GPS-Based Measurement of Height and Pressure with Vaisala Radiosonde RS41

WHITE PAPER

Table of Contents

CHAPTER 1

CHAPTER 2

CHAPTER 3

CHAPTER 4

CHAPTER 5

CHAPTER 6

CHAPTER 1

Introduction

The purpose of this document is to introduce GPS-based height and atmospheric pressure measurements with Vaisala RS41 GPS radiosondes and the Vaisala DigiCora® Sounding System MW41.

The Global Positioning System (GPS) is a global navigation satellite system (GNSS) that provides accurate height and time estimates from satellites orbiting the Earth. GPS observations of wind, height, and horizontal location have been used in radiosounding since the 1990s. Furthermore, atmospheric pressure can be derived from both GPS height and radiosonde temperature and humidity observations. The GPS-based pressure measurement method has been validated in WMO intercomparisons in Mauritius in 2005 [1] and Yangjiang in 2010 [2], and has been available in Vaisala radiosondes since the launch of the RS92 series.

The Vaisala Radiosonde RS41 provides high-quality GPS-based height and pressure measurements. This white paper gives an overview of the measurement methods and GPS technology used in the RS41, along with an analysis of the measurement performance. Performance is compared to silicon pressure sensor and GPS-based measurements from the Vaisala Radiosonde RS92. This paper also provides technology recommendations for different environments and applications, as well as for successful transition to the RS41 from RS92-series radiosondes.

GPS wind measurement performance and other RS41 measurements are described in a separate document [3].

Executive Summary of Measurement Performance

The accuracy of RS41-SG height and pressure measurements was evaluated using a comprehensive uncertainty analysis. The method was based on the recommended evaluation of measurement data described in JCGM 100:2008 [4], and used theoretical estimates and performance tests in different geographical locations.

Table 1 presents a summary of the performance of RS41-SG, with height expressed in geopotential meters (gpm). The height range where the results are valid is unlimited in balloon soundings. RS41-SG radiosondes obtain a good level of reproducibility for both height and pressure, which demonstrates the solid performance of the GPS design and algorithms.

Table 2 compares the performance with that of the RS92-SGP radiosonde. GPS-based observations in RS41-SG and pressure sensor observations in RS92-SGP compare well with small height differences in standard pressure levels.

Measurement	RS41 accuracy	RS41 reproducibility
	Combined uncertainty with k=2 confidence level (95.5%)	Standard deviation of differences in twin soundings (n=42)
Geopotential height	10 gpm	< 6 gpm
Pressure		
> 100 hPa	1 hPa	< 0.5 hPa
100 – 10 hPa	0.3 hPa	< 0.2 hPa
< 10 hPa	0.04 hPa	< 0.04 hPa

Table 1. *Summary of GPS-based geopotential height and atmospheric pressure measurements with RS41 radiosonde. Reproducibility results are from sounding campaigns in Malaysia (lat. 5° N) and Finland (lat. 60° N).*

Standard pressure level	RS41 - RS92 average differences in height	RS41 - RS92 standard deviation of differences in height
	GPS-based height and pressure in RS41, sensor-based in RS92 (n = 20)	
850 hPa	-0.2 gpm	2.1 gpm
100 hPa	5.5 gpm	4.9 gpm
20 hPa	-0.6 gpm	7.8 gpm

Table 2. *Differences in standard pressure level heights of 850, 100, and 20 hPa between RS41 and RS92 radiosondes.*

CHAPTER 2

GPS Technology in the Vaisala Radiosonde RS41

Radiosonde GPS Receiver

The Vaisala RS41 GPS receiver has a new design compared with the Vaisala RS92 series. The receiver consists of the antenna, RF front-end, and the GPS chip. The GPS antenna is a robust, high-efficiency integrated antenna. The GPS receiver components have been selected to improve tolerance of interference sources and to provide high measurement precision. RS41 radiosonde models equipped with code-correlating GPS use the public C/A code in the L1 frequency (1575.42 MHz). The performance of the RS41 GPS receiver has been extensively tested and performs similarly to the RS92 series, as detailed in Table 3.

Typical time to first satellite tracking after cold start is 35 seconds. However, due to the high sensitivity of the receiver, the RS41 usually also finds some GPS signals indoors during sounding preparation, which shortens the time to proper satellite tracking.

Test site	**Test site**		**Malaysia**	
Radiosonde type	RS41	RS92	RS41	RS92
Number of radiosondes used	118	28	57	10
Average number of satellites tracked	11.3	10.9	11.3	10.9
Average number of satellites used	8.6	8.7	8.9	9.0
GPS availability	99.99%	99.95%	99.99%	99.87%

Table 3. *Comparison of RS41-SG and RS92-SGP GPS performance in sounding campaigns in Finland and Malaysia.*

Local GPS Receiver

The Vaisala DigiCora® Sounding System MW41 includes a GPS receiver with a local GPS antenna at the station. The GPS receiver setup is identical to that of the MW31, reducing the need for hardware upgrades at existing sounding stations. The antenna is a Vaisala GPS Antenna GA31 [5], which meets the specified height and GPS-based pressure measurement performance requirements of most installation sites.

