Comparison of nine RTK GNSS devices

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The aim of the comparison and the background information

The purpose of this comparison has been to find out what kind of differences there are between the results measured from the same measurement points with different brands and types of RTK GNSS satellite receivers. In 2022, more than 140 satellites and 7 different satellite systems (constellations) were used worldwide for satellite positioning, the most important of which are the USA's GPS, Russia's GLONASS, EU's GALILEO and China's BEIDOU, which are available, for example, in northern Finland, in the area of this testing. In addition to these, e.g. Japan and India have their own systems, but their satellites do not travel in such orbits that they would be useful in Finland. Typically, the satellites of one system use 5-6 different frequencies and they can be partly the same in different systems. Consequently, there are clearly fewer frequencies than satellites [1]. A satellite receiver uses at least one frequency, but today usually two or more. The superiority of using multi-frequency and multi-constellation systems over the use of one frequency and one constellation has been proven by measurements [2]. There are several sources of error in the satellite receiver, such as ionosphere and troposphere delays in signal flow, local signal reflections, timing (clock) errors in satellites, solar activity, etc. [3]The RTK (Real Time Kinematic) GNSS system is based on one or more base stations transmitting either via the internet or directly on the radio to a device that receives correction information (Rover) and this way the measuring device is able to immediately measure the exact location [4]. The rover therefore actually measures the distance to stationary base stations all the time. The horizontal (NE) accuracy of the system has typically been around 2 cm in the NRTK environment (Network RTK i.e. multiple base station systems) [5]. A measurement in Beijing in 2022 achieved less than 2 cm RMS_error outside the city center and 4-5 cm in the center using a multi-frequency receiver using all available satellite systems [6]. Since the accuracy of the system is affected by so many things, usually the accuracy of the devices is not defined in the data sheets of the devices, but the performance is described with the word " Precision ", i.e. measurement uncertainty. It describes the distribution of the measurement, i.e. often the sigma value of the Gaussian (i.e. random) distribution, which in turn is also called the RMS value (of the Gaussian distribution) [7]. The measurement takes place in the global WGS-84 level coordinate system maintained by the United States Ministry of Defense [8], and the software of the receivers changes the measurement results to the desired local coordinate system, which in Finland are e.g. the ETRS-TM35FIN throughout Finland and the local GK coordinate systems. Such are the GK25 and GK26 coordinate systems used in Oulu. The measurement result is expressed in latitude-longitude or north coordinate-east coordinate format. Northing means the distance of the measurement point from the equator, and easting means the distance in the west - east direction from the central meridian, which is e.g. the Greenwich meridian in the ETRS-TM35FIN coordinate system. In the Finnish GK (Gauss-Kruger) coordinate systems, the central meridian is the meridian of the east degree number, i.e. in the GK26 coordinate system, the 26 degree meridian, for which the number is 500,000 m, in order to avoid negative east coordinates. Numbers are always meters. In addition to the coordinate system, a geodetic datum is required. It tells how the coordinate system is attached to the Earth. The datum defines the origin of the coordinate system, i.e. the zero point, the scale, and the orientation, i.e. the directions of the coordinate axes. [9]In addition to the plane coordinate system, the so-called geoid model is needed.

Geoid means a model describing the shape of the earth. The geoid is the equalization surface [10]of the gravity field potential that best coincides with the mean sea level, either globally or locally , which is why the geoid is not flat on the surface of the earth, because the earth's gravitational force is not completely constant everywhere. The geoid model is a numerical modeling of the geoid. For example, the FIN2005N000 and FIN2023N00 geoid models are used in Finland [11].

Measurement location and measured devices

In order to find out the performance of the devices, 6 measurement points were made in the yard area of Tokantie 34 and the surrounding park area in Oulu. The measurement point 1 is the best in terms of satellite visibility, a point typical of the built environment, partly open from trees. All other points are either partially or very much limited in terms of satellite visibility, either due to buildings or trees. Especially points 5 and 6 are like this. The measurement points with pictures are shown next to the results of each measurement point. The measurement points were marked with a 25 x 25 mm x 300 mm wooden pole sunk into the ground, the top end of which has a hemispherical cup, 10 mm in diameter, drilled for the tip of the measuring pole. The measuring points were not made at ground level, but they were made only for comparison, i.e. they are at varying heights from the ground and are marked with bright paint.

In the measurements, Karera Ltd's [12]VRS (Virtual Reference Station) service was used, which utilizes the National Land Survey's base stations. In the system, the correction signal is calculated from the signals of several base stations and the system forms a so-called Virtual Reference Station near the user. During the test, it was observed to form at distances of approximately 100 m to 5000 m from the rover. All devices used all available satellite systems and the device settings were at factory settings. The softwares used in the measurements were the equipment manufacturers' own softwares.

The measurements were made in August-September 2024 with eight different types of devices representing five different brands. The devices were 1) Emlid RX, 2) Emlid RS3, 3) Emlid RS2, 4) SingularXYZ Sfaira One Plus, 5) Alpha 4i, 6) South G4, 7) South G5 and 8) FJDynamics V10i. Of these, the Emlid RS2 and RS+ are no longer in production. Emlid RS+ was capable of measuring only 2/6 measurement points and thus is not included in the final evaluations. However, its measurement results are presented in the following chapters. Image 1shows the tested measuring devices in the following order: top row from left Emlid RX, Emlid RS2, Emlid RS+, Emlid RS3 and SingularXYZ Sfaira One Plus and bottom row from left: Alpha 4i, South G4, South G5 and FJDynamics V10i. Among the tested devices, Emlid RX and Sfaira One Plus differ in antenna shape from the others with their rod-shaped, smaller antenna, while the others have an integrated plate-like antenna. Alpha 4i is clearly the lightest and smallest of the plate-like antennas, its diameter is less than 10 cm.

There are big differences in the number of channels in the devices (Table 1). The single-frequency device Emlid RS+ has only 72 channels, and South G5 has the most channels, 1760. An interesting detail is that in three devices, SingularXYZ Sfaira One Plus, Alpha 4i and FJDynamics V10i all have the same number of channels, i.e. 1408. It is possible to guess whether the receiver circuits used in these originally came from the same factory. There were clear differences in performance between the devices. All tested devices, except Emlid RS+ , RX and RS2, have tilt correction (IMU = Inertial Monitoring Unit), which was in use during the measurements. Table 1shows the size and weight differences between the devices. Emlid RX is clearly the lightest, only 250 grams. In the next category are Alpha 4i and SingularXYZ Sfaira One Plus, whose weight is around 400 grams, although the shape of the device is clearly different. Emlid RS2, RS3, and FJD V10i and South G4 are close in weight and size. South G5 is clearly the heaviest. The G5 and FJDV10i are the only ones equipped with their own screen, which in the case of the South G5 is also a touch screen. FJD V10i has also 2 cameras for measuring remote targets. Those devices with a UHF modem or a Lora modem can be used as a base station for another device either with a direct radio connection or with the help of a service such as Emlid's service or the rtk2go.com service. These services are free. Emlid's devices differ from others in that they only use the Lora frequency (868 MHz) as a direct radio connection and the others use 450 MHz radios, which are compatible with each other, i.e. devices of different brands can be used with each other in a base-rover radio connection, as long as the frequency and protocol are set to the same . Common protocols are e.g. Trimtalk and Satel protocols. The Emlid RS3 also has a 450 MHz radio and is compatible for receiving local base station signal in this frequency range.

Image 1. Tested gauges, from top left Emlid RX, Emlid RS2, Emlid RS+, Emlid RS3 and SingularXYZ Sfaira One Plus. In the bottom line, Alpha 4i, South G4, South G5 and FJDynamics V10i.

Device	Size	Weight	Communication	IMU	Channels [pcs]	Memory	Controller available
Emlid RS+	145 x 145 x 85mm	690 gr.	BT 4.0, Lora, Wifi , RS-232, micro-USB	No	72	8 Gb .	No
Emlid RX	172x51x51 e.g	250 gr.	BT 4.2, USB-C	No	184	-	No
Emlid RS3	126x126x142mm	950 gr.	BT4.0, UHF, Lora, 4G, Wifi , RS-232, USB-C	There is	184	16 Gb	No
Emlid RS2	126x126x142 e.g	950 gr	BT 4.0, Lora, 3.5G, Wifi , RS-232, USB-C	No	184	16 Gb	No
SingularXYZ Sfaira One Plus	Φ50mm x 149mm	409 gr.	BT 2.0, USB-C	There is	1408	-	Yes
Alpha 4i	Φ98mm*53mm	380 gr.	BT5.0, UHF, USB-C	There is	1408	-	Yes
South G4	135mm×135mm×85mm	890 gr ,	BT4.1, Wifi , NFC, 4G, UHF, RS-232, USB-C	There is	1698	4 Gb - 128 Gb .+ ext . USB	Yes
South G5	165mm(ϕ) × 108mm(H)	1.35 kg	BT4.1, Wifi , NFC, 4G, UHF, RS-232, USB-C	There is	1760	16 - 64Gb. + external USB	Yes
FJDynamics V10i	Φ 130 × 83 mm	950 gr.	BT4.2&BLE, Wifi , NFC, 4G, UHF, USB-C	There is	1408	32 Gb	Yes

