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On the accuracy of GNSS in Forests

A test of consumer-grade GNSS equipment, smartphones and open-source

postprocessing software under forest canopies, for mapping of forest species.

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Abstract

The forests are home of two thirds of the red listed species in Norway. To safeguard these species when doing forest management, it is important to know where their respective biotopes are. When mapping species the Global Navigation Satellite System (GNSS) is often used. However, forest canopies also represents a challenge for this technology. In Norway, volunteers and hobbyists do most species mapping and it is expected that mappers will apply smartphones for obtaining coordinates in the future. This thesis assess how smartphones, as GNSS units, function under forest canopies.

The smartphones running the new versions of the Android operating system now allow GNSS raw parameters to be captured and stored. With these parameters, enhanced coordinates can be calculated using postprocessing software and additional correction data. Two smartphones and one GNSS-only device, the Samsung Galaxy S8, the Sony Xperia ZX Premium and the Emlid Reach, were tested. The coordinates from the devices were compared to reference points, which were set up in different forest environments. The devices were also tested in a clear sky environment. RTKLIB was used to postprocess the parameters from all devices by using different postprocessing algorithms. There were no clear indications of different forest densities was important for accuracy and precision. However, the effects of forest canopies on GNSS signals when compared to the clear sky environment was distinctly.

The Emlid Reach device was able to yield centimeter accuracy when using carrier-phase measurements, with the use of differential corrections from a nearby base station. However, RTKLIB was unable to contain precise coordinates from the Samsung Galaxy S8 carrier-phase measurements, and the Sony Xperia XZ Premium was unable to even record them.

In addition, forest canopies turned out to be a huge obstacle for carrier-phase measurements. This resulted in false fixes with offsets up to several hundred of meters. When, however code-based measurements (pseudoranges) were used, five-meter accuracy could be obtained for the Emlid Reach and ten-meter accuracy for the smartphones, within five minutes of data collection under forest canopies. By accumulating data over several minutes, the effect of forest canopies could be compensated. However, if the device captured data for less than five minutes, the accuracy was less predictable.

If a device output a single coordinate, the coordinate is unlikely to hit within five meters from the true location when used under a forest canopy. This suggests that positions assessed of forest living species, mapped by hobbyists, should be given a wider buffer zone than suggested in the dataset itself. This is important for taking effective measures to reduce both the loss off biodiversity and the conflicts between foresters and environmentalists.

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1   Introduction

Today, the use of satellite based-navigation systems is an important tool in many disciplines. The Global Navigation Satellite System (GNSS) is all available navigation satellite systems, including the established American and Russian satellite systems, GPS (Global Positioning System) and GLONASS (GLobal NAvigation Satellite System). It also includes the relatively new systems like the Chinese BDS (BeiDou Navigation Satellite System), the Japanese QZSS (Quasi-Zenith Satellite System), the Indian IRNSS (Indian Regional Navigation Satellite System) and the European Galileo. These satellites are placed in orbit and transmit coded electromagnetic signals back to Earth. By observing and analyzing signals from several satellites, a GNSS device is capable of calculating its position in both space and time. Although the system has many capabilities, in ecology the GNSS devices are mostly used to obtain positions of for example insect traps, plant measurement plots, soil boring test locations, tree ring age measurement locations and species occurrences.

In ecology, the science of interaction among organisms and their environment, precise positions are important for any spatial analyses. Today, species mapping is based on the principle of crowd-sourced science, which means that data are collected by both hobbyists and professionals all over the world, and committed to databases like Species Occurrences (Artsobservasjoner.no) in Norway, the Swedish Species Gateway (Artportalen) or the Global Biodiversity Information Facility (GBIF). GBIF maintains a huge dataset of species occurrences worldwide and provides an open-access website for everyone who would like to download it [32]. These kind of services are heavily used for ecological analyses, natural resource management and decision making. However, these kinds of databases provide little information on how the geographical positions were obtained. A single coordinate output from a GNSS device does not tell much about how likely this coordinate is to be correct.

Since GNSS requires uninterrupted access to the navigation satellites, the use of GNSS in semi-open locations yields unpredictable results. Trunks, branches or tree crowns might block, reflect or otherwise disturb the GNSS signal, and this problem is expected to increase with increased forest density. In many cases the use GNSS under forest canopies is a common part of the mapping workflow. By not issuing the problems with signal degradation in forest environments, this mapping might fail to contribute with the right information for the natural resource management. It might also be hard to take these coordinates into consideration, because the presented coordinates does not provide any information on how far it is expected to be from its true position. The consequence could be unintentional loss of biodiversity or ineffective measures to safeguard it. This is especially important in Norway because the forest is home to close to half of Norway's red listed species [4] in addition to being an important commercial resource. Methuselah's beard (*Usnea longissima*) is an example of a non-moving species which require humid old grown forests habitats with a certain structure. This species has lost many of its known habitats in Norway due to forest management since 1980 [3]. The most important habitats would be degraded if clear-cut and should be left untouched in the interest of conflict reduction.

About 130 000 fungi occurrences and 314 000 plant occurrences in Norway are submitted along with an alleged accuracy below five meters [16]. Previously, I've experienced that collected coordinates might have offsets of up to hundred meters, without the device giving any indications or performing any quality check. Considering this, there might be a substantial portions of misplaced occurrences in the GBIF-database, and the knowledge about how GNSS devices act under signal-degraded locations should be investigated.

There are a number of different GNSS devices available on the market. Their capabilities and reliability are designed for different purposes and price variate accordingly. In surveying, construction and certain types of sciences, high accuracy is required. These kinds of devices, referred to as survey-grade devices, might not be as accessible due to their high cost. Consumer-grade devices represent a cost-effective

alternative for private users, underfunded projects and small businesses, who might not need extreme accuracy or reliability.

As of 2018, the biggest group of GNSS devises is assumed to be smartphones. Smartphone GNSS devices are by some regarded as its own category, denoted as "smartphone-grade" devices [23]. Smartphones are multi-functional-devices capable of doing a wide variety of different tasks other than making phone calls. In essence they are more like minicomputers and are used for texting, web-surfing, playing media files and taking pictures. These are just a few examples of their functionality apart from obtaining a geographic position. The devices are open for developers and consumers to introduce their own programs, commonly known as "apps" (short for applications). To facilitate writing programs for the platform, an Application Programming Interface (API) is provided. The API is the link between the device and the "app", and provides the app with input information. Previously, the Android API only provided geographic information as coordinates, but the newer versions of the Android operating system, Nougat and Oreo, also provides the GNSS raw parameters which can be used to calculate coordinates [9]. In addition to being able to record raw GNSS parameters, some of the new smartphones are also capable of observing satellites from the new European Galileo constellation. The Samsung Galaxy S8 even support carrier-phase measurements, which has previously been limited to survey-grade devices.

Access to stored GNSS raw data makes it possible to calculate improved coordinates on the computer afterwards. This method is known as postprocessing and offers a lot of possibilities. The most significant advantage of this technique is that it allows coordinates to be calculated by applying different algorithms. Different algorithms can utilize different parts of the available GNSS raw parameters. In postprocessing it is even possible to utilize "future" measurements relative to the calculated coordinate. Observations from a base station with a known and fixed position may be applied to correct for signal delay caused by for example local atmospheric effects. These calculations are known as differential. Also, additional data, like clock and ionospheric corrections, precise satellite ephemerides, earth rotation parameters or gravity corrections could be added to enhance the solutions.

The downside of using a smartphone as a GNSS device, is that it is in fact a multi-functional-device. Its priority might not necessarily be to provide the best GNSS accuracy, and it is likely to be compromised by power-saving functions or internal electrical interference. While some mappers might invest in a GNSS-only device, like a Garmin device, it is likely that multi-functional-devices like smartphones are used for most species mapping. Thus the results from testing the smartphone devices are likely to apply to most species registrations in the future.

If the devices are allowed to observe satellite signals for several minutes, they will accumulate data and are expected to preform better. This is known as static measurements. GNSS users will typically not spend too much time to get a geographical position, but it is useful to know how much time is needed to obtain a precise coordinate. If the user wants a coordinate with sub-meter accuracy, the user should know how much time is needed to preform those kinds of accuracies. This thesis also addresses how short observations are affected by different environments compared to longer observations.

This thesis focuses on the use of consumer-grade GNSS devices for static measurements. While most mappers are likely to use real-time coordinates, this thesis addresses the potential of postprocessing coordinates by using consumer-grade devices in combination with open-source software.

If a forest living species is mapped by using a poor GNSS device, it is likely to miss the true location. In this thesis two smartphone devices were tested in order to know if it is possible to use smartphones for precision mapping in forests. By testing these devices in forests it is possible to find out what kinds of accuracy could be expected from smartphones. Also, by testing different approaches it is possible to learn the best way to generate a accurate coordinate. The best method should whether be

implemented or a more realistic measure of accuracy should be used.

2 Theoretical framework

2.1 Constellations

Since ancient times, humans have looked for the stars to find their way during night-time. Understanding how the stars move relative to the earth, gave them the ability to ascertain their direction, time of year and position. For example, the Pole star, which is a part of the Ursa minor constellation, indicated direction of north. This star is aligned with the Earth rotation axis, which means its position is fixed relative to us. Navigators all over the northern hemisphere, used this knowledge to travel across oceans.

The constellations used in today's navigation are human made; In GNSS a constellation is a set of satellites which provides its own navigation system. Satellites are several small moons invisible to the human eye, which are broadcasting coded signals, which could be received by devices on Earth. When at least four satellites are visible, the device is able to calculate its position and time [6].

2.1.1 Global Positioning System (GPS)

The GPS is one among many constellations, this constellation contains of several satellites which are orbiting Earth in predictable ellipsoidal orbits. The GPS project, first known as Navstar GPS, started in 1973 as a military application run by the United States Department of Defense (US DoD) [6]. It took only a few years before they started launching the first generation of experimental satellites. After several years, the experience gathered from the first generation of satellites had proved the concept of space based radio navigation, and the launch of the second generation of satellites, the known as the Block-II satellites, began in 1989. The system was utilized during the Gulf War between 1990 and 1991, but it was not declared to be at full operational capacity (FOC) before 1995[6].

In 1983 the Korean Air Lines Flight 007 set up a flight between Anchorage in Alaska and Seoul, South Korea. By an accident the airplane drifted off and flew towards the Kamchatka Peninsula in the Soviet Union. The plane was shot down by a Soviet interceptor, resulting in 269 casualties. After this accident, the U.S. president Ronald Reagan announced that the GPS system should be made available for civilians to prevent such accidents in the future [40]. However, the process of making the GPS system open to the public was not issued before 1996 [6]. Decoding of the L1 Coarse/acquisition signal (L1 C/A) was made publicly available, while the Precision code (P-code) remained unavailable. However, the L1 C/A code remained intentionally degraded until the year 2000. This intentional signal degradation was called Selective Availability (S/A) and when deactivated the usability for civilians improved [6]. Today, the third generation of GPS satellites are being employed. These are not capable of even activating S/A [6].

2.1.2 Global Navigation Satellite System (GLONASS)

As a consequence of the Cold War, the Union of Soviet Socialist Republics (USSR) military started the development of their own satellite based navigation system. The first satellite was launched in 1982 and the constellation was first declared to be at FOC already in 1993. However, because of underfunding during the 1990's, the system was not maintained. During the 2000's the restoration of GLONASS started, and it was declared to be restored to FOC in 2011 [21]. The GLONASS signals has been open to civilians since 1999 [6]

2.1.3 Galileo

In contrast to GPS and GLONASS, the European navigation satellite system Galileo is a non-military system. It it developed and maintained by the European Space

Agency (ESA) in the interest of being independent on other nations navigation systems. Galileo provides both an open service and a commercial service for paying costumers [6] and the system is scheduled to be at FOC in 2020 with 27 operational satellites [21].

2.1.4 BeiDou

The BeiDou-1 system was operational in 2000, but limited to users located in China. The Chinese officially joined the Galileo project in 2004, but left to initialize the BeiDou-2 project, their own satellite system, in 2008. Both the BeiDou-1 and 2 aims for regional coverage limited to Asia, but the BeiDou-3 aims to be a global positioning system. By 2018 there are nine BeiDou-3 satellites in orbit [39].

2.2 RINEX

All navigation satellites constantly broadcasts coded signals back to Earth. Today, the signals from navigation satellites are available at all times everywhere. While most devices just uses the signal to either obtain a coordinate or a time estimate in real-time, it is also possible to store the raw data from the receiver for later use.

A lot of devices store their GNSS data in proprietary file formats, which is a problem because they are hard to analyze. RINEX (Receiver INdependent EXchange format) is an open format for storing GNSS information. It was invented both to serve as a common file format to make it easier to work with GNSS units from different manufacturers [19]. In contrast to raw formats, like Topcon's .tps-format or u-blox's .ubx-format, the RINEX format is human-readable, which means that all data are stored as numbers or letters in a text-file. This makes it easier to manually assess or correct the data, as well as to develop applications to use it. This also makes GNSS data more accessible to scientists.

2.2.1 Observation data

The RINEX-format consists of several separate files, which holds different categories of data. The observation file, with the filename extensions .obs or .<%y>o (<%y> for year), holds the following parameters from each satellite:

Pseudorange The pseudorange is the perceived distance between the device and the satellite. It is calculated by utilizing the time-code, which is modulated on to the carrier-wave. The carrier-wave is the radio-wave the satellite uses to broadcast information. This message holds a time-code generated by the satellite and by comparing this time-code to when it was received by the device, a time-lag is calculated. This time-lag translates to the approximate range between the satellite and the receiver, when multiplied by the speed of light, as shown in equation 1.

$$pseudorange = \Delta t \times c \tag{1}$$

The light travels at a speed of approximately 300 000 m/s, which means that an offset of only a microsecond ($\frac{1}{1000000}$ of a second) will translate into an offset of 300 meters relative to the satellite. All satellites holds a precise atomic clock, however these are both heavy and expensive. The clock of the receivers, in the other hand are inexpensive, and their time needs to be estimated and set regularly.

Doppler The doppler effect is a change in the frequency of the carrier-wave, due to the velocity of the satellite relative to the receiver. The satellites are traveling by a few km per second [21], and the values are reflected as positive if the satellite is approaching [20].

Carrier-Phase measurements   When the GNSS device starts collecting data, it accumulates the number of whole cycles of the carrier-wave from each satellite [10]. These phase measurements are often used when high accuracy is needed. However, for these kinds of measurements to be correct, the device need to keep track of the satellites without any interruptions, known as "cycle-slips" [21]. In the case of the L1 signal from GPS, which has a fixed frequency at 1575.42 MHz, one full cycle represents approximately 19 centimeter [6]. The length of the phase will variate slightly due to the velocity and direction of the satellite, thus increasing or decreasing the rate of observed cycles. This is why the carrier-phase measurement is also known as the "accumulated Doppler range" [27].

Signal to Noise Ratio   This value indicates how strong the signal is compared to the background noise. If a receiver is in a signal-degraded environment, it is likely to receive weak signals. Weak signals are more likely to have a higher bit-error-ratio, which results in a disturbed or unreadable code. Thus this value serves as an important quality check and weak signals could be excluded from calculations [5].

2.2.2   Navigation message

The navigation message, which is also modulated on to the carrier-wave, holds the information on satellite orbits [6]. Basically they are Kepler ellipses, which points out the satellites position at every given time. These data are also known as ephemerides and are crucial for the GNSS device to be able to calculate its position [21].

