FACTORS CONTRIBUTING TO RS41 GPS-BASED PRESSURE AND COMPARISON WITH RS92 SENSOR-BASED PRESSURE

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ABSTRACT

Vaisala Radiosonde RS41-SG derives atmospheric pressure from measurements of GPS height, temperature and humidity. The GPS-based pressure measurement method is well proven and has been optionally available in previous Vaisala Radiosonde RS92. However, for many RS92 users a transition to RS41 involves a change from direct pressure sensor measurements to a new technology. This paper discusses factors that affect measurement uncertainty of RS41 GPS-based pressure measurements, and compares the performance of the two measurement techniques.

Accuracy of RS41 GPS-based pressure measurements was evaluated using a comprehensive uncertainty analysis, and experimental results were collected from radiosonde comparison tests in several geographic areas. GPS derived pressure measurements showed improved reproducibility compared with pressure sensor measurements. In the upper atmosphere the difference between the two methods is more pronounced. High quality of measurements can be ensured with careful station setup and accurate surface pressure and radiosonde temperature measurements. However, some applications benefit from consistent use of direct pressure measurements or from data redundancy of two measurement methods. To meet this need, RS41 model with an integrated pressure sensor will be available.

PRESSURE MEASUREMENT METHODS WITH RADIOSONDE

Atmospheric pressure is equivalent to the force per unit of area exerted on a surface by the weight of the air column above the surface. It is an important component in meteorology and other atmospheric sciences. The conventional method of determining atmospheric pressure profiles is to equip the radiosonde with an electronic pressure sensor that measures the physical quantity.

RS41-SG uses a method where atmospheric pressure is derived from radiosonde measurements of height, temperature, and humidity [1]. This technique requires a properly calibrated reference pressure sensor at the sounding station. The reference sensor measurement defines the first value and calibrates all subsequent values in the pressure profile. Air density varies along the flight path according to temperature and humidity conditions. The radiosonde determines the change between each observation point during the flight by measuring these quantities. The vertical position and distance between observation points are obtained from the Global Positioning System (GPS) height measurements. The magnitude of the change in pressure can then be derived e.g. from hydrostatic equation and ideal gas law.

Radiosondes equipped with a pressure sensor, such as RS92, calculate height based on the same principle but in reverse order. Height is derived from radiosonde observations of pressure, temperature and humidity. As a result, height and pressure measurements are closely related in both GPS-based and sensor-based techniques.

GPS-BASED PRESSURE MEASUREMENT ACCURACY

The accuracy of GPS-based pressure measurement is determined by the quality of GPS height measurement, surface pressure measurement, temperature and humidity measurements during flight, and parameters related to the sounding station setup. A comprehensive uncertainty analysis was carried out to evaluate the relative contribution of the uncertainty factors in RS41. The uncertainty analysis software uses RS41 accuracies for input factors, and estimates pressure uncertainty at all heights using an atmosphere model [2]. Uncertainties from RS41 height, temperature and humidity [3] are included in the analysis. Figure 1 shows an example profile of combined uncertainty for pressure, along with contributions of individual factors.

