GNSS Performance Monitoring

SiS availability parameter definition and evaluation

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by

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Preface

This thesis forms the end of my period at the TU Delft. I enjoyed studying the bachelor of civil engineering and the master track of geoscience & remote sensing. The track contained several interesting topics in which GNSS had my attention from the start.

Many people make use of GNSS on a daily basis without actually knowing how it works. Position, velocity and timing results are obtained using satellites at 20000 kilometres above the Earth. Good performance is usually taken for granted, but performance monitoring is essential for any system. Using a monitoring tool with substantiated parameters can give the system more trust and can lead to new insights.

I would like to thank my daily supervisors, Axel van den Berg and Hans van der Marel, for introducing me to this topic. Both were really helpful with all their knowledge, experience and feedback. I would also like to thank the people of the space department of CGI the Netherlands with their input and for giving me a place to work on the project. I would like to thank Ramon Hanssen for being my graduation supervisor and Wim Simons for being the co-reader.

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Abstract

Nowadays, many people and organizations depend on Global Navigation Satellite Systems (GNSS) for navigation, positioning, timing and scientific applications. Monitoring of individual GNSS, such as the American Global Positioning System (GPS) and the European Galileo system, is important to ensure the quality of GNSS measurements. The availability of the signals-in-space (SiS) is an essential part of the monitoring of GNSS, but it is not clear how availability is defined and standards for monitoring are lacking. The main research question for this thesis is therefore: *Which are the key performance indicators related to availability that unambiguously describe sensor station and system performance in time, how can these be computed in an operational manner, and how can they be presented in a condensed form to the stakeholders?* This includes a clear objective of defining unambiguous performance parameters for sensor station and system, and address the considerations related to the definition. A prototype software tool is created to study the algorithms and compute the key performance indicators.

Availability is in the basis a binary operation: a signal is available or unavailable. When this is applied on daily measurements, daily statistics can be computed by dividing the amount of available observations by the amount of expected observations. A signal is considered available if the code, carrier phase and C/N0 measurements are present, and meet certain standards, which are discussed in the thesis. A signal is said to be expected if the satellite is expected to transmit that signal, the receiver is configured to receive that signal, and the signal is not blocked by objects in the signal's path to the sensor station. For this it's needed to define and compute an elevation mask for each station.

The sensor station and system performance parameters are computed from a network of sensor stations, using observation and navigation files in the Receiver Independent Exchange format (RINEX) as input. The sensor station and system performance are each described by their own set of parameters. Four key performance indicators are defined for the sensor station performance. The Daily Station Availability describes the part of the day that the station is operational, the Daily Station Total Availability gives the percentage of available versus the expected observations, and the Effective Mean Elevation quantifies the elevation mask and thus the location of the sensor station. These three parameters are summarized into the Overall Station Quality parameter, which gives and overall performance class to the sensor station.

For the system performance monitoring a satellite is considered available if all signals are received by a sensor station of the monitoring network and the health status is healthy. The satellite is considered unavailable if the signals are received by none of the monitoring stations, while expected by atleast two stations, or the health status is unhealthy. Two key performance indicators are defined for the system performance. The Daily GNSS Availability gives the percentage of the day that the satellite was available and the Daily Available number of Satellites tells how many satellites were available during the day.

The parameters are computed for a period of 100 days. Results are presented using color codes and by showing only detailed information in case of anomalies or specific investigations. The results showed that no sensor station performs perfectly and some worse than others. During the testing phase of Galileo, several events took place. In the initial operational phase, which occupied 17 days of the test period, only a single Galileo event took place.

The proposed key performance indicators showed to be very useful at pointing out good performances or anomalies. While SiS availability gives much insight in the performance, a monitoring tool can be improved when combined with other performance aspects.

Contents

1 Introduction

1.1. Motivation

Global Navigation Satellite Systems (GNSS) become more and more important in our society. Worldwide many people and entities depend on it for positioning and timing. Position, Velocity and Time (PVT) solutions always have small measurement errors associated to it. The quality of the measurements and PVT solutions depend on the performance of the systems in space and ground segment on one hand, and sensor stations and environmental factors on the other hand. The performance of the space and ground segment must be separated from the sensor station performance and environmental effects, which are equipment and location dependent. Knowing each is essential for monitoring the performance of GNSS. The Earth is monitored by the means of GNSS, so it's important that GNSS itself is also monitored.

There are already several groups involved with monitoring performances related to GNSS. Many use their own software, parameters and algorithms as there is no single best way to determine performances. When those groups display their results, it's often unclear how it's obtained. This is a problem as different algorithms may lead to other results. Without knowing the decisions made in the algorithms, the performance parameter results become not comparable, and as such not verifiable. It's therefore important that all decisions are thoroughly treated and the definition and goal of the parameter is clear, so results can be rightfully interpreted. This means that when speaking about performance, it's important that everybody speaks the same 'language' and knows how the performance parameters have been defined. Performance can be defined based on different aspects, in which one of them is the availability of the signals-in-space (SiS). Due to time constraints and because this important aspect is often used without clarifications, the research will focus primarily on performance related to SiS availability. Also, many parameters represent a combination of sensor station and system performance, making it hard to interpret the results. This is unwanted as results depend on the sensor station configuration and location, which is why we must separate the GNSS system performance from the other effects.

1.2. Research Question

This report will focus and tries to answer the following research question:

Which are the key performance indicators related to availability that unambiguously describe GNSS sensor station and GNSS system performance in time, how can these be computed in an operational manner, and how can they be presented in a condensed form to the stakeholders?

The use of key performance indicators (KPIs) is a quantitative method to analyse performances. According to the Cambridge Dictionary the definition of a KPI is:

> "one of the most important indicators (= something that shows what a situation is like or how it is changing) that show how well an economy, company, project, etc. is doing, or how well an employee is working" (Cambridge Univsersity press, 2015)

KPIs should be in a way that the goals and definitions are clear, so that misconceptions are prevented. They are usually computed during a fixed period to standardize processes. Performance based on availability can be expressed as the ratio of available over expected observations. So what is available and what is expected should be defined. This applies for the sensor station and for the system performance individually. A way to automate processes and execute algorithms is by using a software tool. During this research a prototype of such a software tool is created in Matlab (MATLAB, 2015). Algorithms and functions should be created for this purpose, in which the sequence of processes is important. For a tool and parameters to be useful, the results must be interpretable and easy to understand. They should therefore be presented in a logical manner to stakeholders. Users and their motives, interested in a such a tool must first be described.

In order to answer the main research question, this report addresses a set of sub-research questions, which can be divided into sensor station performance, system performance and operations related questions.

Sensor station performance :

- *When is a GNSS signal said to be available at the sensor station?* A GNSS signal can be stated available if it's just observed, or only if it meets certain criteria. When using criteria on good and bad signals, the criteria must be defined. Different measurements are taken of each signal, so it needs to be clear what has to be observed.
- *When is a GNSS signal said to be expected at the sensor station?* Since availability can be expressed as available over expected observations, it should be determined when a GNSS signal is said to be expected. For this it needs to be stated when the satellite is in view of the sensor station. Since not all sensor stations have an optimal view to the sky, an elevation mask can be desired. If an elevation mask is considered necessary, it should be defined: *How is the elevation mask defined?*
- *What are the recommended sensor station KPIs related to SiS availability?* The key performance indicators are considered the most useful quality indicators of the sensor station. Each having a clear goal and definition.

System performance :

- *When is a GNSS satellite said to be available?* The system performance depends on the performance of the satellites. Satellite availability can be expressed as the available over expected period. It should be defined when a satellite is expected, but more challenging is to define when a GNSS satellite is said to be available, as more options are possible.
- *What are the recommended system KPIs related to SiS availability?* A recommendation of the most useful performance parameters will be given and alternatives will be discussed.
- *How are the system and sensor station performance parameters related?* Observations at the sensor station are due to transmitted signals by the satellites. How do we know if bad performance at the sensor station is actually due to sensor station malfunctioning?
- *Which sensor stations can be used in the monitoring network?* Satellite information can be found in files at sensor stations. When a sensor station is sufficient for the use of a monitoring network, how many are needed and which stations are recommended should be investigated.

Operational :

- *How does the process flow of a monitoring tool look like?* A monitoring tool will likely be an accumulation of processes, which can best be described in a process flow showing the sequences of steps. This can be done both high level as low level.
- *How can the KPIs be computed?* KPIs are computed using algorithms, which need to be defined. Also Matlab functions need to be created containing the algorithms to execute the processes.
- *How can the KPIs be presented?* The presentation of the KPIs must be done in a way that users can easily understand and interpret them. Therefore, the potential users must be defined and what their goal of using a monitoring tool is.

1.3. Objective

The main goal is to create unambiguous parameters that represent the performance of either sensor station or system. A list of the most useful parameters will be created. In order to define the parameters, all decisions that need to be made are discussed. A description of a monitoring tool will be given as in which steps need to be done. A prototype tool will be created in Matlab to test the algorithms, to get results and to visualize the parameters. This will be elaborated in a testcase.

1.4. Scope

The research is focussed using a scope:

- RINEX version 3 from IGS MGEX is the primary source of data
- Only the opens service will be considered
- Performance will only be assessed based on availability of signals-in-space
- Focus is primarily on Galileo, which is the new European GNSS, and GPS, which is the most established GNSS

1.5. Outline

The report consists of seven chapters, in which this chapter is used to describe the research. Background is given in Chapter 2. Information on the different GNSS is showed including extra info on the European Galileo project. Also information on positioning and the several error sources that influence measurements can be found. Since the research is about aiming to define performance parameters, relevant groups that are already involved with performance monitoring of GNSS are treated. How availability can be used is described in Chapter 3: Availability. This includes details on when a signal is available and when a signal is expected at a sensor station. Sensor station performance parameters are defined in Chapter 4 and system performance parameters in Chapter 5. Results of a testcase containing 100 days of data is presented and discussed in Chapter 6. Conclusions and recommendations are given in the final chapter.

2

Literature review

In this chapter background information is given on the different GNSS and especially Galileo. It's explained how GNSS is used for positioning and which error sources there are. These error sources are related to the performance of the system or sensor stations. There are already some existing activities in GNSS performance monitoring. A selection of those activities are discussed.

2.1. Background on GNSS

2.1.1. History

The history of satellite navigation goes back as far as 1957, during the time of the cold war (Bonnor, 2012). Using the first ever satellite Sputnik-1, Americans discovered that by using the Doppler shift it's possible to determine the position and orbit of a satellite. The Doppler shift is caused when the source of the transmitting waves moves relative to the observer (Rees, 2013). By reversing this principle, it would be possible to determine ones position once the satellite's orbit is known, which would be very useful to track positions of submarines carrying missiles during the cold war. They elaborated the method within the TRANSIT project, which started around 1960 and was funded by the American Department of Defence (DoD). Transit became operational in 1964 and became available for civil use three years later. It continued to be used until late 1996, while it grew to be a precursor of GNSS as it's known nowadays. Two signals were broadcast by the satellites on 150 MHz and 400 MHz. The orbits used were low Earth and near polar. In the meantime the Russians build their own military system called Parus and a civilian system called Tsikada. Drawbacks of a Doppler shift based system like Transit were that a position fix could take up to 30 minutes, a moving receiver would degrade the accuracy significantly, height determination was inaccurate and in many areas the satellite visibility wasn't guaranteed (Langer et al., 2010). That's why the DoD was looking for something new.

In 1973 the Americans started the project called NAVSTAR (NAVigation System with Time And Ranging), which is now better known as the Global Positioning System (GPS). The first GPS satellite was launched in 1973 and by July 1995 the system became fully operational. Biggest difference between TRANSIT and GPS is the way the range between receiver and satellite is obtained. TRANSIT used to do this by measuring the Doppler shift, but GPS uses another technique. Because GPS satellites carry atomic clocks, it's possible to determine ranges by measuring the time delay between transmit time of the satellite and time of receiving by the receiver.

Initial purpose of GPS was for military reasons. As technology and knowledge advances, the accuracy of the obtained positions increases. This was helpful for the DoD, but they didn't want all civilian users or other governments to have this advantage. For this reason they activated selective availability (SA), which caused to decrease the accuracy for users other than the American military to around 100 meters by introducing pseudo-random errors. During the nineties a new technique was introduced called differential GPS. By using a reference station at a fixed and known location, many errors are decreased to a great extend including SA, making SA useless. Since the second of May 2000 the US government decided to cease SA, causing the accuracy of GPS to increase drastically. In the meantime the Russians were developing GLONASS. Their first satellite was launched 1982 and by 1995 the system was fully functional. Due to a weak economy in Russia, GLONASS degraded while it didn't have their priority. It was until a few years in the 20th century that they invested again in new satellites and improved technology.

2.1.2. Global Navigation Satellite Systems

GPS and GLONASS are not the only GNSS around. There are two more GNSS under development, being Galileo and BeiDou. Each system can be used independently, provided that there are enough satellites, or systems can be used together. Using more GNSS together results in more usable satellites, which results in a better accuracy and performance for the users. Main reason to initiate a GNSS besides the already existing GPS is to be independent. This can be useful as it can be turned off or be used strategically during international conflicts. Table 2.1 shows the main characteristics for every system, which will be described in each dedicated paragraph.

Table 2.1: Characteristics of the space segments of the GPS, Galileo, GLONASS and BeiDou

	GPS	**Galileo**	**GLONASS**	**BeiDou**		
Origin	Unites States	European Union	Russia	China		
Nominal number of satellites [#]	27+4	24+6	21+3	5 (geo)	3 (isgo)	24+3 (meo)
Inclination angle [deg]	55	56	64.8	0	55	55
Orbital planes [#]	6	3	3	1	3	3
Orbital radius [m]	20180	23222	19140	42164	42164	27878
Orbital period	11h58m	14h08m	11h15m	23h56m	23h56m	12h50
Coordinate reference frame	WGS-84	GTRF	PZ-90.11	BTRF	BTRF	BTRF
Time frame	GPST	GST	GLONASST	BDT	BDT	BDT

Galileo

Galileo is the GNSS initiated by the European Union (EU). Last years 11 operational satellites have been launched and four are still under commission. By 15 December 2016 initial operational services were declared live (European Commission, 2016). Since Galileo is the European system and a little less well known than GPS and GLONASS we give it some extra attention in this report. The main features of Galileo are similar to the other GNSS.

The use of GNSS for civilian use became worldwide much more important than initially expected. Until now for both civilian and military applications Europe was dependent on the Unites States (GPS) and the Russians (GLONASS). As an reliable and accurate alternative, the EU started the Galileo project: Europe's own GNSS. Big difference between Galileo and the other GNSS is that Galileo is in civil hands. Galileo will be the largest infrastructure project ever by Europe (European Union, 2011), but the satellites won't be the first satellites used for navigation exploited by Europe. They already have the European Geostationary Navigation Overlay System (EGNOS) in use. This is an augmentation system, Satellite Based Augmentation System (SBAS), which is used to improve accuracy, reliability and availability of GNSS. The first Galileo test satellite, GIOVE, was launched in 2005 and the first Galileo satellite in 2011. Expected is that the system is fully operational by the end of 2020.

Galileo has four services, each for different types of users, based on the need of users and market analysis (Galileo Interim Support Structure, 2002).

Open Service (OS) Position, velocity and timing (PVT) information which is freely available. Three frequencies are in use: E1, E5a, E5b and the combination E5ab, but determining a position using a single frequency receiver is also possible. Since it's an open service, no integrity information or service guarantee is offered.

Commercial Service (CS) This encrypted service offers a more accurate solution and aims at professional and commercial use. Users have to pay to use this service in which the service provider can give access. It will work on the E6 band. The CS can be used to add value to the open service.

Public Regulated Service (PRS) The PRS is especially made for government authorized or other high security users as access is limited. This encrypted service is more reliable and robust as it's designed for anti-jamming. Reason for the PRS is that many national and global infrastructure is dependent on GNSS services like timing and navigation. Therefore disruptions in the signals may lead to huge (financial) trouble. The signal includes integrity information.

Search And Rescue Service (SAR) Galileo is part of a search and rescue mission called COSPAS-SARSAT. The satellites are able to receive signals from emergency beacons, which are send to a rescue center that can determine the position of the person in need. Subsequently feedback can be send back to the user.

A large project like Galileo must deal with many different stakeholders. An important group is the European Commission (EC) with its headquarters in Brussels. The EC is end responsible and takes care of the political aspect. Next to that they initiated and funded the Galileo mission together with the European Space Agency (ESA). ESA is also responsible for most of the space activities happening in Europe. Just like the EC it's funded by EU member states, but includes input of some extra countries. Different ESA offices are spread over Europe. So is ESTEC, the research and technology center, located in Noordijk (NL). Most of the space and ground segment of the Galileo mission is developed under supervision of ESA. The EC is supported by the European GNSS Agency (GSA) in their GNSS programs, which is next to Galileo also the EGNOS mission. While the GSA oversees the Galileo mission, a lot of work they do is contracted out to other parties. One important group of parties is the the Galileo service operator (GSOp). They are responsible for the day to day operations and performances of the system and they will operate the Galileo Service Center (GSC).

A GNSS can be divided into three main segments: the space segment, the ground segment and the user segment. GNSS satellites form the space segment. Information about the Galileo satellites is shown in Table 2.1. The Full Operational Capability (FOC) will consist of 24 satellites, but in total there will be 30 since there will be two spare satellites per plane. While GPS satellites repeat ground tracks within a day, for Galileo it takes 10 days before the ground tracks of the Galileo satellites repeat itself. There are currently two types of Galileo satellites: in orbit validation (IOV) and full operation capability (FOC) satellites. The IOV satellites were the first operational satellites, former used for signal validation. Both types will be part of the operational constellation. Although the IOV satellites were the first operational satellites, they were not the first Galileo satellites. The already retired GIOVE satellites were used to claim the Galileo frequencies (Bradford et al., 2006). Figure 2.1 shows an example of a Galileo satellite.

Figure 2.1: Example of a Galileo satellite, source: `http://www.esa.int/spaceinimages/Images/2013/12/Galileo_FOC`

The Galileo ground segment can be subdivided in two parts: the ground mission segment and the ground control segment. Two ground control centres based in Germany and Italy are used to control the constellation together with five telemetry tracking & control stations. The ground mission segment's role is to determine accurate orbits for the navigation message, uplink it to the satellites and to monitor the navigation signals of the satellites. This is done by the means of Galileo sensor stations and uplink stations.

The Galileo user segment consists of GNSS receivers, which are mostly able to track multiple systems. There are only very few receivers that only track Galileo and then only for the PRS service. For most other users there is a clear benefit in tracking multiple systems. In the 21th century GNSS is completely integrated in our society. Direct and indirect everybody is using its applications on a daily basis. The best known applications for civil use are location-based services. Examples are in-car navigation, navigation on mobile phones or other apps which use position as input, see Figure 2.2a. In the transport sector it's used for rail, maritime and aviation (GSA, 2010). GNSS also becomes more and more important in the agriculture business as automatic steering for tractors raises popularity as shown in Figure 2.2b. Likewise emergency services like police, ambulance and fire-fighters are dependent on navigation too. Surveying by Kadaster or engineering companies is mainly done with GNSS. As already mentioned, GPS originally was meant for military purposes. They use it for navigation, plan and track convoys, and weapon guidance systems (Figure 2.2c). Another user of GNSS is the scientific community. By analysing time-series of measurements they can do deformation and movement studies on for example plate boundaries (Figure 2.2d). It can be used for Earthquake predictions and be used for atmospheric studies. Because of the accurate satellite clocks, next to positioning, GNSS can also be used for timing purposes. Many infrastructure facilities rely on the time synchronizations. Examples include communication networks and the energy sector. Also financial activities like banking and insurance are dependent on accurate timing provided by GNSS.

This shows that there are many different types of users varying between personal, commercial, scientific and governmental use. Each user type has it's own requirements for the costs, accuracy and portability. This means that there's a wide variety of suppliers with each having its own hardware and software. With newer techniques and newer satellites each manufacturer has to update its product range, making the choices between hard- and software types even bigger.

(a) GNSS is used for navigation, source: `http://fox59.com/`

(b) GNSS is used for precision agriculture, source: `http://www.sbg.nl/`

(c) GNSS is used by the military, source: `http://www.worldwide-military.com/`

(d) GNSS is used for monitoring the Earth

Figure 2.2: Four examples of GNSS applications of different users

GPS

As already stated, GPS is the longest operating GNSS and it's originated and is in the hands of the American DoD. The fact that GPS already exists for several years, doesn't mean the system isn't changing. Satellites have a limited lifespan and therefore need to be renewed once in a while. The updating of the satellites is done in different blocks, where each newer block contains improved or extra features. This holds for every GNSS. Block I satellites were launched between 1978 and 1985, and were able to transmit signals on L1 and L2. With the gained knowledge block II satellites were developed, which are subdivided in blocks II, IIA, IIR, IIR(M) and IIF. Satellites from blocks IIR, IIR(M) and IIF are still in use. The updates include a longer designed lifespan, better clocks and extra signals. The newest satellites, block III, are not able to switch on SA anymore. An overview of the GPS satellites in use during mid 2016 is shown in Figure 2.3. When a satellite is decommissioned the pseudo random number (PRN) can be assigned to a new satellite, which is equivalent to the space vehicle id (SVID).

PRN	G01	G02	G03	G05	G06	G07	G08	G09	G10	G11	G12	G13	G14	G15	G16	G17
Block	IIF	IIR	IIF	IIR(M)	IIF	IIR(M)	IIF	IIF	IIF	IIR	IIR(M)	IIR	IIR	IIR(M)	IIR	IIR(M)

PRN	G18	G19	G20	G21	G22	G23	G24	G25	G26	G27	G28	G29	G30	G31	G32
Block	IIR	IIR	IIR	IIR	IIR	IIR	IIF	IIF	IIF	IIF	IIR	IIR(M)	IIF	IIR(M)	IIF

Figure 2.3: Operational GPS satellites during mid 2016 including the blocks/ From G01 up to and including G32 only G04 is decommissioned, making it a total of 31 satellites

GPS used to have a constellation of 24 satellites: six orbital planes each containing four satellites. By positioning the spare satellites in a smart way, three spare satellites now belong to the full operational capability, making it a total of 27 satellites. In addition there are still four spare satellites, making the full total 31.

GLONASS

GLONASS is owned and operated by the Russian government. They started during the early years of GNSS in 1982, but due to economic decay, the system degraded. In the course of the 21th century they renovated the system. Now it's in full operation and used all over the world in different devices. GLONASS has 24 satellites, excluding spares in three orbital planes with an inclination of 64.8 degrees. This inclination is higher than GPS and Galileo and due to this fact it's better suitable for locations with high latitude. Many of the GNSS receivers in the market today also track GLONASS, in addition to GPS.

BeiDou

China has a satellite system called BeiDou, which is just like Galileo still under development. The system is also known as BeiDou-2 or Compass. It originated as a regional system but it's now being transformed and updated into a GNSS. In order to function optimal over the area of China, they use different orbits than the other GNSS. BeiDou consists of 35 satellites in which five are in geostationary orbit. Three satellites are in inclined geosynchronous orbit travelling around the latitudes of China and Australia, while the rest are in 'normal' medium Earth orbits. 2020 is planned to be the year when BeiDou has full global coverage.

Other Navigation Satellite Systems

So GPS, Galileo, Glonass and BeiDou are the different GNSS. There are also two regional satellite systems. One of them is the Indian Regional Navigation Satellite System (IRNSS). Reason for this system is to be independent of foreign governments on positioning and timing. The system only covers India and neighbouring countries due to satellites in geostationary orbit and geosynchronous orbits. With the seven satellites it's possible to determine positions without the need of other GNSS. However, accuracy will improve significantly when used together with GNSS. Quasi-Zenith Satellite System is the name of the Japanese satellite system. It consists of four satellites and is therefore not very accurate on its own. It's more considered as an augmentation system used to improve accuracy and reliability of GNSS positioning.

Satellite Based Augmentation Systems

There are many different satellite based augmentation systems (SBAS) that use geostationary satellites such as the American WAAS and the European EGNOS, which are controlled by government. Commercial forms also exist in the means of Starfix by Fugro and Starfire by John Deere. These satellites are mostly placed in geostationary orbits.

2.1.3. PVT algorithm

An important function of GNSS is to determine positions. A way to do this is by measuring the travel time of the signal. This is achieved by observing the time delay (τ) of the time of transmitting from the satellite (t^s) and the time of receiving at the sensor station (t_r). Each satellites transmits repeatedly pseudo-random signals on its carrier frequency. Each receiver also creates the same pseudo-random signals. By autocorrelating both signals it's possible to determine the travel time of the signal. Signals travel approximately with the speed of light ($c \approx 3 * 10^8$ $[m/s]$), so when multiplying the time delay with c, an approximate distance between receiver and satellite can be obtained as shown in Equation 2.1. The approximate distance is called the pseudo-range, because of the receiver's clock offset, which varies per receiver and over time. These pseudo-ranges, or code measurements, are one of the main observables of GNSS.

$$\rho = (t_r - t^s) \cdot c = \tau * c \tag{2.1}$$

The observed pseudo-range isn't directly the geometrical range but contain sources of errors. The different error sources will be discussed in more detail in Section 2.1.4. The main observation equation used for the pseudo-range observations (Misra and Enge, 2006) is shown in Equation 2.2. ρ is the observed pseudo-range, it contains tropospheric delay (T) and frequency dependent ionospheric delay (I). The part between the square brackets is the receiver clock bias and the satellite clock bias, while ϵ stands for the remaining errors and noise. r is the geometrical range between receiver and satellite as shown in Equation 2.3.

$$\rho = r + I_\rho + T_\rho + c[\delta t_r - \delta t^s] + \varepsilon_\rho \tag{2.2}$$

Vector $\mathbf{x}$ = (x,y,z) is the position of the receiver, while $\mathbf{x}^{(k)} = (x^{(k)}, y^{(k)}, z^{(k)})$ is the position of satellite k. Note that both should be in the same reference frame. For this the Earth Centered Earth Fixed (ECEF) reference is generally used in which the satellite's coordinates should be corrected for the Earth's rotation.

$$r^{(k)} = \sqrt{\left(x^{(k)} - x\right)^2 + \left(y^{(k)} - y\right)^2 + \left(z^{(k)} - z\right)^2} = \left\| x^{(k)} - x \right\| \tag{2.3}$$

The satellite clock offset and position can be obtained from the broadcast ephemeris, while the troposphere and ionosphere delay follows from models or can be computed in various other ways, and applied as corrections to the observed pseudo-range, resulting in the corrected pseudo-range of Equation 2.4, in which ε_ρ is the remaining error. So there are four unknowns which need to be resolved: x, y, z and δt^s. The index (k) means that the variable belongs to satellite k.

$$\rho^{(k)}{}_{cor} = r^{(k)} + c \cdot \delta t_u + \varepsilon_\rho^{(k)} \tag{2.4}$$

Equation 2.4 can than be rewritten to Equation 2.5 as $c \cdot \delta t_u$ is stated as b.

$$\rho^{(k)}{}_{cor} = \left\| x^{(k)} - x \right\| + b + \varepsilon_\rho^{(k)} \tag{2.5}$$

This means that there are four unknowns: $\mathbf{x} = (x, y, z)$ and b, which are the position of the receiver and the receiver's clock error respectively, all expressed in meters. It also means that the number of satellites used must be at least four, so $k \geq 4$. Since Equation 2.5 is nonlinear due to Equation 2.3, a way to solve it is to linearize it at an approximate receiver position and solve iteratively. This method is also known as the Newton-Raphson method (Ben-Israel, 1966). As initial guesses for the unknowns could $\mathbf{x}_0 = (x_0, y_0, z_0)$ and b_0 be used. When filled in, the result is Equation 2.6.

$$\rho^{(k)}{}_0 = \left\| x^{(k)} - x_0 \right\| + b_0 \tag{2.6}$$

The true position and clock error will than be the initial guesses plus the difference between the true value and the guess: $\mathbf{x} = \mathbf{x}_0 + \delta\mathbf{x}$ and $b = b_0 + \delta b$. Just the differences $\delta\mathbf{x}$ and δb should be computed as shown in Equation 2.7 and 2.8. Equation 2.8 is obtained by using a Taylor approximation at the initial guess.

$$\delta\rho^{(k)} = \rho^{(k)}{}_c - \rho^{(k)}{}_0 \tag{2.7}$$

$$\delta\rho^{(k)} \approx -\frac{(x^{(k)} - x_0)}{\left\| x^{(k)} - x_0 \right\|} \cdot \delta\mathbf{x} + \delta b + \varepsilon_\rho^{(k)} \tag{2.8}$$

This can be written shorter using the estimated line-of-sight unit vector $\mathbf{l}^{(k)}$. Equation 2.8 will than be like Equation 2.9.

$$\delta\rho^{(k)} \approx -\mathbf{l}^{(k)} \cdot \delta\mathbf{x} + \delta b + \varepsilon_\rho^{(k)} \tag{2.9}$$

Since we're not dealing with one equation, but a set of linear equations with length $k \geq 4$, it can be written as Equation 2.10.

$$\delta\rho = \begin{bmatrix} \delta\rho^{(1)} \\ \delta\rho^{(2)} \\ \vdots \\ \delta\rho^{(k)} \end{bmatrix} = \underbrace{\begin{bmatrix} -\mathbf{l}^{(1)} & 1 \\ -\mathbf{l}^{(2)} & 1 \\ \vdots & 1 \\ -\mathbf{l}^{(k)} & 1 \end{bmatrix}}_{\mathbf{G}} \begin{bmatrix} \delta\mathbf{x} \\ \delta b \end{bmatrix} + \varepsilon_\rho \tag{2.10}$$

A way to estimate the unknowns is to use the least squares method as shown in Equation 2.11

$$\min \left\| \delta\rho - G \begin{bmatrix} \delta\mathbf{x} \\ \delta b \end{bmatrix} \right\|^2 \tag{2.11}$$

Now it can be solved using Equation 2.12. Q_{yy} is the variance matrix of the observations. It results in estimates of $\delta\mathbf{x}$ and δb and therefore also of $\mathbf{x}$ and b. These approximations can then be used as input for the next iteration until the results converge, which is usually after two to four iterations.

$$\begin{bmatrix} \delta\mathbf{x} \\ \delta b \end{bmatrix} = (G^T Q_{yy}^{-1} G)^{-1} G^T Q_{yy} \delta\rho \tag{2.12}$$

The pseudo-range measurements usually come together with a measure of the signal strength. This is the Carrier-to-Noise ratio (C/N0) expressed in dBHz (IGS, 2015). The value is the ratio between the carrier power over the power of the noise per unit bandwidth (Joseph, 2010). The power of the noise is mainly due to antenna noise and noise at the receiver, while the carrier power is dependent on the transmitting power of the satellite and the atmospheric influences. The value can be used as a quality indicator of pseudo-range measurements. An higher value generally means a higher quality.

Using the pseudo-range observations isn't the only option to determine the distance between satellite and receiver. The carrier phase measurements use a different principle, which leads to more precise results. Instead of measuring the time difference between receiving and transmitting of the signal, it takes notice of the amount of cycles of the carrier frequency. This can be done with a much higher accuracy, yet this comes at a price: only the phase of the last cycle can be observed. So the integer amount of cycles need to be resolved before the distance between receiver and satellite can be obtained. This can be done with integer ambiguity resolution algorithms like the one described in (Teunissen, 1994). Carrier phase measurements, which can result in higher accuracies are used in more high-end receivers where a high accuracy is necessary. Equation 2.13 shows the basic formula used for carrier phase observations. Φ is the observed distance between receiver and satellite, measured by the amount of cycles multiplied by the wavelength. The integer amount of full cycles is represented as N. During tracking of the satellite this value will not change, but it needs to be resolved before accurate results can be gained.

$$\Phi = r + I_\Phi + T_\Phi + c \cdot [\delta t_r - \delta t^s] + \lambda \cdot N + \varepsilon_\Phi \tag{2.13}$$

2.1.4. Error sources

Signals transmitted by satellites travel trough space for over 20000 km, dealing with many uncertainties. This makes it prone to all kinds of errors. In this paragraph the most important and largest error sources for GNSS are discussed. Determining the size of the different error sources is linked to the performance of the GNSS, since knowing the sizes of the error sources gives insight in the quality of the measurements. According to (Misra and Enge, 2006) error sources can be divided in three groups:

1. Errors introduced by parameters computed by the Control Segment. These parameters are broadcast by the satellites to the receivers.

2. Because signals don't travel trough vacuum but trough a medium, the travel time is influenced, which introduces unknown delays.

3. Errors due to receiver level noise.

Errors introduced by to the control segment

Part of the method of calculating the receiver's position is that the position, also called ephemeris, and clock of the satellites are known. The satellites carry very accurate atomic clocks, but even those clocks may and will drift. As the pseudo-range is dependent on time measurements, even a small clock error leads to errors in the observations. These parameters are calculated by the control segment on the ground by models and Kalman filters. The parameters are send to the satellites and then send back by the satellites. This means that the parameters are predictions, which will degrade once age increases.

There are three ways of dealing with the satellite clock and ephemeris errors. First option is to use more precise estimates. This can be achieved by using corrections from SBAS or other commercial providers. More precise parameters can also be obtained when doing post-processing. As predictions are normally used for the parameters, more accurate estimates can be used by calculating them afterwards. Accurate estimates can be obtained from the International GNSS Service (IGS), which will be discussed later in Section 2.2.3. The last option is to make use of relative positioning. For this an extra receiver at a known location is needed. Since the orbit and clock errors from satellites are similar to both receivers, by taking a position relative to the base station, the errors can be mitigated to a great extend.

Satellite outages and failures also have impact on the PVT solution. A decrease in satellites leads to a decrease in measurements at the sensor station. This can be due to expected maintenance, bugs or other errors. Satellites can be temporarily out of use or transmit incorrect signals.

Signal propagation modelling errors

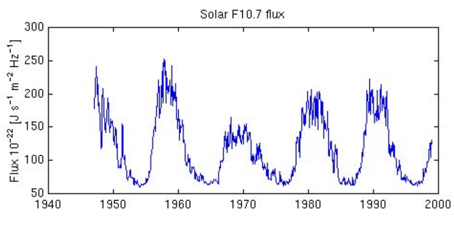
Signals need to travel trough the atmosphere in order to reach the Earth's surface. There are two main layers that affects the signals: the ionosphere and the troposphere. Within these layers particles refract the signals causing it to change speed and direction slightly, which causes an extra time delay. The upper layer of the atmosphere is the ionosphere and reaches between 50 km and 1000 km above the Earth's surface. It consists mainly of free electrons and ions. The amount of electrons, or Total Electrical Content (TEC), defines the amount of refraction as shown in Equation 2.14. TEC is the amount of electrons between satellite and receiver in a tube with a diameter of 1 meter. $n_e(l)$ is the location-dependent electron density along the path. Not all signals are effected the same, since the effect is frequency dependent. Also the effect is not constant, but changes significantly over time. Solar radiation is the major source of ionization. As this varies quite a lot, the total error is affected as well on a regular base, which is usually between one to several tens of metres.

$$\mathrm{TEC} = \int_{Satellite}^{\mathrm{Rec}eiver} n_e(l) \cdot dl \tag{2.14}$$

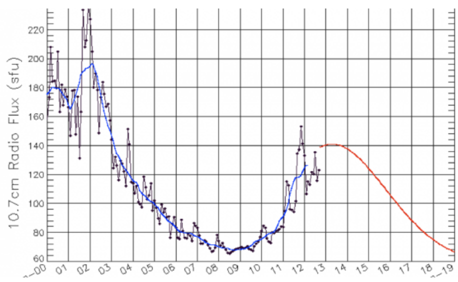
Receivers compute the ionospheric delay using the Klobuchar model (Klobuchar, 1987) for GPS. This model reduces the error by about 50 % (Feess and Stephens, 1987) and uses receiver's position, satellite's elevation and azimuth, and time as input. For Galileo, the Nequick model (European GNSS (Galileo) Open Service, 2016) can be used. Both models work also for single frequency users. The correction parameters are broadcast by the satellites. Another way to deal with the ionospheric delay is to use linear combination as explained briefly in paragraph 2.2.1.

The lowest part of the atmosphere is the troposphere. It consist of two components, namely a dry component and a wet component. Both causing a delay on the transmitted signal. The tropospheric effect is non-dispersive and can therefore only be estimated by models. The dry component delay is caused by the dry gasses in the atmosphere and is dependent on the temperature and pressure of the air. This effect is much bigger than the wet component, 2.3 meter versus 0.2 meter on average, but is very stable and therefore good predictable. The smaller wet component is caused by water vapour and depends on the weather and is thus hard to model.

Refraction due to atmospheric effects are highly variable since the ionosphere and troposphere are not uniform. Different places along the track have different amount of particles, pressure and temperature. Receivers are in different locations and as elevation of satellites differ, so is the signal's length trough the atmosphere. Also over time the effects are varying as ionization is dependent on solar activity, which is changing over various time scales. As there are variations at the atmospheric delays they are hard to model. This causes an error which is left between the modelled parameters and the actual delays. A common used method to measure solar activity is the solar radio flux at a wavelength of 10.7 centimeter (National Oceanic and Atmospheric Administration, 2017). Figure 2.4 shows that the solar activity is highly variable on different timeframes.



(a) Solar activity f10.7 data for 50 years, source: `http://magbase.rssi.ru/REFMAN/SPPHTEXT/f107.html`



(b) Solar activity f10.7 data for the first half of May 2017, source: `http://www.swpc.noaa.gov/phenomena/f107-cm-radio-emissions`

Figure 2.4: Solar activity varies over different timeframes

Errors at receiver level

Errors also occur at receiver level due to multiple effects as given by (Langley, 1997). One of them is the thermal noise, which depends on the noise temperature and the bandwidth. As every object radiates signals, the GNSS antenna also receives those signals. This radiation can come from the sky as well as objects. The antenna itself also creates noise and even the different compartments of the receiver create noise. GNSS signals are not the only radio-waves around. Other waves can cause interference and therefore extra errors. Most receivers compute the C/N0, as explained in Section 2.1.3, which is a measure of these sources of errors.

If the distance between the receiver and the satellites is measured, the direct and shortest distance is wanted. Unfortunately this is not always the case for all observations. Signals can reflect and bounce from surfaces surrounding the receiver and thus arrive later. This time delay caused by the so called multipath leads to an error in the distance estimation. A position clear of obstacles and a high-end antenna such as a choke-ring antenna are able to reduce the multipath. Using signals from satellites higher than a chosen cut-off elevation can also help, as signals coming from underneath are more likely to be reflected. The multipath error on carrier phase measurements is generally much smaller than the multipath error for pseudo-range measurements. For pseudo-range it's generally below 2 meters and for the phases below 1/4 of a wavelength.

Overview

So GNSS deals with several sources of errors due to different factors. Many errors can be minimized by smart processing, better models or better equipment. One thing should be noticed is that signals coming from satellites at a low elevation are more subjected to errors. This is due to the larger distance travelled trough the atmosphere. Also multipath is more likely to happen at signals from low elevation satellites. Figure 2.5 shows the described error sources.

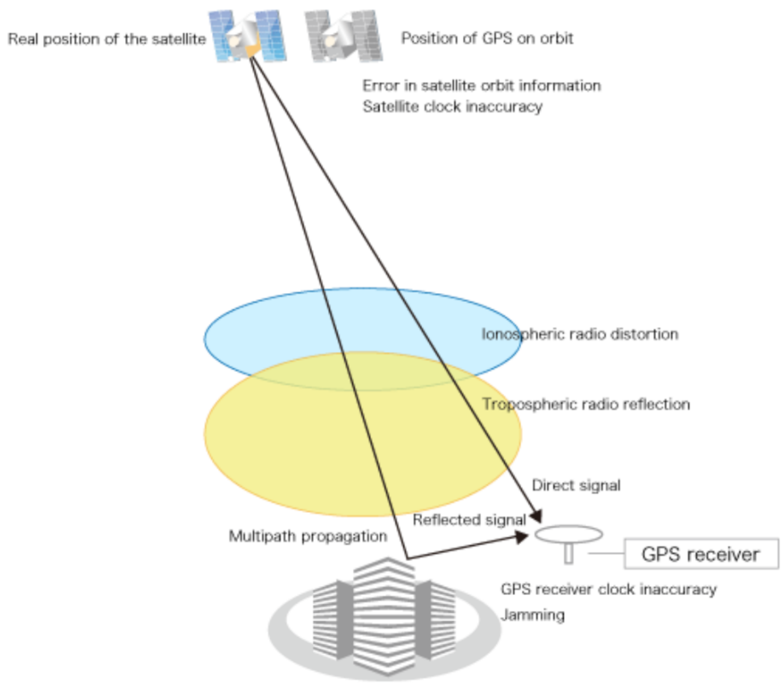


Figure 2.5: This figure shows the most important error sources that influence the accuracy of GNSS, source: `http://www.furuno.com/en/gnss/technical/tec_what_gps`

Approximate values of the error sources are displayed in Table 2.2 (Misra and Enge, 2006). The combined error, or total user range error (URE) is obtained by taking the root of the sum of the squared root mean square (RMS) of the individual errors.