Table 1. Characteristics of the measured devices

The measurements were made with a measuring pole typical for land surveying, which the surveyor held straight, so in principle there was not much to correct with tilt correction. Each point was measured 10 times, of which each measurement contained 3-5 individual measurements. The final result of the above point is the average of the measurements. Each measurement therefore contained 10 x 3-5 = 30-50 individual measurements, measured from one point, and these measurements were made 1-4 times. In the case of other than Alpha, the length of the measuring pole is 180 cm (the same pole for all, measured 180 cm), with Alpha 160 cm (measured 159.5 cm without the rubber tip protection). The measurements were tried to be repeated either with the same or, if possible, also with a different device. Measurements were made on different days over a long period of time in order to compensate for the variation in the number and position of the satellites and the sun's activity. The number of measured device units and measurement times is shown in Table 2. The activity of the sun affects the reliability of the measurements, especially during this study, because the activity of the sun is expected to be at its peak in 2024. In practice, the activity of the sun is shown in such a way that the RTK FIX mode is more difficult to reach and the device is in FLOAT mode ([13]) for a longer time. The activity of the sun in Finland can be checked, for example, on the website of the Space Weather Center (RWC Finland) [14]. Unfortunately, the RWC pages do not show the real-time situation and the closest station to the measurement location is Oulujärvi, which is about 100 km from Oulu. One parameter describing the activity is the geomagnetic activity (unit nT) and the other is the electron density in the ionosphere (Image 2). Electrons in the ionosphere slow down and scatter electromagnetic signals from satellites to receivers [15]. Because several measurements were made, even with the same device, and on different days, it was noticed that sometimes the same device really remained in FLOAT mode for a long time (it could be in the order of minutes or even longer), while the next day with the same device it was possible to start the measurement very quickly (less than a minute from start-up) . During the measurements, it was noticed that the user of the device should study the behavior of the device in a situation where the activity of the sun clearly interferes with the success of the measurement. If the device does not get into FIX mode quickly enough or falls out of it during the measurement, even if the measurement location is not particularly demanding, you should be cautious about the accuracy of the results, even if the device sometimes goes into FIX mode. However, this publication has not documented these differences between the devices, which may be due to the activity of the sun, because there was no real-time data and not all devices could be measured simultaneously. The measurement was always started from the "easiest" place, i.e. the place with the best sky visibility (place 1), so if a device did not get into RTK FIX mode in the easiest place within the device's characteristic start-up time, it is possible that it was due to solar activity and it was compensated by starting the measurement at some other time. Another possible source of wide-area interference would have been intentional GPS interference (Image 3The disturbance can be monitored, for example, from the source [16]. where the user can select the period of time for detecting interference. Table 1 describes the number of measurement times and tested device units with different device types. Naturally, more measurement times with several devices give a more reliable result. All measurements used the ETRS-TM35FIN coordinate system and the FIN2005N00 geoid model.

Activity forecast, 1 hour

Issued at 20241019 13:16:03 UT

Solar wind parameters of the latest hour by NOAA			
parameter	min	max	mean
IMF Bz [nT]	-6.5	0.3	-4.2
velocity [km/s]	400.4	454.7	434.5
density [cm^{-3}]	0.6	4.3	2.7

Geomagnetic activity (RX [nT])			
site	latest hour	next hour (RXmin, RXmax)	
Kevo (KEV)	85	14	192
Maasi (MAS)	92	13	165
Kilpisjärvi (KIL)	100	13	168
Ivalo (IVA)	75	11	177
Muonio (MUO)	86	12	160
Sodankylä (SOD)	64	11	156
Pello (PEL)	72	10	127
Oulujärvi (OUJ)	52	9	104
Mekrijärvi (MEK)	32	8	50
Hankasalmi (HAN)	-	7	68
Nurmijärvi (NUR)	26	7	60
Tartu (TAR)	16	6	45

Geomagnetic activity forecast based on solar wind data. The two values for the next hour give an interval, where RX will be at a 90 % probability. RX is the range of the North component of the geomagnetic field. The colours indicate the level of activity:

low – increased – moderate – high – very high.

Ionospheric TEC

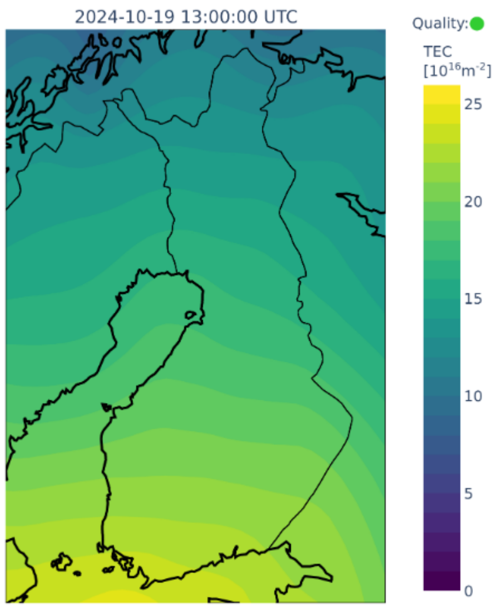

Image courtesy of Tomoscand project.

Image 2. Parameters describing the sun's activity from the website of the Space Weather Center (RWC).

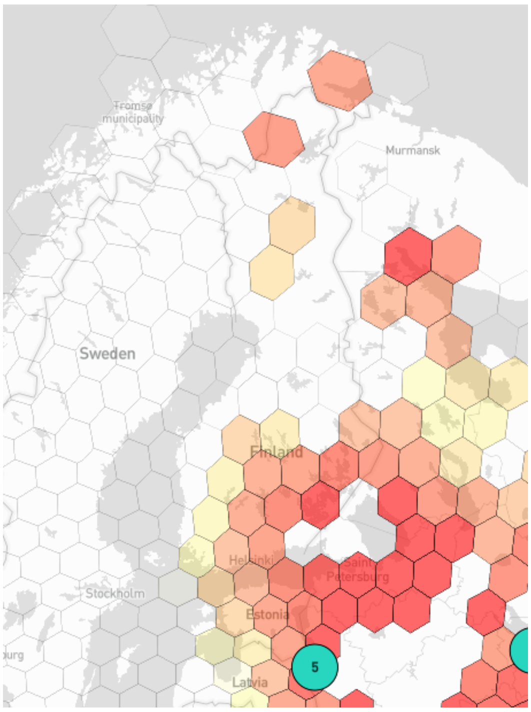

Image 3. Map image of Finland showing GPS interference detected during the last 24 hours.

Device	Measuring device units, pcs	Measurement sessions, pcs
Emlid RS+	1	1
Emlid RX	1	2
Emlid RS3	2	4
Emlid RS2	1	2
SingularXYZ Sfaira One Plus	1	1
Alpha 4i	1	4
South G4	2	3
South G5	2	4
FJDynamics V10i	2	4

Table 2. The number of measured devices and measurement times

The results measured with the devices can be directly compared with each other, i.e. the differences in the results are absolute. When talking about the accuracy of devices, it should be possible to distinguish between device-independent factors, such as errors caused by the base station signal, and variable error sources that depend on the measurement time, such as the variation of available satellites. As far as we know, no intentional disturbance with satellite measurements has been observed in the measurement area, in Oulu, at the time of measurement. Due to device-independent factors, we have tried to verify the measurement results by measuring with several devices over several days. The reference coordinates of the measurement points, i.e. the "correct" places, have been defined so that places 1 and 4 have been measured with all devices and the average values of the coordinates of all their measurements have been defined as the reference points, i.e. the "correct" values. The reference coordinates of other places have been measured with an Alpha Ti total station so that prisms corresponding to the Leica GMP104 prism with a prism constant of 34.4 mm have been placed at reference points 1 and 4 at a height of approx. 70 cm from the end of the measuring pole on the ground. The total station's own location, which was exactly at measurement point 3, and the orientation was measured using these reference coordinates. The accuracy of the total station measurement system and prism constants was checked by measuring the length of the 9 meter long roof line in the area, where the reference measurement was made with a metal measuring tape. After that, the coordinates of other places were measured, trying to use the shortest possible measuring pole, at the end of which a similar prism was placed, with the pole set in a vertical position. The total station and the measuring pole and prism used in the measurement of the reference positions are shown in the picture " Image 4".

Image 4. Alpha Ti total station and measurement of reference points with a prism.

Sources of errors in the RTK GNSS system

Sources of error have been discussed in the source [17], from which the following are quotes slightly shortened.

Base station coordinate accuracy

The coordinates of the base station must be known with an accuracy of 10 meters in the WGS-84 datum for optimal operation of the system. Incorrect or inaccurate base station coordinates reduce the accuracy of the measuring device (rover). It is estimated that every 10 meter error in the location coordinates of the base station causes an error of one millionth in the baseline vector between the base station (or base stations) and the measuring device.

