11.1 COMPARISON OF TWO RADIOSONDE PRESSURE MEASUREMENTS: PRESSURE SENSOR VS. GPS-DERIVED PRESSURE

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1. INTRODUCTION

Radiosonde measurements of atmospheric pressure are important both as the vertical coordinate for temperature, humidity, and wind profiles from the radiosonde, and for understanding the evolution of weather systems. Radiosondes use two main principles for determining the atmospheric pressure: one is a direct pressure measurement with a sensor; the other derives pressure from the radiosonde measurements of height from the Global Positioning System (GPS), temperature, and humidity. While the two methods are accepted for operational use and they have been shown to agree within a specified measurement uncertainty in various test campaigns (Nash, 2011), the differences in their physical assumptions and accuracy may have an impact in some conditions. For example, the GPS-based method assumes hydrostatic balance, while the performance of the pressure sensor is limited by the required large dynamic range.

In this study we describe the characteristics of each measurement method and provide results from measurement uncertainty analysis. Results from test soundings with Vaisala Radiosonde RS41 are presented. We also discuss criteria for selecting the best method for various radiosonde applications.

2. TWO OBSERVATION METHODS FOR PRESSURE AND HEIGHT

Atmospheric pressure and height measurements are closely related. As the height increases, the pressure decreases, following a nearly logarithmic profile. Pressure and height profiles can be derived from each other with small corrections, taking into account the air density variations. Consequently, there are two main principles available for radiosondes for determining the atmospheric pressure.

Pressure can be measured indirectly using the radiosonde measurements of GPS height, temperature, and humidity through the hypsometric equation (Stauffer, 2014), or directly with a pressure sensor. Similarly, height can be measured directly from the GPS satellite navigation system, or indirectly from pressure, temperature, and humidity sensor measurements (Richner, 1995). The two procedures are depicted in Figure 1.

The two independent methods provide useful options suitable for different radiosonde applications. In the following we will describe their respective strengths and weaknesses in terms of precision and accuracy of measurement. Choice of the optimal observation method depends on the application in question.

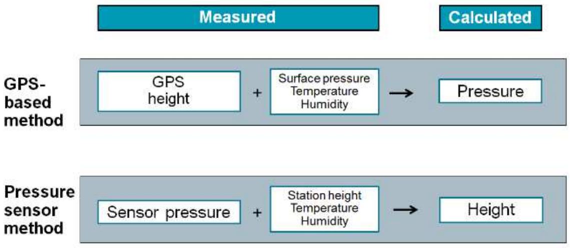

Figure 1. Comparison of GPS-based and sensor-based pressure measurement methods.

3. GPS-BASED PRESSURE MEASUREMENT

The use of GPS height, temperature, and humidity for estimating pressure is the most common method applied at upper air sounding stations. Omitting the pressure sensor allows simpler radiosonde design and pre-flight preparations. The ground level value of the pressure profile is obtained from a barometer at the sounding station. The barometer observation also calibrates all values in the profile. The change in pressure between each measurement point is solved using the height, temperature, and humidity information with hypsometric equation (Stauffer, 2014), as depicted in Figure 2. The method assumes a hydrostatic balance, which is a valid model for most situations.

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The height observation is the most important factor. It is obtained from a global satellite navigation system, typically the Global Positioning System (GPS), which provides accurate location estimates using timing and position information from satellites. 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. For calculations the geometric height value is converted into geopotential height, expressed in geopotential meters (gpm), which adjusts the height to compensate for gravity variation with latitude and elevation.

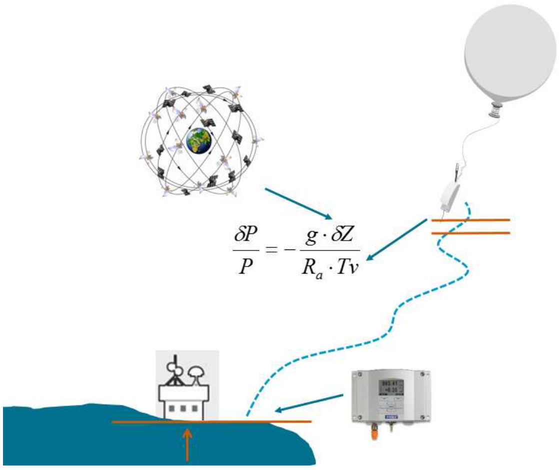


Figure 2. Illustration of the GPS-based pressure measurement method, showing the hypsometric equation which gives the pressure change δP between each measurement point on the flight path.

4. ACCURACY OF GPS-BASED PRESSURE MEASUREMENT

There are several factors affecting the measurement uncertainty of the GPS-based pressure method, of which the GPS height measurement is the dominant factor. Other factors include the surface pressure and sounding station height used in initialization, and the radiosonde measurements of temperature and humidity.