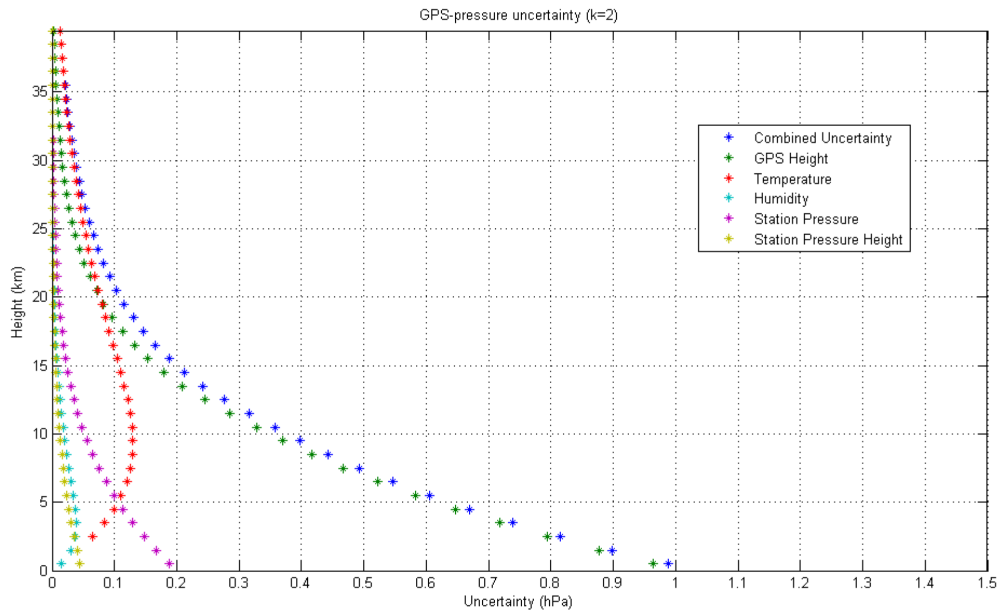

Figure 1. Combined uncertainty (k=2) and main uncertainty components for GPS-based pressure measurements in the RS41 radiosonde, evaluated assuming the ISA standard atmosphere for pressure and temperature.

GPS height

As indicated by the analysis in Figure 1, quality of height measurements is the main contributor to pressure accuracy. GPS height uncertainty remains fairly constant through the radiosonde profile. As the pressure decreases exponentially, the contribution from GPS height uncertainty decreases almost exponentially. This is an advantage compared with sensor-based pressure measurements, where the relative uncertainty increases in low pressures. However, accuracy of pressure measurement with a high quality pressure sensor is typically better than the GPS method at the lowest heights. GPS-based pressure accuracy improves quickly as the radiosonde ascends higher above the ground. GPS measurement accuracy can be affected by using proper filter algorithms, a good quality GPS antenna, and correction algorithms for atmospheric propagation effects on GPS signal.

Station surface pressure

The accuracy of the surface pressure sensor at the station is an important factor. The uncertainty analysis in Figure 1 assumes a high quality measurement with uncertainty of 0.2 hPa (k=2), in which case the effect on combined uncertainty is negligible. However, an inaccurate sensor with an error of 0.5 hPa or more causes a clear increase in the uncertainty of pressure measurement.

Temperature and humidity

Good quality temperature measurement is essential to the accuracy of GPS-based pressure measurement. The red curve in Figure 1 demonstrates the impact of a small 0.1 °C temperature bias throughout the profile, causing an error of up to 0.15 hPa along the pressure profile. The impact is linear, i.e. 1.0 °C bias causes an error of up to 1.5 hPa.

A pressure error of around 0.1 hPa could result if evaporative cooling occurs when the radiosonde emerges from a cloud, causing a short-term bias in temperature measurements. These effects are minimized by the high quality of RS41 temperature measurement, and they are small compared with the contribution of GPS height measurement. The impact of humidity measurement is small compared to temperature.

Station height parameters

GPS-based pressure measurements require that station parameters are properly configured. The altitudes of the local GPS antenna and the station pressure sensor must be correctly entered in the sounding system. A one meter error in altitude causes an error of approximately 0.12 hPa. The Sounding System MW41 enables configuration of these height parameters via a convenient graphical interface.

EXPERIMENTAL RESULTS

Results of the uncertainty analysis are supported by experimental tests. RS41 measurements of GPS heights and atmospheric pressure were evaluated in sounding campaigns in several locations to cover different satellite geometries and site environments. The results presented here are from three locations: Penang, Malaysia (lat. 5° N), Camborne, UK (lat. 50° N) and Vantaa, Finland (lat. 60° N). Each flight used a cross-shaped rig where two RS41 and two RS92 radiosondes were hanging. This setup allowed an assessment of the reproducibility of each type of measurement, and a comparison between GPS-based RS41 and sensor-based RS92 pressure measurements.

The data from all radiosondes were carefully synchronized using GPS time stamps. Statistical analyses and radiosonde comparison results were processed using RSKOMP Radiosonde Comparison Software [4].

