Vaisala Radiosonde RS41 Measurement Performance

WHITE PAPER

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CHAPTER 1

The purpose of this document is to present the measurement performance of the Vaisala Radiosonde RS41.

The Vaisala Radiosonde RS41 introduces improvements in accuracy and consistency of upper air measurement data. Each technical solution of RS41, from the state-of-the-art sensor technology to the highly automated manufacturing process, has been carefully planned and thoroughly tested. This, together with extensive quality control – applied all the way from the manufacturing stage to the sounding preparation and the sounding process – results in excellent measurement performance. In practice this is demonstrated in upper air measurements that are extremely responsive yet highly reproducible in all atmospheric conditions.

The Vaisala Radiosonde RS41 fulfills all recommendations for radiosonde accuracy detailed in Annex 12.A of the current version of the WMO Guide to Meteorological Instruments and Methods of Observation [1]

This document presents a technical assessment of the measurement performance of the Vaisala Radiosonde RS41-SG, -SGP, and, -SGM. The assessment covers measurement uncertainty analysis as well as results from sounding campaigns carried out during the product development phase. Comparison results against applicable reference instruments are also included. The Vaisala Radiosonde RS41 and Vaisala Radiosonde RS92 are compared in detail in the Comparison of Vaisala Radiosondes RS41 and RS92 White Paper [2]. RS41 pressure measurement technologies are reviewed in more detail in separate white papers: GPS-based Measurement of Height and Pressure with Vaisala Radiosonde RS41 [3], and, Vaisala Radiosonde RS41-SGP Pressure Measurement Performance [4].

1.1 Executive summary

In terms of measurement performance, the key characteristics of the Vaisala Radiosonde RS41 are its excellent repeatability and reliability in all sounding conditions.

A number of factors contribute to this high-level performance. The first of these is the state-of-the-art sensor technology and advanced correction methods used in the RS41:

- The temperature sensor is tailored for sounding applications. It is based on platinum resistor technology, which gives reference-class linearity and stability. In sounding conditions the excellent measurement accuracy is a result of optimized sensor design and thoroughly verified radiation correction.
- The humidity sensor chip combines a capacitive polymer sensor with a temperature sensor and a heating element. This enables accurate, ice-free humidity measurement in clouds and in varying solar radiation exposures.
- GPS-based height, atmospheric pressure, and wind measurements use customized signal processing algorithms developed by Vaisala. These algorithms are optimized for sounding applications, taking into account such factors as typical radiosonde motion.

In addition to the sophisticated measurement technologies highlighted above, three other important factors help ensure high-quality sounding data:

- Extensive quality control is deployed throughout the manufacturing and calibration processes. The final quality assurance checks before launch are done automatically during sounding preparation.
- Basically, if corrections are made in conjunction with sounding preparation, the references on which the corrections are based must be carefully maintained. For the RS41, the only correction applied in the preparation phase is physical zero humidity correction. As this correction is based on sensor heating, it does not require desiccant-based zero RH conditions.
- The user interface of the Vaisala DigiCORA® Sounding System MW41, as well as the functionality of the RS41 and the ground check device, are designed to be user friendly and to minimize the risk of human error. As a result, the Vaisala fourth-generation sounding system is efficient to operate and delivers consistent results.

Over one thousand test soundings, numerous laboratory tests, and in-depth uncertainty analysis carried out during the product development phase have demonstrated that the Vaisala Radiosonde RS41 takes sounding data quality to a whole new level.

RS41 specification	P (hPa)	T (°C)	U (%RH)
Uncertainty after ground preparation	N/A	0.2	3
Uncertainty in sounding			
>100 hPa	1.0		
100 ... 10 hPa	0.3		
<10 hPa	0.04		
<16 km		0.3	4
>16 km		0.4	4
Reproducibility in sounding			
>100 hPa	0.5	0.15	2
100...10 hPa	0.2	0.30	2
<10 hPa	0.04	0.30	2

Table 1.1. *Key measurement performance figures for the Vaisala Radiosonde RS41. For detailed specifications, see Table 2.1, 3.1, 4.1, 5.1, and 6.1.*

1.2 How the Vaisala Radiosonde RS41-SG measurement accuracy specifications are derived

During the development of the Vaisala Radiosonde RS41, a wide range of laboratory tests and over one thousand comparative test soundings were conducted. These results served as input data for a comprehensive uncertainty analysis that was carried out in order to estimate measurement uncertainties in a wide range of atmospheric conditions. For temperature, the considered range covered +60°C to -100°C, and for relative humidity, 0 % to saturation.

The uncertainty of a measurement defines the amount of dispersion in a measurement result that arises from the applied measurement method as well as from the prevailing measurement conditions. For the RS41, the measurement uncertainties are expressed using a coverage factor of k=2. This indicates that approximately 95% of practical measurement results fall within the given uncertainty limits. A detailed uncertainty analysis deepens the understanding of how the measurement instrument performs in varying measurement conditions. It is a basic tool for deriving an instrument's measurement performance specifications.

The uncertainty analysis is implemented following the recommendations of JCGM 100:2008 [5]. In short, the uncertainty analysis consists of the following steps (adapted from the guide):

- The relationship between the measurand and all the input quantities are expressed mathematically. For example, a relative humidity reading measured by a radiosonde is a mathematical function of sensor capacitance according to the sensor model – including calibration adjustments and applied corrections – and even of the ambient temperature by the saturation vapor pressure equations.
- Covering all typical measurement conditions, the uncertainty of each input quantity is estimated. In this analysis dynamic conditions during soundings are also taken into consideration, as well as uncertainties arising from storage time.
- The combined uncertainty for the measurand is determined by calculating the effect of each uncertainty component on the end result. This is based on the mathematical model created in the first step and the general rules for combining uncertainties.

The calibration uncertainty is defined according to the guidelines given in EA-4/02, Expression of the Uncertainty of Measurement in Calibration [6].

In order to help the reader follow the text in the subsequent chapters, some definitions related to measurement performance analysis are provided in the appendix at the end of this document.

CHAPTER 2

Temperature Measurement

The temperature measurement of Vaisala Radiosonde RS41 is based on resistive platinum sensor. This sensor type was chosen for its reference-class linearity and stability.

In order to fulfill the requirements of high-quality atmospheric temperature measurement, RS41 has a tailored temperature sensor design. The sensor is developed and manufactured by Vaisala.

2.1 Specifications

If not explicitly stated otherwise, the specifications in **Table 2.1** are expressed using expanded uncertainty (k=2), encompassing approximately 95% of the dispersion of results.

Temperature Sensor	
Type	Platinum Resistor
Measurement range	+60 °C to -90 °C
Resolution	0.01 °C
Response time (63.2%, 6 m/s flow, 1000 hPa)*	0.5 s
Stability (1 year/3 years)	<0.05 °C/0.1 °C
Accuracy	
Repeatability in calibration	0.1 °C
Combined uncertainty after ground preparation	0.2 °C
Combined uncertainty in sounding 0–16 km	0.3 °C
Combined uncertainty in sounding above 16 km	0.4 °C
Reproducibility in sounding **	
1080–100 hPa	0.15 °C
100–3 hPa	0.30 °C

* Temperature data time lag-corrected, negligible residual uncertainty

** Standard deviation of differences (k=1) in twin-soundings, ascent rate > 3 m/s

Table 2.1. *Temperature sensor performance.*

2.2 Temperature measurement performance after ground preparation

The analysis of temperature measurement performance after ground preparation includes all relevant uncertainty components present prior to launch. Uncertainty components related to solar radiation and dynamic sounding conditions are considered in chapter 2.3.

2.2.1 Calibration

Traceability

Reference platinum resistance thermo-meters used in the calibration of Vaisala Radiosonde RS41 temperature measurement are traceable to international standards (SI units).

Traceability is composed of:

- an unbroken chain of calibrations to the international standards (SI units)
- the defined measurement uncertainty of each calibration step
- regular calibration of the measurement devices involved
- the calibration and maintenance of measurement equipment by qualified personnel.

Repeatability

The repeatability of the RS41 temperature calibration has been evaluated in various tests. The results show that the calibration repeatability is better than 0.1°C, expressed as two times the standard deviation of differences in two successive calibrations.

Linearity and accuracy

The linearity of the RS41 temperature measurement was investigated in a laboratory test chamber. The uncertainty of the reference temperature measurement was 0.04°C (k=2) and the studied range covered temperatures from -98°C to +39°C. According to the test results, the uncertainty related to nonlinearity of the RS41 temperature measurement is 0.05°C (k=2), and there is no systematic bias in sensor calibration. An example of the test results is presented in **Figure 2.1**.

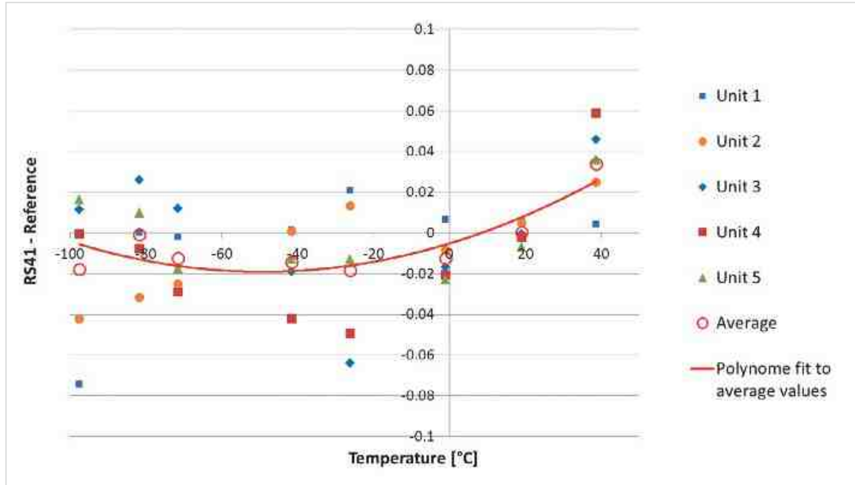

Figure 2.1. *Typical linearity of the Vaisala Radiosonde RS41 temperatture measurement studied in a temperature test chamber.*

2.2.2 Stability and ground check

Stability

The stability of the RS41 temperature measurement has been studied in storage tests. The RS41 radiosonde units under the test were factory-calibrated and packed according to standard manufacturing procedures of RS41 production. The radiosonde units were stored in outdoor temperature and humidity conditions at Vaisala's factory area in Finland in an unheated shelter-type warehouse. The stability test results of twenty radiosonde units after a three-year storage period, in **Figure 2.2**, show that no systematic drift is observed during the storage and the dispersion of the results is also in a good low level.

