ATMOSPHERIC TEMPERATURE AND HUMIDITY MEASUREMENTS OF VAISALA RADIOSONDE RS41

Petteri Survo*, Eero Hiltunen, Hannu Jauhiainen, Johanna Lentonen,
Jukka Leppänen, Tomi Salo, Markus Turunen
Vaisala Oyj, P.O. Box 26, FI-00421 Helsinki, Finland
*e-mail: petteri.survo@vaisala.com

ABSTRACT

For meteorological and climatological observation needs, temperature and humidity are the key parameters received from an atmospheric sounding. Requirements for sounding data quality are high, and especially climate research has called for measurement performance that has not been fully met by operational radiosondes. Vaisala Radiosonde RS41 temperature and humidity measurements involve several new features, which upgrade sounding data quality, and thus, narrow the recognized performance gaps.

In RS41, both temperature and humidity sensors are designed and manufactured in-house, enabling optimization of sensor chip, sensor boom, and measurement electronics designs. This has resulted in features such as temperature measurement relying on highly linear and stable platinum resistor technology, and humidity measurement with negligible sensitivity to variations in prevailing solar radiation exposure. In addition to optimized sensing technologies, comprehensive sensor characterization (sensor models), and appropriate sensor calibration are also essential factors in producing trustworthy data. Reference instruments used for sensor modeling, as well as for individual calibration of RS41units, are all traceable to international standards (SI units). Ground preparation of RS41 supports the goal of improved data quality, of which the new, desiccant-free zero humidity check is an illustrative example. In a sounding, the RS41 measurements are subjected to well-reasoned corrections: Time-lag and solar radiation corrections are applied for temperature, and time-lag correction is applied for humidity measurement. To verify the corrections, RS41 sounding results have been compared to reference instruments, such as a multi-sensor instrument for temperature, and a cryogenic frost-point hygrometer (CFH) for humidity.

The results of hundreds of test soundings and the comprehensive uncertainty analysis conducted for RS41 demonstrate that the new temperature and humidity measurements result in upgraded repeatability and measurement accuracy, benefiting all user groups of upper air data.

INTRODUCTION

In the development project of Vaisala Radiosonde RS41 the focus was set to improve the reliability and consistency of operational upper air measurements. Thus, factors identified to have a significant effect on the dispersion of results were to be minimized by means of design and algorithms. In addition to technology development, the human factor was also taken into account. In order to reduce anomalies originating from the sounding preparation phase, user- centric design was utilized in the development of radiosonde RS41, sounding system software MW41, and ground check device RI41. A general picture of Vaisala Radiosonde RS41, highlighting some of the design features, is given in Figure 1.

This study focuses on the new technologies applied in temperature and humidity measurement, while GPS-based pressure, height and wind measurements are discussed in detail in references [1,2].

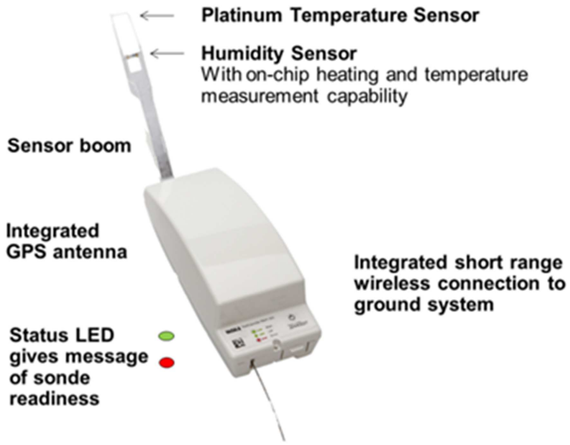

Figure 1. Design overview of RS41.

TEMPERATURE AND HUMIDITY SENSORS OF RS41

The temperature measurement of Vaisala Radiosonde RS41 is based on resistive platinum sensor technology. The sensor type was chosen for its reference-class linearity and stability enabling good measurement accuracy over a wide temperature range. The sensor design, along with the supporting structures (see Figure 2), diminishes solar and IR radiation induced measurement uncertainties predominant in upper air temperature observations. That is, with the help of the small size of the sensor, combined with a highly reflective aluminum coating and the fine supporting structures, the level of solar radiation error is low and, when compared to Vaisala Radiosonde RS92, a significantly attenuated solar radiation induced noise is achieved in low pressure conditions. Response time of the sensor, 0.5 s at 1000 hPa, meets the requirements of WMO's Guide to Meteorological Instruments [3], but in order to keep the measurement free from systematic errors, a time lag correction is applied to temperature data calculated with MW41. And finally, the RS41 temperature sensor incorporates effective protection against evaporating cooling, the phenomenon occasionally encountered when a radiosonde emerges from a cloud top.

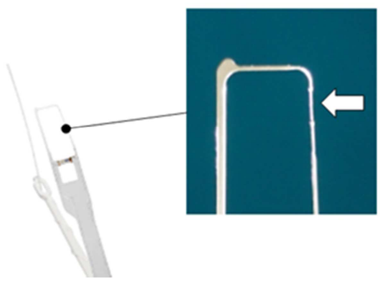

Figure 2. RS41 temperature sensor assembly.

The humidity measurement of Vaisala Radiosonde RS41 is based on capacitive polymer technology. The sensor chip is designed for atmospheric sounding applications integrating humidity and temperature sensing elements with a heating resistor, see Figure 3. As elaborated in the following sections in this paper, the new sensor design provides enhanced measurement accuracy by enabling new functionalities such as:

- On-chip temperature measurement to compensate for the warming effect of solar radiation.
- Controlled heating of the sensor enabling active de-icing during sounding.
- Automated preflight reconditioning and zero humidity check procedures to effectively remove possible chemical contaminants and storage drifts.

