideal behavior of air when it is used as the carrier gas.

For basic humidity definitions refer to: http://www.thunderscientific.com/site_map/index.html
For Wexler/Hardy humidity equations refer to: http://www.rhsystems.net/papers/its90form.pdf

For this test each set point in Table 1 was attained by adjusting saturator temperature and pressure as well as test pressure in the vessel. This approach proved to offer superior control of the test system, its response time and overall performance. Since PPMv is temperature-independent the vessel temperature was not controlled and was left at room temperature. The hated input hose of the WVSS-II warmed the air from the generator.

Table 1. Test Validation Points for Temperature, Moisture and Pressure

Set Point Number	Air Pressure hPa	Relative Humidity % (WMO)	TS4500 Saturation Pressure hPa	TS4500 Saturation Temperature °C	TS4500 PPMv	WV g/Kg	Td °C	Tf °C
1	200	37.6	8079.97	−28.0	60.0	0.037	−63.8	−59.2
2	250	25.0	5948.79	−28.0	80.7	0.05	−59.7	−55.3
3	300	15.0	5015.88	−28.0	95.3	0.06	−56.9	−52.6
4	300	50.0	1480.61	−28.0	317.7	0.197	−46.5	−42.6
5	400	15.0	1548.81	−28.0	303.8	0.189	−44.3	−40.5
6	400	50.0	2593.10	−10.0	1013.5	0.630	−32.4	−29.4
7	400	70.0	1846.84	−10.0	1419.5	0.883	−28.9	−26.1
8	500	15.0	4598.69	−10.0	575.7	0.358	−35.9	−32.7
9	500	50.0	1362.47	−10.0	1921.5	1.195	−23.1	−20.8
10	500	78.7	2040.03	0.0	3027.7	1.884	−17.9	−16.0
11	700	15.0	4733.63	0.0	1315.1	0.818	−23.6	−21.2
12	700	50.0	1403.41	0.0	4397.2	2.736	−9.2	−8.2
13	700	95.0	1484.40	10.0	8387.8	5.218	−0.7	−0.6
14	900	15.0	6100.00	10.0	2058.3	1.280	−15.5	−13.8
15	900	50.0	1805.21	10.0	6894.0	4.289	0.06	N/A
16	900	95.0	1809.58	20.0	13180.5	8.200	9.2	N/A
17	Ambient	15.0	3718.80	20.0	6406.5	3.986	0.6	N/A
18	Ambient	50.0	1107.13	20.0	21679.1	13.487	18.5	N/A

2. Test Methodology

The test vessel of the TS4500 was covered with a hermetically sealed plate. A ¼ inch stainless steel tube was inserted through this plate to the output of the TS4500 humidity generator. Inlet (port A) of the WVSS-II was connected via a tee fitting at the top of the tube with its heated hose. Port B of the WVSS-II was connected with a non-heated hose to another tee fitting and vented back into the vessel using ¼ inch stainless steel tube.

The input and output of a laboratory standard chilled mirror hygrometer — RHS373 was also connected to the tees with ¼ inch stainless steel tube. RHS373 chilled mirror hygrometer is not specifically designed for vacuum applications and its accuracy checked at the factory only down to 500 hPa. That is why PPMv values for RHS373 was calculated using its dew/frost point temperatures and corresponding pressures measured by a pressure standard Ruska 6220 gauge. Thunder Scientific HumiCalc© was used for these calculations.

Ruska gauge was connected to the RHS373 output using flexible Teflon hose. In this configuration most of the air is passed through WVSS-II and only a portion of it is diverted to RHS373. (See Diagram 1).

Three separate tests were performed with the flow rate of the generator's output set at four, five and six liters per minute. Five liters per minute appears to be the optimum flow rate. (See Graph 2). This flow rate also satisfied the RHS373 flow requirement of no more than one liter per minute.

The saturator pressure and temperature of the generator and the vessel pressure were manually programmed and were controlled by the ControLog™ 4500 software of the generator. All instruments in the setup were connected to the RS-232 ports of the Data Acquisition System (DAS). Their outputs were displayed in graphical form on the DAS monitor.

When the dew/frost point temperatures generated and measured by the references were stable and differed by no more than ±0.2 °C, the data collection was initiated. Two hundred samples of pressure, temperature and humidity from the TS4500, RHS 373, Ruska 6220 and the WVSS-II were recorded to the hard disc of the DAS at six second interval. After the data collection for a test point was finished, the TS4500 was programmed to the next test point and the procedure was repeated.

