Optimizing the Number of Characters for Downlinking Water Vapor Information

Report

July 1, 2002

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Acknowledgments

FAA's Aviation Weather Research Program and NOAA's Office of Global Programs supported this work. Thanks go to JOSS staff and Vanessa Carney for typing the manuscript.

1. Introduction

Measuring atmospheric water vapor accurately has been a difficult problem. We now have a second-generation water vapor measurement system (WVSS-II) that measures water vapor very accurately from commercial jet aircraft. One wants to retain this accuracy in the information sent to the users on the ground in real time. However, mindful of communication costs, one wants to convey this accuracy with as few characters as possible. This is the purpose of this short summary showing the optimal number of characters used for downlinking mixing ratio information (r) or relative humidity (RH).

2. WVSS-II Accuracy and Acceptance

Knowledge of water vapor over the four dimensions of space/time is important, but, unfortunately, its spatial and temporal variability far exceeds the current synoptic scale capability of the radiosonde network, e.g., Melfi, et al. (1989), Fleming (1996), Hanssen, et al. (1999). Moreover, the accuracy of radiosondes with respect to water vapor has always been questioned under certain conditions, e.g., Wade (1994), Wade, et al. (1993), Miloshevich, et al. (1998). Finally, water vapor is not dynamically constrained like the wind, pressure, and temperature fields (cf. Emanuel, et al., 1995), thus making it more variable and more difficult to measure properly.

Water vapor concentrations can range over four orders of magnitude. It can vary from a volume mixing ratio of 3 parts per million by volume (ppmv) in the stratosphere to over 60,000 ppmv in the moist tropical planetary boundary layer. The diode laser system of Randy May (1998) could measure precise stratospheric mixing ratios with a laser path length of over a meter. Subsequent versions of this laser system were shown to measure the very moist conditions found in hurricanes (with a 40 cm path length) and to measure the range of moisture conditions expected at 18,000 – 20,000 feet (the WVSS-II described by Fleming, et al, 2002).

The only concern with the WVSS-II technology, using such a short path length (10.8 cm) inside a total air temperature (TAT) probe also used to measure total and ambient air temperature, was the expected sensitivity at the very low water vapor concentrations found in atmospheric conditions of very cold temperatures and low pressures above 30,000 feet. Since this is the area of concern, Table 1 contains data from that region of interest—a depiction of the volume mixing ratio of water vapor for the range of altitudes from 18,000 to

36,000 ft. and for the relative humidity (RH) values of 5% RH to 50% RH. Table 1 is constructed using the "standard atmosphere" values for pressure (P) and temperature (T) as a function of height, and the relevant water vapor equations:

$$RH = (e/e_s) \times 100 \qquad (1)$$

$$e_s = 10^{**}((10.286 * T - 2148.909)/(T - 35.85)) \qquad (2)$$

$$e = Pr/(0.62197 + r) \qquad (3)$$

$$r = 0.62197 r_v \qquad (4)$$

$$r_v = n_{H2O} / n_{dry} \qquad (5)$$

$$n_{dry} = P/kT \qquad (6)$$

where:

P = Pressure (Pascals)
T = temperature (degrees Kelvin (K))
RH = relative humidity in %
e = atmospheric vapor pressure (Pascals)
e_s = saturation vapor pressure (Pascals)
r = mass mixing ratio for water vapor
r_v = volume mixing ratio
n_{dry} = number density of moluecules of dry air = [molecules m^{-3}]
k = Boltzman's constant = 1.38×10^{-23} [J $molecule^{-1}$ K^{-1}]

The tabular entries are parts per million by volume (ppmv). All WVSS-II data are computed at 4 Hertz (four times per second) and averaged to one second. For the "flight level" (above 20,000 ft) data only, the data is further averaged to 6 seconds. This data will have a random error of 3 – 6 ppmv. Thus, the minimum detectable signal at 36,000 feet will be 2.5% to 5% RH if we use the tabular values in Table 1.