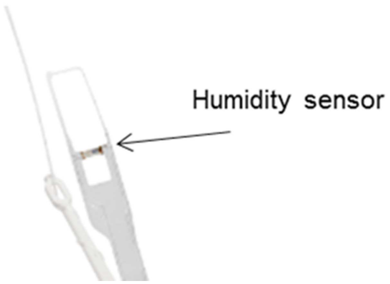

Figure 3. RS41 humidity sensor assembly.

TEMPERATURE AND HUMIDITY CALIBRATION

It is essential, especially for climate research, that all calibrations of the radiosonde measurements are SI traceable and the uncertainties related to calibrations are carefully analyzed [3]. For RS41 both temperature and humidity calibrations are traceable to SI-units (National Institute of Standards and Technologies, NIST, USA) and the calibration uncertainties have been studied as part of the comprehensive uncertainty analysis of RS41 [5], see Figures 4 and 5. The uncertainties are expressed using a coverage factor of k=2, indicating that approximately 95% of practical measurement results fall within the given uncertainty limits.

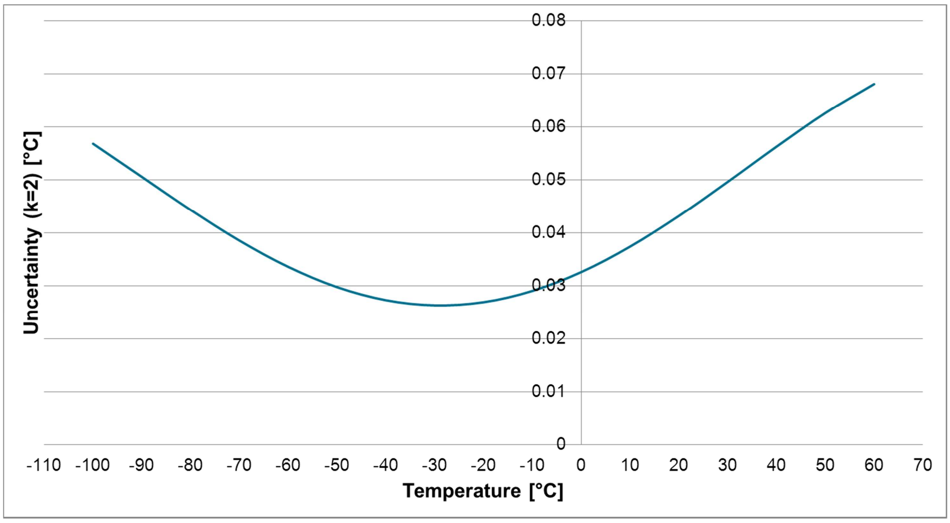

Figure 4. The calibration uncertainty of RS41 temperature measurement (k=2).

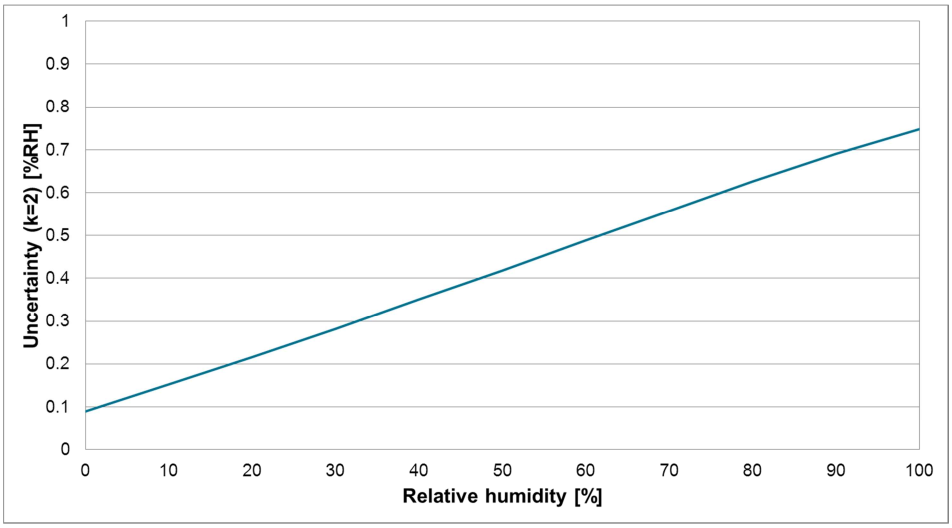

Figure 5. The calibration uncertainty of RS41 humidity measurement (k=2).

For defining the uncertainty of the relative humidity measurement of a calibrated radiosonde unit, uncertainties of air and humidity sensor temperature readings, used in relative humidity calculations, need to be included. In a calibration situation these readings come from the temperature reference measurements, whereas for an independent radiosonde unit from its own temperature measurements. As well as the previously mentioned uncertainties, components arising from sensor model formulas also need to be taken into account in the uncertainty budget of humidity measurement. Regarding RS41, the uncertainty analysis resulted in combined uncertainties presented in Figure 6.