Number of visible satellites

Satellite geometry directly affects the quality of the position solution estimated by the receiver. The Global Positioning System (GPS) is designed so that at least 5 satellites are always above the local horizon. Several times during the day there may be up to 8 or more satellites above the horizon. Because the satellites orbit, the geometry of the satellites changes during the day, but repeats itself from day to day. The more satellites used, the better the quality and integrity of the solution.

PDOP (Position Dilution Of Precision) measures the prevailing satellite geometry. Low PDOP values in the range of 4 or less indicate “good” satellite geometry, while a PDOP value greater than 7 indicates poor satellite geometry. At best, PDOP can go below one, in which case it is "ideal" [18]. In the measurements, the PDOP was at its worst below 2.5, which means that all observed PDOP readings were either in the good or even excellent category, although in the most difficult places the devices took some time to get into the RTK FIX mode and it even happened that you had to wait for hours for the FIX mode (which, of course, could be due to the sun activity).

Although only 4 satellites are required to determine a 3D position, RTK initialization requires at least 5 common satellites to be tracked at the base and rover locations. In addition, the L1 and L2 carrier (in the

GPS system) phase data must be monitored by five common satellites to ensure successful RTK initialization. Once initialization is obtained, at least 4 continuously tracked satellites must be maintained to produce an RTK solution.

When tracking other satellite systems such as GLONASS, one of the satellites is used to resolve timing offsets between that constellation and the GPS constellation. Monitoring of additional satellites helps in the RTK solution.

Altitude mask

The altitude mask prevents the receiver from using satellites that are low on the horizon. Atmospheric errors and errors caused by signal multipath are the largest for low-altitude satellites. Instead of the receiver trying to use all visible satellites, it can use e.g. the default 10 degree altitude mask. Using a lower height mask may reduce system performance. Height masks vary between 5-15 degrees by default. For example, Alpha has a default value of 5 degrees, South has 10 degrees and Emlid has 15 degrees. The user can change the height mask reading.

Environmental factors

Environmental factors affecting the quality of GPS measurements include *e.g. ionospheric activity, tropospheric activity, signal interference, multipath propagation and radio interference*. High ionospheric activity can cause rapid changes in GPS signal delay even between receivers located a few kilometers apart. The activity of the ionosphere can affect the equatorial and polar regions of the earth. Periods of high solar activity can have a significant impact on RTK FIX initialization times and RTK FIX availability.

The troposphere , i.e. the 50 km long area in the atmosphere, causes a delay in GPS signals, which varies above sea level, depending on the prevailing weather conditions and the satellite's elevation angle. The receiver includes a tropospheric model that attempts to reduce the effect of tropospheric error. If possible, try to place the base station at approximately the same height as the measuring device (Rover).

Signal obstacles limit the number of visible satellites and can also cause signal multipath propagation. Flat metal objects near the antenna can cause the signal to be reflected before reception by the GPS antenna. In phase measurements and RTK positioning, multipath errors are around 1-5 cm. If possible, place the base station in a clear environment with an open view of the sky. If possible, use the antenna at ground level to minimize multipath propagation.

Radio or radar transmission directed at the GPS antenna can cause severe signal degradation or complete loss of signal tracking. Do not place the base station in an area where radio transmission interference may become a problem.

Area of operation

Operating range refers to the maximum distance between the base and the rover devices. Often, the characteristics of the data transmission connection determine the operating range of the RTK. There is no maximum limit to the distance of the receiver from the base station for RTK operation, but the accuracy decreases and the initialization time increases as the distance increases. The specifications given for the receivers determine the distance at which these specifications are valid, and no specifications are given outside this range.

Description of the measurement site

The measurement site was located in Oulu in the area bordered by Tokantie and Sahantie streets, where part of the measurement area was in the yard of Tokantie 34 and part in the park area between the plots, where there were old pines and also young spruces and mixed forest. The diameter of the trunk of the pines at a height of 1 m varied between 30-50 cm. The top height of the tallest trees was approx. 22 meters. The measurement was made by laser scanning the area with an FJDynamics (FJD) P1 scanner. Point 1 was in the middle of the yard and the easiest point for measuring devices. It was almost open to the south-west direction. In point 2 and partly in point 3, the reflected signals from the walls were a challenge. Point 3 was actually surrounded by 3 buildings, one of which was an old building located in a park area. One of the buildings was a storehouse with metal walls. Point 4 was in the middle of a reasonably large empty part of the park area, but it was surrounded by large trees from almost all directions. There were large trees and branches around and on top of points 5 and 6. Point 5 was the most difficult because there was a branch of a pine tree directly above the measuring point. There were also spruces next to place 6, whose branches were directly attached to the measuring pole. More pictures are shown in connection with the measurement results.

Image 5. all measurement locations (locations 4, 5 and 6 are behind the trees).

Measurement results

Measurement location 1

Image 6. Measurement locations 1, 2 and 3 photographed with a drone .

Measurement site 1 was in the yard of a private house and had the best satellite visibility of all the points (Image 6). The standard deviation between the average values of all devices was 6.1 mm (the distance from the correct result, i.e. from the origin shown in Image 7). In measurement location 1, the origin of the picture means the average of the measurements of all the devices. RS+, RS2 and Sfaira are the farthest from the origin (Image 7). The closest to the origin were South G5 and Emlid RS3. The average values of all measurements fit into a circle with a radius of approx. 22 mm, so based on this measurement it can be said that regardless of the device, the accuracy of the result measured under such conditions is in the order of 2 cm, which is typical for RTK GNSS devices. In the height direction, the errors on all devices remained in the 2-3 cm range (Image 8). Emlid RS2 had a slightly bigger error than the others. With small antenna receivers (Emlid RX and Sfaira One Plus) with a different structure, the errors in the height direction were less than 1 cm. The single-frequency device Emlid RS+ also gave good results at this point in both the horizontal and vertical directions.

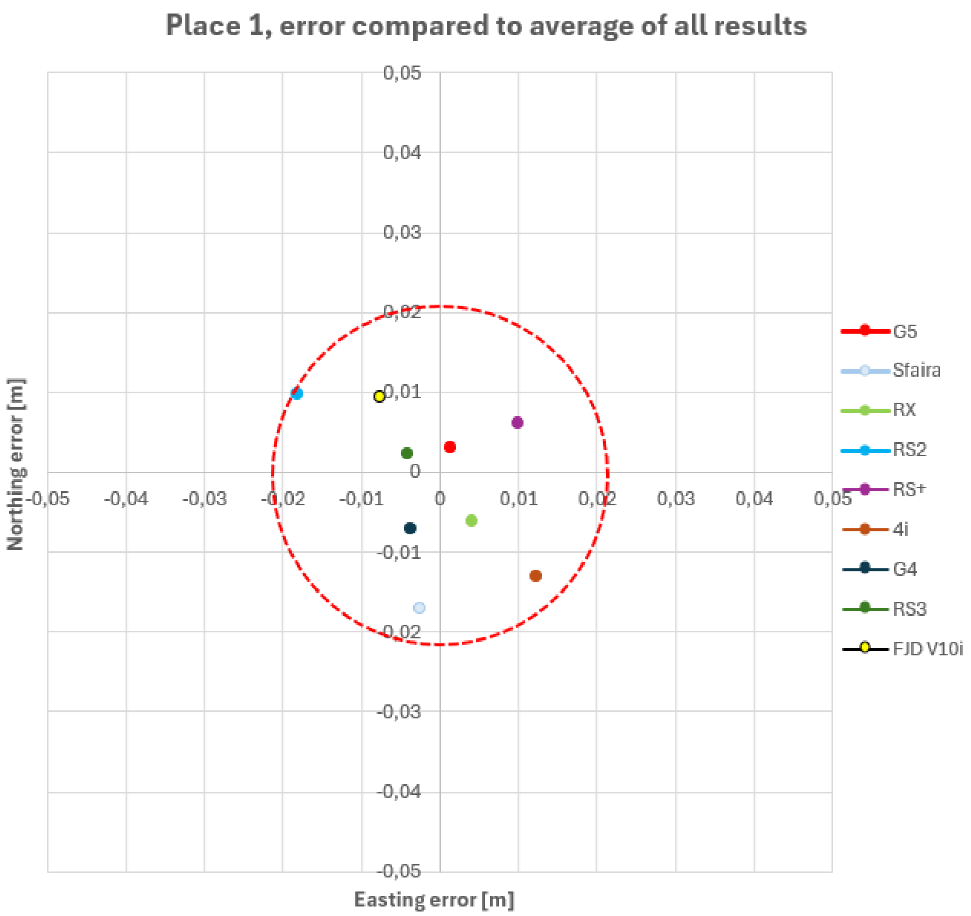

Image 7. The results of measurement site 1 compared to the average of all devices, east coordinate on the horizontal scale and north coordinate on the vertical scale