Some installation sites present challenges for GPS-based measurements in terms of multipath propagation or other radio frequency disturbances. It is advisable that these sites upgrade to a Vaisala Enhanced Multipath Rejection Antenna GA41 [6]. For more information, see Chapter 6.

Calculation Algorithms

The Vaisala Sounding System MW41 uses custom signal processing for location and GPS-based pressure and wind measurements. Vaisala has optimized the algorithms for radiosonde applications. High-quality height measurements are essential for accurate atmospheric pressure observations.

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 measurement. In addition, fixed stations combine GPS measurements from the radiosonde and the local GPS receiver to produce differential GPS corrections. These eliminate many common GPS positioning errors.

CHAPTER 3

GPS-Based Measurement Methods

Height Measurement

The GPS receiver calculates the location of the radiosonde using timing and position information received from GPS satellites. Each satellite generates a unique pseudo random code containing the transmission time and satellite position. The GPS receiver calculates the time differences between the transmission and reception of the coded messages and, multiplying by the speed of light, determines the so-called “pseudorange” distances between the radiosonde and satellites. Pseudoranges from four or more satellites are required to obtain the horizontal and vertical position of the radiosonde.

Raw GPS height is expressed relative to the WGS 84 reference ellipsoid model of the Earth. This value is then converted to express height from local mean sea level (MSL), specified in WGS 84 using the EGM96 Earth geoid model. MSL height is also converted into geopotential height, which adjusts the MSL height to compensate for gravity variation with latitude and elevation. It is expressed in geopotential meters (gpm). The difference between the two is negligible, especially in the lower atmosphere. Geopotential height is the height reported by the radiosonde in TEMP and BUFR messages.

Pressure Measurement

Atmospheric pressure is equivalent to the force per unit of area exerted on the Earth’s surface by the weight of the air column above the surface. It is an important component in meteorology and other atmospheric sciences.

The RS41-SG uses a GPS-based measurement principle for estimating the atmospheric pressure. This technique requires a pressure sensor at the sounding station. The pressure-sensor value calibrates all observations in the pressure profile. It is very important to use a properly calibrated reference pressure sensor. Station height parameters, including the height of the pressure sensor and the height of the local GPS antenna, are also essential factors in the calculation. The MW41 system enables configuration of these height parameters via a convenient graphical interface.

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. The vertical position and distance between measurement points are obtained from the GPS height measurement. The magnitude of the change, δP, can then be derived e.g. from hydrostatic equation and ideal gas law,

$$\frac{\delta P}{P} = -\frac{g \cdot \delta Z}{R_a \cdot Tv}$$

where P is pressure, g is the gravity constant, δZ is the change in geopotential height, R_a is the gas constant for dry atmosphere, and Tv is the virtual temperature. The virtual temperature of moist air is the temperature that dry air should have in order to have the same pressure and density as moist air. The calculation is illustrated in Figure 3.1. Air pressure contributions over each layer are added up from ground level to obtain the pressure at the measurement height.

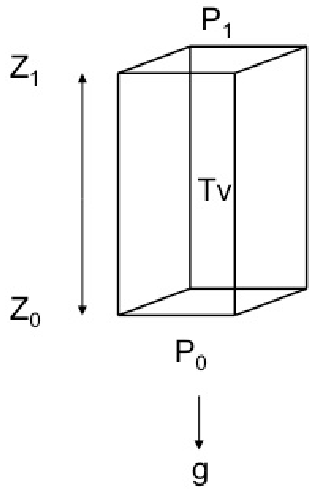

Figure 3.1. *Calculating atmospheric pressure at the top of an air layer.*

Measurement Accuracy

GPS measurements have a high accuracy, determined by the GPS receiver quality and the geometry and availability of GPS satellites. Errors in the location may be caused by various factors, including atmospheric disturbances. The impact of these factors can be reduced, for example using modeling and differential corrections. The RF environment is more challenging when the radiosonde is flying close to the ground, where reflections and diffractions of GPS signals may cause multipath propagation. GPS height estimates are typically less accurate than horizontal location estimates, but vertical accuracy of 10 m or less is obtainable in most conditions with the Vaisala Radiosonde RS41, which is sufficient for radiosonde applications.

GPS-based radiosonde pressure accuracy is almost entirely determined by height accuracy. The relation between the two is illustrated in **Figure 3.2**. Other factors include the accuracy of the surface pressure and the radiosonde temperature measurements. **Figure 3.2** show the effect of temperature bias in different conditions.