Table 2.2: Overview of the biggest error sources that influence GNSS measurements (Misra and Enge, 2006)

Error	**RMS range error [m]**
Errors introduced by the control segment	3
Signal propagation modelling errors	5
Errors at receiver level	1
Total User Range Error	**6**

2.1.5. Position accuracy

Accuracy

Two common used terms when dealing with measurements are accuracy and precision. Both are introduced by a different type of error (Rutledge, 2010), which can basically be grouped in systematic biases and random errors or noise. Accuracy is described as a measure of statistical bias, introduced by systematic biases, while precision is a measure of statistical variability, introduced by random errors. Figure 2.6 shows the differences between accuracy and precision, which tells that measurements can be accurate and precise, accurate and not precise, not accurate and precise or have a low accuracy and low precision. The left plot shows measurements that have low accuracy, but high precision. This means that the measurements are close together and repeatable, but away from the truth.

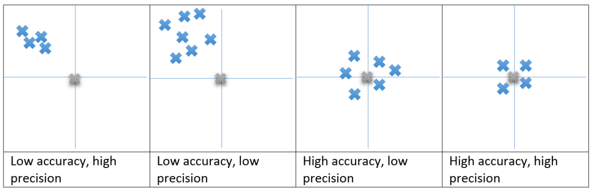


Figure 2.6: Difference between accuracy and precision, source: `http://www.lasersurveyingequipment.com.au/technical-articles/gnss-accuracy-and-precision`

According to (Balazs, 2008) accuracy is: "closeness of agreement between a measured quantity value and a true quantity value of a measurand". From long time average of positions or by using advanced methods like network Real Time Kinematic (RTK) (Rizos et al., 2009), an accurate estimate of the position of the sensor station can be obtained. After that for every epoch the position can be calculated using standard techniques. Using the difference with the true position it's possible to determine statistical values like the standard deviation or circular error probable (CEP), meaning that 67 and 50 percent respectively of every measurement has an error lower than the accuracy value. It can be calculated in three directions: X, Y, Z or north, east, up. An example of positional accuracy in 2D can be seen in Figure 2.7. Every epoch the position is calculated and plotted as a blue dot. The centre of the figure is the average over the time frame and therefore an estimate of the actual position. The red circle, or circular error probable (CEP), shows the area in which 50 percent chance the sensor station is located. For 95 % the station is located within the green circle. These values can be calculated on a regular basis to detect trends.

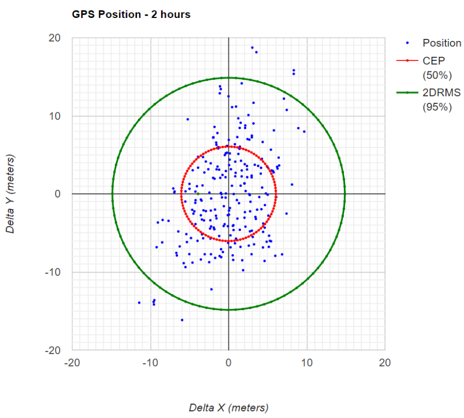


Figure 2.7: Positional accuracy of GPS, source: `http://blog.oplopanax.ca/2012/11/calculating-gps-accuracy/`

Another method is the 3D RMS error of the position estimates in north, east and up direction. Equation 2.15 shows how it can be computed.

$$\text{3D RMS error} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(\Delta E_i^2 + \Delta N_i^2 + \Delta U_i^2)} \tag{2.15}$$

Dilution of Precision

The covariance matrix of the least-squares solution of Equation 2.12 can be expressed as Equation 2.16 (van der Marel, 2016). G depends on geometry of the satellites and Q_{yy} depends on the covariance matrix of the observations, so it doesn't depend on the observations itself. The RMS of the position error can be computed using Equation 2.17, in which D is related to the satellite geometry.

$$Q_{\hat{v}\hat{v}} = \left(G^T Q_{yy}^{-1} G\right)^{-1}$$
$$Q_{\hat{v}\hat{v}} = \sigma^2 \cdot \underbrace{(G^T G)^{-1}}_{D} = \begin{pmatrix} \sigma_x^2 & \sigma_{xy} & \sigma_{xz} & \sigma_{xt} \\ \sigma_{xy} & \sigma_y^2 & \sigma_{yz} & \sigma_{yt} \\ \sigma_{xz} & \sigma_{yz} & \sigma_z^2 & \sigma_{zt} \\ \sigma_{xt} & \sigma_{yt} & \sigma_{zt} & \sigma_t^2 \end{pmatrix} \tag{2.16}$$

$$\text{RMS} = \sqrt{\sigma_x^2 + \sigma_y^2 + \sigma_z^2} = \sigma \cdot \sqrt{D_{11} + D_{22} + D_{33}} = \sigma \cdot \text{PDOP} \tag{2.17}$$

The geometry between user and satellite has impact on the position accuracy. Figure 2.8 shows an simplified situation of two satellites S1 and S2 in 2D and their range measurements. Each measurement has uncertainties, meaning that the position of the user is within the black region. The quality of the measurements decreases the black region, but also the geometry. It can be seen that satellites which are better spread over the area, so not in a straight line, results in a smaller black region and so a better position estimate. The predicted accuracy based on the user-satellite geometry is called the Dilution of Precision (DOP).

Figure 2.8: Positional accuracy of GPS, source: http://what-when-how.com/gps-with-high-rate-sensors/geometric-dilution-of-precision-gps/

The DOP gives information on the geometry of the constellation (Langley et al., 1999). There are four different DOP types: Horizontal DOP (HDOP), Vertical DOP (VDOP), Position DOP (PDOP) and Time DOP (TDOP), in which the PDOP is the most general. The lower the DOP value the better. This means that there are more satellites in view and/or more optimal located in the sky. Optimal located in the sky means that the satellites are spread in all directions. So if the PDOP result is good during an epoch, for instance below five, it means that the constellation is no obstruction of a good position accuracy. The PDOP can be computed based on the satellite positions and the user position.

2.2. GNSS performance monitoring

2.2.1. Sensor station performance

Performance monitoring involves GNSS sensor stations at fixed and often well known positions. There are many different set-ups possible for the hardware and software for GNSS sensor stations. It can be very small in order to fit inside a mobile phone, or as big as the size of a shoebox. At least all consists of a receiver and an antenna. For monitoring purposes high-grade equipment will be used, see: https://igscb.jpl.nasa.gov/network/guidelines/guidelines.html. The receiver is mostly placed inside and is connected to power and an antenna. The antenna is firmly mounted, mostly on a pole, so that movements caused by forces like wind are minimized. A choke-ring type antenna is used in order to block signals coming from beneath. The location of the station is chosen so that it has a clear view to the satellites. This means that it should be on a high location relative to the surroundings, so that signals won't be blocked. Figure 2.9 is an example of the antenna of a sensor station, which is located in Delft. Every day the data of different monitoring stations is uploaded to ftp servers. Many stations (for scientific use) provide their data for free.

The core of a GNSS sensor station consists of a receiver, an antenna and dedicated software. For each of these parts different suppliers exists, which can lead to differences in performance. Especially when dealing with a rather new system like Galileo, the software can contain bugs leading to errors or unreliable data. When sensor stations will be used for the monitoring network, a check must be made on the performance of the sensor stations in order to assess the quality and reliability. So the used equipment is an important aspect

Figure 2.9: Station DLF1 in Delft is an example of a sensor station with good visibility, source: http://www.igs.org/igsnetwork/network_by_site.php?site=dlf1

of a sensor station. Better receivers, antennas and better software and algorithms will lead logically to better results.

Paragraph 2.1.5 showed that position accuracy is an important measure of the performance of a sensor station. This report focuses on the performance based on SiS availability, but there are other monitoring options too, like based on the quality of the received signals. One example is the amount of cycle slips. This occurs when the receiver loses track of the satellite (Sanz Subirana et al., 2011). It's especially a problem when using carrier phase measurements, since it may result in a jump in the integer amount of carrier phase cycles. The measured C/N0 itself is a quality indicator for each observation. Since it partly depends on the noise level of the sensor station, analysing the C/N0 can give insight in the performance of the sensor station. Using linear combinations also gives extra information on the performance of the sensor station. An example is the multipath linear combination as shown in Equation 2.18 and 2.19.

$$MP_i = \rho_{Li} - \frac{f_i^2 + f_j^2}{f_i^2 - f_j^2} \cdot \phi_{Li} + \frac{2 \cdot f_j^2}{f_i^2 - f_j^2} \cdot \phi_{Lj} \tag{2.18}$$

$$MP_i = M_i - \frac{f_i^2 + f_j^2}{f_i^2 - f_j^2} \cdot m_i + \frac{2 \cdot f_j^2}{f_i^2 - f_j^2} \cdot m_j + A_i + \varepsilon_i \tag{2.19}$$

Equation 2.18 shows that both code and phase observations are needed. In addition, dual frequency data is needed: $i \neq j$. Considering the fact that for monitoring purposes high-grade geodetic receivers are used, dual-frequency data is in general always available. M_i is the multipath on the code observation for frequency i. m_i and m_j are the multipath errors on the carrier phase observations, A_i is the ambiguity effect and ε the combined noise. The noise and multipath on the carrier phase observations are significantly lower and can therefore be neglected for most purposes. However the ambiguity term is still present and needs to be dealt with. Between cycle slips the ambiguity term is constant. It's therefore possible to remove this term by removing the mean of the period between cycle slips. What is left is the multipath effect on the code measurements and the receiver noise. By using the linear combinations it's possible to compute the multipath plus noise value for every epoch. This can be done on for every signal and every satellite while there are observations of at least two signals.

A problem with many sensor station performance methods is that the parameter is related to both the quality of the signals or system and the quality of the sensor station, making it hard to interpret. This holds for the C/N0 as well as the multipath linear combination and other parameters.

The time to first fix (TTFF) is the time it takes for the receiver the get a position fix after it's turned on (Anghileri et al., 2010). For continuously operating monitoring stations it's less of an issue, but for other applications it's a relevant measure of performance. The measured TTFF depends on the starting conditions, resulting in three variations:

Cold start : No data is present at the receiver, so a full search of the sky is needed. A cold start takes the most time.

Warm start : An up-to-date almanac is available, meaning that clock correction and ephemeris are already present. However, a time reference and an accurate initial position are still missing.

Hot start : Next to the information of a warm start is also information on the frequency offset and an accurate initial position known. This means that no new navigation message is needed for a position fix.

2.2.2. System performance

The performance of the system, being the space and ground segment, can be determined by the accuracy of the parameters of the broadcast ephemeris. By using reference orbits, the error of the estimated orbit parameters can be computed. This can be done in along-track, cross-track or radial direction (Warren and Raquet, 2003). Many possible performance parameters can be related from this principle. Similar research can be done with the satellite clocks. As the clocks need to be highly accurate, this is a great way to assess the satellites and system.

Section 2.1.5 showed that the DOP can be used as a accuracy indication of PVT solutions. Since the DOP is partly based on the position of the satellites it gives information of the constellation. If the satellites are positioned well in their orbits, the DOP may decrease, which is beneficial. More insight in the performance of the geometry is gained if the DOP, like the PDOP, is computed for a grid of locations spread over the Earth. This is often done since the DOP is dependent on the user's position. Using the grid a minimum PDOP over the Earth can be computed for a given period.

2.2.3. Examples of GNSS performance monitoring groups

In this section several examples of GNSS performance monitoring are given. The list is far from complete as there are many groups both big and small. A selection of the most relevant groups is presented. For each of those groups a description will be given of who they are and what their aim of the performance monitoring is. It will be explained how they monitor and on what parameters. Special attention will be given to parameters related to availability. The following questions will be answered for each party:

- Who are they?
- What is their aim of the monitoring?
- How do they monitor?
- How is availability used?

International GNSS Service

The International GNSS Service (IGS) is a voluntary federation that aims to provide high quality products that are used to improve GNSS performances and support scientific progress on GNSS (Dow et al., 2009). Worldwide they have a network of over 400 high quality permanent GNSS tracking stations. An open data policy makes sure all their data is freely available. The sensor stations are operated by different people or organizations.

The main product of IGS is high accurate satellite orbits and clocks. The IGS uses the so called RINEX files to produce these products. The format for the GPS and GLONASS orbit data is the sp3 format and it can be accessed in three time steps. Ultra-rapid orbits are released four times a day and are partly computed from observations and partly predicted (IGS, 2016). The rapid orbits come with a delay of around 17 hours and the final, most accurate orbits after 12 to 18 days. In addition to the orbit data, clock data is provided. Also atmospheric correction parameters for the atmosphere and ionosphere, Earth rotation parameters and more are distributed by the IGS, as well as basic station monitoring parameters on their web-site.

Since September 2013 the IGS is working on a project to handle more constellations including Galileo. The project is called MGEX: Multi-GNSS experiment (Montenbruck et al., 2017). Using this project they want to distribute and analyse all GNSS signals.

Performance monitoring of GNSS is not the main task of the IGS. Their main goal is to supply high-quality products and stimulate scientific research on GNSS. What they do monitor is the Earth by means of the International Terrestrial Reference Frame, polar motion of the Earth, the Total Electrical Content (TEC) over the Earth, the Earth's gravity field and others. As the Earth is monitored by the means of GNSS, it's important that the GNSS itself are also monitored (Beutler, 2016).

The IGS monitors GNSS on several aspects. One of them is the signal transmission, in which Figure 2.10 shows an example from Galileo taken from `http://mgex.igs.org/analysis/index.php`. Several gaps in the signal transmission can be noticed, which is because the system was for most of the period still in testing phase. A thorough description about the figures lacks, but a figure like this gives a clear overview for a longer period. Other parameters they use are orbit errors, by the means of comparing broadcast ephemeris with sp3, and satellite clock accuracy.

Each sensor station within the network undergoes basic monitoring. For each day the amount of cycle slips, the RMS of multipath on two signals, the latency, the residual in east, north and up direction and the

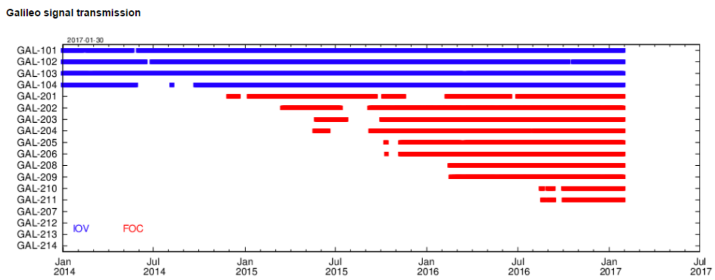


Figure 2.10: Galileo signal transmission from the IGS. It shows the availability of Galileo satellites, source: `http://mgex.igs.org/analysis/index.php`

daily amount of observations are given. Figure 2.11 shows the amount of observations for the second half of 2016 for the sensor station DLF1 in Delft, retrieved from `http://www.igs.org/igsnetwork/network_by_site.php?site=dlf1`. It gives a quick impression of the functioning of the sensor station, but that's it. These results are obtained by the software tool teqc, which is described in the next section.

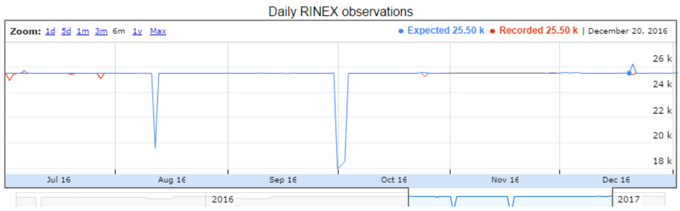


Figure 2.11: Amount of observation from DLF1, taken from the IGS at `http://www.igs.org/igsnetwork/network_by_site.php?site=dlf1`

EUREF Permanent Network

Just like IGS, the EUREF Permanent Network (EPN) is a voluntary organization which has the main task to maintain the European Reference Frame (EUREF) ETRS89. This is done by a large amount of continuously monitoring GNSS stations spread over Europe. Daily, weekly and yearly position and velocity estimates are made for every station, just like estimates of the tropospheric delay and satellite and clock corrections. Their software is based on G-Nut/Anubis, which is based on teqc from UNAVCO. See section 2.2.4 for a brief explanation of the software.

The EPN uses availability in the means of the presence of files for a sensor station. Three data sources are checked on presence: daily data, hourly data and real-time data, which are summarized in the overall data availability as seen in Figure 2.12.

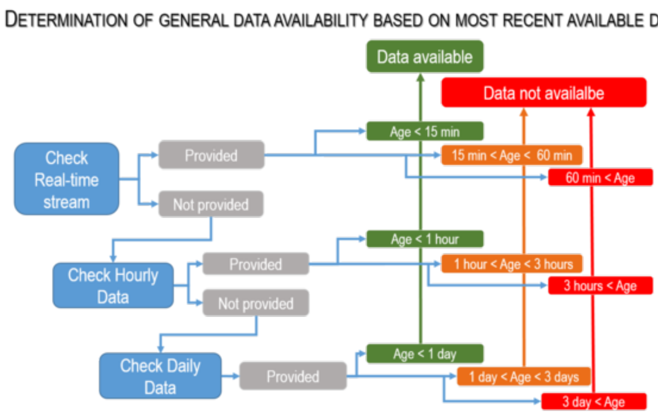
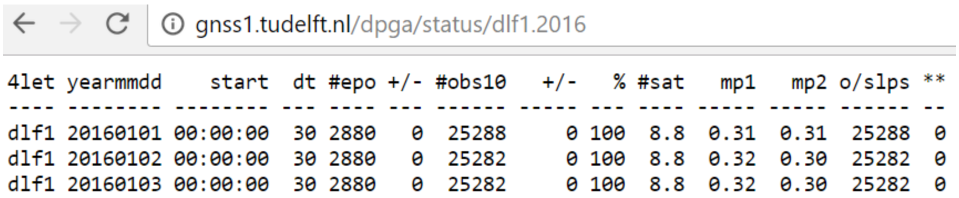


Figure 2.12: Process flow of availability of data for the EPN, source: `http://www.epncb.oma.be/_networkdata/network_status/networkstatus.png`

The quality of the data is assessed based on the ratio of present observations versus expected observations. This is done for each system separate and in total as the mean of all systems. It's also done in two classes: satellites above 0 degrees elevation and satellites above 15 degrees of elevation. Also the maximum number of observations are calculated for both RINEX 2 and RINEX 3, for each system separate and in total. It can be seen that the RINEX 3 files contain more observations. Next to that also the number of cycle slips are given on a daily basis.

Local Data Centre Delft

Part of the IGS network are data centres, which are divided into global, regional and local data centres. One of the local data centres is the one in Delft, which can be reached at `gnss1.tudelft.nl`. On this platform it's possible to download RINEX files of several stations, mostly located in the Netherlands. Some quality control is done on the RINEX files in order to get a brief overview of the performance of the stations. The parameters are computed with teqc and read with perl scripts. An example of the quality monitoring can be found on `http://gnss1.tudelft.nl/dpga/status/dlf1.2016` and Figure 2.13 gives a short impression. It contains some information from the header like the station name, data and interval. Next to that it shows the number of epochs which contain data (2880 for a full day with 30 second interval) and the amount of epochs that are missing. It also displays the amount of observations above 10 degrees of elevation under obs10. The average number of satellites, the average values of multipath on L1 and L2 are also shown. Finally o/slps is the number of observations per cycle slip. It also shows the amount of files and data missing of the current year and the average values of the number of satellites and multipath within the year.



4let	yearmmdd	start	dt	#epo	+/-	#obs10	+/-	%	#sat	mp1	mp2	o/slps	**
dlf1	20160101	00:00:00	30	2880	0	25288	0	100	8.8	0.31	0.31	25288	0
dlf1	20160102	00:00:00	30	2880	0	25282	0	100	8.8	0.32	0.30	25282	0
dlf1	20160103	00:00:00	30	2880	0	25282	0	100	8.8	0.32	0.30	25282	0

Figure 2.13: Screenshot of a performance report from the LDC Delft of the station DLF1, source: `http://gnss1.tudelft.nl/dpga/status/dlf1.2016`

This is done for both GPS and GLONASS, and gives a brief overview of the performance of the stations. However, the amount of information it gives is limited. From the data it's hard to tell when or how something happened. Interpreting the information needs a profound knowledge of the set-up and data, and even then it's hard to say more than whether the station functions good or not on a certain day.

EGNOS Data Access Service

The EGNOS Data Access Service (EDAS) provides EGNOS data and monitors the performance of the EGNOS system. EDAS is managed by ESSP, which stands for European Satellite Service Provider. They supply monthly and yearly performance reports , which are freely availably from their website on `https://egnos-user-support.essp-sas.eu`. Examples of parameters are the (location) accuracy, availability, continuity, integrity and the signals-in-space status, as these are common parameters to determine the performance of SBAS. As input of their network 33 sensor stations are used which are spread over Europe and northern Africa (ESSP, 2016). The EGNOS SIS availability is defined as "the percentage of time in the month during which at least one geostationary satellite broadcasts EGNOS messages". The plots of Figure 2.14 show the SIS availability for December 2016.

Galileo Reference Centre

The Galileo Reference Centre (GRC) will be commissioned by the GSA. Its main purpose is to provide the European Commission an independent means to monitor the quality of the Galileo services as delivered by the Galileo service operator (GSOp). The GRC will be deployed in the Netherlands, but is currently not yet operational. Goal is to build up an archive with measurements and to generate periodic reports with performance Figures of Merit (FOM) that can be used to verify the compliance to the Service Level Agreements (SLA) with the Galileo service operator. The GSOp itself also has a monitoring capability as part of the system support facilities which is also used to report on the performance FOMs, but it's main purpose is to identify and react to possible performance degradations before SLA agreements are violated.

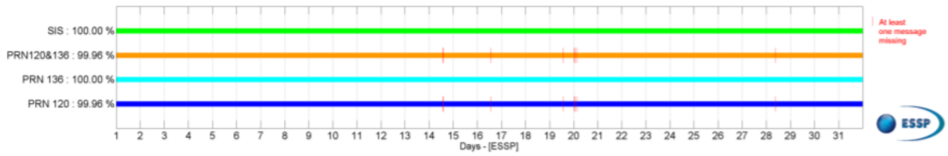


Figure 1 – EGNOS SIS & PRN Availability for December 2016.

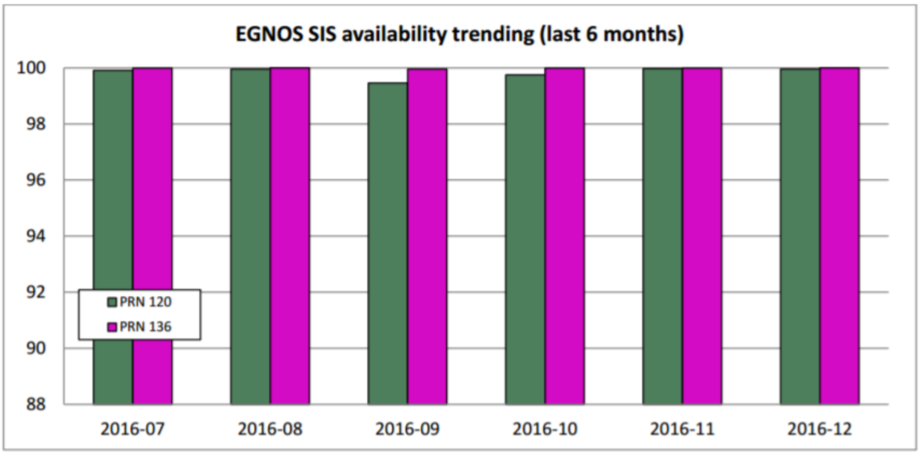


Figure 2 – Trend of EGNOS SIS Availability per GEO.

Availability (%)	2016-07	2016-08	2016-09	2016-10	2016-11	**2016-12**
PRN 120	99.91	99.96	99.46	99.75	99.97	**99.96**
PRN 136	99.99	100	99.96	99.99	99.99	**100**
At least one EGNOS GEO satellite	100	100	100	100	100	**100**

Table 1 – EGNOS SIS Availability (%) on EGNOS GEO satellites.

Figure 2.14: SIS availability for the ENGOS satellites shown per day, summarized per month and the trend (ESSP, 2016)

Federal Aviation Administration - WAAS test team

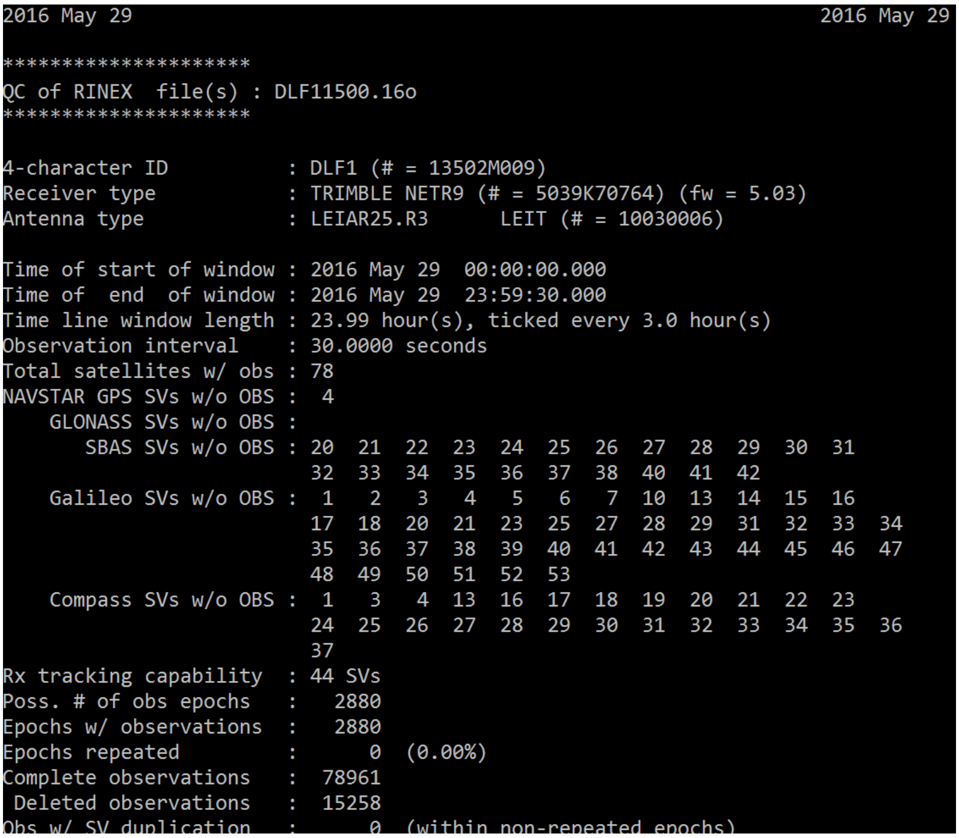
The William j. Hughes Technical Center WAAS Test Team is part of the Federal Aviation Administration (FAA), which is responsible for the American civil aviation. WAAS is short for Wide Area Augmentation System, just like the European EGNOS, it's a SBAS. Performances of both the WAAS and the GPS SPS are measured frequently. They provide both (semi) real-time statistics as periodically generated reports. There are 28 WAAS enabled receivers located in the United States used for this purpose. These stations are also part of the IGS. GPS SPS is tracked with and without WAAS in order to notice differences in performance. For instance, the almanac is used to calculate the PDOP for sampled locations based on a 5 by 5 degrees grid and they evaluate the NANU. Much attention is paid to the PDOP and how it behaves over time. It's also checked whether the 24 slots of the original constellation are filled with healthy (Department of Defence, USA, 2008) and broadcasting satellites.

2.2.4. Examples of GNSS performance monitoring software

University navstar cooperation: teqc

UNAVCO (University NAVstar COoperation), originated in 1984, is a non-profit organization based in the United States. It's governed by universities and funded by NASA and the National Science Foundation (NSF). Their mission is to educate and do research in geoscience using geodesy. One of their activities is (assist in) studying deformation of the Earth by using GNSS stations. Next to high precision GNSS measurements, they also deal with lidar and inSAR techniques. UNAVCO is responsible for the Geodesy Advancing Geosciences and Earthscope facility, or GAGE in short. In this facility they archive and process geodetic data. High accurate GNSS is used for plate boundary observations in combination with other sensors and the IGS is supported with their services of continuous operational receivers.

They don't do monitoring themselves, but make software and encourage research. A well known software tool from UNAVCO is teqc (Estey and Meertens, 1999), which stands for translation, editing and quality-checking of GNSS data. It's a command line tool that can perform the three functions stated in its name and is provided for free. Unfortunately the software is not open source, which is caused by deals with receiver manufacturers since confidential information is used in some processing steps. Some high-end receivers are able to transform the binary data into RINEX files themselves. Teqc is also able to transform the raw binary data into the RINEX standards. Further main input for the tool is the RINEX format as explained in Section 3.3.1. Main drawback is that teqc only handles RINEX formats until version 2.11, which is a problem since most recent version is 3.03. However, it's possible to transform RINEX version 3 to RINEX 2.11, but this may lead to a loss of data and may introduce transformation errors. Editing RINEX files is one of its possibilities. Files can be split or merged and header data can be extracted or altered. Most used function is the quality checking of the RINEX data. Examples of quality parameters are: number of epochs with data, multipath combinations, clock offset, cycle slips, C/N0 and more. Figure 2.15 shows output of the command '+qc', which produces a light version of the quality report. The availability related parameters are shown at the bottom of the figure. Possible number of observation epochs is the maximum number of epochs that can be used within the file. For the example a full day of data is used with a 30 second interval. So observations were taken from 00:00:00 - 23:59:30. This leads to a possible number of observation epochs of $2 * 60 * 24 = 2880$. Considering the statement epochs with observations is 2880, we can say that the receiver received observations every possible epoch. Deleted observations means that the observation is either below the set elevation mask, a lack of code or phase data, or a low C/N0.


```
2016 May 29                                                          2016 May 29

*********************
QC of RINEX  file(s) : DLF11500.16o
*********************

4-character ID          : DLF1 (# = 13502M009)
Receiver type           : TRIMBLE NETR9 (# = 5039K70764) (fw = 5.03)
Antenna type            : LEIAR25.R3      LEIT (# = 10030006)

Time of start of window : 2016 May 29  00:00:00.000
Time of  end  of window : 2016 May 29  23:59:30.000
Time line window length : 23.99 hour(s), ticked every 3.0 hour(s)
Observation interval    : 30.0000 seconds
Total satellites w/ obs : 78
NAVSTAR GPS SVs w/o OBS :  4
    GLONASS SVs w/o OBS :
       SBAS SVs w/o OBS : 20  21  22  23  24  25  26  27  28  29  30  31
                          32  33  34  35  36  37  38  40  41  42
    Galileo SVs w/o OBS :  1   2   3   4   5   6   7  10  13  14  15  16
                          17  18  20  21  23  25  27  28  29  31  32  33  34
                          35  36  37  38  39  40  41  42  43  44  45  46  47
                          48  49  50  51  52  53
    Compass SVs w/o OBS :  1   3   4  13  16  17  18  19  20  21  22  23
                          24  25  26  27  28  29  30  31  32  33  34  35  36
                          37
Rx tracking capability  : 44 SVs
Poss. # of obs epochs   :   2880
Epochs w/ observations  :   2880
Epochs repeated         :      0  (0.00%)
Complete observations   :  78961
 Deleted observations   :  15258
Obs w/ SV duplication   :      0  (within non-repeated epochs)
```

Figure 2.15: Screenshot of a teqc quality report, obtained via the teqc software

G-Nut/Anubis

Many software tools are based on the functioning of teqc. An example is G-Nut/Anubis (Vaclavovic and Dousa, 2015) by VÚGTK in Czech Republic. Just like teqc it gives the expected amount of epochs and the received and usable amount of epochs. This is even more specified in the amount of epochs with single frequency code or phase observations. It also gives the amount of missing data per signal over an elevation bin of ten degrees. Receiver clock jumps and cycle slips are also shown. Just like many other software tools it gives a screen full of numbers as output. Specialized knowledge is needed to make use of the data and to be able to interpret it.

SENDAI

SENDAI is a project and tool funded by ESA, created to investigate the satellite orbit and clock errors (Polívka et al., 2015). It uses data-mining, which is processing large amounts of data, to compare broadcast ephemeris found in RINEX navigation files from the IGS with other high quality products. It concerns mainly the orbit and clock parameters and are therefore system performances. The goal of their study is to provide easy accessible and long time information of the different GNSS.

They note that the navigation files contain errors and inconsistencies. The data therefore first needs cleansing. By combining data from many sensor stations, anomalies can be detected and correct broadcast parameters can be found by majority voting.

Results are shown in daily, weekly, monthly or yearly summarized reports. Also manually chosen figures and results can be obtained per satellite and period. Figure 2.16 shows a summarized plot of the Galileo satellite statuses and Figure 2.17 shows an example of orbit and clock errors.

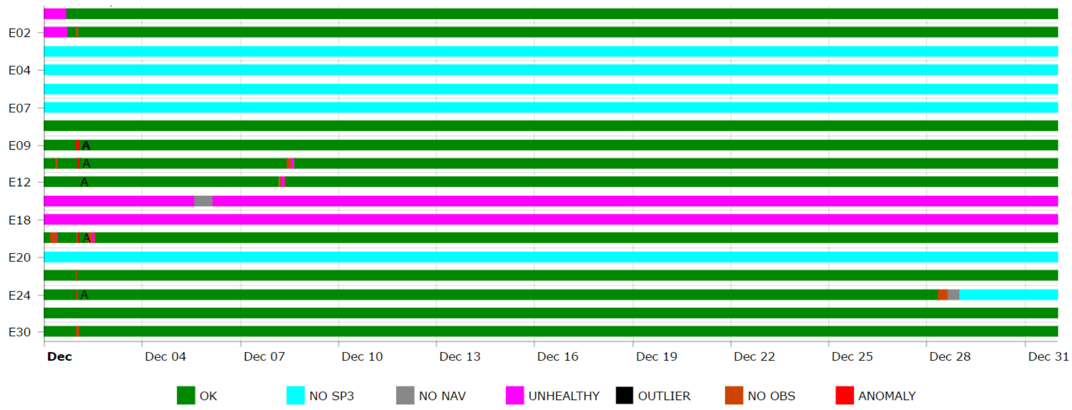


Figure 2.16: Overview of the statuses of Galileo satellites during December 2016, obtained via the SENDAI software

Block	Clocks	Along [m]		Cross [m]		Radial [m]		Clocks [m]		Worst [m]	
		σ	Max	σ	Max	σ	Max	σ	Max	σ	Max
GAL FOC	PHM	1.3	2.3	0.5	1.0	0.4	0.7	0.6	1.0	0.4	1.1

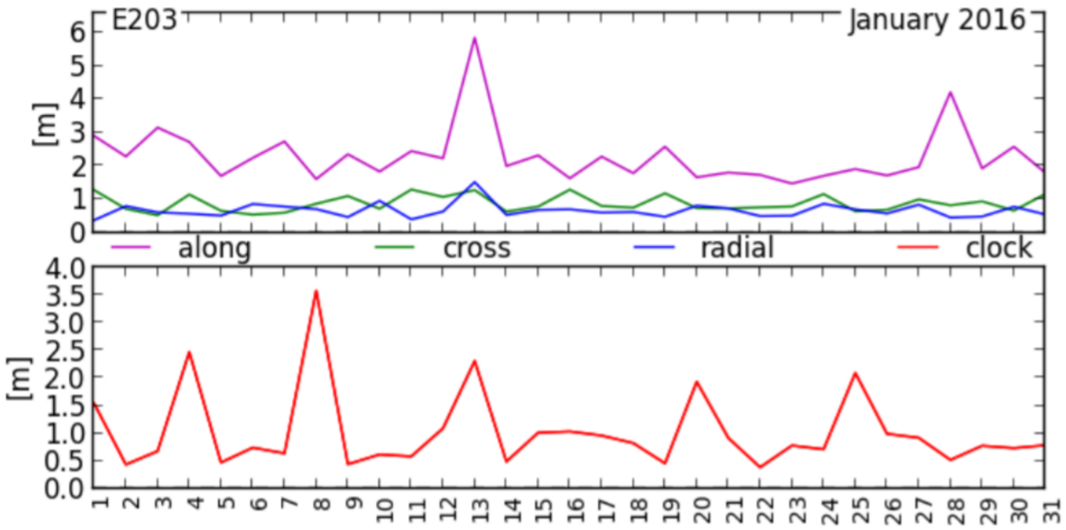


Figure 2.17: Overview of orbit and clock error for satellite E26 during January 2016, obtained via the SENDAI software

2.3. Summary

Several things have been explained within this chapter. Important fact is that the different GNSS are not exactly similar. The constellation exist of different satellites with different orbital periods and ground tracks. However the basis is similar, they all exist out of a space segment, ground segment and a common user segment. Errors can be present in each of these segments, among errors introduced by the atmosphere and others. These have an influence on the performance of the sensor stations and GNSS.

This chapter also showed that parties monitor performances for different reasons. Some, like IGS, UNAVCO and EPN, want to monitor the Earth and for that they need reliable and accurate sensor stations. Others, like the GRC and FAA, monitor in order to assess the satellites and therefore the system operator.

All groups use their own way of monitoring. The tool teqc by UNAVCO surely had a great impact on monitoring software. However, every group uses their own definitions and common agreements seem to lack. It's unclear almost everywhere how the parameters are calculated and what considerations and decisions have been made. Furthermore performances of system and sensor station often are assembled in a single parameter. Whether this is done on purpose or simply overlooked is unclear.

The research of the SENDAI project showed that RINEX navigation files may contain errors. Whether the source of error is the wrongly broadcast message or a receiver software issue can only be determined by processing many files simultaneously.

3 Availability

At its lowest level, that of a single measurement at a single epoch, availability is a binary parameter: yes or no. Yes in case a measurement is expected and received by a GNSS sensor station, no if a measurement is expected but not received by the station. However, for aggregated data, availability is often expressed as a percentage, aiming for 100 % availability over a period of time. This chapter describes how availability can be computed, when a satellite's signal is considered to be available, when it's expected, and which data is used.

3.1. Stakeholders

Before designing a monitoring tool and defining performance parameters it's important to understand what information is desired by who. This section deals with the different stakeholders that are interested in performance information of GNSS related to SiS availability.

Sensor station operator A sensor station operator, like for station DLF1 in Delft, is responsible for the functioning of the sensor station. These sensor stations are often part of a network like the IGS or EPN. If problems occur, or updates should be rolled out, it should be done by the operator. Operating a sensor station usually isn't a core job, but is in general a side task. Therefore, the operator isn't interested in analysing the results daily, but only wants to know from time to time whether the station is working properly, in particular with respect to other stations, and receive a warning (by e-mail) in case something out of the ordinary occurs. Information that is of interest to the station operator is:

- Is the sensor station operational?
- Does the sensor station function as it should: does it receive all expected data?
- Is the location of the sensor station well chosen?
- Is the behaviour of the sensor station nominal: how does it behave in relation to other sensor stations?

Network operator A network operator can be part of the IGS, EPN, a national network provider, or being responsible for part of the Galileo ground segment. The network of sensor stations may be used for obtaining information about the Earth, defining a reference frame or calculating augmentation data or orbit parameters. The quality of its products depend on the performance of the sensor stations. The network operator therefore wants to know how each sensor station is functioning. Next to that, it's useful to know which stations perform best or worst in order to make improvements. In order to track satellites during the full day, the position of the sensor stations should be well chosen. The environment of the station should be chosen well too, as a station next to tall buildings is less useful because satellites and their signals gets blocked. He would like the following questions being answered:

- How do the sensor stations being part of the network perform?
- Are the locations of the stations well chosen?
- Which sensor stations perform best or worst?

System operator The system operator is responsible for the space and ground segment of a GNSS. In the case of Galileo, this can be the GSOp, or the group monitoring the GSOp, the GRC. They're not interested in the performance of a single sensor station, but rather in the performance of the satellites. They would like to know which and when satellites are healthy and transmitting signals. Events or problems with the satellites should be clearly pointed out. They want to know if these events are scheduled or unscheduled and which satellites have problems more often. Comparisons of performances with other systems are interesting. The constellation consists of several satellites being part of the full operational capability and several spare satellites. Part of the task of the system operator is to maintain the full operational capability, so it's useful information if this capability is reached.

- When are satellites transmitting healthy signals?
- How many of the satellites are transmitting healthy signals?
- Are there unscheduled events?
- Are there enough satellites for an accurate PVT everywhere on Earth?

GNSS user As already stated in Section 2.1.2, GNSS has different types of users, which need different information from a monitoring tool. Users may use a standalone receiver, or may use more advanced methods like differential GNSS, (network) RTK or Precise Point Positioning (PPP) techniques. Main separation between users is professional and personal use.

Reliability is important for all users, but especially for professional user with safety critical applications. In that case a bad performance can have serious consequences. Liability becomes an issue for users of the commercial service and especially PRS users (see section 2.1.2). For them performance requirements must be met and the service guaranteed. In that case terms like accuracy, availability, integrity and continuity become relevant. Since GNSS is critical in the aviation industry, they would like to know if a constant accuracy is guaranteed and integrity of the signals is provided.

This research focuses on SiS availability of the open service. Personal users of course desire constantly high accuracy, but no harm is done when for example a single satellite is temporary down. Their biggest concern is if there's a PVT solution possible.

- Are there enough satellites for an accurate PVT?

3.2. Availability definition

Availability is a broad concept. Section 3.2.1 explains the strategy and outline of how availability can be used in performance parameters. The main definition of availability is treated in Section 3.2.2. How determining the availability performance of system and sensor station is related, is described in Section 3.2.3.