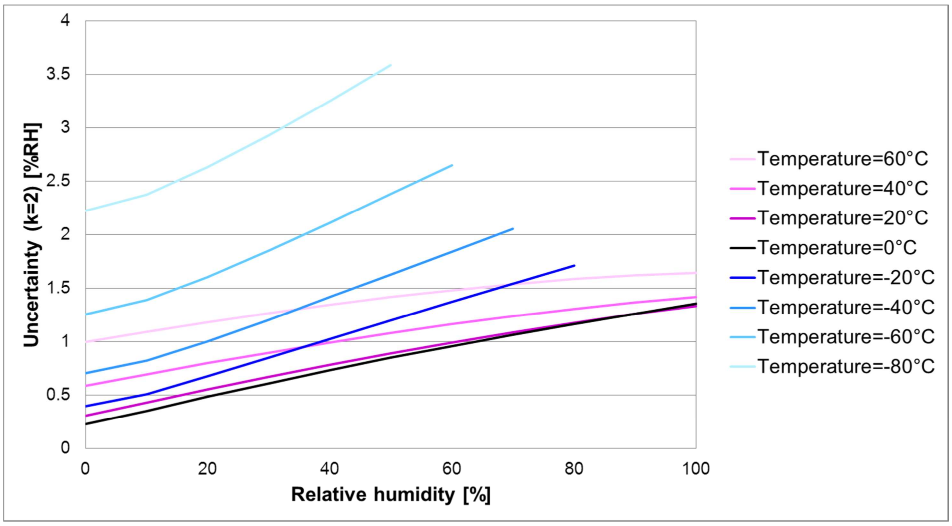

Figure 6. The combined calibration uncertainty (k=2) of RS41 humidity measurement including uncertainty components of temperature measurements and sensor model.

GROUND PREPARATIONS

When performing ground check for RS41, the radiosonde unit is placed on ground check device RI41, and the preparations start and proceed automatically. Communication between the two devices takes place wirelessly, refer to Figure 7. The ground preparation procedure is reproducible and reliable in operational use, owing to the fact that the RI41 operates without reference condition generation or even reference sensors, both of which would need careful maintenance.

Figure 7. Ground check device RI41 with a radiosonde.

Regarding measurement accuracy, prior to the launch the ground check of the radiosonde can actually be a controversial issue. On one hand, it is important to check the proper function of the instrument and to correct the sensor drifts that are possible due to long storage times, but on the other hand, in some cases the applied corrections may introduce additional sources of uncertainties and biases to the end results. In case of RS41, the design and technology have been utilized of to avoid the drawbacks of ground checks, as described below.

The functionality of the RS41 temperature measurement is checked by comparing the actual temperature sensor against the temperature sensor on the humidity sensor chip. Platinum resistor temperature sensors are generally considered to be extremely stable and the stability test conducted with RS41 supports that assumption. As an example, the stability test results after six months storage, illustrated in Figure 8, fall within the 0.07°C uncertainty (k=2) of the test equipment. Because of the inherent stability of platinum technology and the challenges to control uncertainties in ground check the same strict manner as they are controlled in factory calibration, no ground check correction is applied to RS41 temperature measurement. Thus, one potential source of error is eliminated. Combining uncertainty terms of calibration and storage result in an uncertainty named here as uncertainty after ground preparation. For RS41 the uncertainty is of a magnitude of less or equal to 0.11°C, see Figure 9.

Uncertainties of RS92 measurements have been analyzed in the framework of GCOS Reference Upper Air Network (GRUAN) data processing [4]. According to the analysis, the uncertainty after ground preparation (≥ 0.15 °C for RS92) is the dominating source of dispersion in temperature data at lower parts of the troposphere in daytime. Obviously for night-time soundings the dominance appears throughout the profile. As illustrated in Figure 8, RS41 introduces a significant improvement to temperature measurement accuracy in terms of reduced uncertainty after ground preparation.

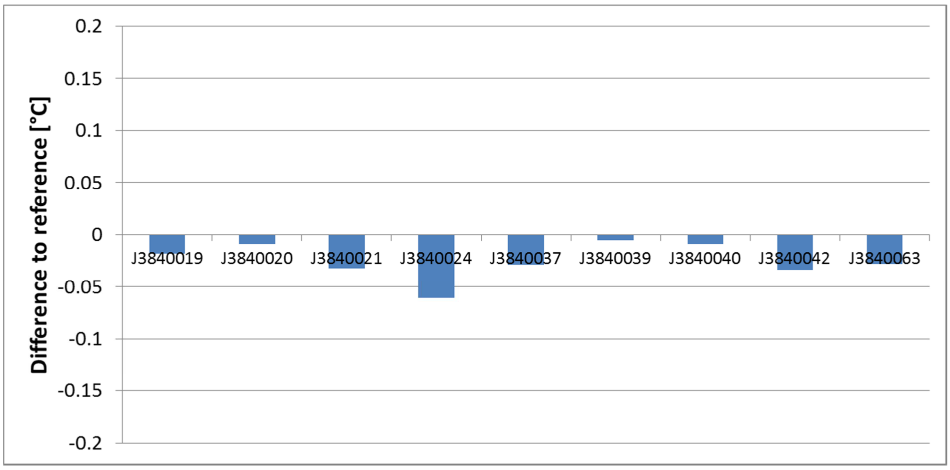

Figure 8. Stability test results after a six month storage, measurements at 20°C, test uncertainty 0.07°C (k=2).