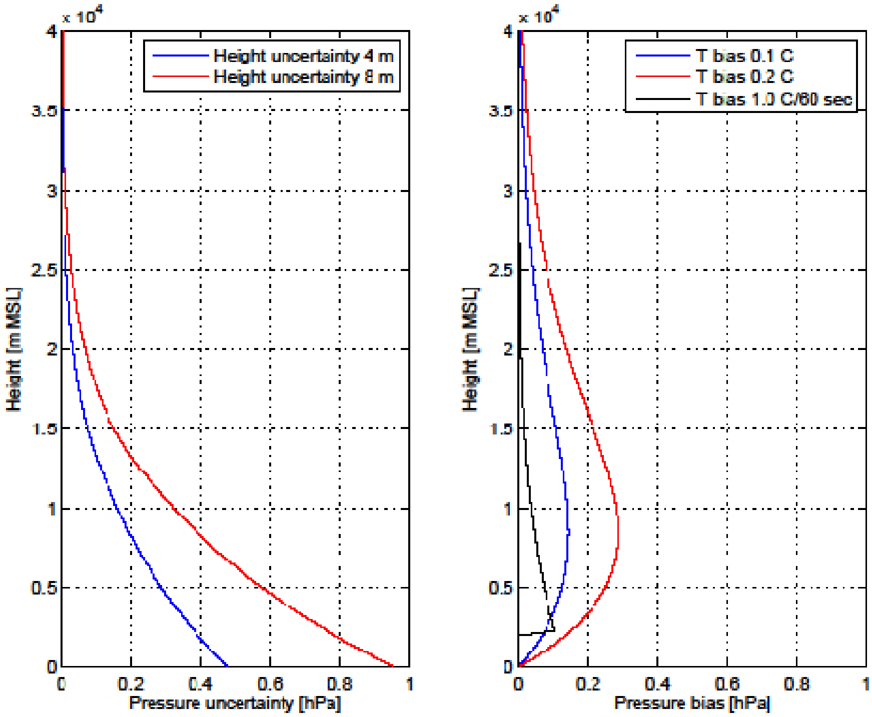

Figure 3.2. *1) Impact of height measurement uncertainty on pressure. 2) Impact of persistent temperature errors (=bias) on pressure. Results were calculated using the ISA standard atmosphere model.*

A persistent bias of 0.1 – 0.2 °C causes a small error of up to 0.15 – 0.3 hPa in the pressure profile. A short period (60 sec) bias of 1.0 °C in lower troposphere causes an error of around 0.1 hPa. The accuracy of station-height settings (station altitude, GPS antenna, and barometer heights) also contributes to measurement accuracy.

CHAPTER 4

Performance of Vaisala Radiosonde RS41

Method of Evaluation

The accuracy of the RS41-SG height and pressure measurements was evaluated using a comprehensive uncertainty analysis. The analysis was based on results from rig soundings, factory tests of GPS reception quality, and theoretical estimates of other contributors.

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 test site in Malaysia had a metal sheet roof and other structures in the vicinity of the antennas. The Finland site had some metal structures in the vicinity of the antennas.

The combined uncertainty of measurement was estimated in different conditions and through the full radiosounding height range. The analysis follows the principles in JCGM 100:2008 [4], and is explained in more detail in the RS41 performance document [3]. Statistical analyses and radiosonde comparison results were processed using RSKOMP Radiosonde Comparison Software [7].

Height

Reproducibility in Soundings

Two RS41-SG radiosondes were flown in the same rig to assess the reproducibility of measurements. Separate GA31 local GPS antennas 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. 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.

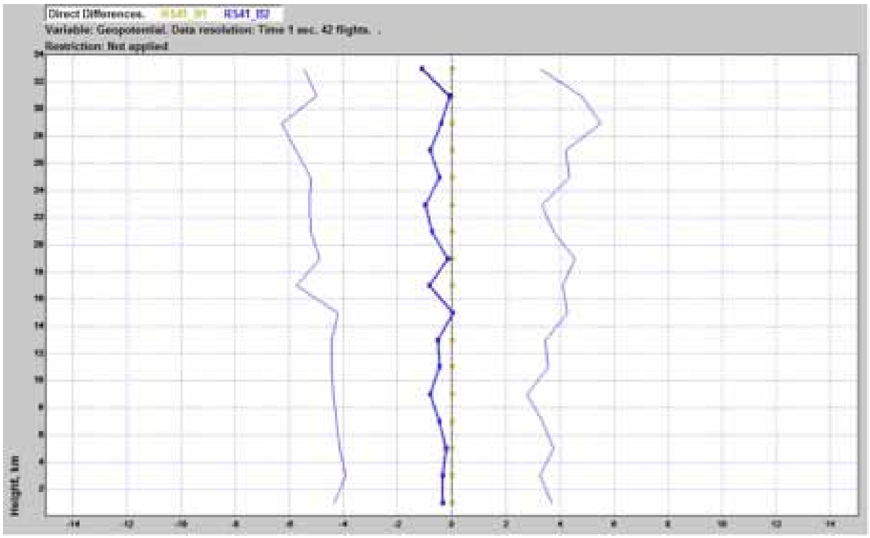

Figure 4.1. *Results of geopotential height comparison between two RS41-SG radiosondes in 42 flights. Showing average differences and standard deviation of differences (thin lines).*