Reproducibility of pressure measurements

Reproducibility describes how closely two radiosondes flying in the same rig measure the atmospheric pressure profile. In order to have two independent GPS-based height measurements, two separate GA31 local GPS antennas were installed at the measurement site to follow each RS41 radiosonde. The antennas were installed an adequate distance from each other to ensure the measurements were not affected by the same multipath effects. This site setup was available at Malaysia and Finland locations.

Figure 2 demonstrates the characteristics of GPS-based and sensor-based techniques. Geopotential height, or gravity corrected height, is the dominant factor in pressure calculation. Figure 2 (left) shows differences for GPS-based geopotential heights between two RS41 radiosondes during one flight, and Figure 2 (right) differences for RS92 geopotential heights, derived from sensor measurements. The differences between GPS height measurements remain consistently at < 10 gpm during the flight. Sensor-based measurements show less noise overall, but there are differences between individual sensors which become evident in height and pressure comparisons at high altitudes. Observed differences can be up to a few hundred meters at high altitudes where the pressure sensor is less accurate.

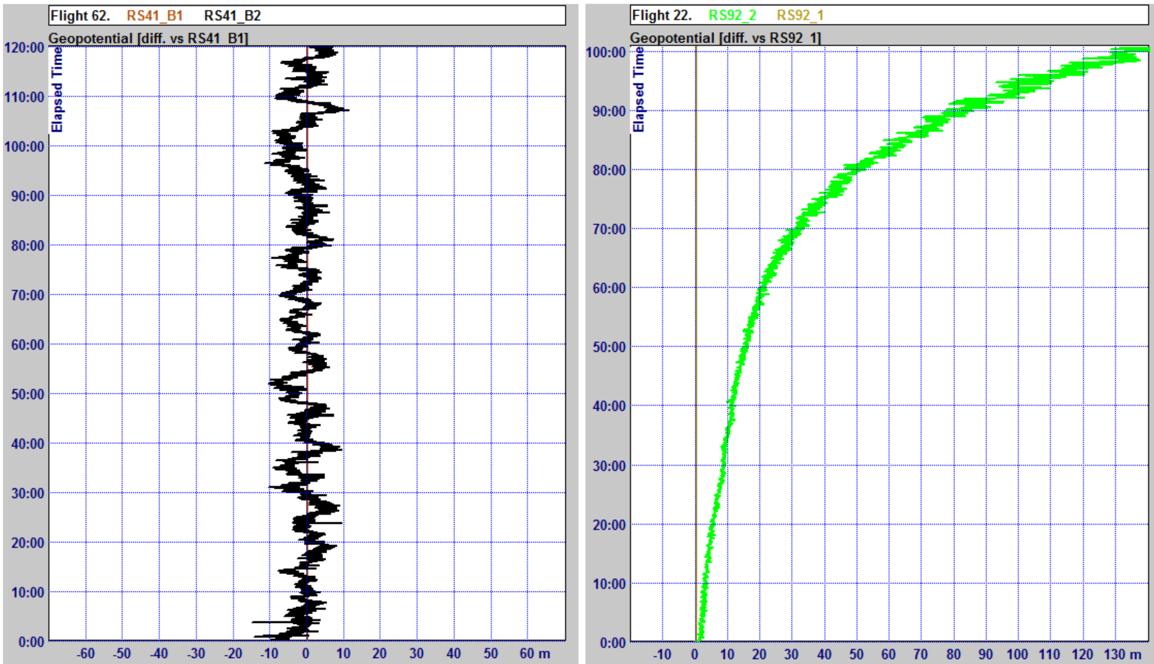

Figure 2. Examples of geopotential height differences measured in Vantaa, Finland, between two RS41-SG radiosondes using GPS (left) and between two RS92-SGP radiosondes using a pressure sensor based method (right).