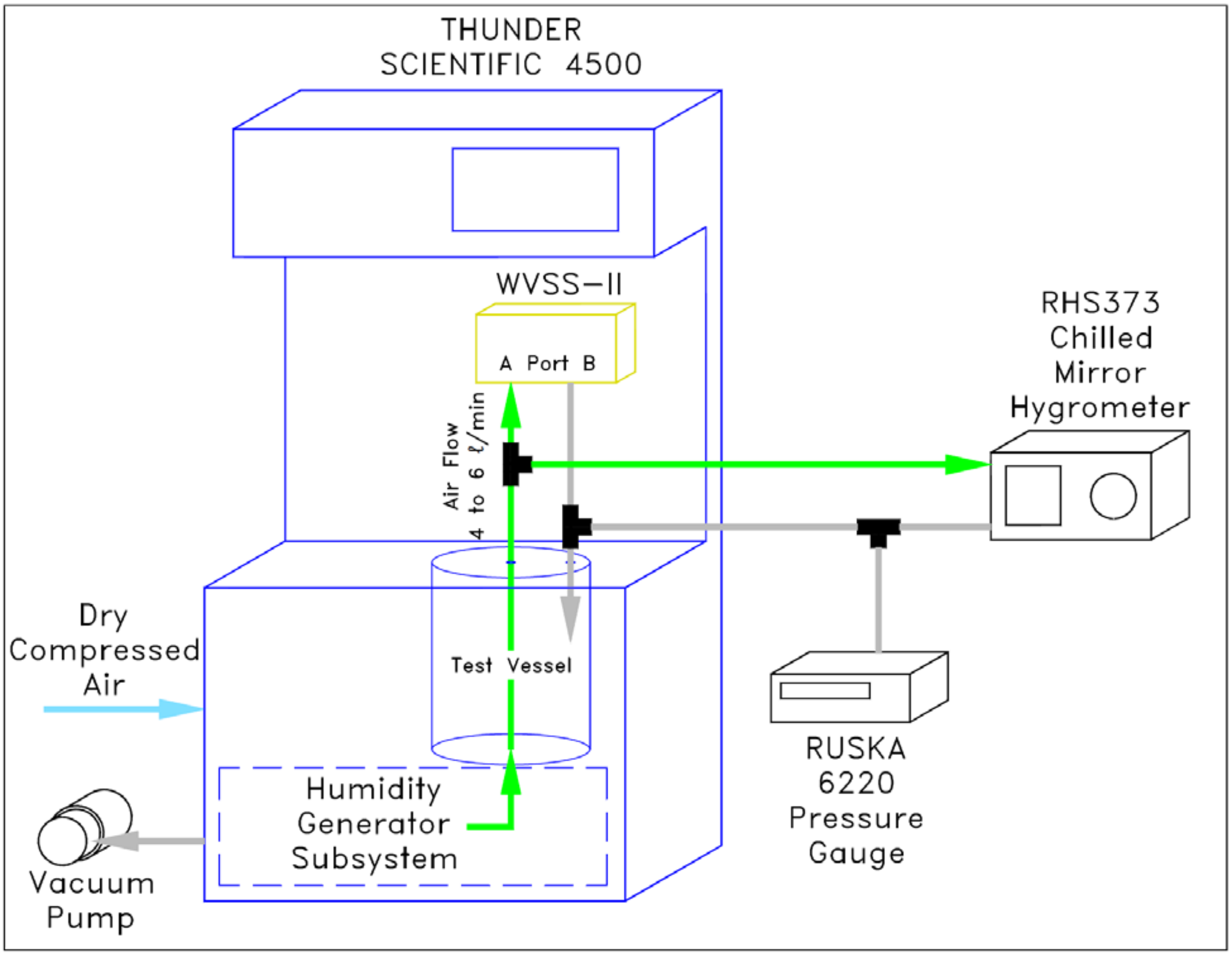

THUNDER
SCIENTIFIC 4500
WVSS–II
A Port B
Air Flow
4 to 6 ℓ/min
RHS373
Chilled
Mirror
Hygrometer
Dry
Compressed
Air
Test Vessel
Humidity
Generator
Subsystem
Vacuum
Pump
RUSKA
6220
Pressure
Gauge

Diagram 1


WVSS2
spectra


208.76
RUSKA
Portable Pressure Gage
-58.68
Frost Point
°C
210.3
Head Pressure
hPa
61.45
Volume Ratio
ppmv
950
Flow Rate
ml/min
RH

3. Test results

Spectra Sensors Water Vapor Sensing System II (WVSS-II) Serial Number 300 have undergone Phase 1 of the calibration retest in the Relative Humidity Laboratory of the SFSC, as specified in the WVSS-II Test Plan dated October 1, 2008.