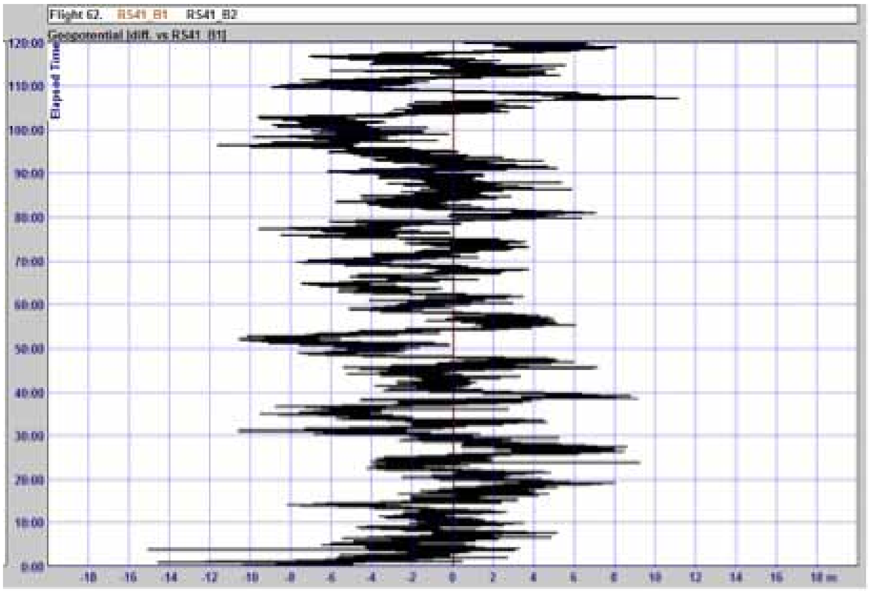

Figure 4.2. *Example of geopotential height differences between two RS41-SG radiosondes.*

Comparison with Vaisala Radiosonde RS92

RS41-SG radiosondes were compared to RS92-SGP radiosondes flying in the same rig. The RS92-SGP provides both GPS-based and sensor-based pressure and height measurements.

Figure 4.3 compares geopotential heights between the RS41 and RS92 when both radiosondes measured with GPS. Although the GPS receivers are different, they are similar in performance, and the RS41 uses an updated version of the GPS calculation algorithm. The geopotential height results show small average differences of 2 gpm or less, and standard deviations of 6 gpm or less for heights above the first two kilometers.

Figure 4.4 compares GPS-based heights from the RS41 with sensor-based heights from the RS92. The average differences are 0.9 gpm with standard deviations of 4.9 gpm at 0–2 km above ground. The good agreement indicates that the RS41 GPS algorithms handle the lowest heights well. The GPS-calculated lowest heights in the RS92-SGP varied more compared to the sensor reference.

The differences increase at higher altitudes due to differences in the measurement principles and the lower accuracy of the RS92 sensor observations at low pressures. However, standard pressure level heights are in excellent agreement, as shown in **Table 2 in Chapter 1**. The reproducibility comparisons in **Table 4** show that the GPS method produces a highly repeatable observation compared to the pressure-sensor method.

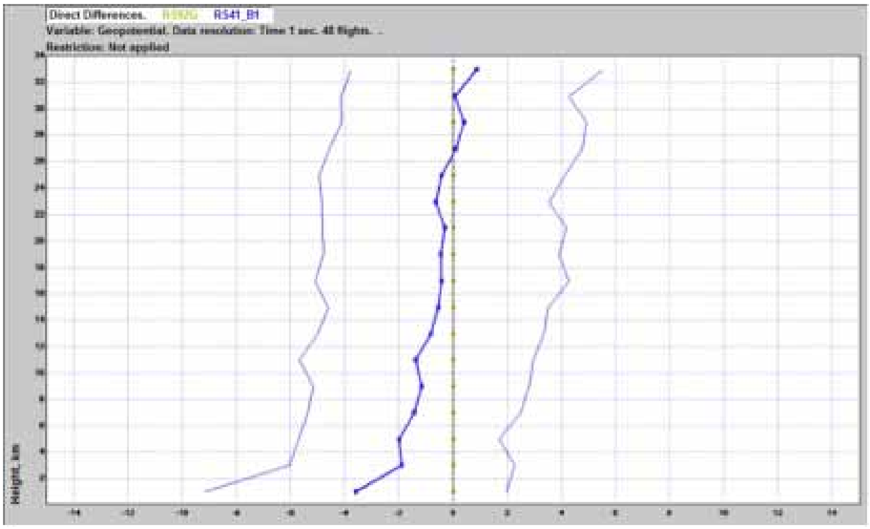

Figure 4.3. *Comparison of GPS-based geopotential heights between the RS41-SG and RS92-SGP radiosondes, using the RS92-SGP as the reference. Showing average differences and standard deviation of differences (thin lines) from 48 flights.*