3.2.1. Availability strategy

Availability is in the basis a binary operation: something is either available or unavailable. This can be applied on high level, like saying whether a sensor station is available or unavailable during the day. It can also be applied on a lower lever, like saying whether a single epoch or single measurement is available. This low level information is necessary to compute availability statistics. The binary low level availability principle is used for the performance parameters. This section will describe the strategy used to define this availability.

A sensor station receives data per epoch, which is stored at a fixed interval. The station can be declared available during an epoch if the epoch header containing the time is present. For a satellite to be available during a given epoch from station perspective, the first step is that the epoch header must be present. This tells us that the sensor station was at least operational during that epoch.

Next step is that the satellite is listed for that particular epoch. When the satellite is listed, it means that the satellite is tracked by the sensor station. Sensor stations receive normally three measurements per signal: Code, carrier phase and C/N0 observations. For a satellite's signal to be available all three observations should be present. Just the fact that these three observations are present can still mean that the observations are wrong due to software errors, or that the observations are of poor quality. Therefore, the observations need to meet quality requirements, which are defined in Section 3.4.

Satellites transmit several signals as stated in Section 2.1.2. This means that for a satellite to be stated available during an epoch from station perspective, all signals should be present and meet the quality requirements. The necessary steps are visualized in Figure 3.1.

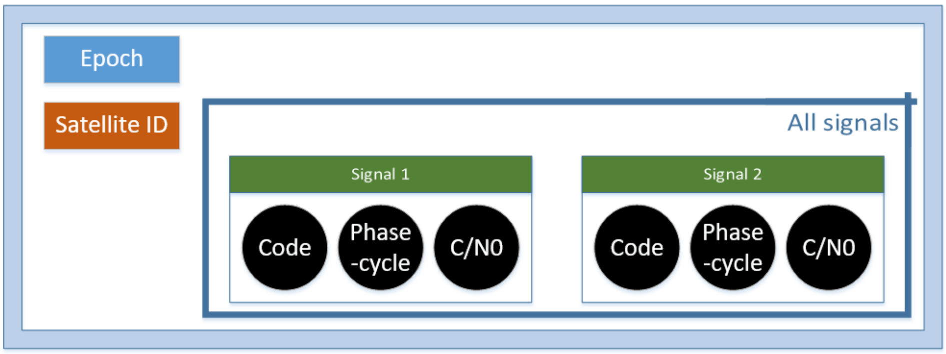


Figure 3.1: Requirements for a satellite to be defined as available from station perspective

1. The epoch header must be present, which tells that the sensor station was operational at that epoch
2. The satellite ID must be present at the epoch, which tells that the satellite was tracked
3. For each signal, the code, carrier phase and C/N0 observations must be present and meet quality limits
4. For the satellite to be available, all signals must be fully present and meet quality limits

Section 3.4 goes into more detail when a signal and satellite is said to be available. Section 3.5 explains when signals of a satellite are said to be expected at a sensor station. Using this information availability can be determined and used for the performance parameters.

3.2.2. Main availability equation

The performance will be assessed based on the availability of the signals-in-space. Before going into details, the definition of availability must be clear. It can be applied on a single possible measurement at a single epoch, which results in telling whether the measurement is either available or unavailable. So it's a binary parameter as the result is either a yes (available) or a no (unavailable), or in other words either a 1 or a 0. Availability has many different variations and definitions, and can be used for different applications. It can be expressed as a percentage over a period of time in a basic form as shown in Equation 3.1. Using the low level binary principle, the data present and data expected are integer counts.

$$\text{Availability}[\%] = \frac{\#\ \text{Data present}}{\#\ \text{Data expected}} \cdot 100\% \tag{3.1}$$

Availability expressed like this basically tells us what percentage of the period that something should work, it actually worked. For this principle two are terms needed: when is data present and when is data expected. This seems straightforward and easy computable, but as we will see later it takes many decisions and computations. Equation 3.1 will be used as a basis for both the sensor station performance parameters as well as the system performance parameters. Equation 3.1 can be applied easily using simplifications, assumptions and estimations. This would give a quality indication which is sufficient for many situations and applications. However, when it's desired to know the performance into more detail and really understand what's happening, the question becomes more advanced as the definitions of which observations are expected and present become more complicated.

3.2.3. Availability monitoring

Availability as expressed in Equation 3.1 is the ratio of observed over expected observations. If an expected observation is not present in the observation file from a sensor station, it doesn't say why it's not present. Reason can be due to local problems like with the sensor station, but also due to problems with the satellite. This connection between sensor station and system performance is one of the main issues when defining a performance parameter. A performance parameter for the sensor station should only represent the performance of the sensor station and thus not the performance of the satellite. The same holds the other way around for the system performance. Luckily there are more sensor stations receiving the same signals from the same satellites. By smart processing the performances can be separated. Figure 3.2 shows this situation.

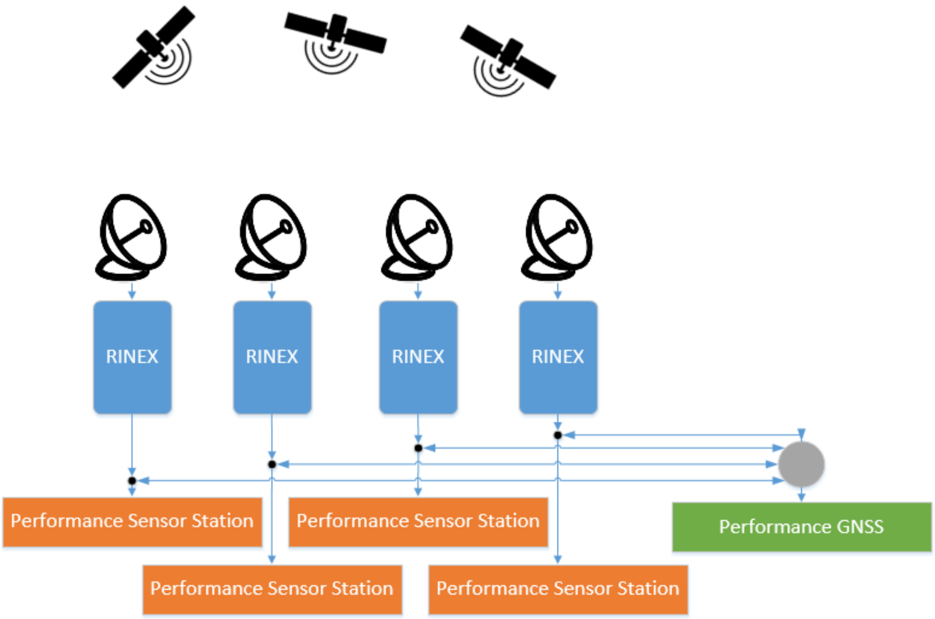


Figure 3.2: Main situation of the connection between sensor station en system performance. By combining information from several sensor stations, the system performance can be determined, which in turn is used determining the performances of the sensor stations

For each sensor station, the corresponding RINEX observation file will be used to determine the sensor station performance parameters. GNSS data is widely available in the RINEX (Receiver Independent Exchange) format, and if not, there are tools to convert the data into RINEX (see Section 3.3 for more information). Existing sources of RINEX data, or purposely installed monitoring stations, can be used for monitoring. For the system performances the RINEX observation files of several sensor station will be processed together. The main principle is that when a signal is expected at several sensor station simultaneously, but none of them received it, it's due to a problem with the satellite. On the other hand, if a signal is received at any sensor station, the satellite is transmitting the signal. So when other stations don't receive it, it's likely due to an issue at the sensor station.

3.3. Input data

RINEX is the commonly used exchange format for GNSS data. Observatations coming from the satellites and supporting information can be found in these files. The most current version is RINEX 3.03 (IGS, 2015). Changes compared to version 2 is that it can handle more frequencies and systems, and the naming convention is extended to make it more clear. There are three types of RINEX files, all in ASCII style: observation file, navigation file and meteorological file. The observation files give the measurements from the receiver, while the navigation file gives the satellite broadcast ephemerides. The meteorological files are used to store meteorologic observations if available at the site. The latter is not used during this research.

3.3.1. RINEX observation files

Each RINEX observation file consists of a header and a body. Information on the type of data and observations can be found in the header in a defined structure. An example of a filename is:
$DLF100NLD\_R\_20161500000\_01D\_30S\_MO.rnx$. DLF100NLD is the name of the station (four characters) and country (three characters), separated by two zeros. The data-source is given as R or S, in which R means that the RINEX file is retrieved directly from the Receiver and S means that the data comes from a data Stream. 20161500000 is YYYYDDDHHMM, where DDD is the day of year number. So it's taken from the 29th of May 2016. 01D means that the observations took place during a full day, while 30s means that measurements were taken once every 30 seconds. MO is mixed observations, meaning different navigational satellite systems were used for input. The last term .rnx states that it's a RINEX file. Files ending with .crx also exists, but that's a Hatanaka compressed RINEX file (Hatanaka, 2008). The RINEX files don't give the position of the receiver instantly. With additional use of the RINEX navigation file it's possible to obtain (estimates) of the position of

the satellites and with addition of information from the RINEX observation files the position can be calculated for each epoch.

```
     3.02           OBSERVATION DATA    M (MIXED)           RINEX VERSION / TYPE
NetR9 5.03          Receiver Operator   29-MAY-16 00:00:00  PGM / RUN BY / DATE
DLF1                                                        MARKER NAME
13502M009                                                   MARKER NUMBER
GEODETIC                                                    MARKER TYPE
HANS VAN DER MAREL  DELFT UNIVERSITY OF TECHNOLOGY          OBSERVER / AGENCY
5039K70764          TRIMBLE NETR9       5.03                REC # / TYPE / VERS
10030006            LEIAR25.R3      LEIT                    ANT # / TYPE
  3924697.7800   301125.1300  5001905.2900                  APPROX POSITION XYZ
        0.0000        0.0000        0.0000                  ANTENNA: DELTA H/E/N
G   12 C1C L1C S1C C2W L2W S2W C2X L2X S2X C5X L5X S5X      SYS / # / OBS TYPES
S    6 C1C L1C S1C C5I L5I S5I                              SYS / # / OBS TYPES
R   12 C1C L1C S1C C1P L1P S1P C2C L2C S2C C2P L2P S2P      SYS / # / OBS TYPES
E   12 C1X L1X S1X C5X L5X S5X C7X L7X S7X C8X L8X S8X      SYS / # / OBS TYPES
C    6 C1I L1I S1I C7I L7I S7I                              SYS / # / OBS TYPES
    30.000                                                  INTERVAL
  2016     5    29     0     0    0.0000000     GPS         TIME OF FIRST OBS
G L2X -0.25000                                              SYS / PHASE SHIFT
R L1P  0.25000                                              SYS / PHASE SHIFT
R L2C -0.25000                                              SYS / PHASE SHIFT
J L2X -0.25000                                              SYS / PHASE SHIFT
GIOVE-A if present is mapped to satellite ID 51             COMMENT
GIOVE-B if present is mapped to satellite ID 52             COMMENT
DBHZ                                                        SIGNAL STRENGTH UNIT
                                                            END OF HEADER
> 2016  5 29  0  0  0.0000000  0 32        .000000000000
G22  20888900.648 8 109772015.001 8        48.100     20888903.406 6  85536708.708 6        40.900
G14  24932073.438 7 131018996.515 7        42.000     24932079.055 3 102092780.091 3        22.600
R24  24663352.234 5 131886063.196 5        32.400     24663351.012 5 131886063.212 5        31.800
```

Figure 3.3: Example of part of a RINEX observation file. It's the daily file of a station in Delft (DLF1), containing data of the 29th of May 2016. The original file contains more observations on the right and more epochs of observations below the shown figure

First thing that can be noticed from Figure 3.3 is that the file consists of two parts. The first 25 lines, until the statement 'END OF HEADER' are part of the header. The left part gives the information and the right part tells what information it is. The RINEX version is 3.02, which is besides minor adjustments very similar to the newest 3.03 version. It's an observation file and contains observations from mixed GNSS, as seen on the first line. The receiver used is a Trimble NetR9, a common used reference receiver, and a Leica AR25 choke-ring antenna. One of the most important lines of the header are left of the statement 'SYS / # / OBS TYPES'. Explanation of the symbols can be found in table 3.4. This shows that signals from GPS, SBAS (EGNOS), GLONASS, Galileo and Beidou are received. The first line of this part shows the GPS satellites. The number 12 indicates that in total 12 different observation types are possible for GPS. C1C means pseudo-range observations on L1, in which the third character is an attribute giving extra information on the used channel. The interval time, which is 30 seconds, and the time of the first observation, which is the 29th of May, correspond with the information from the header.

Sysem ID	C	E	G	J	R	S
	BeiDou	Galileo	GPS	QZSS	GLONASS	SBAS
Observation type	C	D	L	S		
	Pseudo range [m]	Doppler [Hz]	Carrier phase [cycles]	Signal strength [dB Hz]		
Frequency type	1	2	5	7	8	
	L1/E1	L2	L5/E5a	E5b	E5a+b	

Figure 3.4: Explanation for the symbols for the header line 'SYS / # / OBS TYPES'. Only relevant frequency types are shown

After the header comes the data itself. This is divided in blocks for each epoch. It starts with the date and time (year, month, day, hour, minute, seconds. In Figure 3.3 it's shown after the '>' symbol. Also on this line are the number of satellites for the current epoch shown, here it's 32. The next lines show the observations for each satellite within the epoch. G22 means a GPS satellite with pseudo-random number 22 and thereafter the measurements are given. 20888900.648 is the pseudo-range on L1 in meters, 109772015.001 is the carrier phase in amount of cycles. The signal strength on L1 for GPS satellite 22 is 48.1 [dB-Hz]. Thereafter measurements of L2 can be found. Notice that different measurements can be done on a single frequency and also not every satellite transmits all the possible signals.

3.3.2. RINEX navigation files

Next tot the observations itself, RINEX navigation files are also necessary. These files contain information about the satellites (IGS, 2015). Figure 3.5 shows an example of a typical Galileo navigation message. The values are in strict order and each has it's own definition and use. Among these numbers are the orbit parameters, which can be used to compute satellite positions. Receivers need these orbit parameters for calculating PVT solutions. All parameters are computed or estimated by the ground segment of the GNSS. The navigation message also contains satellite clock drift information to improve the satellite clock accuracy. An important parameter of the RINEX navigation message is the one highlighted in yellow in Figure 3.5. It represents the satellite health status. An health status value of zero means that the satellite is healthy, while values other than zero mean that the satellite is unhealthy or something else is going on.

```
E19 2016 03 11 12 10 00-1.616025110707e-05-5.968558980385e-13 0.000000000000e+00
     2.500000000000e+01 4.459375000000e+01 3.007625279665e-09-2.155498324220e+00
     2.184882760048e-06 2.895845100284e-04 1.503713428974e-05 5.440625865936e+03
     4.758000000000e+05-7.450580596924e-09 7.113753161173e-01-9.313225746155e-09
     9.593514890688e-01 1.603125000000e+01 2.854643396499e+00-5.445226815553e-09
     6.785996949726e-11 5.130000000000e+02 1.887000000000e+03
     3.120000000000e+00 0.000000000000e+00-5.820766091347e-09-6.286427378654e-09
     4.764850000000e+05
```

Figure 3.5: Example of a part of the RINEX navigation message. Galileo satellite E19 is shown on the 11th of March 2016. The yellow highlighted parameters represents the health status. The satellite was healthy since the value is zero

The navigation message of Galileo and GPS are very much alike. GPS only has two parameters extra, but the orbit parameters are almost similar and in similar order. So also the satellite health status is in the seventh row and second column. The navigation message structure of GLONSASS is different than that of Galileo and GPS. Instead of orbit parameters it contains the satellite position, velocity and acceleration in X,Y and Z direction. GLONASS satellites won't be processed during this research, but when adding these to the monitoring tool it's important to keep track of the differences.

Each sensor station receives the navigation messages directly from the satellites. It can either store the messages in separate files per GNSS or in a mixed file. Nominal condition is that the messages are stored in a fixed interval, but this depends on the receiver configuration. For Galileo satellites this is usually every 10 minutes and for GPS every 2 hours. So also the satellite health status is only known at these intervals. Since the orbit parameters are estimates, they degrade over time. Knowing the parameter with an age of 2 hours is however accurate enough for our purposes. Evaluating the orbit parameters is outside the scope, but can be a useful addition to a monitoring tool. Sensor station can only track satellites part of the day. This means that when a satellite is not tracked by the station, no navigation message is received. Next to that, when a station isn't operational, no messages are stored. So it's inconvenient to use a single RINEX navigation file from one sensor station for all stations and using separate files for each station is not practical either. A solution to this is to use a merged navigation file. These merged files contain navigation messages from all GNSS and all satellites during the full day. This data is gained from several sensor stations. The CDDIS (Noll, 2010), which is part of NASA, provides these files from their FTP-server. The 2016 merged navigation files can be accessed using `ftp://ftp.cddis.eosdis.nasa.gov/gnss/data/campaign/mgex/daily/rinex3/2016/brdm`. These files will be used for all the processing.

The RINEX navigation files are not the only possible source containing information regarding the satellite positions. There are three main alternatives:

Almanac : The almanac contains orbit parameters, just like the broadcast ephemeris from the navigation message. A disadvantage is that the parameters are older predications and therefore less accurate. Many parameters are similar between the navigation message and the almanac, although the navigation message contains more parameters. A GPS almanac is created once a day, while Galileo almanacs can be found around once every four days. So also the satellite health status is given at maximum only once a day. Almanacs are broadcast by the satellites, but can also be found online. Galileo files are on the website of the GSA: `https://www.gsc-europa.eu/system-status/almanac-data`. For

GPS there are two different kind of almanacs: YUMA and SEM, both can be accessed from Celestrak (`https://celestrak.com/GPS/`). Both types can be used to compute satellite positions. Biggest difference is that the YUMA almanac tells what each parameter is, for example the eccentricity, while the SEM almanac is in ASCII format and contains only the parameters without further explanation.

Two-line elements : The two-line elements are an even shorter version of the orbit parameters. Like the name already suggest, the parameters can be found on just two lines. Celestak also provides the two-line element for Galileo and GPS on: `https://www.celestrak.com/NORAD/elements/`.

SP3 format : The most accurate source for orbit parameters are in sp3 format. This data gives the satellite positions and clock correction every 15 minutes. The most accurate final version is precise to 1 millimetre or 1 picosecond. These are in standardized ASCII format. Multi GNSS sp3 availability of sp3 files are stimulated by the IGS MGEX. The files can be downloaded from several FTP servers like the Center for Orbit Determination in Europe (CODE) (Prange et al., 2015).

3.4. Individual signal availability

An observation is present when it's present in the RINEX observation file. This seems obvious, but just like the expected period, several things need to be made clear. First of all, an observation consists of three different measurements: carrier phase, pseudo-range (code) and C/N0. The Doppler shift will be ignored since only few sensor stations store Doppler shift measurements. Whether carrier phase, code and C/N0 count together as one or as three has a significant effect on the result of availability. Since these measurements are always expected together, these will count as one. So for a signal to be considered present, code, carrier phase and C/N0 measurements should all be present.

Received measurements may not always be of good quality. It may even occur that some measurements are completely unrealistic and wrong. It's therefore important to check whether the measurements are realistic. The aim of this process is not to evaluate the quality of the measurements extensively, as it's out of the scope, but to check whether the measurements are realistic and within reasonable bounds. This is done based on set thresholds.

3.4.1. Code measurements

First condition is that a code measurement should be present. The code measurements represent the pseudo-range between the sensor station and the satellite. Next to that, the true-range can also be calculated as the positions of both the station and satellite are known. An estimate of the station position can be found in the RINEX observation file or on the IGS website, while the satellite positions can be computed from the RINEX navigation files as shown in Appendix A.2.3. There are some differences between the pseudo-range and true-range, as already stated in Chapter 2. The biggest differences are due to clock errors of the satellites. Luckily satellite clock corrections can be found in the broadcast ephemeris.

Figure 3.6 shows the averages of the daily satellite clock biases obtained from the RINEX navigation files for day of year (doy) 300. The clock bias is multiplied by the speed of light the get the introduced range error. It can be seen that for GPS the range error is approximately between -2000 and +2000 meters, while for Galileo it's between -4000 and +10000 meters. This shows that it's necessary to correct for each satellite individually.

The maximum minus the minimum clock bias is computed for each satellite on doy 360. This is visualized in Figure 3.7. It can be seen that for GPS the daily difference is close to 0, while for Galileo it varies between 0 and 100 meters. This means that the satellite clock bias is fairly constant during the day. On the total range this is negligible. Therefore the daily average clock bias is used.

GPS and Galileo satellites use a different timing system. These systems, GPST and GST, differ only 50 ns, which represents a range error of 15m. So this factor is negligible. Next to the satellite clock error the biggest error source between the pseudo-range and true-range is the receiver clock error. During PVT calculations this is estimated using the algorithms. As these are raw measurements it's not estimated yet. Some receivers have an highly accurate clock, while some clock drifts are kept within 1 millisecond. While 1 ms sounds small, it results in a range error of 300 km. This maximum receiver clock error will be used as the threshold. When a narrower threshold is desired, the receiver clock type can be taken into account. The corrected pseudo-range is considered realistic if it differs maximum 300 km from the true-range. Equation 3.2 gives the equation that's used for the code threshold.

$$\left|\text{pseudo.range} + (\text{daily.mean.satellite.clock.offset} \cdot c) - \text{true.range}\right| \leq 300\text{km} \tag{3.2}$$

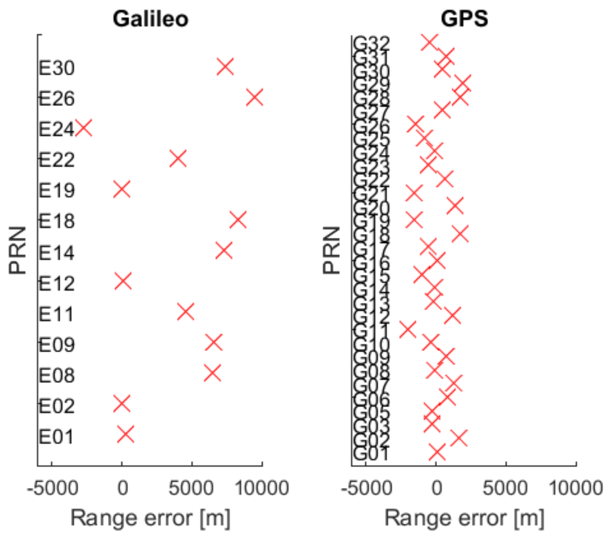


Figure 3.6: The average range error introduced by the daily mean satellite clock bias for doy 300. Information is retrieved from the RINEX navigation file

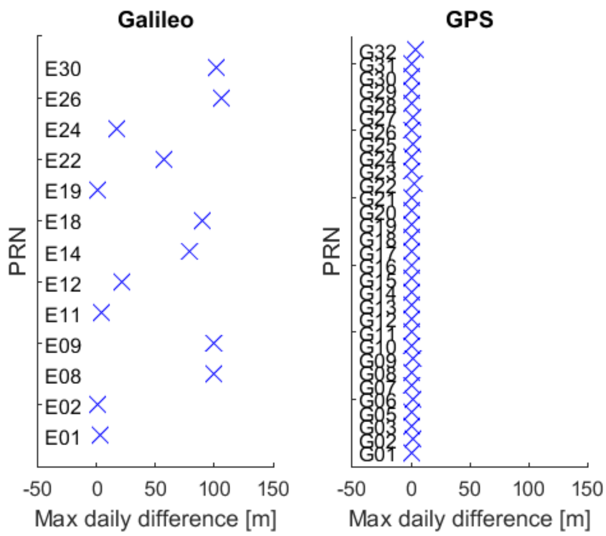


Figure 3.7: Difference between the maximum and minimum satellite clock correction for doy 360. It's multiplied by the speed of light to get the influence on the range error

Figure 3.8 shows an example of the created thresholds for the code measurements. It can be seen that in this example the observed pseudo-range is very close to the true-range. This is due to the highly accurate receiver clock. All measurements are realistic and between the created thresholds that are shown in green. These green lines are 300 km above and below the computed true-range. So a custom time, satellite and sensor station dependent threshold is used for the code measurements. The algorithm needs the satellite positions and the station position to compute the true-range and the average daily clock correction. Furthermore it uses the margin of 300 km that the pseudo-range is allowed to be within range to the true-range.

The code threshold is now created to filter likely wrong measurements using a rough threshold. By extending the algorithms it's possible to reduce the threshold. For the satellite clock error it's chosen to take the average clock bias over the day. In the RINEX navigation files are besides the clock bias also the clock drift and the clock drift rate, so the satellite clock error can be computed more accurate for every epoch using Equation 3.3 (Bidikar et al., 2014). In this equation is α_0 the clock bias, α_1 the clock drift and α_2 the clock drift rate. The 300 km threshold is now based on the receiver that has the worst clock drift, which is in our case 1 ms. Some receiver clocks have a lower clock drift. When using the receiver clock drift of each individual station, the threshold can be decreased.

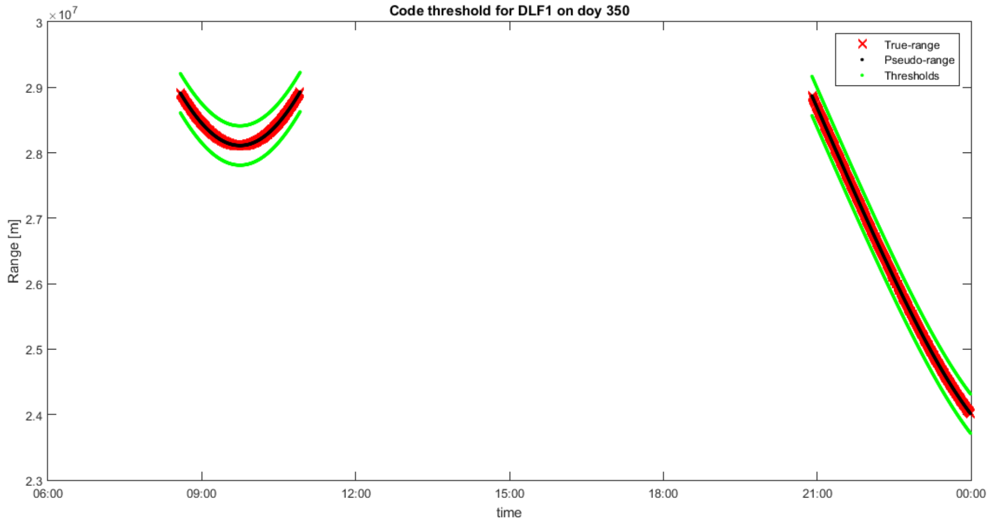


Figure 3.8: Thresholds for code measurements for station DLF1 on doy 350. This plot shows satellite E01.

$$\varepsilon^{sc} = \alpha_0 + \alpha_1 \cdot dt + \alpha_2 \cdot dt^2 \tag{3.3}$$

3.4.2. Carrier phase measurements

Just like the code measurements, also a carrier phase measurement should be present in the data. On first sight, similar thresholds as used for the code measurements can be applied. By dividing the true-range by the wavelength the amount of carrier phase cycles can be calculated. However, it cannot be used as a threshold. The raw carrier phase measurements are not resolved for integer ambiguities. This means that the measurements may have large jumps or can even be negative. It's therefore not possible to set a threshold limit, without estimating the ambiguities first, which is not in the scope of this research. Just the presence of the carrier phase measurement is therefore sufficient. Jumps in the carrier phase measurements, or cycle-slips, still is a performance aspect of the sensor station, but not considered within this thesis.

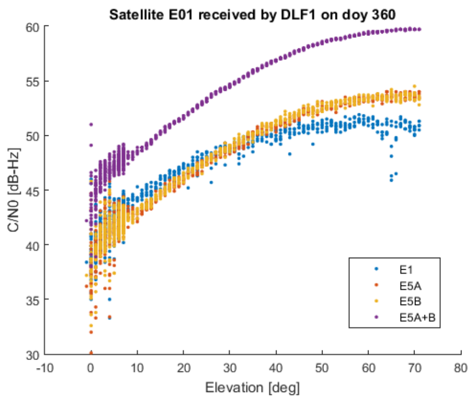
3.4.3. Carrier-to-noise ratio measurements

The carrier-to-noise ratio should also be present in the RINEX observation file for every observation, as it's part of the complete observation. Furthermore, the carrier-to-noise ratio is related to the noise level of the receiver and the power of the signal. It can therefore be used as a quality indicator of the measurements. A minimum threshold ensures a minimum quality of the measurements and is needed as a signal with a too low C/N0 is too much affected by noise and of low quality. However, it doesn't imply that signals with a low C/N0 are completely wrong and of a too low quality to be used for positioning. It means that the measurement shows behaviour that's not nominal, which may mean that something is going on. Most receivers don't track satellites with a C/N0 below 28 dB-Hz as they consider these signals unreliable, so the minimum threshold is set at 28 dB-Hz. An exception is made for the L2W signal of GPS, since its pattern is much lower. This threshold is set at 8 dB-Hz. The lower limit can be seen in Figure 3.10a. Since this is not the GPS L2W signal, the lower limit is set at 28 dB-Hz.

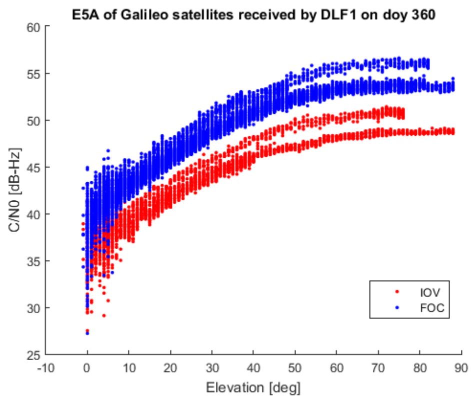
Over time the C/N0 changes, but this is mostly due to change in elevation of the satellites, as Figure 3.10a shows. The strong relation between the C/N0 and the elevation is caused by free space loss, antenna gain patterns and multipath interference. At low elevation the path trough the atmosphere is longer, resulting in a lower C/N0.

While there's a clear relation between the C/N0 and the elevation, it has to be made clear if the relation is similar between stations, satellites or signals. This is necessary for knowing if a single threshold can be used for all stations, satellites and signals, or that separate thresholds need to be made.

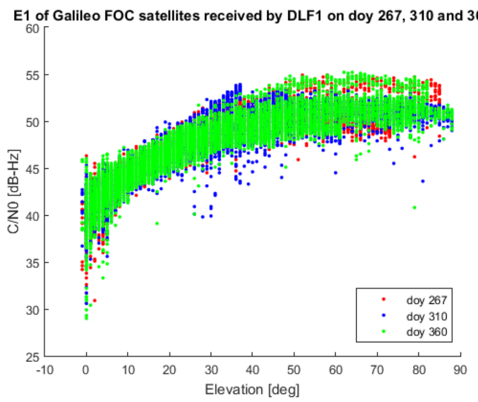
Figure 3.9a shows the strong relation with the elevation for a single satellite. It also shows that different signals have a different relation. Galileo signals E5A and E5B show however an almost exactly similar pattern. It can also be noticed that the satellite is tracked two times during the day, in which once the maximum elevation was around 75 degrees and once around 8 degrees. Figure 3.9b shows the E1 signal of all Galileo satellites received by DLF1 on doy 350. Galileo basically has two satellites types: the IOV and FOC satellites. Both are shown in a different color. First of all it can be noticed that the FOC satellites have an higher power output than the IOV satellites. Although each satellite has its own pattern, there's a relation between the satellite types and the behaviour over elevation. In Figure 3.9b it seems like there are four trends, but this is because only a small dataset is shown. When using more data, the similar behaviour of the satellites will stand out more, as shown in Figure 3.9c which uses three days of data. For GPS the differences are also present for each satellite block. The threshold should therefore be made differently for each type of satellite. Another possibility is to make the threshold separate for each satellite. Doing this can make the margin narrower for each satellite, but it doesn't add much, since all satellites of the same type have a clear and similar behaviour over elevation. Over time the relation between C/N0 and elevation stays similar. This can be seen at Figure 3.9c, which shows the E1 signal of Galileo FOC satellites for three different days of 2016. The threshold therefore doesn't have to be updated, unless major updates are applied to the station. When the same signal and same satellite type is plotted for three stations in Figure 3.9d, it can be seen that the patterns are different for the different stations. This means that the threshold should be made station dependent.



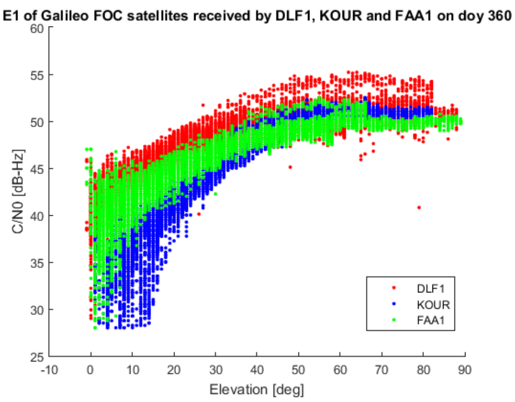
(a) One day (doy 350), one station (DLF1),
one satellite (E01),
four signals (E1, E5A, E5B, E5A+B)



(b) One day (doy 350), one station (DLF1),
all Galileo satellites, one signal (E5A),
two satellite types



(c) Three days (doy 267, 310 and 360),
one station (DLF1),
one satellite type (Galileo FOC), one signal (E1)



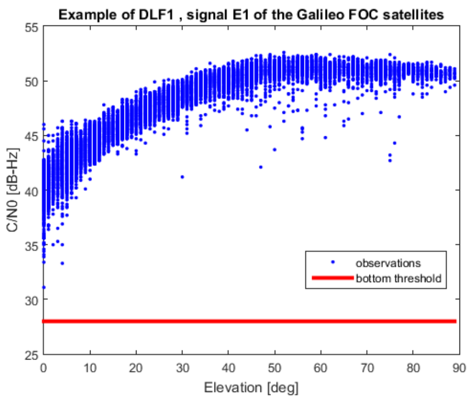
(d) One days (doy 360), three stations (DLF1, KOUR and FAA1),
one satellite type (Galileo FOC), one signal (E1)

Figure 3.9: Four figures showing the relations of the C/N0 over elevation. Figure 3.9a shows that signals have different patterns, while Figure 3.9b shows that different satellite types have different patterns too. Figure 3.9c shows that the pattern stays the same over different days and Figure 3.9d shows that the pattern is different for different stations.

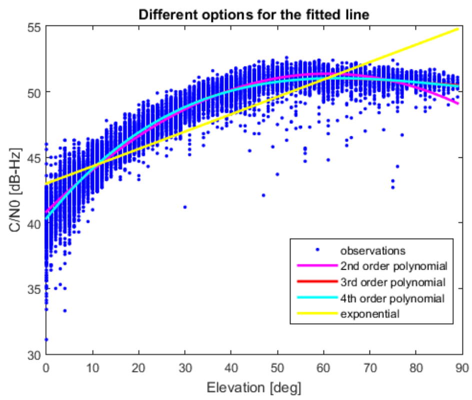
Nominal behaviour is that the C/N0 is higher from satellites of higher elevation. So it's useful to add an elevation dependent threshold next to the bottom threshold. A way to achieve this, is to fit a line through the data. There are two main options for doing this: an exponential or an polynomial. Both options are shown in Figure 3.10b. An exponential fit is clearly not sufficient for the data, but the polynomials show a better fit. The second order fit is unwanted as the line goes down much at high elevations. The third and fourth order polynomial show a better fit. At Figure 3.10b the third order fit is hardly visible as it's almost exactly similar as the fourth order fit. This means that the third order polynomial is preferred. An higher polynomial is unnecessary and undesired as it won't represent reality any more. Equation 3.4 shows the equation of a third order polynomial, in which x is the elevation.

$$C/N_0 = a \cdot x^3 + b \cdot x^2 + c \cdot x + d \tag{3.4}$$

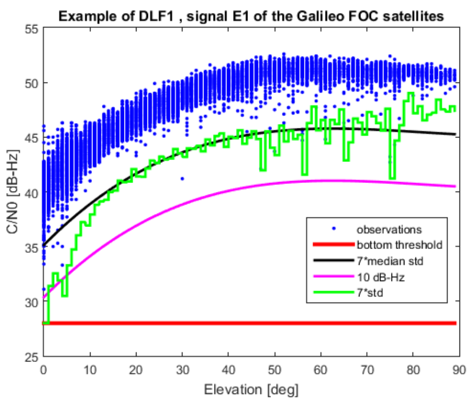
To use this fitted line as a bottom threshold, the measurements must be within a certain range from this fit. Also for this range are several possibilities. It can be within a fixed margin of the fit. A value of 10 dB-Hz can be used since it means that the C/N0 is a factor ten below the expected value. Another option is to link the margin with the data itself. This can be applied by using the standard deviation per elevation bin, or to get an overall measure of the spread of the data it's possible to use the median of the standard deviations per elevation bin. If we assume that the data is normally distributed, subtracting 6.806502 times the standard deviation results in a confidence level of 99.999999999 %. Note that both the mean value is estimated, the standard deviation is estimated and the data is not perfectly normally distributed. However, this gives a good estimate of the spread of the data. Figure 3.10c shows the three different lower margins. The different margin per elevation is undesired, as it's hard to reproduce and arbitrary if all the assumptions hold. Also using the median standard deviation is not optimal. It may occur that some elevations have a high standard deviation, so many measurements will get rejected. Therefore the fixed margin of 10 dB-Hz is recommended. For some signals or stations this is a very wide margin, but it can be applied to all. If wanted, the fixed margin can be easily adjusted to the user's needs.



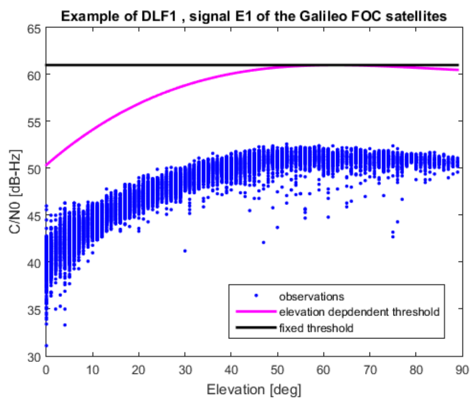
(a) First step of the C/N0 thresholds: the bottom threshold



(b) Options for fitted line



(c) Lower margin options

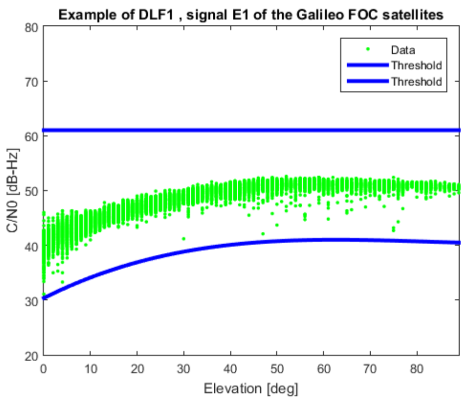


(d) The upper threshold

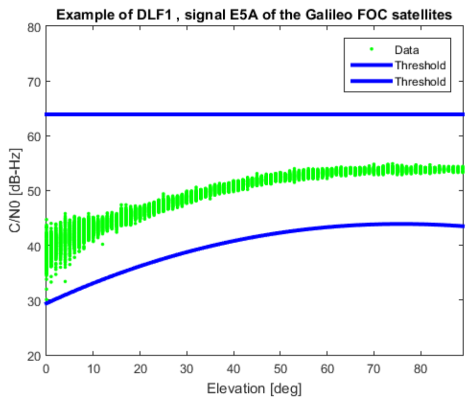
Figure 3.10: Necessary steps to create C/N0 thresholds, giving the station, satellite type and signal

Usually an high C/N0 means that the signal is of high quality. However, if the value is much higher than expected, it can can also be an indication that something is going on. A too high C/N0 is simply not realistic, making an upper threshold also needed. Two main options are again possible: create an elevation dependent threshold like the lower margin, or set a fixed margin. Figure 3.10d shows these two examples, in which the fixed margin is created by the maximum of the other. The elevation dependent upper threshold is created by a 10 dB-Hz margin, just like the lower margin. Since the upper threshold is only created to see if the measurements are realistic, the more conservative fixed threshold is preferred. The threshold seems high, but if the C/N0 measurements are above average low, it may mean that the measurements are of low quality, but if the measurements are above average high it may mean that the measurements are of high quality. However, if the measurements are unrealistically high something may be wrong, so therefore the relatively high upper threshold is used.