Table 1. Standard Atmospheric ppmv for Various RH Values and Altitude

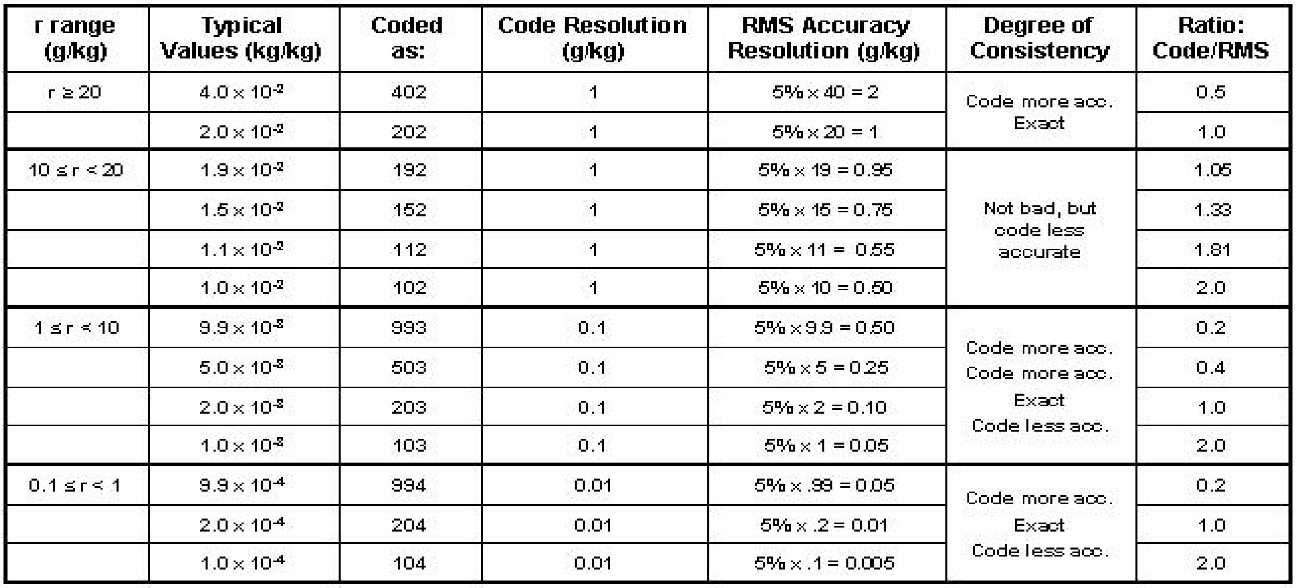
	5	10	15	20	25	30	35	40	45	50
36,000	6.2	12	19	25	31	37	43	49	56	62
34,000	9	18	27	37	46	55	64	73	82	91
32,000	13	26	40	53	66	79	93	106	119	132
30,000	19	38	57	75	94	113	132	151	170	189
28,000	26	53	79	106	132	159	185	212	238	265
26,000	37	73	110	146	183	219	256	292	329	365
24,000	50	99	149	199	248	298	348	369	447	497
22,000	67	133	200	267	334	400	467	534	600	667
20,000	88	177	265	354	442	530	619	707	796	884
18,000	115	231	347	463	588	695	810	926	1042	1158

Now consider only values for the column of 50% RH, which is the mid-range of RH (1 to 100%) that one will encounter at all levels of the atmosphere—in order to simplify the discussion. The error "as a percent of signal" will range from ± 3/62 (4.8%) to ± 3/1158 (0.26%) for altitudes from 36,000 feet down to 18,000 feet. This seems to imply that the error as a percent of signal gets smaller and smaller as one goes to lower levels of the atmosphere. This would be true except that another factor influences the WVSS-II accuracy. This is the fact that the absorption cross-section for water vapor has theoretical uncertainties that become larger at higher temperature and pressure values. Thus, the WVSS-II accuracy can be estimated to fall from 5% error as a percent of signal to 2 – 3% in mid-troposphere levels, and rise again approaching 4 – 5% error near the surface. **For simplicity, we will use the general statement that the error is 5% of signal at all levels.**