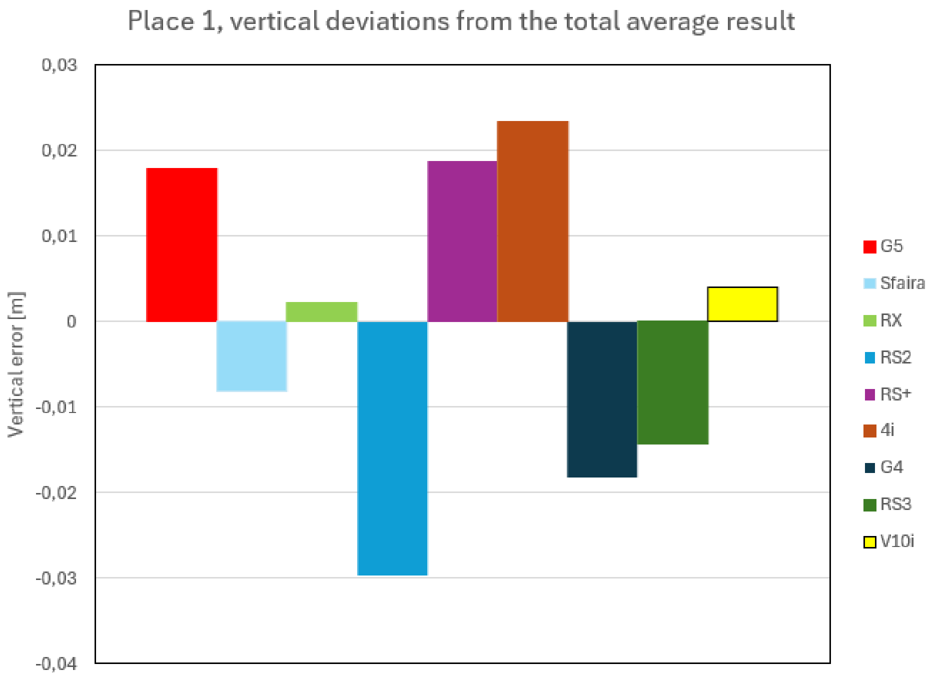

Image 8. Errors in the height direction at measurement location 1, compared to the average of all devices.

Measurement location 2

Measurement location 2 (Image 6) was next to the carport of the yard building, from where the signal reflection from the wall was possible. It was also surrounded by large trees to the southeast, south and southwest, so the place was not easy, which can be seen from the results. The standard deviation of the average values was 35.9 mm, i.e. the largest of all places, but it was mainly due to the abnormal result of Emlid RX. The average values of all measurements fit into a circle with a radius of approx. 130 mm (Image 9). Especially the Emlid RX clearly showed a different value at this point. Emlid RX except that the measurement results of the other devices fit into a circle with a radius of approx. 41 mm. It may be that the directional pattern of the RX rod antenna is such that it received more diffuse reflection from the wall than other devices. For some reason, the Sfaira One Plus device of the same model gave a clearly better result in this point, even though its antenna is visually estimated to be of the same type as the Emlid RX's antenna. Emlid RS2 was the second worst. Emlid RS3 and South G4 and surprisingly also Emlid RS+ were the closest to the original here. There was also a large dispersion in the height measurement results (Image 10). Emlid RX paradoxically gave the most accurate result for the NE measurement, while Sfaira One Plus gave the least accurate result. It can be speculated that the directional patterns of the rod antennas and the proximity of the reflective wall at location 2 appear differently in Emlid RX and Sfaira One Plus . The errors in the vertical direction (Image 10) were on the whole clearly larger than in location 1. With several devices, the error was 4-5 cm in the class.

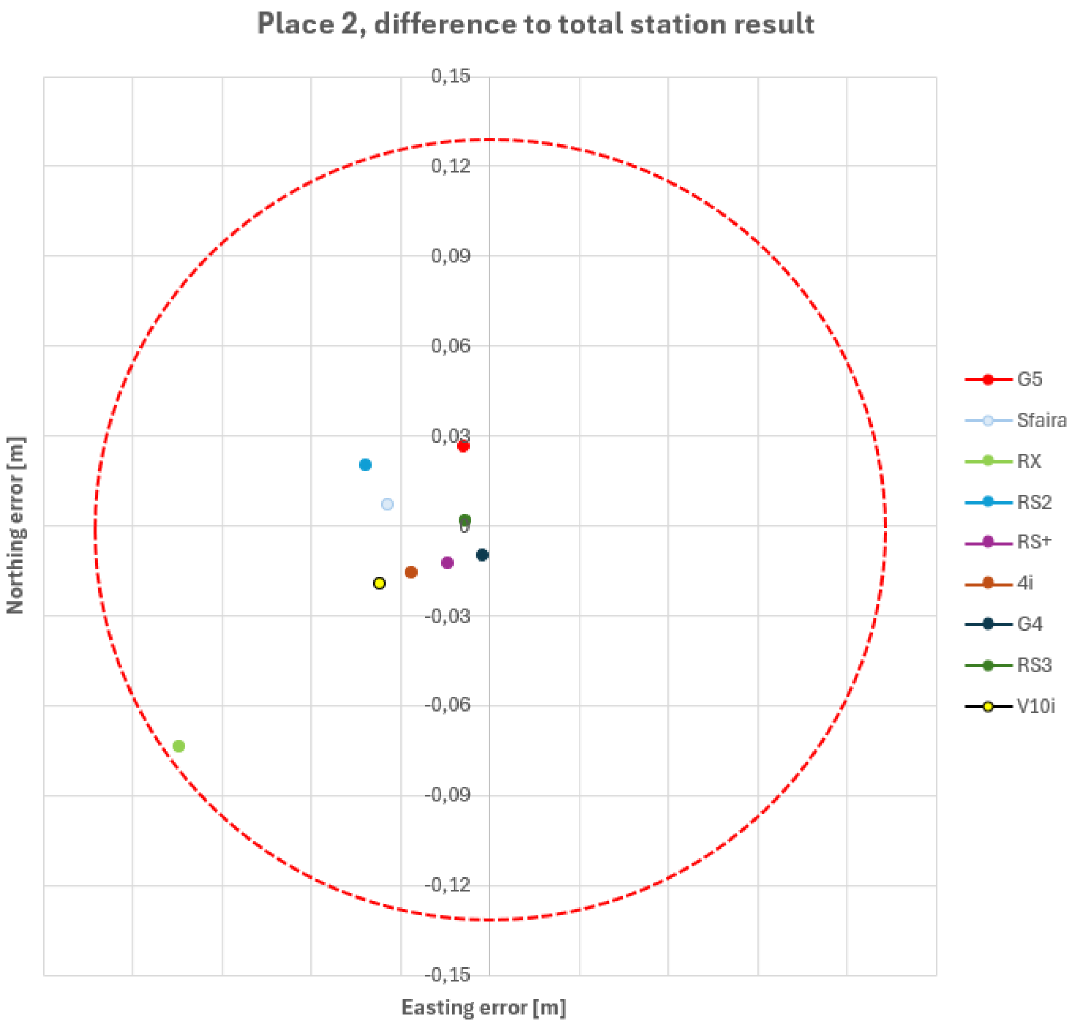

Image 9. The results of measurement site 2, the east coordinate on the horizontal scale and the north coordinate on the vertical scale, compared to the result obtained with the tachymeter .

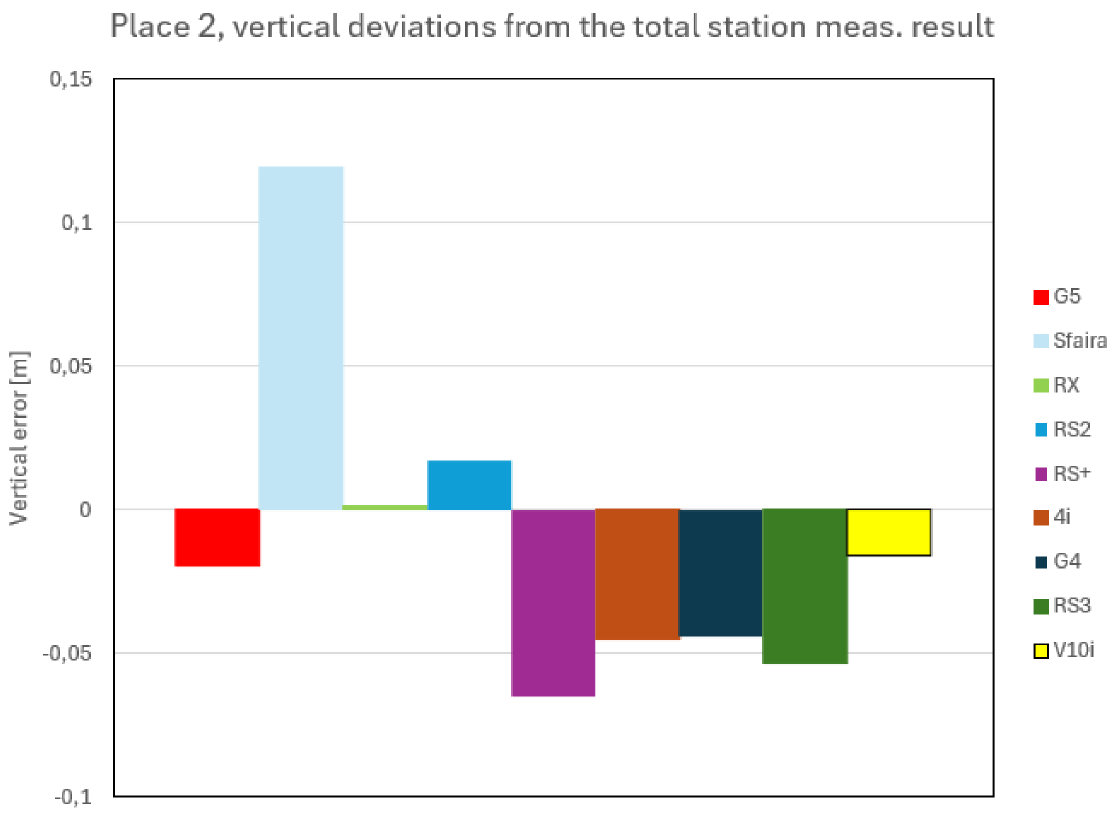

Image 10. Errors in the height direction at measurement location 2, compared to the reading given by the tachymeter.

