Veijo Antikainen, M.Sc. (Physics)
Product Manager

Ari Paukkunen, Ph.L. (Physics).
Research Manager, Sensors
Vaisala Helsinki
Finland

Hannu Jauhiainen, M.Sc. (EE)
R&D Manager

Measurement Accuracy and Repeatability of Vaisala RS90 Radiosonde

The accuracy of the Vaisala RS90 Radiosonde is based on the improved sensor technology and individual calibration of the radiosondes. High-performance in-house calibration technology was developed to enhance this accuracy. In this article, the accuracy of pressure, temperature, relative humidity measurements and total uncertainties are discussed.

This article summarizes the paper (Paukkunen et al 2001) presented at the AMS 2001 conference, focusing on accuracy and repeatability. Please note that some details on the measurement and calibration accuracy and repeatability of RS90 Radiosonde have been updated. The Vaisala RS90 Radiosonde participated in the WMO International Radiosonde Intercomparison in Brazil in 2001, the results of which will be reported later.

Performance characteristics of the RS90

Factory calibration of RS90

Calibration and sensor quality play a key role in the performance of radiosondes. For optimum accuracy, all Vaisala radiosonde sensors are individually calibrated with sensor electronics. The calibration equipment measures the output data of the radiosonde sensors in defined environmental conditions and then computes individual calibration coefficients for each sensor. Ground equipment uses these coefficients during sounding to calculate accurate measurement values from the sensor output data transmitted by the radiosonde.

Vaisala's CAL4 Calibration Machine was specially designed for calibrating the advanced RS90 radiosonde sensors. The new calibration technique also further improved the accuracy and reliability of Vaisala's calibration procedures.

Temperature

In the construction of the radiosonde temperature sensor the most important design criteria was to minimize the time lag and the effects of solar and infrared radiation. To meet these requirements the sensor had to be as small as possible. The size of the RS90 temperature sensor complies with this requirement, with a diameter of only 0.1 mm. Moreover, the response time of the RS90 temperature sensor has been reduced to less than one tenth of the RS80 response time (0.2 s vs. 2.5 s at 1000 hPa, 6m/s, see Fig.1). The solar radiation correction has also been reduced remarkably: the correction of RS90 is about 1/5 of that of RS80 (Fig. 2).

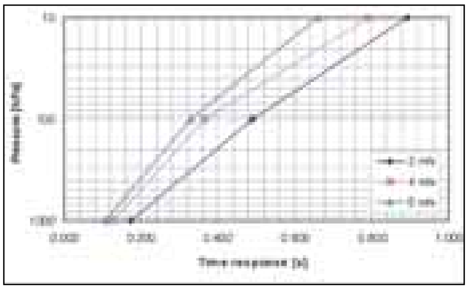

Figure 1. Response time (63.2%) of the RS90 temperature measurement. Averaged over T-range.

Humidity

Wide-range factory calibration against well-defined references has lowered production variability with the RS90 Radiosonde (Table 1). This has also further improved sounding accuracy.

In radiosonde humidity measurements, the following factors require special consideration:

- response time
- solar radiation
- correction of sensor temperature dependence
- elimination of possible condensation of water vapor when emerging from a cloud
- elimination of possible contaminating gases from the radiosonde materials.

The minimized sensor allows improved humidity measurement performance. The response time of the RS90 humidity sensor in comparison to that of RS80 is presented in Fig. 3.

Possible condensation of water vapor when emerging from a cloud is eliminated through the use of two heated humidity sensors. As a result, in most cases where condensation could happen, the RS90 humidity sensor performs correctly.

Possible contaminating gases reaching the sensor from organic materials in the radiosonde can be eliminated by performing a sensor regeneration (heating) procedure before the factory calibration and during the ground check procedure just before a sounding. With this procedure, the original highly accurate calibration of the sensor is recovered for optimum performance.