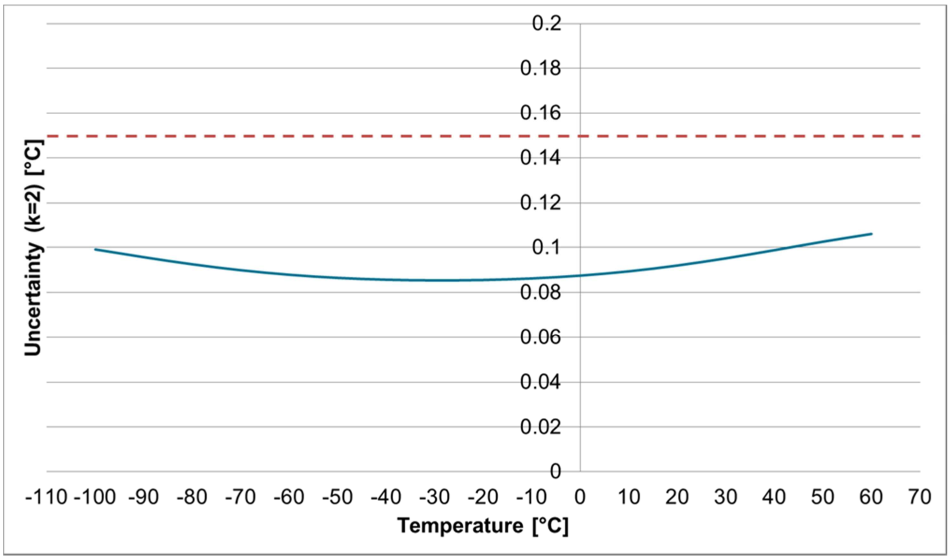

Figure 9. The combined uncertainty of the Vaisala Radiosonde RS41temperature measurement after ground preparation (k=2). The dashed line indicates the calibration accuracy of RS92.

During sounding preparations, the reconditioning of the humidity sensor begins soon after the radiosonde unit has been placed on ground check device RI41. This heating phase vaporize contaminating compounds that affect the humidity measurement. An inbuilt zero humidity check is also conducted in conjunction with the reconditioning. The zero humidity check detects and corrects possible drifts in the humidity measurement. During the check a dry reference condition is generated in ambient room air by heating the humidity sensor. Compared to the earlier radiosonde models, the reliability of the correction is improved as its accuracy is no longer dependent on a measurement chamber with desiccants of limited drying capability. Figure 10 presents the results measured in dry conditions (dew point < -60°C), as the ground check is applied for radiosondes that have been stored for six months. Figure 11 presents the respective results in saturated humidity conditions, generated with a standard humidity chamber SPRH 100.

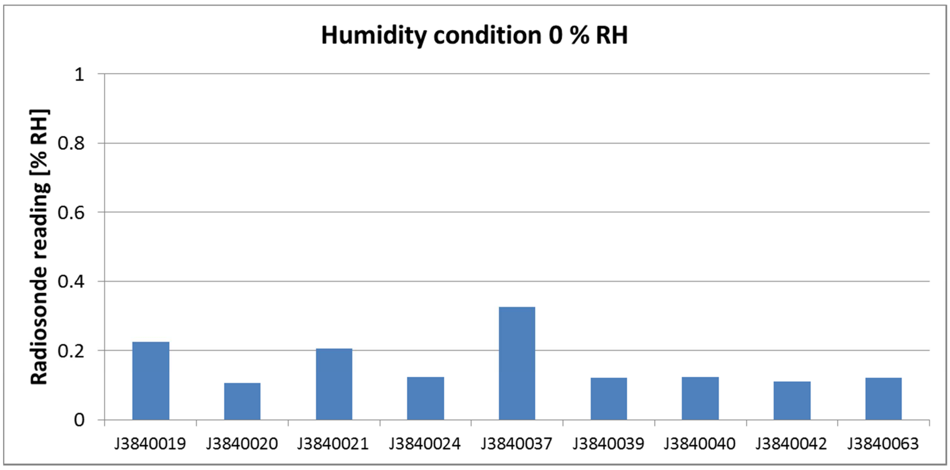

Figure 10. Stability test results after a six month storage, measurements in dry condition at room temperature.

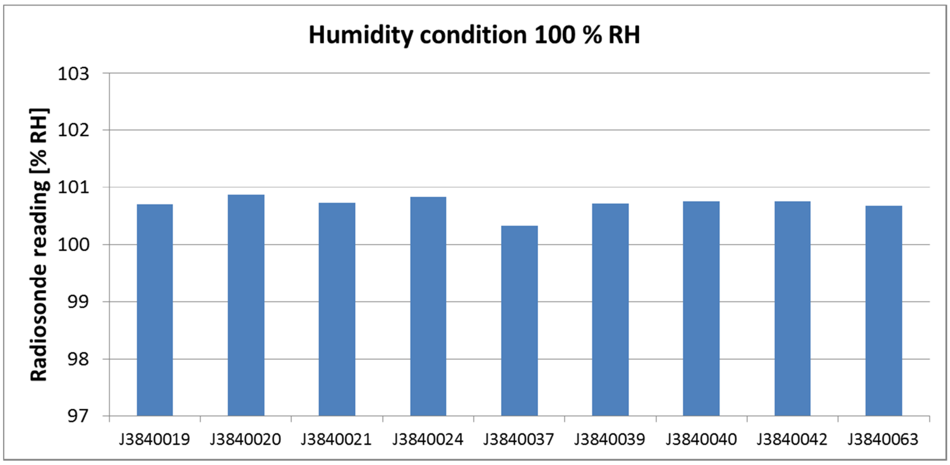

Figure 11. Stability test results after a six month storage, measurements in saturated humidity, temperature approximately 30°C.

Figure 12 shows humidity measurement uncertainties after ground preparation, including the uncertainty terms of calibration and residual storage drifts after the ground check. The stability test results presented in Figures 10 and 11 are in accordance with the estimated uncertainties.

According to the GRUAN performance analysis of RS92, the uncertainty after ground preparation is the dominant source of uncertainty for the retrieval of the integrated precipitable water column (IPW) from the soundings [4]. The theoretical lower limit of uncertainty after ground preparation, as explained in the GRUAN analysis, is indicated with a dashed line in Figure 12. Thus, the improvements in accuracy gained with RS41 can be considered substantial in this respect as well.