3. A Three-character Code for Mixing Ratio

The three-character code for mixing ratio in ARINC 620 (see Fleming, 2000) is nnn = $n_1n_2n_3$ which implies $n_1 \bullet n_2 \times 10^{-n3}$; e.g., 123 = 1.2×10^{-3} (kg/kg). An analysis of the effectiveness of this code in light of the accuracy of the WVSS-II is summarized in the results shown in Table 2. The first two columns of Table 2 show various ranges for mixing ratio (r) expressed in grams per kilogram (g/kg) and typical values within those ranges. Column three is the three-character code for those typical values. Column four of Table 2 shows the **code resolution** in g/kg for the various ranges: 1, 0.1, and 0.01 for the ranges $10 \le r < 20$, $1 \le r < 10$, and $0.1 \le r < 1$ respectively.

Column five of Table 2 shows the root mean square (RMS) **accuracy resolution** in g/kg for the typical values. These are all computed by taking 5% of the values (signals) as discussed above. The last two columns of Table 2 compare the degree of consistency between the **code resolution** and the accuracy resolution. One would like the ratio of these to be near 1. One sees from the last column that these ratios are indeed near the value of 1. The code resolution is consistent with the accuracy of the WVSS-II.



r range (g/kg)	Typical Values (kg/kg)	Coded as:	Code Resolution (g/kg)	RMS Accuracy Resolution (g/kg)	Degree of Consistency	Ratio: Code/RMS
$r \geq 20$	4.0×10^{-2}	402	1	5% x 40 = 2	Code more acc. Exact	0.5
	2.0×10^{-2}	202	1	5% x 20 = 1		1.0
$10 \leq r < 20$	1.9×10^{-2}	192	1	5% x 19 = 0.95	Not bad, but code less accurate	1.05
	1.5×10^{-2}	152	1	5% x 15 = 0.75		1.33
	1.1×10^{-2}	112	1	5% x 11 = 0.55		1.81
	1.0×10^{-2}	102	1	5% x 10 = 0.50		2.0
$1 \leq r < 10$	9.9×10^{-3}	993	0.1	5% x 9.9 = 0.50	Code more acc. Code more acc. Exact Code less acc.	0.2
	5.0×10^{-3}	503	0.1	5% x 5 = 0.25		0.4
	2.0×10^{-3}	203	0.1	5% x 2 = 0.10		1.0
	1.0×10^{-3}	103	0.1	5% x 1 = 0.05		2.0
$0.1 \leq r < 1$	9.9×10^{-4}	994	0.01	5% x .99 = 0.05	Code more acc. Exact Code less acc.	0.2
	2.0×10^{-4}	204	0.01	5% x .2 = 0.01		1.0
	1.0×10^{-4}	104	0.01	5% x .1 = 0.005		2.0

If one were to try and economize and consider using just two characters, then one would have:

nn = n_1n_2 that implies $n_1 \times 10^{-n2}$

e.g., 13 = 1×10^{-3} (kg/kg).

Here one could interpolate in the range $1 \leq r < 10$ g/kg;

1.5 to 2.4 = 2 g/kg = 2×10^{-3} kg/kg = code 23

2.5 to 3.4 = 3 g/kg = 3×10^{-3} kg/kg = code 33 but the code resolution is now only 0.5 g/kg or five times poorer than with three characters. The corresponding ratios in the last column of Table 2 for this range are now 1 to 10 instead of the previous 0.2 to 2. This format does not support the accuracy of the WVSS-II.

Consider adding another character to the code:

$nnnn = n_1n_2\,n_3n_4$ that implies $n_1 \bullet n_2\,n_3 \times 10^{-n4}$ e.g., $1233 = 1.23 \times 10^{-3}$ (kg/kg).