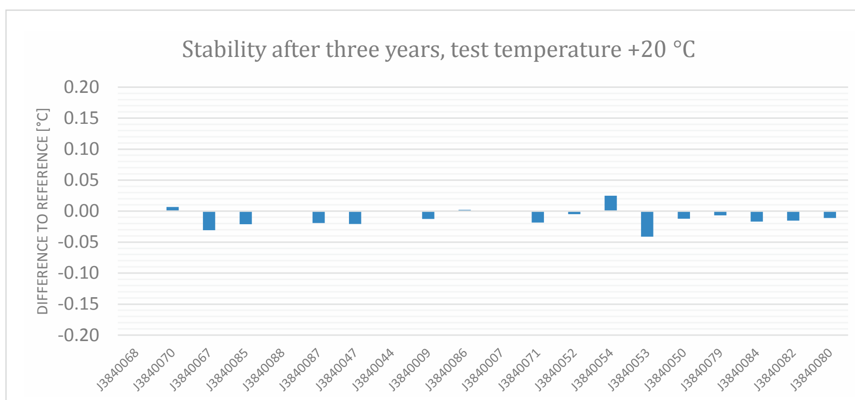

Figure 2.2. *Stability of the RS41 temperature sensor after a three year storage period. The measurement uncertainty of the test system was 0.07 °C (k=2).*

Ground check

Platinum resistor temperature sensors are known to be extremely stable, as demonstrated in the RS41 stability tests. Therefore a check against an external reference sensor in conjunction with sounding preparation is not necessary. For quality control purposes an inbuilt functional test is carried out during preflight preparations for the RS41 with a Vaisala Ground Check Device RI41.

2.2.3 Accuracy after ground preparation

To assess the combined uncertainty in the Vaisala Radiosonde RS41 temperature measurement after ground preparation, the uncertainty components of the sensor model and calibration, together with uncertainties relating to storage, are taken into consideration. Uncertainty factors related to solar radiation and dynamic sounding conditions are excluded. The results of the uncertainty analysis model are shown in **Figure 2.3**.

2.3 Temperature measurement performance in sounding

This section summarizes all relevant uncertainty components present in dynamic sounding conditions.

2.3.1 Response time / Time lag correction

In sounding conditions, the response time of a radiosonde temperature sensor is dependent on the ambient pressure, sensor ventilation, and the thermal properties of the sensor.

To remove all systematic errors from the Vaisala Radiosonde RS41 temperature measurement, a time lag correction algorithm was developed and introduced in the Vaisala DigiCORA® Sounding System MW41. As the correction is applied, the remaining temperature measurement uncertainty due to time lag is insignificant. For example, at 18 km (75 hPa) with a temperature lapse rate of 0.01°C/m and an ascent rate varying from 3 to 9 m/s, the remaining uncertainty in the temperature reading due to time lag is 0.02°C (k=2). At lower altitudes the uncertainty is even smaller.

The response time of the RS41 temperature sensor has been tested in various pressure and ventilation conditions. The key figures at a ventilation speed of 6 m/s are summarized in **Table 2.2** below.

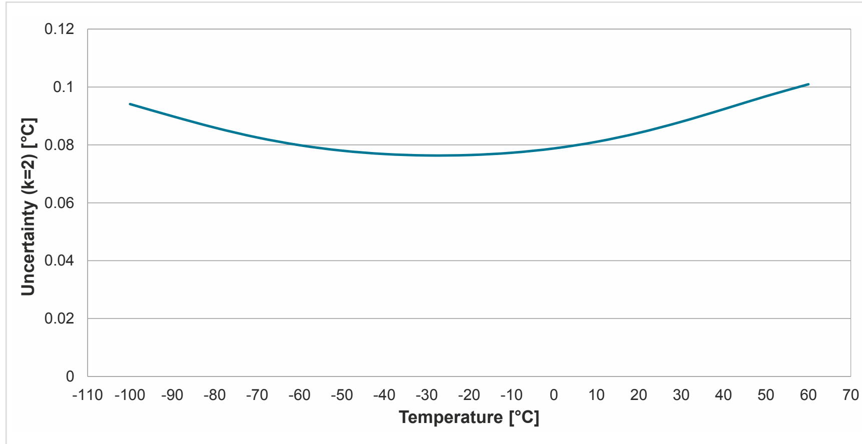

Figure 2.3. *The combined uncertainty of the Vaisala Radiosonde RS41 temperature measurements after ground preparation (k=2).*

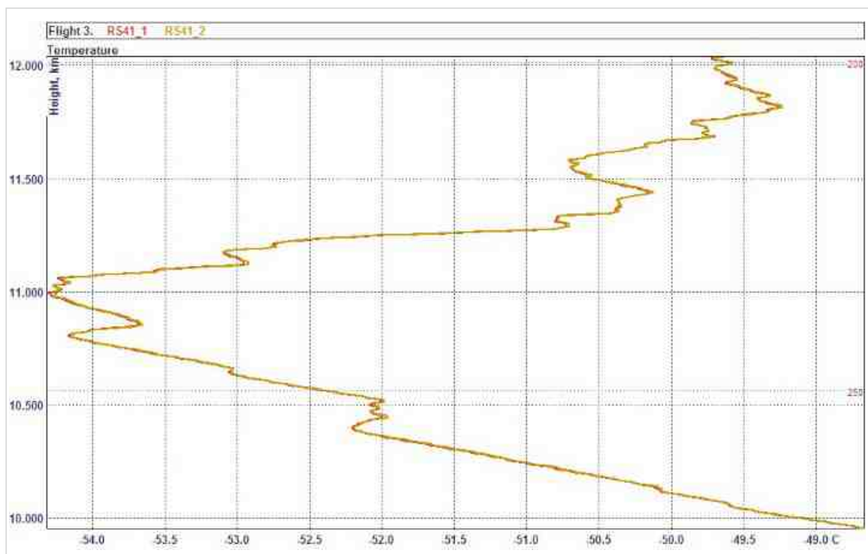

Figure 2.4. *An example of the Vaisala Radiosonde RS41 highly responsive temperature measurement. The results are of two units in the vicinity of the mid-latitude tropopause.*

Pressure [hPa]	Sensor response time 63.2% without time-lag correction, ventilation speed 6 m/s [s]
1000	0.5
100	1.2
10	2.5

Table 2.2. *Response time of the Vaisala Radiosonde RS41 temperature sensor. Time-lag correction is applied to sounding data, resulting in negligible measurement uncertainty.*

2.3.2 Radiation correction

In the daytime temperature measurement of a radiosonde, the most significant source of uncertainty is solar radiation. Therefore, when developing the Vaisala Radiosonde RS41 special attention was paid firstly to minimizing and secondly to characterizing and modeling the effects of radiation on temperature measurement. As a result, the applied radiation correction is small (**Table 2.3**.), and more importantly the radiation correction-related uncertainty shows good low values. Another important factor in achieving the improved measurement accuracy is the new sensor boom design, which significantly reduces the measurement noise originating from solar radiation. According to the uncertainty analysis, the uncertainty of the radiation correction is typically less than 0.2°C (k=2) in the troposphere; uncertainty gradually increases in the stratosphere.

Radiation correction table

Radiation corrections for the RS41 are presented in **Table 2.3**. Any future changes to radiation correction will be included in an updated radiation correction table and published on the Vaisala sounding data continuity web pages.

hPa/deg.	-7.0	-4.0	-2.0	0.0	3.0	10.0	30.0	45.0	60.0	90.0
1000	0.00	0.00	0.00	0.00	0.01	0.03	0.08	0.10	0.11	0.11
500	0.00	0.00	0.02	0.03	0.05	0.09	0.15	0.17	0.18	0.19
200	0.00	0.02	0.06	0.09	0.13	0.19	0.27	0.29	0.31	0.32
100	0.00	0.05	0.10	0.16	0.21	0.29	0.39	0.42	0.44	0.45
50	0.00	0.10	0.18	0.24	0.32	0.42	0.55	0.58	0.60	0.62
20	0.01	0.18	0.29	0.39	0.49	0.63	0.81	0.85	0.88	0.9
10	0.05	0.27	0.42	0.53	0.65	0.83	1.04	1.10	1.14	1.16
5	0.09	0.37	0.55	0.68	0.83	1.05	1.31	1.39	1.42	1.45

Table 2.3. *Radiation correction of Vaisala Radiosonde RS41 temperature measurement at various pressure levels and solar angles at ground level, ventilation speed 6 m/s.*

2.3.3 Accuracy in sounding

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

- Temperature profile: U.S. Standard Atmosphere 1976
- Ascent rate: 6 m/s
- Velocity in respect to air: 7 m/s
- Solar angle: 60° relative to the horizon

These conditions, combining all the uncertainty components from calibration, storage, and sounding, resulted in the uncertainties presented in **Figure 2.5**.

This analysis shows that uncertainty in the RS41 temperature measurement is nearly constant in the troposphere. In the stratosphere uncertainty gradually increases due to the emerging dominance of uncertainty in radiation correction.