Figure 4.4. *Comparison of GPS-based geopotential height with the RS41 and sensor-based geopotential height with the RS92 radiosonde, using the RS92 as the reference. Showing average differences and standard deviation of differences (thin lines) from 45 flights.*

Combined Uncertainty

The uncertainty analysis for geopotential height considered 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 impact of tropospheric and ionospheric effects was estimated as the uncertainty of applied 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 4.5 shows the combined uncertainty along with the uncertainty components. The results were evaluated through all height ranges. The combined uncertainty is fairly constant, with a small increase at the highest heights due to atmospheric effects. The combined uncertainty results were used as a basis for the specified RS41-SG accuracy shown in **Table 1**.

Standard pressure level	RS41 reproducibility of height	RS92 reproducibility of height
	Standard deviation of differences in twin soundings using GPS-based pressure and height (n=20)	Standard deviation of differences in twin soundings using sensor-based pressure and height (n=20)
850 hPa	1.3 gpm	1.9 gpm
100 hPa	2.8 gpm	9.3 gpm
20 hPa	7.8 gpm	14.9 gpm

Table 4. *Reproducibility of standard pressure level heights of 850, 100, and 20 hPa with RS41 and RS92 radiosondes. Results are from 20 flights.*

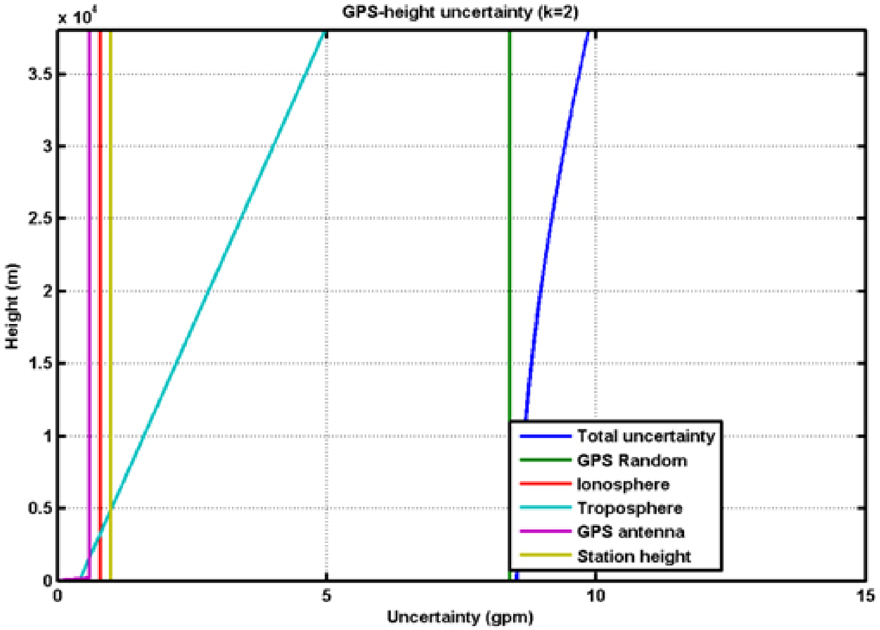

Figure 4.5. *Combined uncertainty (k=2) and main uncertainty components for GPS-based geopotential height measurements in the RS41-SG radiosonde.*

Performance in RF-Challenged Conditions

This test series was carried out to test the Enhanced Multipath Antenna GA41. Two separate antennas were used in twin soundings in Malaysia and Finland. The height reproducibility results in **Figure 4.6** show that the antenna type performs excellently, with standard deviations 40% smaller than with the GA31 (**Figure 4.1**). The example in **Figure 4.7** shows the difference in heights between two RS41-SG radiosondes during one sounding in Malaysia.

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.