Measurement location 3

Measurement location 3 (Image 11, Image 12) was between two buildings, and in fact a third building, a 3.5 meter high storagehouse with metal walls, was relatively close to the measurement point. The standard deviation of all measurements (Image 13) was 18.8 mm, i.e. clearly larger than in location 1, but despite that, all measurements fit into a circle with a radius of approx. 33 mm (Image 13). At this point Emlid RX was surprisingly the best followed by Emlid RS3, South G4 and G5 with very even results. The worst results were given by Sfaira One Plus and Alpha 4i, but even their errors were not particularly large. Emlid RS+ didn't give any result in this place and also not in places 4-6. In the vertical direction (Image 14), there was a relatively large amount of dispersion between the devices. Alpha 4i and especially Emlid RS2 gave the biggest errors, but the errors of the others were around 2 cm. Place 3 was not too demanding in that everyone got a reasonable result, except for the Emlid RS2 and RS+ devices .

Image 11. Measurement location 3, photographed from the ground level.

Image 12. Measurement location 3 photographed from the air with a drone .

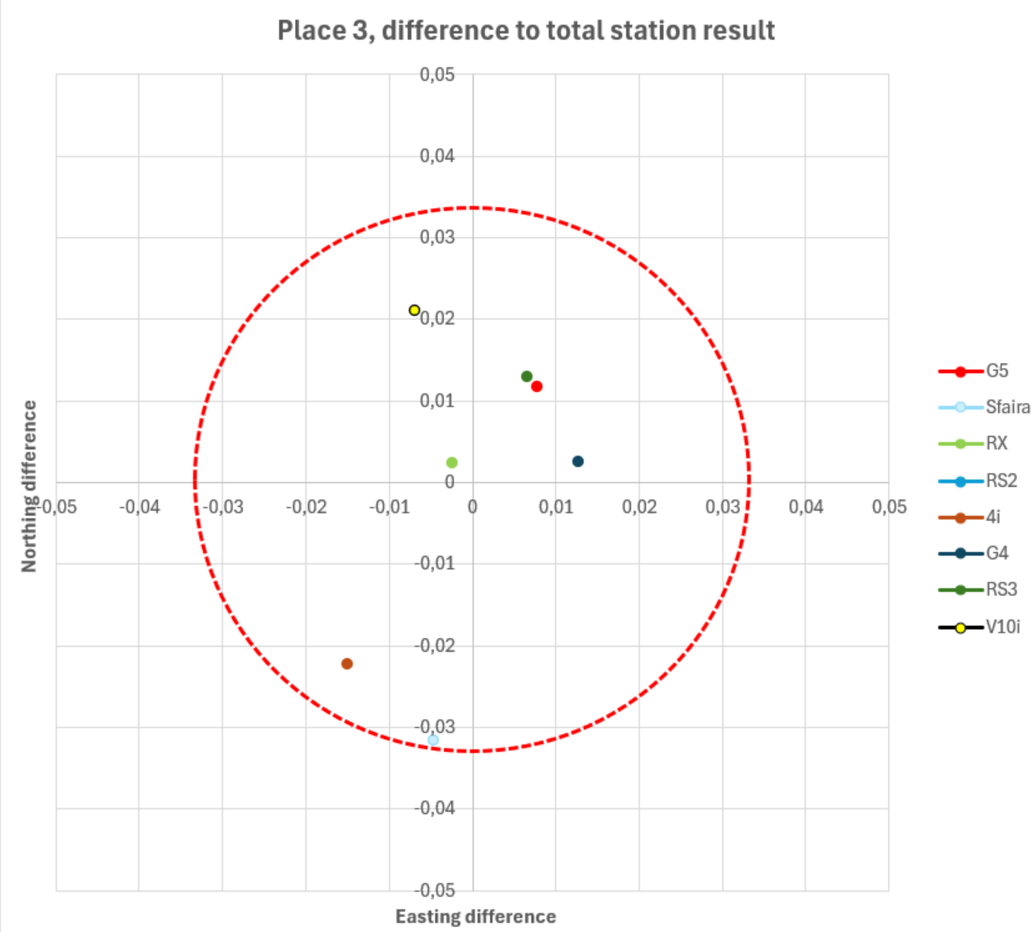

Image 13. Results of measurement site 3. The origin of the measurement site was measured with a tachymeter .

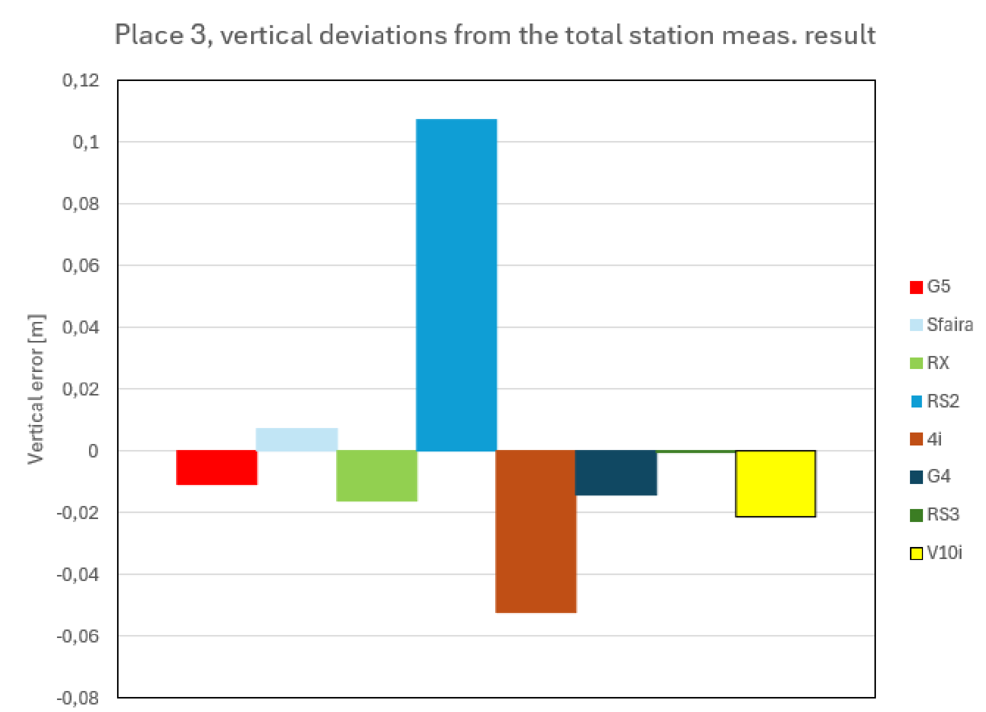

Image 14. Errors in the height direction at measurement location 3, compared to the reading given by the tachymeter.

Measurement location 4

Measurement site 4 was in an empty park area, but surrounded by trees from almost every direction (Image 15). However, there was relatively open sky in two narrow directions from the place. There was also one old empty wooden warehouse in the area. It was one of the places that were used as the so-called reference places, i.e. the "correct" result of the measurement is the average of all measurements and the coordinates of places 2,3,5 and 6 were measured using places 1 and 4 as references and the position of the total station was measured using them. The standard deviation between the average values of all measurements at site 4 was 8.1 mm (direct distance from the origin), i.e. slightly worse than at site 1, but compared to other sites, it indicated that sites 1 and 4 were correctly chosen as reference sites. The furthest from the origin were RS2 and RS3. The closest to the zero point were South G4 and G5. the FJD V10i was also not far away and overall the differences were not big. The average values of all measurements fit into a circle with a radius of 32 mm (Image 16), which means that measurement location 4 and measurement location 3 are equally "difficult", but based on the standard deviation, measurement location 4 was a better choice as a reference point than measurement location 3. However, Emlid RS+ did not give a result at this location at all. The error in the vertical direction (Image 17) had surprisingly a very large variation and there were large errors in several device’s results. All of Emlid's devices had a large error (15-20 cm), while in South's devices, Sfaira and V10i, the error was only 1-2 cm. It can be speculated that site 3 would have been a better reference site than site 4, because there the error dispersion of the vertical measurements was smaller. Visually, there was little difference between the locations in terms of satellite visibility.