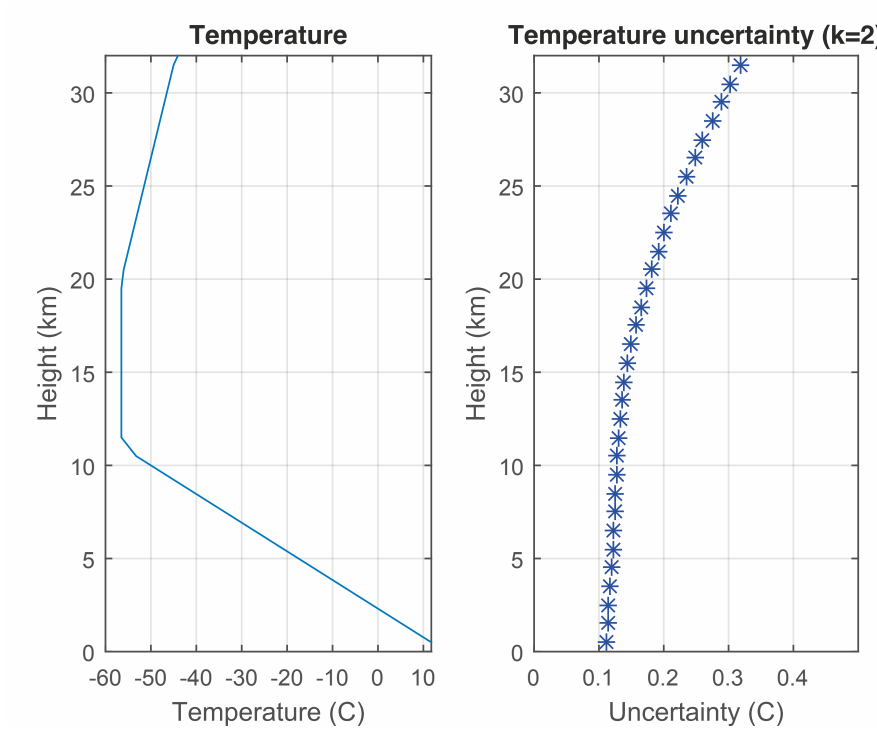

Figure 2.5. *The combined measurement uncertainty of Vaisala Radiosonde RS41 temperature measurement (k=2). The U.S. Standard Atmosphere 1976 temperature profile used in the uncertainty analysis (left) and the resulting temperature measurement uncertainty (right).*

2.3.4 Reproducibility in soundings

The reproducibility of the Vaisala Radiosonde RS41 temperature measurement has been analyzed in several sounding campaigns. As an example, the results from a sounding campaign carried out during summer 2013 in Finland are presented in **Figure 2.6** and the results from a campaign carried out in Malaysia in 2013 in **Figure 2.7**. The data in both figures is from daytime twin-soundings in various weather conditions.

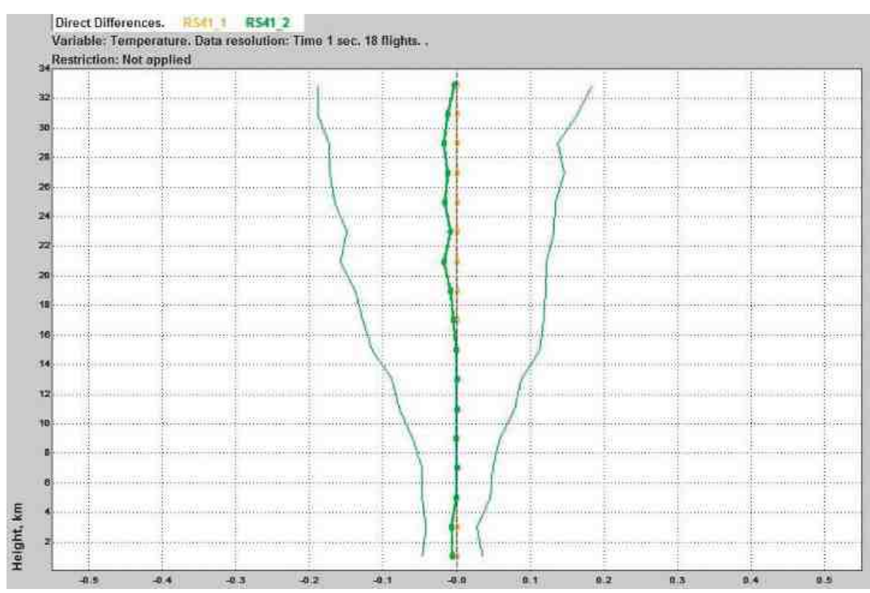

Figure 2.6. *The reproducibility of temperature measurement in 18 daytime twin-soundings at high latitudes. The average difference between the two RS41 radiosondes is indicated by the bold line and the standard deviation of difference by the thin lines.*

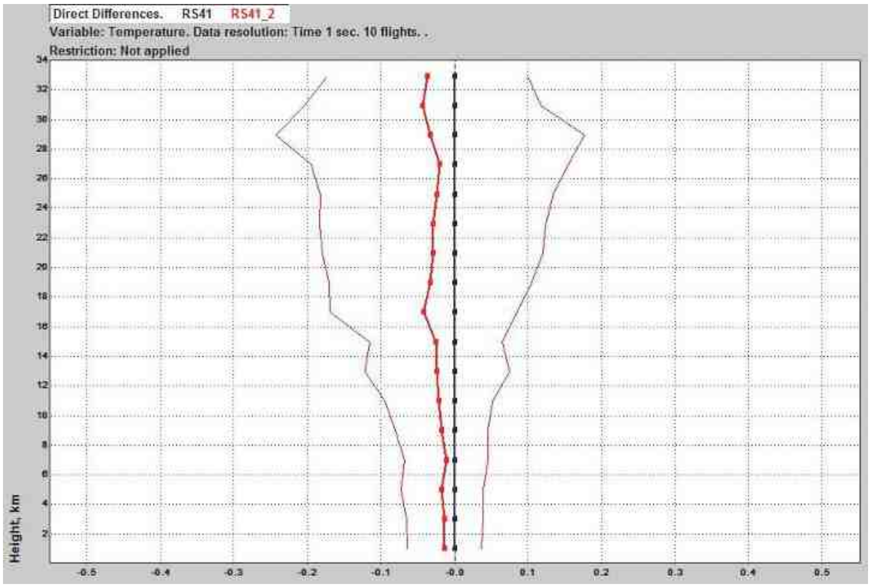

Figure 2.7. *The reproducibility of temperature measurement in ten daytime twin-soundings in the tropics.*

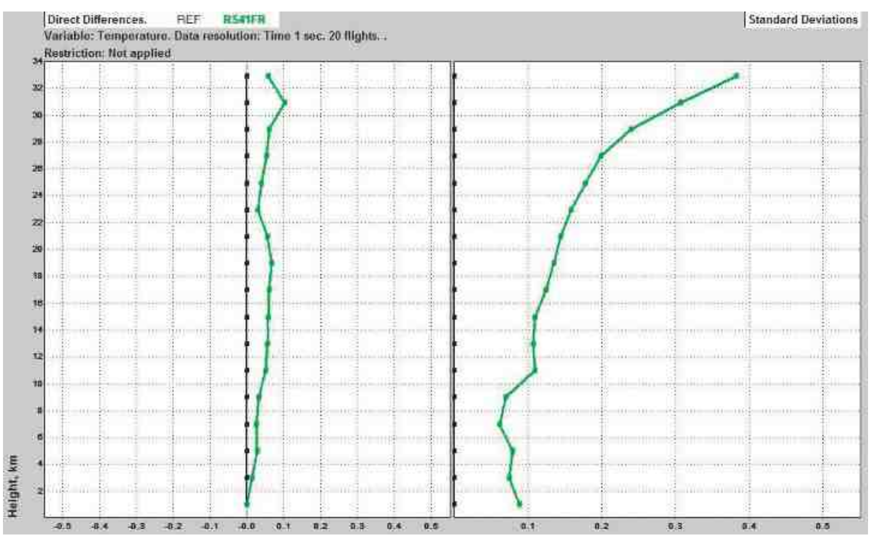

Figure 2.8. *A twin-sounding comparison of RS41 temperature measurement against a multi-thermometer reference instrument – average temperature difference (left) and standard deviation of differences (right).*

These results show that standard deviation of measured temperature differences in sounding increases gradually with altitude, starting at the level of 0.05°C on the ground and ending at the level of 0.2°C at 34 km. These excellent results are due to small uncertainty after ground preparation as well as improvements in sensor boom design that minimize measurement noise, especially at high altitudes.

2.3.5 Comparison against reference instrument in sounding

The temperature measurement of the Vaisala Radiosonde RS41 was verified in 20 daytime test soundings in Finland (lat. 60° N) and Malaysia (lat. 5° N) using a multithermometer measurement as a reference. A statistical analysis of the soundings is presented in **Figure 2.8**.

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.

CHAPTER 3

Humidity Measurement

The humidity measurement of the Vaisala Radiosonde RS41 is based on proven capacitive polymer technology. The sensor is designed in Vaisala for atmospheric sounding applications and the sensor chips manufactured in Vaisala's own cleanroom facilities.

The sensor design integrates humidity and temperature sensing elements with a heating resistor, providing several unique features. For example, automated preflight recondition and zero humidity check procedures effectively remove possible chemical contaminants and storage drifts, thus laying the foundations for excellent humidity measurement accuracy. Furthermore, the sensor heating capability enables active de-icing during sounding. The effects of solar radiation are compensated by the on-chip temperature measurement, resulting in enhanced measurement accuracy throughout the profile.

Humidity Sensor	
Type	Thin-film Capacitor
Measurement range	0 to 100% RH
Resolution	0.1% RH
Response time	
6 m/s, 1000 hPa, +20°C	< 0.3 s
6 m/s, 1000 hPa, -40°C	< 10 s
Accuracy	
Repeatability in calibration	2% RH
Combined uncertainty after ground preparation	3% RH
Combined uncertainty in sounding	4% RH
Reproducibility in sounding*	2% RH

* Standard deviation of differences (k=1) in twin-soundings, ascent rate > 3 m/s

The given specifications are valid for the temperature range -60 to +60°C.

Table 3.1. *Humidity sensor performence.*

3.1 Specifications

If not explicitly stated otherwise, the specifications in Table 3.1 are expressed using expanded uncertainty (k=2), encompassing approximately 95% of the dispersion of the results.