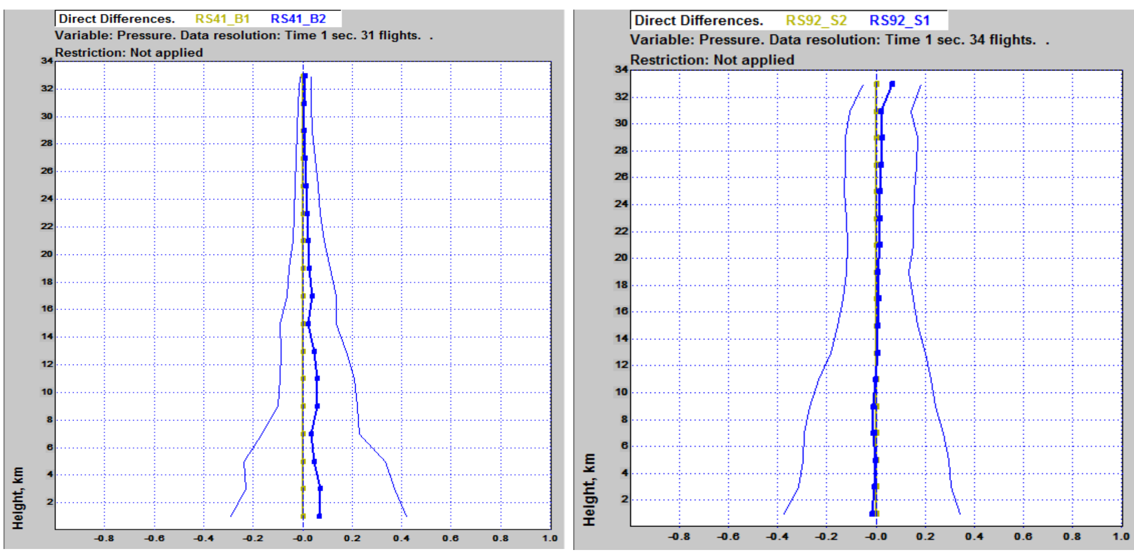

Figure 3. Reproducibility of pressure measurements between two RS41 radiosondes in 31 flights (left) and between two RS92 radiosondes in 34 flights (right). RS41 uses GPS-based and RS92 sensor-based method. Average differences are indicated by bold lines and standard deviations of differences by thin lines.

Figure 3 presents a statistical summary of pressure measurement reproducibility for RS41 radiosondes using GPS, and for RS92 radiosondes using pressure sensor. Results are combined from Malaysia and Finland measurement campaigns in 2013. GPS-based measurements are more consistent and have a smaller variance than sensor measurements in the upper atmosphere. GPS-based and sensor-based results have similar variance in the lowest heights. GPS results show a small < 0.1 hPa bias which may result from small uncertainties in the measured heights of the two GA31 GPS antennas.

Comparison of RS41 and RS92 pressure measurements

GPS-based pressure profiles from RS41 radiosondes were compared with sensor-based pressure from RS92 radiosondes flying in the same rig. The differences were calculated at the same time instances, and a statistical summary presented as a function of height. Figure 4 shows the average differences between RS41 and RS92 in sounding campaigns in Camborne, UK, and Vantaa, Finland. The two measurement methods are well aligned, showing average differences of 0.1 hPa to 0.2 hPa. The differences were mostly positive in the UK campaign, and negative in Vantaa. Overall, the comparison results are within the specified RS92 pressure measurement uncertainty of 1.0 hPa at below 100 hPa, and 0.6 hPa above.