This format would increase the code resolution by a factor of 10. However, the extra accuracy is not justified by the existing accuracy of the WVSS-II and this would be an unjustified extra communication cost!

4. A Proper Code for Relative Humidity

The three character code was optimized for mixing ratio. When one considers downlinking relative humidity (RH) we have a more complicated situation. One of the limitations we face in atmospheric science is the definition of RH

$$RH = (e/e_s)(100)$$

and its susceptibility to uncertainties in temperature (T) due to the nonlinear nature of the saturation vapor pressure (e_s) dependence upon T. This affects applications, modeling, observations on radiosondes, and observations on aircraft if we measure RH directly. Thus, the problem is certainly not unique to aircraft measurements. The following short analysis will quantify this error in RH due to temperature error. Once quantified, it will appear that today's uncertainty in aircraft temperature measurements would justify a relaxation of the number of characters needed to optimize the downlinking of RH. However, the subsequent discussion will show that it would be shortsighted to do so and a better strategy is offered.

Fleming, et al, 2002 in the Appendix of that paper show that the error in RH (ΔRH due to an error in temperature, ΔT) as a "percent of signal", i.e., delta RH divided by RH, or

$$\%\ R = ABS(\Delta RH/RH)(100)$$

is only a function of temperature, independent of the value of RH. Using the definition of Fan and Whiting (1987) for the saturation vapor pressure given by Eq. 2, it can be shown that

$$\%\ R = 409{,}896.07\ \Delta T/(T - 35.85)^2 \qquad (7)$$

where T is in degree Kelvin.

Table 3 shows %R for various values of ΔT over the range T = 243.15K (-30°C) to T = 303.15K (+30°C). The first column is for for ΔT = 0.1K. The second column for ΔT is the standard deviation of the difference (0.59K) between aircraft and radiosonde found by Schwartz and Benjamin (1995), and the third is for ΔT = 1K. Thus, using T = 283.15 (10°C) and ΔT = 1K, the **actual** ΔRH is **6.7%** for RH = 100%, **3.35%** for RH = 50%, and **0.67%** for RH = 1%.

Table 3. Error as a percent of signal for a range of T and ΔT

T (°C)	0.10	0.59	1.00
-30	0.954	5.627	9.538
-20	0.868	5.121	8.680
-10	0.793	4.681	7.93
0	0.728	4.294	7.279
+10	0.670	3.954	6.702
+20	0.619	3.653	6.191
+30	0.574	3.385	5.737

Observing the large error as a percent of signal in columns two and three of Table 3, it has been proposed to reduce the character requirement for downlinking RH by discretizing the range of RH into 36 bins, each with a range of 3% RH. Thus, a single "character symbol" would be required, e.g., using "0" for RH values 0 – 3%, "1" for values 6 – 9%, . . . "A" for values 30 – 33% . . . "X" for values 99 – 102%, etc. This scheme is not appropriate for the WVSS-II for several reasons today and will be less than optimal for aircraft environmental measurements expected in the future.

It has been shown that it is far better to measure mixing ratio or even dew point on the aircraft than to measure RH (Fleming, 1996). With the WVSS-II, one can measure and downlink mixing ratio quite accurately and one need not be concerned with downlinking RH. However, suppose one still wishes to downlink RH converted from the measured mixing ratio. The software would use the formulas Eqs. 1 – 6 as appropriate, the static temperature measured by the aircraft, and compute RH. The software would also check for RH > 100% and set RH = 100%--like the practice of virtually all countries using radiosondes—especially Vaisala radiosondes where this is done internally within their software.

This RH would depend upon the static temperature (T) measured by the aircraft. This (T) could be in error, making the indicated RH in error. **This can be solved by telling**

modelers and others (who use mixing ratio) to recalculate the mixing ratio on the ground using the indicated RH and T (even if the T is in fact wrong), thus giving them the original measured mixing ratio correct to 5% accuracy. The only problem with this approach is the case where the RH was > 100% and then set back to RH = 100%. Then the correct mixing ratio cannot be recovered correctly! Was the RH > 100% because there was an error in temperature or was the RH in nature actually 101 – 103% (which we believe the WVSS-II can detect)? The above reason makes downlinking RH an undesirable choice.