3.2 Humidity measurement performance after ground preparation

The analysis of humidity measurement performance after ground preparation includes all relevant uncertainty components present prior to launch. Uncertainty components related to dynamic sounding conditions are considered in Chapter 3.3.

3.2.1 Calibration

Traceability

The reference instruments used in the calibration of Vaisala Radiosonde RS41 humidity measurement and in the modeling of the humidity sensor response are traceable to international standards (SI units).

Repeatability

The repeatability of the RS41 humidity calibration has been evaluated in various tests. The results show that the calibration repeatability is better than 2% RH, expressed as two times the standard deviation of differences in two successive calibrations.

3.2.2 Stability and ground check

Stability

The stability of the RS41 humidity measurement has been studied in storage tests. The RS41 radiosonde units under the test were factory-calibrated and packed according to standard manufacturing procedures of RS41 production. The radiosonde units were stored in outdoor temperature and humidity conditions at Vaisala's factory area in Finland in an unheated shelter-type warehouse. The stability test results of twenty radiosonde units after a three-year storage period, in **Figure 3.1**, show that no systematic drift is observed during the storage and the dispersion of the results is also in a good low level.

Ground check

During sounding preparation, reconditioning of the humidity sensor begins soon after the radiosonde is turned on. This heating phase removes possible contaminants that may affect the measurement result.

When a Vaisala Ground Check Device RI41 is used in sounding preparation, an inbuilt zero humidity check is also conducted in conjunction with the reconditioning. This check detects and corrects possible offset type errors in humidity measurement. During the check a dry reference condition is generated by heating the humidity sensor. Compared to 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.

As a result of the two quality-assurance procedures – the reconditioning and the desiccant-free zero humidity check – the factory calibration of the RS41 humidity sensor is restored with enhanced consistency.

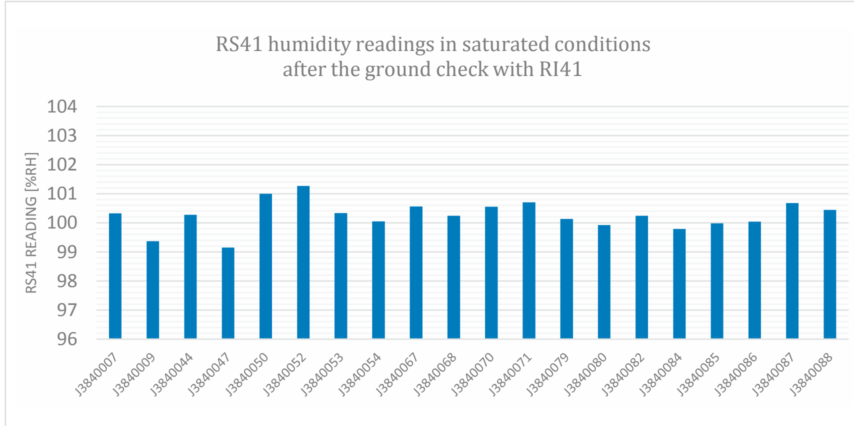

Figure 3.1. *Stability of the RS41 humidity sensor after a three year storage period. Measurements were conducted in saturated humidity conditions generated with a Standard Humidity Chamber by Dr. Schulz & Partner GmbH.*

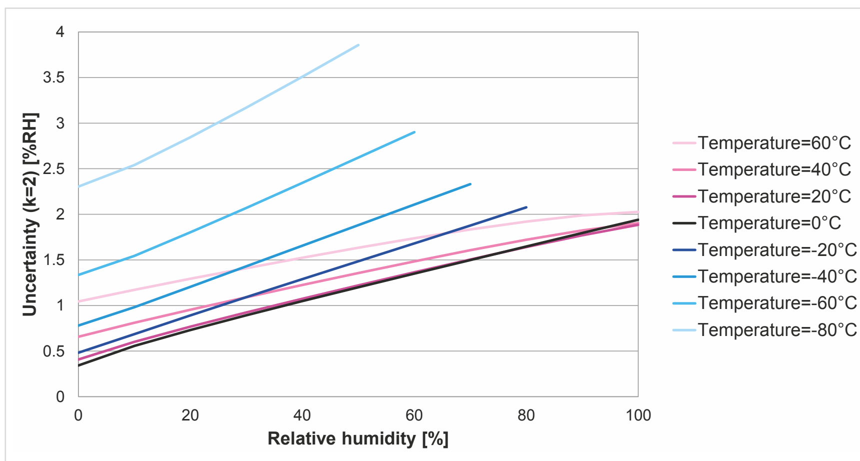

Figure 3.2. *The combined uncertainty of the humidity measurement of the Vaisala Radiosonde RS41 after ground preparation. The humidity range is restricted by water vapor saturation at the coldest temperatures.*

3.2.3 Accuracy after ground preparation

To assess the combined uncertainty in the humidity measurement of the Vaisala Radiosonde RS41 after ground preparation, the following sources of uncertainty are taken into consideration:

- sensor model and calibration
- storage
- humidity sensor temperature measurement
- ambient temperature measurement

Uncertainty factors related to dynamic sounding conditions are excluded. The results of the uncertainty analysis model are shown in **Figure 3.2**.

3.3 Humidity measurement performance in sounding

This section summarizes all relevant uncertainty components present in dynamic sounding conditions.

3.3.1 Response time / Time lag correction

In sounding conditions, the response time of a polymer-based capacitive humidity sensor is dependent on the ambient temperature. As temperature decreases, the sensor responsiveness is reduced and time lag correction is needed to diminish systematic errors in cold dynamic conditions.

The response time of the RS41 humidity sensor was determined in laboratory tests in various temperature and humidity conditions. Based on the test results, a time lag correction method was developed specifically for this sensor type. See **Figure 3.3** below.

3.3.2 Measurement performance in clouds

The accuracy of humidity measurement in clouds is of great meteorological importance; however, due to the presence of condensing and potentially freezing moisture, clouds are among the most challenging environments to measure.

The Vaisala Radiosonde RS41 humidity sensor can be operated at elevated temperatures, enabling the use of a smart de-icing feature that is efficient at preventing water condensation and frost formation on the sensor surface. The combination of the active de-icing and the on-chip temperature measurement makes the RS41 humidity measurement highly robust and accurate even in harsh sounding conditions **Figure 3.4**.

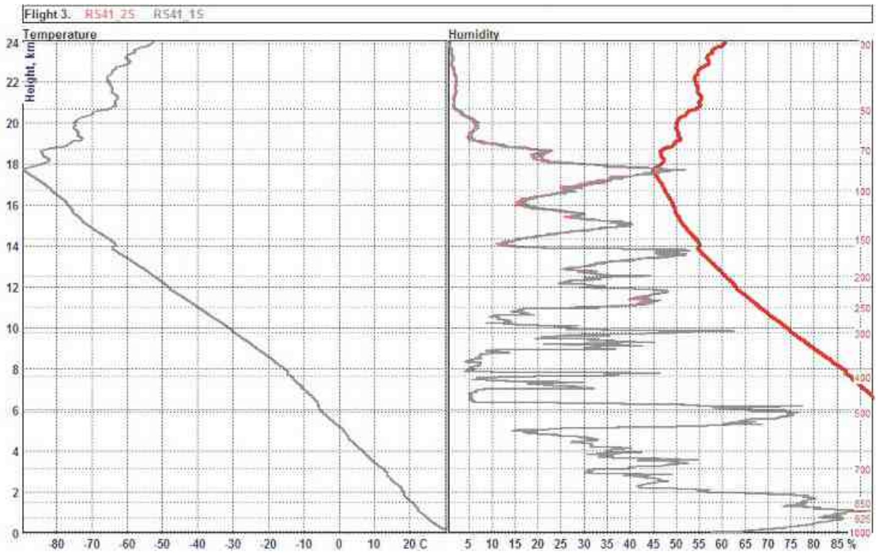

__Figure 3.3.__ An example of responsive yet highly reproducible humidity profiles (right) measured by two RS41 units at daytime in the tropics. The thick red profile indicates a saturated RH level. The temperature profile (left) extends close to -90°C.

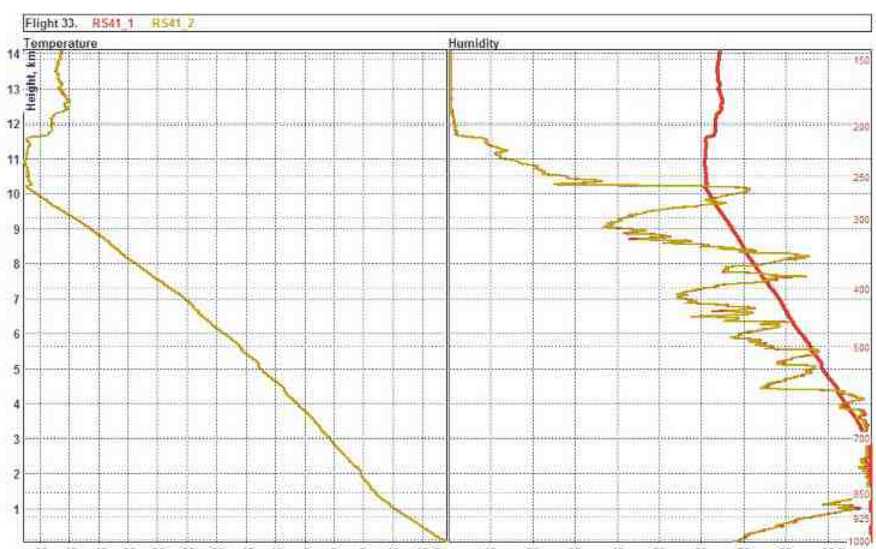

__Figure 3.4.__ An example of a challenging sounding profile for humidity measurement at high latitudes during daytime. The thick red profile indicates a saturated RH level. The RS41 units (thin red and beige profiles) show good measurement consistency.