Image 15. Measurement location 4 from the air.

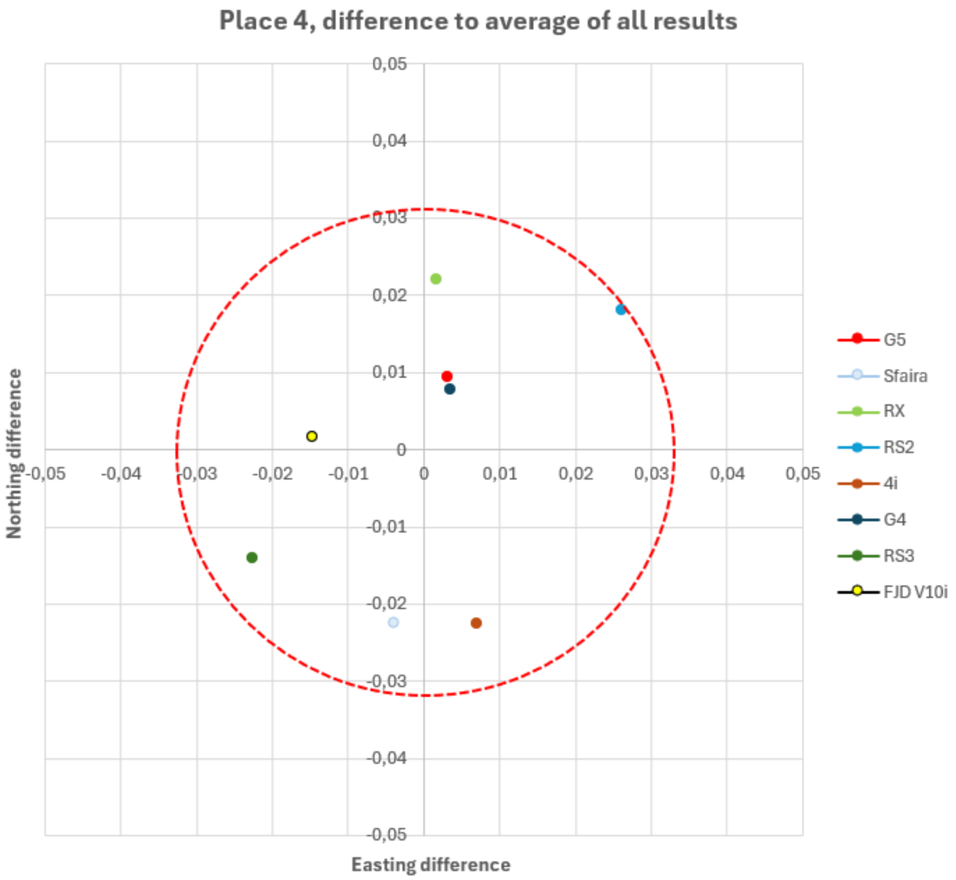

Image 16. Results of measurement site 4. The origin of the measurement location is the average of all measurements.

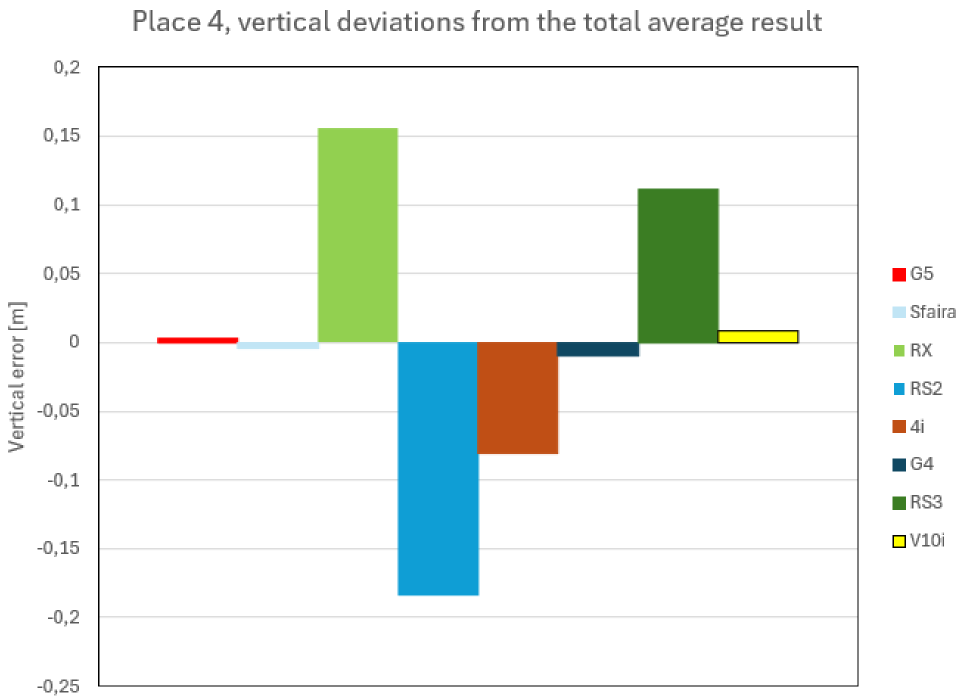

Image 17. Errors in the height direction at measurement location 4, compared to the average of the measurement results of the devices.

Measurement location 5

In measurement location 5 (

Image 19and image 18), the standard deviation was 18.0 mm, which was surprisingly a little smaller than in location 3, despite the fact that location 5 had trees much closer and it was the most difficult location to get devices into RTK FIX mode. Often the device first had to be moved a few meters away from the above location and then when measuring location 5 was slowly approached, the device remained in RTK FIX mode and the measurement could be made at location 5. The difference between South's devices was that the G4 reached the fix slightly faster than the G5, but the latter stayed well fixed after achieving it. For the Emlid RS3, this place was the most difficult to reach FIX mode and possibly it is also reflected in the height measurement result. South G4 and FJD V10i were the only devices that reached the 2 cm accuracy class at this measurement location (Image 20). The error of RS2 and especially Sfaira was clearly larger (approx. 5 cm and 7 cm, respectively). The measurements fit into a circle with a radius of about 70 mm.

In the vertical results of measurement at location 5 (Image 21), one can speculate whether the Alpha 4i suffered from the shorter rod used in the measurements, as a result of which the measuring device was 20 cm lower near the branches than with the other devices. As expected, the errors were large. Perhaps the surprise was the small error of South G4 and FJD V10i.

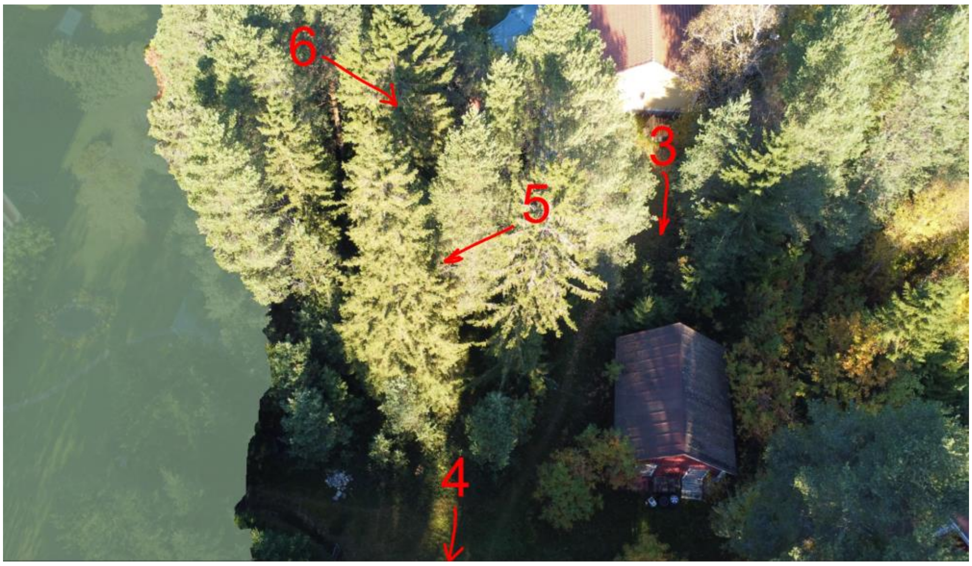

Image 19. Measurement locations 3, 4, 5 and 6 photographed from the air with a drone.

image 18. Measurement location 5, photo taken from ground level..