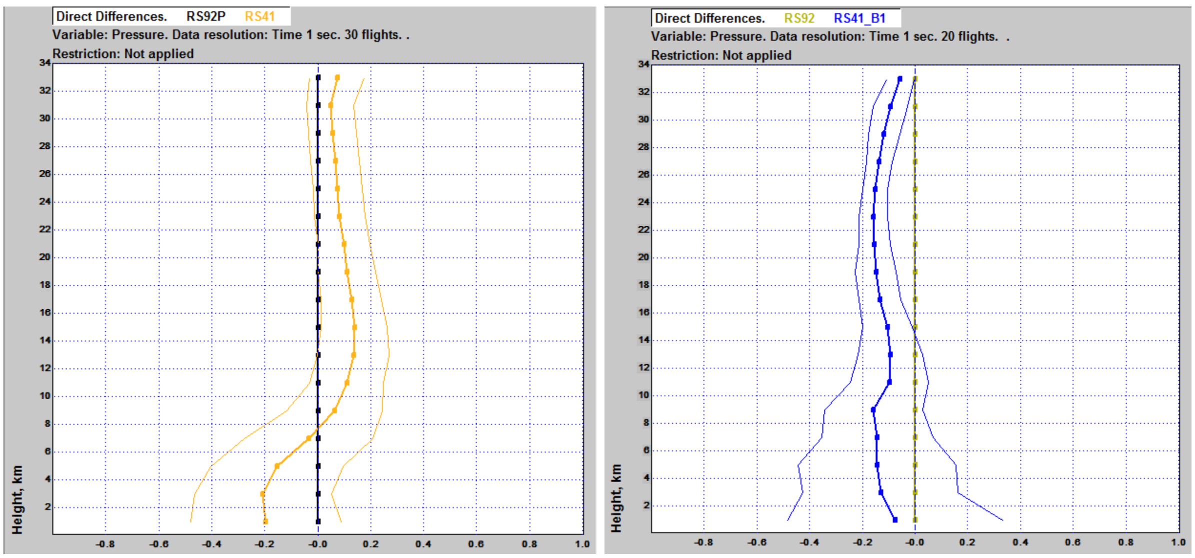

Figure 4. Comparison of pressure measurements between RS41 and RS92, using RS92 as the reference. RS41 uses GPS-based and RS92 sensor-based method. Showing results from two measurement campaigns: 30 flights in Camborne, UK, in October 2013 (left), and 20 flights in Vantaa, Finland, in July 2013 (right).

Comparison of RS41 and RS92 pressure level heights

A typical quality diagnostics for sounding stations are the heights of standard pressure levels. These are compared with nearby stations and numerical model predictions. As height and pressure are closely related in both GPS-based and sensor-based techniques, the differences are smaller than when comparing heights at given time instances. The expected changes during a transition from RS92 to RS41 are small and mostly indicate differences of temperature and humidity measurements in each radiosonde. Figure 5 shows average differences between geopotential heights of RS41 and RS92 at 15 pressure levels in two sounding campaigns. The two methods have an excellent agreement, with differences less than 10 gpm for all pressure levels.

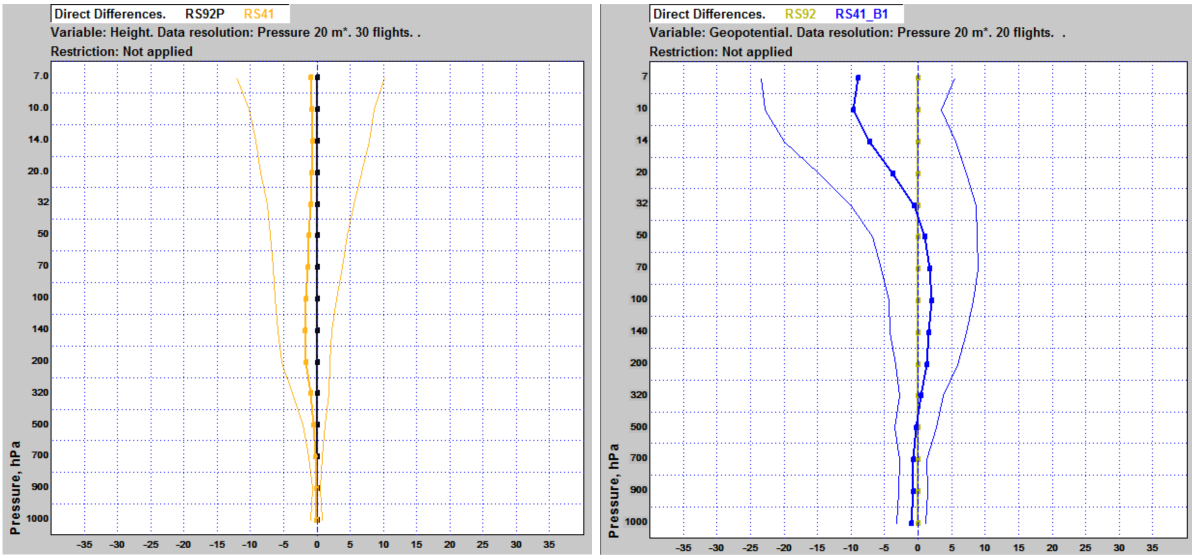

Figure 5. Comparison of geopotential heights of pressure levels between RS41 and RS92, using RS92 as the reference. Showing results from two measurement campaigns: 30 flights in Camborne, UK, in October 2013 (left)[1)], and 20 flights in Vantaa, Finland, in July 2013 (right).