3.3.3 Accuracy in sounding

Humidity measurement accuracy was modeled with a specific analysis software that uses given atmospheric profiles and sounding-specific parameters. To assess the performance of the Vaisala Radiosonde RS41 humidity measurement, the U.S. Standard Atmosphere 1976 temperature profile was chosen. For humidity, a set of five profiles was used for the troposphere: saturated humidity and an 80, 60, 40, and 20% portion of the vapor pressure of the saturated humidity. These conditions, combining all the uncertainty components from sensor model and calibration, storage, and sounding, resulted in the uncertainties presented in Figure 3.5. Because the equation for saturated water vapor (ITS-90 compatible form of Wexler's formula by Hardy [7]) used in relative humidity calculation involves temperature, the analysis also includes the combined uncertainty of temperature measurement presented in Chapter 2.

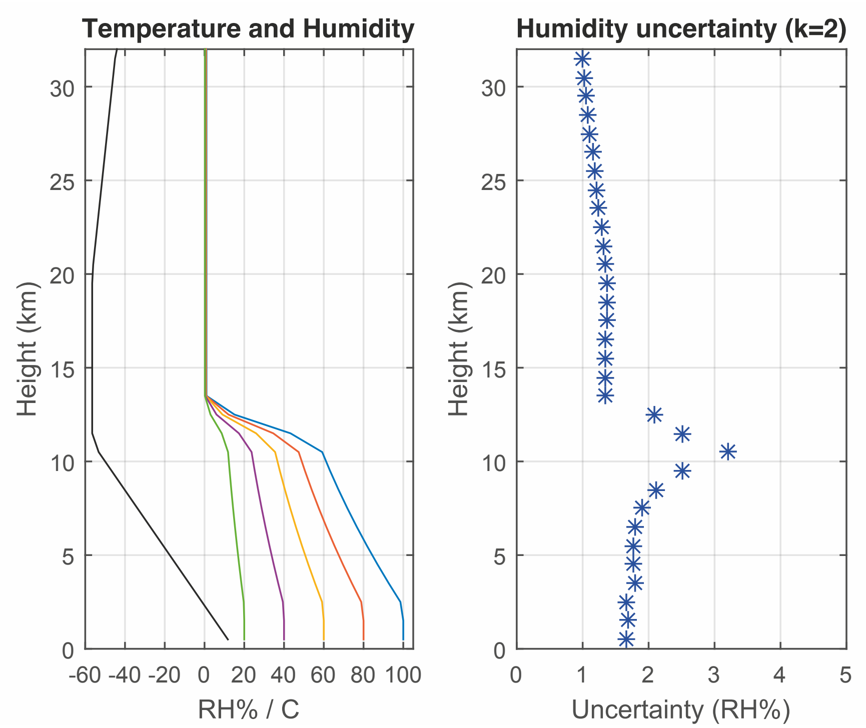

Figure 3.5. The combined measurement uncertainty of Vaisala Radiosonde RS41 humidity measurement (k=2). The uncertainty analysis model applied U.S. Standard Atmosphere 1976 temperature profile and a set of humidity profiles (left), and the resulting humidity measurement uncertainty (right).

3.3.4 Reproducibility in soundings

The reproducibility of the Vaisala Radiosonde RS41 humidity measurement has been analyzed in several sounding campaigns. As an example, the results from a sounding campaign carried out during summer 2013 in Finland are presented in **Figure 3.6** and the results from a campaign carried out in Malaysia in 2013 are shown in **Figure 3.7**. The data in both figures is from daytime twin-soundings in various weather conditions.

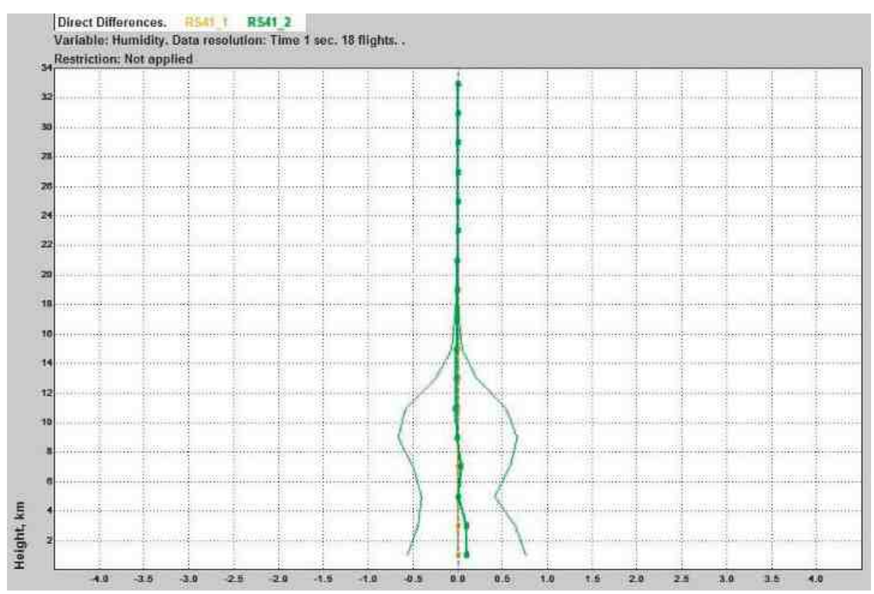

Figure 3.6. The reproducibility of humidity measurement in 18 daytime twin-soundings at high latitudes. The average differences of the two RS41 radiosondes is indicated by the bold line and the standard deviation of differences by the thin lines.

These results show that the standard deviation of measured humidity differences in sounding is typically less than 1% RH, and even in the most demanding cold and humid conditions of the tropical tropopause the reproducibility is better than 2% RH.

3.3.5 Comparison against reference instrument in sounding

The Vaisala Radiosonde 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 3.8**. 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

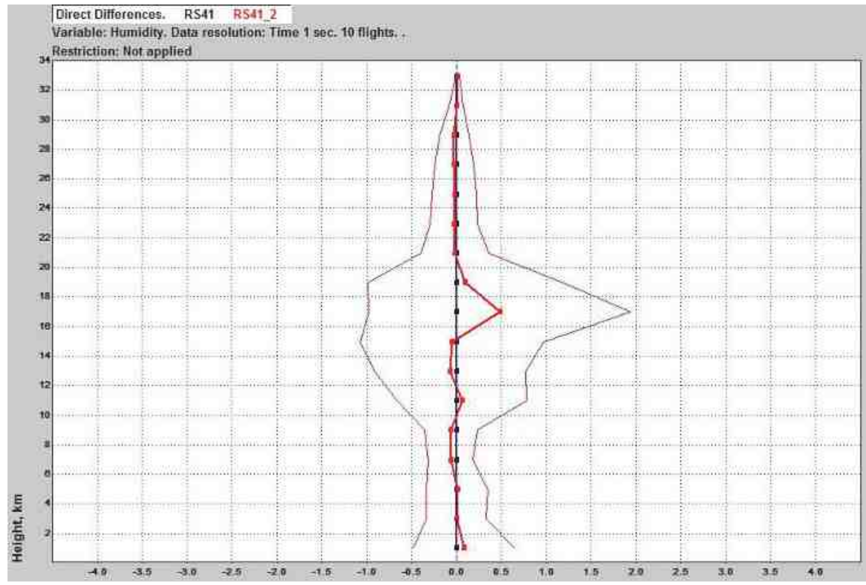

__Figure 3.7.__ The reproducibility of humidity measurement in ten daytime twin-soundings in the tropics.

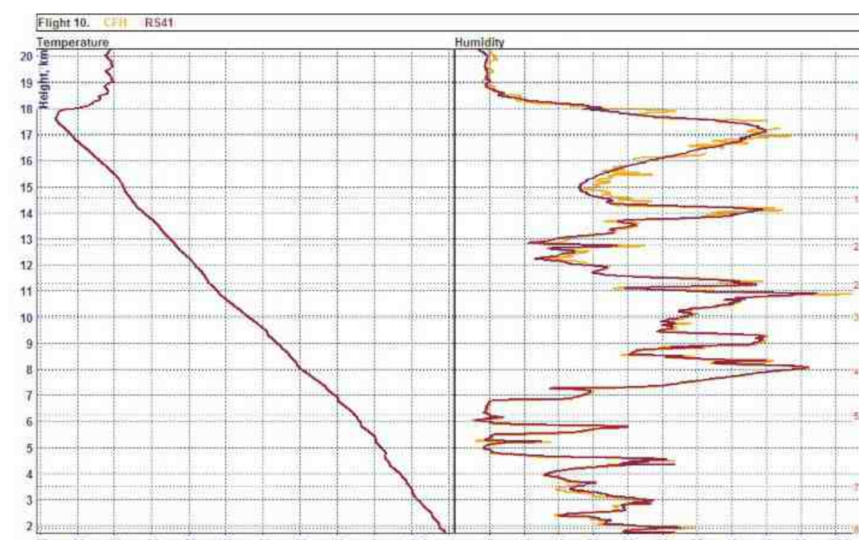

__Figure 3.8.__ An example of a sounding carried out in 2013 in Penang, Malaysia, against a CFH reference measurement. The figure shows relative humidity as measured by CFH (yellow) and the RS41 (brown).

CHAPTER 4

Geopotential Height Measurement

The Vaisala Radiosonde RS41 uses Global Positioning System (GPS) technology to provide high-quality height, pressure, wind, and horizontal location measurements. The GPS antenna is a robust, high-efficiency integrated antenna. The GPS receiver components have been selected to improve the tolerance of interference sources and to provide high measurement precision.

GPS signal processing is implemented in the Vaisala DigiCORA® Sounding System MW41 and is optimized for high performance in radiosonde applications. The algorithms include methods such as filtering designed for typical radiosonde ascent rates. Ionospheric modeling is used to minimize the impact of atmospheric effects on measurements.

This chapter summarizes the GPS-based geopotential height performance of the RS41 in terms of measurement reproducibility and combined uncertainty. The GPS-Based Measurement of Height and Pressure with Vaisala Radiosonde RS41 White Paper [3] provides a more detailed description of the RS41 GPS-based height and pressure measurement performance. The measurement performance of the pressure sensor in Vaisala Radiosonde RS41-SGP is described in the RS41-SGP Pressure Measurement Performance White Paper [4].