The GPS height measurement accuracy is determined by the GPS receiver quality and the geometry and availability of GPS satellites. Errors in location estimates may be caused by various factors, including atmospheric disturbances. The impact of these factors can be reduced by, for example, using modeling and differential GPS corrections. With appropriate corrections the accuracy of GPS height measurement is fairly constant through the range of heights used in a radiosounding. GPS height estimates are typically less accurate than horizontal location estimates, however, vertical accuracy of 10 m or less is obtainable in most conditions (Vaisala, 2013). As a result, the GPS-based method provides a very high precision of measurement in the stratosphere, where the pressure change with increasing height is relatively small. The measurement quality is more critical in the lowest kilometers of the atmosphere, where an error of a few meters in height will lead to a pressure error of several tenths of hPa, as indicated in Figure 3.

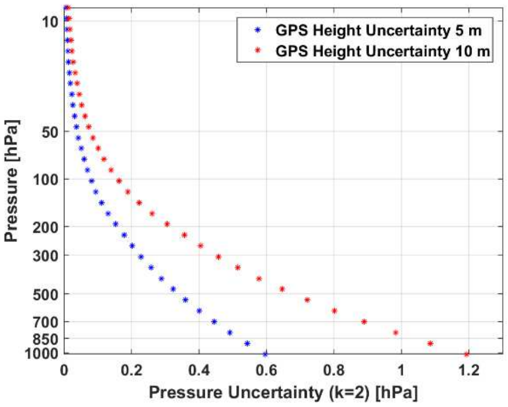


Figure 3. Measurement uncertainty in the GPS-based pressure profile caused by 5 m or 10 m uncertainty in height.

Another important factor affecting the accuracy of the GPS-based pressure measurement is the quality of the surface pressure. The station barometer must be properly calibrated, and the height of the barometer with respect to the sounding station height correctly configured in the sounding software. In fact, several initialization values affect the pressure measurement through the sounding, as indicated in Figure 4. The GPS local antenna height affects through differential corrections, if in use. In addition, the MSL height of the sounding station impacts the reporting of pressure heights. The importance of the correct configuration of the sounding workstation is worth emphasizing, as the erroneous values may not be evident from data messages.

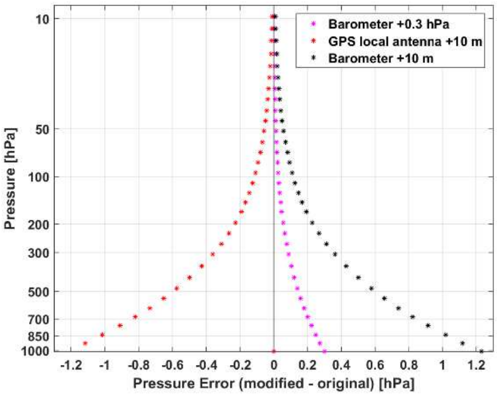


Figure 4. Measurement error in the pressure profile caused by erroneous sounding station barometer reading or erroneous height settings.

The accuracy of radiosonde temperature measurement has a moderate impact on pressure accuracy, while the humidity measurement has a very minor impact. A constant offset error in temperature or humidity accumulates in the integral of pressure calculation. As an example, a persistent temperature bias of 0.1 – 0.2 °C causes an error of up to 0.15 – 0.3 hPa in the GPS-derived pressure profile, as shown in Figure 5a. In addition, a larger short-term temperature offset may cause a small error at and above the height where it occurs. The dash-dotted lines in Figure 5a demonstrate the impact of 1 or 2 °C errors in a 300 m layer. If the sensor is not protected with hydrophobic coating, such errors could arise due to wet-bulb cooling when the radiosonde is emerging from a cloud.

Quality of the humidity measurement has a very small impact, with on error of up to 0.1 hPa arising from a -10 % RH offset, see Figure 5b.

Combining all the uncertainty components and using reasonable assumptions for the accuracy of the user-set configuration values results in the combined uncertainty of pressure shown in Figure 6. This example uses height, temperature, and humidity uncertainties evaluated for Vaisala Radiosonde RS41-SG. It is notable that while GPS height is the dominant uncertainty factor up to the tropopause level, the accuracy of the temperature measurement is estimated to have the largest impact on pressure in the stratosphere.