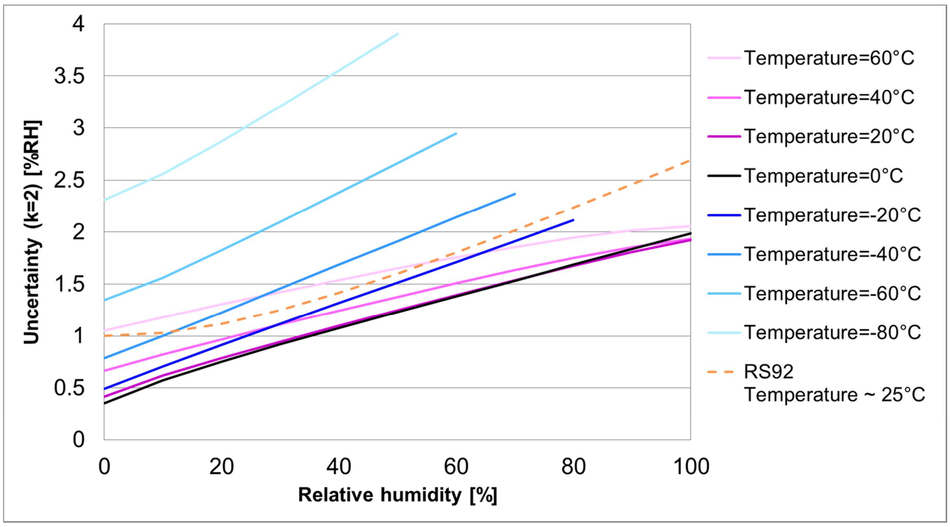

Figure 12. The combined uncertainty of Vaisala Radiosonde RS41humidity measurement after ground preparation (k=2) for various ambient temperatures. The dashed line indicates the corresponding RS92 uncertainty (lower limit) at room temperature derived in GRUAN data processing.

UNCERTAINTY ANALYSIS

During the development of Vaisala Radiosonde RS41, a wide range of laboratory tests and experimental soundings were conducted. These results served as input data for a comprehensive uncertainty analysis that was carried out in order to estimate the measurement uncertainties in a wide range of atmospheric conditions. For temperature, the considered range covered temperatures from +60°C to -100°C, and for relative humidity, humidity levels from 0 % to saturation. The uncertainty analysis is implemented following the recommendations of JCGM 100:2008 [6]. More detailed presentation of the analysis is given in reference [5].

The impact of the identified uncertainty factors on temperature and humidity measurement accuracy was modeled with a specific analysis software that uses a given atmospheric model and sounding specific parameters. The following parameters were chosen when assessing the performance of Vaisala Radiosonde RS41:

- Temperature profile: U.S. Standard Atmosphere 1976
- Ascent rate: 6 m/s
- Solar angle: 60° relative to the horizon

These conditions, combining all the uncertainty components from calibration, storage, ground preparations and sounding, resulted in the uncertainties presented in Figure 13.