Geopotential Height Type	calculated using GPS
Measurement range	Ground level to 40,000 m*
Resolution	0.1 gpm
Accuracy	
Combined uncertainty in sounding	10.0 gpm
Reproducibility in sounding**	6.0 gpm

* In practice unlimited

** Standard deviation of differences (k=1) in twin-soundings

Table 4.1. *Geopotential height specifications*

4.1 Specifications

The following specifications for geopotential height are determined using expanded uncertainty (k=2), encompassing approximately 95% of the dispersion of the results.

4.2 Geopotential height measurement performance in sounding

4.2.1 Reproducibility in soundings

Two RS41-SG radiosondes were flown in the same rig to assess the reproducibility of measurements. Separate Vaisala GPS Antenna GA31 units followed the radiosondes. The antennas were installed an adequate distance from each other to ensure the measurements were not affected by the same multipath effects. Sounding campaigns were carried out in two locations, Malaysia (lat. 5° N) and Finland (lat. 60° N), to cover different satellite geometries and site environments. The standard deviation of the measured differences describes the sounding reproducibility.

Figure 4.1 shows the geopotential height results from all soundings. Performance is uniformly good at all heights, with average differences of 0–1 gpm and standard deviations of less than 6 gpm. **Figure 4.2** shows the differences in heights between two RS41-SG radiosondes during one sounding in Finland.

4.2.2 Combined uncertainty

The uncertainty analysis for geopotential height includes the following components:

- reproducibility in soundings
- tropospheric and ionospheric effects
- uncertainty in station-height settings

Reproducibility tests quantified random and uncorrelated errors coming mostly from the quality of the available satellite reception, the external RF environment, and receiver noise. The impacts of tropospheric and ionospheric effects were estimated as the uncertainties of corrections. The accuracy of the station-height settings was assumed to correspond to careful measurements, for example an accuracy of 0.3 m for the GPS antenna offset from barometer height.

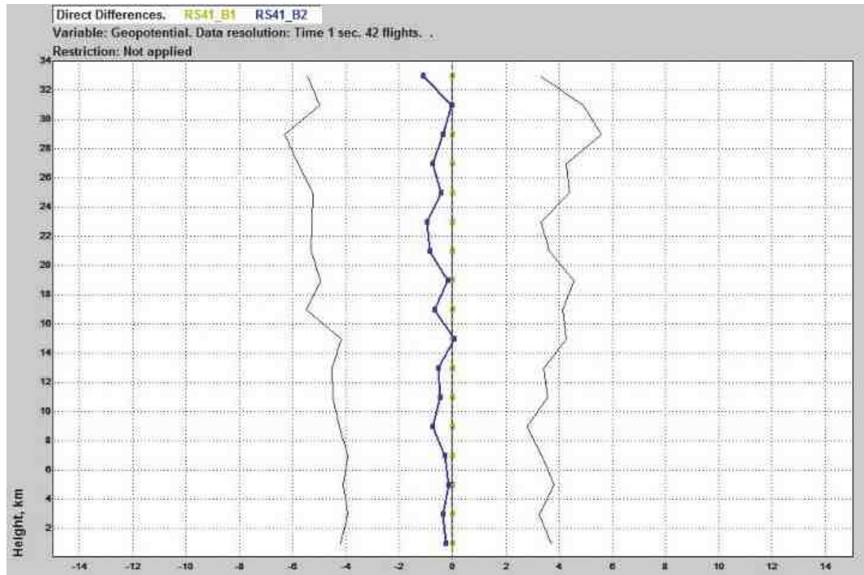

__Figure 4.1.__ Reproducibility of geopotential height measurements with RS41-SG radiosondes in 42 twin-soundings. Average differences are indicated by bold lines and standard deviations of differences by thin lines.

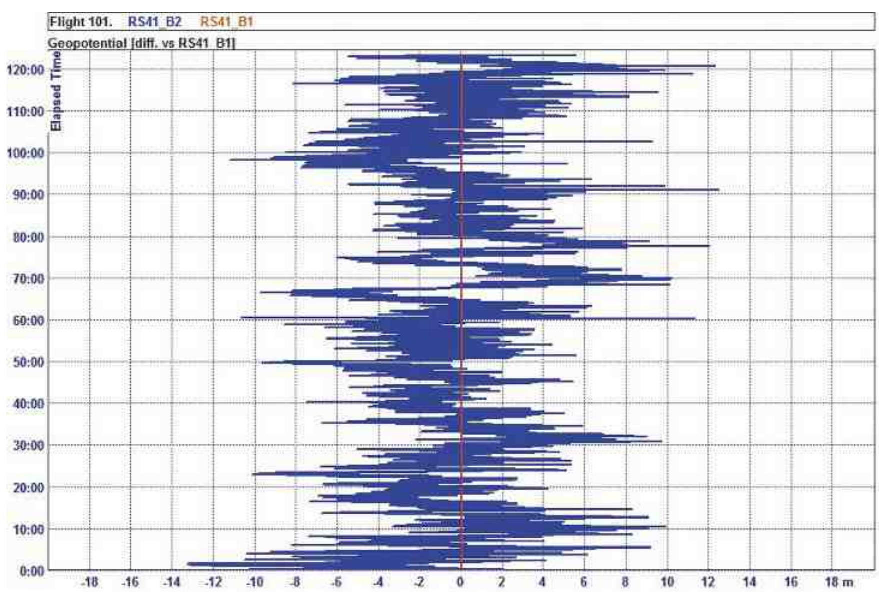

__Figure 4.2.__ Example of geopotential height differences between two RS41-SG radiosondes.

Figure 4.3 shows the combined uncertainty along with the uncertainty components. The results were evaluated through all height ranges. The combined uncertainty is fairly constant with respect to altitude, with a small increase at the highest altitudes due to atmospheric effects. The combined uncertainty results were used as a basis for the RS41-SG accuracy specified in Section 4.1.

4.2.3 Performance in RF-challenged conditions

This test series was carried out to test the performance of the Vaisala Enhanced Multipath Rejection Antenna GA41. Two separate antennas were used in twin-soundings in Malaysia and Finland. The height reproducibility results in **Figure 4.4** show that the GA41 performs excellently, with standard deviations 40% smaller than those demonstrated by GA31 (**Figure 4.1**).

While results with the Vaisala GPS Antenna GA31 were of sufficient quality at both measurement sites, the GA41 demonstrated improved reproducibility and higher resistance to external RF disturbances.

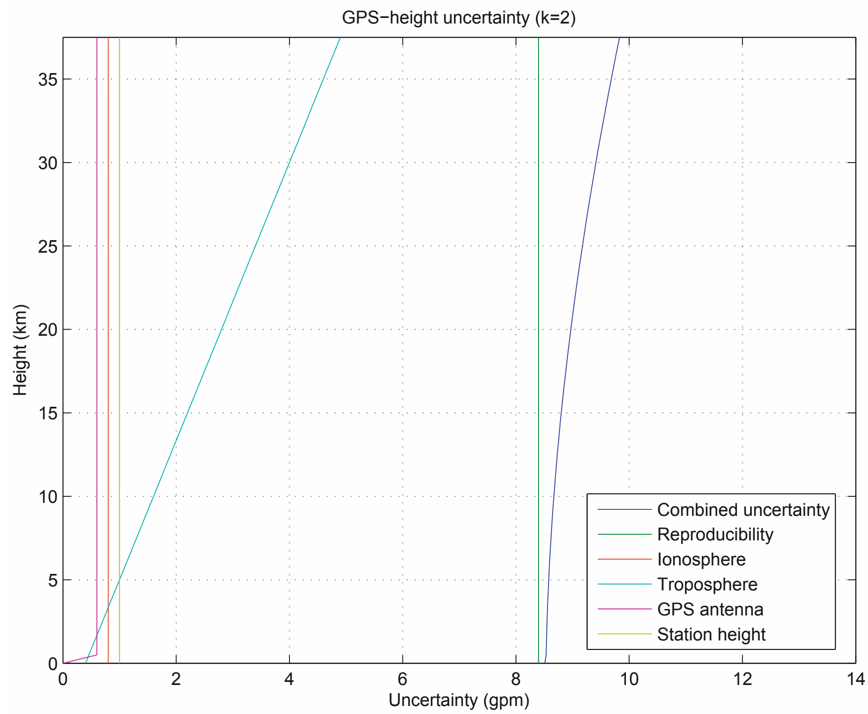

Figure 4.3. *Combined uncertainty (k=2) and main uncertainty components for GPS-based geopotential height measurements of the Vaisala Radiosonde RS41.*

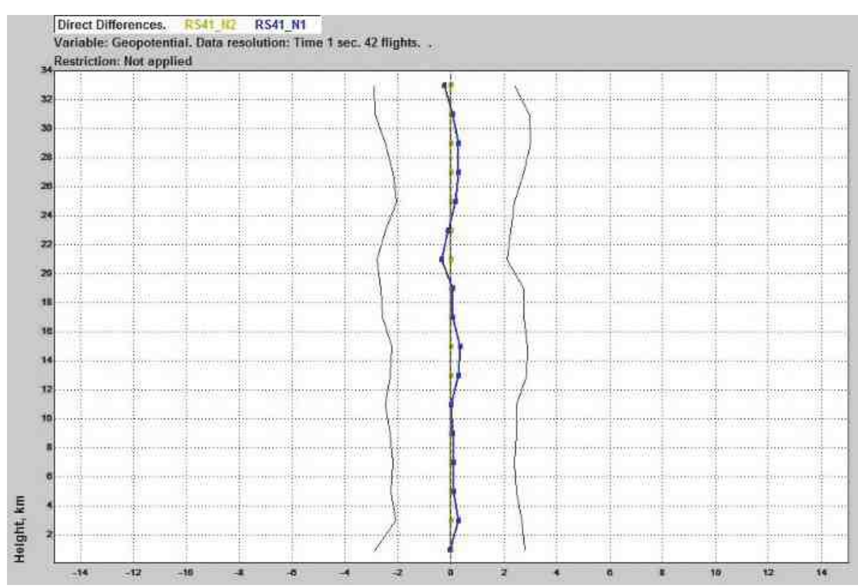

Figure 4.4. *Reproducibility of geopotential height measurements with RS41-SG radiosondes in 42 twin-soundings, using the Vaisala Enhanced Multipath Rejection Antenna GA41. Average differences are indicated by bold lines and standard deviations of differences by thin lines.*

CHAPTER 5

Pressure Measurement

The Vaisala Radiosonde RS41-SG uses a GPS-based measurement principle for high-quality atmospheric pressure measurements. Air density along the flight path varies according to temperature and humidity conditions. The radiosonde measures the change in pressure between each measurement point during the flight by observing these quantities and the change in vertical position. The vertical position and distance between measurement points are obtained from the GPS height measurement. This technique requires a pressure sensor at the sounding station to calibrate the observations in the pressure profile.