The collected data were imported into a spreadsheet. An average of two hundred samples for each parameter at each test point was calculated and displayed in a table.

The differences of the PPMv measurements of the TS4500, RHS373 and WVSS-II was calculated and presented for analysis. At five liters per minute flow rate the WVSS-II performance was well within specification at all test points. See Table 2. Its output was less stable than the references, as indicated by calculated values of standard deviation in Table 2 and in graphic form in Graph 1.

The uncertainties of the TS4500 humidity generator are:

Temperature:	±0.05 °C,
Dew/frost point temperature:	±0.1 °C,
Relative humidity:	±0.5%,
Pressure:	±0.01% of reading.

With the HumiCalc© software these uncertainties were used to calculate uncertainties of volume ratio in PPMv. The maximum uncertainties at the low humidity end of the set points spectrum is ±2.8%, and at the high humidity end it is ±1.3%, which are lower than the NWS and the SpectraSensors specifications.

Comparison Test of TS4500 vs. WVSS-II using TS4500 Saturator Pressure and Temperature for Set Points 2009-09-22

Test Number	Ruska Pressure hPa	WVSS Pressure hPa	TS4500 Td/f °C	RHS373 Td/f °C	TS4500 Volume Ratio PPMv	RHS373* Volume Ratio PPMv	WVSS Volume Ratio PPMv	WVSS-4500 Errors %	WVSS-373 Errors %	TS4500 PPMv STDEV	RHS373 PPMv STDEV	WVSS PPMv STDEV	TS4500 Flow l/min	RHS373 Flow l/min
1	204.71	208.22	-59.23	-58.92	60.02	61.31	62.48	4.11%	1.91%	0.27	0.33	1.36	4.99	0.99
2	253.68	257.23	-55.30	-55.22	80.73	81.21	82.25	1.88%	1.27%	0.22	0.46	1.65	4.99	0.98
3	303.06	306.21	-52.57	-52.45	95.34	94.95	96.01	0.71%	1.11%	0.24	0.31	2.02	4.99	0.92
4	303.13	306.25	-42.62	-42.50	317.80	320.63	320.13	0.73%	-0.16%	0.80	0.92	2.26	4.99	0.92
5	402.26	404.96	-40.50	-40.45	303.96	304.77	306.64	0.88%	0.61%	0.52	0.58	1.88	4.99	0.97
6	402.26	405.14	-29.41	-29.33	1013.37	1017.65	1023.74	1.02%	0.60%	2.43	1.56	2.69	5.00	0.89
7	402.28	405.22	-26.11	-26.03	1419.79	1425.69	1429.74	0.70%	0.28%	3.13	2.30	6.14	4.99	0.95
8	501.81	504.59	-32.67	-32.63	575.62	576.59	582.90	1.26%	1.09%	1.20	0.66	1.32	4.99	0.91
9	501.70	504.48	-20.79	-20.76	1922.22	1922.93	1926.77	0.24%	0.20%	4.75	3.10	7.16	4.99	0.90
10	501.75	504.63	-16.00	-16.00	3027.67	3017.78	2999.38	-0.93%	-0.61%	7.86	3.48	25.82	4.99	0.83
11	701.20	704.24	-21.24	-21.26	1314.87	1308.91	1329.38	1.10%	1.56%	3.10	1.24	3.55	5.00	0.82
12	701.24	704.27	-8.16	-8.17	4396.75	4384.61	4389.20	-0.17%	0.10%	11.17	4.35	14.55	4.99	0.82
13	701.34	703.96	-0.61	-0.58	8390.60	8398.62	8421.47	0.37%	0.27%	18.72	9.01	32.06	5.00	0.81
14	900.86	902.99	-13.82	-13.79	2058.09	2062.99	2073.05	0.73%	0.49%	3.88	2.27	6.32	4.99	0.92
15	900.81	902.95	0.06	0.09	6892.33	6902.26	6938.50	0.67%	0.53%	17.24	14.16	22.08	5.00	0.85
16	900.77	903.17	9.23	9.28	13173.06	13223.79	13455.69	2.15%	1.75%	24.43	16.22	47.73	4.99	0.81
17	1030.55	1032.01	0.91	0.95	6407.04	6421.72	6431.97	0.39%	0.16%	10.57	6.05	21.69	4.99	0.78
18	1030.38	1031.83	18.84	18.88	21672.58	21723.82	22278.08	2.79%	2.55%	24.11	17.38	42.00	4.99	0.81