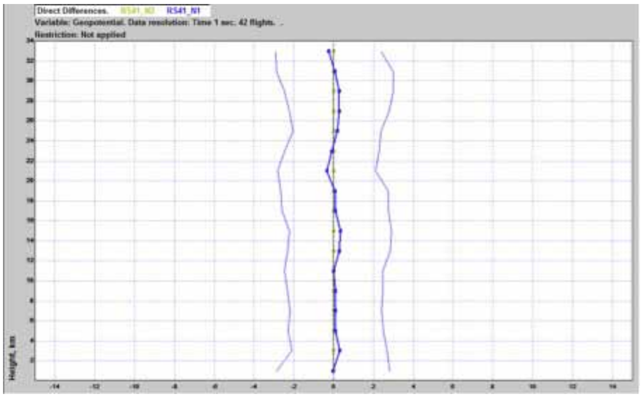

Figure 4.6. *Results of geopotential height comparison between two RS41-SG radiosondes in 42 flights, using the Vaisala Enhanced Multipath Antenna GA41. Showing average differences and standard deviation of differences (thin lines).*

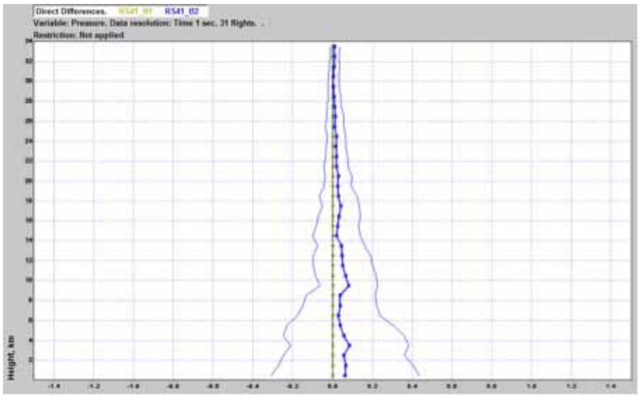

Figure 4.8. *Results of pressure comparison between two RS41-SG radiosondes in 31 flights. Showing average differences and standard deviation of differences (thin lines).*

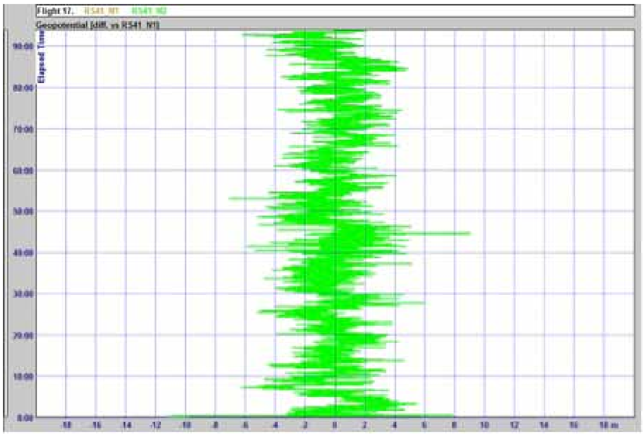

Figure 4.7. *Example of geopotential height differences between two RS41-SG radiosondes, using the Vaisala Enhanced Multipath Antenna GA41.*

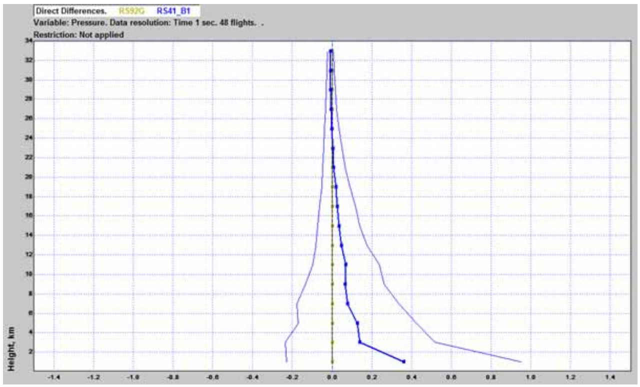

Figure 4.9. *Comparison of GPS-based pressure measurements between RS41 and RS92 radiosondes, using the RS92-SGP as the reference. Showing average differences and standard deviation of differences (thin lines) from 48 flights.*

GPS-Based Pressure

Reproducibility in Soundings

Figure 4.8 shows the reproducibility of GPS-based pressure measurements between two RS41-SG radiosondes. The results agree with the reproducibility of geopotential height, which is the dominant factor in pressure accuracy. The random differences decrease rapidly as a function of altitude, following the exponential decrease in atmospheric pressure. Observed standard deviations were 0.4 hPa near ground and <0.04 hPa at above 30 km.

Comparison with Vaisala Radiosonde RS92

Figure 4.9 compares atmospheric pressure measurements between the RS41-SG and RS92-SGP in rig soundings. Both radiosondes measured with GPS. Average differences were <0.4 hPa near ground and <0.02 hPa above 30 km.

Figure 4.10 compares GPS-based pressure with sensor-based pressure in the RS41-SG and RS92-SGP, respectively. The two measurement methods are well in alignment, with average differences <0.3 hPa near ground and <0.2 hPa above 30 km. Standard pressure-level heights are in excellent agreement, as shown in **Table 2 in Chapter 1**.