Algorithms for solar radiation correction of the RS90 humidity measurement are currently under development. The algorithms for eliminating the temperature dependence error in cold temperatures have been improved in comparison with the RS80 (Balagurov et al. 1998, Miloshevich et al. 2000, Wang et al, to be published). Details will be available later in the report from the WMO International Radiosonde Intercomparison 2001.

Pressure

The RS90 incorporates a silicon micro-mechanical pressure sensor which solves the problems of temperature dependence during fast temperature changes and improves mechanical strength during transportation and against other mechanical shocks.

The excellent performance of the RS90 pressure sensor during rapid temperature changes is illustrated in Fig 4. The test was performed in extreme conditions with rapid temperature changes from 25°C to -55°C and back. In actual soundings, the maximum change is few hectopascals in RS80 and negligible in the RS90 compared to the RS80.

The new calibration facility with accurate temperature dependence correction has improved measurement accuracy.

RS90 uncertainty estimation in soundings

Definition of accuracy

When discussing accuracy, it is important to agree on its definition. Based on the definitions of the International Organization of Standardization (I.O.S. 1993), the following definitions are used in this article:

Accuracy is the closeness of the agreement between the result of a measurement and a true value of the measurand (I.O.S. 1993; EARL 1997). Accuracy is a qualitative concept.

Uncertainty of measurements is a parameter, associated with the result of a measurement, that characterizes the dispersion of the values that could reasonably be attributed to the measurand. The parameter may be, for example, a standard deviation. Uncertainty gives a certain confidence in the result of a measurement.

Repeatability is the closeness of the agreement between the result of successive measurements of the same measurand carried out under the same conditions of measurement. Repeatability can be expressed quantitatively in terms of the dispersion characteristic of the results (standard deviation).

Reproducibility is closeness of the agreement between the result of successive measurements of the same measurand carried out under changed conditions of measurement. It can be expressed quantitatively in terms of the dispersion characteristic of the results (standard deviation).

Calibration is a set of operations that establish, under specified conditions, the relationship between values of quantities indicated by a measuring instrument or system, and the corresponding values realized by standards.

The concrete basis for radiosonde accuracy is the calibration procedure, the calibration equipment and the international traceability of the references used in calibration (Paukkunen 1998).

The starting point for the estimation of uncertainties in operational radiosoundings are the short-term (σ_r) and long-term (σ_l) uncertainties of the calibration equipment CAL4. These uncertainties arise from such factors as: reference uncertainty, conditions in the calibration chamber.

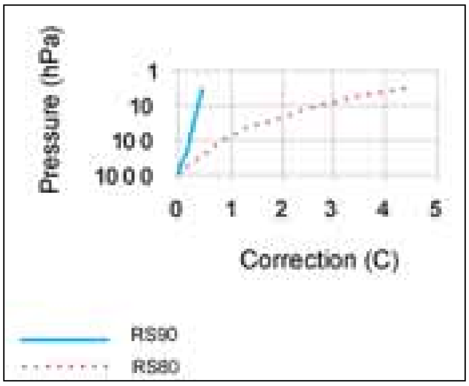

Figure 2. Solar radiation correction of the RS90 and RS80.

Estimated short and long-term uncertainty values of CAL4 calibration at various calibration points at a 2 sigma confidence level are presented in Table 1.

In the calibration procedure there are also radiosonde-based uncertainties (σ_s) from such factors as curve fitting, electronic noise, and resolution.

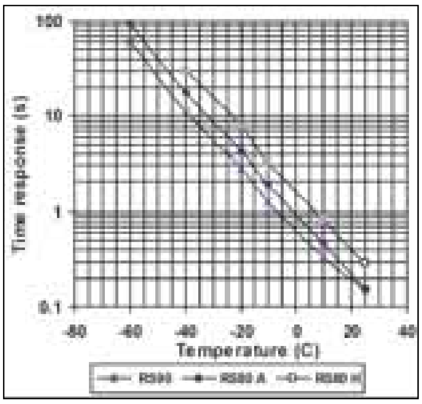

Figure 3. Response time of the RS90 humidity measurement. Sample size 20 pcs.