* PPMv was calculated using HS373 Td/f °C and Ruska pressure hPa

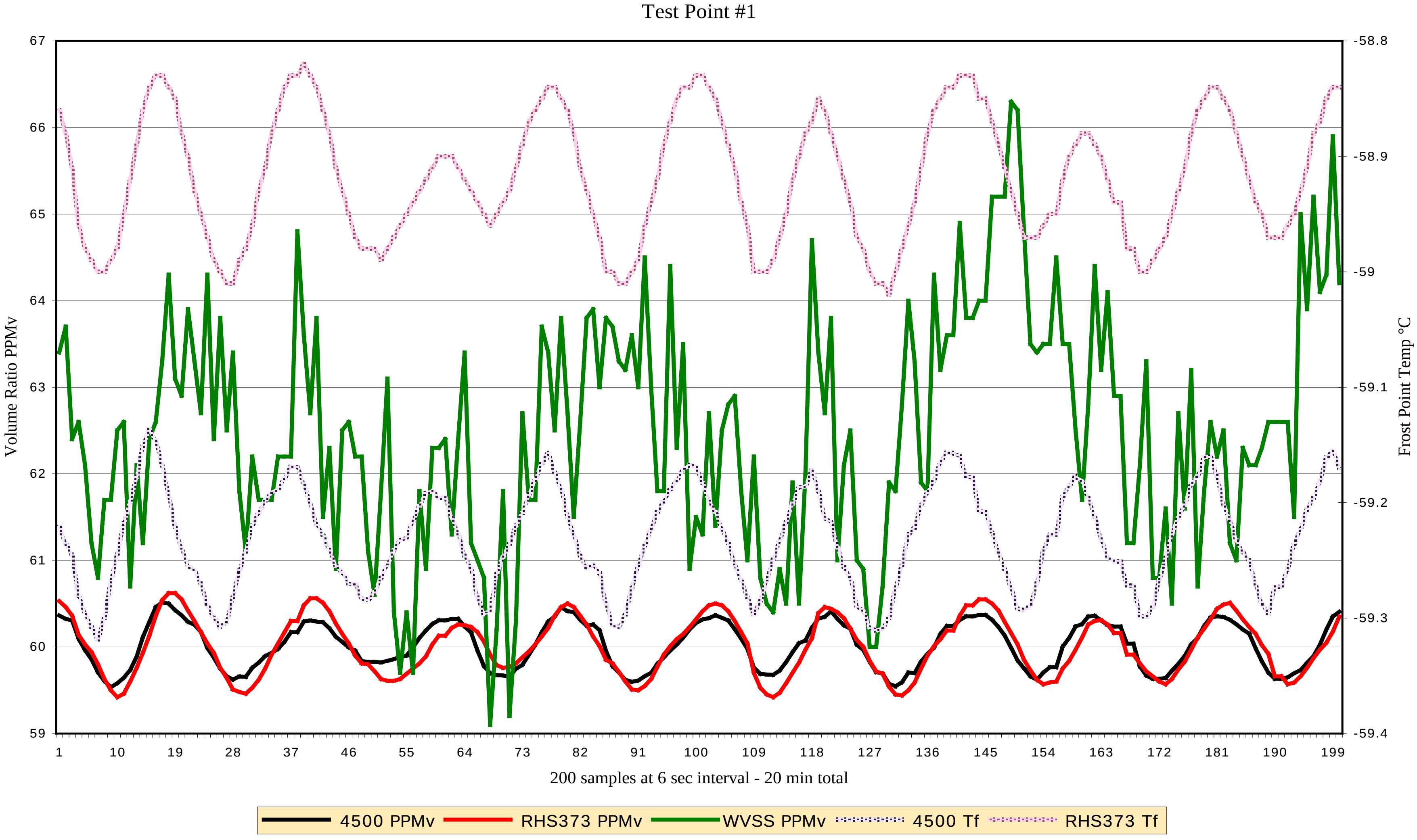
Table 2

4500 Paroscientific Pressure Calibration Date: 13 Aug 2009