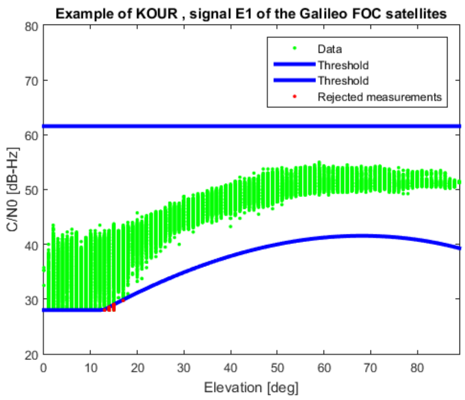
The thresholds are defined using a dataset of 10 days that include around 100000 measurements, depending on the satellite type. A third order polynomial is fit to the data and the lower margin is 10 dB-Hz below this fit. However, the minimum of this threshold is set at 28 dB-Hz with an exception of the GPS L2W signal. The upper threshold is created using the maximum of the fitted polynomial plus 10 dB-Hz. Figure 3.11 shows four examples of the threshold over the used dataset. The first plot, Figure 3.11a shows the E1 signal for all FOC satellites tracked by the station in Delft and Figure 3.11b signals E5A for the same station. In both datasets no data was rejected. At Figure 3.11c, which is station KOUR, shows 23 rejection out of the 91000 used measurements. It can be seen that at low elevation the bottom threshold of 28 dB-Hz is used, while from 13 degrees elevation the threshold goes up. This is also where the rejections take place. Figure 3.11d shows the same signal of Galileo for station AREG. It can be seen that this is a station that stores measurements lower than 28 dB-Hz. The amount of rejection is also for this dataset 23 out of approximately 91000 measurements, which corresponds to approximately 0.025 %. The rejections of Figure 3.11d are mainly because station AREG stores measurements below 28 dB-Hz, while the rejections of Figure 3.11c are below the fitted trend. Since only a small selection of measurements are rejected, the impact on the availability results is small.



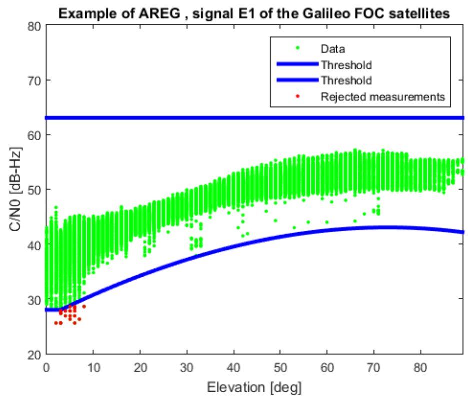
(a) DLF1, Galileo FOC, E1



(b) DLF1, Galileo FOC, E5A



(c) KOUR, Galileo FOC, E1



(d) AREG, Galileo FOC, E1

Figure 3.11: Four examples of the final C/N0 thresholds

Note Whether a signal is available or not is evaluated using the fact that code, carrier phase and C/N0 are present and code and C/N0 are within thresholds. This is an important aspect of determining availability, as it has direct impact on the results. It can be chosen to extend the threshold with other performance measures like receiver noise or cycle-slips. After resolving the integer ambiguities also the carrier phase measurements can be evaluated.

The thresholds of the C/N0 itself can be used as a performance parameter too. As the receiver noise is part of the C/N0, the fitted polynomial can give information about the noise level of the receiver. An extensive C/N0 evaluation or a C/N0 performance parameter is out of the scope of this research, but it can be a great extension. Next to that, the set thresholds are mainly based on logical reasoning. A relation between the C/N0 and the elevation angle of the satellites is clearly present, which is caused by the atmospheric travel time, antenna gain patterns and multipath. Although the effects are mostly related to the elevation of the satellites, they are also related to the azimuth angle. By doing more research on those effects, the margins can be improved, which will have impact on the processing and therefore improve the results.

3.5. Expected signal definition

Availability defined as a statistic of available over expected observations need the epochs at which the satellites are expected to be observed by the sensor station. This needs several steps which are discussed in this section and summarized in Section 3.6.

3.5.1. Sensor station and satellite configuration

An obvious but important boundary condition telling whether a signal from a satellite is expected, is that the satellite should be able to transmit it and the sensor station should be able to receive it. It's necessary as not all satellites from a system transmit all signals. For Galileo this is not the case yet, as all satellites are from the same block. So all operational Galileo satellites, including the IOV satellites, transmit all signals. For GPS there are differences. As already explained in the Chapter 2, newer satellites often come with improvements and new functionalities like new signals. So a lookup table should be made that links the satellite ID with the corresponding satellite block and so the corresponding expected signals. Table 3.1 shows the GPS blocks and signals. If a satellite is expected to be tracked by the sensor station, it means that all expected signals are expected to be tracked.

Table 3.1: Current GPS satellite blocks and their signals

Block	**Signals**			
IIR	L1	L2W		
IIR (M)	L1	L2W	L2	
IIF	L1	L2W	L2	L5

Not all sensor station receive all signal types either. Since stations being part of the MGEX IGS network are used, high-grade receivers are used and therefore most do receive all signals and all gnss. Table 3.2 shows an example of the signals received by 20 stations. Why these stations are chosen will become clear later.

Table 3.2: Signals received by 20 sensor stations, including the tracking method as third attribute

Stations	**L1**	**L2W**	**L2**	**L5**	**E1**	**E5A**	**E5B**	**E5AB**
Areg	L1C	L2W	L2X	L5X	E1X	E5X	E7X	E8X
CAS1	L1C	L2W	L2X	L5X	E1X	E5X	E7X	E8X
DLF1	L1C	L2W	L2X	L5X	E1X	E5X	E7X	E8X
DUND	L1C	L2W			E1X	E5X	E7X	E8X
FAA1	L1C	L2W	L2L	L5Q	E1C	E5Q	E7Q	E8Q
JFNG	L1C	L2W	L2X	L5X	E1X	E5X	E7X	E8X
KOUR	L1C	L2W	L2L	L5Q	E1C	E5Q	E7Q	E8Q
KRGG	L1C	L2W	L2S	L5Q	E1C	E5Q	E7Q	E8Q
KZN2	L1C	L2W	L2X	L5X	E1X	E5X	E7X	E8X
MAJU	L1C	L2W	L2L	L5Q	E1C	E5Q	E7Q	E8Q
MAL2	L1C	L2W	L2L	L5Q	E1C	E5Q	E7Q	E8Q
NKLG	L1C	L2W	L2X	L5X	E1X	E5X	E7X	E8X
OHI3	L1C	L2W	L2S	L5Q	E1C	E5Q	E7Q	E8Q
RGDG	L1C	L2W	L2X	L5X	E1X	E5X	E7X	E8X
STFU	L1C	L2W	L2X	L5X	E1X	E5X		
SUTM	L1C	L2W			E1X	E5X		
TOW2	L1C	L2W	L2L	L5Q	E1C	E5Q	E7Q	E8Q
WARK	L1C	L2W		L5X	E1X	E5X	E7X	E8X
XMIS	L1C	L2W	L2X	L5X	E1X	E5X	E7X	E8X
YEL2	L1C	L2W	L2L	L5Q	E1C	E5Q	E7Q	E8Q

It can be seen that from this sample of stations DUND, STFU, SUTM and WARK and don't receive all signals. Receivers can track the signals using different tracking methods. This is represented in the third attribute of the signal ID (IGS, 2015). So different satellites types may transmit a different number of signals, different stations may receive a different number of signals and different stations may use different tracking methods. When processing RINEX observation files, this must be taken into account. The signals that are considered for this thesis are given in Table 3.3 for Galileo and Table 3.4 for GPS.

Table 3.3: Considered Galileo signals

Signal	RINEX signal ID	tracking methods
E1	E1	Q, X
E5A	E5	Q, X
E5B	E7	Q, X
E5AB	E8	Q, X

Table 3.4: Considered GPS signals

Signal	RINEX signal ID	tracking methods
L1	L1	C
L2W	L2W	W
L2	L2	L, S, X
L5	L5	Q, X

3.5.2. Mapping to elevation bins

After it's known which signals are expected, it should be determined when the signals are expected. For this the satellite should be in view of the sensor station. Under ideal conditions the satellite is expected to be tracked if the elevation of the satellite relative to the sensor station is above 0 degrees, assumed that the stations are set to track satellite above 0 degrees elevation. This is the case for all used sensor stations. So it should be determined when the satellite is at 0 degrees elevation and thus comes and leaves view. Figure 3.12 shows the azimuth angle (left) and the elevation angle (right) between sensor station and satellite. To determine these angles, two things are needed:

- Sensor station position
- Satellite position

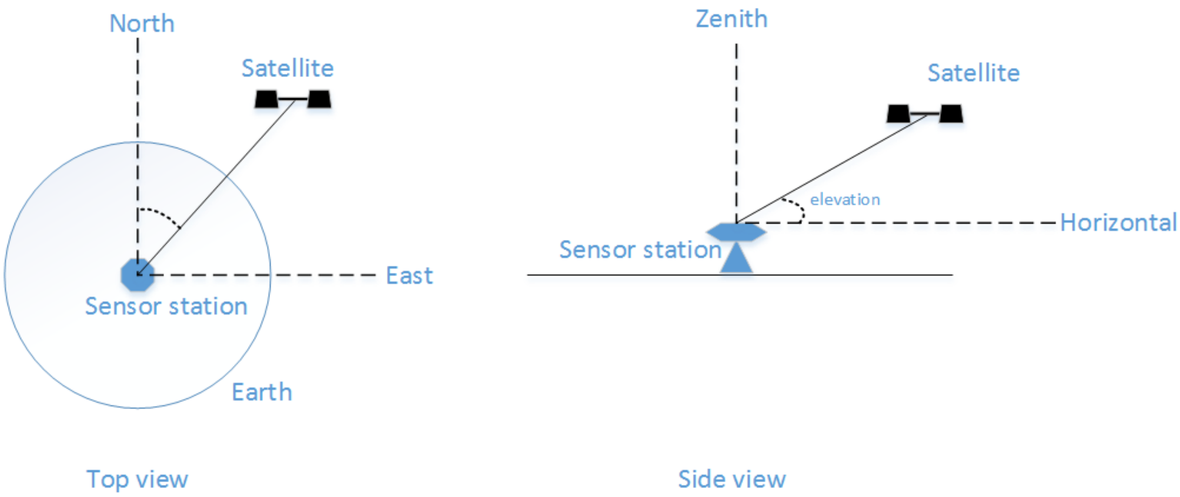


Figure 3.12: Example of the azimuth angle (left) and the elevation angle (right) between sensor station and satellite

The sensor station position can be obtained from the RINEX obseration file header or from a lookup table, while the satellite positions need to be calculated using the RINEX navigation files. This is explained in Appendix A.

Main purpose of computing the elevation and azimuth angles is to determine when the satellite is in view of the sensor station. It can also be used to link observations to the elevation in order to investigate elevation dependent influences. When the elevation is computed for a 30 second interval, the differences between two consecutive epoch can be almost as small as a tenth of a degree. For our purpose that's unnecessary accurate and lead to an increase in storage space over time.

There are four options for storing the elevation and azimuth data per satellite for every sensor station, which are visualized in Figure 3.13

1. Every epoch
2. Every new degree of elevation
3. Every new degree of azimuth
4. Every new degree of elevation and azimuth

Figure 3.13: Examples of dealing with elevation and azimuth data. Vertical is the elevation angle and horizontal the azimuth angle

We want to determine when a satellite is at 0 degrees elevation, and several factors like multipath and the C/N0 are elevation dependent. So the third option does not compete. Figure 3.14 gives an example of option 1 and option 2. The figures and results of this paragraph are obtained from station DLF1 on doy 150, but give a representable indication. In this example the amount of entries for elevation and azimuth decreases from 1040 to 190. Reason that option 2 is not exactly on top of option 1 is because option 2 is rounded down. Option 2 is proffered since the amount of data is decreased while there are enough data points.

The remaining options 2 and 4 are showed in Figure 3.15. For this representable example option 2 has 190 entries and option 4 has 340. That's a big reduction compared to option 1, but still 1.8 times as much as option 2. For our purposes the coarseness of option 2 is accurate enough and will be used.

So for every station is per satellite a matrix stored that contains the rounded down elevation angle, the rounded down azimuth angle and the GPS week number and seconds of week of the time that that the satellite crosses the new degree of elevation.

3.5.3. Elevation mask

Not all satellites from an elevation above 0 degrees are actually expected to be visible. Preferably the location of a sensor station is chosen to have a clear view to the sky, but this is not always the case. Most sensor stations are positioned in a way that part of the sky is blocked permanently or atleast for a long period of time. This can be due to trees, buildings or other objects. Signals coming from satellites behind these objects are therefore not expected at the sensor station and the RINEX observation files.

The system performance will be partly based on RINEX observation files from sensor stations. When an elevation mask is not used, a satellite that's behind an object may be determined as unavailable. However, there's no information of the satellite from that particular position and sensor station. Furthermore, if the functioning of the sensor station will be assessed based on the present over expected observations, satellites

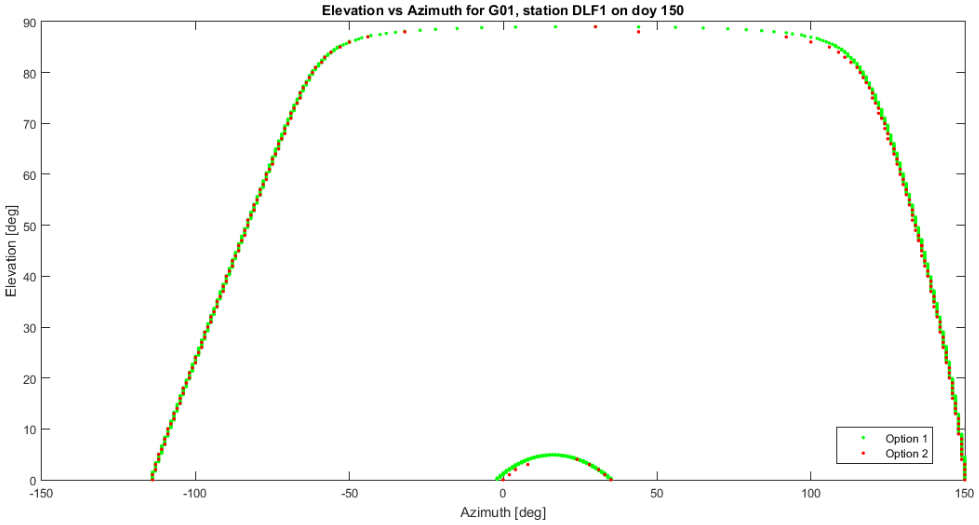


Figure 3.14: Two options for storing the elevation and azimuth. The first is storing every epoch, the second only when a new degree of elevation is reached. The latter is rounded down.

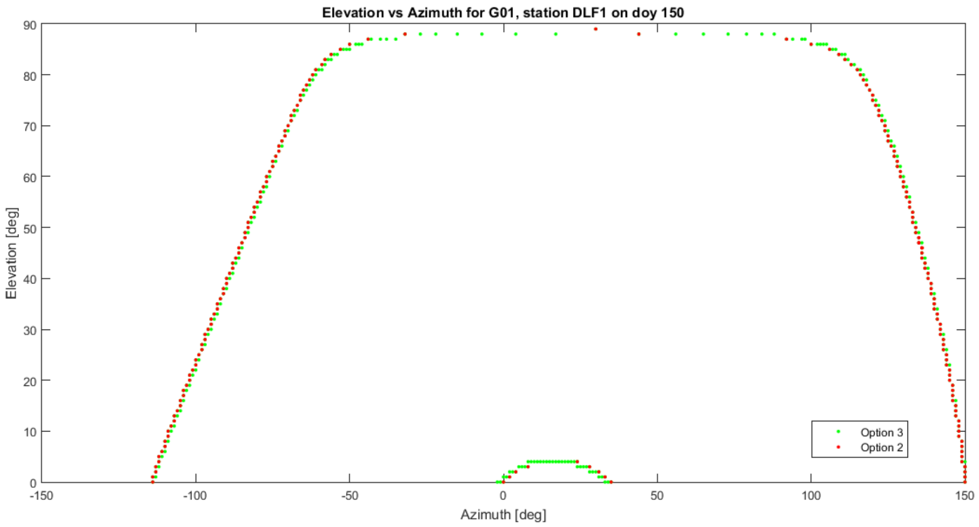


Figure 3.15: Two options for storing the elevation and azimuth. Option 2 only stores when a new degree of elevation is reached. Option 3 stores when a new degree of both elevation and azimuth is reached. Logically option 2 data points are also part of option 3

from behind the mask are not expected and should therefore not be accounted for. In addition, the elevation mask is a good measure of the suitability of the location and environment of the sensor station. Several decisions and algorithms are needed for this purpose:

Update of mask Under normal circumstances the blocking objects are fixed and so is the elevation mask. When the antenna is placed on top of an high building nothing will change, unless a high neighbouring building or object is destroyed or built. Also trees can be planted or undergo seasoning grow. These changes are slow and usually take some time. Therefore, it's not needed to determine the elevation mask again every day. However, as changes in the surroundings may occur, updating the mask is necessary from time to time. The best way to deal with this is to update the mask on a fixed basis. An ever increasing dataset is undesired as changing circumstances are hard to determine this way. Using a moving time-frame, like adding a new day of data and removing an old day each is possible, but results in much extra processing for an effect that's likely not present.

All satellites should pass at least once to get information of their full orbit. Since the repeat time of

Galileo is 10 days, at least 10 days of data should be used. However, it may occur that some satellites are not tracked within these 10 days. This can be due to the station being not operational, software issues or satellites having issues. Therefore, a multiple of 10 days need to be used. An update time of 50 days is chosen, which means that the Galileo satellites can be tracked five times. Reason is that it contains enough data to determine a new elevation mask, but is also short enough to deal with changing surroundings.

Resolution The mask can be determined very exact, or more rough. Determining the mask very accurate can be useful for determining the locations of blocking objects, but for our purposes a very accurate masking is undesired. Satellites from close to the mask and thus objects, which just come into view may have tracking problems or higher noise levels. This may lead to false alarms, which lead to a bad sensor station performance and the possibly of stating the satellite wrongly as unavailable. The mask is therefore created slightly conservative, but not too conservative as there will be more sensor stations needed within the monitoring network. This will be explained in more detail in Section 5.2. In order to be save and deal with tracking problems, a boundary layer of 1 degree in elevation and azimuth direction will be added. This means that the minimum elevation mask is at 1 degree elevation. Also the elevation mask is determined in a grid of integer elevation and azimuth angles. Reason is that these values are already set to integers, which is considered sufficient.

Being conservative comes at a cost. If a signal from behind the created boundary layer of the elevation mask is not received, it's stated as *no information*. If the signal is received, it's stated as *available*. This means that results are presented slightly positive. So more signals are defined *no information* as strictly necessary. Creating the mask conservative also has impact on the visibility of the satellites. Since the elevation of the mask is created higher, the view to the satellites is decreased. This results in the fact that more sensor stations could be necessary for the monitoring network.

Main options for the input data are 1 Hz data or 1/30 Hz data. The 1 Hz input data results in more dense data and more occurrences on a point. This doesn't lead to a better determination of the mask, as still the same points are known when taking a large period. Just a few points (elevation, azimuth) extra would be known and mostly it's only higher occurrences. This holds for both if it's present or not present, so the impact is negligible. Therefore, 30 second interval data is sufficient and will be used.

Different satellites have different orbits and thus different elevation and azimuth angles. When using information from several satellites together, more information from the total visibility is gained. So when using different GNSS together for the elevation mask, even more information of azimuth/elevation points is gained. It's therefore recommend to use data from all satellites and all GNSS for the same elevation mask.

Coverge When the elevation and azimuth points of where a satellite passes is put into a matrix, not every point contains information. Reason is because satellite orbits repeat and do not cover the sky completely. There are two different unknown parts: points between satellite tracks, an example is shown in red in Figure 3.16, and an area due to the inclination of the satellite orbits, which is shown in yellow in Figure 3.16. These unknown parts should be treated differently. The hole in the data due to the inclination will never be crossed by a satellite, because the satellites don't cross the north pole. So it won't matter if there's an object blocking the view at these locations. For the other parts, due to satellite tracks, it does matter. New satellites may be launched, due to inaccuracies of satellite positions or because of the satellite's ascending node that changes at a different rate than the solar year, the elevation and azimuth angles may differ slightly. These points must therefore be filled based on the surrounding points.

The description can be summarized in the following points:

- The elevation mask is updated every 50 days
- The elevation mask uses 50 days of data
- The frequency of the data is 30 Hz
- All GNSS (GPS and Galileo) and satellites are used together for a single elevation mask
- A boundary layer of 1 degree is used
- Special attention need to be paid on points which are not covered by satellite tracks

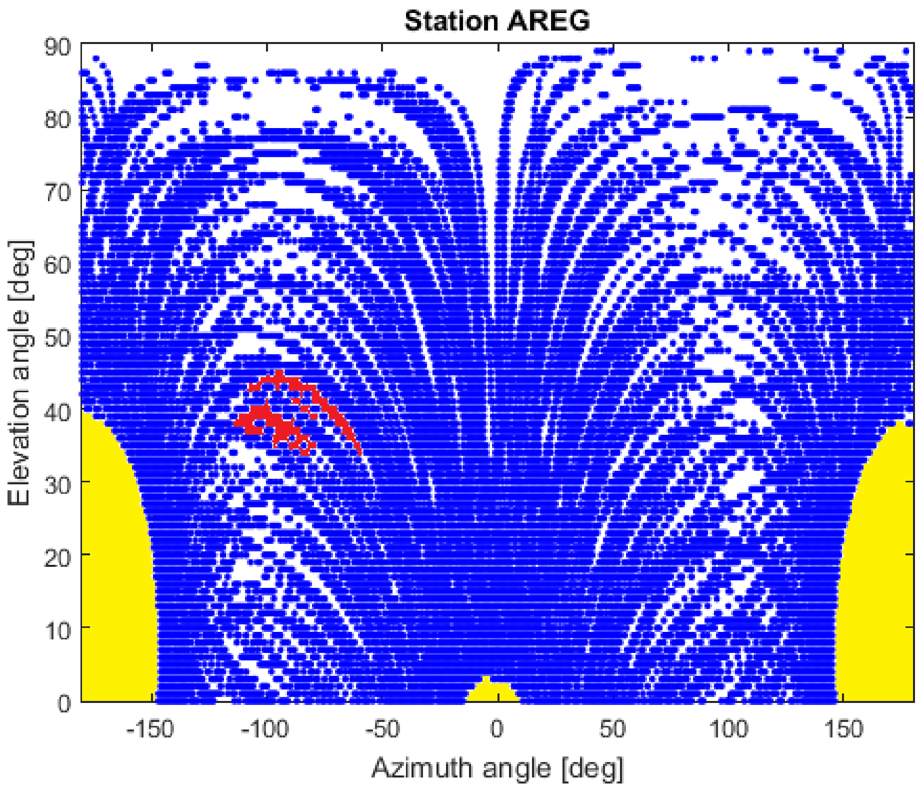


Figure 3.16: Plot showing expected points in blue. The yellow part is the 'hole' due to the satellite inclination and the latitude of the station and the red part is an example of an unknown part between the tracks. The red part should be filled, while the yellow part can be ignored.

Creating the elevation mask

Day by day a processed file is loaded as described in Figure A.6 of Appendix A.2.4. Using this information it can be determined when the satellite is above 0 degrees elevation and thus when it's expected to be tracked, and it gives the epochs when no signals are tracked. Table 3.5 shows that for the full period that the satellite was above 0 degrees elevation it's determined when any signal was received and when it's not. In case the station was not operational during an epoch, the epoch is ignored as there's no information from the satellite.

Table 3.5: For every day and every satellite three temporary arrays are created, each contains the epochs that any signal was received (present), no signals were received (masked) or the station was not operational.

Satellite elevation >0 degrees	Present	Masked	Station not operational
t_1		t_1	
t_2		t_2	
t_3		t_3	
t_4			t_4
t_5	t_5		
t_6	t_6		
t_{end}	t_{end}		

The elevation and azimuth angles of the satellites are linked to the epochs, which results in Table 3.6, which is created for every satellite on every day. Note that the elevation and azimuth can be similar for two consecutive epochs.

Matrices like Table 3.6 are created consecutively for all 50 days and for all satellites. These matrices are used to create two other matrices. The matrix *Present* and *Masked* contains the unique elevation and azimuth angles, and the amount of times it occurred at the daily satellite matrices. This step is visualized in Figure 3.17.

When the elevation and azimuth angles of the aggregated present and masked matrices are plotted, it re-

Table 3.6: The epochs of the arrays of Table 3.5 are used to obtain the elevation and azimuth angles of periods when the satellite's signals were received or not received

Present			**Masked**		
t_5	$Elevation_5$	$Azimuth_5$	t_1	$Elevation_1$	$Azimuth_1$
t_6	$Elevation_6$	$Azimuth_6$	t_2	$Elevation_2$	$Azimuth_2$
t_{end}	$Elevation_{end}$	$Azimuth_{end}$	t_3	$Elevation_3$	$Azimuth_3$

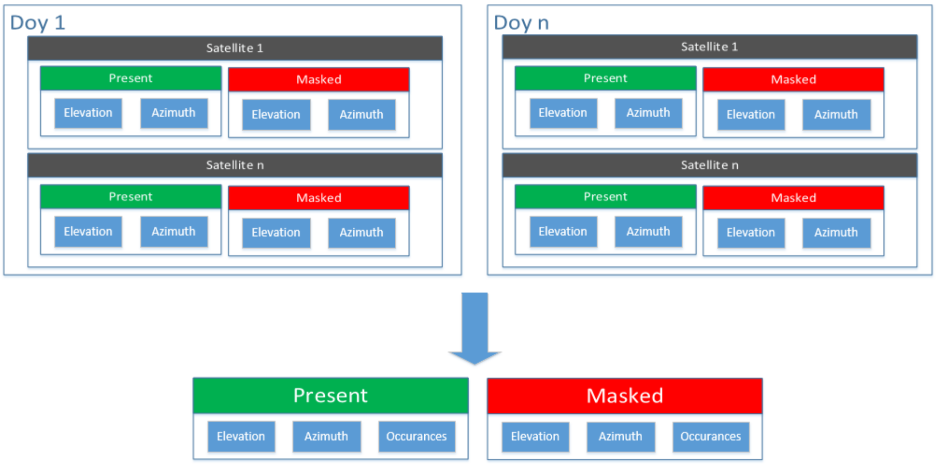


Figure 3.17: Elevation and azimuth data of all satellites over all days is used to create two matrices. The *present* matrix contains elevation, azimuth and the amount of times that a satellite was tracked from that elevation and azimuth. The same thing is done for the matrix *masked*, which tells when the satellite was not tracked while above the horizon

sults in a plot like Figure 3.18. Data from the matrix present is shown in green and the marix masked is shown in red. If the elevation and azimuth occurs in both, it's shown in blue. The fact that points are sometimes present and sometimes masked can be due to tracking issues of low elevation satellites as seen in the lower part of Figure 3.18. It can also be due to internal software related problems as shown in Figure 3.19, which is an example of station MAL2 on doy 270. During this epoch the station was operational as some satellites are tracked, but there was obviously something wrong.

The points which occur in both the present and masked matrices are filtered so that they will only occur in one of them. If the elevation and azimuth combination is at least 90 % of the times it occurred masked, the point is declared masked and removed from the *present* matrix, otherwise it's declared present and removed from the matrix *masked*. This makes sure only points which are really masked are declared masked.

Although filtering steps are done in order to know which points are masked and which are present, it's still possible that there are some inaccuracies. It may be possible that signals are not received due to unexpected issues, like a software problem. Usually this is corrected by taking data of several repeating orbits, so that the signal is present other times. While this works most of the times, it may lead to badly assigned masked data. Reason is that there could be small inaccuracies in the orbit determinations, so that repeating orbits can be off by 1 degree. If this happens only when the data was expected but not observed, it's hard to filter out, since the signals were never present at that particular elevation and azimuth angle. To filter these effects, a masked point is removed if it only occurs 10 times. A difficulty is that there's no truth to compare the results to, besides going to the exact location. Pictures give an idea of blocking objects, but it's hard to take pictures at the exact location of the antenna and determine the elevation and azimuth angles of those objects. After the filtering, points only occur in the *present* matrix or in the *masked* matrix, not in both. This is shown in Figure 3.20.

With the use of the matrices *present* and *masked*, each having an elevation column and an azimuth column, a matrix containing 90 by 360 entries can be filled. This matrix is visualized in Figure 3.21a. Each entry represents an elevation and azimuth angle, which can have one out of three classes:

Not masked: The satellite can be tracked from this point

Masked: The satellite is behind the elevation mask from this point

Unknown: It has to be determined whether this point belongs to the mask or not

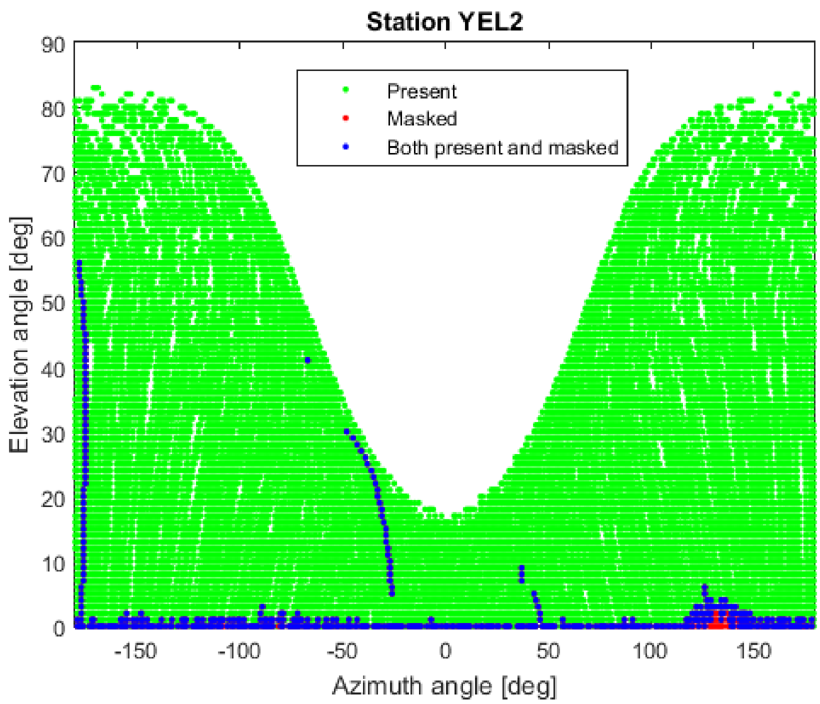


Figure 3.18: Sensor station YEL2, located in northern Canada. In green are the points that the satellite is present, red is masked and blue it's both present and masked

```
> 2016 09 26 17 30 30.0000000  0  3
G30
S20  38880281.326 5 204317291.87605        -2.189 5        30.000
R18  21544046.471 6                     -1572.500 6        36.250
> 2016 09 26 17 31  0.0000000  0 43
```

Figure 3.19: Example of a local software issue of station MAL2 on doy 270. The station was receiving at 17:30:30, but for some reason almost none observations were stored.

The so called 'hole' where data is never received due to the inclination is selected and declared present, so that it wont effect the elevation mask. With the use of the latitude of the sensor station, the hole can be determined. Figure 3.22 shows three examples of the holes in which satellites never cross view.

The other unknown points are filed based on neighbouring points. For every unknown point the four first closest known (masked or not masked) points in all directions are searched. If all those four points are not masked, the unknown point is stated as not masked too. If a closest known point is masked, horizontally or vertically, the unknown point is declared masked too. This is again a conservative way to deal with the data. Note that the already selected 'hole' is neglected for this algorithm. When all unknown points are filled, it leads for YEL2 to Figure 3.21b, in which each pixel corresponds with an elevation and azimuth angle.

For every azimuth angle, the maximum masked elevation is selected. By creating a boundary layer of 1 degree in elevation and azimuth direction, the final elevation mask is established using the maximum values. It results in a matrix of two rows: azimuth (-180:179) and the associated maximum elevation of the mask. This can be seen in Figure 3.23. In this plot the created elevation mask is the blue line. For every sensor station a mask like this is created.

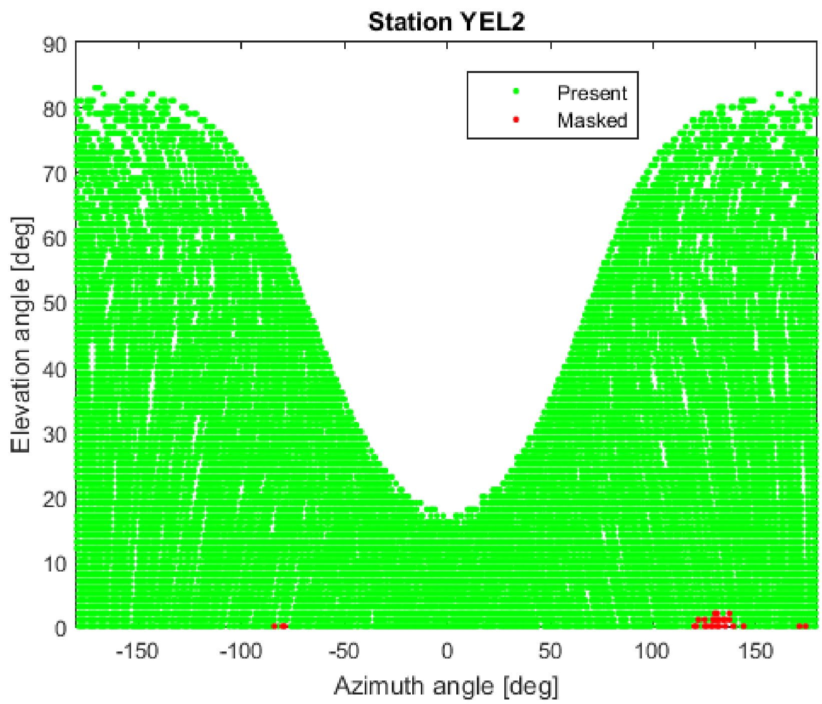
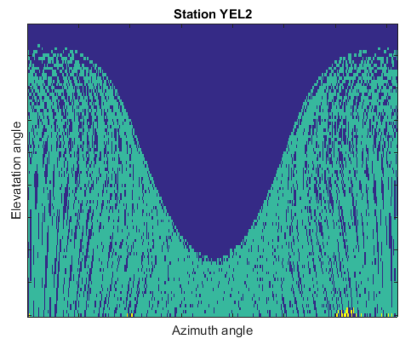
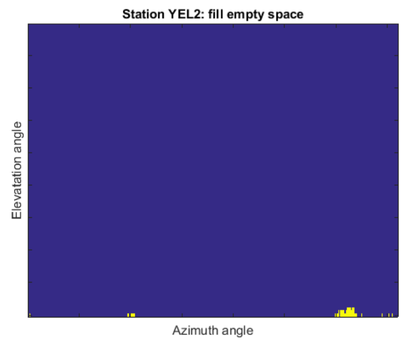


Figure 3.20: Present and masked points of YEL2



(a) Image representation of the matrix. Vertically the points are from 0 to 89 degrees elevation and horizontally the points are from -180 to 179 degrees azimuth. Green is not masked, yellow is masked and blue is unknown



(b) Image representation of the matrix. Vertically the points are from 0 to 89 degrees elevation and horizontally the points are from -180 to 179 degrees azimuth. The yellow part is behind the mask and the blue part not masked

Figure 3.21: Two steps of creating the elevation mask

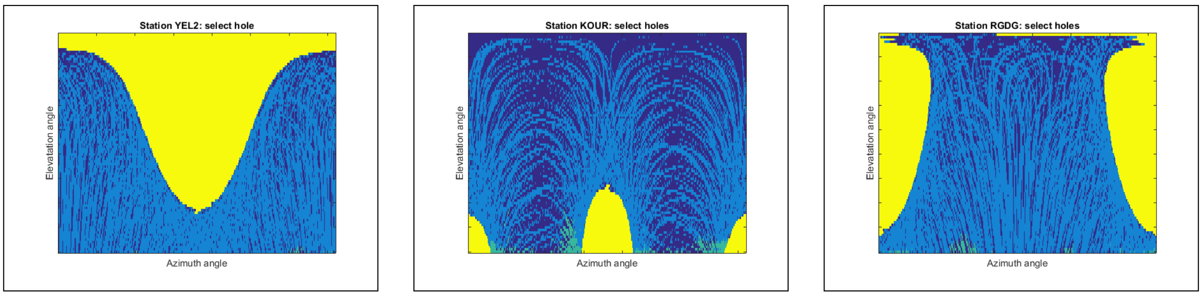


Figure 3.22: Station YEL2, KOUR2 and RGDG on respectively high, mid and low latitudes. All have a different area where the satellites won't cross, shown in yellow. Each plot has elevation on the vertical axis and azimuth on the horizontal axis

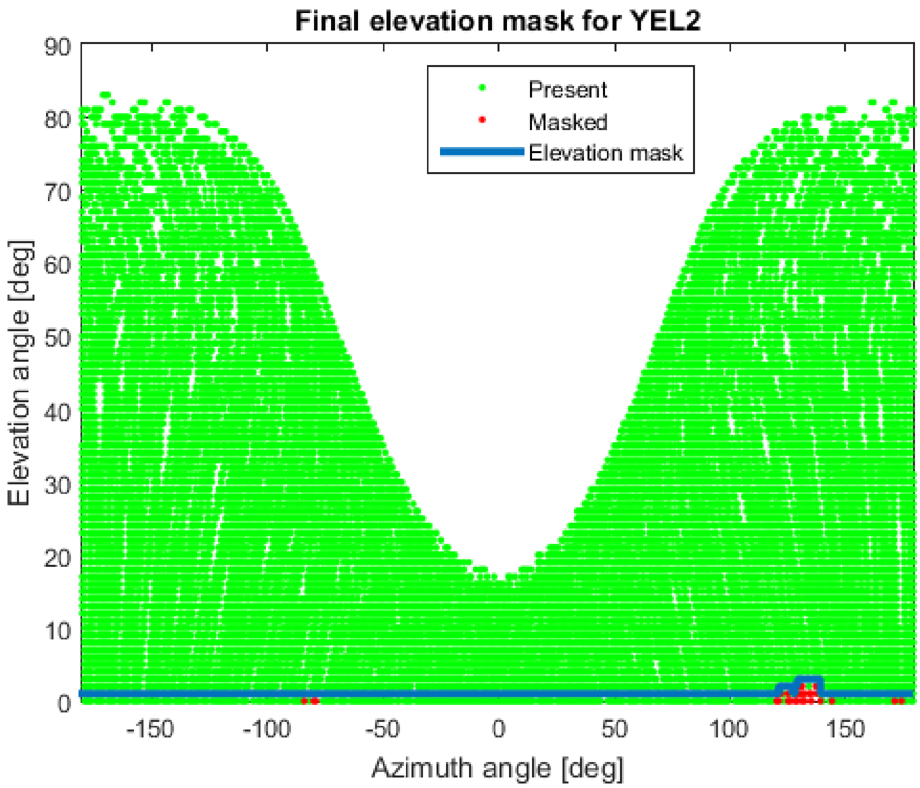


Figure 3.23: Final elevation mask of YEL2 shown in blue.

3.5.4. Sensor station is receiving

For a signal to be expected at the sensor station, the sensor station must be operational. This means that the period when a signal is expected must be corrected for the period that the station is not receiving. The operational period of a sensor station is captured in the Daily Station Availability, which will be explained in Section 4.1. This means that the Daily Station Availability is necessary for computing the expected period and the associated availability statistics.

3.5.5. Satellite is transmitting

Just as the sensor station must be operational and receiving data, the satellite must transmit it. This is normally the case, but due to satellite problems, the satellite may not be transmitting (healthy) signals. Since this is not part of the sensor station performance, this effect should be removed. Satellites may also not transmit signals from time to time for maintenance reasons, in which users are warned via notices. Signals are only expected at the sensor station if the satellite is available. This is one of the reasons that sensor station performance and system performance are computed within the same software tool. The satellite performance is needed to remove its effect on the station performance. The satellite performance should tell when the satellite is available and transmitting its signals.

3.6. Summary

Before being able to create the performance parameters, several steps have been done. It's made clear when a signal is expected and when it's available:

Available :

- Code observation is present and within thresholds
  - The threshold is created using the true-range, satellite clock offset and maximum allowable receiver clock offset.
- C/N0 observation is present and within thresholds
  - The threshold is created using a signal dependent bottom threshold combined with a system, satellite type and elevation dependent lower bound. The lower and upper bounds are created using a third order polynomial fit and a 10 dB-Hz region in which the measurements are allowed to be off the regression line
- Carrier phase observation is present

Expected :

- Sensor station is configured to receive it and the satellite is configured to transmit it
- Elevation > 0 degrees
- Satellite is not behind objects
- Sensor station is operational at a given epoch
- Satellite is operational at a given epoch

4

Sensor station performance parameters

Sensor stations should be reliable and of high quality. Especially if the sensor stations are used for monitoring purposes like system performance or geodetic products. There are four main questions that should be answered in order to know how well the sensor station performs.

- Is the sensor station operational?
- Does the sensor station receive all expected signals?
- How well is the location of the sensor station?
- How does the sensor station perform compared to others?

All these four questions are related to the availability of signals-in-space. One by one these will be treated and worked out into a performance parameter. The parameters are explained within this chapter and a short example is given. More results are given in Chapter 6, where the parameters are computed for a longer period of time.