Comparison of temperature and humidity measurements with pressure as a reference

In many applications radiosonde measurements of temperature, humidity and other variables are expressed as a function of pressure. The transition from RS92 sensor-based to RS41 GPS-based pressure may thus impact the reporting of temperature and humidity results, in addition to the changes in the temperature and humidity measurements themselves. The effect would be more notable in upper altitudes, where small differences in pressure correspond to greater differences in height. The significance of this effect was studied by comparing temperature between RS41 and RS92, using either time or pressure as a reference variable.

Figure 6 shows average differences in RS41 and RS92 temperature measurements. The results are from Camborne, UK, including 10 night and 20 day soundings. Figure 6 (left) presents the differences between the two radiosonde models calculated at the same time instances, and Figure 6 (right) at the same pressure levels. The vertical axis in both cases is the height axis. The use of pressure as a reference caused no detectable bias between RS92 and RS41 temperatures, despite the small difference in average pressure seen in Figure 4.1. This can be explained by the relatively constant mean temperature in this data set in the upper heights. As discussed in [5], individual flights may show larger differences between temperature and humidity values at given pressure levels. Standard deviations of differences are larger in the upper heights, where the uncertainties in pressure estimates contribute to the comparison. Analysis of the temperature reproducibility between two RS92 radiosondes indicated that most of the variance comes from RS92. As RS41 pressure measurements are more accurate in the upper heights, it is expected that the reproducibility of temperature results will improve when GPS-based pressure is used as a reference.

1) The shown variable is geopotential height, not height as indicated in the figure header.

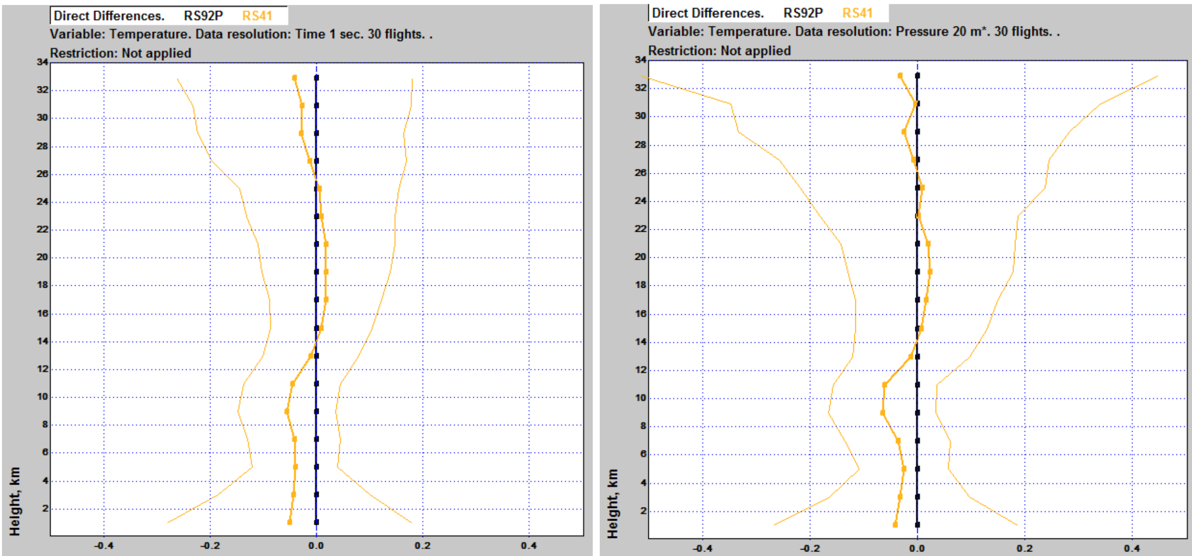

Figure 6. Comparison of temperature between RS41 and RS92 in a set of 30 flights in Camborne, UK, in October 2013. Differences calculated at the same time (left), and at the same pressure levels (right).