This chapter summarizes the atmospheric pressure performance of the RS41 in terms of measurement reproducibility and combined uncertainty. The GPS-Based Measurement of Height and Pressure with Vaisala Radiosonde RS41 White Paper [3] provides a more detailed description of the RS41's GPS-based height and pressure measurement performance. The measurement performance of the pressure sensor in Vaisala Radiosonde RS41-SGP is described in the RS41-SGP Pressure Measurement Performance White Paper [4].

5.1 Specifications

The following specifications for pressure measurement are determined using expanded uncertainty (k=2), encompassing approximately 95% of the dispersion of the results.

Pressure Type		calculated using GPS
Measurement range		surface pressure to 3 hPa
Resolution		0.01 hPa
Accuracy		
Combined uncertainty / Reproducibility in sounding**		
	> 100 hPa	1.0 hPa / 0.5 hPa
	100 – 10 hPa	0.3 hPa / 0.2 hPa
	<10 hPa	0.04 hPa / 0.04 hPa

** Standard deviation of differences (k=1) in twin-soundings

Table 5.1. *Pressure measurement specifications.*

5.2 GPS-derived pressure measurement performance in sounding

5.2.1 Reproducibility in soundings

Figure 5.1 shows the reproducibility of GPS-based pressure measurements between two RS41-SG radiosondes. Sounding campaigns were carried out in two locations, Malaysia (lat. 5° N) and Finland (lat. 60° N). The results agree with the reproducibility of geopotential height, which is the dominant factor in pressure accuracy. The random differences in pressure decrease rapidly as a function of altitude, following the exponential decrease in atmospheric pressure. Observed standard deviations were 0.4 hPa near the ground and <0.04 hPa at altitudes above 30 km.

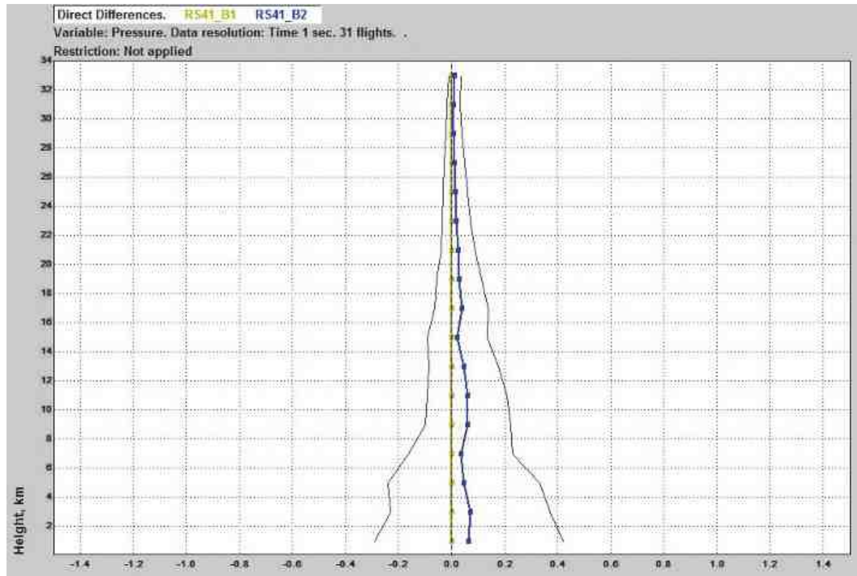

Figure 5.1. *Reproducibility of pressure measurements with RS41-SG radiosondes in 31 twin-soundings. Average differences are indicated by bold lines and standard deviations of differences by thin lines.*

5.2.2 Combined uncertainty

The uncertainty analysis for pressure includes the following components:

- GPS-based geopotential height
- radiosonde temperature and humidity measurements
- accuracy of surface pressure measurements

The impacts of these factors were modeled using custom analysis software that uses different atmospheric models, and even different scenarios of solar angles, to estimate the pressure uncertainties along the sounding trajectory. According to the analysis, the effects of environmental conditions are small, with geopotential height being the dominant factor.

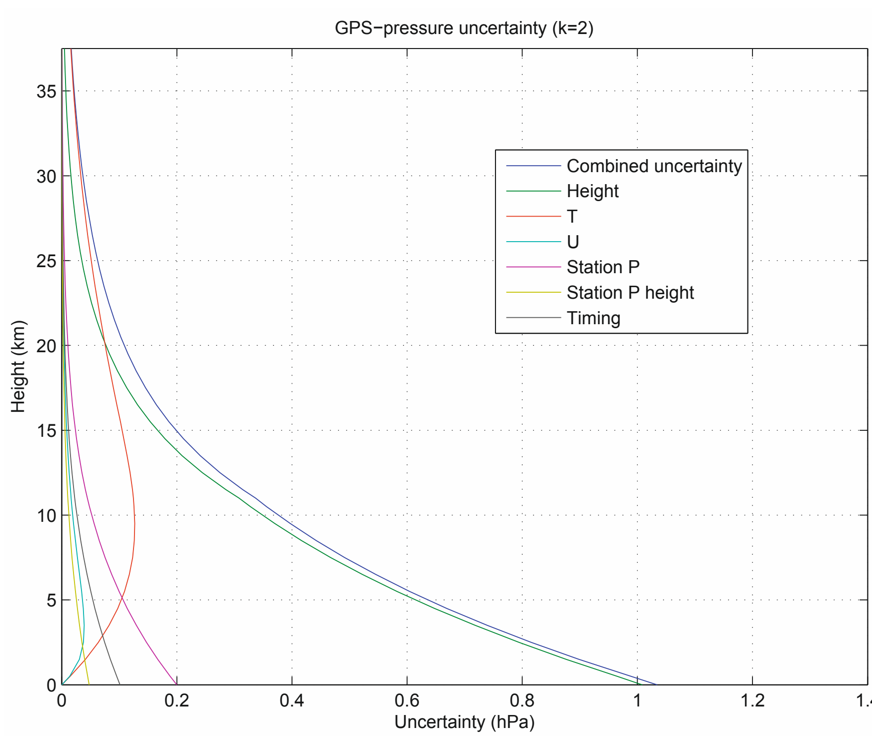

Figure 5.2. *Combined uncertainty (k=2) and main uncertainty components for GPS-based pressure measurements of the Vaisala Radiosonde RS41, evaluated assuming the ISA standard atmosphere for pressure and temperature.*

Figure 5.2 shows the combined uncertainty along with the uncertainty components. The uncertainty decreases as a function of altitude, corresponding to the exponential decrease in atmospheric pressure. The combined uncertainty results were used as a basis for the RS41-SG accuracy specified in Section 5.1.

CHAPTER 6

Wind Measurement

The Vaisala Radiosonde RS41 uses GPS technology for high-quality wind speed and direction measurements. The Vaisala DigiCORA® Sounding System MW41 calculates results using custom signal processing.

6.1 Specifications

The following specifications for wind speed and direction are determined from the standard deviation of differences in twin-soundings, encompassing approximately 68% of the dispersion of the results. Directional measurement uncertainty applies for wind speed above 3 m/s.

6.2 Wind measurement performance at ground level

In the test, the RS41 radiosonde was attached to a fixed position near the ground, and measurements were taken over a period of several hours in order to evaluate GPS wind-measurement performance. **Figure 6.1** shows that GPS wind components are within 0.05 m/s (k=2) of the expected 0.0 m/s wind result.

Wind Speed	
Velocity measurement uncertainty	0.15 m/s
Resolution	0.1 m/s
Maximum reported wind speed	160 m/s
Wind Direction	
Directional measurement uncertainty	2 deg.
Resolution	0.1 deg.
Wind direction range	0 to 360 deg.

Table 6.1. *Wind measurement specifications.*

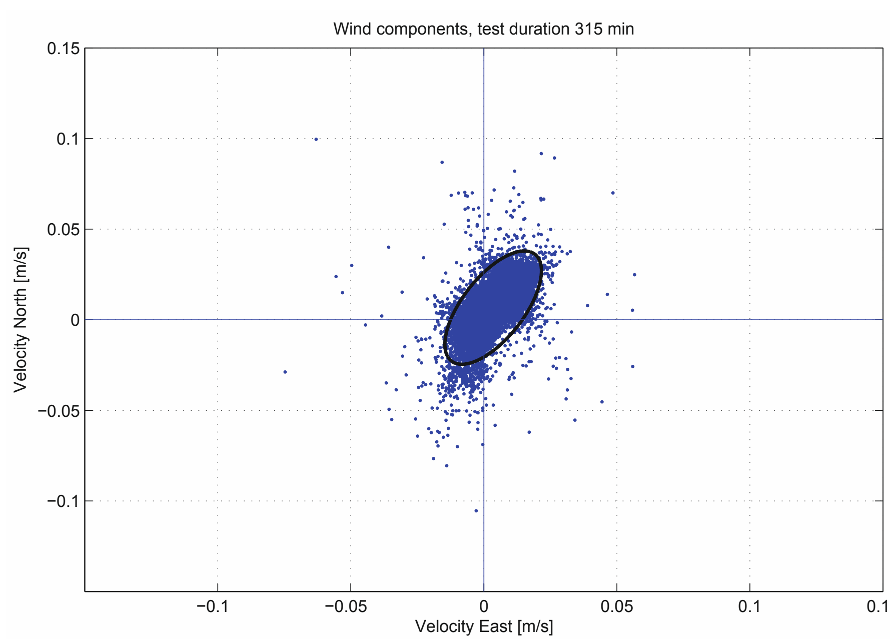

Figure 6.1. *Horizontal wind components during zero-wind test and ellipse of 95% confidence for wind speed.*

6.3 Wind measurement performance in sounding

Figures 6.2 and **6.3** show the reproducibility of GPS-based wind speed and direction, respectively, between two RS41-SG radiosondes in the sounding campaigns. The reproducibility for wind speed is < 0.15 m/s and for wind direction < 2° (for wind speeds > 3.0 m/s).