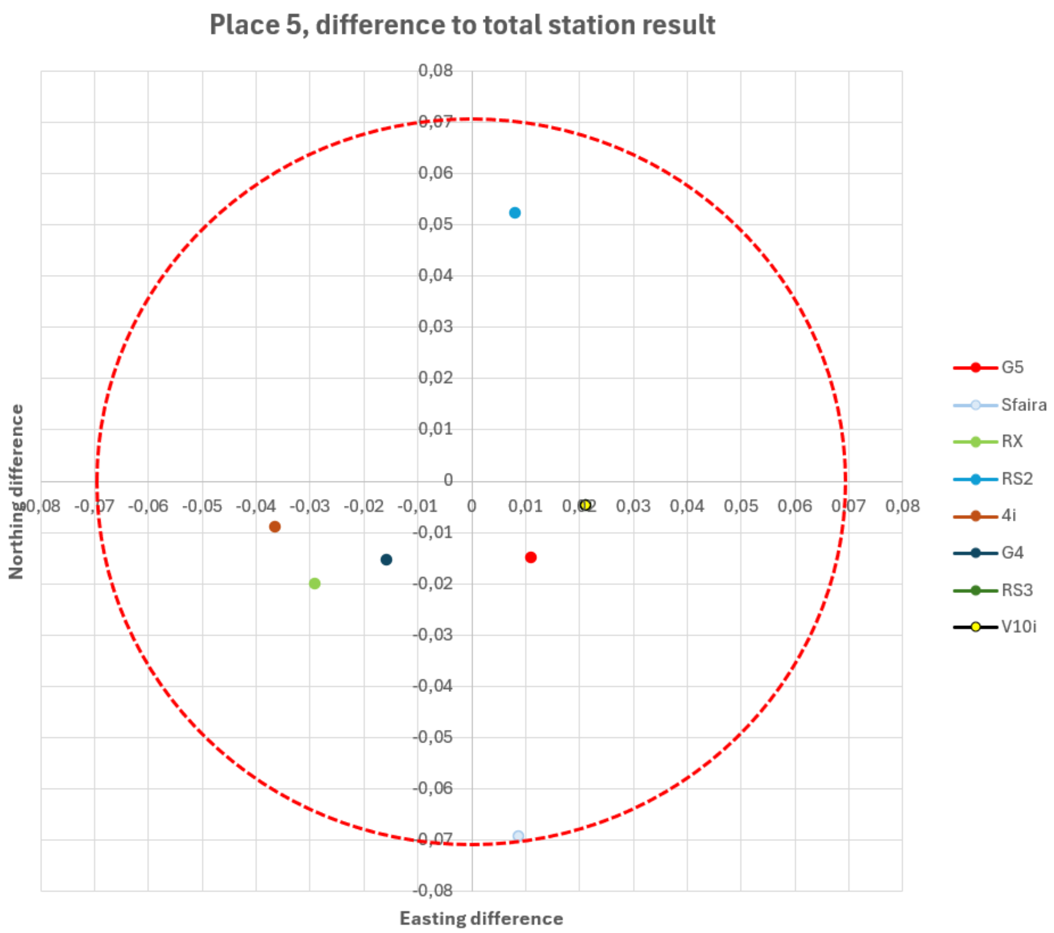

Image 20. Results of measurement site 5. The origin of the measurement is measured with a tachymeter .

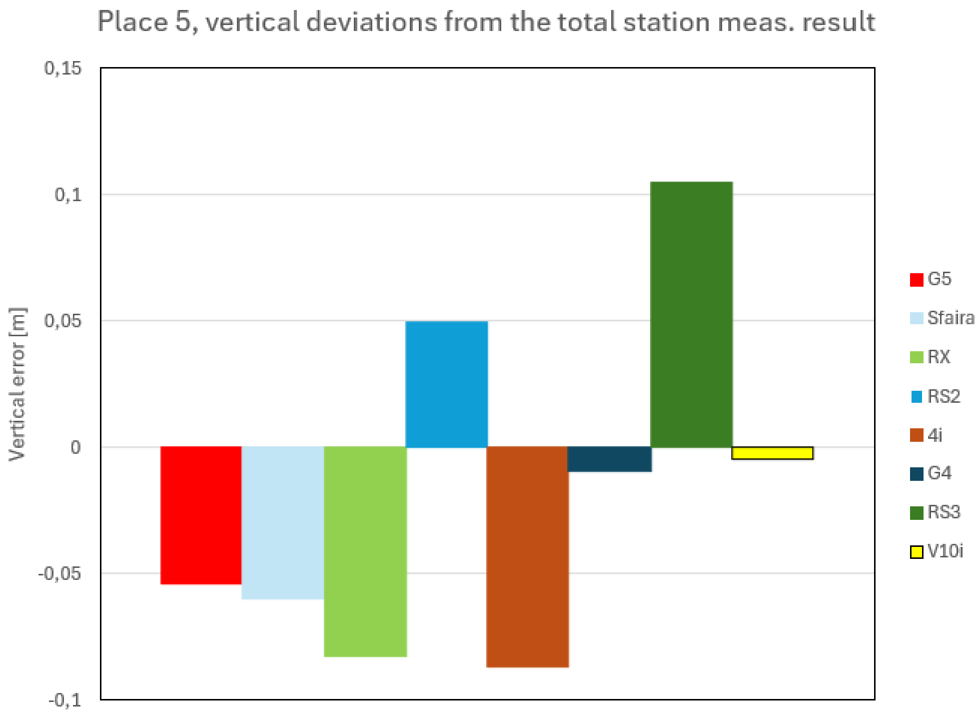

Image 21. Errors in the height direction at measurement location 5, compared to the reading given by the tachymeter.

Measurement location 6

Measurement site 6 (Image 22) was visually the second most difficult and it was also the second most difficult to reach the RTK FIX mode with the devices. The branches of the neighboring spruce caught the measuring pole directly. Considering this, the results (Image 23) were very surprising: the standard deviation was 8.9 mm and all the results fit in a circle with a diameter of 38 mm. And the surprises continued to the extent that the best result was given by Emlid RX and the second best by Sfaira One Plus, i.e. both devices equipped with a rod-shaped antenna gave a good result here. The worst results were given by Alpha 4i and South G4, but their errors were also in the 3-4 cm range, which is acceptable considering the quality of the site (spruce branches very close to the measuring pole). However, there was an open sky in one direction from the place, which can explain the fact that all devices achieved at least a reasonable result.

The vertical measurement (Image 24) gave variable results. With several devices (South's devices, RX, RX and V10i) the error was at most 2-3 cm, but with two devices (4i and RS3) the error was clearly larger, 10 cm on both sides.

Image 22. Measurement location 6 photographed from the ground.

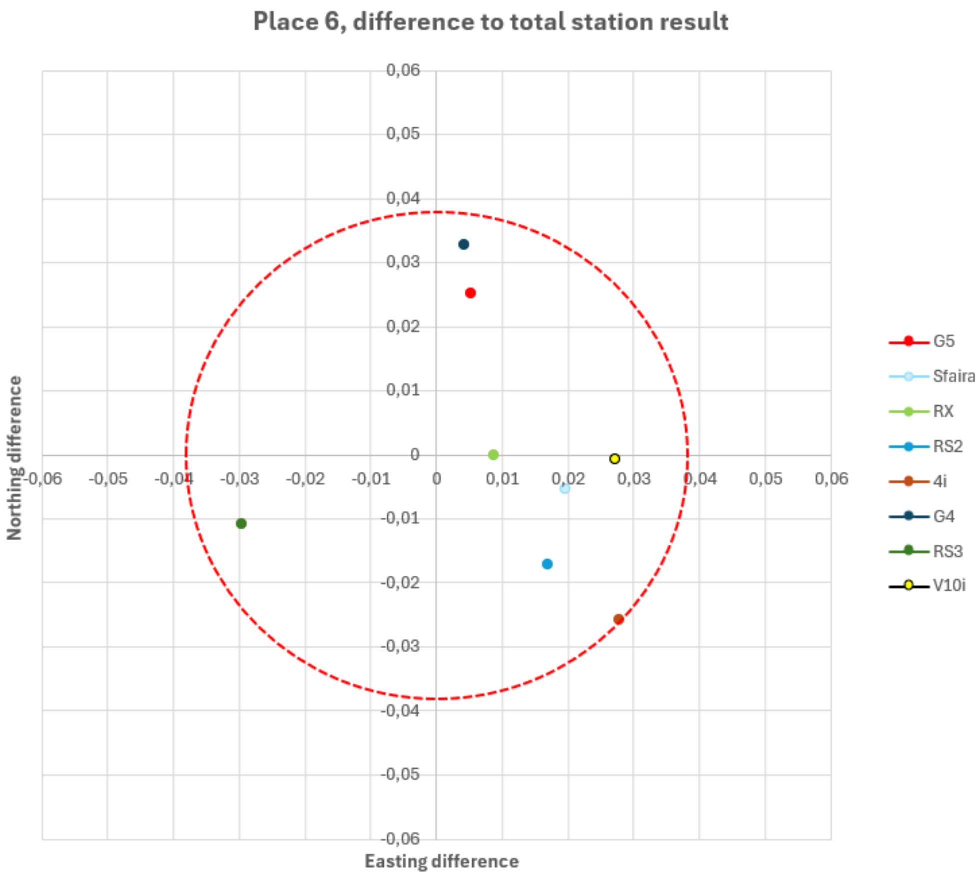

Image 23. Results of measurement site 6. The origin of the measurement is measured with a tachymeter .