2.3   Base stations

When high accuracy and precision is needed, there can be added additional data from a base station. The base station is stationary, which means that perceived movements or offsets are due to inaccuracies in the GNSS system. Factors which generate inaccuracies can be due to air humidity [25], ionospheric refraction [24] or changes in the gravity-field [25].

When a base station is used, the device collecting data is called a "Rover". When processing data from the rover, the mobile GNSS device, the offsets can be canceled out by using the base station. The length between the base station and the rover, is denoted as the "baseline". Baselines with a length below 10 km are considered to be short [34]. If longer baselines are used, the atmospheric effects detected by the base station might not apply to the rover and they might not yield precise coordinates.

Open-access observations from base stations are provided by The EUREF Permanent GNSS Network (EPN)[29] or the International GNSS Service (IGS) [33], and could be downloaded from a ftp server. However, there are only five active EPN base stations [29] and only one active IGS base station located in Norway [33]. This makes open-access base station data difficult to use for certain applications, because the distance between the base station and the rover are often too long. The closest EPN base station to Ås had a baseline of approximately 25 km [29].

The Norwegian mapping authority has a much denser set of base stations, which is used to provide the CPOS service [22]. Observations from these base stations however are not publicly available.

2.4   RTKLIB

RTKLIB is a package of applications used for GNSS Positioning [15]. It is distributed under the Open-Source BSD 2-clause license [15], which means that its source-code is available and that users are free to study the source code, change it and redistribute it, for free.

This piece of software is capable of analyzing the GNSS raw parameters and calculate enhanced coordinates. By using RTKLIB one can push smartphone devices

to yield more accurate coordinates than the smartphone would give in real-time. In comparison to proprietary software it is open to everyone to use. This is important, because it makes it easier for users to implement the conclusions and results from this thesis. Also, since it is open-source, it is possible for students to assess the source-code, improve it or achieve a better understanding of how GNSS works.

The part of RTKLIB developed for postprocessing is called "rnx2rtkp" [36]. This program is run through a command-line interface, which means it is run in a terminal, command prompt or a script and allows the work-flow to be automated. When using a command-line interface application "flags" are used. These are equivalent to buttons or input options, which are commonly used in graphical-user-interfaces.

It is possible to choose from several different types of calculation algorithms within rnx2rtkp. This is done by applying the `-p` flag and the ID-number of the mode [36]. rnx2rtkp output a list of coordinates, with information on how many satellites were used, satellite geometry and a value known as Quality-flag. The quality-flag indicates what algorithm was used to calculate the coordinate.

2.5 Satellite obits

When the satellites are placed in orbit, they are given a state of eternal free fall. Earth's gravity constantly pulls the satellites, but Earth's movement around the Sun causes the satellite to miss. This causes the satellites to move in ellipsoidal orbits, which can be predicted by the Keplerian laws of orbital movements [21].

The orbits height above Earth determinate the properties of the orbit. The altitude of the determines what velocity the satellite should have in order maintain an orbit [21].

2.5.1 Medium Earth Orbit (MEO)

The GPS satellites are placed in Medium Earth Orbit (MEO) approximately 20 200 km above Earth [21]. Satellites at this altitude orbits the Earth and returns to the same position, relative to Earth, after two sidereal days (earth rotation relative to itself and the distant stars). This causes all satellites to be visible within two sidereal day [6].

To avoid collisions, satellites of the GLONASS constellation, were placed in orbit at the altitude of 19 100 km [11], which is causing them to move faster relative to Earth. A GLONASS satellite orbits Earth in 11 hours and 15 minutes [11].

The Galileo constellation however is placed in a higher orbit, at 23 222 km [12], causing the satellites to orbit Earth about every 14 hours [6].

2.5.2 Inclination angle

The inclination angle is the angle of the satellites orbital plane relative to the equator. This affects the constellations ability to cover the Northern and Southern hemispheres. The GPS system focus to cover the areas around the equator, and these satellites has an inclination angle of 55°. The satellites of the Galileo constellation has a slightly increased angle of 56° [6]. However, because Russia is located further to the North, the satellites in the GLONASS constellation has an inclination angle of 64.8° [6].

Figure 1a and 1b shows a skyplots from the base station located in Ås generated by the teqc software [38], and plotted by the teqcplot python script [38]. Skyplots are a way to illustrate how the satellites passes a receiver. The azimuth (figure 2a), the angle relative to North, is represented by the directions of the plot, North is 0° and South is 180°. The center of the skyplot represent the sky directly above the receiver, with an elevation angle of 90°. The elevation angle is the angle between the horizon and the satellite, as illustrated in figure 2b. Satellites towards the edges of the sky plot represents satellites of lower elevation angles.

The satellite free areas on these skyplots are direct results of the fact that there are no navigation satellites directly above the poles. As shown in figure 1a there are

(a) Orbits of the GPS constellation

(b) Orbits of the GLONASS constellation
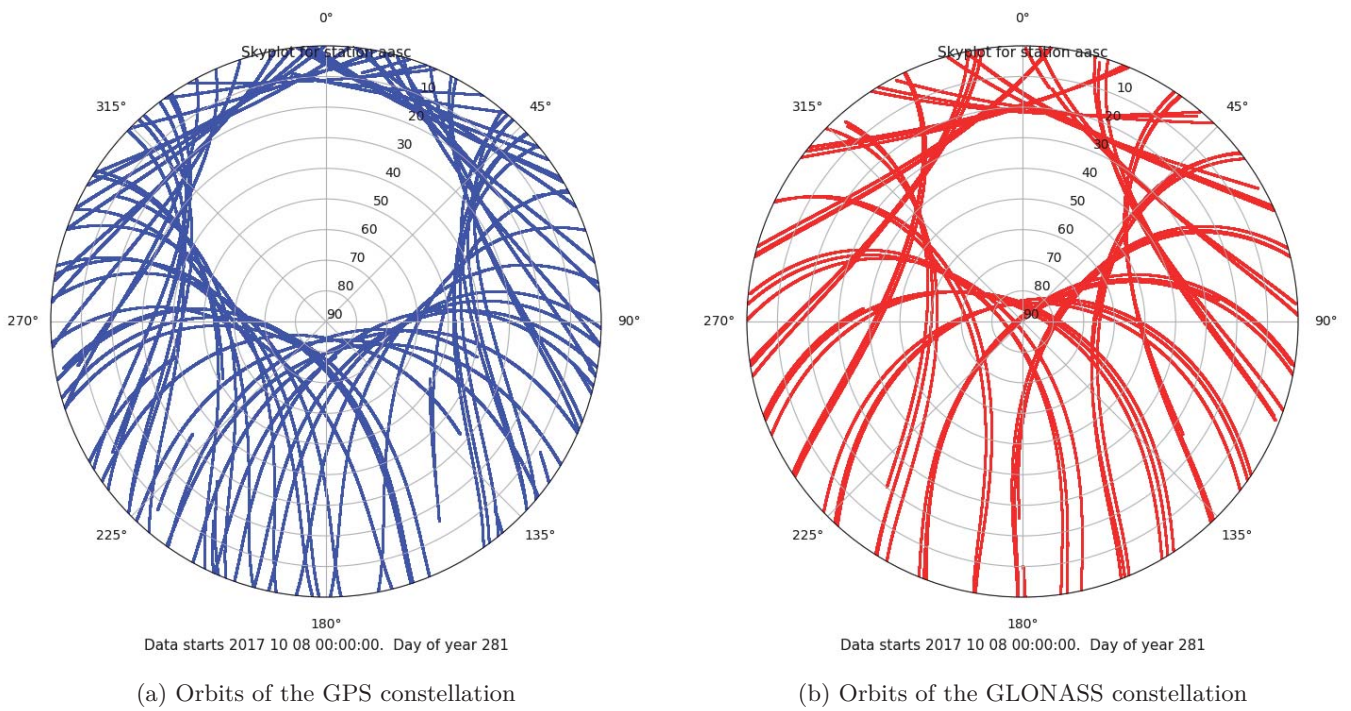
Figure 1: Skyplot from the base station in Ås

(a) Azimuth
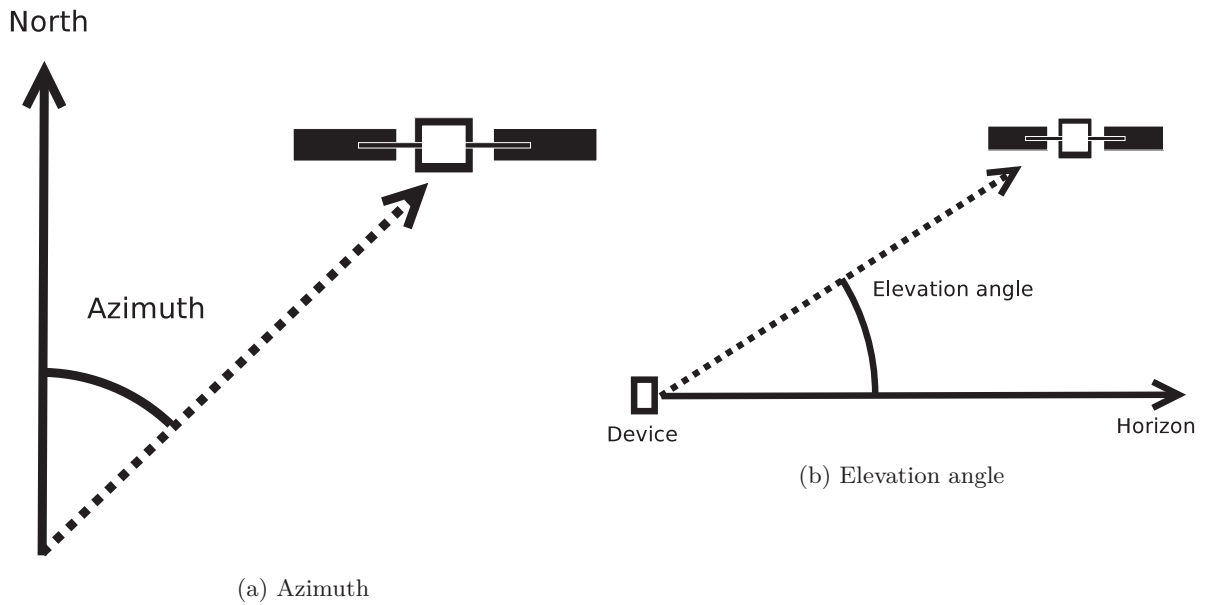
(b) Elevation angle

Figure 2: Elevation angle and azimuth

never any GPS satellites directly above Ås and most satellites signal from the North, has an elevation angle lower than 15°, which makes them unsuitable for calculations [34]. The consequence of this is that GPS devices in Norway mainly depend on open view to the South [7], and few satellites are available in canyon-like environments. However the GLONASS constellation, illustrated in figure 1a, shows a pattern where the elevation angle of the satellites are improved.

This is important to consider when using GNSS in forests, because forest biomass is more abundant around the edges of the skyplot. If satellite signals are only available

from lower elevations, and not from above, the device would not receive any undisturbed signals. Thus the amount of the visible clear sky through a forest canopy, would not matter, because these are satellite free areas.

2.6 Signal strength

Satellites close to the horizon, meaning that they have a low elevation, are more likely to transmit degraded signals compared to satellites of higher elevations. The same skyplots are shown in figure 3a and 3b, for GPS and GLONASS respectively. These plots illustrate that the signals from lower elevations are weaker, because the signal needs to travel through more of Earths atmosphere. The same effect can be seen when the Sun sets, which causes higher frequencies of the light to be filtered out by a thicker atmosphere, thus changing its color.
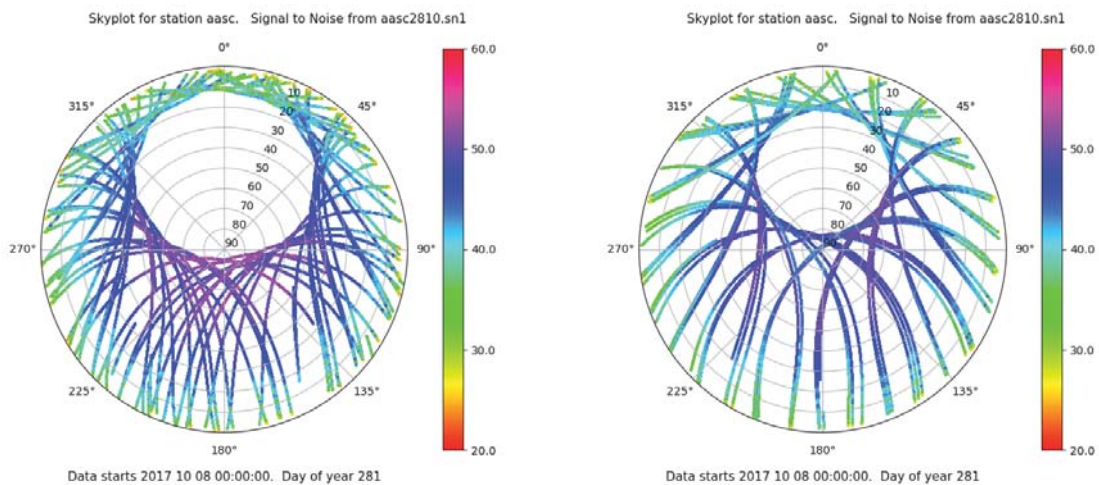
(a) Skyplot from the base station in Ås, showing the orbits of the GPS constellation. With signal to noise ratio.

(b) Skyplot from the base station in Ås, showing the orbits of the GLONASS constellation. With signal to noise ratio.

Figure 3: Elevation angle and azimuth

The frequencies GNSS uses, is chosen based on their transparency through the Earths atmosphere. The L1 band, which transmits the legacy C/A signal for GPS, has a frequency of 1575.42 MHz, which determines many of its properties. However, when the signals travel through the atmosphere, variation causes the signal to both bend and slow down, according to Snell's law [21]. This causes a longer perceived pseudorange. This is a issue when using receivers that exclusively rely on coded signals. However, this issue can be exploited and used to map air-pressure and atmospheric humidity, which also makes GNSS an important tool for climate scientists [18].

To meet this issue, some satellites emit an identical signal modulated to a carrier-wave of another frequency. A signal with another frequency will be reflected differently, thus the device will perceive them as having distinct pseudoranges. By using a dual-frequency receiver the atmospheric effects can be canceled [21]. The strength of the new L5 signal is higher than that of the L1 (figure 4), and could potentially make GNSS more resistant to signal degradation [21].
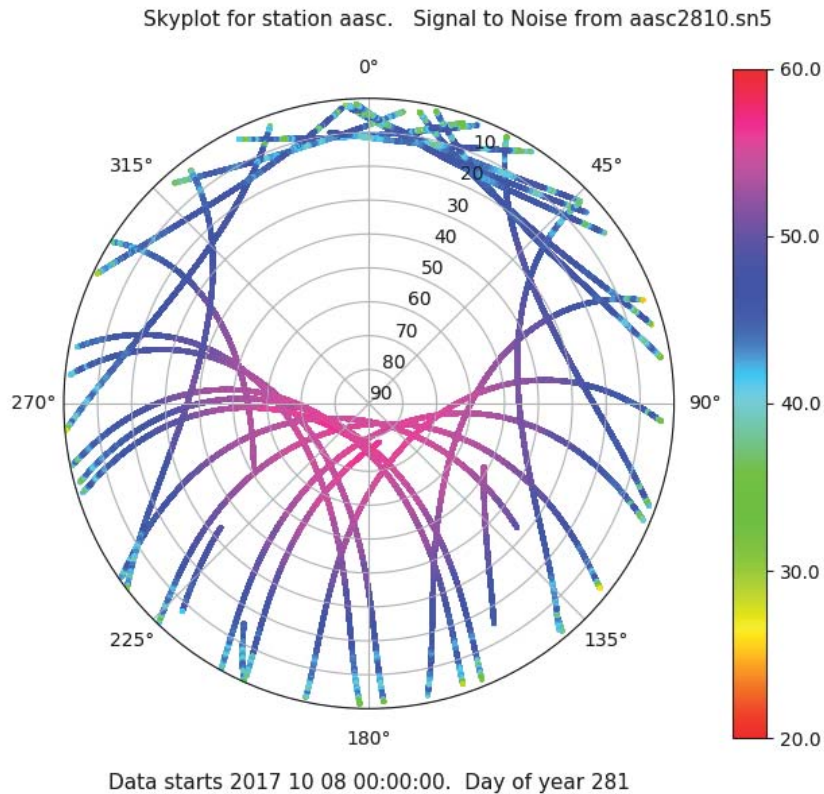
Figure 4: Skyplot from the base station in Ås, showing the orbits of the GPS constellation with the L5-band. Signal to noise ratio.