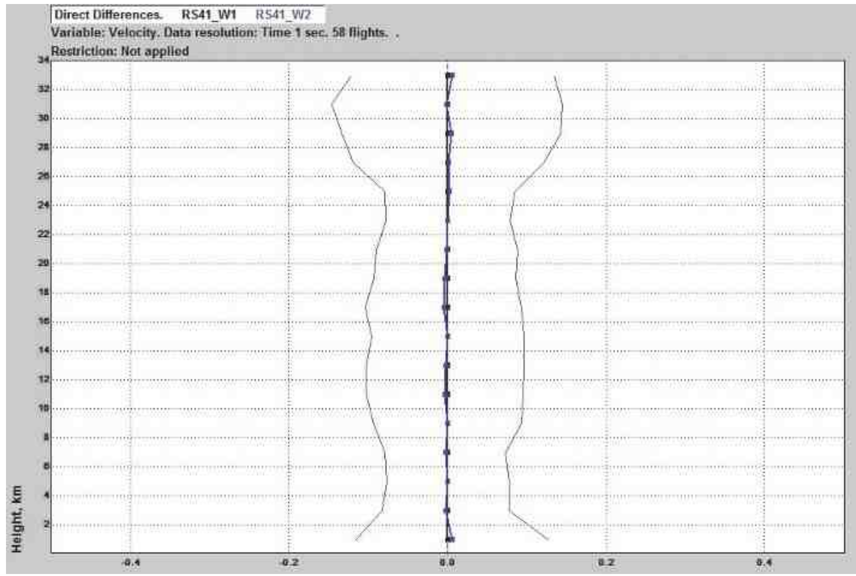

Figure 6.2. *Reproducibility of wind speed measurements with RS41-SG radiosondes in 58 twin-soundings. Average differences are indicated by bold lines and standard deviations of differences by thin lines.*

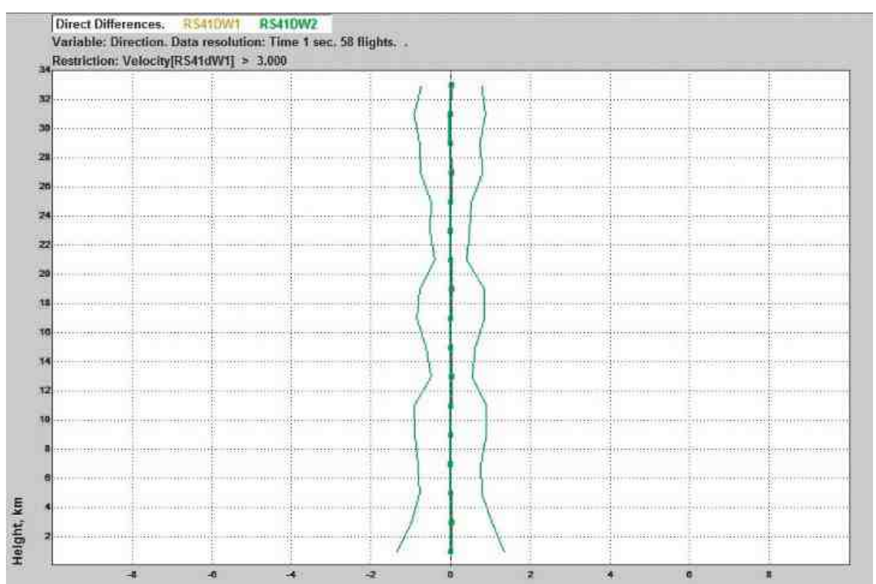

Figure 6.3. *Reproducibility of wind direction measurements with RS41-SG radiosondes in 58 twin-soundings, for wind speeds > 3 m/s.*

CHAPTER 7

Data Continuity

Climate change is a pressing scientific problem and a major worldwide societal and political challenge. Fundamental to all facets of the climate debate is the need for an extremely accurate, precise, and representative record of atmospheric changes – especially temperature, water vapor, and precipitation, which need to be measured over multi-decadal timescales and on geographical scales ranging from local to regional and global [8].

In addition to introducing more precise instruments for operational and research use, it is imperative to guarantee continuity of observation datasets. Accordingly, Vaisala has established a public, web-based database that will provide radiosonde-related information to facilitate the homogenization of climatological time series [8].

All relevant changes in sensor design, procedures, and related software have been documented on Vaisala's website, www.vaisala.com, since the launch of the RS92 radiosonde in 2003 [9].

7.1 Data continuity following the replacement of RS92 with RS41

The impact of the switch from the RS92 to the RS41 on climatological time series is estimated to be moderate. The improved accuracy of RS41 data does not affect average measurement values as much as it affects the consistency or reproducibility of the data. So far, tests indicate that the most significant impact on average values will be seen in humidity measurements of the tropical climates, especially in the humid conditions of the upper troposphere.

The statistical differences between the RS92 and RS41 are described in Comparison of Vaisala Radiosondes RS41 and RS92 [2] using experimental sounding results. The information will also be made available at vaisala.com to ensure easy and open access to this important metadata for end users.

7.2 Data continuity with RS41 in operational use

Vaisala intends to offer the best possible tools for climate research, including accurate measurement instruments with carefully estimated uncertainty budgets, as well as tools and metadata for managing data continuity.

Vaisala will announce all changes to the RS41 product that could affect the homogeneity of climatological data series on vaisala.com.

APPENDIX I

Definitions of terms related to measurement performance analysis

The definitions presented here are quoted from JCGM/WG_1, 2008, Evaluation of measurement data – Guide to the expression of uncertainty in measurement. Illustrative notes have been adapted to ensure a clearer fit with the context of this white paper and also for brevity.

Accuracy of a measurement: closeness of the agreement between the result of a measurement and a true value of the measurand.

NOTE. "Accuracy" is a qualitative concept.

Uncertainty of a measurement: a parameter – associated with the result of a measurement – that characterizes the dispersion of the values that could reasonably be attributed to the measurand.

NOTE 1. In this document the parameter is standard deviation, as is typically the case.

NOTE 2. Uncertainty of measurement comprises many components, thus the term **combined uncertainty** is sometimes used.

NOTE 3. It is understood that the result of the measurement is the best estimate of the value of the measurand, and that all components of uncertainty contribute to the dispersion.

Expanded uncertainty: a quantity defining an interval about the result of a measurement that may be expected to encompass a large fraction of the distribution of values that could reasonably be attributed to the measurand.

NOTE. For the uncertainties presented in this document, an expanded uncertainty with a coverage factor of k=2 is used. In practice this encompasses approximately 95% of the distribution of the results.

Coverage factor (k): the numerical factor used as a multiplier of the combined standard uncertainty in order to obtain an expanded uncertainty.

Repeatability of results of measurements: closeness of the agreement between the results of successive measurements of the same measurand carried out under the same conditions of measurement.

Reproducibility of results of measurements: closeness of the agreement between the results of measurements of the same measurand carried out under changed conditions of measurement.

NOTE. In this document the changed condition is the measuring instrument unit, which is in accordance with the definition.

Correction: the value added algebraically to the uncorrected result of a measurement to compensate for systematic error.

NOTE. Since systematic error cannot be accurately determined the compensation cannot be complete, thus some uncertainty is still associated with each correction.

APPENDIX II

Standards and recommendations

The Vaisala Radiosonde RS41-SG is fully compliant with the following standards and recommendations:

1. Recommendations for radiosonde accuracy defined in Annex 12.A of the 2014 revision of the WMO Guide to Meteorological Instruments and Methods of Observation [1].
2. ETSI EN 302 054-1 V1.1.1 (2003-03) and ETSI EN 302 054-2 V1.1.1 (2003-03), European ETSI standard for digital radiosondes operating in the 400 MHz band.
3. ETSI EN 301 489-1 V1.9.2 (2011-09), Electromagnetic compatibility and Radio spectrum Matters (ERM); ElectroMagnetic Compatibility (EMC) standard for radio equipment and services; Part 1: Common technical requirements.
4. Waste Electrical and Electronic Equipment Directive (WEEE) 2002/96/EC.
5. RoHS Directive 2011/65/EC.
6. SJ/T11364-2006 Marking for Control of Pollution Caused by Electronic Information Products (China RoHS).
7. Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH) EC 1907/2006.
8. The batteries supplied with the RS41-SG fulfill the European Battery Directive 2006/66/EC and the UN ST/SG/AC.10/27/Add.2 Transport of Dangerous Goods standard Part III, subsection 38.3 pertaining to lithium batteries.
9. UN3091 regulations of IATA Dangerous Goods Regulations, 54th edition, 2013.
10. Rules of the Air, ICAO Annex 2 to the Convention on International Civil Aviation, 10th edition, 2005, Appendix 4: Unmanned Free Balloons.

References

[1] WMO Guide to Meteorological Instruments and Methods of Observation, WMO Guide 8 Edition 2014.

[2] Comparison of Vaisala Radiosondes RS41 and RS92 White Paper.

[3] GPS-based Measurement of Height and Pressure with Vaisala Radiosonde RS41 White Paper.

[4] Vaisala Radiosonde RS41-SGP Pressure Measurement Performance White Paper.

[5] JCGM 100:2008, Evaluation of Measurement Data – Guide to the Expression of Uncertainty in Measurement.

[6] EA-4/02, M, 1999, Expression of the Uncertainty of Measurement in Calibration.

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