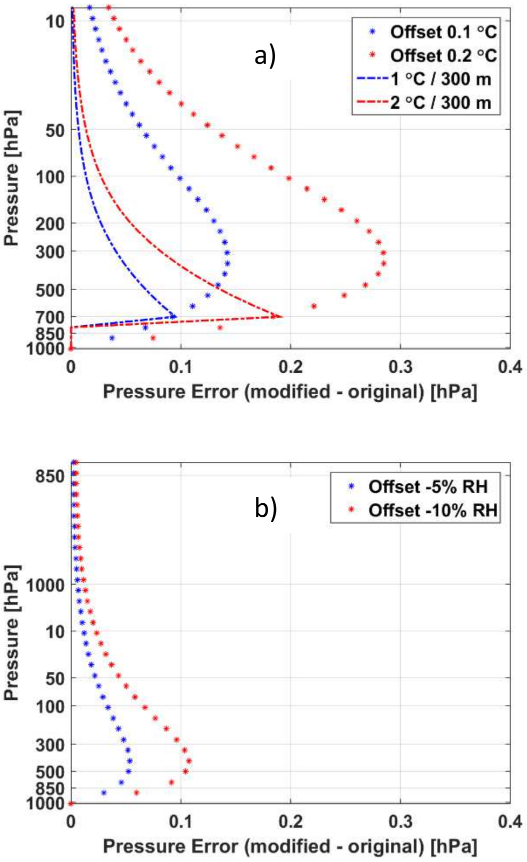
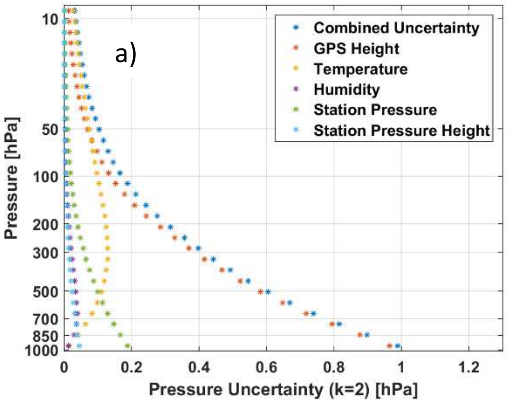


Figure 5. Measurement error in the pressure profile caused by a) persistent temperature offset, and b) persistent humidity offset.



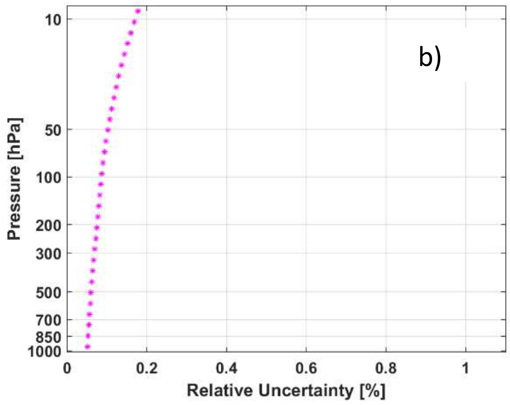


Figure 6. a) Combined uncertainty of GPS-based pressure measurement, showing also the main uncertainty components, and b) the corresponding relative uncertainty, evaluated for Vaisala Radiosonde RS41-SG.

5. SENSOR-BASED PRESSURE

A pressure sensor observes the atmospheric pressure directly by measuring the force produced by the column of the atmosphere above the radiosonde. This is the “true” atmospheric pressure, in contrast to the GPS-based method which assumes a hydrostatic balance in the atmosphere. A typical sensor design consists of an upper electrode, a base electrode, and a vacuum chamber, as shown in Figure 7. The upper electrode position is dependent upon the ambient pressure. Pressure value is obtained by measuring capacitance between the electrodes.

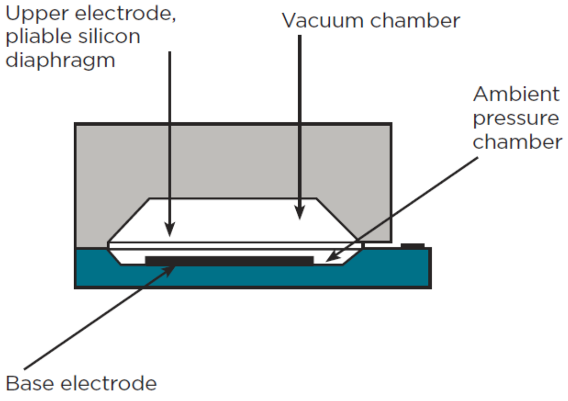


Figure 7. Pressure sensor construction in Vaisala radiosondes.

The measurement range of a pressure is wide in the sounding application, from about 1080 hPa down to 3 hPa, which is a challenge for the sensor-based measurement. A well calibrated pressure sensor provides very high accuracy and precision in the lowest kilometers of the atmosphere, whereas the accuracy of the sensor measurement is more limited in the upper atmosphere. The absolute accuracy (hPa) remains fairly constant through all heights, however, relative errors become larger in high altitudes. This is demonstrated in Figure 8, showing a significant increase in relative uncertainty in upper heights.