2.7 Correction data

The ionosphere, which is the upper part of the atmosphere from 60 km to 2000 km above earth is one of the biggest issues for refraction [21]. This is mapped by the International GNSS Service (IGS) who manages a network of base stations all over the world. Inaccuracies detected by the base stations are used to produce correction data [25]. The corrections are made public available on NASA's Crustal Dynamics Data Information System (CDDIS), along with Earth rotation data and satellite clock corrections.

The "Standard Product 3" (.sp3) includes precise satellite ephemerides. This is useful because Earths gravity field is not completely uniform [1], thus disturbing the orbits of the satellites [25]. All correction data are available one to two weeks after the observations are done [25].

However, since there are only one IGS base station available in Norway [33] most of the ionospheric correction data are expected to be interpolated. Interpolated correction data results in degraded accuracy [24], thus limiting its usability.

2.8 Power management

Battery life-time is a common issue for smartphones. In order to save power the Android devices has two oscillators. Oscillators are devices that is able to count

phases of the emitted waves from a material. These devices are used for time keeping. In a smartphone, the Crystal Oscillator (XO) is used for internal timekeeping. This oscillator however has a time accuracy degradation of 6 seconds per week, which makes it unsuitable for GNSS. The Temperature Compensated Crystal Oscillator (TCXO), has a higher power consumption, and is only activated when accurate time is needed [2].

Duty-cycle is a function that shuts down electronic components in a cycle in order to save battery lifetime. This function is used in Android devices. While the TCXO has to be on continuously to keep track of time, the GNSS receiver is turned on and off. This is not expected to affect the observations of code-based signals, but in order to count carrier-phases the device needs to be on continuously [2]. The expected results would be that only a few phases are counted, while the rest will pass by undetected.

This is important to keep in mind when using the smartphones, because some of the raw parameters might not append useful information.

3 Methods

3.1 Reference points

Several reference points in the clear sky environment were created by using a Topcon Legacy-E dual-frequency receiver with a PG-A1 antenna on a 2 meter GNSS Pole. To establish a web of reference points under the forest canopies, visual availability from an outside clear sky enviornment was required. This requirement was met by forests close to resent clear-cuts. By using free stationing (resection) close the forest edge, it was possible to meassure the reference points, under the forest canopy, by using a Topcon PS-103A total station (figure 5). All reference points were marked by an ID-number and the reference points altitude were considered to be at the top of each pole. The coordinates for the reference points under the forest canopy was calculated by using Norkart's GISLINE Landmåling (GISLINE Surveying).
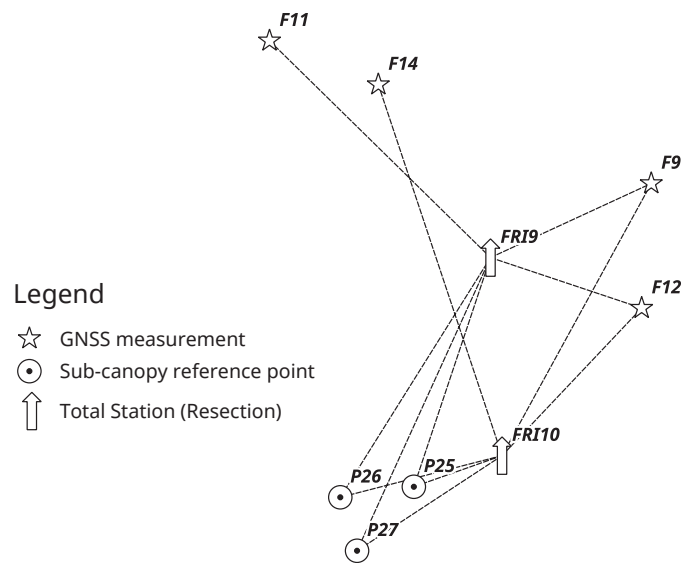
Figure 5: Use of Total Station, when measuring the reference points P25, P26 and P27

3.2 Forest density(Basal area)

In this thesis basal area was used as a measure of forest density and it was measured by using a relascope. This value quantifies the area occupied by tree-trunks, in square meters, relative to the area of the total forest floor. It is commonly used to estimate timber abundance. The basal area were counted for each reference point in order to catch up the variation within the locations. The trees were counted into tree different categories: Norway spruce (*Picea abies*), Scots pine (*Pinus sylvestris*) and deciduous trees. Both the Basal Area Factor (BAF) of 1 and 2 were used, which eventually could result in slightly different results depending on the forest structure. A mean of the two results were considered to be the true basal area. However, only the total basal areas were used.

3.3   GNSS data collection

In the data collection the devices were placed in the top of tribrachs with optical plummets. The devices were placed in the center of the tribrach. The bull's eye spirit level and optical plummet ensured that the devices were right above the reference point. The tripod were approximated to breast height (1.3 meters above ground). This setup is illustrated in figure 6 and 7.
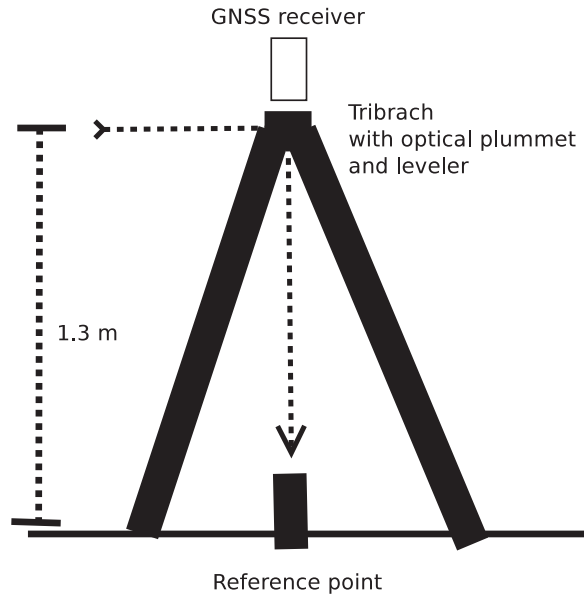
Figure 6: Setup used when collection GNSS data

The devices were set up on each reference point for sensing in half an hour before they were swapped. All devices were rebooted between each reference point and this cycle was repeated three times for each location. In total this yielded 108 separate log files for all the four locations.

One of the four locations was a clear sky control environment. At this location the direct results from the Topcon GNSS was used.

Figure 7: Setup for GNSS data collection, Emlid Reach

3.4 Rinex conversion and RTKLIB script-generator

To efficiently work with this amount of data a python script was written to link the observation files to the right reference point and basal-area value and convert all data into RINEX files that could be used in RTKLIB. A python script was also written to combine the navigation files and the correction data to the observation files, and output a script of rnx2rtkp commands. Examples of commandes generated with this script is shown in appendix A. When applied, all RTKLIB commands for this thesis would be executed in an automated manner.

3.5 RTKLIB modes

3.5.1 single mode (-p 0)

Single mode applies the code-based measurements (pseudoranges) and calculates single positions. This mode does not need either carrier-phase measurements [30] or any base station. The only data needed for this mode is the observations and the navigation messages.

3.5.2 dgps mode (-p 1)

dgps mode also uses the pseudoranges, but it includes a base station for correction. By matching the data between the basestation and the rover, corrections to the pseudoranges are made [30].

3.5.3 static mode (-p 3)

Static mode utilizes the carrier-phase measurements and compares them with a base station. This algorithm strives towards solving the phase-ambiguity as an integer value, if it succeed it will output a "fix"-position. If the ambiguity is solved, but as a float value, it will output a "float"-position. In this thesis, only the fix solutions were used.

3.5.4 ppp-static mode (-p 7)

The ppp-static mode was developed to be able to obtain precise positions without a base station. This mode utilize a combination of pseudoranges and carrier-phase measurements, but is expected to need several hours of data accumulation to converge to centimeter accuracy. Instead of using a base station, the ppp-static mode can utilize additional correction datasets [25].

3.5.5 Length of data accumulation

In the data processing the files were cropped to simulate how long the devices were allowed to accumulate data. All processing done started from the start of the observation file, and ended after a given time interval. The different time durations used are listed in table 1.

Normally one would cancel out the first few minutes of observations when doing static surveying. In this thesis however this routine were skipped on purpose, in order to observe the performance of short observations files. For a regular GNSS user short observations would be expected.

3.6 Calculation of coordinates

3.6.1 Median Accuracy

The output from rnx2rtkp is a coordinate list, these are denoted as solution files. These solutionfiles were filtered by using the Quality flag, as viewed in table 2. This

Table 1: List of time intervalls

	Convergence time
10	Seconds
30	Seconds
60	Seconds
2	Minutes
4	Minutes
5	Minutes
6	Minutes
8	Minutes
15	Minutes
18	Minutes
20	Minutes
25	Minutes
30	Minutes

had to be done because RTKLIB calculates the coordinates by using single mode (Q-flag 5) if the intended calculation fails.

Table 2: Modes with Q-flags used

-p	**Mode**	**Q-flag Nr.**	**Q-flag name**
0	single	5	single
1	dgps	4	dgps
3	static	1	fix
7	ppp-static	6	ppp

For each solution file the coordinates were converted to WGS 84 / UTM zone 32. A median from both the North and East axises were used. In comparison to using the average, the median is less affected by outliers. The distance of the median point from the reference point was calculated by using the Pythagoras sentence, which output the horizontal offset from the reference in meters.

3.6.2 Precision (2DRMS)

For precision twice the Distance Root Mean Square (2DRMS) was used. The value of 2DRMS represents the radius of a circle in meters. This circle is centered around the reference point and represents a 95% to 98% confidence interval for all coordinates. However, 2DRMS normally requires that the latitude and longitude coordinates to be Gauss distributed, which might not be the case for all solution outputs. To meet this issue, the proportion of coordinates within the 2DRMS boundary were calculated. This was done to check if the confidence circle actually covers 95% to 98% of the coordinates. Points far from the known location will also drastically increase the overall 2DRMS value. This value is relevant for users who choose to rely on one single coordinate.

Root Mean Square Error (RMSE) were calculated for both the North (equation 3) and East (euqation 2) axis, these values represents a 68% interval centered around the true value. To obtain a horizontal intervall, the RMSE values for both axis were used in equation 4 to calculate the Distance RMS (DRMS, also known as Horizontal RMS). Equation 5 was used to move increase the level of confidence from 68% to 95%. This was done because most users expect most coordinates to be within the

expressed interval. 2DRMS is a common way to illustrate GNSS precision [41] [37].

$$RMSE_x = \sqrt{\sum_{i=1}^{n}(x_i - \hat{x})^2} \tag{2}$$

$$RMSE_y = \sqrt{\sum_{i=1}^{n}(y_i - \hat{y})^2} \tag{3}$$

$$DRMS = \sqrt{\frac{1}{2} \times (RMSE_x^2 + RMSE_y^2)} \tag{4}$$

$$2DRMS = 2 \times DRMS \tag{5}$$

3.7 Devices

All smartphones in this test were able to record GNSS signals and save it as raw parameters. The devices were also capable of generating and saving real-time coordinates. Table 3 specifies all devices used in this thesis.

Table 3: Devices used

Name	Operating System	Model	Chip-set
Samsung Galaxy S8	Android Nougat	SM-950F	Exynos8895Mader
Sony Xperia ZX Premium	Android Nougat	G8141	Qualcomm Snapdragon 835
Emlid Reach	Reach v2.9.3		u-blox NEO-M8T-0-01

3.7.1 Android Nougat Smartphones

Both smartphones were capable of feeding GNSS observation data through the Android Nougat API. In this project the app "GNSS Logger v1.4.0.0" was used to save the GNSS raw paramaters [17]. All data can be stored inside textfiles and can easily be downloaded by an USB connection.

The output from the android devices contains both all data needed to calculate pseudoranges and real-time coordinates. To be able to use it in RTKLIB it needs to be converted to RINEX. This is done by using the android_to_rinex.py python script provided by rokubun on GitHub [31], which can convert the raw parameters to RINEX 2.11. However this script does not export navigation messages, and RINEX files are limited to GPS observations.

A few changes were made to this script. The Galileo constellation were added to the constellation list, and a filter were set up to remove satellites with a clock uncertainty (`ReceivedSvTimeUncertaintyNanos`) above 150 ns.

The app worked on both smartphones, however, while the Samsung Galaxy S8 was able to measure carrier-phases, the Sony Xperia ZX Premium was not.

3.7.2 Emlid Reach

The Emlid Reach is a device with an u-blox GNSS receiver. The chip was connected to a low quality Tallysman TW4721 antenna and a 5V iiglo power bank, connected to the USB port. The operating system is based on GNU/Linux, and the GNSS processing software is a modified version of Tomoj Takasu's RTKLIB.

The device is capable of receiving GPS, GLONASS, Galileo, BeiDou and QZSS. It is a single frequency receiver, which means it is only able to utilize the L1 signal, or equivalent signals from other constellations. This device is also capable of measuring carrier-phases.

The raw data is stored in both the .ubx-raw format, and can be converted into a RINEX file of choise with RTKLIB's "convbin". Coordinates can also be calculated in real-time, and these data are stored in a seperate textfile.

The device generates is own WI-FI access point and is controlled through a web interface or the android app "ReachView". The web-interface could be used to change settings or just simply activate and deactivate GNSS Logging. All files can efficiently be downloaded by using Secure Copy (SCP) recursively. An image is shown in figure 8.

3.7.3 The AASC Base station

The base station used in this experiment belongs to the Norwegian Mapping Authority and it is located along with a wether station at the crop field called Søråsjordet in Ås. Figure 9 shows an image of this base station. It has a Trimble Netr9 antenna capable of observing GPS, GLONASS, Galileo, BeiDou and QZSS, with dual-frequencies. This
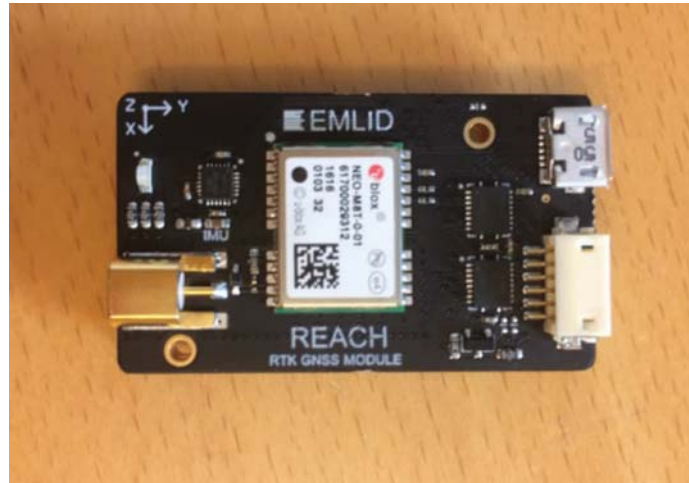
Figure 8: Emlid Reach

basestation has a sampeling rate of 1 second, which means it saves observation data each second.