Uncertainty estimated as the standard deviation of differences in repeated calibration (σ_{rc}) includes uncertainties (σ_r) and (σ_s). This means that:

$$(1)\quad \sigma_{rc} \geq \sqrt{(\sigma_r)^2+(\sigma_s)^2}$$

The measured values for (σ_{rc}) are given in Table 2.

Long-term uncertainty is related to systematic errors. The uncertainty is calculated according to (I.O.S. 1993; EARL 1997).

Calibration uncertainty

The calibration uncertainty of the CAL4 Calibration Machine is the main factor in RS90 uncertainty estimation in soundings.

If σ_l is added to σ_{rc}, an initial (low) estimate (σ_{t1}) of total uncertainty (σ_t) for an individual RS90 radiosonde is reached

$$(2)\quad \sigma_{t1} \geq \sqrt{(\sigma_{rc})^2+(\sigma_l)^2}$$

If a specific general-purpose (laboratory) measurement system, independently from the CAL4 Calibration Machine, is used to monitor and specify the uncertainty of the RS90 Radiosonde, a standard deviation of measured differences against measurement reference (σ_m) and average value (x_m) are calculated from a sample inspection of RS90 production. This measurement system has its own uncertainty (σ_{ar}). The measured differences are related to σ_t, σ_{ar}, σ_s, and they can be summed up as squares of the deviations:

$$(3)\quad x_m+3\sigma_m \geq 3\cdot\sqrt{(\sigma_t)^2+(\sigma_{ar})^2+(\sigma_s)^2} \geq x_m-3\sigma_m$$

(σ_t) can be estimated as (σ_{t2}) if the maximum value of ($x_m \pm 3\sigma_m$) is used

$$(4)\quad \sigma_{t2} \geq \sqrt{(x_m/3+\sigma_m)^2+(\sigma_{ar})^2-(\sigma_s)^2}$$

and the high estimate is now

$$(5)\quad \sigma_{t2} < \sqrt{(x_m/3+\sigma_m)^2-(\sigma_{ar})^2}$$

When a radiosonde is ascending carried by a weather balloon, a new set of uncertainties must be considered. They are mainly attributable to dynamic measurement or new phenomena (compared to CAL4), such as solar radiation. All these factors

Uncertainty	**Pressure** **hPa**	**Temperature** **°C**	**Humidity** **%RH**
	0 ... 1070	**+60 ... - 90**	**0 ... 90**
Short term	2 ... 1080		0.1 ... 93
(σ_r, k=2)	< 0.22	< 0.01 ... 0.03	0.1 ... 0.5
Long term			
(σ_l , k=2)	< 0.10	0.05 ... 0.06	0.1 ... 0.6
Total	< 0.24	0.05 ... 0.07	0.2 ... 0.8

Table 1. Estimated short-term (σ_r) and long-term (σ_l) uncertainty of CAL4 calibration at various calibration points at a 2 sigma confidence level (95.5%).

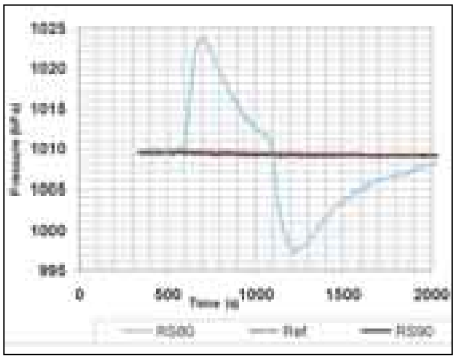

Figure 4. RS90 and RS80 pressure sensor responses to fast temperature changes in extreme conditions. The temperature was changed rapidly from 25°C to - 55°C and back to 25°C.