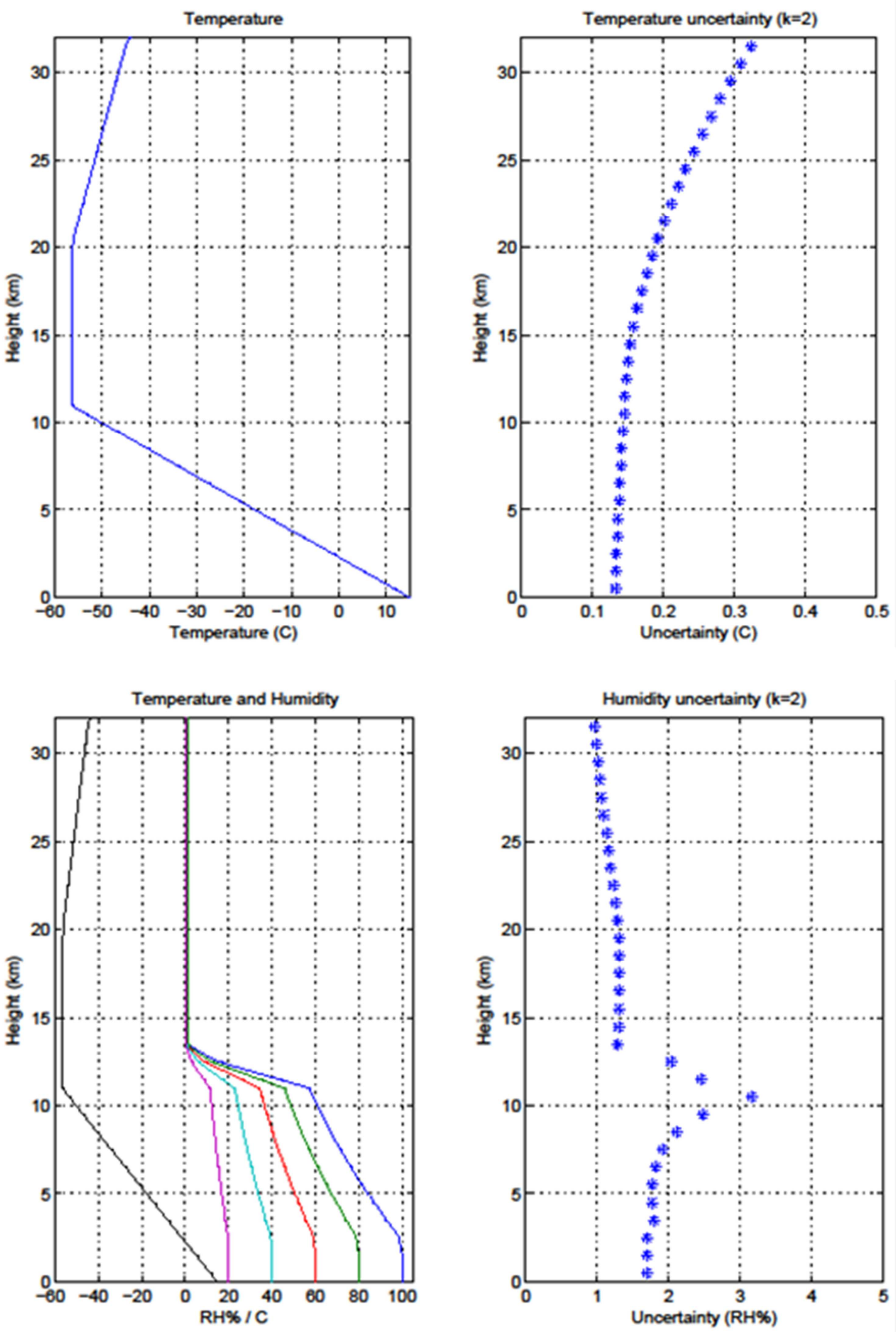

Figure 13. Top: The combined measurement uncertainty of RS41 temperature measurement (k=2). The U.S. Standard Atmosphere 1976 temperature profile used in the uncertainty analysis (left) and the resulting temperature measurement uncertainty (right).
Bottom: The combined measurement uncertainty of RS41 humidity measurement (k=2). The uncertainty analysis model applied the U.S. Standard Atmosphere 1976 temperature profile and a set of humidity profiles (left), and the resulting humidity measurement uncertainty (right).

RESULTS IN SOUNDING CAMPAIGNS AND COMPARISONS AGAINST REFERENCE INSTRUMENTS

The measurement performance of RS41 has been studied in several sounding campaigns representing a wide range of climate conditions. In addition to campaigns at Vaisala Oyj Vantaa office, beta customers and campaign sites include:

- FMI, Sodankylä Finland
- Penang, Malaysia
- CHMI, Libus, Czech Republic
- UK Met Office, Camborne, UK

The comparison report concluding test campaigns and implications due to chance from RS92 to RS41 can be found in references [7,8]. The performance differences between RS41 and RS92 were thoroughly analyzed based on two week campaign in Camborne, UK, held in November 2013 [9]. In the Camborne campaign, a doubled twin-sounding was found to be the most efficient sounding configuration for studying the reproducibility of measurements and the direct differences between the two radiosonde models RS41 and RS92. In the set-up, a pair of RS41 units together with a pair of RS92 units was attached to a cross-shaped boom, and the system was elevated by a single large balloon, see Figure 14. The average ascent rate varied from 5.7 to 6.5 m/s and, as a rule, the soundings reached altitudes in range of 30 to 34 km. The results shown here were analyzed by Vaisala research and development team with Radiosonde Comparison Software RSKOMP [10].

Figure 14. An illustration of typical rig configuration used in test campaigns.

The statistical analysis of the conducted twenty daytime soundings in Camborne illustrates the improvements achieved in RS41 precision. Due to smaller calibration uncertainty and ground preparation relying on stability of the platinum sensor, the reproducibility of the RS41 temperature measurements shows values of approximately one third of the RS92 results in the lower troposphere, refer to Figure 15. In the stratosphere part of the profiles, where solar radiation is the dominant source of uncertainty, RS41 reproducibility is roughly two thirds of what is measured with

RS92. This can be mostly explained with the lower noise in RS41 measurement, but also with a fine-tuned, well verified solar radiation correction.

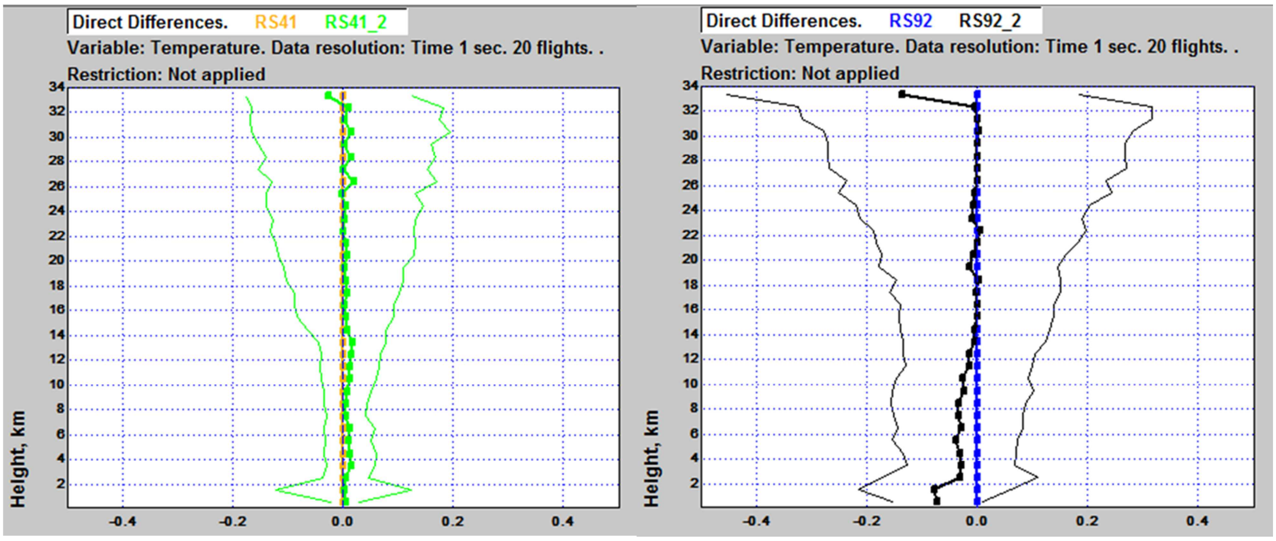

Figure 15. Reproducibility of daytime temperature measurement in Camborne campaign, RS41 on the left, RS92 on the right.