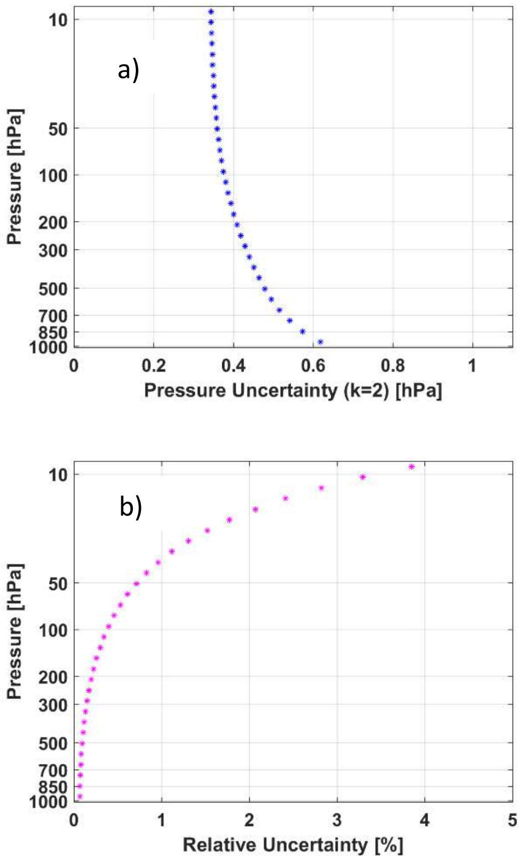


Figure 8. a) Combined uncertainty of sensor-based pressure measurement b) and the corresponding relative uncertainty, evaluated for Vaisala Radiosonde RS41-SGP.

At 10 hPa level a measurement uncertainty of 0.344 hPa (indicated in Figure 8.a) corresponds to 229 m uncertainty in height, assuming the ISA standard atmosphere. At 5 hPa level a similar measurement uncertainty corresponds to 478 m uncertainty. Consequently, when sensor-measured pressure is used as the vertical coordinate for other quantities, such as temperature and humidity, the pressure measurement uncertainty can be a major source of error in the stratosphere. The same has been shown for total column ozone (Stauffer, 2014).

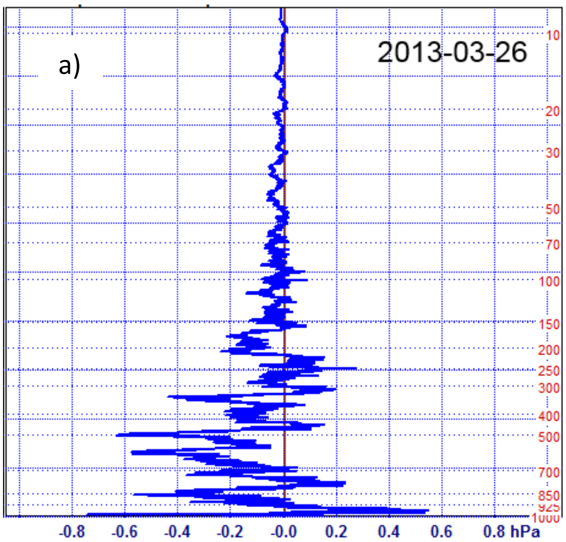
6. RESULTS FROM SOUNDING CAMPAIGNS

The GPS-based and sensor-based pressure measurement methods were evaluated in sounding campaigns in Penang, Malaysia (lat. 5° N), and Vantaa, Finland (lat. 60° N), in 2013 and 2014. The Vaisala radiosonde models used in the tests were RS41-SG, which uses the GPS-based method (Lehtinen, 2014), and RS41-SGP, which uses a pressure sensor measurement as the default. Each flight used a rig where at least two, and in most cases four, radiosondes were hanging. This setup allowed an assessment of the reproducibility of each measurement method, and their comparison.

In order to have two independent GPS-based height measurements, two separate Vaisala GA31 local GPS antennas were installed at the measurement sites to follow each RS41-SG radiosonde. 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 (WMO, 1996).

Reproducibility of pressure measurement

Figure 9 demonstrates some characteristics of the two measurement methods by showing pressure differences during two example flights. At the lower altitude levels, the GPS-based measurement results (Figure 9a) have more noise and oscillations, mostly due to the quality of the GPS height estimate. In high altitudes the method is very accurate. The pressure sensor measurement has much higher precision in the lower atmosphere, however, differences between the two sensors show some offset in high altitudes.