This base station is used to generate corrections to the CPOS-service, which is a real-time kinematic (RTK) service developed to provide centimeter accuracy in real-time [22].

Figure 9: The aasc basestation located at Søråsjordet, Ås

3.8 Correction data

Correction data from the IGS (International GNSS Service) were downloaded from NASA's Crustal Dynamics Data Information System (CDDIS) ftp server. For this thesis only the correction from the European Space Agency (ESA) data center were used. Table 4 lists the correction data which were used in this thesis. Links to the correction data are provided in appendix B.

Table 4: Available correction data

File type	File-extension
IGS Standard Product 3	.sp3
IGS Clock corrections	.clk
IGS Ionosphere exchange format	.<%y>i
IGS Earth rotation data	.erp

3.9 Locations

The forest locations used in this thesis had a variation of density, however all forest areas were relatively closed. All forests showed typical signs of intensive forest management, by being even-aged, having a dense forest structure and being dominated by only one species. The forest in figure 10b was at a young stage, thus representing the lower part of the forest density scale. Figure 10c shows an older forest, while the forest in figure 10d is ready for harvesting. The control group is represented by figure 10a, which shows a clear sky environment.

(a) Reference point F01 (clear sky control)

(b) Reference point P01 ($39m^2/10000m^2$)

(c) Reference point P20 ($53m^2/10000m^2$)

(d) Reference point P27 ($99m^2/10000m^2$)

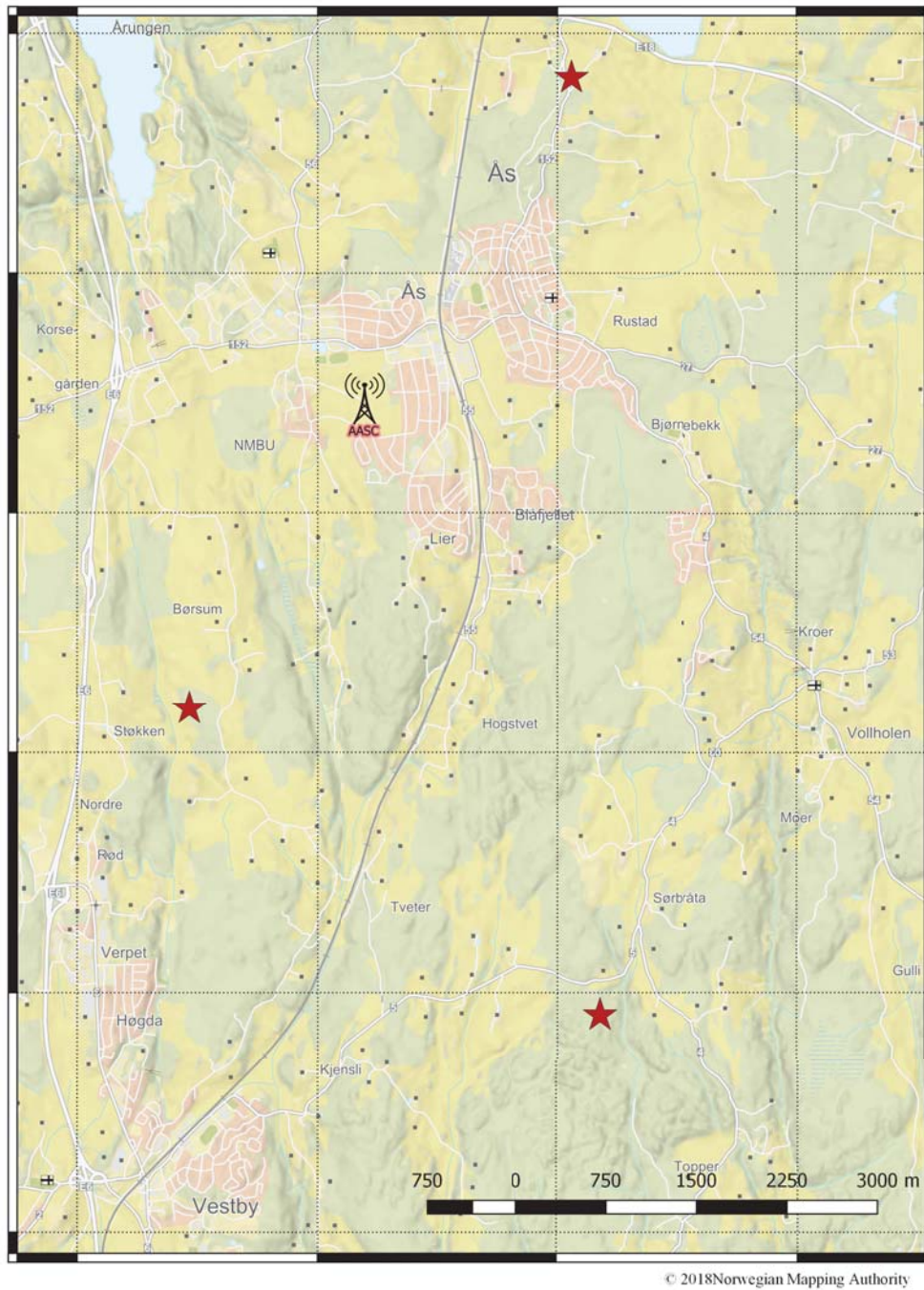Figure 10: Canopy images captured with a Nikon D600 (FX) with a 10mm lens

3.10   Map

Figure 11: Map showing the AASC base station, and the used locations are marked by the stars

4 Results

4.1 Data processing

In total, the RTKLIB command script generator generated 6784 commands. It took about 24 hours for RTKLIB to execute all commands and export the coordinate lists.

For the Emlid Reach data, BeiDou was not recorded. Also RTKLIB failed to utilize the Galileo data, thus leaving it to GPS and GLONASS only.

4.2 Reference points

All points from the GISLINE Landmåling software had an output with a standard deviation considered to be precise enough for this test. Only one reference point (P03) had a standard deviation above 20 cm. GISLINE Landmåling considered the coordinate input from the Topcon Legacy-E dual-frequency receiver to be known, thus setting the standard deviation to zero. All reference coordinates, with basal area measurements, applied in this thesis are listed in table 5. There were no pine trees in the used plots, thus omitted in the table.

Table 5: Table of all reference points used in this test

|	Coordinates WGS 84 / UTM Zone 32 (m)		Standard deviation (m)		Basal area $(m^2/10000m^2)$		
ID	**North**	**East**	**North**	**East**	**Total**	**Spruce**	**Deciduous**
F01	6612342.860	599024.571	0.000	0.000	**0.0**	0.0	0.0
F02	6612299.968	599021.290	0.000	0.000	**0.0**	0.0	0.0
F03	6612300.352	598986.927	0.000	0.000	**0.0**	0.0	0.0
P01	6609816.823	602345.619	0.127	0.153	**39.0**	34.5	4.5
P02	6609814.733	602354.382	0.146	0.167	**32.5**	32.5	0.0
P03	6609805.649	602350.807	0.227	0.216	**44.0**	43.0	1.0
P12	6612366.686	598940.272	0.005	0.005	**47.5**	47.5	0.0
P14	6612350.976	598933.914	0.005	0.006	**50.0**	49.0	1.0
P20	6612368.516	598920.490	0.006	0.006	**53.0**	45.0	8.0
P25	6617631.748	602121.506	0.085	0.062	**104.5**	104.5	0.0
P26	6617630.260	602110.863	0.091	0.066	**101.5**	101.5	0.0
P27	6617622.520	602113.265	0.095	0.075	**99.0**	99.0	0.0

4.3 Performance of Median Accuracy

4.3.1 Real-time performance

Clear sky Control Group When used in the clear sky enviornment all devices managed, with a few exceptions, to achieve an accuracy under 10 meter from the reference points by using the real-time coordinates. The smartphones often performed an realtime accuracy around 5 meters in the open area control, when they were allowed to accumulate coordinates for half an hour. This is illustrated in figure 12a and 12b. The Emlid Reach had an overall better real-time accuracy than the smartphones and managed to keep the accuracy within ±4 meters, as shown in figure 12c.
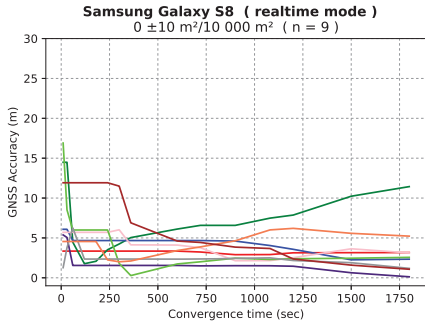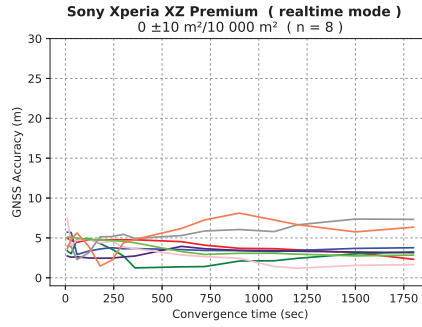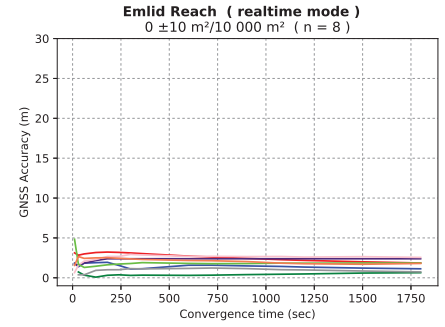
Figure 12: Real-time, clear sky
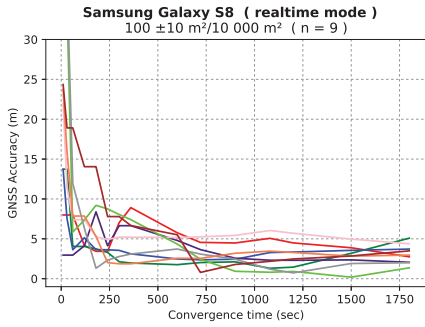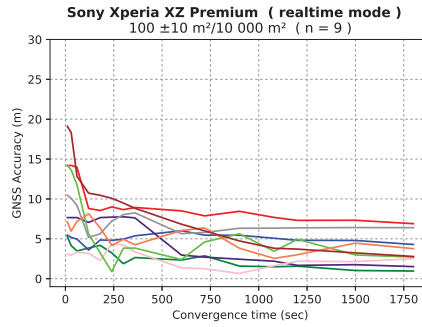
Under a forest canopy As expected, the accuracy decreased when a forest canopy was introduced. However, after the first five minutes it seems that the median accuracy is almost as good as in the clear sky enviornment. This is illustrated in figure 13.
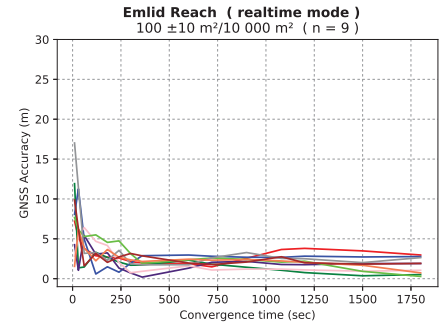
Figure 13: Real-time, forest canopy

As seen in figure 14 the devices put in the forest with the highest basal area indicated a slightly better performance than those surrounded by forest with lower basal areas.
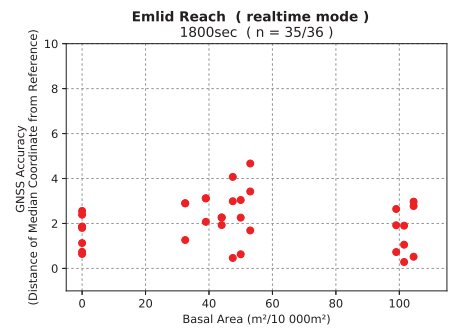
Figure 14: Real-time, accuracy after 30 minutes

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4.3.2 Performance of RTKLIB Single mode (`-p 0`)

Clear sky Control Group   The results from the RTKLIB single mode were similar to the realtime solutions. This is shown in the figures 15 and 16. The accuracy displacement, after 30 minutes, was also similar to the realtime solutions, this is illustrated in 17.

(a) Samsung Galaxy S8   (b) Sony Xperia XZ Premium   (c) Emlid Reach
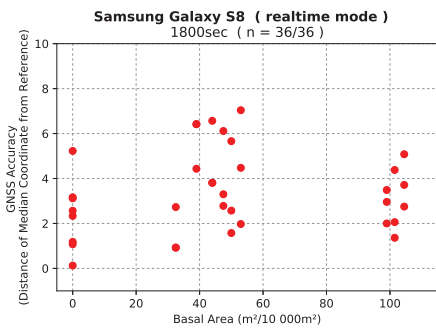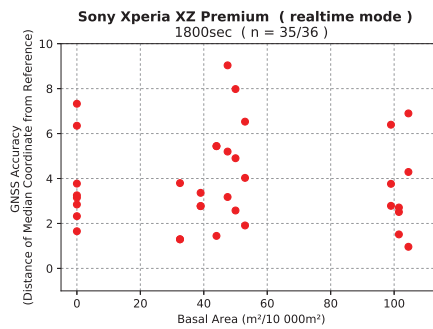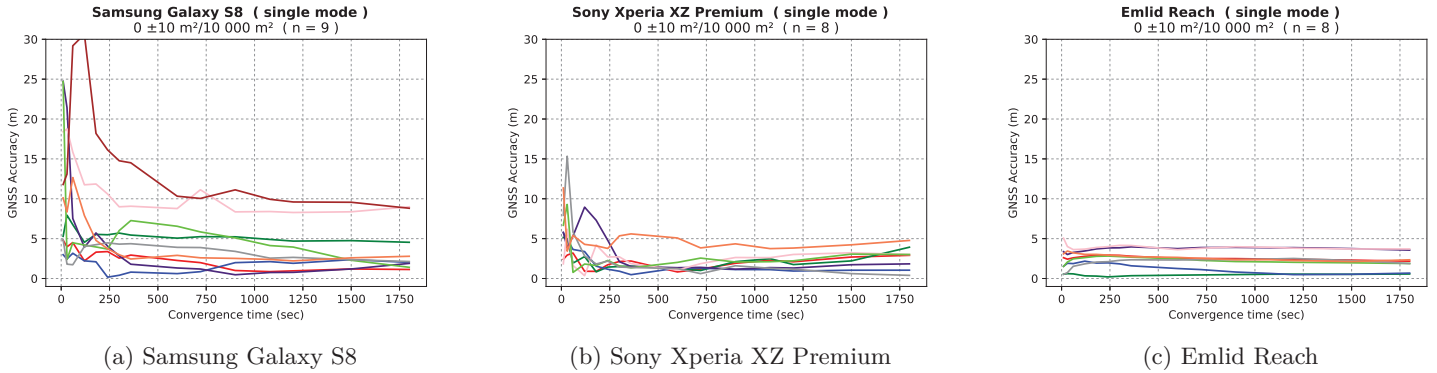
Figure 15: Single mode, clear sky

Under Forest canopy   In this mode the accuacy seem to be degraded for the smartphones when under a forest canopy. However, they seem to converge to a ten meter accuracy after five minutes. The Emlid Reach seemed almost unaffected as long as it was allowed to accumulate data for at least five minutes.