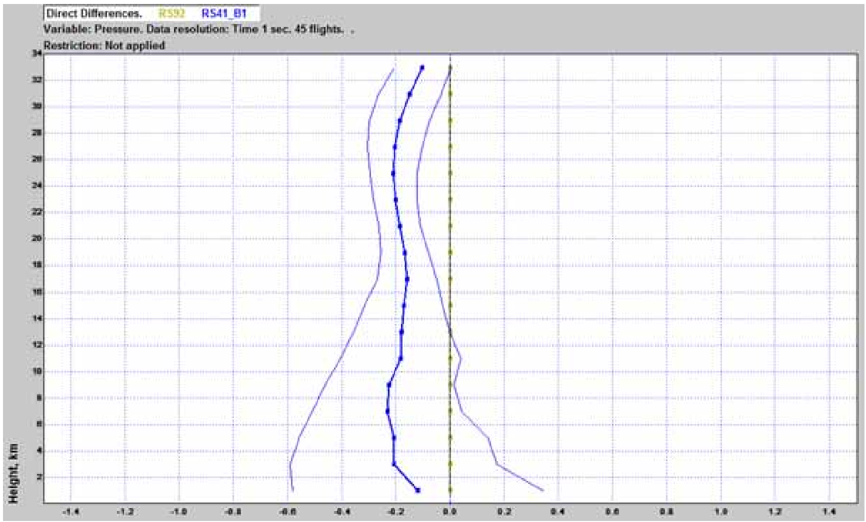

Figure 4.10. Comparison of GPS-based pressure from the RS41 and sensor-based pressure from the RS92 radiosonde, using the RS92 as the reference. Showing average differences and standard deviation of differences (thin lines) from 45 flights.

Combined Uncertainty

The uncertainty analysis for pressure considered the following components:

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

The impact of these factors was modeled using custom analysis software that uses different atmospheric models, and even different scenarios of solar angles, to estimate the pressure uncertainty through all heights. The effect of environmental conditions was small as geopotential height is the dominant factor.

Figure 4.11 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 specified RS41-SG accuracy shown in **Table 1**.

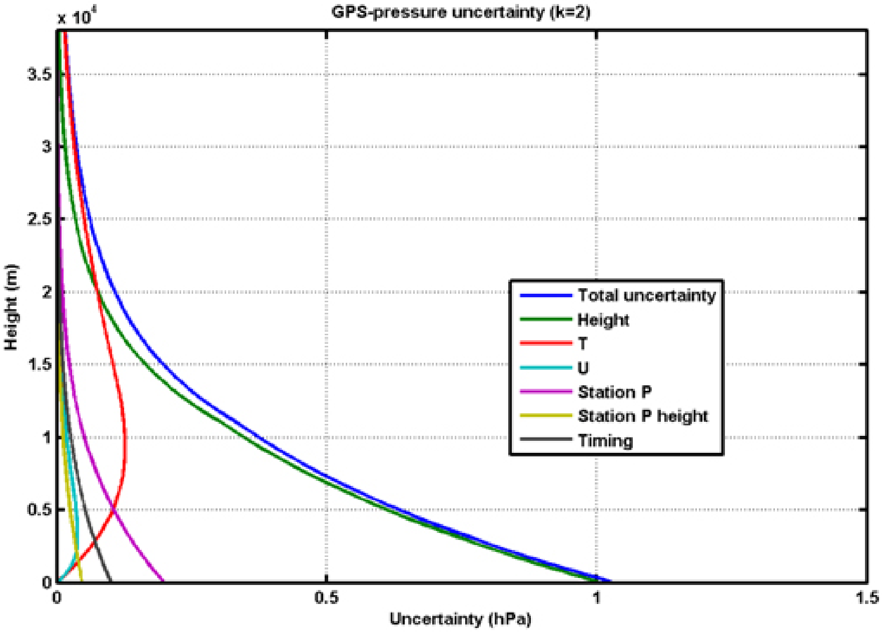

Figure 4.11. Combined uncertainty (k=2) and main uncertainty components for GPS-based pressure measurements in the RS41-SG radiosonde evaluated assuming the ISA standard atmosphere for pressure and temperature.

CHAPTER 5

Comparison of GPS-Based and Sensor-Based Pressure Measurements

Pressure Sensor Measurement Method

The conventional method of determining atmospheric pressure is to equip the radiosonde with an electronic pressure sensor that measures the physical weight of the atmosphere. Beginning with the RS90 series, Vaisala radiosondes have used the proven Vaisala silicon pressure sensor. The sensor combines two powerful techniques for barometric pressure measurement: single crystal silicon as a sensor material, and capacitive measurement. The main advantages are excellent stability, repeatability, a wide dynamic range, and low temperature dependence.

Height and geopotential height can be obtained from pressure sensor measurements using the hydrostatic equation and ideal gas law. The calculation procedure is analogous to the calculation of pressure from GPS height.