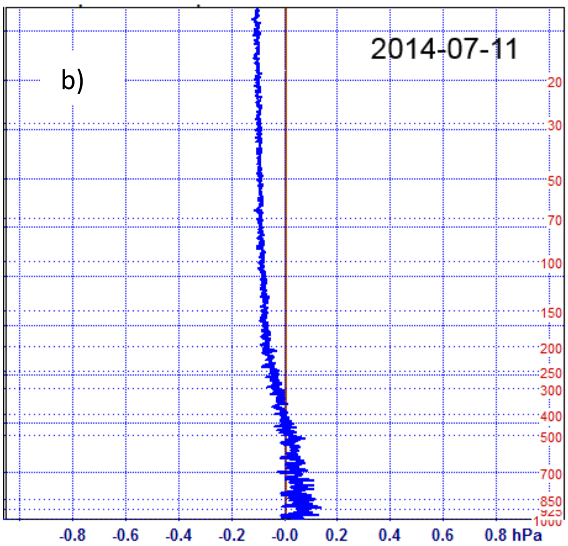


Figure 9. Example of pressure differences [hPa] between two RS41 radiosondes in rig soundings a) using GPS-based pressure and b) sensor pressure. Pressure levels [hPa] are indicated with the values on the right.

Figure 10 presents statistical results of measurement reproducibility for both methods. The results are combined from Malaysia and Finland measurement campaigns, which showed similar performance. GPS results (Figure 10a) show a larger variance than the sensor measurements in the troposphere, and a smaller variance in the stratosphere. The reproducibility is within the specified measurement reproducibility of 0.5 hPa in the lower atmosphere, and 0.04 hPa at above 10 hPa level. The small < 0.1 hPa bias may result from small uncertainties in the measured heights of the two GPS local antennas.

The sensor-based results (Figure 10b) show a rather constant reproducibility of 0.2 hPa or smaller throughout the profile. The reproducibility for sensor-based pressure was much better than the specified 0.5 hPa in these tests. The sensor-based measurements were not entirely independent because the same reference barometer was used for the ground check adjustment for both sensors. The tested radiosondes had experienced a short storage period of less than one month.

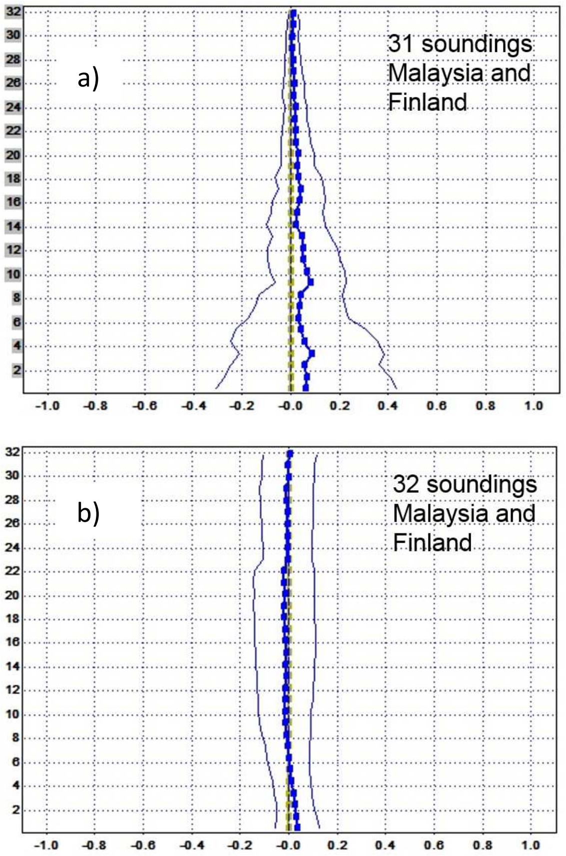
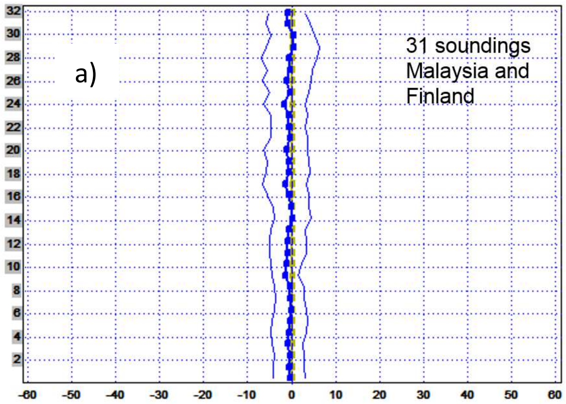


Figure 10. The reproducibility of RS41 pressure measurement for a) GPS-based pressure and b) sensor pressure as a function of height [km]. Average differences [hPa] between two radiosondes are indicated by a bold line and standard deviation of differences by thin lines.