can be estimated as uncertainty components (I.O.S. 1993; EARL 1997) and further combined as the sum of squares of deviations (σ_f). The value of (σ_t) changes as a function of several variables and therefore the expression is complicated to formulate. If (σ_{SO}) is the RS90's uncertainty of calibration, the total uncertainty of the RS90 Radiosonde (σ_{rs}) in soundings can be estimated as

$$(6)\quad \sigma_{rs} = \sqrt{(\sigma_{so})^2 + (\sigma_f)^2}$$

Uncertainty (σ_{SO}) can be estimated with σ_{t1}, σ_{t2},for example. Further, (σ_{rs}) can be compared to the reproducibility of soundings (giving the general variability of sounding measurements).

Specifications based on uncertainty evaluations

On the basis of these uncertainty evaluations, the following specifications can be presented:

Repeatability (Standard deviation of differences between two successive repeated calibrations, k = 2 confidence level).

Uncertainty in sounding (2-sigma (95.5%) confidence level (k=2), cumulative uncertainty including repeatability, long-term stability, effects due to measuring conditions, dynamic effects (such as response time) and effects due to measurement electronics).

Reproducibility in sounding (standard deviation of differences, in dual soundings divided by √2).

Uncertainty in factory calibration is sampled and tested as an integral part of production control. Additionally, an independent laboratory facility is used as part of the quality control system. Measurement results are used in uncertainty evaluations mentioned earlier in this chapter.

Comparison flight tests

Some of the comparison flight tests were performed as twin or triple soundings from 1999-01-26 to 1999-02-15 at Vaisala Helsinki sounding station. A total of 27 soundings were performed. The compared radiosonde types were 1 - 2 pcs RS90-AL Radiosondes with RS80-15L Radiosonde. The average of maximum direct differences and maximum average standard deviations are shown in Table 3.

The standard deviation of the RS90/RS90 difference gives an estimate for reproducibility of the pressure, temperature, humidity and geopotential height readings (PTUH) of the RS90 in soundings. This can be compared to standard deviation of differences in RS90 calibration and specified total uncertainty in soundings (Table 2).

The RS80/RS90 temperature differences are greatly affected by different types of atmospheric temperature profiles due to the fast response time and small radiation correction of the RS90.

Large differences in height data between the RS90/RS90 and RS90/RS80 values are mainly due to differences in pressure sensors and the different response times of the temperature sensors. In the troposphere, the faster RS90 temperature sensor indicates slightly colder temperatures. The reproducibility in test soundings meet the specified values (in Table 2 the standard deviation of differences is divided by √2).

Specification	P (hPa)	T (°C)	U (%RH)
Uncertainty in soundings	1.5 ... 0.7	0.5	5
Reproducibility in soundings			2
1080-100 hPa	0.5		
100-3 hPa	0.3		
1080-50 hPa		0.2	
50-20 hPa		0.3	
20-3 hPa		0.4	
Repeatability	0.4	0.1	2

Table 2. Accuracy specifications for RS90.

	P (hPa)	T (°C)	U (%RH)	H (gpm)
RS90/RS90 Max. average	0.25	0.13	0.50	25
RS90/RS90 Max. std. dev.	0.40	0.51	0.17	28
RS80/RS90 Max. average	1.39	0.52	3.6	455
RS80/RS90 Max. std. dev.	1.1	0.90	6.0	125

Table 3. Maximum direct differences and maximum standard deviations of test flights (27 soundings).

Conclusion and discussion

The main goals of the RS90 radiosonde design were to respond to the increasing demand for well-defined uncertainties of measurement and the need for improved repeatability of calibration and reproducibility in soundings. Many of the known weaknesses in earlier radiosonde designs have been corrected. The uncertainty analysis seems to agree with the uncertainties observed in operational use.

Extensive testing and analysis of the radiosonde during operational use makes it possible to further improve the product in the future. The test facilities for a wide range of atmospheric conditions using high-accuracy methods are being constantly improved to reach the best possible product know-how for our users. ●

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