4.1. Daily Station Availability

The Daily Station Availability (DSA), tells whether the sensor station is operational and receives any data during the day. This is important to know since stations that don't receive have a clear problem and are not useful. It can be determined for each system separately, but as the goal of this parameter is to gain insight in whether the station functions at all, not how good, this is not needed. A single entry during an epoch already tells that the station was operational and receiving. There are enough GNSS satellites visible that it can be assumed that for every epoch a satellite can be tracked. So a measurement of a single satellite already tells that the sensor station was operational. Therefore, it's purely a sensor station parameter which is not affected by the functioning of the system (satellites and such). Information can be found in the RINEX observation file alone. The parameter will be calculated on a daily basis using formula 4.1.

$$\begin{aligned} \text{Daily Station Availabiltiy [\%]} &= f(station, doy) \\ \text{Daily Station Availability [\%]} &= \frac{\text{N}_{\text{unique}}}{f \cdot \text{P}} \cdot 100\% \end{aligned} \tag{4.1}$$

The Daily Station Availability is a function of the station ID and the day of year, as it can be calculated for every station and every day. The amount of unique epochs within the RINEX observation file is divided by the maximum possible amount of unique epochs within the file. The last is calculated by the amount of epochs per second (f), which can be found in the RINEX header and filename, multiplied by the period of the RINEX observation file (P) in seconds. So for a full day using 1 second interval data this is $1 * 60 * 60 * 24 = 86400$ and using 30 second interval data $(1/30) * 60 * 60 * 24 = 2880$. This way the parameter can be applied to files of different length and interval. The standard is a daily file of 30 second interval.

This parameter can directly be used as a first insight in the IGS MGEX sensor stations. By November 2016 there are a total of 168 sensor station being part of the network. The number is slowly increasing. All RINEX files can be found on several FTP (File Transfer Protocol) servers. Since many files are stored redundant on more than one FTP server, the FTP servers of CDDIS, BKG, GA and IGN are checked for files as they contain together files of all stations. This way not all FTP servers have to be checked. The FTP servers are searched one by one. If the file is found, other servers won't be accessed as it's assumed that those files are duplicates. In case the RINEX file is present at none of the FTP servers, the results of the Daily Station Availability is directly 0. More details can be found in Appendix A. As a small test-case, 13 days of 2016 are used: one full week, being doy 206-212, and two short periods: doy 66-69 and doy 239-240. We're only interested in the newest version of RINEX, version 3, so only these files will be downloaded and evaluated on the Daily Station Availability. Furthermore, the data can have two sources, being the receiver (R) or real-time (S). As this data-source is part of the naming convention of RINEX 3, both filenames must be searched on the FTP servers.

	66	67	68	69	206	207	208	209	210	211	212	239	240
ABMF	100,00	100,00	100,00	100,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
AIRA	-2,00	-2,00	-2,00	-2,00	0,00	-2,00	0,00	0,00	0,00	0,00	0,00	100,00	-2,00
AJAC	0,00	0,00	0,00	0,00	100,00	100,00	100,00	100,00	100,00	100,00	100,00	100,00	100,00
ALIC	100,00	100,00	100,00	100,00	100,00	100,00	100,00	100,00	100,00	100,00	100,00	99,69	100,00
ANMG	0,00	0,00	0,00	0,00	99,72	99,86	100,00	99,83	99,51	99,79	100,00	99,83	99,93
AREG	100,00	100,00	100,00	100,00	100,00	100,00	99,72	100,00	100,00	100,00	100,00	-2,00	-2,00
ASCG	100,00	0,00	0,00	0,00	100,00	100,00	100,00	100,00	100,00	100,00	100,00	-2,00	-2,00
AUCK	-2,00	-2,00	-2,00	-2,00	100,00	100,00	100,00	100,00	96,53	100,00	100,00	4,17	100,00
BIK0	-2,00	-2,00	-2,00	-2,00	-2,00	-2,00	-2,00	-2,00	-2,00	-2,00	-2,00	-2,00	-2,00
BOR1	-2,00	-2,00	-2,00	-2,00	-2,00	-2,00	-2,00	-2,00	-2,00	-2,00	-2,00	-2,00	-2,00
BRST	100,00	100,00	100,00	100,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	100,00	100,00
BRUN	0,00	0,00	0,00	0,00	88,54	73,78	82,47	83,44	94,24	96,15	99,27	0,00	0,00
BRUX	100,00	100,00	100,00	100,00	100,00	100,00	100,00	100,00	100,00	100,00	100,00	100,00	100,00
CAS1	100,00	100,00	100,00	100,00	100,00	100,00	100,00	100,00	100,00	100,00	100,00	100,00	100,00
CCJ2	-2,00	-2,00	-2,00	-2,00	0,00	-2,00	0,00	0,00	0,00	0,00	0,00	100,00	-2,00
CEBR	100,00	100,00	100,00	100,00	100,00	100,00	100,00	100,00	100,00	100,00	100,00	100,00	100,00
CEDU	-2,00	-2,00	-2,00	-2,00	-2,00	-2,00	-2,00	-2,00	-2,00	-2,00	-2,00	-2,00	-2,00
CHOF	0,00	0,00	0,00	0,00	99,86	99,97	99,90	99,83	99,76	99,20	99,90	99,79	99,79
CHPG	100,00	100,00	100,00	100,00	100,00	100,00	100,00	100,00	100,00	100,00	100,00	-2,00	-2,00
CHTI	-2,00	-2,00	-2,00	-2,00	100,00	100,00	100,00	100,00	100,00	100,00	100,00	100,00	4,17
CKIS	100,00	100,00	100,00	100,00	100,00	100,00	100,00	100,00	100,00	100,00	100,00	100,00	100,00
CMUM	0,00	0,00	0,00	0,00	99,86	99,93	99,79	99,97	96,04	100,00	99,79	0,00	0,00
CPNM	0,00	0,00	0,00	0,00	99,34	100,00	99,72	99,10	98,51	96,77	93,99	100,00	100,00
CPVG	100,00	100,00	100,00	100,00	0,00	0,00	0,00	99,86	100,00	100,00	100,00	-2,00	-2,00
CUT0	0,00	0,00	0,00	0,00	100,00	100,00	100,00	100,00	100,00	100,00	100,00	100,00	100,00
CUUT	100,00	100,00	100,00	100,00	100,00	100,00	100,00	100,00	100,00	100,00	100,00	100,00	100,00
CZTG	0,00	-2,00	0,00	-2,00	98,02	98,85	98,19	97,01	98,72	95,94	53,26	0,00	0,00
DAE2	0,00	0,00	0,00	0,00	92,05	88,82	84,58	94,41	93,47	88,33	93,33	100,00	100,00
DARW	0,00	0,00	0,00	0,00	-2,00	-2,00	-2,00	-2,00	-2,00	-2,00	-2,00	-2,00	-2,00
DJIG	100,00	99,55	0,00	100,00	0,00	5,45	0,00	0,00	100,00	6,88	0,00	-2,00	-2,00
DLF1	100,00	100,00	100,00	100,00	100,00	100,00	100,00	100,00	19,65	100,00	100,00	100,00	100,00
DLTV	0,00	0,00	0,00	0,00	100,00	100,00	98,47	99,27	99,72	99,03	100,00	100,00	99,48
DUND	-2,00	-2,00	-2,00	-2,00	100,00	100,00	100,00	100,00	100,00	100,00	100,00	100,00	100,00
DYNG	100,00	100,00	100,00	100,00	100,00	100,00	100,00	100,00	100,00	100,00	100,00	-2,00	-2,00

Figure 4.1: Part of the DSA parameter obtained for all sensor stations of the IGS MGEX. The full results can be found in Appendix B

Part of the results of the used test-case is shown in Figure 4.1. The full figure can be found in Appendix B. The left column shows the station name and the top row the day of year. The value -2 means that only RINEX version 2 is present on the servers, which is done only for this example since RINEX version 3 will be used as input for the tool. A value of 0 means that there's no RINEX file from the sensor station on that day. 100 means that the station was operational and receiving data the full day. So results are between 0 and 100 %, except for -2 as presented in this example. Within this example the results are shown with two digits. This is done to ensure that all possible behaviour is visible. The input data consists of a 30 second interval, the maximum possible epochs is $2(per\ minute) * 60(minutes) * 24(hours) = 2880$. If the station is not operational only for a single epoch during the day it results in Equation 4.2. So when using only one digit this wouldn't be visible.

$$\text{DSA} = \frac{2879}{2880} \cdot 100\% = 99.97\% \tag{4.2}$$

It's striking that many sensor stations have issues during the assessed period and often more than one day. As an example, the blue circled result of Figure 4.1, DLF1 on doy 210, is shown for that day in Figure 4.2.

When looking closely at the data, it can be seen that the station had problems from 04 : 43 : 00 until the end of the day. What happened during this particular event was that the station had problems creating the RINEX files.

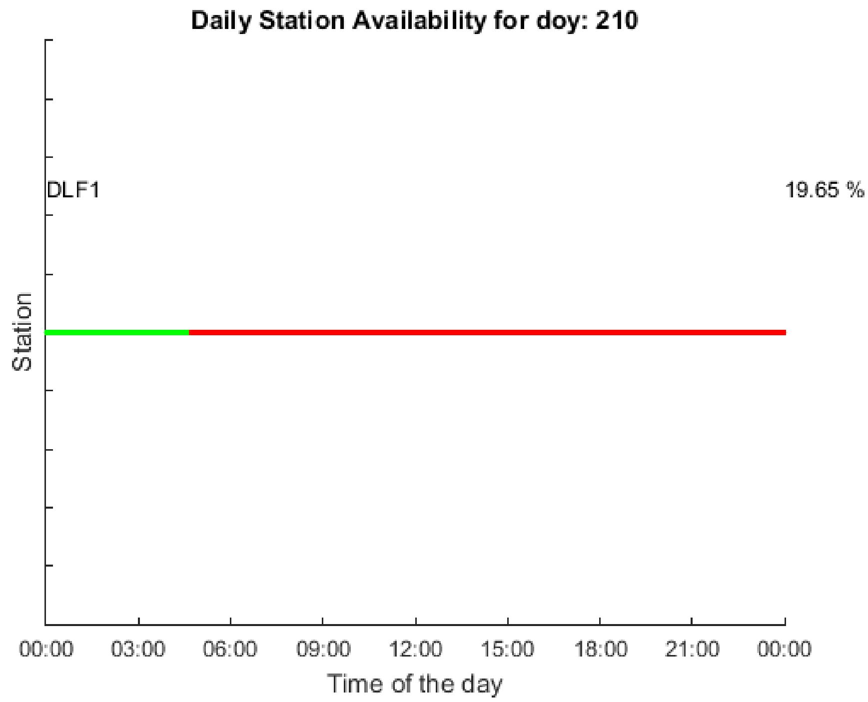


Figure 4.2: Example of problems at station DLF1 on doy 210

The obtained DSA information of all IGS MGEX stations is a good first quality indication. A world-map including all stations is shown in Figure 4.3 and summarized in Table 4.1. Notice that only 13 days are evaluated and some stations stopped working, while others just become operational during 2016. For Table 4.1 all DSA results bigger than 0 are counted evenly, just to show how often the stations are operational at all. The average DSA over the 13 days can be found in Appendix B.

Table 4.1: Functioning of all MGEX stations. It can be seen that 22.6 percent of the stations work all 13 days, while 23.8 percent don't work at all. In total there are 168 stations

Range	Amount of stations	Percentage of total
0 days	40	23.8
1, 2, 3, 4, 5 or 6 days	14	8.3
7, 8 or 9 days	49	29.2
10, 11 or 12 days	27	16.1
13 days	38	22.6

4.2. Daily Station Total Availability

The Daily Station Total Availability aims at answering the question: How well does the sensor station receive? This can be done based on the availability equation of Section 3.2.2, which is the ratio of available over expected observations. When a signal is said to be available and expected is explained in Section 3.4 and Section 3.5 respectively. Before we can say something about the sensor station we should first address the availability for each signal of every satellite.

The basis is a file as described in Figure A.6 of Appendix A. This files contains for each satellite:

- Time that the satellite crosses the horizon. So it's known when the satellite is expected to be tracked during ideal circumstances

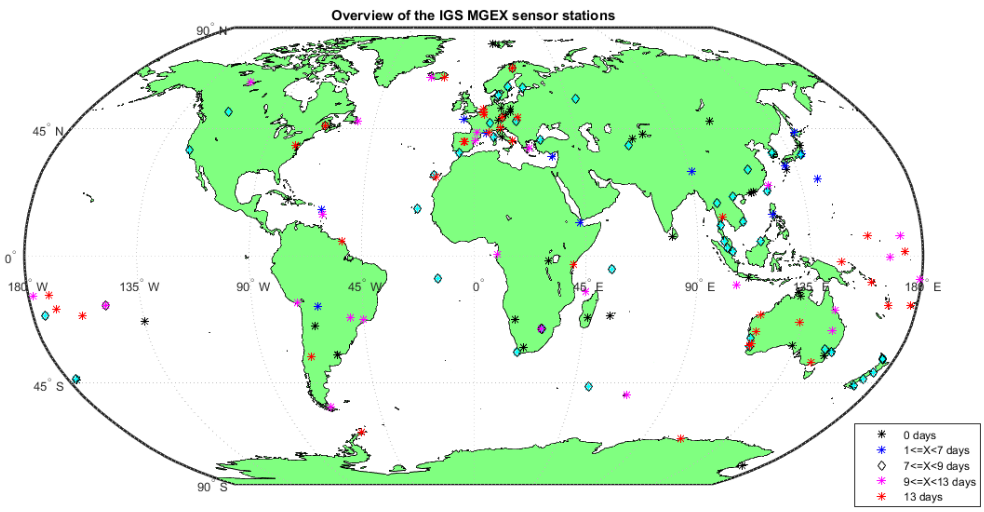


Figure 4.3: All IGS MGEX stations including how many days the DSA is above 0

- The epochs that the satellite's signals are not expected due to the satellite being behind the elevation mask, the station being not operational or after more processing due to the satellite being unavailable
- The epochs of the expected period that no quality signal is received. This is done separately for each signal of the satellite
- Therefore, it's also known during which epochs a quality signal is received

The first step is to compute how well each signal of a satellite is received. It's computed what percentage of the expected epochs the signal is received by the sensor station. Note that each signal consists of a code, carrier phase and C/N0 measurement, and the code and C/N0 measurements should be within thresholds. Equation 4.3 is used to compute how well a single signal is received, which is called the *Daily Station Satellite Signal Availability*. In this equation Q_{obs} is the amount of observations that are present and within the thresholds. $P_{expected}$ is the period of time in seconds that observations are expected to be present at the sensor station. f is the rate at which data is stored by the receiver in Hz, which is generally 1 Hz or 1/30 Hz. By multiplying $P_{expected}$ by f, the amount of epochs that are expected to have observations is obtained. The elevation mask is created slightly conservative. Therefore, it may occur that signals which are not expected are available. These periods are added to $P_{expected}$ and to the epochs of the nominator of Equation 4.3.

$$\text{Daily Station Satellite Signal Availability} = \frac{\sum_{\text{epochs}} \mathrm{Q_{obs}}}{\mathrm{P_{expected}} \cdot \mathrm{f}} \cdot 100\% \tag{4.3}$$

Since we're interested in the total performance of the sensor station, the next step is to determine what part of the period all expected signals of a satellite are received. So for Galileo: E1 ∩ E5A ∩ E5B ∩ E5AB and for GPS: L1 ∩ L2W ∩ L2 ∩ L5, provided that the station receives all signals and the satellite transmits all signals. This is checked for every epoch. The Equation for this process, which is shown in Equation 4.4, is basically similar to Equation 4.3. The only difference is that all expected signals should be present during an epoch.

$$\text{Daily Station Satellite Availability} = \frac{\sum_{\text{epochs}} \mathrm{All}_{Qobs}}{\mathrm{P_{expected}} \cdot \mathrm{f}} \cdot 100\% \tag{4.4}$$

Using Equation 4.3 and Equation 4.4 for every signal of every satellite, the percentage of received over expected signals can be calculated, just as the percentage that all signals are received. This results in a daily table per station and per system as shown in Table 4.4. These values are called the *Daily Station Satellite Signal Availability* and the *Daily Station Satellite Availability*. It tells how well the sensor station is receiving each signal and satellite. Figure 4.4 shows two different tables. The left table is created without using the elevation mask and corrections for the stations being not operational and satellites being not operational, while these corrections are applied for the right table.

FAA1		signals			
	Satellite	**L1**	**L2W**	**L2**	**L5**
G01	96.86	98.69	96.86	98.17	98.17
G02	81.34	82.65	81.34	NaN	NaN
G03	87.08	88.54	87.08	88.08	88.08
G05	80.92	82.05	80.92	81.79	NaN
G06	79.86	80.99	79.86	80.82	80.82
G07	84.87	88.56	84.87	87.92	NaN
G08	97.09	98.12	97.09	97.78	97.78
G09	93	94.4	93	93.56	93.56
G10	75.74	78.23	75.74	78.14	78.14
G11	94.24	97.08	94.24	NaN	NaN
G12	90.44	90.89	90.44	90.89	NaN
G13	94.34	98.09	94.34	NaN	NaN
G14	74.93	79.3	74.93	NaN	NaN
G15	92.42	96.12	92.42	95.69	NaN
G16	83.8	86.66	83.8	NaN	NaN
G17	80	82.25	80	80.69	NaN
G18	74.64	79.14	74.64	NaN	NaN
G19	79.44	81.87	79.44	NaN	NaN
G20	81.85	83.54	81.85	NaN	NaN
G21	85.65	88.61	85.65	NaN	NaN
G22	90.51	92.47	90.51	NaN	NaN
G23	92.55	95.57	92.55	NaN	NaN
G24	96.58	97.46	96.58	97.11	97.02
G25	93.48	94.55	93.48	94.1	94.1
G26	90.51	92.84	90.51	92.58	92.58
G27	95.55	97.38	95.55	96.86	96.86
G28	74.56	78.76	74.56	NaN	NaN
G29	91.87	94.92	91.87	93.35	NaN
G30	92.27	94.91	92.27	94.25	94.44
G31	79.64	81.11	79.64	80.94	NaN
G32	78.5	81.27	78.5	80.82	81.09

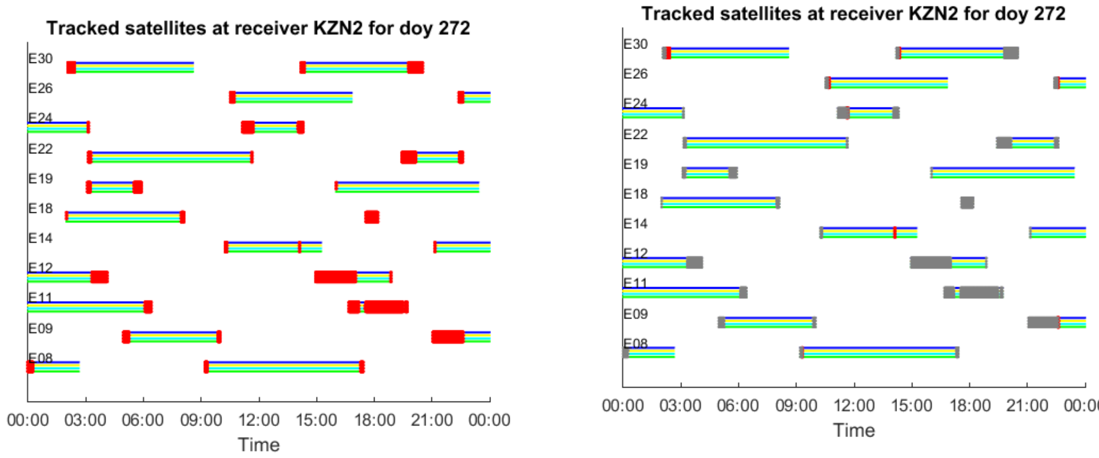
FAA1		signals			
	Satellite	**L1**	**L2W**	**L2**	**L5**
G01	99.55	99.91	99.55	99.82	99.82
G02	99.79	100	99.79	NaN	NaN
G03	99.9	100	99.9	100	100
G05	99.79	100	99.79	100	NaN
G06	100	100	100	100	100
G07	100	100	100	100	NaN
G08	99.91	100	99.91	99.91	99.91
G09	100	100	100	100	100
G10	100	100	100	100	100
G11	98.79	100	98.79	NaN	NaN
G12	100	100	100	100	NaN
G13	98.91	100	98.91	NaN	NaN
G14	97.79	100	97.79	NaN	NaN
G15	100	100	100	100	NaN
G16	98.77	100	98.77	NaN	NaN
G17	99.68	100	99.68	99.68	NaN
G18	99.28	100	99.28	NaN	NaN
G19	99.77	100	99.77	NaN	NaN
G20	99.78	100	99.78	NaN	NaN
G21	100	100	100	NaN	NaN
G22	100	100	100	NaN	NaN
G23	100	100	100	NaN	NaN
G24	98.92	99.64	98.92	99.28	99.28
G25	99.24	99.72	99.24	99.24	99.24
G26	99.62	99.91	99.62	99.72	99.72
G27	99.91	100	99.91	99.91	99.91
G28	98.27	99.42	98.27	NaN	NaN
G29	99.8	99.9	99.8	99.8	NaN
G30	100	100	100	100	100
G31	99.89	100	99.89	99.89	NaN
G32	99.89	100	99.89	99.89	99.89

Figure 4.4: Both tables show information of station FAA1 on doy 270. It gives information of each signal of each GPS satellite that's tracked. The percentage tells how much of the signal is received from the satellite being above 0 degrees elevation. *Satellite* is when all signals are simultaneously received during epochs. The table on the right is corrected for satellites not transmitting, the station being not receiving and for satellites being behind the elevation mask. Tables as shown on the right are used for further processing

The tables show that without applying those extensive corrections and computations, different and lower results are retrieved. Looking at the results of the left table may suggest there's something wrong, since most results are far from 100 %. However, when the corrections are applied, the results are close to 100 %, which indicate that on this aspect there's nothing wrong. Some signals show a Not a Number result because the satellite doesn't transmit that signal. It can also be noticed that the results of the satellite column are even or lower than the results of the individual signals. The reason is that for the *Daily Station Satellite Availability* all signals should be present during an epoch.

Figure 4.5 show two visualizations of the daily results of the *Daily Station Satellite Signal Availability* for station KZN2 on doy 272. For each Galileo satellite it shows the four signals over time, these are for every satellite from bottom to top: E1 (green), E5A (cyan), E5B (yellow) and E5AB (blue). The left plot, Figure 4.5a, is without using the corrections, while Figure 4.5b used all the corrections. These corrections are made gray. During these times there's no further information of the satellites. If a signal is expected but not received, it's shown in red. Figures like 4.5b can be made daily per station and per GNSS to identify problems.

Analysing many tables like the right table of Figure 4.4 and plots like Figure 4.5b is time-consuming and unwanted. It's therefore better to combine the information from all satellites within a system, making it more easily visible if a sensor station is under-performing. The corresponding parameter is called the Daily Station



(a) Before using the elevation mask and other corrections

(b) After using the elevation mask and other corrections. Plot like these can be created daily per station and per GNSS

Figure 4.5: Before and after using the elevation mask. The figures show the satellites are received by a sensor station over the day, with the time horizontally and the different Galileo satellites vertically. The different signals from the satellites are displayed on top of each other in different colors. It's red when a signal is not received while the satellite is above 0 degrees elevation. In gray is the part that the satellite is behind the elevation mask

Total Availability and the already created Daily Station Satellite Availability is used as input. The Daily Station Total Availability, or short DSTA, is a measure of the functioning of the sensor station, as it tells how well each system is received. It's done for each GNSS separately as a sensor station may receive one GNSS better than the other.

The Daily Station Total Availability is the weighted average of the individual Daily Station Satellite Availabilities. These are the first columns of Figure 4.4. Not all satellites are in view for the same amount of time. Therefore, the values will be weighted by the amount of time the satellite is expected to be in view. This leads to Equation 4.5, that is used to calculate the DSTA. DSSA in Equation 4.5 means the Daily Station Satellite Availability, which is computed for each satellite. $P_{expected}$ is the amount of epochs that the satellite is expected to be tracked by the sensor station. The denominator consists of the total amount of epochs that the satellites of the constellation are expected. Note that during a single epoch more satellites can be expected. The result is a percentage between 0 and 100.

$$\text{Daily Station Total Availability} = \frac{\sum_{\text{Satellites}} \text{DSSA} \cdot \text{P}_{\text{expected}}}{\sum_{\text{Satellites}} \text{P}_{\text{expected}}} \cdot 100\% \tag{4.5}$$

Using the information from the right of Figure 4.4 and Equation 4.5 the Daily Station Total Availability can be calculated for the GPS observations. It results for this example in a percentage of 99.59 %.

Three parameters have been defined related to the receiving of the sensor station. The *Daily Station Satellite Signal Availability* tells how well a single signal of a satellite is received. The *Daily Station Satellite Availability* tells what part of the expected epochs all signals are received of a satellite. The parameters are called daily parameters since they are computed on a daily basis. The key performance parameter is the *Daily Station Total Availability*, which tells how well the satellites of a constellation are received. It's considered a KPI since a lot of crucial information is stored in a single parameter.

4.3. Effective Mean Elevation

The already computed elevation mask can be used to quantify the environment of the sensor station. It can be used to answer te question: How well is the location of the sensor station chosen? It's therefore a measure of the performance of the sensor station as well. Several options to use the elevation mask as a performance parameter are discussed. The basis for this parameter is the matrix containing for each azimuth angle the elevation angle of the mask. The elevation mask of station AREG is taken as an example. This is shown in red in Figure 4.7.

Maximum elevation : The maximum elevation is the maximum elevation of the elevation mask. It's the black line of the example of Figure 4.7, which corresponds with an elevation of 8 degrees. The maximum can be useful since it means that the rest of the mask is even or below that elevation. The disadvantage is that much information is ignored. If there's only a single high spike, while the rest is low, only the spike is represented in the parameter.

Minimum elevation : This is the minimum height of the elevation mask at any azimuth angle. Just as the maximum elevation, this can directly be retrieved from the elevation mask. Since a minimum elevation of 1 degree is used, also the minimum of the minimum elevation is 1 degree. It highlights the best part of the mask, but ignores the rest. Therefore it doesn't give much useful information.

Median elevation The median of the elevation mask is the middle value when all elevation values are ordered by height. It's an indication of the elevation mask as it neglects the lowest and highest values, but gives a representation of the mask in general. However, since only the mid value is used and the rest is ignored, also the median value is not sufficient.

Mean elevation mask The mean elevation takes into account all elevations of the mask and treats those evenly. It therefore gives already more information than only the maximum, minimum or median elevation. Since it treats all parts of the mask evenly as it's the mean, it doesn't deal with the fact that some parts of the mask block more than others.

Effective mean elevation Just like the standard mean elevation, which uses only the elevation mask, also the effective mean elevation mask can be computed. This incorporates the real effect of the elevation mask. So an blockage at an azimuth angle where more satellites are behind, has a greater weight. It can be computed using Equation 4.6. In this equation is n the amount of observations within an azimuth bin that fall under the elevation mask. This is shown in Figure 4.6. To do this, the elevation and azimuth data of the satellites are needed for a chosen period of time. For the minimum, median, mean and effective mean elevation the best possible result is 1 degree. Adjusting the algorithms and results so that 0 degree is the ideal result in unwanted since it makes it harder to interpret the results.

$$\text{Effective Mean Elevation} = \frac{\sum_{-180}^{179} n \cdot el}{\sum_{-180}^{179} n} \tag{4.6}$$

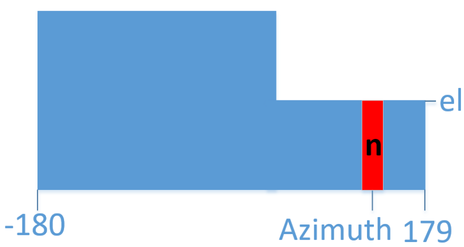


Figure 4.6: For the computation of the Effective Mean Elevation, for each azimuth bin, n is the amount of possible observations that are even or lower than the elevation mask

Percentage blocked Another option is to compute the percentage of the total view that falls under the elevation mask. In Figure 4.7 this is the area of the gray surface divided by the total area. It can also be turned around an divide the orange area by the total area to get the percentage that's visible. It's a measure of the total view that's usable. When doing it correctly, an equal area transformation should be applied since not every bin is of similar size. The minimum value of the mask is 1 degree, which can be dealt with in two ways when computing the percentage blocked. When taking the full view, the most ideal result would be 1 %. When taking the view from 1 degree and up, the most ideal result becomes 0 %. The last option is preferred as the result is better interpretable, making the best possible result 0 %.

Effective percentage blocked Just as the mean elevation can be computed based on the elevation and azimuth data of the satellites over a period of time, the effective percentage blocked can also be computed. The amount of observations that fall under the elevation mask is divided by the total amount of observations. Equation 4.7 can be used to compute the effective percentage blocked. For the denominator it's counted for each azimuth the amount of observations that should come from an elevation equal or smaller than the elevation mask (EM is elevation mask), while the divisor is the total amount of observations during the used period.

$$\text{Effective Elevation Mask} = \frac{\sum_{-180}^{179} n_{\leq EM}}{\sum_{-180}^{179} n_{total}} \cdot 100\% \tag{4.7}$$

For the effective percentage blocked are also two options on how to deal with the fact that the minimum elevation of the mask is 1 degree. When correcting for this fact, all observations at 0 and 1 degree elevation are ignored. The advantage of doing this is that it's directly visible if the station has the best possible visibility. Therefore this correction is recommend, which results in a best possible result of 0 %.

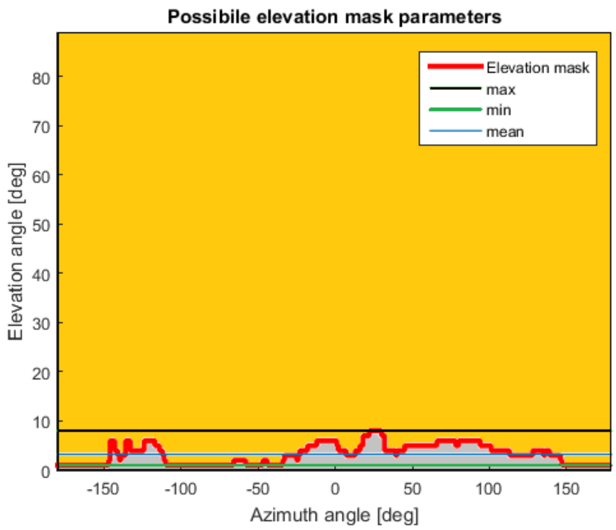


Figure 4.7: Examples of possible solutions of the elevation mask performance parameter for station AREG

Table 4.2: Possibilities of elevation mask parameters. The addition (1) means that no special correction is applied for the fact that 1 degree is the minimum elevation of the mask, while the parameters with the addition (2) had an ideal result of 0 %

Name	Parameter
Max elevation	8 [deg]
Min elevation	1 [deg]
Mean elevation	3.2 [deg]
Median elevation	3 [deg]
Effective mean elevation	4.4 [deg]
Percentage blocked (1)	3.6 [%]
Percentage blocked (2)	2.5 [%]
Effective percentage blocked (1)	13.3 [%]
Effective percentage blocked (2)	8.4 [%]

As described, there are several options possible to incorporate the elevation mask into an performance parameter. While each gives some specific information, it's undesired to use all. A key performance indicator is wanted that represents the performance the best, however, what's the best may be different for different users. The table of Figure 4.2 gives an overview of the results of the individual parameter options. The minimum elevation mask is undesired as it doesn't give much information. The maximum is more useful, but is still very limited as it can be a single spike while the rest is good. The median elevation is undesired as it doesn't take into account all high elevations. The mean elevation is already more representative as it deals with each height of the elevation mask evenly.

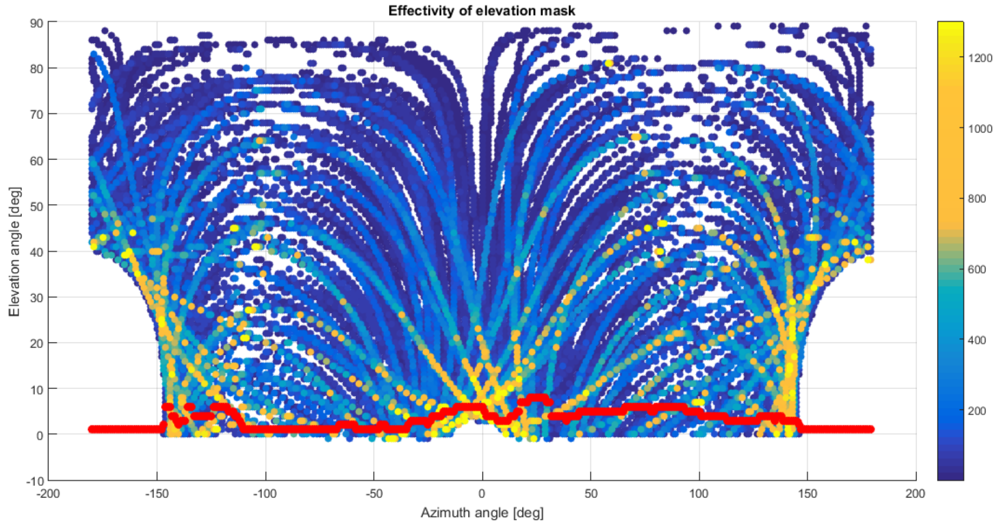
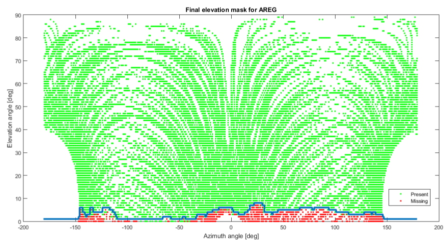


Figure 4.8: This plot shows the number of occurrences at a specific azimuth and elevation angle during 50 days. The maximum of the colorbar is set to 1300 is visualize the effect the best, and the elevation mask is in red. It gives a slightly wrong view since the occurrences per elevation and azimuth are counted. This means that when a point differs by 1 degree, it counts again. However, it still shows that at some azimuth angles the effect of the elevation mask is stronger than other points

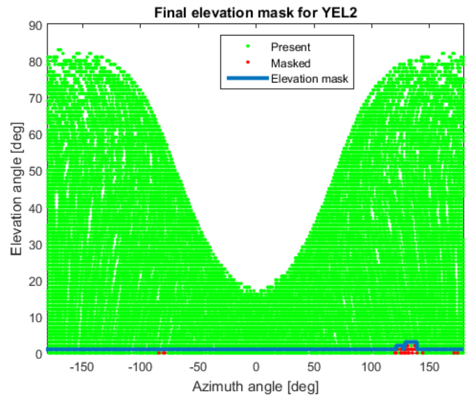
Figure 4.8 shows that at some azimuth angles the effect of the elevation mask is bigger. So it could be the case that an elevation angle of 2 degrees blocks more observations than an elevation mask angle of 10 degrees at a particular azimuth angle. For that reason it's recommended to include the observations that could be blocked by the elevation mask and therefore include the effectiveness of the mask. This leaves two best remaining options: the effective mean elevation and the effective percentage blocked. Which performance parameter is preferred depends on the goals of using it and the ways it can be interpreted. The effective mean elevation and the effective percentage blocked are compared based on four points: comparability between stations, interpretability, usability and how it assesses the location. The elevation mask is generally computed by using 50 days of data. Therefore, for the effective elevation mask also 50 days of data is used. This data exists only out of the satellite positions and station location in order to compute the elevation and azimuth angles, and the already created elevation mask. It's not checked whether these signals were actually present in the RINEX observation files, so it represents the measurements that could arrive during optimal circumstances and a perfect visibility. For station AREG the effective percentage blocked when ignoring possible measurements of 0 and 1 degrees is 8.4 %, while the effective mean elevation is 4.4 for the example of Figure 4.8 and 4.9a.

Comparability : One of the goals of using performance parameters is to use it as an comparison between sensor stations. This means that the parameter should work similar for all sensor stations. When dealing with the elevation mask, one of the main differences between sensor stations is the effect of the satellite orbits at the poles. Figure 4.9 shows this effect for a station close to the north pole and a station close to the equator. Figure 4.8 already showed that the mask has a different effect on different azimuth angles. When the effective percentage blocked is computed while using a fixed elevation mask of 1 degree elevation, it gives different results for different stations. The effective percentage blocked for YEL2 is 4.0 percent, while the result for AREG when using the same mask is 5.3 percent. Reason that it's relatively high is that all satellites cross low elevations, while not all reach high elevations. The same is done for the effective mean elevation. When applying a fixed elevation mask of 1 degree it results both in an effective mean elevation of 1 degree. This means that the effective mean elevation is better comparable between sensor stations.

Interpretable : A key performance parameter must be easily interpretable. It should mean something that the user can understand. The effective mean elevation can be interpreted as the weighted mean elevation of the elevation mask, while the effective percentage blocked means the amount of observations that are blocked because the satellite is behind objects. So both parameters can be interpreted easily. However, the effective percentage blocked is considered better understandable.



(a) Station AREG in Peru, relatively close to the equator



(b) Station YEL2 in Canada, relatively close to the north pole.

Figure 4.9: Influence of satellite orbit at poles

Assess the location : Goal of the elevation mask related performance parameter is to assess the location of the station. It should be made clear which stations have a better visibility to the sky than others. Both parameters do this in a different manner, using the same dataset. One is not clearly better than the other on this aspect.

Usable for station operator The station operator is the one that's most interested in the elevation mask parameter. So it should be useful information to him. The effective percentage blocked gives useful information about the data itself, but not on the actual elevation. The effective mean elevation gives information about the elevation while taking into account the data. This is considered more useful.

So while the effective percentage blocked is also useful, the effective mean elevation is preferred and recommended. It can be presented like the value itself, but there are other possibilities too. An option is to make it relative to an ideal situation or relative to the best performing sensor station. It can be relative to an elevation of 1 degree, since that's the minimum possible elevation mask. So for example an effective mean elevation of 2 will be given the value 1, as it's 1 degree above the minimum. While this can be beneficial as it shows how much the mask is above the minimum, it also makes things more complicated. Users first have to think about the fact that it's above the minimum and not the real elevation itself. It's therefore recommended to keep it simple and use the result of the effective mean elevation itself. Another option is to give the elevation mask parameter a certain class telling whether it's good or bad. This has the advantage that it gives a direct quality indication, which is easy to understand. The disadvantage of giving it a class is that a class limits the accuracy of the parameter, as it only says whether it's good, bad or another option. Next to that, using classes for separate performance parameters can make it unclear or confusing and the class determination can be arbitrary. It may be better to give the sensor station a single class based on several performance parameters. So the effective mean elevation is directly used as a performance parameter.

4.4. Overall Station Quality

A selection of performance parameters are proposed, in which the Daily Station Availability, the Daily Station Total Availability and the Effective Mean Elevation are independent of the system performance as much as possible and each evaluates a different performance aspect. A way to be able to quickly assess to quality of a sensor station is to take these three key parameters together into one single parameter. This doesn't give new information in a way that specific problems can be pointed out, but tells quickly which station performs better or worse. Many computations and decisions are needed to determine the key performance parameters and using the summary parameter, which is called the Overall Station Quality (OSQ), it's combined into a single statement.

The Overall Station Quality tells how well the performance of the sensor station in general is. There are three main ways of presenting this new summary parameter. It can be used to order the sensor stations and present it like 3/15, which means that the station is the third best out of 15 sensor stations. Advantage is that it immediately shows the relation to the other sensor stations. Although this information is useful, it doesn't tell how good it actually is. When all stations are underperforming, it doesn't say much if it performs third best out of 15. Another option is to express it as a single value or percentage. This way it's unrelated to other sensor stations. The disadvantage by using a single value is that the user has to interpret if the result means that the station performs good or bad. A better options is the give the station a class depending on the other three key performance parameters. A class gives more information than a single value and can be compared between stations. The only drawback of using classes is that the ranges of the classes have to be defined, which is somehow arbitrary. It can be chosen to use many classes or only a few. Using many classes only makes it more complicated, while using for example only two classes is oversimplified. How many classes are needed depends on what you want to achieve. It's useful to know which stations are the very best and which are the very worst. It's also useful to know which are still good and which are just OK. This makes it already four classes. An extra class is added to show which stations are completely out of use. This results in five classes: Excellent, Good, OK, Bad and Out of use.

Excellent Sensor station that are given the class Excellent belong to the highest performing sensor stations

Good These stations are not the very best, but still considered good

OK Stations from the class OK perform just OK. It's preferred not to use these stations for a monitoring network or other purposes. However, if no other possibilities exist, they can still be used

Bad The worst performing stations are given the class bad. These are not recommended to be used in a monitoring network

Out of use These stations are not operational during the selected period and are therefore not usable

The classes can be defined for different periods of time. A possibility is to compute it over the full period that the station was operational. However, using a period of years is not desired, as the performance can improve or degrade over time. The station can be functioning well for months, while it was off for a few weeks giving it a bad overall performance. A better solution would therefore be to use a shorter period of time. One thing that can be applied anyway is to compute the Overall Station Quality for the full period that's been investigated. That can be for a weekly, monthly or yearly report, or for a chosen amount of days. Another possibility is to compute it on a daily basis and thus give the stations a new class every day. While using daily classes gives the station the most up-to-date status, it also has a drawback. It will become very unclear if it alternates a lot. Next to that, the daily performance is already visible in the other daily key performance parameters. It's therefore better to compute the Overall Station Quality over a short period of time, being a couple of days. A logical period would be 10 days, since the repeat time of Galileo is 10 days. This period is not too long and not too short. It can be fixed periods of 10 days, for example doy 1-10, 11-20, 21-30, but a better solution is to take the previous 10 days. This will give the most up-to-date status, while not being directly dependent on only the current daily parameter.