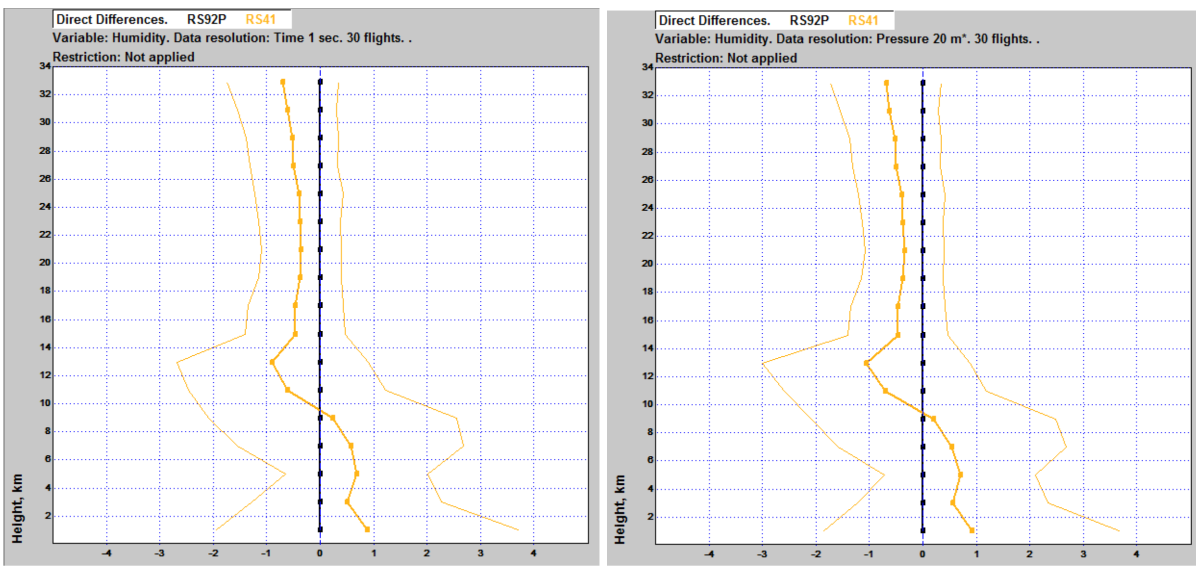

Figure 7. Comparison of humidity between RS41 and RS92 in a set of 30 flights in Camborne, UK, in October 2013. Differences calculated at the same time (left), and at the same pressure levels (right).

Figure 7 presents average differences in relative humidity between RS41 and RS92. The results are almost identical when time or pressure is the reference variable. This is due to the fact that at upper heights, where pressure measurements have more variability, humidity profiles have little variance and are consistently close to zero humidity.

SUMMARY

Vaisala Radiosonde RS41-SG derives atmospheric pressure from measurements of GPS height, temperature and humidity. The GPS-based measurement of atmospheric pressure is a reliable and accurate technique that is suitable for operational sounding applications. High quality of GPS-based measurements can be ensured with careful station setup and accurate surface pressure and radiosonde temperature measurements. Experimental sounding campaigns showed that reproducibility of pressure in RS41 improved compared with RS92 at higher altitudes, from 0.15 hPa to less than 0.05 hPa at above 30 km. Average pressure differences between RS92 and RS41 were 0.1 to 0.2 hPa, and differences in geopotential heights of pressure levels were 10 gpm or less. A comparison of temperature and humidity data as a function of pressure showed no average bias between RS92 and RS41.

Some applications benefit from consistent use of direct pressure measurements, or from data redundancy of direct pressure and GPS-based pressure. To meet this need, RS41 model with an integrated pressure sensor will be available.

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