Reproducibility of height measurement

Figure 11 presents the reproducibility of geopotential height from the same sets of flights, illustrating the major differences in height measurement accuracy between the two methods. The reproducibility of GPS-based height remains within 10 gpm at all heights, while the reproducibility of sensor-based height is about 80 gpm at 32 km altitude.



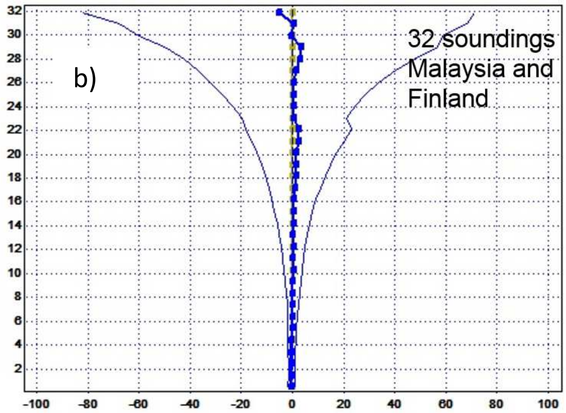


Figure 11. The reproducibility of RS41 geopotential height measurement for a) GPS height measurement b) pressure sensor-based method as a function of height [km]. Average differences [gpm] between two radiosondes are indicated by a bold line and standard deviation of differences by thin lines.

Differences between methods

An example of differences between simultaneous sensor and GPS-based measurements of pressure during one sounding in Finland is shown in Figure 12. The variability in differences in the lower heights is mostly due to noise in GPS height measurements, while the small offset in the upper heights is likely a result of the sensor measurement uncertainty.

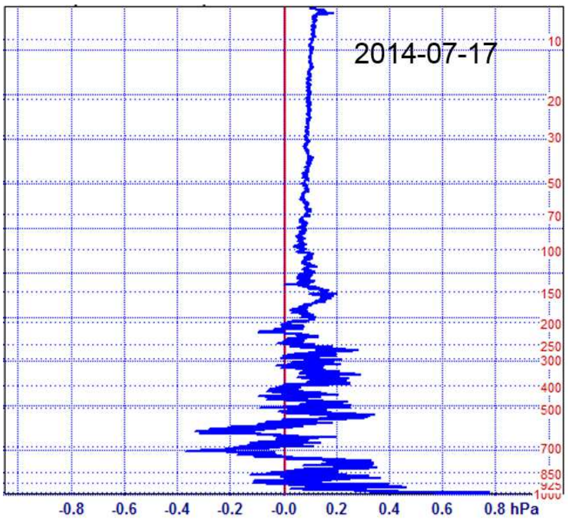


Figure 12. Example of pressure differences [hPa] between sensor-based and GPS-based measurement with RS41 radiosonde. Pressure levels [hPa] are indicated with the values on the right.

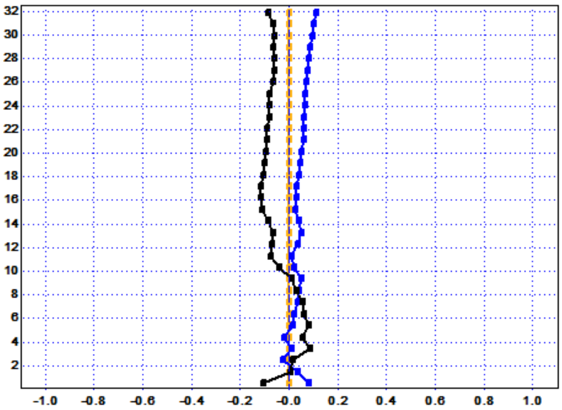


Figure 13. Average differences [hPa] between RS41 sensor-based pressure (blue), RS92 sensor-based pressure (black), and GPS-based pressure (orange) in 32 soundings in Malaysia and Finland. Results are shown as a function of height [km].

Figure 13 shows average differences between GPS-based and sensor-based pressure in the sounding campaigns, including also RS92 radiosonde sensor-based pressure. The average differences between GPS and sensor pressures are less than 0.2 hPa. Results were similar in both campaign locations in Finland and Malaysia. The differences are well within the measurement accuracy.

7. EXAMPLE OF A NON-HYDROSTATIC SITUATION

Highly non-hydrostatic and horizontally non-homogeneous environments, such as those observed near the eye of a tropical cyclone, are interesting when comparing the two pressure measurement methods. Some differences between the results can be expected as the assumptions used in the GPS-based method may not describe the state of the atmosphere accurately.