To give the station a class based on the results of the three key performance parameters, the ranges of the classes should be defined. These ranges have a direct influence on the class that will be appointed. As a start, a single value must be obtained from the Daily Station Availability and Daily Station Total Availability of e.g. 10 days. This is done by taking the sum of the Daily Station Availability results and divide it by the amount of days. It's shown in Equation 4.8, which returns a value between 0 and 100 %. The Daily Station Total Availability has a result for every system. Using the principle of Equation 4.8, a single value can be obtained for each system. There are basically two options to combine the results of GPS and Galileo into a single value: take the average (100% & 80% = 90%) or take the minimum (100% & 80% = 80%). One of the main goals of a monitoring tool is to detect anomalies. Anomalies stand out more if the minimum value is used, so that's the preferred option. Computing a single value for the Daily Station Total Availability can be done using Equation 4.9. The elevation mask parameter is already a single value. However, it may occur that a new elevation mask and parameter was computed during the period. In that case the highest, and therefore the worst, parameter will be used for determining the class.

$$DSA_{\text{Single value}} = \frac{\sum_{\text{days}} DSA}{N_{\text{days}}} \tag{4.8}$$

$$DSTA_{\text{Single value}} = \min\left(\frac{\sum_{\text{days}} DSTA_{\text{Galileo}}}{N_{\text{days}}}, \frac{\sum_{\text{days}} DSTA_{\text{GPS}}}{N_{\text{days}}}\right) \tag{4.9}$$

The single results of the DSA, DSTA and EME can be summed up and be given a class, but it's preferred to give each parameter first an individual class. This way more information of the individual parameters can be shown if necessary. Let's start with the Daily Station Availability. If the DSA is 0, it means that the station wasn't operational the past 10 days. So this results is appointed to the class Out of use. It seems obvious to appoint the class Excellent only to a value of 100, which means that the station was continuously operational during the past 10 days. However, it happens regularly that only during a single or a handful of epochs no data is stored during a day. As this is unfortunately semi-nominal behaviour for some stations, it should be taken into account. If a station is not operational during three epochs of a 30 second interval it's considered negligible. Since the results of the Daily Station Availability are rounded to two decimal places, this corresponds with a threshold of 99.90 % as shown in Equation 4.10. When using a 1 second interval, the same thresholds can be used, since it corresponds with approximately the same period of time that the station is not operational.

$$\frac{2880-3}{2880} \cdot 100\% \approx 99.90\% \tag{4.10}$$

A result of 95 % is considered Good. This corresponds with the station being not operational for halve a day during a 10 day period. This is not perfect, but still acceptable. A station can be down due to maintenance or other events. When a station is not operational for 2 out of the 10 days, it's not good and undesired, but it can be worse. The class OK is given to a results higher than 80 %. Everything lower than 80 % is simply bad and not acceptable. This is shown in the first column of Figure 4.10.

The Daily Station Total Availability result, which is a quality measure for the period that the station was operational, is also given a class. If the single result, of for example 10 days, is Not a Number (NaN), it means that the station didn't receive anything. So NaN is given the class Out of use. Again a result of 100 % is something that's more an exception than standard, as a single expected measurement not received occurs regularly. Therefore results of 99 % and up are given the class Excellent. Since the parameter is already corrected for several possible reasons of not receiving the signals, so a high result is expected. Results between 95 and 99 are appointed to the class Good. Values between 80 and 95 are still considered OK, but results lower than 80 are given the class Bad. It seems a wide range to give results between 0 and 80 the class Bad, but since all measurements are really expected, it does hardly occur. So results below 80 % are considered Bad and are special events.

The Out of use class is not relevant for the elevation mask parameter. Only when the station was not operational for a long period and therefore the elevation mask couldn't be computed, the class Out of use is given. The best possible Effective Mean Elevation is 1 degree. Because of that, the class Excellent is given to a result of 1 degree. IGS sensor stations are expected to have a clear visibility above 5 degrees elevation (IGS, 2013). So an effective mean elevation of max 5 degrees is considered Good. In general, satellites below 15 degrees are considered of low elevation. Therefore an Effective Mean Elevation smaller than 15 degrees is given the class OK. An Effective Mean Elevation higher than 15 degrees is assigned to the class Bad.

The given ranges are used to give the three key performance parameters a class. The table of Figure 4.10 shows the ranges and classes. They are determined from top to bottom.

DSA	DSTA	EME	OSQ
≥99.9	>=99	1	**Excellent**
≥95	>=95	<=5	**Good**
≥80	>=80	<=15	**OK**
>0	>=0	>15	**Bad**
0	NaN	NaN	**Out of use**

Figure 4.10: Figure showing how each station gets classified using information from the previous 10 or X days

The next step is to combine the three classes into a single class for the sensor station. There are basically two options for doing this. One options is to use the worst out of three classes, while the other options is to create an average out of the three classes. Using the average class would mean that a station that's only operational a single day, but receives all signals during the period and has a good mask would be given the class OK or Good. This is undesired as the the station was only shortly operational, which is far from good. So it's recommend to give the sensor station the lowest out of the three classes of the parameters.

4.5. Alternative parameters

Many variations are possible of each key performance parameter, because each tiny change can be adapted to a new parameter, which presents other information or presents it differently. The key performance parameters give unique and useful information, and are unaffected by system performance. Unaffected by system performance means that the sensor station parameters are not effected by a bad performance of satellites, since they are corrected for those effects. There are however other parameters possible that can give extra information. A selection of those parameters are briefly explained within this paragraph.

Related to amount of observations received are several possibilities. An option is to count all the observations that are received during the day by the sensor station. This is done for example at IGS stations and shown on the IGS website. Accumulated over the day this can be an high value, making it hard to interpret, but by comparing the value with previous days it can be seen if it's a good or a bad day. The parameter will be called the 'Daily Station Observations' and is calculated per GNSS each day. All observations should be within the already defined thresholds. A limitation is that by counting the observations, the parameter is affected a lot by the system performance. If a satellite has problems, it's directly visible in the amount of observations received. Variations are the amount of observations for all GNSS combined, without using the thresholds and amount per satellite or signal.

Just as the observations can be counted, the amount of satellites tracked can be counted too. Like the Daily Station Observations this will result in a high value over the day. When this high value is divided by the amount of epochs, the average amount of satellites per epoch can be computed. In addition to the maximum and minimum amount of satellites in view this gives easy understandable information. Long term median of daily average/min/max satellites in view gives information of the suitability of the location of the sensor station. Although all this info is straightforward (it's the amount of satellites in view) the parameter represents both sensor station and system performance. If satellites have issues, the average, minimum or maximum satellites tracked goes down and the same holds for the case when the station has tracking problems. It's also related to the constellation and location of the sensor station. This is one of the main difficulties when defining performance parameters. Often the results are influenced by both the sensor station and system performance, which makes it hard to interpret the results correctly. However, although parameters like this are not ideal, they can give extra information when used together with the performance parameters as described in previous sections .

All observations should be within the appointed threshold limits in order to be defined as a quality observation for further processing. The amount of rejected observations tells both how well or how badly the signals are received. This can be computed using Equation 4.11, by dividing the amount of quality observations by the total amount of observations, and subtract that from 1. Once again, a parameter like this gives extra information and can be used as an supporting parameter. However, it's dependent on the system performance, by the signal strength and quality, and by the sensor station, by the tracking algorithms and noise level.

$$\text{Daily Station Bad Observations}[\%] = (1 - \frac{\mathrm{N}_{Qobs}}{\mathrm{N}_{obs}}) \cdot 100[\%] \tag{4.11}$$

4.6. Summary

Three individual key performance indicators for the sensor station performance are defined and one summarizing parameter. The definitions of these parameters are:

Daily Station Availability DSA [%]

Goal: Tell what part of the day the station is operational

Input data: RINEX observation file

Explanation: The amount of unique epochs that can be found in the RINEX observation file is divided by the maximum possible amount of unique epochs during this period. The information at the epochs is neglected

Result: A single percentage per station per day

Daily Station Total Availability DSTA [%]

Goal: Tell how well the sensor station is tracking each GNSS

Input data: RINEX observation file, RINEX navigation file, DSA, Elevation mask, system performance

Explanation: It's the weighted average of how well each satellite is received. During an epoch, a satellite is received good if all expected signals are received by the sensor station. The daily percentage for each satellite is corrected for the station being not working and satellites having problems. The weights of the weighted average are related to the time that the satellite is expected to be in view. Two supporting performance parameters are used to compute the Daily Station Total Availability

- **Daily Station Satellite Signal Availability** Tell how well a single signal of a single satellite is received
- **Daily Station Satellite Availability** Tell how well all signals of a single satellite are received

Result: A percentage per station per day for each system

Effective Mean Elevation EME [deg]

Goal: Tell how well the location and environment of the sensor station is

Input data: RINEX observation file, RINEX navigation file, Elevation mask

Explanation: It's the weighted mean elevation of the elevation mask. The weights are based on how many observations are behind the elevation mask.

Result: A single value per 50 days

Overall Station Qualiy OSQ [-]

Goal: Give a quick indication of the performance of the sensor station, especially in relation to other sensor stations

Input data: DSA, DSTA, EEM, based on the previous 10 days, or the amount of days of the chosen period of investigation

Explanation: The three other key performance parameters are combined to a single quality indicator

Result: A class is given based on the previous 10 days. The classes are: Excellent, Good, OK, Bad and Out of use

5

System performance parameters

The aim of the system performance parameters is to assess the performance of the system based on the availability of signals-in-space and the satellite status. This is done for each GNSS separately. The data used for this purpose are the RINEX navigation files, RINEX observation files created by the sensor stations and the processed sensor station performances, see Figure 5.1 for an overview. This information tells whether signals from satellites are received by a sensor station or not. This means that in order to asses the satellites continuously, it must be tracked continuously by sensor stations. Within this section a monitoring network from MGEX IGS sensor stations will be selected for this purpose. Two key performance parameters are created and presented using a small example.

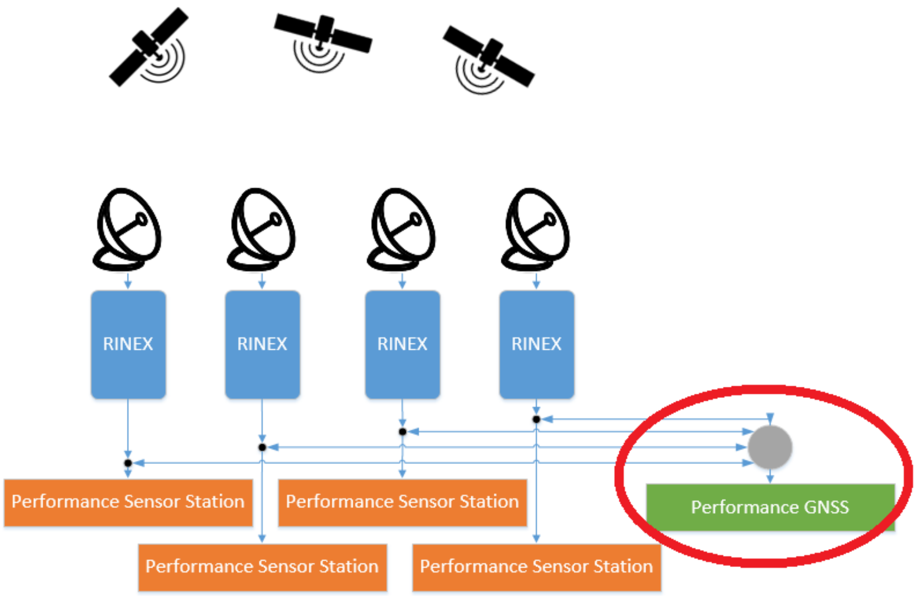


Figure 5.1: The system performance is determined from RINEX files of several sensor stations. The system performance is used for computing the sensor station performance

It's always important to keep in mind the goal of performance monitoring. Using the software tool and the key performance indicators, we want the following questions, which are related to the SiS availability, to be answered. As already explained this list can be extended by monitoring the orbit and clock parameters, the geometry and the signal quality, but this exceeds the scope of the research.

- Which and when are satellites available?
- What is the amount of available satellites?

5.1. Satellite availability

Before being able to define system performance parameters, it should be clear when a satellite is considered available and when it's considered unavailable. The main availability equation of Section 3.2.2, which is the available period divided by the expected period also holds for the satellite availability. For the expected period two main options are possible: all operational satellites are expected to be available all day the full day, or take into account planned outages. Both versions could be interesting and be worked out into a performance parameter. However, from a user perspective it's much more useful to know when and how much the satellite did function correctly. GNSS users are less interested in what part of the outages were scheduled, so all operational satellites are expected to be available all day the full day. It's mainly the system operator who wants to know if unscheduled events occur. If a tool is focussed especially on the system operator is created, processes can be added to keep track of unscheduled events.

There are two main ways of determining when a satellite is available. The first is by using observations from the sensor stations. Already pre-processed RINEX observation files containing measurements of the satellite's signals are used, which is shown in Appendix A. The thresholds set for quality signals for the sensor station also hold for system performance, as the measurements should be realistic in order to be reliable. If the signals are received at a particular sensor station, it obviously means that the satellite transmitted the signals and the satellite is thus available. In case the satellite is expected to be tracked at a single sensor station, but the signals are not received, it can be due to local sensor station issues or due to system issues. Because expected signals are corrected for the effects of Section 3.5, it's very likely that when signals are expected to be received by two sensor stations, but received by none, are due to satellite issues. This is visualized in Figure 5.2, which results in three options: available, unavailable or no information.

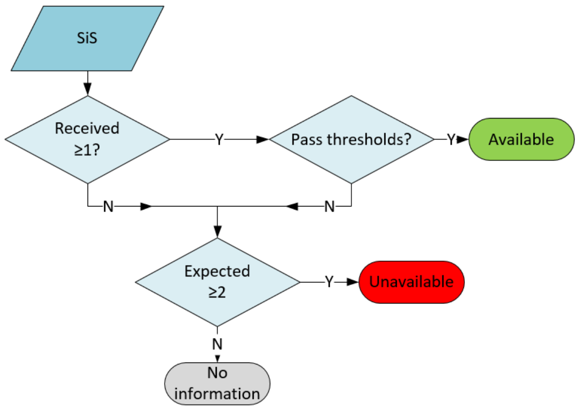


Figure 5.2: Steps showing when the signals of a satellite can be declared unavailable. Input is the signals-in-space information obtained from RINEX observation files

A complementary method to determine if the satellite is available, is to use the satellite health status. The satellite health status parameter of the broadcast ephemeris can be found in the RINEX navigation files. When the satellite status in healthy, the satellite is expected to transmit its signals. When a satellite is unhealthy, there may or may not be signals transmitted, or the transmitted signals are unreliable. Many of the IGS stations track unhealthy satellites, but depending on receiver settings they may or may not. So by just taking into account the RINEX observation files, the unhealthy periods cannot be determined. This is undesired since many GNSS users cannot make use of unhealthy satellites. Because of that, the unhealthy period is defined as unavailable. This means that evaluating the navigation files is necessary too. Figure 5.3 shows an example of a navigation message of an unhealthy satellite. The disadvantage of using the RINEX navigation file is the frequency of the data. It depends on the receiver configuration, but nominal condition is that the navigation messages are stored at a 10 minute interval for Galileo and a 2 hour interval for GPS. For the RINEX navigation files used during this research, this is also the case. The consequence is that the exact moment of a status change cannot be known. The data is dealt with conservatively to not define the satellite available while it's actually unhealthy. Therefore, the unhealthy period is one period (2 hours for GPS and 10 minutes for Galileo) before the first unhealthy status, until the satellite is declared healthy again. This can be seen in Figure 5.4, in which H means an healthy satellite status according to the RINEX navigation file and UH an unhealthy status.

```
E19 2016 09 28 01 10 00 1.774285919964e-06 3.979039320257e-13 0.000000000000e+00
     2.730000000000e+02 8.715625000000e+01 3.335496079657e-09 2.551119641836e+00
     4.164874553680e-06 2.019847743213e-04 1.026131212711e-05 5.440618724823e+03
     2.634000000000e+05-1.862645149231e-09-2.877843720691e+00-3.911554813385e-08
     9.591070647162e-01 1.230625000000e+02-2.602368959570e+00-5.680950920123e-09
     6.696707516177e-10 5.130000000000e+02 1.916000000000e+03
     1.070000000000e+02 6.500000000000e+01-9.778887033463e-09-1.117587089539e-08
     2.634250000000e+05
```

Figure 5.3: Example of a RINEX navigation message showing the unhealthy Galileo satellite E19. The yellow highlighted value is the satellite status parameter. Values higher than zero mean that the satellite is unhealthy, so this satellite is unhealthy

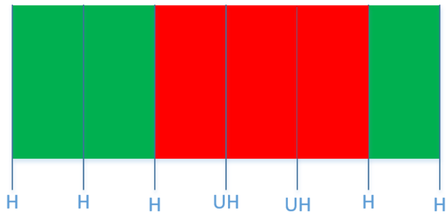


Figure 5.4: The satellite health status is treated in a conservative way. It's considered unhealthy (UN) one period before the first unhealthy status until the status is healthy (H) again

It's important to combine information of the RINEX observation files and RINEX navigation files for satellite availability. Since many receivers don't track unhealthy satellites, the health statuses are needed to determine the available and unavailable periods. When only observations from the RINEX observation files are used, signals that are tracked could come from unhealthy satellites.

Table 5.1 shows when a satellite is declared available, which is a combination of the SiS availability and the satellite health status. Using the steps of Figure 5.2 it's determined if the signals-in-space are available, unavailable or no information. They are available if the SiS is received at a particular sensor station and passed the thresholds. The satellite is considered available if the SiS is available and the satellite health status is healthy. There's no information if the there's no SiS information and the health status is healthy. In other cases the satellite is unavailable.

Table 5.1: A satellite is considered available if the SiS are available and the satellite health status is healthy. The SiS are available if the signals are received at a particular sensor station and pass the thresholds

	Healthy	**Unhealthy**
SiS available		
SiS unavailable		
SiS no information		

5.2. Monitoring network

In order to determine the performance of a satellite using observation data, the satellites must be tracked by sensor stations. Using many stations leads to massive data storage over time, so a selection of appropriate sensor stations must be made. The selection of sensor stations will be made out of the IGS MGEX stations since these are capable of receiving GPS and Galileo satellites for sure.

Section 4.1 shows the Daily Station Availability parameter that had been calculated for all MGEX stations for 13 days, which is showed in total in Appendix B. The figures show that not all stations were operational all days and also they are not spread evenly over the Earth. Goal of selecting sensor stations for the monitoring network is to have all the satellites in view during the full orbit. The first question that need to be answered is: by how many sensor stations must the satellite be tracked at any given time?

The minimum number of sensor stations seen by a satellite is called the Depth of Coverage (DOC) (Blomenhofer et al., 2005). When an high DOC is used, the reliability of satellite's being given the unavailable status goes up. An high DOC comes at the cost of the need for more sensor stations. Section 5.1 showed that satellites must be expected to be tracked by at least two sensor stations, so the minimum possible DOC is two. Section 4.1 showed that stations are occasionally not operational. This will have direct influence in the determination of satellite availability in case a DOC of two is used. In order to be more robust, a DOC of three is recommend and will be used. If storage space and the amount of sensor stations isn't an issue, it can be beneficial to use more sensor stations than strictly necessary. This way the chance that the satellite can be tracked by less than two sensor stations simultaneously, due to station outages, decreases.

The location of the sensor stations have a large effect on the visibility of the satellites. Figure 5.5, created using AGI's Systems Tool Kit (STK) software, shows ground-tracks of Galileo satellites in red. The cyan color shows the visibility of the sensor station in Kiruna, based in the northern part of Sweden. It can be seen that it can track the most northern part of the satellite tracks in all longitudes, but the view is limited in latitude direction. The visibility of the station in Kourou, which is near the equator, is shown in blue. It can be seen that it can see satellites over all latitude directions, but the view is limited in longitude direction. The extend of the blue circle and therefore the visibility is influenced by the elevation mask and the location of the sensor station. An robust monitoring network should have both stations near the poles, as well as stations closer to the equator in order to be able to track satellites constantly.

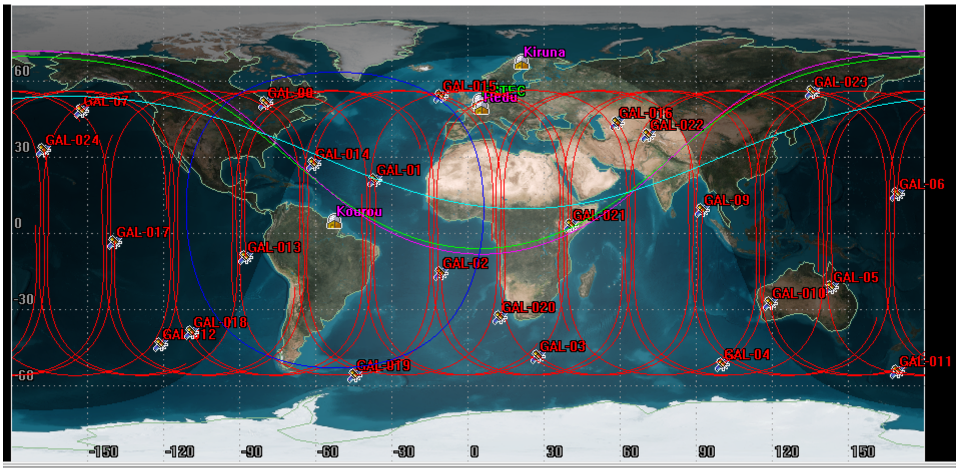


Figure 5.5: Map showing the ground tracks of Galileo satellites and the visibility of a station in Kiruna (Sweden) and Kourou (French Guyana), created using STK software

There are 16 sensor stations selected based on above information. Ideally the stations should work continuously during the 13 test days. However, as Section 4.1 showed, only 22.6 % of the stations are operational during all days. These stations are also not spread evenly over the Earth. Therefore, also stations from the second class are selected, which are operational between 9 and 13 days. In the east part of North America, Russia and Asia the amount of sensor stations that were operational during the test period is limited. For that reason some sensor stations were only operational 7-9 out of 13 days. The selected stations are: AREG (Peru), DLF1 (The Netherlands), FAA1 (French Polynesia), JFNG (China), KOUR (French Guyana), KRGG (French Southern Territories), KZN2 (Russia), MAJU (Marshall Islands), MAL2 (Kenia), NKLG (Gabon), RGDG (Argentina), STFU (USA), TOW2 (Australia), WARK (New Zealand), XMIS (Australia) and YEL2 (Canada). Figure 5.6 shows these stations on a map. The selected sensor stations are not the only solution. More combinations are possible and performance information is limited, but this selection is tested and proven to be sufficient. Only after processing data for a longer period of time, it can be said whether this selection is expected to be always sufficient.

Day of year 208 is used as an example of the visibility. During this day the 16 selected sensor stations all were receiving over 99 % of the day, as shown in Table 5.2. By using the periods that the satellite is expected to be visible during this day, it's possible to compute the amount of stations that track the satellite during the day. In Figure 5.8 for Galileo and Figure 5.7 for GPS it can be seen by how many stations the satellites can be tracked at any given time during the day. The percentage on the right tells the percentage of the day the DOC is not reached. So during this day a DOC of three is constantly obtained.

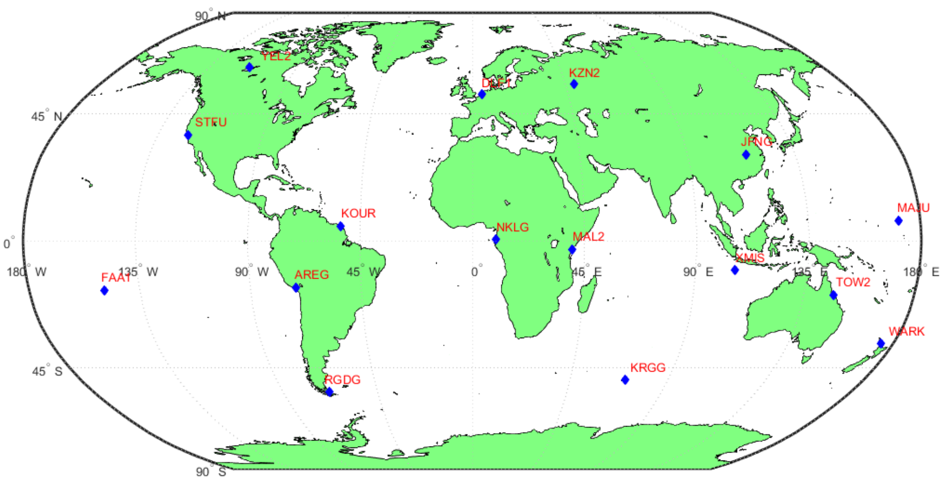


Figure 5.6: The selected sensor stations

Table 5.2: The Daily Station Availability of doy 208 shows that all stations work at least 99 percent of the time. The results of 99.97 and 99.93 corresponds with the station being one and two epochs not operational respectively

STATION	**DSA [%] doy 208**
AREG	99.72
DLF1	100
FAA1	99.93
JFNG	100
KOUR	100
KRGG	100
KZN2	99.97
MAJU	100
MAL2	99.97
NKLG	99.51
RGDG	100
STFU	99.93
TOW2	100
WARK	100
XMIS	100
YEL2	100

5.3. Daily GNSS Availability

When talking about GNSS or satellite availability, the information that you want to retrieve is above all when and which satellites were transmitting quality signals. Or in other words: when did anomalies or outages took place? The parameter 'Daily GNSS Availability' is created to do exactly that.

The Daily GNSS Availability has two different options. It can be computed for a satellite entirely, or per signal of the satellite. When the input is only the satellite ID, the algorithm will check what part of the day all signals are transmitted and healthy. First station by station the file telling when the satellite come and leaves view is loaded, which is explained in Appendix A.2.4. This is already corrected for the elevation mask and includes when each signal is expected but not received. The parameter can be computed using Equation 5.1 and it's displayed as a percentage. $N_{present\ \&\ healthy}$ is the amount of epochs that the satellite is available. This means that all signals of the satellite are received and the satellite is healthy. $P_{expected} * f$ is the amount of epochs during the period of investigation, which is usually a full day. $N_{no\ info}$ is subtracted from this value as it's the amount of epochs that there's no information from the satellite in case there are not enough sensor stations operational. If $N_{no\ info}$ is larger than 0 it should be highlighted. When there are enough sensor stations operational, which is usually the case for a thoughtfully selected monitoring network, $N_{no\ info}$ is 0.

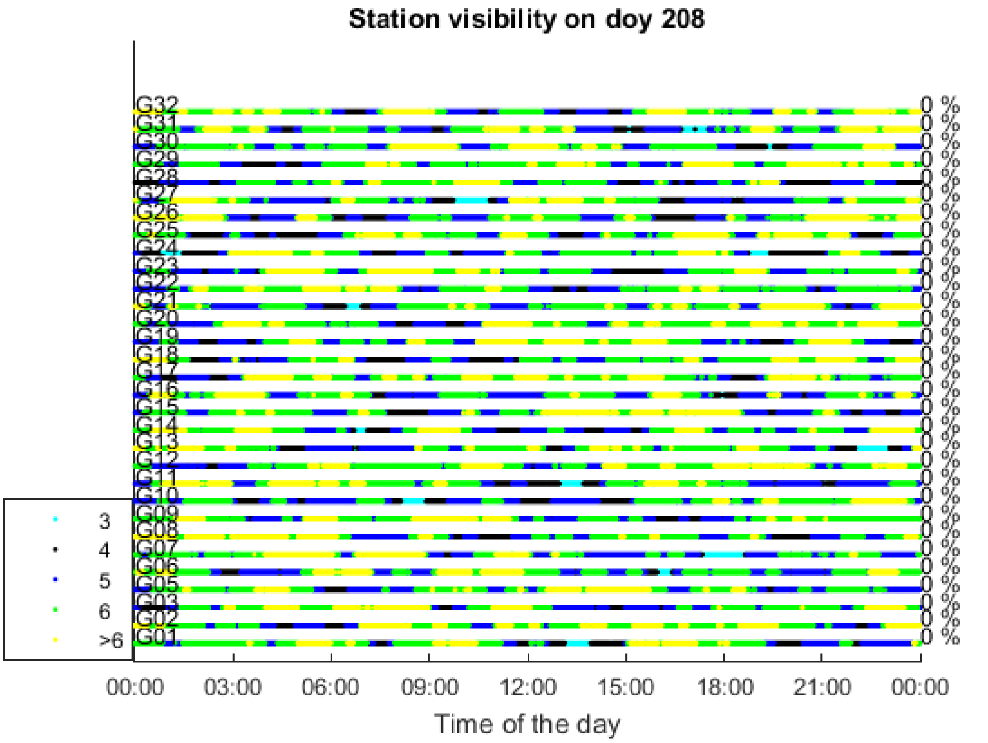


Figure 5.7: Visibility for GPS on doy 208. The result shows by how many sensor stations the satellite can be tracked at any given moment

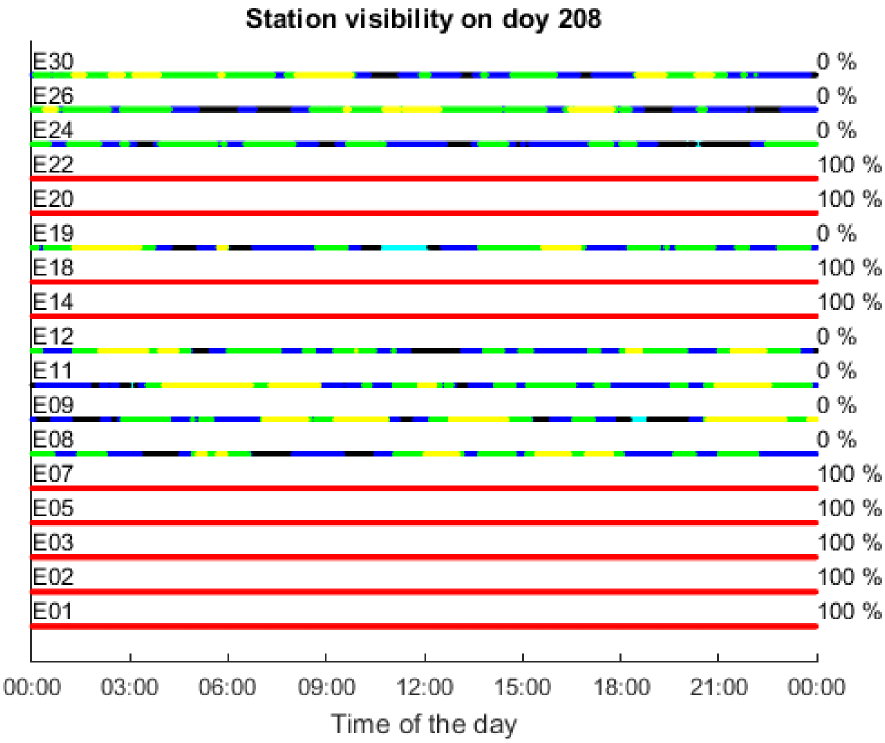


Figure 5.8: Visibility of Galileo on doy 208. The color codes are similar as used at Figure 5.7. The red lines show that the satellites are not tracked during the day. Reason is that no broadcast ephemeris was present of those satellites. Therefore, the satellite positions couldn't be computed using standard procedures. These satellite are launched but not yet operational, or have other other long term problems. The other satellites are all tracked by at least three sensor stations continuously

$$\text{Daily GNSS Availability} = \frac{N_{present\ \&\ healthy[\#]}}{\text{P}_{\text{expected}} \cdot \text{f} - N_{no\ info}} \cdot 100\% \tag{5.1}$$

As an example doy 301 is evaluated for Galileo. Notice advisories can be used to quickly check if major events happened during a selected period. Satellite events can be found in the NANU (Notice Advisory to NAVSTAR Users) for GPS and in the NAGU (Notice Advisory to Galileo users), which can be found on `https://www.navcen.uscg.gov/?pageName=gpsAlmanacs` and `https://www.gsc-europa.eu/system-status/user-notifications` respectively. These messages are used to inform users about upcoming events if possible, or give a users a notice and summary during and after events. An example of an event is a satellite outage or a signal of a satellite outage. The messages are in fixed format. According to NAGU 2016046, which was transmitted after the event, an outage took place from 09:41 - 13:28 for satellite E19. Figure 5.9 shows the corresponding NAGU message.

```
NOTICE ADVISORY TO GALILEO USERS (NAGU) 2016046
DATE GENERATED (UTC):   2016-10-28 16:15

NAGU TYPE:      AVAILABLE
NAGU NUMBER:    2016046
NAGU SUBJECT:   AVAILABLE AS FROM 2016-10-27
NAGU REFERENCED TO:     2016044
START DATE EVENT (UTC): 2016-10-27 13:28
END DATE EVENT (UTC):   N/A
SATELLITE AFFECTED:     GSAT0103
SPACE VEHICLE ID:       19
SIGNAL(S) AFFECTED:     ALL

EVENT DESCRIPTION:      GALILEO SATELLITE GSAT0103 (ALL SIGNALS) IS AVAILABLE SINCE/AS OF 2016-10-27 BEGINNING 13:28 UTC.  PAYLOAD ON PHM CLOCK.  GALILEO SATELLITE GSAT0103
(ALL SIGNALS) WAS UNAVAILABLE FROM 2016-10-27 BEGINNING 09:41 UTC.
```

Figure 5.9: NAGU message for the event on doy 301

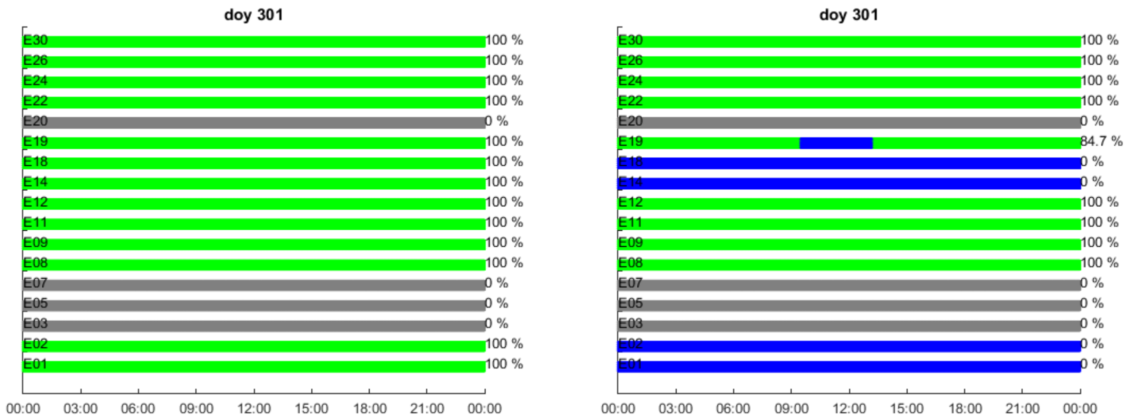
First, for all of the signals of the satellites it's checked if they are received at the sensor stations. Figure 5.10a shows that the SiS availability for Galileo satellites E01, E02, E08, E09, E11, E12, E14, E18, E19, E22, E24, E26 and E30 is 100 percent during the day. Even satellite E19, which is expected to have an issue, was transmitting signals that pass the quality check at the sensor stations the full day. It shows for each satellite from bottom to top: E1, E5A, E5B and E5AB. Green means that the signal is available, red (which is not present on Figure 5.10a) means that signals are unavailable. If the signal is gray, it means that no navigation message was present. Therefore standard algorithms cannot be executed. Figure 5.10a shows for Galileo only a selection of satellites. Reason for this is that during the period of research some satellites weren't launched yet, so they won't be available anyway. Satellites which are launched but not yet operational are shown since they could become operational.

When the satellite health statusses from the navigation message are added, see Figure 5.10b, it looks more as expected. The blue color means that the satellite or signal is uhealthy and therefore unavailable. E14 and E18 were launched into incorrect orbits and are therefore only used for testing (GPS world staff , 2016). Also E01 and E02 weren't operational yet and therefore only used for testing. The event of satellite E19 can also be seen now. E19 was available for 84.7 percent of the day. According to the algorithms E19 was unavailable from 9:30 - 13:10. This is slightly off from the NAGU and is due to imperfections of the RINEX navigation file and satellite health status processing. Health statuses were unhealthy from 09:30 -13:10, while on 9:30 and 13:10 also healthy statuses were found. The Daily GNSS Availability is a combination of received quality signals at sensor stations and the satellite health status, so Figure 5.10b is the final used figure. Final percentages of doy 301 are shown in Figure 5.11.

5.4. Daily Available number of Satellites

A way to quickly notice how many satellites are availability within a GNSS is to express the amount of operational satellites as a single value. For GPS this is expected to be fairly constant, while for Galileo this amount should rise over time. For every satellite it's already known what percentage of the day the satellite is transmitting healthy signals via the Daily GNSS Availability. These values are used as input. The parameter that represents the amount of operational satellites per system will be called the Daily Available # of Satellites. It can be expressed in several ways in which Galileo for doy 301 is taken as an example (see Figure 5.10b). The following options are considered:

- Give the amount of satellites that are 100 % available. For the example of Galileo for doy 301 the result would be eight. The disadvantage is that it treats all satellites below 100 % similar. Even satellites which are for example 99 % of the day available are not counted.



(a) Only SiS availability

(b) SiS availability combined with the satellite health status

Figure 5.10: Daily GNSS availability of Galileo for doy 301. For both figures the color green means that the satellite is available. On the left only SiS availability is considered, on the right the health status is included. Gray means that the satellite didn't transmit its navigation message and blue means that the satellite is unavailable because of the unhealthy satellite health status

- Express the available satellites as a percentage of the total amount of satellites. This is not straightforward as the total operational amount of satellites may change. Satellites can be decommissioned or new satellites can be launched. So before being able to compute this, it has to be defined thoroughly what the maximum amount of satellites is for each GNSS. So for this example of Galileo it can be 8.85/9 (all available satellites), 8.85/13 (all satellites transmitting broadcast ephemeris), 8.85/17 (all considered satellites), 8.85/24 (all satellites of the full constellation), 8.85/30 (all satellites of the full constellation, including spares). So there are many possibilities for the total amount of satellites.

- Give the minimum amount of satellites that are available at any given time during the day. So for the example this is eight satellites, as between approximately 10:00 and 13:00 only eight satellites were operational. For this example it's similar as the amount of satellites that are fully operational since there was only one satellite which was partly available.

- Give the amount of satellites that are atleast partly available during the day. For Galileo on doy 301 there are nine satellites at least party available: eight are 100 % and one is 84.7 %. An disadvantage is that much information is neglected, since all results above 0 % are treated evenly.

- Give the average amount of satellites that are available during the day. For the example this is 8.85. The advantage is that all percentages are treated evenly, but the disadvantage is that for example two satellites having a Daily Satellite Availability of 50 % give the same result as one satellite of 100 % and the other of 0 %.

The last option is preferred as the amount of satellites is directly visible and is easy to understand. Also it treats each Daily GNSS Availability result similar. Equation 5.2 shows how it can be calculated using the already computed Daily GNSS Availability of all satellites within a GNSS. It results in a single value per GNSS per day.

$$\text{Daily Available Number of Satellites} = \frac{\sum \text{DGA}}{100} \tag{5.2}$$

As an example doy 301 of Galileo is used of the previous example. Figure 5.11 shows that eight satellites functioned the full day and one satellite only part of the day. This results in 8.85 available Galileo satellites during doy 301.

5.5. Alternative parameters

The Daily GNSS Availability and the Daily Available # of Satellites are considered the most important and useful parameters when dealing with signals-in-space availability for the system. There are however many other options too. Using the Daily GNSS Availability, all operational satellites are expected to be available the

Sat	DGA
E30	100
E26	100
E24	100
E22	100
E20	0
E19	84.7
E18	0
E14	0
E12	100
E11	100
E09	100
E08	100
E07	0
E05	0
E03	0
E02	0
E01	0

DAS	8.85

Figure 5.11: Daily GNSS Availability for Galileo on doy 301 including the Daily Available # of Satellites below

full day. It can be useful for the system operator to know which of the events were forecasted. By neglecting forecasted outages, unforecasted outages become more visible. Also using the Daily GNSS Availability signals should be both received at a sensor station and be healthy. By splitting these conditions into two parameters the reason of events become more clear. This is also what Figures 5.10a and 5.10b show. Right now the availability is determined per satellite. This way the performance of each satellite can be seen directly. However, each satellite is appointed to a satellite slot. When determining the availability per slot, more knowledge can be gained about the constellation. It can be known if events take place on the FOC satellites or on the spare satellites. Therefore it can also be checked what part of the day all FOC satellites were available. If the Daily GNSS Availability is computed over a long period of time, extra performance information can be gained for the satellites. Examples are the period they are available or unavailable since launch or per year. This can also be expressed as a percentage or as the time unavailable per day.