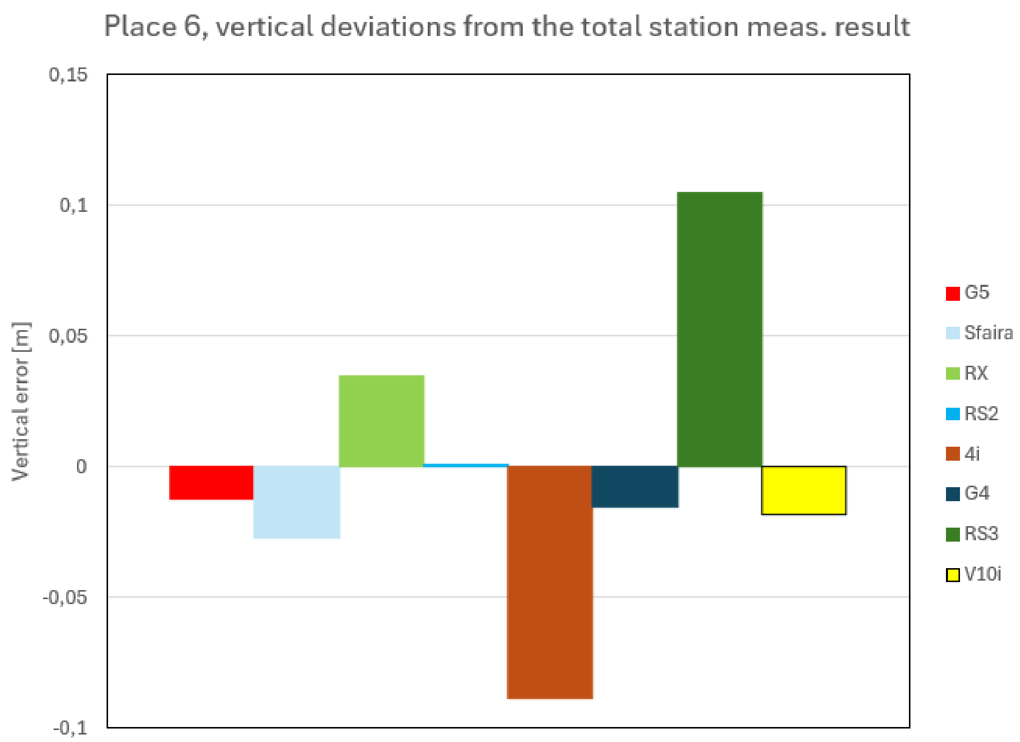

Image 24. Errors in the height direction at measurement location 6, compared to the reading given by the tachymeter.

Final results

The final results can be divided into two parts: the horizontal accuracy of the NE directions and the accuracy of the vertical direction. The NE measurement results table (Table 3) shows the direct distance of the measured point in the xy (NE) direction from the zero points of the measurement locations, as the average of all points measured with each device, and the value is centimeters as a deviation from the correct value. The table is arranged in order of superiority according to the average error. NE - in terms of accuracy, South's devices G4 and G5 and Emlid RS3 were equally good and the FJD V10i was not far behind them. It can be said that all the first four devices reach an accuracy class of about 2 cm in NE measurements. Since the RS+ was only able to measure two of the six locations, it was not included in the final evaluations. The NE standard deviation is calculated as the standard deviation of the averages. When you look at it, the tip is flat, with the South G5 being slightly but still better than the other tip devices. The good result of Alpha4i with the smallest NE standard deviation of the entire test and the pretty poor result of Emlid RX can be considered as surprises. For RX it is mainly due to the large error of measurement location 2 (near the wall). The size of the standard deviation gives an indication of whether the with the device, a clearly wrong result can be expected somewhere, i.e. a lower value is better. One can also speculate as to whether RX, Sfaira and RS2 suffered from being measured on only one individual device and Sfaira only once.

	Device	NE average error [cm]	NE standard deviation [cm]
1.	**South G4**	1.58	1.13
2.	**South G5**	1.65	0.93
3.	**Emlid RS3**	1.71	1.05
4.	**FJD V10i**	2.33	1.05
5.	**Alpha 4i**	2.91	0.79
6.	**Sfaira One Plus**	3.09	1.93
7.	**Emlid RX**	3.41	4.74
8.	**Emlid RS2**	4.01	1.74

Table 3. Final results as the mean of the NE measurement error and NE as the standard deviation of the measurement error, unit of centimeters.

In the accuracy of the vertical direction (Table 4), there was clearly more dispersion in the averages. The measurement table shows the difference from the zero point of the heights, as the average of the absolute values of the error (because there are both positive and negative numbers in the readings), all measurement points are included and the value is in centimeters as a deviation from the correct value. The biggest surprises were that the Emlid RS3 was clearly worse in the height measurements than in the NE measurements and the FJD V10i was clearly better. There were 2 places in the measurements (4 and 6) where the height error of the RS3 was large. The results of the best ones, i.e. FJD V10i, South G4 and South G5, were surprisingly good considering that the measurement accuracy in the vertical direction should be clearly worse than in the horizontal direction.

In the standard deviation of the vertical direction, the top of the top three is clear, with FJD clearly having the smallest standard deviation. The differences are large, as is in the average height result. All of Emlid's devices have a surprisingly large standard deviation of the height measurement, and Sfaira is on the same level with them , whose result can be assumed to have been influenced by the small size of the antenna. Alpha 4i, on the other hand, has a small vertical standard deviation, which means that Alpha4i can be estimated to measure a consistent result in both horizontal and vertical directions, not the most accurate, but without bad errors. On the other hand, with Emlid's devices, the large standard deviations are caused by large errors in a few places. Especially for the RS3, this is a surprise because it is so accurate in NE measurements. However, RS3 was measured on two individuals, a total of 4 times, and while the NE results were so good in the same measurements, the height measurement results were worse than expected.

	Device	Height average error [cm]	Height standard deviation [cm]
1.	**FJD V10i**	1.21	0.73
2.	**South G4**	1.86	1.30
3.	**South G5**	1.96	1.80
4.	**Sfaira One Plus**	3.76	4.51
5.	**Emlid RX**	4.88	6.04
6.	**Emlid RS3**	5.08	4.78
7.	**Alpha 4i**	6.28	2.66
8.	**Emlid RS2**	6.47	6.90

Table 4. Final results as the average of absolute values of height measurement errors, unit of centimeters.

The final results are presented in the table (Table 5) as an average, so that the horizontal (NE) result is taken twice in the results, because it has 2 values, the north coordinate and the east coordinate, and the height only once. The Emlid RS3 fell from third place in the NE measurement results to fourth place in this table due to relatively poorer height measurement accuracy. FJD V10i, on the other hand, clearly improves its positions to the level of South G5 with its very good height measurement result. As a final assessment, we can say that the top 3, South G4 and G5 and FJD V10i, gave a consistently good result and are deservedly in the top places. The middle group Emlid RS3, Sfaira One Plus and especially Emlid RX are those that can give a very accurate result, but in another place the result deviates more from the right one. That is, they have a little more dispersion in the results depending on the quality of the measurement location. Emlid RS3 differs from these with a clear difference between the accuracy of the horizontal and vertical directions. An error in the height measurement of two points prevented it from entering the medal positions. At times, RS3 was also challenging to get into FIX mode at some points. It is interesting to note the placements of the 1408 channel devices (FJD, Alpha and Sfaira), where they are relatively close to each other in the results of the NE direction, but there is significantly more dispersion in the height results. One can speculate that if the receivers or at least the receiver circuits are from the same manufacturer, the differences in performance are due to the antennas and the accuracy of the IMU or tilt compensation. These devices also had differences in the number of measurement times in the test. Sfaira was measured only once with one device, Alpha 4 times with one device and FJD 4 times with two devices. Increasing the average value should in principle reduce at least the errors caused by random error sources, so taking that into account, Sfaira's ranking was good. A total of 4 first places in the final results went to devices that were measured 4 times and with two different devices each.

When the 3D standard deviations are also taken into account, the top three stands out (Table 5). South G4 is placed at the top because of the average of the smallest measured 3D error, but with a different weighting, the order could be different. The Sfaira One Plus comes surprisingly close to the Emlid RS3 in both the mean and standard deviation of the 3D error. Alpha4i stands out from the crowd with a remarkably small 3D standard deviation, and for that reason it could be moved up a couple of notches in the table because it gives such a consistent result. The RS2 is an old device and is no longer a relevant benchmark. One can guess how much the Emlid RX's result reflects the small size of the antenna, as it differentiates it from the Emlid RS3. The 3D average error of Emlid RX was close to Sfaira's result, but the 3D standard deviation was clearly larger in RX.

	Device	**3D average error [cm]**	**3D error standard deviation [cm]**
1.	**South G4**	1.67	1.19
2.	**South G5**	1.75	1.22
3.	**FJD V10i**	1.96	0.94
4.	**Emlid RS3**	2.83	2.29
5.	**Sfaira One Plus**	3.31	2.79
6.	**Emlid RX**	3.90	5.17
7.	**Alpha 4i**	4.03	1.41
8.	**Emlid RS2**	4.83	3.46

Table 5. The final results as averages, taking into account the NE measurement error weighted by a factor of 2 and the height measurement error weighted by a factor of 1, unit of centimeters. The rightmost column shows the standard deviation of the 3D averages in centimeters.

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