Typhoon Matmo passed over Taiwan in July 2014, and tropical storm Fung-wong in September 2014. Radiosonde soundings using Vaisala Radiosondes RS41 and RS92 from a sounding station located in Taiwan were inspected from those time periods. A comparison of GPS and sensor pressure profiles from RS92 showed some unusual differences when typhoon Matmo was close to the sounding site, see Figures 14 and 15. The largest observed pressure difference was 5.5 hPa at near 400 hPa level. The heights of the maximum differences correlated with the maximum wind velocities during the flights.

Smaller differences of 1 – 2 hPa were measured after the eye of the storm had passed the area, and also during the lower category tropical storm Fung-wong. Although a more comprehensive study is needed for verification, these results indicate that in highly non-hydrostatic situations observations a high-quality pressure sensor measurement gives a more accurate result than the GPS method.

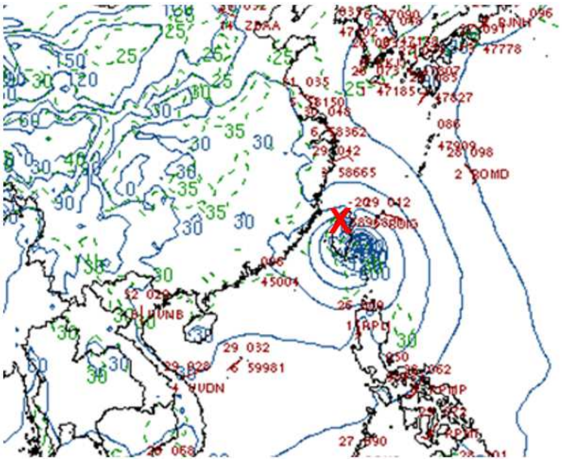
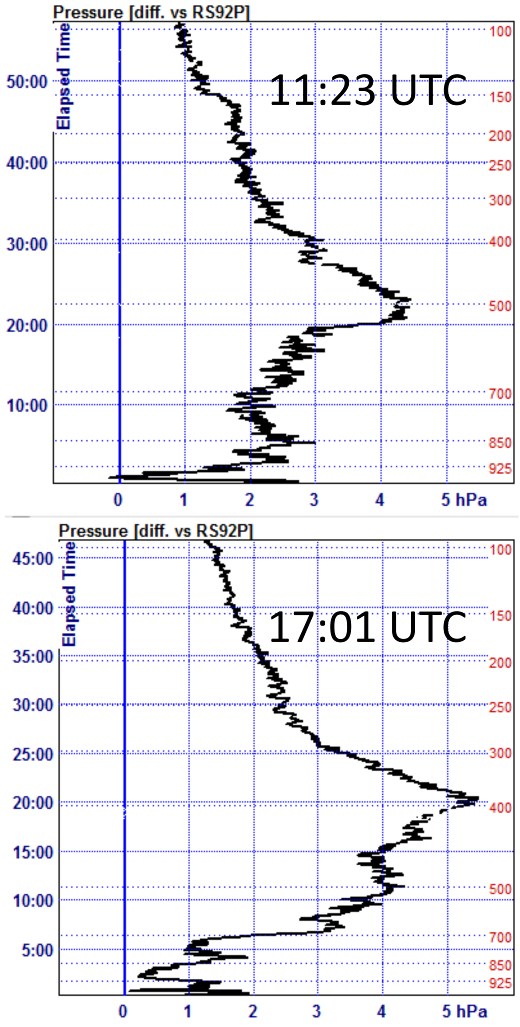


Figure 14. Map of 1000 hPa pressure level heights in South-East Asia at 12:00 UTC on July 22, 2014 during Typhoon Matmo.



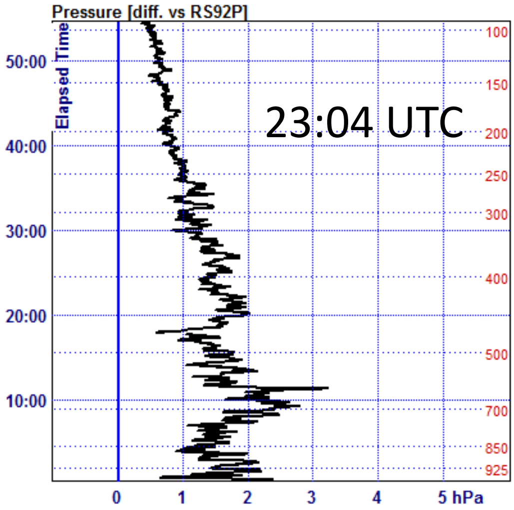


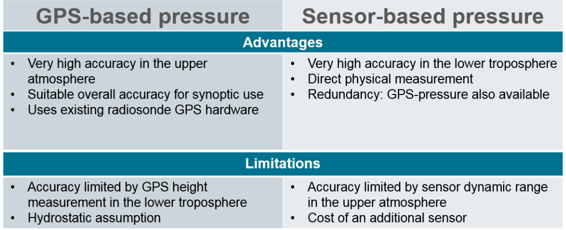
Figure 15. Differences between GPS-based and sensor pressure during three soundings in Taiwan on July 22, 2014 during Typhoon Matmo. Pressure levels [hPa] are indicated with the values on the right.