5.6. Summary

A satellite is available if the signals are received by a sensor station, passed the thresholds and the satellite status is healthy. RINEX observation files from the stations are needed, as well as RINEX navigation files. In order to define the satellite as unavailable, the satellite must be expected to be tracked by at least two sensor stations. Therefore, it's necessary to select sensor stations for a monitoring network. Sixteen stations are selected based on 13 days of Daily Station Availability results. These stations are: AREG (Peru), DLF1 (The Netherlands), FAA1 (French Polynesia), JFNG (China), KOUR (French Guyana), KRGG (French Southern Territories), KZN2 (Russia), MAJU (Marshall Islands), MAL2 (Kenia), NKLG (Gabon), RGDG (Argentina), STFU (USA), TOW2 (Australia), WARK (New Zealand), XMIS (Australia) and YEL2 (Canada). The following two key performance parameters are proposed:

Daily GNSS Availability DGA [%]

Goal: Tell what part of the day the satellite is transmitting healthy signals

Input data: RINEX observation files from a selection of sensor stations, RINEX navigation file

Explanation: Determine if a quality signal is received by a sensor station and the if the satellite status is healthy

Result: A single percentage per satellite per day. If necessary, the (un)available period can be given

Daily Available number of Satellites DAS [−]

Goal: Give the amount of available satellites of a GNSS

Input data: Daily GNSS Availability

Explanation: It's the summation of the Daily GNSS Availability results of a GNSS divided by 100, which gives a single representative value

Result: A single value per GNSS per day

6
Results

A selection of Key Performance Indicators are defined and short examples are shown in Chapter 4 and Chapter 5, but in order to fully know if the parameters are actually useful in practice, they are computed for a longer period of time. Striking things are highlighted and if possible explained. A period of 100 days is used as it contains several repeating tracks of Galileo, which can be used to see if repeating errors occur. The period is in the end of 2016, as during this period new Galileo satellites are launched and become operational, and initial operational services of Galileo are declared live mid December 2016. It's from day of year 267 (23th of September 2016) up to and including day of year 366 (31th of December 2016). The 16 sensor stations that were selected in Chapter 5 are used as data-source.

6.1. Presenting information

There's much information to analyse and not everything is equally important for users of a monitoring tool. The main question is whether the satellite or sensor station is functioning as it should, or if there's an issue. Users must be able to quickly notice events. Static info containing results for a longer period of time, which is displayed as a large list of numbers is hard to interpret, while a list of grouped events and day to day changes is better to understand. If needed, for example even an alarm can be used when a sensor station underperforms. A solution is to present data from big to small. If a sensor station performed excellent during the selected period of time, there's no need to analyse individual performance parameters for every day. However, when the performance is not excellent, you want to know because of which performance aspect this is (time of being operational, quality of receiving, elevation mask), on which day(s) it occurred and if it's a reoccurring event. So first 'big' statements are given, like a sensor station, system or satellite is performing good or bad, and when the performance is bad more detailed information is presented that helps to get more insight in the situation and explain the events. More detailed information is only showed if something is going on or if one wants to investigate a certain part into more detail. Figure 6.1 shows this principle. Note that the detailed information is still necessary to compute and determine the 'big' statements. Next to presenting the data only in details during events, color codes can also help to highlight anomalies. By using smartly chosen color ranges, events can be noticed quickly. This can be summarized in the following two points:

- Detailed information is only shown in case of anomalies or in case of a specific investigation
- Color codes are used to highlight anomalies

6.2. Sensor station results

The parameters described in Chapter 4 are computed for a selection of sensor stations. Those key performance indicators are: Daily Station Availability, Daily Total Station Availability, Effective Mean Elevation and the Overall Station Quality. Results are presents and some events are highlighted.

6.2.1. Daily Station Availability

Let's start by taking a look at the Daily Station Availability calculated over 100 days. Figures 6.2 and 6.3 show the results, which are explained using the legend on Figure 6.4. The color codes correspond with the selected

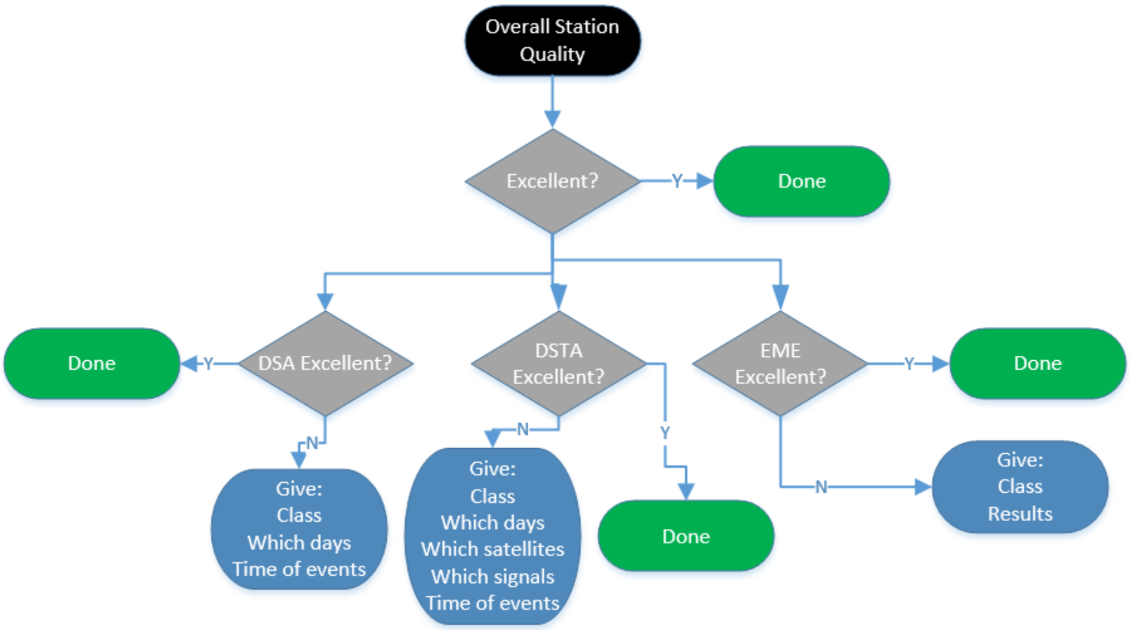


Figure 6.1: An example of how results are shown from big to small: detailed information is only shown if anomalies occur

limits as explained for the Overall Station Quality of Section 4.6. An extra color is added to see which stations often have a result between 99.9 and 100 %. Therefore, the color yellow is given to the class Good and an extra color green is used. The scale is created in a logarithmic way to make differences more clear. The reason that the results are shown in a table using only colors is that it's easier to detect anomalies. This is more user-friendly than showing a list of numbers. The numbers itself are not shown for clarity, but when implementing it in a fully functioning software tool extras can be added. The boxes can become clickable or show more information using a so called mouseover. Since these features are not possible on paper, the percentages are shown in Appendix C.

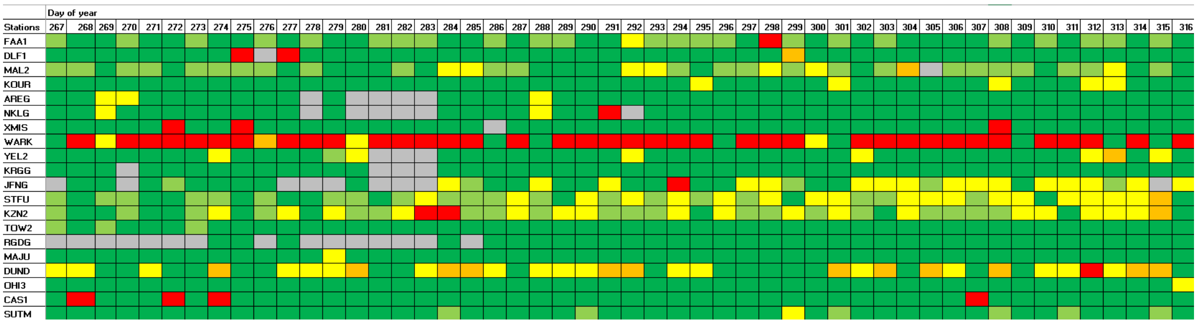


Figure 6.2: Results of the first 50 days for the Daily Station Availability. The legend can be found in Figure 6.4

It can be seen that it hardly occurs that all sensor stations are receiving data the full day. The averages per station of Table 6.1 show that over these 100 days all stations had some issues. The stations WARK and RGDG stopped working from doy 335 and KRGG from doy 342. Because stations WARK and RGDG don't function well for a large part of the period, the stations DUND (New Zealand) and OHI3 (Antarctica) are added, which are close the the former stations. Also station CAS1 (Antarctica) is used as a backup for KRGG and SUTM (South Africa) is extra in Africa. This is needed to unsure that the satellites are tracked by a minimum of two sensor stations during the full period, which is a requirement of the system performance parameters. This makes a total of 20 sensor stations in the used monitoring network. Figure 6.5 shows an overview of the sensor stations.

It can also be noticed that regularly the DSA is even or larger than 99.9 and smaller than 100 %. This happens at some stations more than others and is likely due to receiver software issues. A closer look is taken

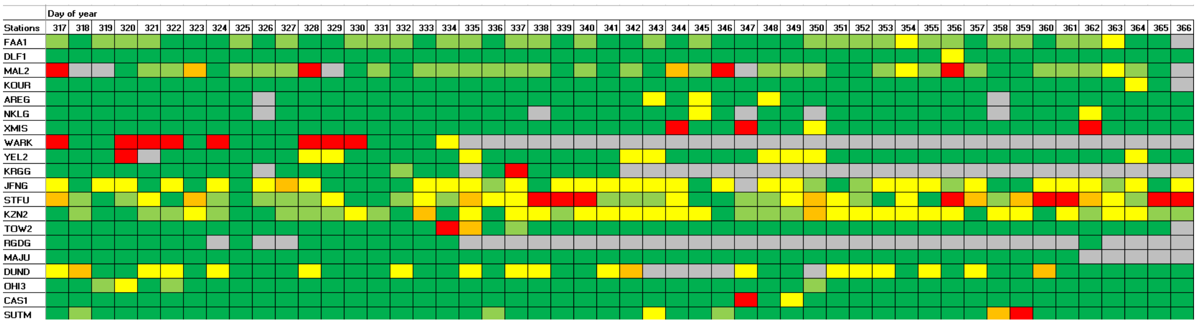


Figure 6.3: Results of the second 50 days for the Daily Station Availability. The legend can be found in Figure 6.4

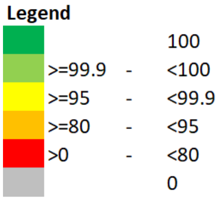


Figure 6.4: Color code legend for Figures 6.2 and 6.3

Table 6.1: Averages of the Daily Station Availability results from Figure 6.2 and Figure 6.3

Stations	Average
FAA1	98.63
DLF1	98.34
MAL2	91.54
KOUR	98.95
AREG	92.94
NKLG	88.68
XMIS	96.31
WARK	24.65
YEL2	95.10
KRGG	68.39
JFNG	88.47
STFU	94.55
KZN2	98.64
TOW2	97.98
RGDG	51.00
MAJU	95.00
DUND	91.16
OHI3	99.97
CAS1	97.39
SUTM	99.58

at station FAA1 on doy 267. The table of Figure 6.2 shows that the DSA is light green, so the station is not operational during 1 to 3 epochs. By looking at the results of Appendix C, it can be seen that it's 99.97 %, meaning that during 1 epoch no data was received. Figure 6.6a shows that it occurred at 14:18. An extraction of the corresponding RINEX observation file, see Figure 6.6b, shows that during this epoch indeed no data is received at 14:18:00. Figures like Figure 6.6a can be created automatically in case of events or other reasons.

A possibility is that stations which often are not operational during 1 to 3 epochs during a day have a similar configuration. The table of Table 6.2 shows the amount of events and important aspects of the configuration of the stations. Note that the configuration could change during the period of 100 days and stations can be not operational for more than 3 epochs during the day. No clear source of the events can be noticed in Table 6.2. Stations with different configuration have similar issues. It strikes that stations MAL2 and FAA1 have events on (almost) halve of the days while having a similar configuration. However, stations with similar receiver or antenna don't have this issue. The amount of stations used is to small to draw conclusions. Linking results over a long period of time with hardware and software can still be useful to confirm or reject assumptions and make better future decisions for future hardware and software.

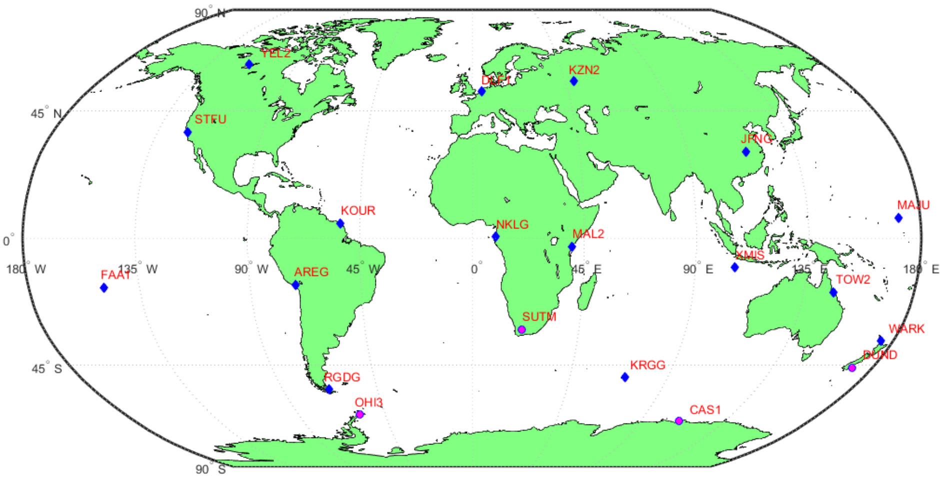
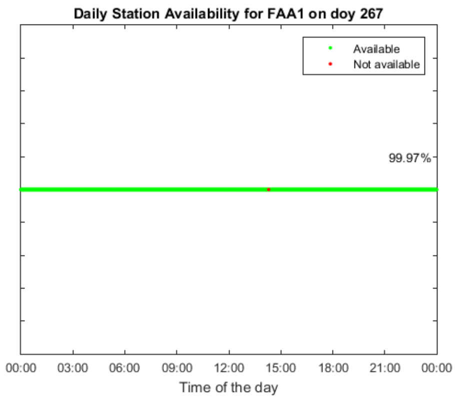


Figure 6.5: World map showing the stations used for the monitoring network. The stations showed as a purple circle were added later



(a) The DSA shown for station FAA1 on doy 267. At 14:18 no data is received

```
> 2016 09 23 14 17 30.0000000  0 33
R03  21016921.498 8 112505313.50308     -2224.867 8        49.750     21016922.33
.................................................................................
R19  22701904.528 7 121439891.86807      4007.382 7        44.000     22701904.21
> 2016 09 23 14 18 30.0000000  0 32
G13  20119668.589 8 105729572.16418       318.531 8        48.250     20119668.27
```

(b) The RINEX observation file of FAA1 on doy 267 does not contain observations for the epoch at 14:18:00

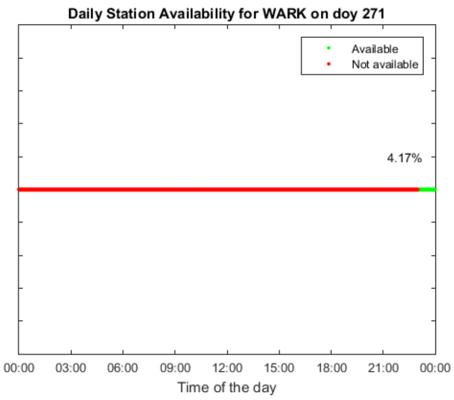
Figure 6.6: The RINEX observation files confirms what Figures 6.6a and 6.2 already showed: during epoch 14:18 no data is received.

On the overview figures for the DSA it can be seen that some stations have more issues than others. For example does the station WARK often show red. According to Appendix C this corresponds often with a DSA of 4.17 %. Figure 6.7 shows this in more detail for 4 days. This tells us that de station often receives data only the last hour of the day. Using information like this can help to point out reoccurring problems and fix them.

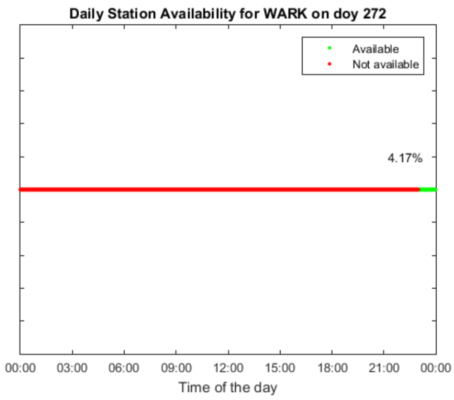
Figure 6.3 shows that three stations stopped working properly at the end of 2016 for at least 25 consecutive days. At doy 366 even eight out of the 20 sensor stations were not operational. The averages tells us that no station is operational 100 % of the time. Therefore, when defining a monitoring network, backup stations are needed. This way another station can cover the loss of information. However, in parts of the world with a dense coverage of stations this is possible, but in other parts this is not. In that case it can be solved by using two extra stations which are relatively close. So for the rest of the results 20 stations are used and not 16, as proposed in the previous chapter. This ensures that the satellites are continuously tracked by at least two sensor stations. Without performance information over a long period of time this couldn't be known. It shows that stations can perform well during 13 days, but they may stop working properly thereafter. The original network was selected based on a DOC of three during good circumstances. This means that the network is able to deal with a loss of atleast a single station, since a satellite being tracked by two stations is considered sufficient (see Section 5.2). So when only stations which perform continuously excellent are used, 16 stations are sufficient. However, this is not the case and options are limited on some locations, so more than 16 stations are needed.

Table 6.2: Configuration of the sensor stations and the amount of days (events) that during 1 to 3 epochs the station is not operational. Because the configuration may change, the configuration is given at doy 317, which is halfway of the test period. The number of events is given for the full 100 days

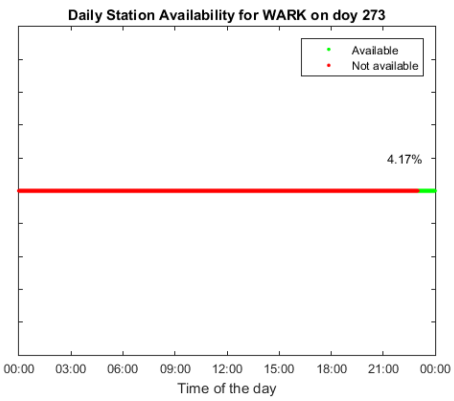
Station	events	Receiver	Receiver fw	Antenna	RINEX version	Data-source
MAL2	50	SEPT POLARX4	2.9.5	LEIAR25.R4	3.03	R
FAA1	49	SEPT POLARX4	2.9.5	LEIAR25.R4	3.03	R
STFU	36	JAVAD TRE_G3TH DELTA	3.6.2	TRM57971.00	3.03	S
KZN2	35	TRIMBLE NETR9	5.14	TRM59800.00	3.03	S
JFNG	10	TRIMBLE NETR9	5.14	TRM59800.00	3.02	R
SUTM	9	JAVAD TRE_G3TH DELTA	3.6.7	JAV_RINGANT_G3T	3.02	R
TOW2	4	SEPT POLARXS	2.9.1-patch2	LEIAR25.R3	3.02	R
OHI3	3	LEICA GR25	4.02/6.522	LEIAR25.R4	3.03	R
YEL2	1	SEPT POLARX4TR	2.9.5	LEIAR25.R4	3.03	R
KRGG	1	LEICA GR10	4.00/6.522	LEIAR25.R4	3.02	R
DLF1	0	TRIMBLE NETR9	5.14	LEIAR25.R3	3.03	R
KOUR	0	SEPT POLARX4	2.9.5-extref1	SEPCHOKE_MC	3.03	R
AREG	0	TRIMBLE NETR9	5.14	TRM59800.00	3.02	R
NKLG	0	TRIMBLE NETR9	5.14	TRM59800.00	3.02	R
XMIS	0	TRIMBLE NETR9	5.10	TRM59800.00	3.02	R
WARK	0	TRIMBLE NETR9	5.14	TRM55971.00	3.03	R
RGDG	0	TRIMBLE NETR9	5.14	TRM59800.00	3.02	R
MAJU	0	SEPT POLARX4TR	2.9.5	JAVRINGANT_DM	3.02	R
DUND	0	TRIMBLE NETR9	5.14	TRM57971.00	3.03	R
CAS1	0	TRIMBLE NETR9	5.10	LEIAR25.R3	3.02	R



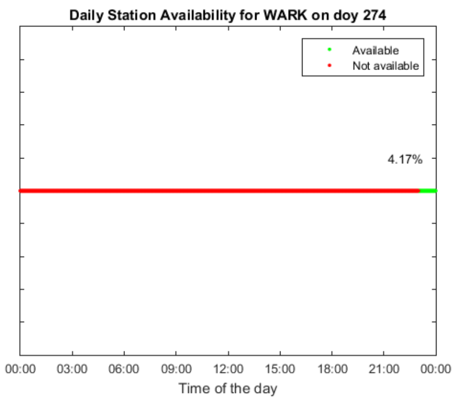
(a) DSA of WARK on doy 271



(b) DSA of WARK on doy 272



(c) DSA of WARK on doy 273



(d) DSA of WARK on doy 274

Figure 6.7: The four figures show that the station WARK only receives data from 23:00 - 23:59:30. According to the overview of Figure 6.2, Figure 6.3 and Appendix C this occurs often at this station.

6.2.2. Daily Station Total Availability

The second key performance parameter that's presented is the Daily Station Total Availability. This tells how well the station is receiving expected observations during the period that it receives data. Results are shown in Figures 6.8, 6.9 and visualized using the legend of Figure 6.10, again for 100 days. The color codes are slightly different than explained for the Overall Station Quality parameter and the one used for the Daily Station Availability. Using the adjusted color codes problems can be highlighted better. If a box is gray it means that the station wasn't operational during the day, while dark red means that the station was operational, but didn't receive all signals of a satellite at any moment. Ordinary red means that the station received between 0 and 80 percent. Gray, dark red and normal red are all classified as bad. For each sensor station there are two rows in which the upper row shows the results of Galileo and the bottom row for GPS.

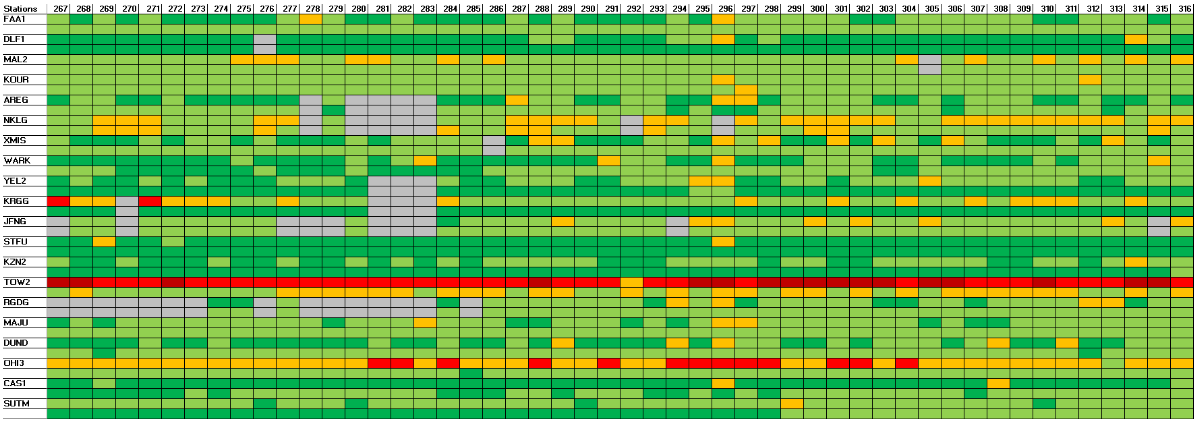


Figure 6.8: First part of the results of the Daily Station Total Availability. For each station the upper row are Galileo results and the bottom row GPS results. The legend for the colors is shown in Figure 6.10

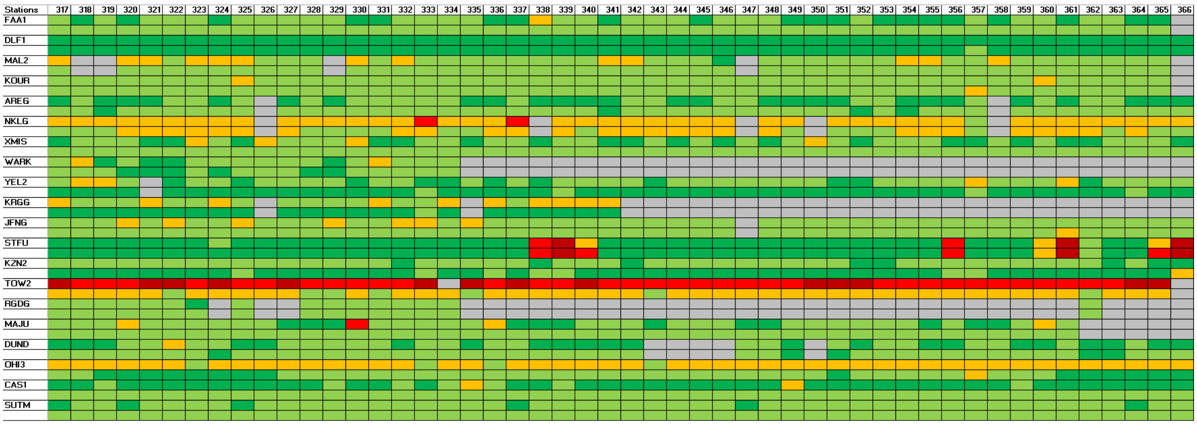


Figure 6.9: Second part of the results of the Daily Station Total Availability. For each station the upper row are Galileo results and the bottom row GPS results. The legend for the colors is shown in Figure 6.10

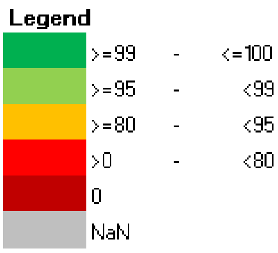


Figure 6.10: Legend of the colors used for the Daily Station Total Availability of Figures 6.8 and 6.9

The first thing that stands out is that the station TOW2 is tracking Galileo satellites much worse than GPS satellites. For example on doy 267 the station is working the full day, see Figure 6.2, but the Daily Station Total Availability for Galileo is 0 %. This means that at at no time during the day all Galileo signal are received of a satellite, while the station is configured to track all signals. As explained in Section 4.2, the DSTA is composed of the Daily Station Satellite Availabilities of the individual satellites. After events like this, more detailed information is desired. How the Galileo satellites and their signals are received by TOW2 on doy 267 is shown in Table 6.3. It can be seen that the observations of $E5A+B$ are never received or aren't of high enough quality, while the E1 signal is received during the complete expected period. The $E5A+B$ signal can be found in observation files of other days and is given in the header, so the station is capable of receiving it. Strangely only the satellites E11, E12 and E19 are tracked. As shown later in Section 6.3.2, the satellites weren't available (not healthy) during the period. Figure 6.11 shows this over the day and Figure 6.12 shows the $C/N0$ for satellite E11 over the day. These figures can be made automatically for every station for every day, but are only relevant in case of events like this. In Figure 6.11 for all satellites are four signals shown from bottom to top: E1 (green), E5A (cyan), E5B (yellow) and E5A+B (blue, not present). Gray means that the satellite was behind the elevation mask and red means that the signal wasn't received while expected during that epoch.

Table 6.3: Daily Station Satellite Availability and Daily Station Satellite Signal Availability for Galileo satellites on doy 267 by TOW2. Each value represents the percentage of received data

Sat ID	**Satellite** [%]	**E1** [%]	**E5A** [%]	**E5B** [%]	**E5A+B** [%]
E11	0	100	95.65	95.65	0
E12	0	100	91.23	90.18	0
E19	0	100	96.82	96.82	0

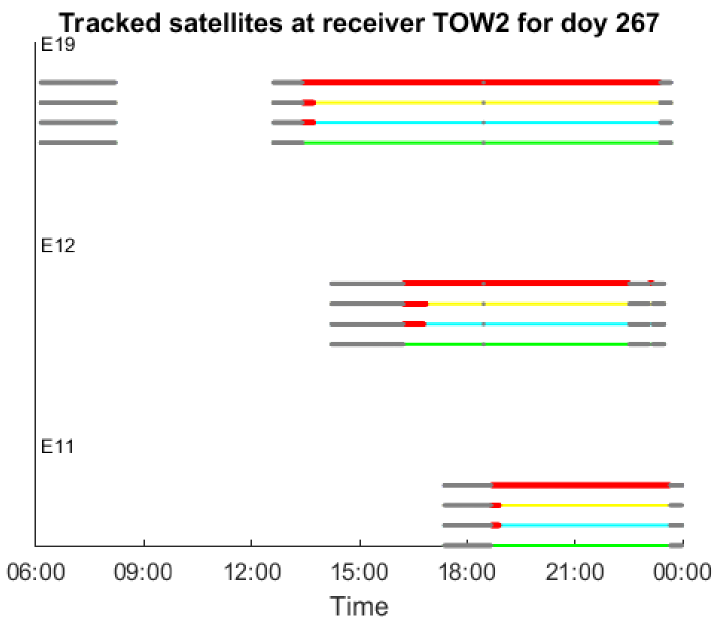


Figure 6.11: Galileo satellites tracked by TOW2 on doy 267. Green, cyan, yellow and blue (not present) show signals E1, E5A, E5B, $E5A+B$ respectively. Red means that the signal was expected but not received and gray means that the satellite was behind the elevation mask or the station was not operational

Another example of an event is FAA1 on doy 278. An anomaly, or deviation from the standard behaviour, is considered an event. This can mean that the station performs worse than other days, or has reoccurring bad behaviour. Compared to the days before and after, the station performs worse on doy 278 as shown in Figure 6.8. During days 277 and 279 the performance is also not excellent, but this is still acceptable. On doy 278 a more significant event takes place. According to the data, the DSTA for FAA1 during doy 278 is 93.73 %. Since this is significantly lower than 100 %, we want to investigate the situation. In that case the Daily Station Satellite Availability and the Daily Station Satellite Signal Availability become interesting.

Figure 6.13 shows that satellites E09, E11 and E24 are received less than 100 percent, while the other

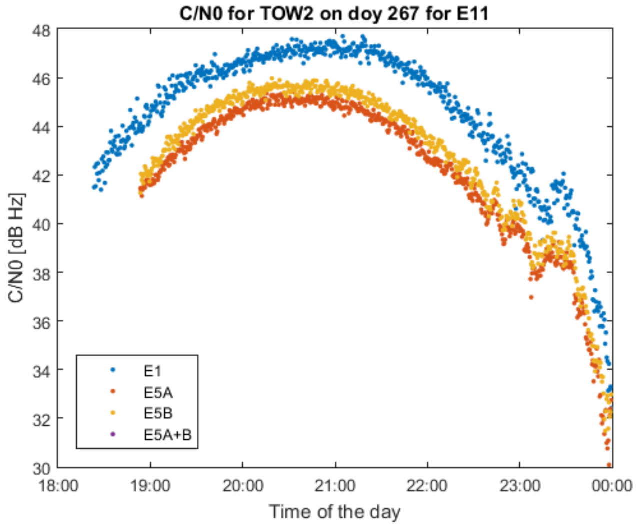


Figure 6.12: Signals of E11 observed by TOW2 on doy 267. Signal $E5A+B$ is not received and signal E1 is received earlier than the other signals

satellites are received 100 percent. The next step is to evaluate how each signal of a satellite is received, which can be seen at the right of Figure 6.13. This tells us that the E5A+B signal is received worse than other signals. The total of satellite E24, 89.37, is lower than E5A+B, 89.72, since the other signals were also not received a few times during another epoch. Figure 6.14 shows this in a plot. For each satellite from bottom to top are E1, E5A, E5B and E5A+B shown. The expected but not received signals are shown in red, which corresponds with the results of Figure 6.13. It can also be noticed that at around 10:00 and 16:30 the station was not receiving at all since all satellites are shown in gray during that time. Other gray parts mean that the satellite is behind the elevation mask.

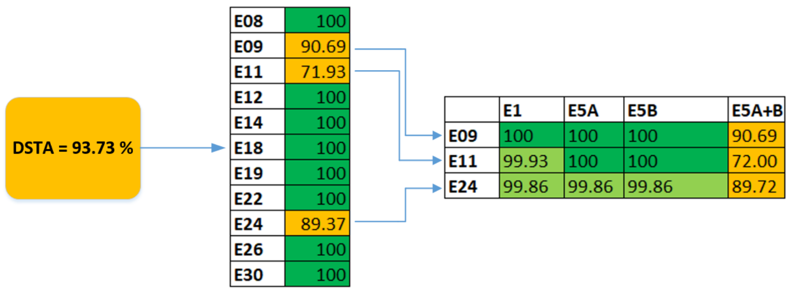


Figure 6.13: Results are presented from big to small. First a single value per GNSS, than per satellite and than per signal. Information of how a single signal of a satellite is received by the station becomes relevant in case of anomalies or specific investigations. If the DSTA is 100%, it means that the satellites and their signals are received 100 % too. So showing them is not necessary in that case

6.2.3. Effective Mean Elevation

For every sensor station the elevation mask is already computed. Using the positions of the satellites and sensor station, the Effective Mean Elevation is computed according the the algorithm described in Section 4.3. The results for the first 50 days of the test period is shown in Table 6.4. It can be seen that station DLF1, located in Delft, has the best visibility. Since the elevation mask is created in such a way that 1 degree elevation is the minimum, it coincides with the best possible result. The stations AREG, CAS1, DUND, FAA1, KRGG, RGDG, YEL2 all have an Effective Mean Elevation of maximum 5.0 degrees, while station STFU is 5.1 degrees. The stations TOW2 and KZN2 are the only stations with a result above 10 degrees. Stations that are part of the IGS network are expected to have a clear visibility above 5 degrees elevation. The results show that many of the examined stations are worse than expected. Figure 6.15 shows two examples of the Effective Mean Elevation. The mask of station AREG, Figure 6.15a, varies between an elevation of 8 and 1 degrees. This

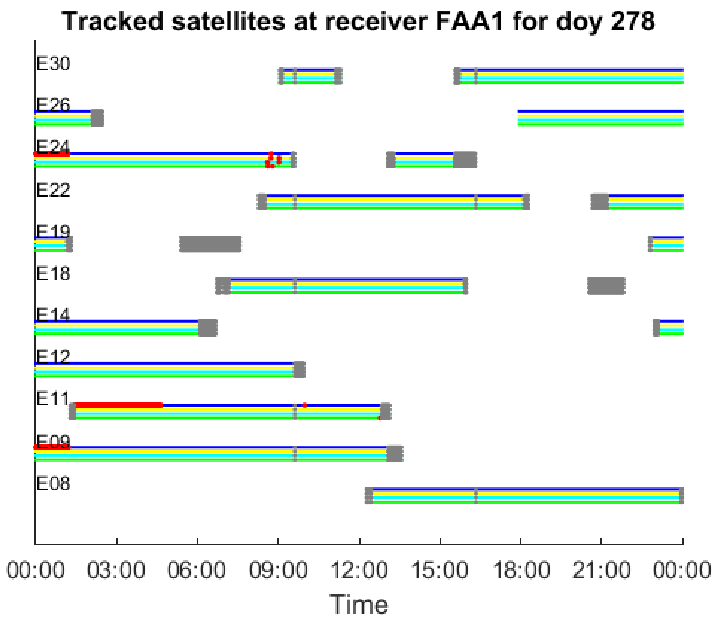


Figure 6.14: Tracked Galileo satellites and signals visualized for FAA1 on doy 278. For each satellite the signals are from bottom to top: E1 (green), E5A (cyan), E5B (yellow) and E5AB (blue). There's no observation while expected at red periods and gray means that the station was not operational or the satellite was behind the elevation mask.

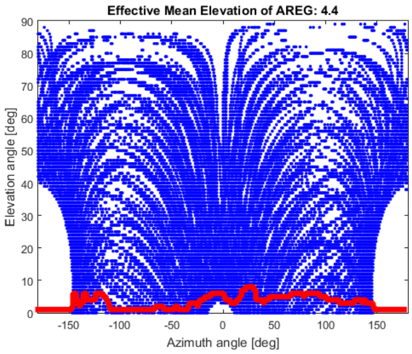
results in an mask parameter of 4.4 degrees. In Figure 6.15b it can be seen that de mask has one point above 1 degree elevation. However, this has no impact on the result, which is still 1.0 degrees. In both figures the red line represents the elevation mask, while the blue dots are possible observations.

Table 6.4: Results of the Effective Mean Elevation, calculated for the first 50 days of the test period

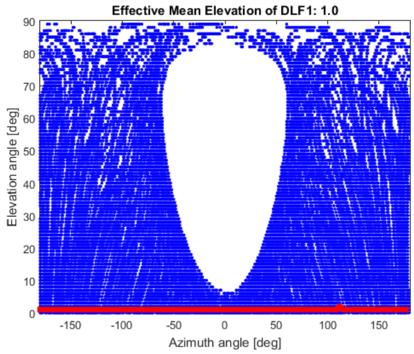
Station	EME
AREG	4.4
CAS1	1.6
DLF1	1.0
DUND	1.3
FAA1	3.7
JFNG	8.3
KOUR	9.3
KRGG	3.3
KZN2	12.7
MAJU	6.4
MAL2	9.7
NKLG	7.6
OHI3	6.9
RGDG	2.1
STFU	5.1
SUTM	6.2
TOW2	10.5
WARK	5.5
XMIS	7.6
YEL2	1.1

6.2.4. Overall Station Quality

The results of the Daily Station Availability, Daily Station Total Availability and the Effective mean elevation for 100 days are taken together to see how the stations perform. As already explained in Section 4.4, the Overall Station Quality can also be computed over the past 10 days, but since this is a specific investigation and it's



(a) Effective Mean Elevation of station AREG



(b) Effective Mean Elevation for station DLF1

Figure 6.15: Two examples of the Effective Mean Elevation

an easier to understand example, it's computed for the full time period of 100 days. Although a new elevation mask and elevation mask parameter is created every 50 days, for simplicity it's chosen to use the Effective Mean Elevation of the first period.

The criteria for the classes are shown on the left of Figure 6.16. Using these ranges and the representative results of the test period each parameter is assigned to a class. No station has the Overall Station Quality class of excellent, since each station has atleast one class lower than excellent. Four stations are considered good, while also four stations are considered bad. These bad stations are not suitable to be used for a monitoring network. The class OK is assigned to 12 out of 20 stations. These stations are not recommend to part of the monitoring network and need improvement, but in case of limited options their use is still acceptable. The DSA shows that the stations KRGG, RGDG and WARK are bad. These stations are covered by other stations within the same area. Station TOW2 has a bad DSTA, but this is covered by the stations in New Zealand and XMIS, which is east of Australia. The bad performance of TOW2 is due to the fact that it has problems receiving Galileo signals, as shown in Section 6.2.2.

DSA	DSTA	EME	OSQ
≥99.9	>=99	1	**Excellent**
≥95	>=95	<=5	**Good**
≥80	>=80	<=15	**OK**
>0	>=0	>15	**Bad**
0	NaN	NaN	**Out of use**

Station	DSA	DSTA	EME	Min
AREG	OK	Good	Good	OK
CAS1	Good	Good	Good	Good
DLF1	Good	Excellent	Excellent	Good
DUND	OK	Good	Good	OK
FAA1	Good	Good	Good	Good
JFNG	OK	Good	OK	OK
KOUR	Good	Good	OK	OK
KRGG	Bad	OK	Good	Bad
KZN2	Good	Good	OK	OK
MAJU	OK	Good	OK	OK
MAL2	OK	Good	OK	OK
NKLG	OK	OK	OK	OK
OHI3	Excellent	OK	OK	OK
RGDG	Bad	Good	Good	Bad
STFU	OK	OK	OK	OK
SUTM	Excellent	Good	OK	OK
TOW2	Good	Bad	OK	Bad
WARK	Bad	Good	OK	Bad
XMIS	Good	Good	OK	OK
YEL2	Good	Good	Good	Good

OSQ
OK
Good
Good
OK
Good
OK
OK
Bad
OK
OK
OK
OK
OK
Bad
OK
OK
Bad
Bad
OK
Good

Figure 6.16: On the left the ranges of the classes are given. In the middle each of the key performance parameters is given a class based on the ranges. The minimum is used to give the station an overall quality class for the investigated period

6.3. System results

Just as the sensor station performance, the performance of Galileo and GPS is evaluated for a period of 100 days. First GPS is presented and then Galileo. Logically first the availability of all satellites is computed, but the Daily Available # of Satellites is presented first. This way first an overview is shown and more detailed information is given in the next steps.

6.3.1. GPS

The Daily Available # of Satellites is shown in Figure 6.17. In general 31 satellites were available during this period and only one event took place in which a satellite was unavailable the full day. Other events were all shorter than a full day.