Certificate Number: 7741

Ruska Calibration Date: 28 Aug 2009
Certificate of Calibration: 3475207

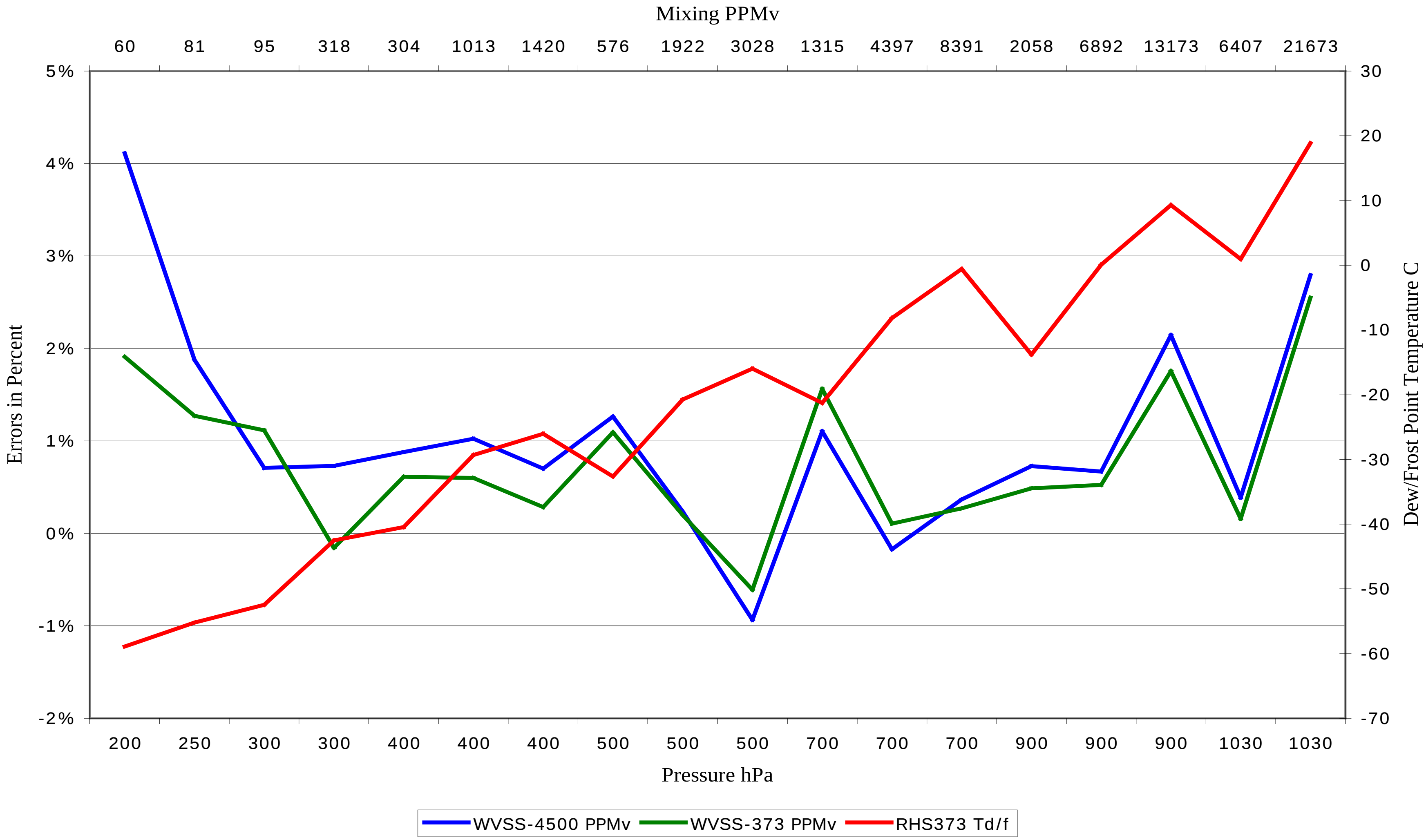
Thermometers Calibration Date: 07 Aug 2009
At SFSC