(a) Samsung Galaxy S8   (b) Sony Xperia XZ Premium   (c) Emlid Reach

Figure 16: Single mode, forest canopy

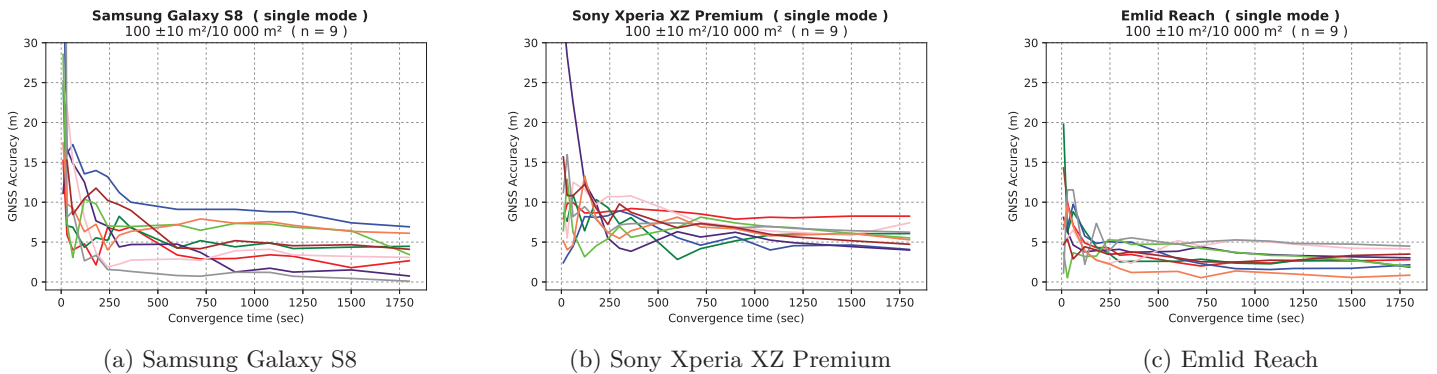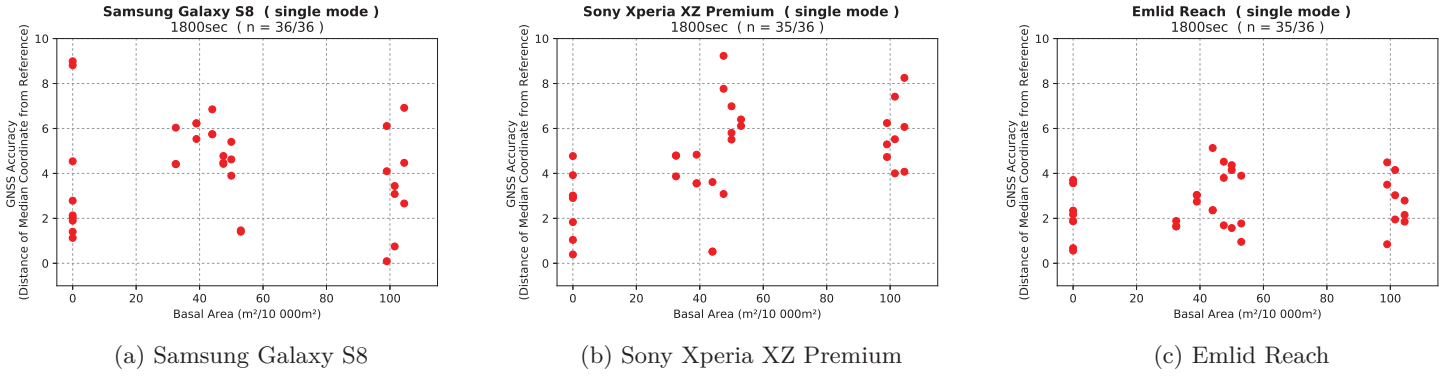(a) Samsung Galaxy S8   (b) Sony Xperia XZ Premium   (c) Emlid Reach

Figure 17: Single mode, accuracy after 30 minutes

4.3.3 Performance of RTKLIB dgps mode (`-p 1`)

By using the RTKLIB dgps mode the accuracy indicated an improvement, compared to both realtime and the RTKLIB single mode. The data from the Sony Xperia XZ Premium did not work in this mode. This is probably due to the lack of the carrier-phase measurements. When the carrier-phase measurements was removed from the Samsung S8, this device did not work either.

Clear sky Control Group While the data from the Samsung S8 started off with dispersed accuracy measures (figure 18a), the Emlid Reach did not provide any solutions at all before the accuracy was improved (figure 18b). All accuracy measures from the Emlid Reach in the clear sky environment were below two meters.

(a) Samsung Galaxy S8   (b) Emlid Reach
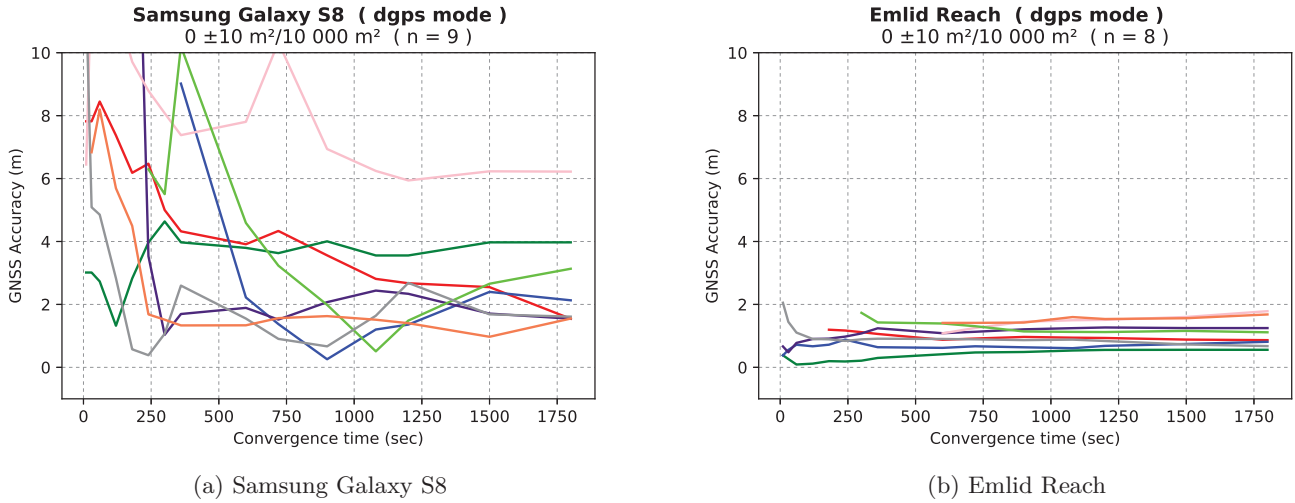
Figure 18: dgps mode, clear sky

Under Forest canopy When the RTKLIB dgps mode was used under the forest canopy, the overall accuracy decreased for both devices and did not preform any better than single mode or real-time. All observations done with the Emlid Reach obtained an accuracy below five meters within 30 minutes, as shown in figure 19b. In the case of the Samsung S8 device the accuracy was whitin ten meters after five minutes (figure 19a).
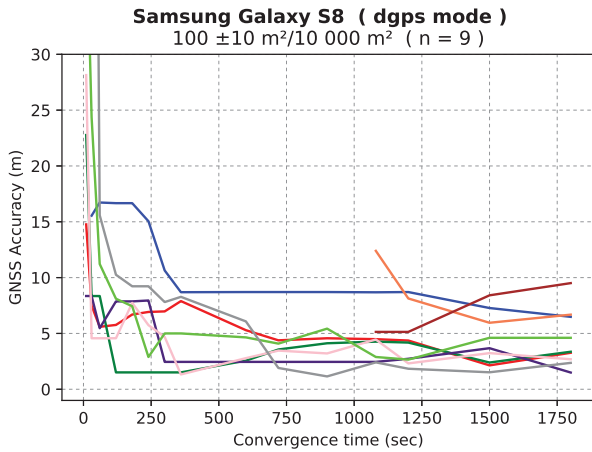
(a) Samsung Galaxy S8
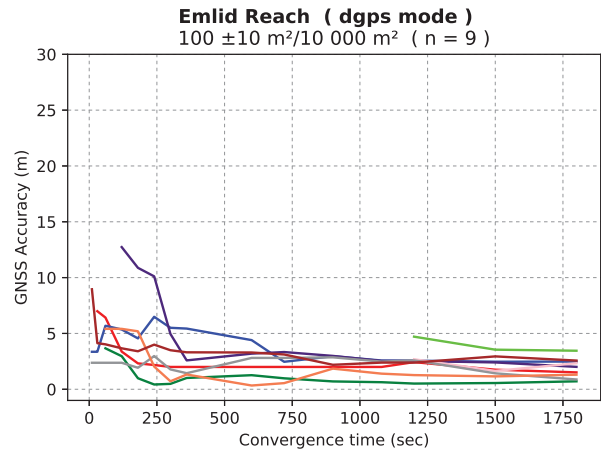
(b) Emlid Reach

Figure 19: dgps mode, forest canopy

(a) Samsung Galaxy S8

(b) Emlid Reach

Figure 20: dgps mode, mode, accuracy after 30 minutes

4.3.4   Performance of RTKLIB static mode (`-p 3`)

Clear sky Control Group   For the Emlid Reach the convergence time was important and by 30 minutes 6/9 results had an accuracy below 4 cm. The best result had an accuracy of 1.39 cm. RTKLIB needed ten minutes of observations before 1/3 of the integer ambiguities were solved and a "fix" was obtained. Two integer ambiguities even remained unsolved after 30 minutes. The accuracy is visualized in figure 21b.

This is a contrast to the Samsung S8 solutions, where the convergence time seem to have a negative impact on the accuracy. By 30 minutes, 6/8 solutions, had an offset above 50 meter from the reference. This is shown in figure 21a.

Under Forest Canopy   The effect from the Samsung S8 also applied to the Emlid Reach when collectiong satellite data under forest canopies, as shown in figure 22. The accuracies for the Samsung S8 also degraded under the forest canopy 22a and 23a.

For the Emlid Reach there were three median solutions which even had an offset higher than 300 meters, but still, there was one (lucy) median coordinate that acctually had a sub-meter accuracy (figure 22b).

26
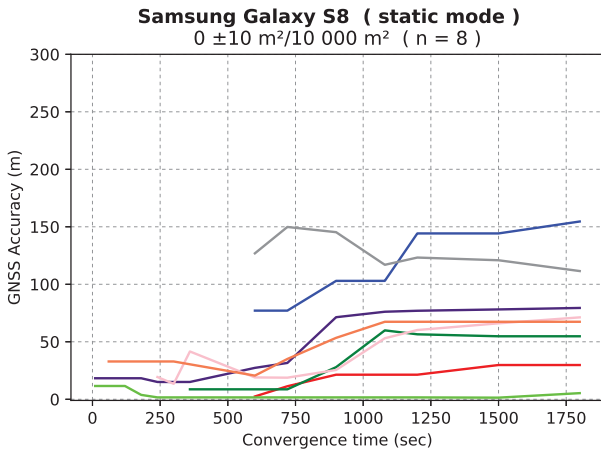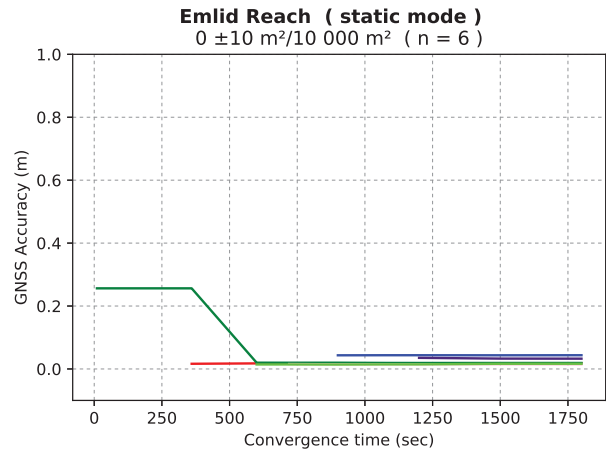
(a) Samsung Galaxy S8

(b) Emlid Reach

Figure 21: static mode, clear sky
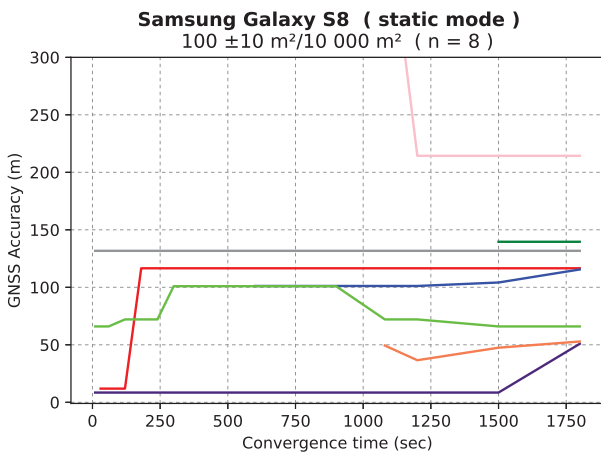
(a) Samsung Galaxy S8
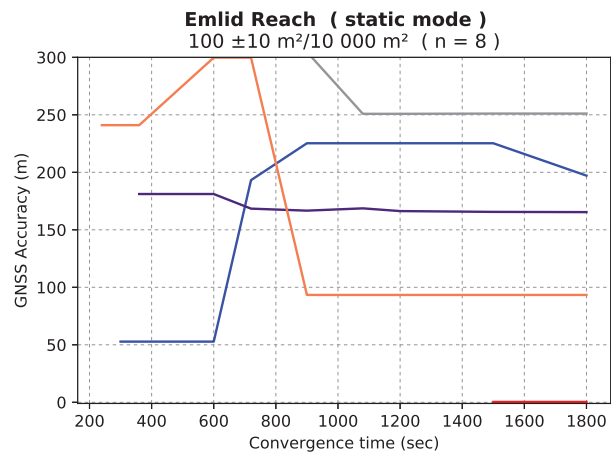
(b) Emlid Reach

Figure 22: static mode, forest canopy

4.3.5 Performance of RTKLIB ppp-static mode `-p 7`

Clear sky Control Group The PPP-static mode showed a positive trend with increased convergence time for both the Emlid Reach and Samsung S8. Under the open area control, 6/9 of the median solutions calculated form the Samsung S8 data were under five meter away from the reference (figure 24a). For the Emlid Reach all points, except one, had an offest below two meters, as shown in figue 24b.

Under Forest Canopy The accuracy of ppp-static mode also struggled with degredation over time when applied under forest canopies. The Emlid Reach had 5/9 median coordinates within 10 meters of the reference point by 30 minutes (figure 25b and 26b), while for the Samsung S8 device 7/9 were within ten meters (figure 25a and 26a).