Comparison of Measurement Methods

GPS-based and sensor-based measurements of atmospheric pressure have been extensively compared e.g. in WMO sounding campaigns. Despite the differences in measurement techniques, the agreement between the methods has been within the required accuracy limits. For example, in the WMO intercomparison in Mauritius in 2005 the difference in RS92-SGP varied from 0.1% at an altitude of 20 km to 0.4% at 34 km [8]. The following sections discuss conditions where performance differences may arise due to the different measurement principles used.

Hydrostatic and Non-Hydrostatic Situations

The GPS-based measurement method assumes hydrostatic equilibrium in the atmosphere. A small deviation from pressure sensor measurements could be detected in non-hydrostatic conditions, such as near frontal zones, urban turbulence, or local storms.

The hydrostatic assumption used in GPS-based pressure measurements is a good approximation for most radiosonde applications, including numerical weather prediction.

Horizontal Inhomogeneity

The station pressure value used in the GPS calculation represents the atmospheric conditions at the time and location of the start of the sounding, while a pressure sensor measures conditions along the flight time and path. Horizontal pressure gradients could produce minor deviations when comparing GPS-based and pressure sensor measurements. These differences are a result of the different measurement principles, and are in general minor compared with the accuracy of the measurement.

Horizontal inhomogeneity may also include precipitating weather systems along the radiosonde's flight path. The pressure sensor measures the sum of the weights of air and hydrometeors in the air column above the sensor. The contribution of the hydrometeors may not be detected by the GPS method if the precipitation area is local. This difference is negligible compared with the accuracy of the measurement.

Other Effects

Pressure sensor measurement accuracy is typically better than the GPS method at the lowest heights. GPS-based pressure accuracy improves quickly when the radiosonde ascends higher above the ground and above possible multipath reflections from the surroundings. At high altitudes the geopotential height values may differ by up to a few hundred meters (gpm) due to the higher performance of the GPS method in low pressures. The relative accuracy of the pressure sensor decreases in the low end of the measurement range of 1080–3 hPa, while the relative accuracy of the GPS method remains almost constant.

Any comparison of the two measurement methods requires accurate station height parameters and the correct use of a calibrated barometer. This is also essential for good climatological continuity at the measurement station.

CHAPTER 6

Recommendations

When to Select GPS-Based Pressure Measurement

Atmospheric pressure measurement using the GPS principle is a high-quality measurement technique that is suitable for operational sounding applications. It is a good option for providing data for numerical weather prediction.

When to Select Pressure Sensor Measurement

A properly calibrated pressure sensor is the recommended choice for research applications where accurate observations of non-hydrostatic pressure profiles are required. A pressure sensor also provides the highest obtainable measurement accuracy at the lowest flight altitudes.

The use of a barometric pressure sensor is also a good option when data redundancy is valued. Users can compare GPS-based and pressure sensor methods for quality control and even choose the optimal combination of measurement methods for different heights.

Some sounding sites may experience persistent external RF interference or suffer from poor satellite reception. Upgrading to a Vaisala Enhanced Multipath Rejection Antenna GA41 provides sufficient improvement in most RF-challenged locations. A barometric pressure measurement is another alternative. These situations are unusual and should be considered on a case-by-case basis, following manufacturer's recommendations.

Choosing a Local GPS Antenna

A standard GPS/GNSS antenna is the recommended choice for most installation sites and radiosonde applications. These antennas are cost efficient, small, and tolerate rugged environments. The antenna should be installed in a location with an unobstructed line-of-sight from horizon to horizon, and as far as possible from reflective objects. Installation sites on sheet metal roofs or with prominent reflective structures close to the antenna will require upgrading to a high-performance antenna in order to obtain the specified GPS-based pressure accuracy. In these environments the antenna should be mounted as high as possible.

The standard option for Vaisala sounding systems is the Vaisala GPS Antenna GA31, and the upgrade option is the Vaisala Enhanced Multipath Rejection Antenna GA41. The GA41 provides excellent multipath rejection and a highly stable phase center, improving the accuracy of calculated height and atmospheric pressure profiles.

Transition from RS92-SGP

Transitioning from sensor-based to GPS-based pressure measurement at a sounding station is easy and convenient. If the transition includes an upgrade to Vaisala Sounding System MW41 it is important to follow the recommended upgrade procedures in document [9]. The station, barometer and local GPS antenna heights should be verified and configured via the convenient graphical interface in the Vaisala DigiCora® Sounding System MW41, as these parameters affect the accuracy of GPS-based pressure measurements.

Small systematic changes may appear especially at high altitudes. This is an expected effect that results from the different measurement principles used. The changes should be small and within the specified measurement accuracy.

The RS41 radiosonde will also be available with a pressure sensor. Sensor-based measurements can be valuable in climatological data series, which can benefit from consistent use of direct pressure measurements.

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