Respectively, the reproducibility of RS41 daytime humidity measurement shows values ranging from one half to one third of the RS92 measurements, see Figure 16. The most evident progress is seen in the troposphere part, where the variability in the amount of solar radiation exposure and the sensor time-lag are the dominant sources of uncertainty. Obviously neither radiosonde model has suffered from sensor freezing, which could potentially ruin the good reproducibility results. Above 14 km the dry conditions of the stratosphere demonstrate the uncertainty of the off-set correction made during the ground preparations. In both regions of the sounding the new humidity measurement technology of RS41, the on-chip temperature measurement and the desiccant-free zero humidity check, promote improved accuracy.

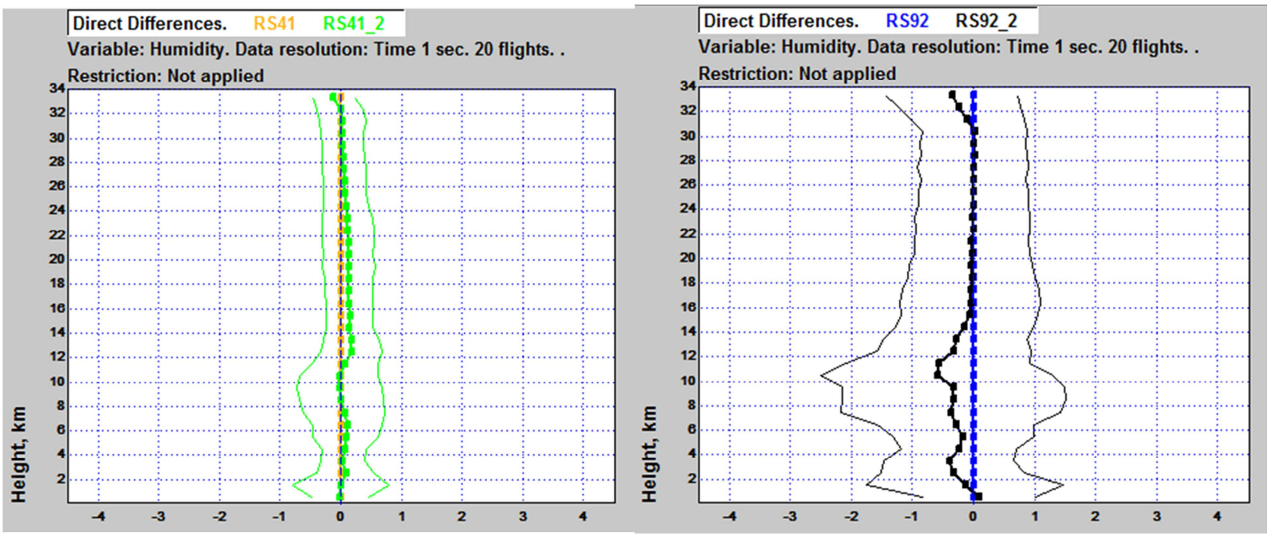

Figure 16. Reproducibility of daytime humidity measurement in Camborne campaign, RS41 on the left, RS92 on the right.

The temperature measurement of RS41 has also been verified in 20 daytime test soundings in Finland (lat. 60° N) and Malaysia (lat. 5° N) using a multi-thermometer measurement as a reference method. The multi-thermometer instrument utilizes the well-known principle of different sensor coatings producing material-dependent response for solar and IR radiation, enabling accurate estimation of true ambient temperature. The reference instruments used in the two campaigns were manufactured and calibrated by the Vaisala research and development team. A statistical analysis of the soundings is presented in Figure 17. The temperature measurement of RS41 is in a good agreement with the reference method showing direct differences less or equal to 0.1°C in all observation altitudes.

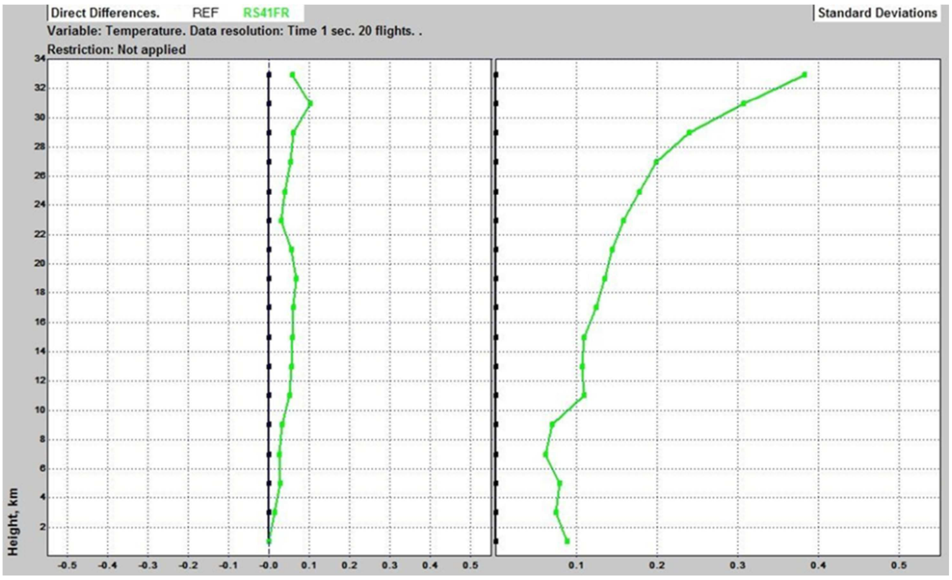

Figure 17. A twin-sounding comparison of RS41 temperature measurement against a multi-thermometer reference method – average temperature difference (left) and standard deviation of differences (right).