8. CHOICE OF MEASUREMENT METHOD FOR DIFFERENT APPLICATIONS

The two measurement methods have different areas of strengths and weaknesses, summarized in Table 1. For most applications, the performance differences are of minor significance, and, as a result, both methods can be used in weather forecasting, climatology and research applications, as suggested in Table 2.

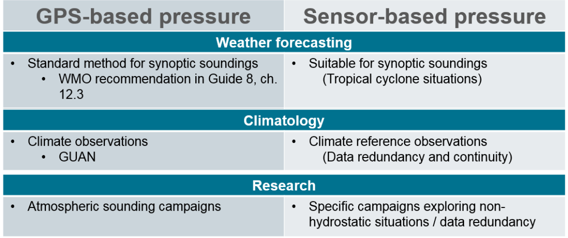
The GPS-based pressure method is the WMO recommended choice (WMO, 2008: CIMO Guide, Chapter 12.3) for synoptic soundings. This method provides sufficient accuracy for the lower troposphere and the benefit of very high accuracy in the stratosphere where the quality of long-term time series of quantities such as temperature and ozone require accurate pressure and height coordinates. The GPS-based method is also suitable for climate observations and atmospheric research campaigns.

The sensor-based pressure measurement is suitable for synoptic soundings. The data redundancy option by measuring both sensor pressure and GPS-based pressure from the same radiosonde sounding can be useful for researchers for understanding the atmospheric conditions. The sensor measurement may also be preferred for continuity of the measurement method for long time series of data for climate research, when very high precision is needed for the lowest kilometers of the atmosphere, or in highly non-hydrostatic conditions.



GPS-based pressure	Sensor-based pressure
Advantages	
• Very high accuracy in the upper atmosphere • Suitable overall accuracy for synoptic use • Uses existing radiosonde GPS hardware	• Very high accuracy in the lower troposphere • Direct physical measurement • Redundancy: GPS-pressure also available
Limitations	
• Accuracy limited by GPS height measurement in the lower troposphere • Hydrostatic assumption	• Accuracy limited by sensor dynamic range in the upper atmosphere • Cost of an additional sensor

Table 1. Comparison of the two pressure measurement methods.



GPS-based pressure	Sensor-based pressure
Weather forecasting	
• Standard method for synoptic soundings • WMO recommendation in Guide 8, ch. 12.3	• Suitable for synoptic soundings (Tropical cyclone situations)
Climatology	
• Climate observations • GUAN	• Climate reference observations (Data redundancy and continuity)
Research	
• Atmospheric sounding campaigns	• Specific campaigns exploring non-hydrostatic situations / data redundancy

Table 2. Recommended pressure measurement method for different applications.

9. SUMMARY

Two main principles for determining the atmospheric pressure with radiosondes were studied using uncertainty analysis and test campaign results.

The GPS-based measurement of atmospheric pressure is the most common method used for operational sounding applications. This method provides a very high accuracy in the stratosphere. The measurement quality is more critical in the lowest kilometers of the atmosphere, where a good design of the GPS receiver and GPS location algorithms, as well as careful station setup and accurate surface pressure measurements are essential. The radiosonde temperature measurements have a moderate impact on pressure accuracy. For example, a persistent temperature bias of 0.1 – 0.2 °C causes an error of up to 0.15 – 0.3 hPa in the GPS-derived pressure profile.

The sensor-based technique provides a very high accuracy in the lower troposphere, however the accuracy is limited by the sensor's dynamic range in the stratosphere. When sensor-based pressure is used as the vertical coordinate for other quantities, such as temperature and ozone, the pressure measurement uncertainty can be a major contributor to the measurement accuracy in the stratosphere. On the other hand, in highly non-hydrostatic conditions the pressure sensor may give more accurate results, as indicated by soundings during tropical cyclones in Taiwan in 2014.

Experimental sounding campaigns with Vaisala Radiosonde RS41 showed average differences between sensor and GPS-based pressure measurements of less than 0.2 hPa. The results are well within the specified measurement uncertainties and indicate a good overall agreement between the two methods.

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