27
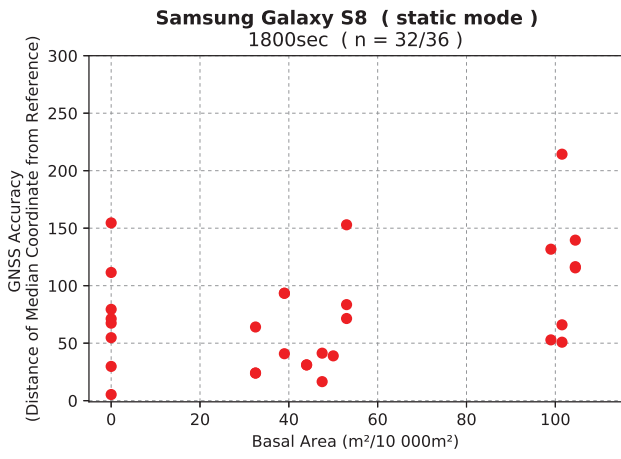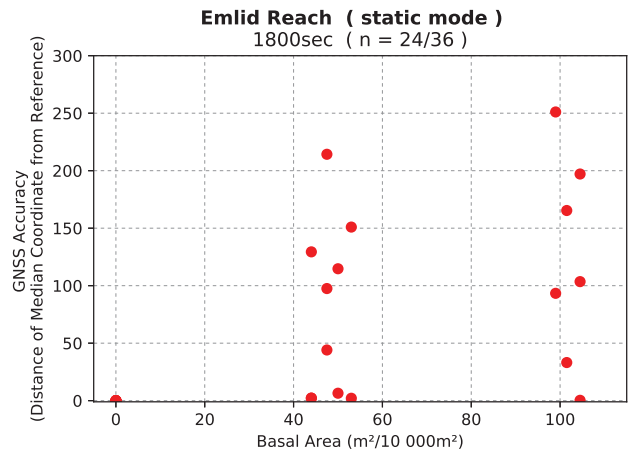
(a) Samsung Galaxy S8

(b) Emlid Reach

Figure 23: static mode, accuracy after 30 min
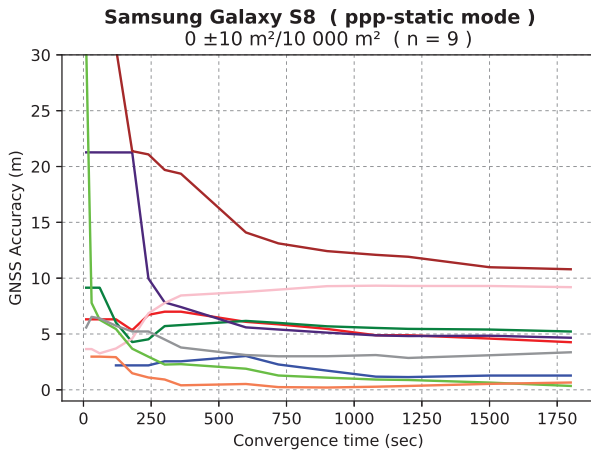
(a) Samsung Galaxy S8
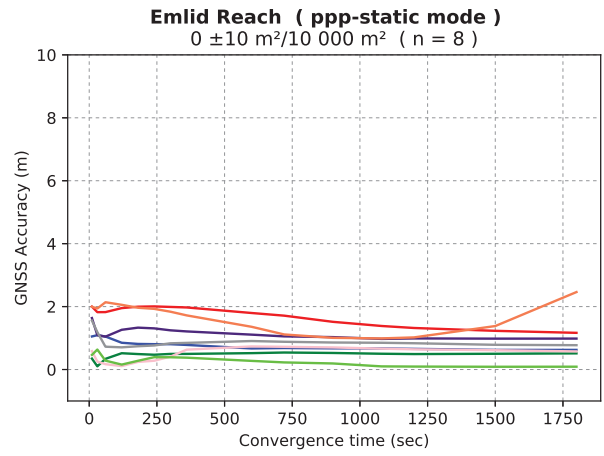
(b) Emlid Reach

Figure 24: ppp-static mode, clear sky
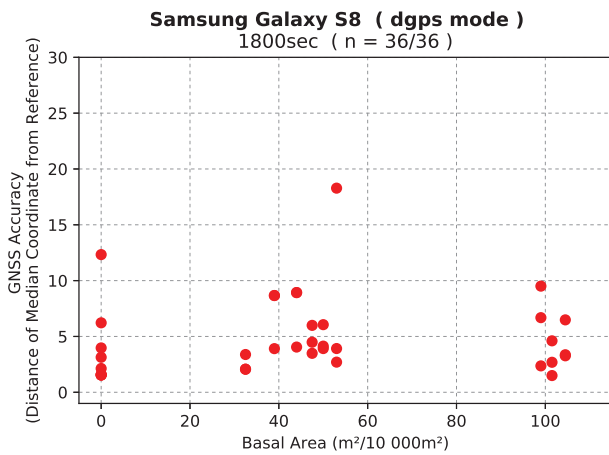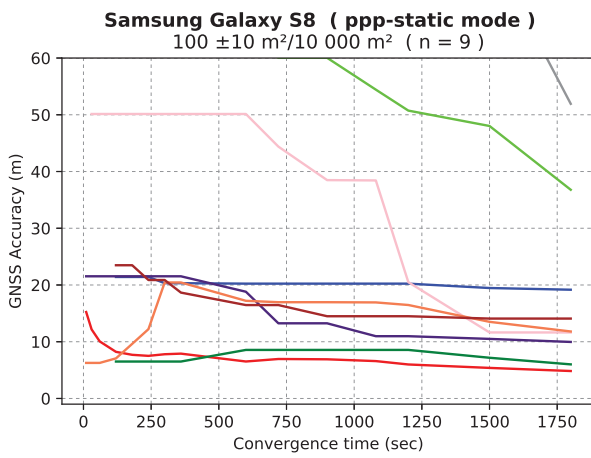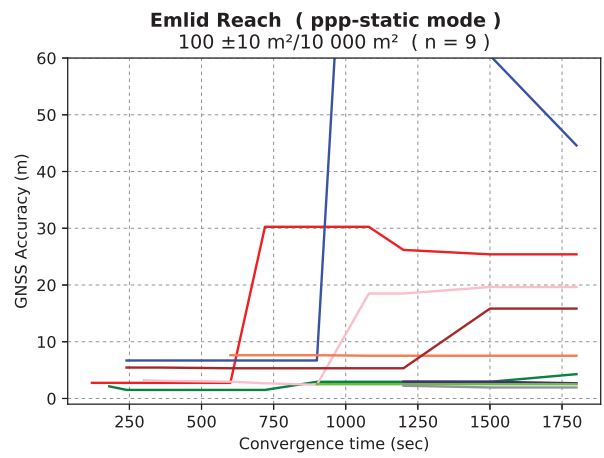

(a) Samsung Galaxy S8
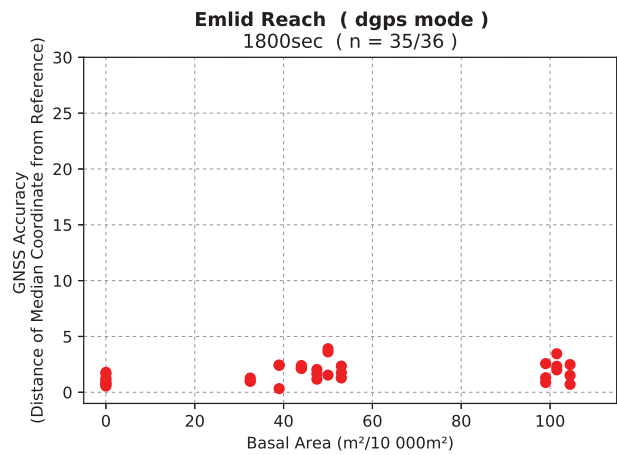
(b) Emlid Reach

Figure 25: ppp-static mode, forest canopy
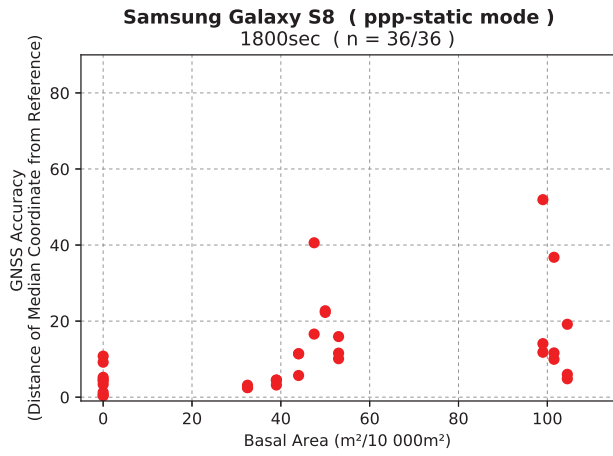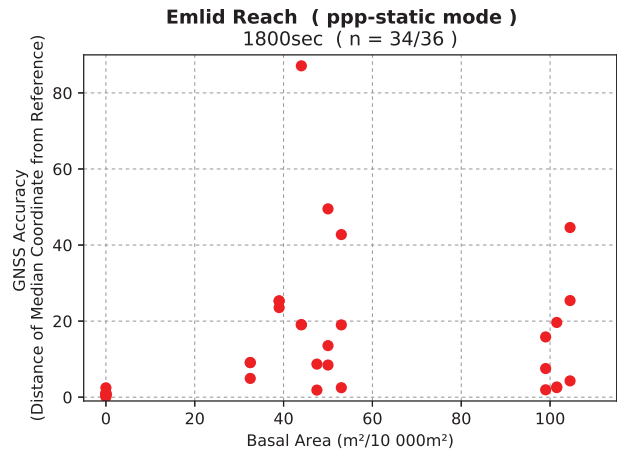
(a) Samsung Galaxy S8   (b) Emlid Reach

Figure 26: ppp-static mode, accuracy after 30 minutes

4.4 Precision

4.4.1 Real-time precision

Clear sky control Figure 27 shows that the Emlid Reach device is much more precise than both the smartphones. The Samsung S8 has a slightly better precision than that of the Sony Xperia XZ Premium. In the plots in figure 27 all coordinates which are within the 2DRMS value is marked by a blue color, while the coordinates outside are marked by red. The percentage of coordinates within the 2DRMS is given in the title of the figures.

| (a) Samsung Galaxy S8 | (b) Sony Xperia XZ Premium | (c) Emlid Reach |
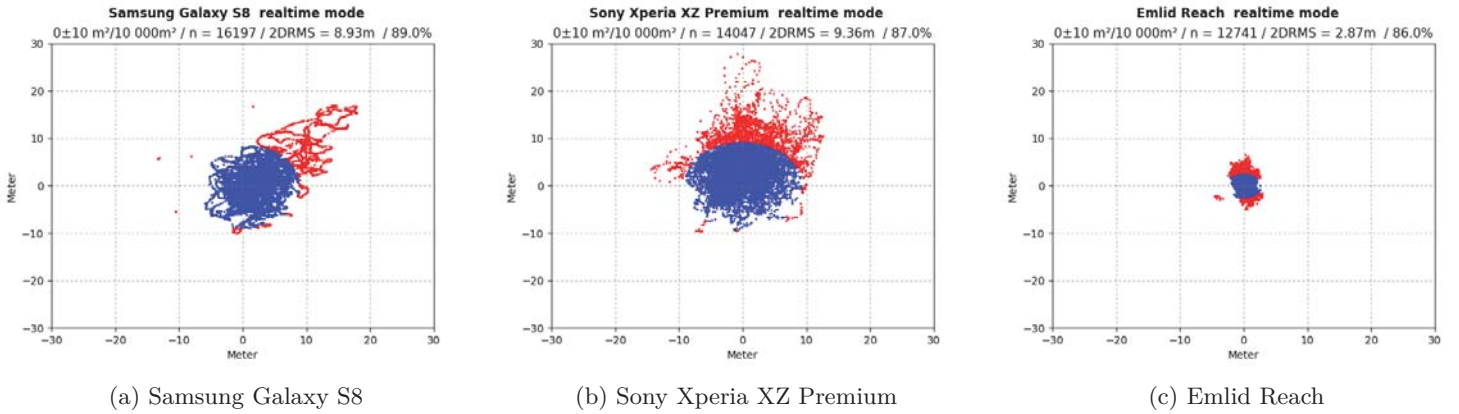
Figure 27: Real-time, clear sky control

Under forest canopy When the devices were put under a forest canopy, the performance for both smartphones slightly decreased 28. The precision of the Emlid Reach device dropped drastically due to the forest canopy. One of the coordinates from this device had an horizontal distance of 14 000 meters from the reference point. This coordinate also had an altitude of about 3000 meters above the ellipsoid. Another coordinate even had an altitude of 10 000 meters.

| (a) Samsung Galaxy S8 | (b) Sony Xperia XZ Premium | (c) Emlid Reach |
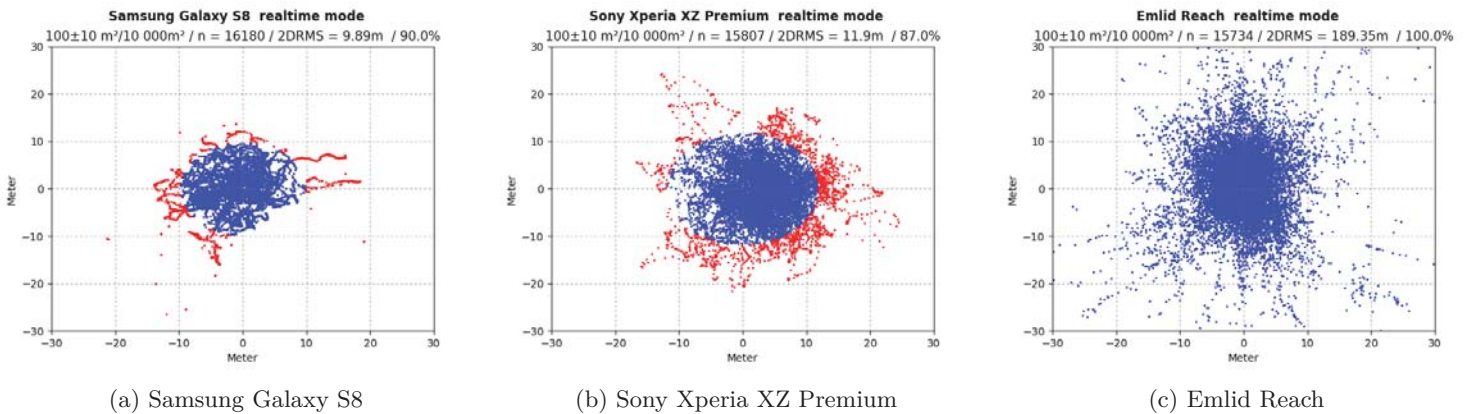
Figure 28: Real-time, under forest canopy

4.4.2 Precision of single mode

Clear sky control The smartphone devices showed a poor precision when the single mode is applied. The Emlid Reach device however has about the same precision as the realtime solution.