If one still insists upon downlinking RH, then one can use the three-character code of

$$NNN = N_1N_2N_3 = N_1 \,.\, N_2 \times 10^{N3}$$

$$\begin{aligned} \text{e.g.,}\quad & 020 = 0.2 \times 10^0 = 0.2\% \\ & 090 = 0.9 \times 10^0 = 0.9\% \\ & 101 = 1.0 \times 10^1 = 10\% \\ & 991 = 9.9 \times 10^1 = 99\% \\ & 102 = 1.0 \times 10^2 = 100\% \end{aligned}$$

This scheme allows the original mixing ratio information (accurate to ± 5% of signal) to be converted and saved to the nearest 1% over the range of RH from 10 – 100% and to the nearest 0.1% for the range of RH from 0 – 99%. Thus, the user on the ground can use this RH data and convert back to the mixing ratio with an uncertainty of approximately ± 5% of signal.

However, if one uses the single "character symbol" representing a 3% RH bin range, then there is an additional uncertainty added, making the mixing ratio uncertainty an additional ± 1.5 % uncertain. This raises the total uncertainty only accurate to approximately ± 6.5% of signal. This is a poor choice of trading characters for the very important value of additional water vapor information accuracy!

There is another coding scheme of simply using two characters to code RH to the nearest 1%. For example, "00" for 0%, "01" for 1% . . . "99" for 99%, "XX" for 100%, "YY" for 101%, etc. This allows the full accuracy of the current WVSS-II to be preserved for the user—**with the exception that the accuracy to the nearest 0.1% would be lost for the RH range 0 to 9.9%**. Thus, some accuracy of the original mixing ratios that yielded RH values in this 0 – 9.9% range would be lost. Whether this is serious or not would have to be determined by consulting with users from a variety of scientific disciplines. Such low RH values can be found at all levels of the atmosphere and their accuracy to a fine level might be important to researchers in studying boundary layer aerosols and chemistry or to climate researchers interested in upper troposphere water vapor balance as just two examples. Such a two-character scheme might be appropriate today with the previous caveat.

A more important reason to maintain a three-character code for RH is found in column one of Table 3. There is no reason for us to be content with the current aircraft temperature measurement accuracy. The technology to measure static temperature at ± 0.1°C exists today. The problem is that there has been no incentive for total air temperature (TAT) probe manufacturers to improve on the existing technology as the aviation industry is currently satisfied with the existing TAT probe performance. This can and should change as the atmospheric science community becomes more dependent upon the accurate temperatures and the resulting more accurate RH values—especially as countries begin paying for the receipt of such data. Column one of Table 3 then suggests that code accuracy to the nearest 0.1 – 1% be used. This requires a three-character code.

5. Conclusion

The most accurate measurement of water vapor information from a commercial aircraft today is via a diode laser. The best way to communicate this accurate information to the ground is via a three-character code as found in ARINC 620. This matches the accuracy of the sensor used on the WVSS-II and allows the full range of mixing ratio (which varies over four orders of magnitude) to be properly conveyed.

The worst technology for a fast-moving jet aircraft is that which measures RH because of the high random error due to the Mach number effect on temperature (Fleming, 1996). However, any sensor that measures **mixing ratio** or **dew point** directly (neither of which are affected by the Mach number effect) could still downlink RH if the measured static air temperature is used in the calculations on the aircraft.

If one is to downlink RH, then a minimum of a two-character code is recommended. Such a code would not represent the accuracy of the WVSS-II in the 0 – 9.9% RH range, however. Only a three-character code would suffice in this case.

In the event that one can eventually convince the TAT probe manufacturers to produce temperature measurements to ± 0.1 degree, then this would warrant using the three-character code for any sensor with the accuracy of the WVSS-II or better.

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