Test of WVSS-II s/n 300 in TS4500 at 5 l/min

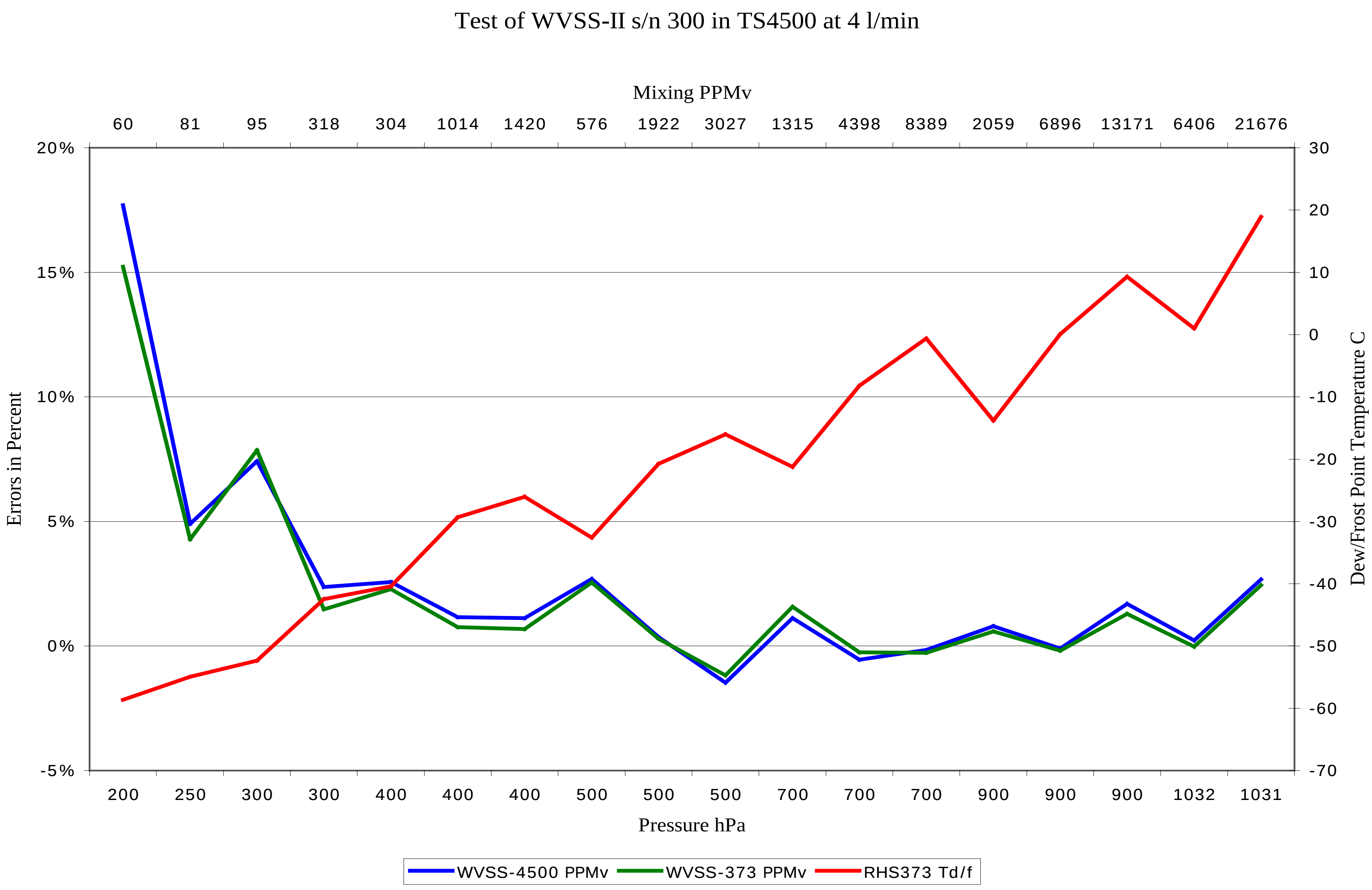


Graph 1

WVSS-II s/n 300 Errors for 18 test points at 5 l/min

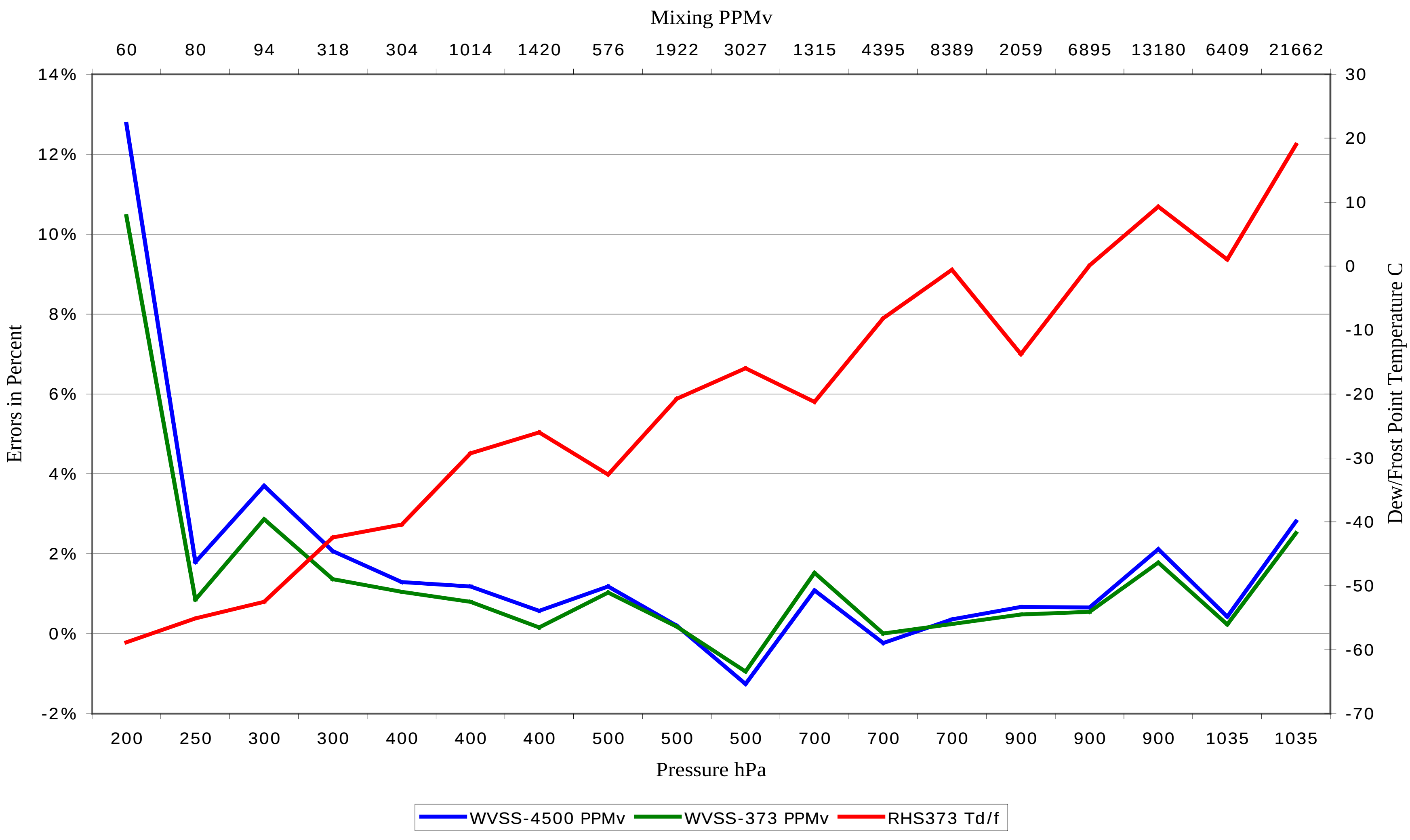


Graph 2


Test of WVSS-II s/n 300 in TS4500 at 4 l/min
Mixing PPMv
60 81 95 318 304 1014 1420 576 1922 3027 1315 4398 8389 2059 6896 13171 6406 21676
20% 15% 10% 5% 0% -5%
Errors in Percent
30 20 10 0 -10 -20 -30 -40 -50 -60 -70
Dew/Frost Point Temperature C
200 250 300 300 400 400 400 500 500 500 700 700 700 900 900 900 1032 1031
Pressure hPa
WVSS-4500 PPMv
WVSS-373 PPMv
RHS373 Td/f

Graph 3

Test of WVSS-II s/n 300 in TS4500 at 6 l/min



Graph 4