(a) Samsung Galaxy S8   (b) Sony Xperia XZ Premium   (c) Emlid Reach
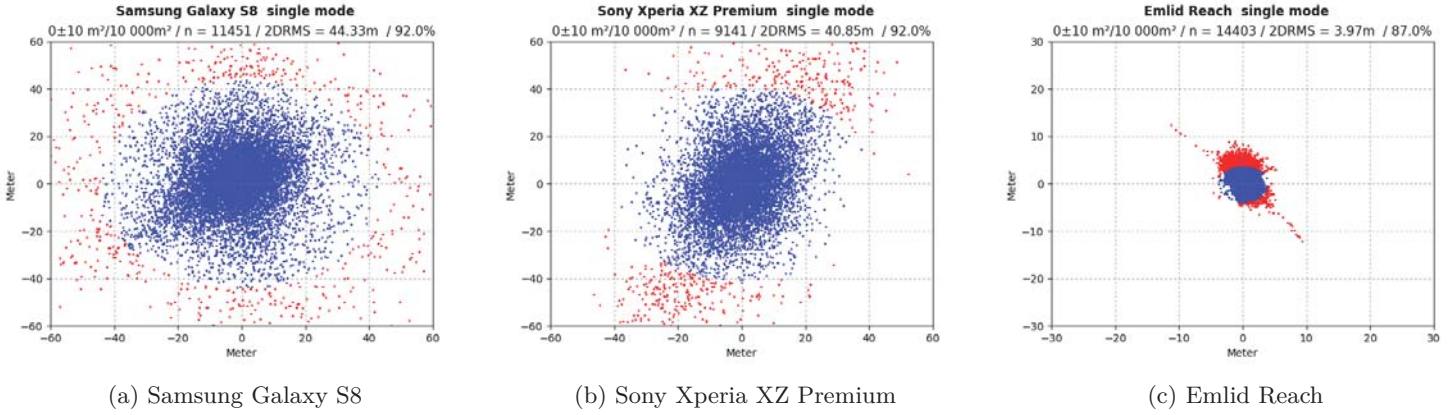
Figure 29: single mode, clear sky control

Under forest canopy There were no clear indication of the forest canopies affecting the precision of the smartphones, as shown in figure 30. When single mode is used for the Emlid Reach, a clear drop in the 2DRMS value were indicated (figure 30c) However, when compared to using the real-time mode, the single mode was a much better option for the Emlid Reach in forest, because there were no outliers.

(a) Samsung Galaxy S8   (b) Sony Xperia XZ Premium   (c) Emlid Reach
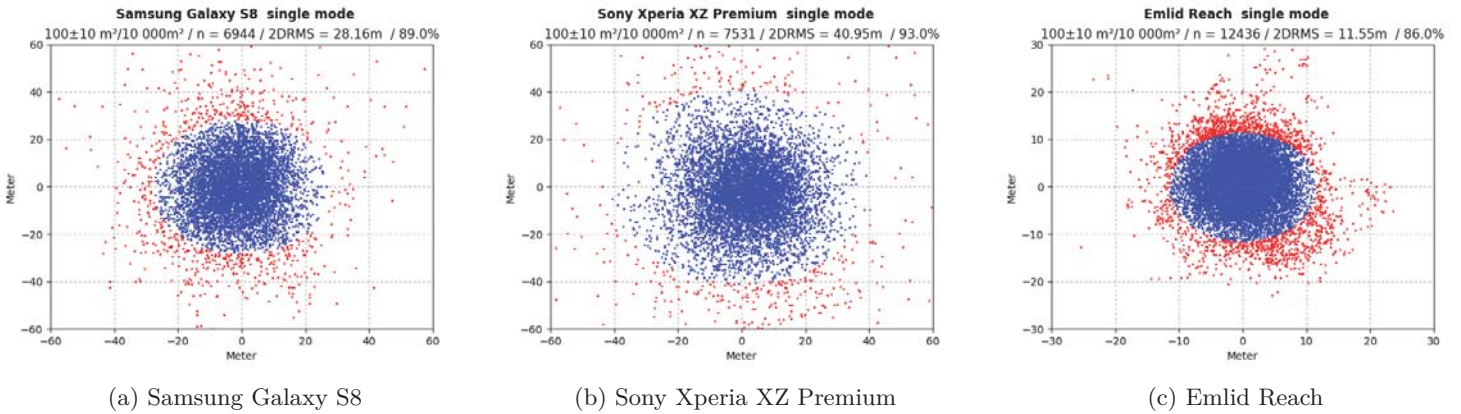
Figure 30: single mode, under forest canopy

4.4.3 Precision of dgps mode

Clear sky control   The 2DRMS value of the Samsung S8 almost reached 60 meters, which is huge compared to that of the Emlid Reach. The Emlid Reach had a 2DRMS value slightly above two meters.

(a) Samsung Galaxy S8

(b) Emlid Reach
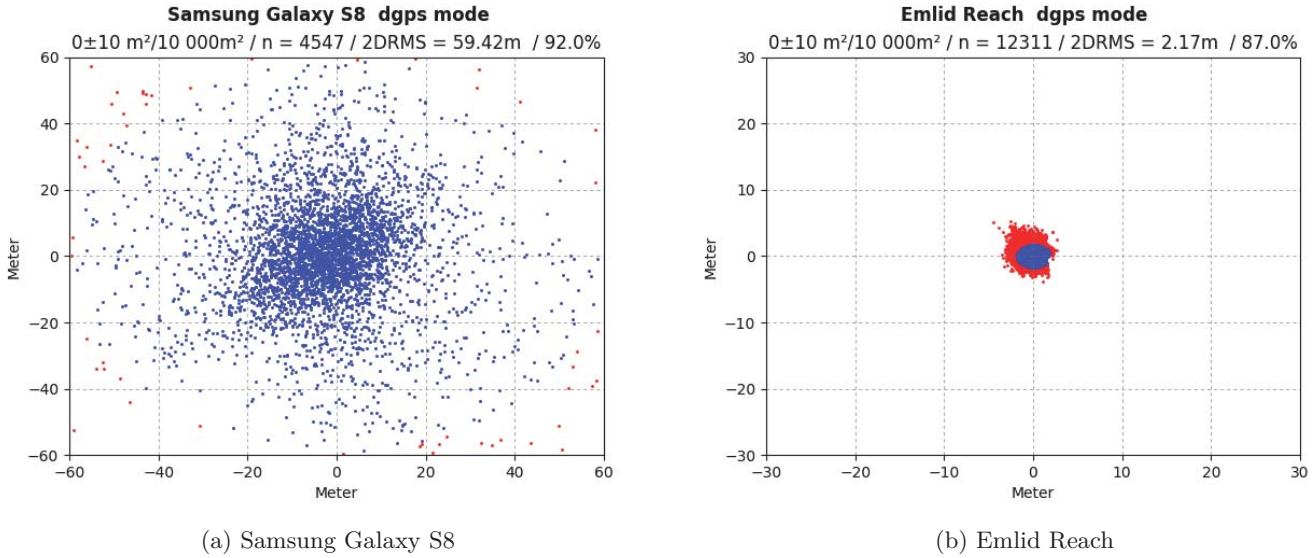
Figure 31: dgps mode, clear sky control

Under forest canopy   When the Samsung S8 device was collecting data in the forest, the precision actually improved (figure 31a). However, this is probably due to far less coordinates being obtained under forest canopies. The precision of the Emlid Reach decreased when put under a forest canopy (figure 32b)

(a) Samsung Galaxy S8

(b) Emlid Reach
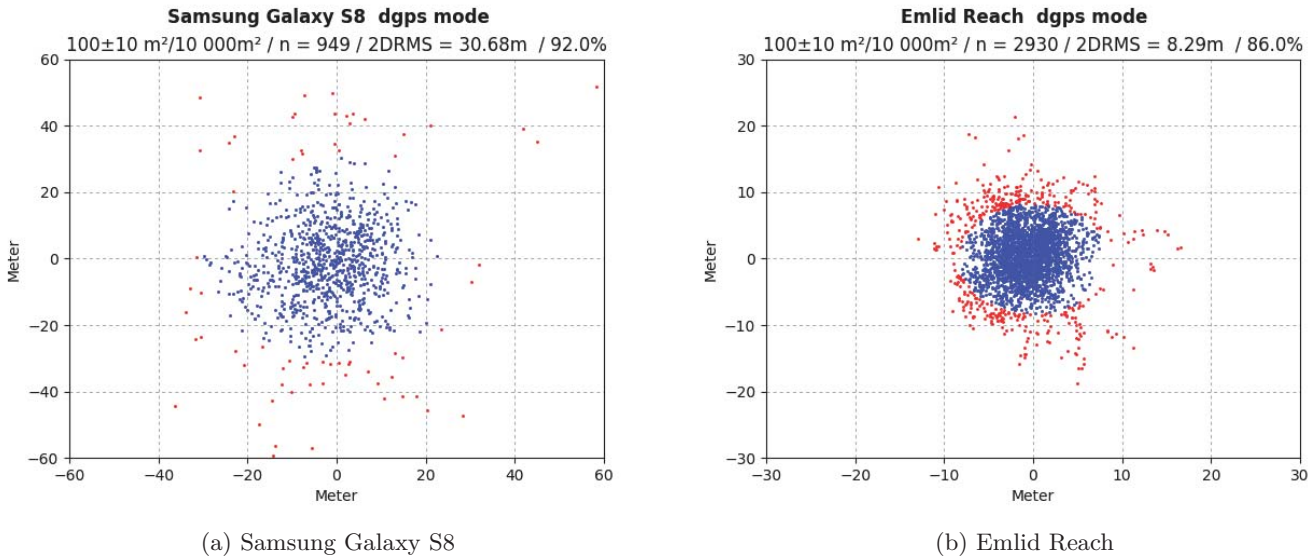
Figure 32: dgps mode, under forest canopy

4.4.4 Precision of all modes

Figure 33 shows how the precision of the different modes are affected by forest density. For the smartphones the real-time mode seem to be unaffected by the forest canopy, while the real-time mode of the Emlid Reach is rather sensitive. However, the Emlid Reach gives much better results, than that of the smartphones, when it comes to the dgps and single modes in the clear sky environment.

(a) Samsung Galaxy S8   (b) Sony Xperia XZ Premium   (c) Emlid Reach
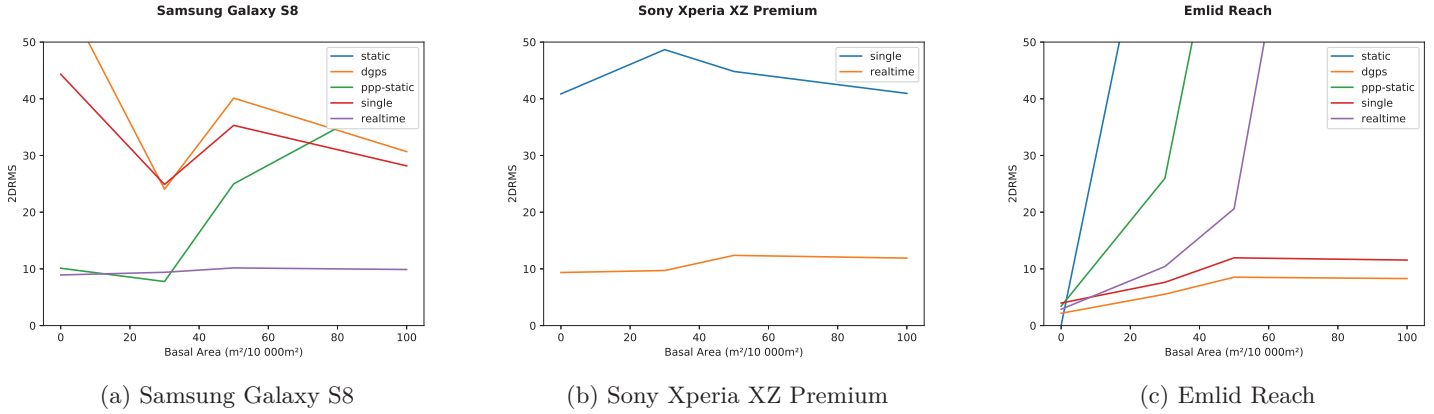
Figure 33: Precision of all modes, in relation to forest density

5 Discussion

The potential of consumer-grade equipment has been demonstrated by performing sub-decimeter accuracy for the Emlid Reach device. This kind of accuracy was totally unexpected for this experiment, and are setting new standards for what can be achieved with present and future devices by utilizing open source software.

In this experiment, the Emlid Reach was considered to be a control device for the smartphones. Since the Sony device did not record carrier-phases, it was excluded by most algorithms in RTKLIB. The Samsung S8 however was able to record the same signals as the Emlid Reach, and could provide comparable results.

The results for the Samsung S8 indicated that although postprocessing can be done with smartphones, it still suffers from huge limitations regarding the carrier-phase measurements. However, Samsung S8 did relatively well when using code-based measurements and the real-time solutions.

5.1 Code-based positioning

In this test, the use of median values extracted from the realtime coordinates, turned out to give the best results regarding accuracy across all forest environments in most cases. When the Emlid Reach was used in the clear sky environment, the dgps mode indicated better performance than the realtime solutions.

In the case of forest environments, most satellites must be observed from higher elevations. Because this is where the forest environment allows satellite signals to pass.

Unfortunately, all postprocessing done in this thesis was limited to GPS and GLONASS. Which means that the real-time mode are likely to enjoy a higher number of satellites, which would be expected to provide a better accuracy. This is indicated by the results, because the use of real-time was an overall better solution than postprocessing in forest environments.

However, the Emlid Reach had a few coordinates, calculated in real-time, with huge horizontal offsets, which massively degraded the precision. This is probably due to bad geometry, caused by limited availability to satellite signals. These offsets also had a huge offset in altitude, and by filtering out every coordinate outside 0 and 300 meter of altitude, the precision showed improvement.

At Northern latitudes a poor satellite geometry in forests should be expected, because the numbers of satellites from above are limited due to their low inclination angle [7]. This issue may be limited to forests or urban canyons at higher latitudes, and should be investigated further.

5.2 Limitation and potential of the carrier-phase measurements

When static mode was applied for the Samsung S8, false moving fixes occurred. The coordinates also showed a trend where the distance from the reference point increased over time. The algorithms for the static mode relies on the carrier-phase measurements, relative to the base station [34]. The results indicate that the problems with the Samsung S8 regarding static mode, may originate from false carrier-phase measurements.

It is well known that carrier-phases are difficult to measure under difficult conditions due to cycle-slips and signal-degradation [26]. When however a quality test of the generated Samsung S8 RINEX files were preformed in teqc, it did not indicate any interruptions in the clear sky carrier-phase measurements. In the case of the Emlid Reach RINEX file under a forest canopy, teqc managed to indicate where the carrier-phase measurements were broken.

The Emlid Reach indicate similar results as the Samsung S8, when put under a forest canopy in static mode. This could indicate that the Samsung S8 carrier-phase

measurements follows a certain pattern which leaves the interruptions undetected by teqc.

The expected result of the an active duty-cycle, would be a lower count of phases than is actually occurring [2]. Since the carrier-phase value is the number of accumulated phases from the start of the measurement, the gap between the actually occurring phases and counted phases will be expected to increase over time. This could explain why the distance between the reference point and the false fix-solutions seem to increase over time, both for the Samsung S8 and the Emlid Reach under a signal degraded environment.

However, when utilizing the PPP-static algorithm, which uses a combination of pseudorange and carrier-phase, the results was not as bad for either the Samsung S8 or the Emlid Reach under forest canopies. This is probably a results of omitting the reference station and letting the device use the carrier-phase measurements relative to itself.

5.3   Different forest densities

Overall, there were no clear indication of differences across forests to have any effect on accuracy. For the realtime results it could even be indicated that a basal area around 100 $m^2/10000m^2$ gave better results than those with lower basal areas (around 50 $m^2/10000m^2$).