The RS41 humidity measurement has been verified in test soundings in Finland and Malaysia, using a cryogenic frostpoint hygrometer (CFH) as a reference. An example of a sounding carried out in Malaysia in 2013 is presented in Figure 18. Here, the frostpoint reading of the CFH is converted to relative humidity based on the temperature data gathered by the RS41. As there are indications that the performance of the CFH may have suffered from the exceptionally large payload of the sounding, the CFH data is quality checked. The agreement between the two instruments is good throughout the profile, although the cold and typically supersaturated tropical tropopause is a challenging environment for the instruments.

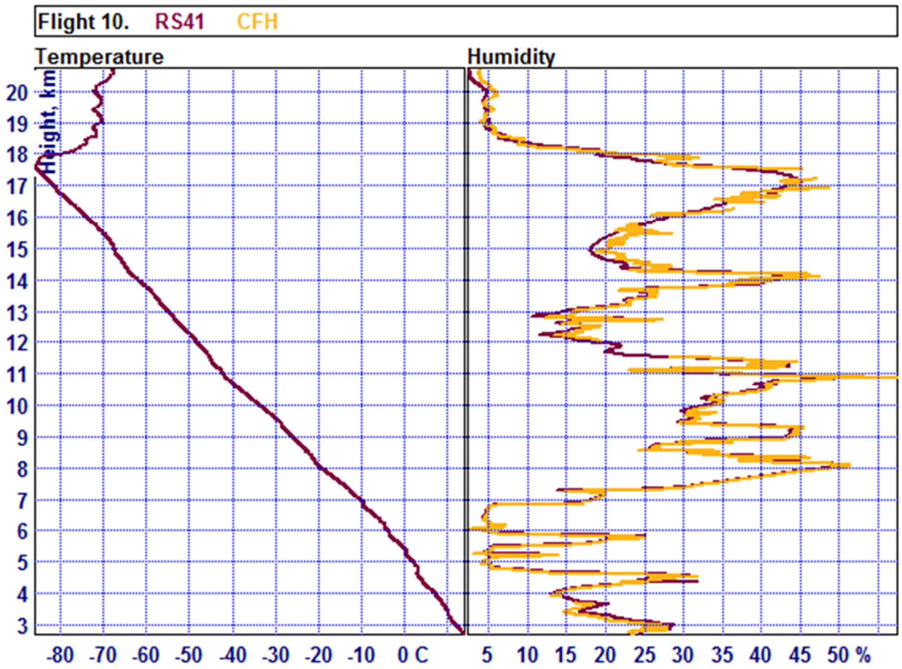

Figure 18. An example of a sounding carried out in Penang, Malaysia in 2013, compred against a CFH reference measurement. The figure shows relative humidity as measured by CFH (yellow) and the RS41 (brown).

CONCLUSIONS

The platinum resistor based temperature sensor of RS41 produces improved calibration uncertainty and reference class stability. In sounding conditions the enhanced measurement accuracy is mainly the result of the following factors:

- Basic measurement accuracy prior to launch – uncertainty < 0.11°C (k=2).
- Design of the supporting structure and the sensor resulting in low radiation error and in low solar radiation induced noise.
- Thoroughly verified radiation correction.

The humidity sensor chip combines a capacitive polymer sensor with a temperature sensor and a heating element. This integrated structure enables the following features, all having significant impact on the accuracy of the sounding results:

- Capability to determine sensor chip temperature diminishing humidity measurement error due to varying solar and IR radiation conditions.
- Capability to operate the sensor at elevated temperatures preventing water condensation and frost formation on the sensor surface.
- Automated preflight reconditioning and zero humidity check procedures to effectively remove possible chemical contaminants and storage drifts, improving the basic measurement accuracy prior to launch – uncertainty 0.5 – 2.0 %RH (k=2) at room temperature when humidity ranges from 0 to 100 %RH, respectively.

Both the conducted uncertainty analysis and the sounding campaigns held in various climate conditions support the conclusion that the new sensing technologies applied in Vaisala Radiosonde RS41 have substantial effects on the consistency of upper air measurements. As

RS41 is designed for operational use, the user-friendliness of the radiosonde, the ground check procedure and the user interface of the sounding software also promote good consistency in upper air observations.

REFERENCES

[1] R. Lehtinen, T. Tikkanen, J.-P. Räsänen and M.Turunen: Factors contributing to RS41 GPS-based pressure and comparison with RS92 sensor-based pressure, TECO 2014

[2] GPS-Based Measurement of Height and Pressure with Vaisala Radiosonde RS41 White Paper, 2013.

[3] WMO Guide to meteorological instruments and methods of observation, WMO-No. 8 (2008 edition, Updated in 2010)

[4] R. J. Dirksen, M. Sommer, F. J. Immler, D. F. Hurst, R. Kivi, H. Vömel: Reference quality upper-air measurements: GRUAN data processing for the Vaisala RS92 radiosonde, 2014

[5] P. Survo, R. Lehtinen, J. Kauranen: SI Traceability of Vaisala Radiosonde RS41 Sounding Data – Calibration and Uncertainty Analysis, TECO 2014

[6] JCGM 100:2008, Evaluation of measurement data – Guide to the expression of uncertainty in measurement, 2008

[7] H. Jauhiainen, P. Survo, R. Lehtinen, J. Lentonen: Radiosonde RS41 and RS92 key differences and comparison test results in different locations and climates, TECO 2014

[8] H. Jauhiainen, J. Lentonen, P. Survo, R. Lehtinen, T. Pietari: The implications of Vaisala's new radiosonde RS41 on improved in-situ observations for meteorological applications, AMS annual meeting, 2014

[9] D. Edwards, G. Anderson, T. Oakley, P. Gault,: UK MET Office Intercomparison of Vaisala RS92 and RS41 Radiosondes, 2014

[10] Description and User Guide for the Radiosonde Comparison and Evaluation Software Package, WMO, 1996.