In the forests with lower basal area the branches both were denser and closer to the receiver. The results could indicate that branches is a bigger issue for real-time GNSS, than trunks. This makes sense, because a signal would more or less travel undisturbed in between trunks, but the signals would face an whole other set of issues if they need to travel through branches. However, this was only a weak indication and more data would be needed to conclude this.

If this is the case, it could be exploited in order to map forest structure, and measure how forests changes over time. Parameter on changes in forest structure over time could be valuable for both forest management and forest ecologists. The concept of biomass retrieval in forests by utilizing GNSS is already up for validation [28].

5.4   Short observation files

It was also indicated in this thesis that a longer convergence time could be used to compensate for signal-degradation, when using code-based measurements. This would not give the same accuracy as in the clear sky environment, if smartphones were used. By five minutes the accuracy results seemed to stabilize, which means the devices needs at least five minutes to avoid random results when used under forest canopies.

The results in this thesis suggest that a median value of real-time coordinates collected over five minutes, could be used to obtain an accuracy within five meters for the Emlid Reach under forest canopies. The smartphones managed to obtain accuracies within ten meters by five minutes under forest canopies.

However, this is not the case for most mappers who only rely on one coordinate, and the result have shown to be very unpredictable for short observations. Since the precision of the smartphones in forests were around ten meters, a user should not expect a better value than this.

5.5   Adapting GNSS in forests

The use of code-based measurements can be enhanced by a carrier-phase smoothing, known as a Hatch-filter [13]. However, the unused doppler value may also be used for smoothing. This has been done by the ESA to improve the accuracy of Android smartphones affected by duty-cycle, and has proven to increase the accuracy of these

devices [2]. This could possibly also be done to enhance the accuracy in forest environments, because the doppler value has shown to be insensitive to signal degradation and doppler smoothing has proven to enhance GNSS accuracy in urban areas [26]. This approach was not tested in this thesis.

The Android API is also able to assess the status of the carrier-phase measurement. The API variable `AccumulatedDeltaRangeState` will tell if the measurement has a cycle-slip, is reset, is valid or has an unknown status [2]. This variable is not considered in the android_to_rinex.py script, which resulted in an uncritical use of carrier-phase values. However, most of the values are known to be considered invalid because of duty-cycle [2].

The easiest fix to this issue would be to make duty-cycle optional. It would be interesting to assess the results of a device with this function turned off. However, if compared to the Emlid Reach, it is likely to collect GNSS data for about half an hour in order to be able to solve the ambiguity resolution. This will still limit its use for precision mapping, because most users will not be patient enough to collect enough data. Also, if this is to be done in real-time, the user would need access to a base station.

5.6   Applying precision mapping in Ecology

One of the most valuable findings is the accuracy of the Emlid Reach by using the RTKLIB static mode under a clear sky. This could potentially be used for precise mapping of long term mountain plant plots, thus improving the precision of any GIS analysis. It could also be utilized to make reference points for image matching in clear sky environments. This could be useful for georeferencing images taken by airplanes or drones.

In contrast to survey-grade equipment, the Emlid Reach is small and could easily be carried around. This is a huge asset if one needs to survey remote locations or needs to travel with airplane. Since the device is cheap, relative to survey-grade equipment, several devices can be used simultaneously. Some of the devices could be used as temporary base stations, which would improve the usability of the other devices.

While the results suggest that the Emlid Reach is only able to map sub-canopy locations with an accuracy of five meters, it also suggests that it might be very inaccurate if it is not done correctly. For the best accuracy possible today, the device should accumulate data for at least five minutes and calculated by single mode, or by using a median of the real-time coordinates.

In the case of species mapping GNSS parameters should be collected. If this information is committed to a database, like artsdatabanken or GBIF, engineers are able to analyze data and produce coordinates with qualified precision estimates. These coordinates would also be reproducible, and can be reassessed in case any doubt occur.

5.7   GNSS in the future

In this thesis, some of the first smartphones that support capturing of GNSS raw data are tested. These smartphone devices should be considered to be at an experimental stage, as improved smartphones are already in development.

Development of the first dual-frequency GNSS chip for smartphone devices is announced by Broadcom [8]. This chip utilizes the stronger L5-signal, and by comparing the L1- and L5-signals it is able to calculate an ionosphere-free combinations [21].

Chip scaled atomic clocks (CSAC), which is in development, could help navigation in forests. Multipath is an issue for code-based receivers in signal-degraded environments like forests [35]. A more precise clock would be able to dissociate direct signals to bounced signals, because the bounced signals would be received sightly later [14].

6 Conclusion

This test has proved that it is possible to use GNSS raw data from an Android smartphone to postprocess coordinates. While this opens many possibilities for positioning with today's smartphones, the work on this thesis suggest that the potential of smartphones GNSS raw parameters are limited compared its own realtime coordinates and the consumer-grade GNSS-only device Emlid Reach. This was true for the Samsung Galaxy S8, which could record both carrier-phase and code based signals. By using realtime with a Samsung Galaxy S8 device, an accuracy within ten meter is to be expected in clear sky environments, but it is also likely to miss. Especially if only a few coordinates are used.

There were no strong indication of different forest densities having any strong effect on the accuracy, however comparing it by a clear sky environment indicated huge differences in accuracy.

The test indicated that in order to converge to ten-meter accuracy under forest canopies, accumulated realtime coordinates for approximately five minutes was needed. By using the median value from more coordinates, randomness was eliminated. It is not likely that mappers have the time to collect data for five minutes when mapping rare forest living species.

In the case of the Samsung Galaxy S8 smartphone, only one coordinate had a median accuracy better than five meters by ten seconds. This suggests that relying on a few, or even just one coordinate, per observation in a forest gives random results, and most of the data on vulnerable forest living species should be given buffer ranges much wider than five meters. Some of the real-time coordinates, preformed with the Emlid Reach in the forest environments, had offsets of several kilometers. This suggests that the coordinates should always be reviewed before committed to a database. Especially if the coordinates are obtained in forests.

In forests, algorithms that relied on and only used the code-based signals did the best results. There were no good results from using carrier-phase measurements for positioning under forest canopies. This is probably due to the inability to receive signals continuously due to trunks and branches, which degrades or blocks the signal. The same result occurred with the Samsung S8 in the clear sky environments, which suggests that carrier-phase measurements from this device are false. However, when used in a clear sky environment, carrier-phase measurements made it possible to obtain centimeter level accuracy for the Emlid Reach device. A base-station was needed and it is expected to collect information for about 20 to 30 minutes before most ambiguity resolutions are solved and a precise position can be obtained. This validates that centimeter accuracy is achievable by using RTKLIB and consumer-grade devices. This could be used for species mapping in alpine environments, but is unlikely to be used because most species mappers will not have time to wait 20 minutes, or more, for a very precise coordinate. It could however be used to precisely mapping of long-term plant plots or for making reference points for image matching and georeferencing.

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Appendix A   RTKLIB command examples

The RTKLIB script-generator written in python wrote all the commands needed for full automation. All commands had "if"-statements to make it possible to control the script. When executed some of the devices and modes could be ignored, and it was made possible to choose from which "process_nr" to start (line 15) and where to end (line 16). The script also generated a simple log file (started in line 18). This makes it easier to keep track of the process.

A.1   Head

Listing 1: Command example for rnx2rtkp dgps mode

```
1   #!/bin/sh
2   out=out_mappe
3   root_dir=/path/to/root_dir
4   mkdir ${root_dir}/${out} 2>/dev/null
5
6   s8=true
7   er=true
8   xz=true
9
10  single=true
11  prange=true
12  cphase=true
13  ppp=true
14
15  st_process=0
16  en_process=10000
17
18  echo Logg >${out}.log
19  start=`date +%s`
```

A.2   Single mode

These commands calls for data stored in different directions inside the *${root_dir}* directory, and output the data to a folder system inside the *${root_dir}/${out}* directory. As shown in listing 2, only the navigation messages from the base station were used, as showed in line 17 (GPS navigation message) and 18 (GLONASS navigation message). This mode didn't need any base observation file. The code for the right time span is set in line 13, in this case limiting the observation file readings to 6 minutes.

Listing 2: Command example for rnx2rtkp single mode

```
1   process_nr=593
2   if $single && \
3     $er && \
4     [ ${st_process} -le ${process_nr} ] && \
5     [ ${en_process} -gt ${process_nr} ]; then
6       mkdir ${root_dir}/${out}/er 2>/dev/null
7       mkdir ${root_dir}/${out}/er/single 2>/dev/null
8       mkdir ${root_dir}/${out}/er/single/sec_360 2>/dev/null
9       echo process nr: 593
10      echo Parameters:  rnx2rtkp -p 0 -m 15 -f 1 -t -s ";"
11      echo Convergence time: 360 sec
12      rnx2rtkp -p 0 -m 15 -f 1 -t -s ";" \
```

```
13        -ts 2017/10/07 10:47:10 -te 2017/10/07 10:53:10 \
14        -o ${root_dir}/${out}/er/single/sec_360/single_er_sec360_P26a2800.csv \
15        ${root_dir}/er_rinex/P26a2800.17o \
16        ${root_dir}/aasc/aasc2800.17n \
17        ${root_dir}/aasc/aasc2800.17g 2>/dev/null
18      echo
19  fi
20  echo process_nr: 593 >> ${out}.log
```

A.3   dgps mode

The use of dgps mode (listing 3) requires a base station observations (line 16) and and the Earth Centered Earth Fixed (ECEF) coordinates of the base station (line 19). In rnx2rtkp the rover observation must always be assigned before the base station observation file.

Listing 3: Command example for rnx2rtkp dgps mode

```
1  process_nr=594
2  if $prange && \
3    $er && \
4    [ ${st_process} -le ${process_nr} ] && \
5    [ ${en_process} -gt ${process_nr} ]; then
6      mkdir ${root_dir}/${out}/er 2>/dev/null
7      mkdir ${root_dir}/${out}/er/prange 2>/dev/null
8      mkdir ${root_dir}/${out}/er/prange/sec_360 2>/dev/null
9      echo process nr: 594
10     echo Parameters:  rnx2rtkp -p 1 -m 15 -f 1 -t -s ";"
11     echo Convergence time: 360 sec
12     rnx2rtkp -p 1 -m 15 -f 1 -t -s ";" \
13       -ts 2017/10/07 10:47:10 -te 2017/10/07 10:53:10 \
14       -o ${root_dir}/${out}/er/prange/sec_360/prange_er_sec360_P26a2800.csv \
15       ${root_dir}/er_rinex/P26a2800.17o \
16       ${root_dir}/aasc/aasc2800.17o \
17       ${root_dir}/aasc/aasc2800.17n \
18       ${root_dir}/aasc/aasc2800.17g \
19       -r 3172870.7170 604208.2810 5481574.2300 2>/dev/null
20     echo
21  fi
22  echo process_nr: 594 >> ${out}.log
```

A.4   static mode

When using rnx2rtkp in static mode, as shown in listing 4 in line 12, the integer ambiguity validation threshold (the -v flag) could be used to set the border between making a fix (Q-flag 1) or a float value (Q-flag 2). If not defined, the the default value of 3 is used. All processing in this thesis used this value.

Listing 4: Command example for rnx2rtkp static mode

```
1  process_nr=595
2  if $cphase && \
3    $er && \
4    [ ${st_process} -le ${process_nr} ] && \
5    [ ${en_process} -gt ${process_nr} ]; then
6      mkdir ${root_dir}/${out}/er 2>/dev/null
7      mkdir ${root_dir}/${out}/er/cphase 2>/dev/null
```

```
 8      mkdir ${root_dir}/${out}/er/cphase/sec_360 2>/dev/null
 9      echo process nr: 595
10      echo Parameters:  rnx2rtkp -p 3 -m 15 -v 3 -f 1 -t -s ";"
11      echo Convergence time: 360 sec
12      rnx2rtkp -p 3 -m 15 -v 3 -f 1 -t -s ";" \
13        -ts 2017/10/07 10:47:10 -te 2017/10/07 10:53:10 \
14        -o ${root_dir}/${out}/er/cphase/sec_360/cphase_er_sec360_P26a2800.csv \
15        ${root_dir}/er_rinex/P26a2800.17o \
16        ${root_dir}/aasc/aasc2800.17o \
17        ${root_dir}/aasc/aasc2800.17n \
18        ${root_dir}/aasc/aasc2800.17g \
19        -r 3172870.7170 604208.2810 5481574.2300 2>/dev/null
20      echo
21    fi
22    echo process_nr: 595 >> ${out}.log
```

A.5 ppp-static mode

Although the use of the ppp-mode (listing 6) didn't require correctiondata, the solution could be improved by applying it. In line 19, the IGS standard product 3, which contains precise ephemerides, was added. In line 20 the clock bias corrections are added. The earth rotation (.erp-file) and ionosphere corrections (.ionex-file) is added through the .conf-file in line 13.

Listing 5: Command example for rnx2rtkp ppp-static mode

```
 1    process_nr=596
 2    if $ppp && \
 3      $er && \
 4      [ ${st_process} -le ${process_nr} ] && \
 5      [ ${en_process} -gt ${process_nr} ]; then
 6        mkdir ${root_dir}/${out}/er 2>/dev/null
 7        mkdir ${root_dir}/${out}/er/ppp 2>/dev/null
 8        mkdir ${root_dir}/${out}/er/ppp/sec_360 2>/dev/null
 9        echo process nr: 596
10        echo Parameters:  rnx2rtkp -p 7 -m 15 -f 1 -t -s ";"
11        echo Convergence time: 360 sec
12        rnx2rtkp -p 7 -m 15 -f 1 -t -s ";" \
13          -k ${root_dir}/esa/corrigate280.conf \
14          -ts 2017/10/07 10:47:10 -te 2017/10/07 10:53:10 \
15          -o ${root_dir}/${out}/er/ppp/sec_360/ppp_er_sec360_P26a2800.csv \
16          ${root_dir}/er_rinex/P26a2800.17o \
17          ${root_dir}/aasc/aasc2800.17n \
18          ${root_dir}/aasc/aasc2800.17g \
19          ${root_dir}/esa/esa280.sp3 \
20          ${root_dir}/esa/esa280.clk 2>/dev/null
21        echo
22    fi
23    echo process_nr: 596 >> ${out}.log
```

A.6   Tail

The tail was written to output a runtime summary.

Listing 6: Command example for rnx2rtkp ppp-static mode

```
1  end=`date +%s`
2  runtime=$((end-start))
3
4  H=$((${runtime} / 3600))
5  M=$((${H} / 60))
6  s=$((${runtime} % 60))
7
8  echo -- Runtime:
9  echo Hour: $H
10 echo Min : $M
11 echo sec : $s
12 echo --
```

Appendix B   Correction data ftp servers

Table 6: Links for correction data. <dc> is data center and the input marked with the "%"-sign marks the input from the datetime python package

ftp://cddis.gsfc.nasa.gov/gnss/products/<gpsweek>/<dc><gpsweek><%U>.sp3.Z
ftp://cddis.gsfc.nasa.gov/gnss/products/<gpsweek>/<dc><gpsweek><%U>.clk.Z
ftp://cddis.gsfc.nasa.gov/pub/gps/products/ionex/<%Y>/<%j>/<dc>g<%j>0.<%y>i.Z
ftp://cddis.gsfc.nasa.gov/pub/gps/products/<gpsweek>/<dc><gpsweek>7.erp.Z
ftp://ems.estec.esa.int/pub/PRN<sbas_prn>/y<%Y>/d<%j>/h<%H>.ems