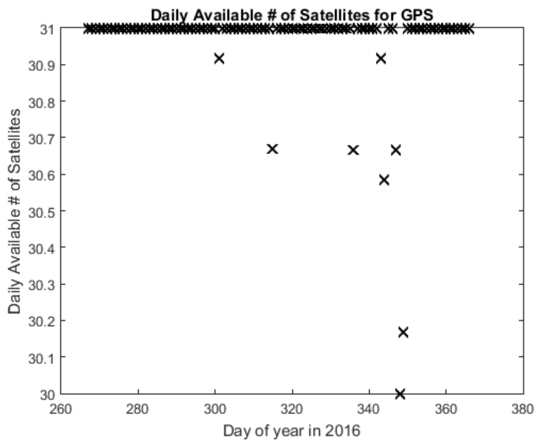


Figure 6.17: Daily Available # of Satellites for GPS

The corresponding Daily GNSS Availability of the GPS satellites are shown in Figures 6.18a and 6.18b. Each row corresponds with a satellite, while each column corresponds with a day. If a box is green it means that the Daily GNSS Availability was 100 %. Yellow means that the daily result is between 90 and 100 %, orange is between 50 and 90 %, red between 0 and 50 % and gray means that the result was 0 %. Every result other than 100 % is an event that needs explanation.

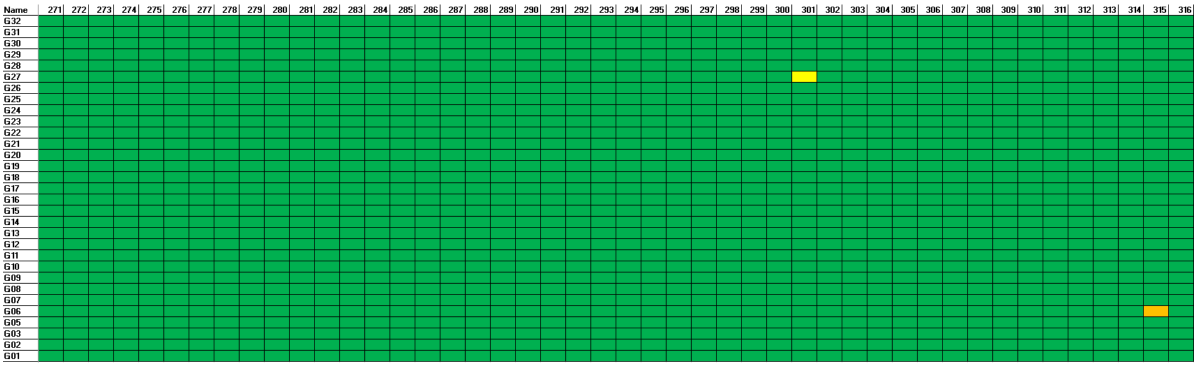
No satellites have significant more events than others. The event in which a satellite was unavailable during a full day took place on doy 348. Doy 347, 348 and 349 are shown in Figures 6.19, 6.20 and 6.21. It can be noticed that satellite G04 is not shown in the results. The satellite is decommissioned and therefore not expected to be available.

The event of satellite G11 on doy 347, 348 and 349 was forecasted in the NANU. Figure 6.22 shows part of the NANU that was created before the event and part of the NANU that was created afterwards, which corresponds fairly similar to the obtained results. An useful addition would be to create two sub parameters that give the part of the day that the satellite is unavailable due to the satellite health status being unhealthy and the part of the day that the satellite is unavailable due to the fact that the satellite is not transmitting signals. This would give extra insight in the performance of the satellites.

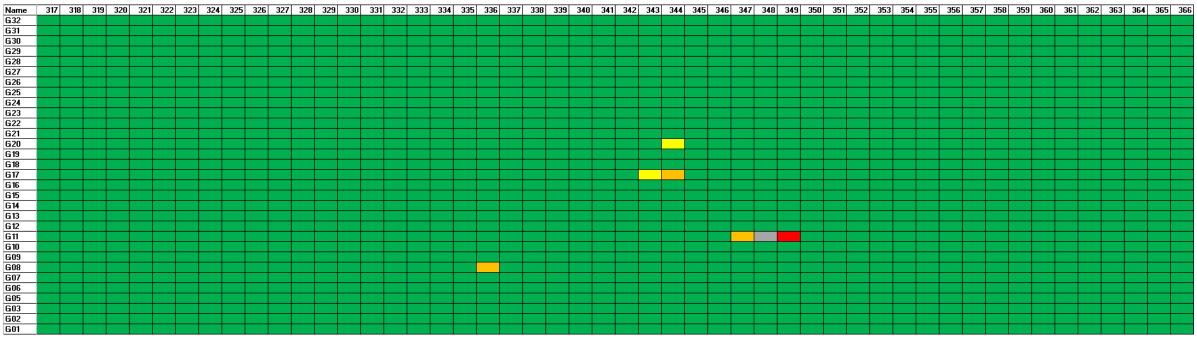
The behaviour of GPS is as expected. In general are all the 31 operational satellites available. Only occasionally is a satellite unavailable for a short period due to updates or small issues. No satellite has more than one separate events. The events are summarized in Table 6.5.

Table 6.5: Summary of all GPS events during the test period

Satellite	**Doy start**	**Time start**	**Doy end**	**Time end**	**Daily Satellite Availability** [%]
G27	301	14:00:00	301	16:00:00	91.6
G06	316	02:00:00	316	09:58:00	66.8
G08	336	16:00:00	336	23:59:30	66.7
G17	343	22:00:00	344	07:58:30	91.7 & 66.8
G20	344	10:00:00	344	12:00:00	91.6
G11	347	16:00:00	349	19:59:30	66.7 & 0 & 16.7



(a) Daily GNSS Availability of GPS part one



(b) Daily GNSS Availability of GPS part two

Figure 6.18: Daily GNSS Availability of GPS

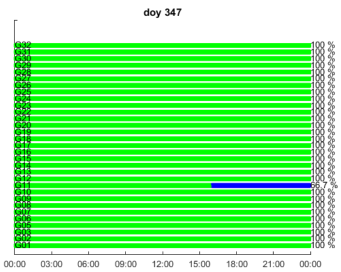


Figure 6.19: Doy 347

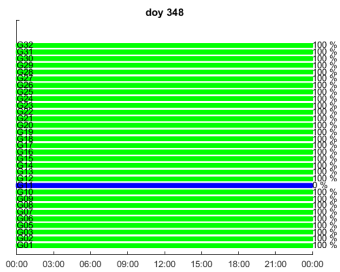


Figure 6.20: Doy 348

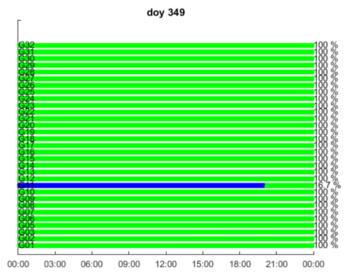


Figure 6.21: Doy 349

CONDITION: GPS SATELLITE SVN46 (PRN11) WILL BE UNUSABLE ON JDAY 347 (12 DEC 2016) BEGINNING 1600 ZULU UNTIL JDAY 351 (16 DEC 2016) ENDING 1600 ZULU.

CONDITION: GPS SATELLITE SVN46 (PRN11) WAS UNUSABLE ON JDAY 347 (12 DEC 2016) BEGINNING 1619 ZULU UNTIL JDAY 349 (14 DEC 2016) ENDING 1615 ZULU.

Figure 6.22: Two NANU messages created before (top) and after (bottom) the event

6.3.2. Galileo

Results of the Daily Available # of Satellites for Galileo are shown in Figure 6.23. Important is that from doy 350 the testing phase was over and initial operational phase started. The initial operational phase is shown in green in Figure 6.23. Galileo has both more smaller and more larger events during the testing phase. Extra satellites became operational making it a constellation of 11 satellites at the end of 2016. Again the Daily GNSS Availabilities are shown in overview tables in Figure 6.24. Some satellites weren't available at all during the test period. Also some satellites weren't launched yet, so they are neglected within the list of Figure 6.24. Satellites E03, E04, E05, and E07 were launched at the end of 2016, but are still in commissioning. The satellites E14 and E18 were launched into an incorrect orbit and therefore only used for testing purposes. This means that their health status was unhealthy the full period and therefore they were also unavailable during the full period. Satellite E20 also faces problems, which results in the satellite being permanently unavailable.

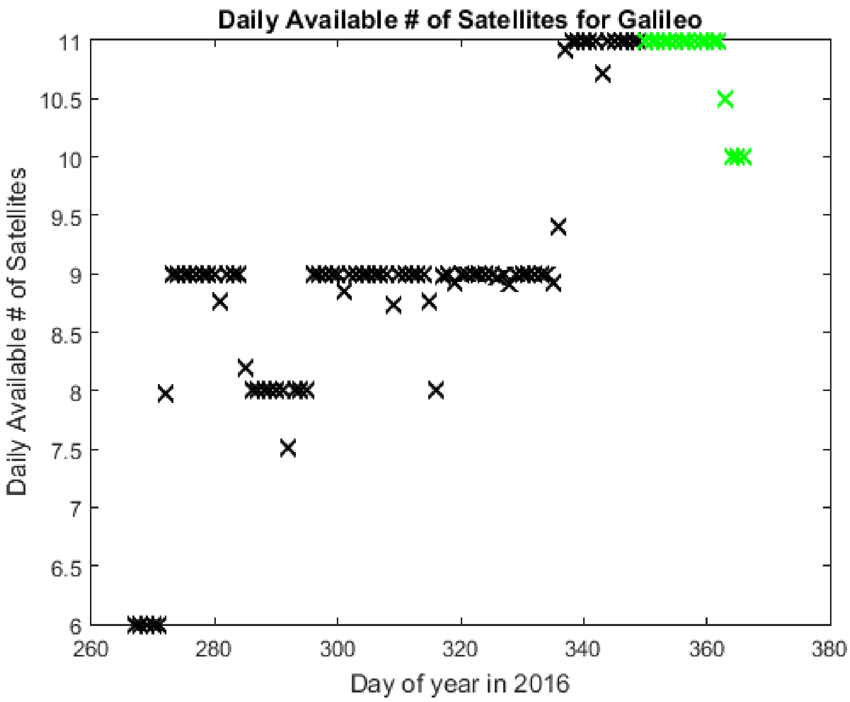
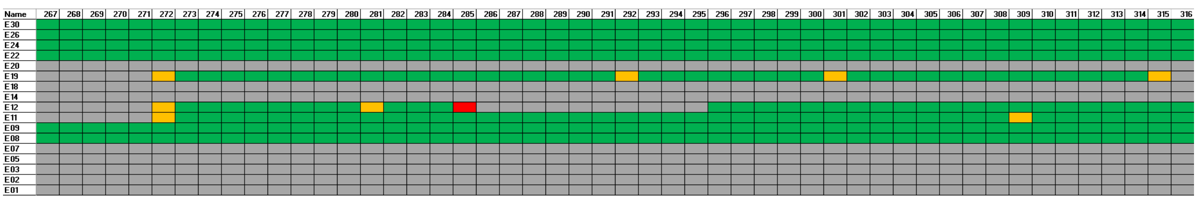
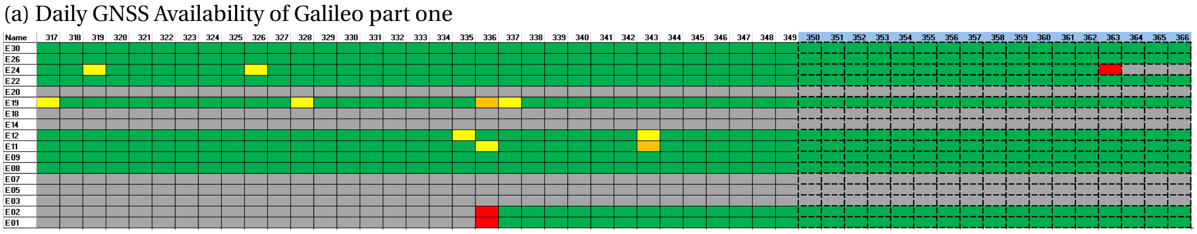


Figure 6.23: Daily Available # of Satellites for Galileo



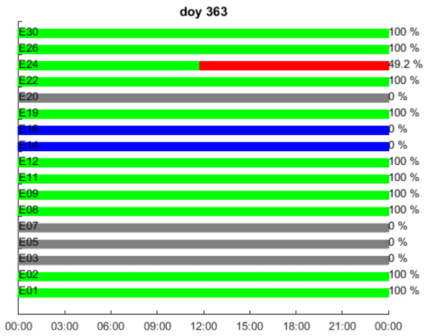
(a) Daily GNSS Availability of Galileo part one



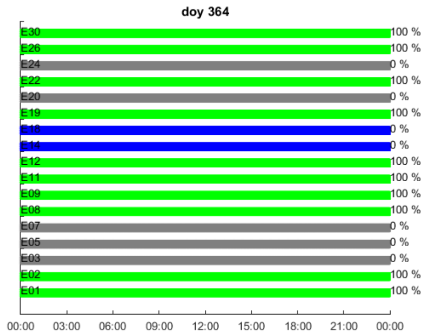
(b) Daily GNSS Availability of Galileo part two. Initial operational phase started at doy 350. These days are shown in blue

Figure 6.24: Daily GNSS Availability of Galileo.

The most interesting part is the period when Galileo became in initial operational phase from doy 350 onwards. During this period one satellite had an event: satellite E24 from doy 363, which is still unavailable at the end of the test period. Figures 6.25a and 6.25b show the first 2 days of the event.



(a) Galileo satellites on doy 363



(b) Galileo satellites on doy 364

Figure 6.25: Two days of the Daily GNSS Availability of the Galileo satellites

The data shows that the last navigation message entry was at 11:30:00. According to this message the satellite was still healthy. The rest of the period no navigation messages were present for satellite E20. The last observation was received at 11:47:30. This coincides closely with the information from the NAGU (GSA, 2016), which tells that the event started at 11:47. This NAGU message was created after the event as it was unscheduled. Even in case for scheduled outages the summary message that's created after the event is more accurate as the exact outage time is hard to predict beforehand and is usually exaggerated.

6.4. Discussion

6.4.1. Connection between sensor station and system performance

There's a clear connection between the sensor station performance and the system performance. Knowing the system performance and therefore the influence of the satellites on the sensor station is not strictly necessary but improves the correctness of the results. Next to that, the information is not used for every performance parameter. For example when you are only interested in the period that the station was operational, it's not needed. When you're only interested in a rough estimate of the parameter that describes how well the sensor station receives (Daily Station Total Availability) it's also not strictly necessary. Nominal condition is that all satellites are available. During the period of research the GPS satellites were over 99.9 % of the time available. So when not correcting the expected period of the Daily Station Total Availability, the effect is small when not taking into account the satellite availability. However, when you want to know the performance of a sensor station into more depth and want to do it right, the system performance, or satellite availability is needed. For knowing when a signal of a satellite is expected at a sensor station the satellite availability is therefore necessary for this purpose.

On the other hand, knowing the sensor station performance is necessary to determine the system performance as a DoC of two need to be assured. The system performance (satellite availability) is determined partly based on the fact whether signals are present in the RINEX observation files. Within the described algorithms it's chosen to use a DoC of atleast two in order to be able to define the satellite as unavailable. This is needed to separate the sensor station performance and local effects of the system performance. Results showed that stations regularly don't receive anything. So without correcting for the periods when the station is not operational, while using a DoC of two, there's a high change satellites are assigned wrongly unavailable. So when using a limited amount of sensor stations to determine the system performance it's necessary to know (part of) the station performance. The elevation mask is needed for the same reason as the time that the station is operational: to correct the period that signals are expected.

So sensor station and system performance are very much connected. Depending on the goal of performance monitoring and the amount of used sensor stations, knowing both within the same tool is necessary. Since this research is about determining the performance into depth and the amount of sensor stations used is limited, it's recommended to compute both performances within the same tool and use them to correct each other.

6.4.2. Interval of input data

The interval rate of all the input data was 30 seconds. Mean reason was that the created software tool is a prototype and therefore changes in code and algorithms had to be made regularly. By using 30 second interval data over a 1 second interval, processes could be executed faster and less storage space was needed. However, the software is made in such a way that 1 Hz data can be used immediately or after only small adjustments.

Processing speed and storage space are the main benefits of using 30 second interval over 1 second interval data. The big disadvantage is that much information is neglected. The 30 second interval data means that the 29 seconds in between measurements are completely ignored. This is however also the case at 1 Hz data. Signals are continuous, so generally are measurements always sampled. The question that rises is: is this a problem?

When using 30 second interval data, for sure short periods that the station is not receiving anything will be missed. Examples of Section 6.2.1 showed that this happens regularly at some stations. However, if it occurs very often it's very likely that some occasions will be noticed. Although not all short events will be noticed, but it can still be determined that the station has issues. This is for example the case for stations MAL2, FAA1, STFU and KZN2. More important is it to determine longer periods that the station is not receiving. For periods longer than 29 seconds it's less important to use 1 Hz data as these periods will be noticed anyway. If it's important for the user to know more accurately the time of events, but still has limited storage space and processing time, there's a solution: 30 second interval data can be used as a basis and in addition 1 Hz data can be used at the beginning and end of the event. In that case only the 15 minute files of 1 HZ data has to be downloaded and processed in which the station outage starts and ends. This is only practical for the Daily Station Availability, as it involves only information from that particular station.

Matlab functions are created in such a way that RINEX observation files can be used of varying lengths. However, the maximum length is set to a full day. When using merged RINEX observation files longer than a day things become more complicated. For example the time in seconds of week have to deal with week rollovers within the same file. Using files shorter than a day is no problem. It's still recommend to use files of a full day. Maintaining a standard in the length of the files enables the possibility to compare easily between different days or sensor stations. Therefore, all parameters are computed on a daily basis.

6.4.3. Parameters

All created parameters give unique and useful information, but the list is not complete. Extra parameters can give a better understanding of performances. However, the created parameters are considered the most useful. Results showed that sensor stations sometimes receive some signals better than other signals. Therefore, an useful addition would be a sensor station parameter that represent the availability per signal, combined over all satellites of a GNSS.

The Daily GNSS Availability uses both the satellite health status and SiS availability. By adding two sub parameters for each aspect, it can quickly be seen why the satellite was unavailable.

The system performance parameters are a good indication on the performance of the GNSS and the satellites. Events can quickly be noticed and it can be seen that more Galileo satellites became operational over time. The disadvantage of the proposed parameters is that it's hard to compare the performances between the GNSS. The Daily Available # of Satellites can be used for this purpose, but atleast for now it's unfair to use it as a comparison since Galileo is not yet fully operational. It would therefore be useful to define an extra parameter which is better suitable for benchmarking between the systems. This could be a variation of the Daily Available # of satellites, in which it's related to the amount of operational satellites.

The research and performance parameters are focussed on SiS availability. By combining this information with other performance aspects, a better picture of the performance can be gained.

6.4.4. Advanced monitoring

The research of this report aims at defining performance parameters the right way. This means that every decision is thoroughly thought about in order to create parameters that are unambiguous and represent only the information that's needed. The cost of doing this is that algorithms become more complicated and processing takes longer. An question that arises is: does the more advanced and more complicated performance monitoring outweigh more simple algorithms?

Let's take the Daily Station Total Availability as an example. It's expressed as the available over expected observations. By expressing it solely as the amount of observations, the process becomes less complicated. If the amount of observations during a day is much smaller than previous days, it implies that something is going on. The problem of doing it the simplified way is that low results can be due to many causes like satellites having issues or the station being partly not operational. Therefore it's hard to interpret the results and understand what's going on. Surely it gives an indication of the performance, especially when compared with previous days, but it's hard to compare between other stations or to find out why the performance is low. So using more advanced monitoring algorithms and software has large benefits compared to simpler monitoring. The main benefits are:

- Day to day results are better comparable
- Results of different stations are better comparable
- Issues are detected easier
- Cause of bad performance can be detected

6.5. Summary

The proposed parameters of Chapter 4 and 5 are computed over a period of 100 days. Main way of presenting the results is by showing a table using color codes. This way anomalies are clearly highlighted. If anomalies occur we can zoom in to see what's going on. Several of those events have been highlighted by a separate plot. Since the software is a prototype this is considered enough, but a fully functioning software tool must be more user friendly. This can be achieved by for example creating pop-up plots when clicked on a box of the table.

Using the performance parameters much insight is gained on the sensor stations and the systems. The results showed that none of the stations perform perfectly. Every station was not operational sometime during the 100 days and only a small selection of the stations have an (near) optimal visibility. The amount of sensor stations used for the monitoring network is therefore extended to 20 sensor stations. For GPS only six events of different satellites were detected. These had a duration of about a day. This is as expected, since maintenance or other adjustments have to be made from time to time. During the testing phase of Galileo many events were detected. Also this is as expected, since the testing phase is there to make adjustments and perform tests on the satellites. During the last 16 days, when Galileo's initial operational phase started, only one event was detected.

The sensor station performance is considered necessary for the system performance in order to separate from the sensor station performance. It's recommend to use the system performance for the sensor station performance to obtain more correct results of the Daily Station Total Availability. Therefore, it's recommend to compute both the sensor station performance and the system performance parameters within the same tool.

7
Conclusions

7.1. Conclusions

Signal availability is in the basis a binary operation: a signal is **available** or **unavailable**, 1 or 0, but it remains to be defined what we understand by available or unavailable.

One of the early conclusions of this thesis was that it's not sufficient to look if data is just present in a data file, but that this data must also be realistic. Therefore, in this thesis the following definition for availability of signals at a **sensor station** is proposed:

> A GNSS signal is said to be **available** at a sensor station if the code, carrier phase and C/N0 measurements are all three present and meet certain requirements. The requirement for the C/N0 measurements is that these should be within an elevation, signal and station dependent upper and lower bounds. The requirement for the code measurements is that these should be within upper and lower bounds which depends on the true-range and expected maximum clock errors. For the carrier phase measurements no threshold has been defined because the carrier phase measurements have phase ambiguities that are not yet resolved.
>
> A GNSS signal is said to be unavailable at a sensor station if the above conditions are not met.

In this thesis a method for the computation of the C/N0 bounds is proposed. This method uses ten days of data to compute a third order polynomial fit of C/N0 with elevation as independent parameter. The allowable C/N0 must be (i) within a fixed and user defined bandwidth of this regression line (e.g. 10 dB-Hz), and (ii) larger than a signal dependent threshold. For each station, satellite type and signal a separate set of bounds is computed. This method was tested on ten days of three stations of the IGS MGEX network. Using a 10 db-Hz bandwidth on the E1 signal of the FOC satellites, it resulted in a rejection of 0 %, 0.025 % and 0.025 % for stations DLF1, KOUR and AREG respectively of approximately 91000 measurements. Without the C/N0 bounds these rejected measurements would be stated as available.

The second conclusion is that it's necessary to investigate the sensor station performance and compute part of the key performance parameters for the sensor station before anything can be said about GNSS availability. We also came to the conclusion that simply counting the observations does not produce the desired result. In order to be able to say anything about the station performance, one should know when signals are expected at a sensor station and use this together with availability to produce statistics.

GNSS signals can be unavailable at sensor stations for two reasons: the signal realistically cannot be tracked by the sensor station, e.g. because the satellite is at the other side of the Earth, or the signal should be available, but is for some reason not tracked. In order to be able to make this distinction, we should know when signals are expected at the sensor station. In this thesis the following definition is proposed:

> A GNSS signal is said to be **expected** at a sensor station if (i) the receiver is configured to receive the signal, (ii) the satellite is able to transmit it, (iii) the satellite is above the horizon and the signal is not blocked by objects in the path between satellite and sensor station, (iv) the sensor station is operational and (v) the satellite is operational.

In order to determine whether a signal will be blocked, an elevation mask need to be computed for each sensor station. In this thesis the elevation mask is computed using 50 days of 30 second interval data from a station of all GNSS combined. The method that is proposed in this thesis uses a binning in one degree elevation intervals. A conservative boundary of 1 degree is added to correct for daily variations and other uncertainties, and make sure that the satellites near the elevation mask are really expected to be tracked. The elevation mask is, and thus the qualification expected, is therefore more conservative than might be necessary. However, considering that this qualifier is only necessary for the computation of sensor station statistics, this slightly conservative approach is preferred.

If these binary availability and expectancy operations are applied on daily files, daily availability statistics can be computed. This is defined as the amount of available observations over the amount of expected observations and expressed as a percentage.

From the work in this thesis we concluded that the **sensor station performance** is 'best' described by using four key performance indicators. Each giving distinctive information. Table 7.1 gives an overview of the described performance parameters. The **Daily Station Availability** tells what part of the day the sensor station is operational. This is obtained by dividing the amount of unique epochs in the RINEX observation file by the maximum possible amount of epochs. The **Daily Station Total Availability** tells how well the sensor station is actually receiving during the period that the station was operational, by dividing the amount of available observations by the amount of expected observations. It's determined per system as each station performs differently for each GNSS. The **Effective Mean Elevation** parameter tells how well the location of the sensor station is chosen in relation to the surroundings. Possible observations and the computed elevation mask are used to determine a weighted elevation mask. These three key performance indicators are summarized in the **Overall Station Quality** in order to determine which stations function best or worst. The station is given a class based on the worst performing Daily Station Availability, Daily Station Total Availability and Effective Mean Elevation. We believe this forms the best, most compact, and yet complete description of the sensor station performance. Other parameters can be defined, and have in this thesis, but these do not add much to the four parameters that have been proposed. However, these may be useful in case there is a station anomaly.

Sensor station performance and system performance are computed from the same RINEX observation and navigation files. If an observation is expected at a sensor station, but not available, this can be due to two reasons: (i) there's a local problem with the receiver not tracking that signal, or (ii) the signal is not available from space due to an system issue. Note that in the definition of expected observations, nominal system outages have already bean included (see definition of expected GNSS observations: (v) satellite is operational). This has implications for monitoring GNSS signal in space availability. Two different scenarios are distinguished:

1. If a GNSS signal is received by atleast one sensor station, the GNSS signal can be said to be available in space. If the same signal is expected at other sensor stations, but not received, this could be due to local problems at these stations. In other words: signal availability at a single sensor station is a sufficient condition for signal availability in space.

2. If a GNSS signal is expected at one or more sensor stations but not received, this can be due to signal unavailability in space or local problems at all sensor stations that expect the signal. In other words: signal unavailability at all sensor stations that expect the signal, is a necessary, but not sufficient condition for GNSS signal unavailability in space. However, the larger the number of expected stations, the larger the probability of GNSS signal unavailability in space.

For this thesis we used as requirement for declaring a GNSS signal unavailable that the signal should be unavailable at two or more sensor stations that expect the signal. This now means that there's also a third state, unknown, which happens when a signal is expected by only one sensor station and is unavailable at that station. Knowing the sensor station performance is essential for understanding the system performance in order to correct for local problems. The other way round, when the proposed sensor station performance parameters are used, the system performance is one of the inputs. If the system performance is not used for the sensor station parameters, the results will be biased and not representative for the sensor station performance.

The definition for **system availability** that is proposed in this thesis is:

- A GNSS satellite is said to be **available** in space at any given moment if all of its signals are received at any sensor station which pass the quality check for sensor station signal availability, and the satellite health status is healthy. This ensures that available defined satellites really are available for all users.
- A GNSS satellite is defined **unavailable** in space if the satellite is expected to be tracked by at least two sensor stations, but no signals are received that pass the check for sensor station signal availability, or the satellite health status is unhealthy.
- A GNSS satellite is in an **undetermined** state if none of the above conditions are met. In this case the satellite is expected by only one (or none) sensor station, but is not available at that station, and the satellite health status is healthy.

From the work in this thesis we propose to use two system key performance indicators based on the satellite availability. The **Daily GNSS Availability** tells what part of the day the satellite was available. This is summarized in a single value per GNSS in the **Daily Availabile # of Satellites**. These can be found in Table 7.2.

To be able to determine the satellite availability during the full day, the satellite must be tracked by sensor stations the full day. If storage space is limited, a monitoring network must be selected. A satellite must be expected to be tracked by at least two sensor stations to be able to define the satellite as unhealthy. However, for a more robust network, a depth of coverage of three is desired. Based on the position of the sensor stations and 13 days of Daily Station Availability results, a network of 20 stations is selected. These stations are: AREG (Peru), DLF1 (The Netherlands), FAA1 (French Polynesia), JFNG (China), KOUR (French Guyana), KRGG (French Southern Territories), KZN2 (Russia), MAJU (Marshall Islands), MAL2 (Kenia), NKLG (Gabon), RGDG (Argentina), STFU (USA), TOW2 (Australia), WARK (New Zealand), XMIS (Australia), YEL2 (Canada), Dund (New Zealand), OHI3 (Antarctica), CAS1 (Antarctica) and SUTM (South Africa). These stations are tested to be sufficient, but are selected based on limited information. Several more options are possible.

A software tool is developed during the thesis to do automatic processing and executing algorithms. First step is downloading and reading the RINEX observation and RINEX navigation files into Matlab. Consecutively is for every station the Daily Station Availability computed, just as the epochs that signals are expected to be received and which of them er not received. To finalize computation for the Daily Station Total Availability, the satellite availability is needed. When this is computed, the sensor station parameters can be computed completely.

Detailed information is needed to make statements about the sensor station or system. So is for the Daily Station Total Availability first computed how well each signal of every satellite is received. This information is aggregated to obtain a single value per GNSS (per station). In turn is the Daily Station Total Availability used for the Overall Station Quality, which gives the sensor station a performance class. While detailed information is necessary for bigger statements like the performance class, it's presented the other way around. First thing someone wants to know is if there's any problem, or all is fine. Only in case of anomalies or specific investigations is the detailed information desired and therefore needed to be presented. Using color codes is a practical way to make results better interpretable. It makes anomalies or good performance stand out more.

A small selection of performance parameters are created and their considerations, goals and algorithms are described in this thesis. These are all based on the availability of signals-in-space. The results showed that by only considering SiS availability a lot of insight in both the sensor station as well as the system performance can be gained. It's therefore a good choice to use SiS availability as the basis of a monitoring tool.

With this, the research question is answered the the fullest extend. Most aspects have been worked out in detail, however, there's still room for improvement. Because of the focus on SiS availability and due to time constraints, some aspects need more elaboration or additional functionalities. These are described in Section 7.2. Altogether, the research question is answered and the objectives as stated in Section 1.3 are met.

Table 7.1: Key performance indicators for the sensor station performance

Name	**Objective**
Daily Station Availability:	Tell what part of the day the station is operational
Daily Station Total Availability:	Tell what part of the expected observations are received
Effective Mean Elevation:	Tell how well the location of the sensor station is
Overall Station Quality:	Indication of the overall performance of the station

Table 7.2: Key performance indicators for the system performance

Name	Objective
Daily GNSS Availability	Tell what part of the day the satellite is available
Daily Available # of Satellites:	Give the average amount of available satellites over the day

7.2. Recommendations

The work of this thesis aims at answering the research question in the best way possible. Considerations and priorities have been made to reach this goal. As always, parts can be investigated in even more detail or related topics can be investigated. This final section gives recommendations for future research related to work already done.

It's important that the station performance parameters and the system performance parameters are computed within the same tool. Both sets of parameters need the other to be meaningful and unambiguous. So is the system performance corrected for sensor station problems. This showed that it's recommend to compute both performances within the same tool and even necessary if the proposed performance parameters are used.

This thesis focuses only on the availability of signals-in-space. While the SiS availability is a great way to gain insight in the performance, it's only one of many groups of performance parameters. To be able to find the cause of performance issues, addition of other performance parameters are desired. So is the threshold of a quality observation now partly based on the C/N0. This can be extended by taking for example the noise level of multipath error into account. The same holds for the performance of the system. This can be extended by looking also at the accuracy of the clock and orbits.

Within this thesis the health status is obtained via the RINEX navigation files. The disadvantage of using RINEX navigation files for the health status is the rate at which satellite info is stored. For GPS this is in general every 2 hours and for Galileo in general every 10 minutes. Next to that, the time of the navigation message entry is not directly the same time as the satellite status change. Now the tool deals with this issue in a conservative way. To be able to determine the unhealthy and therefore unavailable periods more exact, the direct binary data source of the navigation message can be used, but this needs more research. Another way is to set the receiver settings in a way that unhealthy satellites are not tracked.

Initially the network of sensor stations was chosen so that that all satellites were constantly tracked by at least three sensor stations during an optimal day. Unfortunately on a regular basis sensor stations don't receive anything for part of the day or have problems receiving all signals. Also did some stations stop receiving at all during the 100 test days. This showed that it's necessary to have a redundant number of stations in the network. For some parts of the world closeby stations are present, but in parts of the world like Africa this is not. Strategically positioned sensor stations would make the monitoring more robust and by choosing optimal locations, the network can use less stations.

The key performance indicators proposed in this report are worked out extensively. All choices are described and captured, so that it's clear how and why it's computed. As there are so many decisions to make, we recommend that this approach is also used by others: this is essential to better understand the results and for users to be able to use the same definitions. This will in the end result to everybody using similar and optimized performance parameters that are easy to interpret and shareable.

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Nomenclature

$C/N0$ Carrier-to-noise ratio

$CORS$ Continuously Operating Reference Station

DAS Daily Available number of Satellites

DGA Daily GNSS Availability

DoD Department of Defence

DSA Daily Station Availability

$DSSA$ Daily Station Satellite Availability

$DSSSA$ Daily Station Satellite Signal Availability

$DSTA$ Daily Station Total Availability

EC European Commission

$EGNOS$ European Geostationary Navigation Overlay Service

EME Effective Mean Elevation

EPN European Permanent Network

ESA European Space Agency

$ESTEC$ European Space Research and Technology Center

EU European Union

FOC Full Operational Capability

FOM Figures of Merit

$GNSS$ Global Navigation Satellite System

GPS Global Positioning System

GRC Galileo Reference Center

$GSOp$ Galileo Service Operator

IGS International GNSS Service

$IRNSS$ Indian Regional Navigation Satellite System

KPI Key Performance Indicator

MEO Medium Earth Orbit

$MGEX$ Multi-GNSS Experiment

$NAGU$ Notice Advisory to Galileo Users

NaN Not a Number

$NANU$ Notice Advisory to Navstar Users

$NAVSTAR$ NAVigation Satellite Timing And Ranging

OSQ Overall Station Quality

PPP Precise Point Positioning

PRN Pseudo Random Number

PVT Position Velocity Timing

$RINEX$ Receiver Independent Exchange Format

rms Root mean square

SA Selective Availability

$SBAS$ Satellite Based Augmentation System

SIS Signals In Space

SLA Service Level Agreement

STK Systems Tool Kit

$SVID$ Space Vehicle ID

$TTFF$ Time To First Fix

A

The software tool

Analysing GNSS data and retrieving results for a longer period of time for several stations leads to a large set of data. Many computations require complex algorithms for which Matlab functions must be written. Since it's too much to trigger every function manually, a software tool must be created to automate the processes as much as possible. Therefore, a prototype software tool is created in Matlab. The research is not focused on software engineering, so functions are likely not optimal. However, the created algorithms and Matlab scripts can be used to do all the necessary processing and can form the basis of a future software tool. This appendix gives information about the functions, process flow and data stored. Some existing functions are used, but many scripts and functions are created for this thesis.

A.1. Decisions made

Just like the fact that many decisions need to be made to define the performance parameters, decisions need to be made for the prototype software tool too. Decisions made in the beginning or in the first steps of processing, like how information is stored, have impact on processing steps later on. Often functionalities are added or improved, so it's important that the basis of a tool is solid. Experience showed that it costs a lot of effort to change things done at the start of creating the tool. So it's recommended to review functions before going to the next step. However, incorrect designs often stand out in a later stadium. This means that creating a software tool needs several iterations in which each new iteration is an improvement over older versions.

A.1.1. Real-time or post-processing

There are two ways the tool can function: in real-time or by post-processing. When processing in real-time the big advantage is that failures can be detected at the start. The data can be downloaded via a Networked Transport of RTCM via Internet Protocol (Ntrip) client (Heo et al., 2009). Problem is that the infrastructure needs to be more advanced and is more prone to failures. Data in RINEX format can be used during post-processing. This contains also the raw pseudo-ranges and carrier phase measurements in contrast to the NMEA format where only the estimated position is showed. With this raw data more advanced processing and monitoring can be done. The RINEX files can be downloaded from ftp servers that are affiliated with the IGS MGEX network. Post-processing is used as all processes are more transparent and advanced, time consuming, algorithms can be used. Next to that, it has the preference to analyse time series and compute statistics over a certain time period such as a day, over being able to warn in (semi) real-time.

A.1.2. Storing time

Time and clocks are an important aspect for GNSS activities. First of all are the observations strongly dependent on the accuracy of the receiver clock and satellite clock. Furthermore, it's needed to deal with different time zones and leap seconds. A solution for this problem is using UTC, also known as coordinated universal time. UTC originated from the International Atomic time, but also uses leap seconds to deal with the effect of the rotation of the Earth. Since the world is divided into time zones, time is usually expressed in UTC plus the amount of time zones relative to UTC +0, which is the central time zone in which Greenwich (UK) is located. The time in RINEX files are normally stated as UTC +0. This means that the time often differs from the local time. UTC is written as: YYYY-MM-DD, which means year, month and day, and hh:mm:ss, which means hours, minutes and seconds (Kuhn, 1995). For storing time in the software tool the following three options are considered the most convenient in using:

- UTC
- GPS time
- Internal Matlab date numbering

When using UTC the drawback is that there are several variables that need to be stored. For the full time these variables are: year, month, day, hour, minutes and seconds. Advantage is that it's directly interpretable what time it is. GPS time is different from UTC in the fact that it doesn't use leap seconds. This is because introducing leap seconds is more prone to system errors than continuous timing. In 1980 GPS time was similar to UTC, but it's 15 seconds ahead of UTC in 2011 (Lewandowski and Arias, 2011). An approximation of UTC plus the GPS time is broadcasted by the GPS satellites. The Galileo system time is approximately similar to GPS time. An advantage of using GPS time over UTC is that GPS time can be stored as week number and seconds of week into the current week. This saves storage space, since only two variables are needed. It's also less error-sensitive as during the week the time is continuous instead of dealing with the end of day, hour, etcetera. The last option is the use of the internal date numbering of Matlab. This principle uses decimal dates, making it possible to store a date including the time in just one variable. This decreases storage space and increases processing time, but using decimal days introduces some problems. Because all times are stored as decimal numbers, time differences and other processing steps may introduce small errors due to rounding issues. For above reasons, the time used for processing and storing is GPS time in week number and seconds of week. Before plotting the GPS time is converted in Matlab's decimal date numbering. Reason is that by applying the command *datetick* after plotting, the time in UTC is showed. This makes the figures better understandable for users. Table A.1 shows the three different options for representing time.

Table A.1: GPS time will be used as it has only two variables while using only integers

	UTC	GPS	Decimal date
Epoch 1	2016-05-29 00:00:00	1899 0	736479
Epoch 2	2016-05-29 00:00:30	1899 30	7.364790003472222e+05

A.1.3. Variables stored

Information and variables can be stored in many ways. It can be stored in a database like sql, or in ASCII format. Another option, which is the one used during this research, is by storing Matlab variables. These Matlab variables are usually matrices, arrays, or structures containing several matrices. This is convenient as the variables can directly be used for further processing. Disadvantage is that it cannot be read by other software than Matlab without converting or assisting tools. When extending the prototype software tool to fully functioning software, it should be reconsidered what the best way of storing variables and results is. As an example it's possible to store satellite positions as a Matlab variable, but the daily parameters in a database. That way they can be used easily with other software like a website. When extending the current tool to a fully functioning tool it should anyway be reconsidered if Matlab is the right programming language for the job. Matlab is user-friendly and especially optimized for matrix computations, but the processing is slow compared to other languages.

Station files are stored in a folder based on the day of the year. Using the day number is unambiguous and easy to find. The test period only took place during 2016, but when extending it, it's recommended to create a main folder per year. The day numbering is a common used foldername for GNSS applications. This daily folder contains al the already read RINEX observation files for all the selected sensor stations. The .rnx files of the RINEX observation files are deleted, as the Matlab files contain the same information, but are much faster to use. The folder also contains the computed satellite positions per GNSS. The raw RINEX navigation file is kept as it's used for several purposes like the health flags and satellite clock corrections. For each station is per GNSS the elevation and azimuth of the satellites stored in a matrix. Also per sensor station and per GNSS are matrices stored containing the times of rise and set of the satellites including when expected signals are not received. There are two files for this, one before correcting for satellite unavailability and one after all the corrections. The satellite availability is stored separately. This contains the Daily GNSS Availability for the satellites and the time that the satellites are unavailable. Using this information all parameters can be computed. For each performance parameter is a matrix containing a column for each day and a row for each station. The following data is stored:

Update periodically (50 days) :

- Elevation mask (per station, containing azimuth and elevation information)
- C/N0 thresholds (per station, per satellite type)

Updated daily :

- Matrix of Daily Station Availability
- Matrix of Daily Station Total Availability
- Matrix of Daily GNSS Availability

Once a day :

- RINEX navigation file
- Satellite positions (per GNSS)
- Satellite availability (per GNSS)

Once a day per station :

- RINEX observation file (.mat)
- Elevation and azimuth angles (per GNSS)
- Time of rise and set, and not received signals before correcting for satellite unavailability (per GNSS)
- Time of rise and set, and not received signals after correcting for satellite unavailability (per GNSS)

A.2. Process flow

A.2.1. Main processes

The flowdiagram of Figure A.1 shows the main processes of the prototype software tool created in Matlab. In blue are processes and in orange are the key performance parameters. The processes are explained in more detail in the following paragraphs. It can basically be executed in five consecutive steps, each having a specific colored edge in Figure A.1, which are explained in more detail in Section A.2.2 to Section A.2.6.

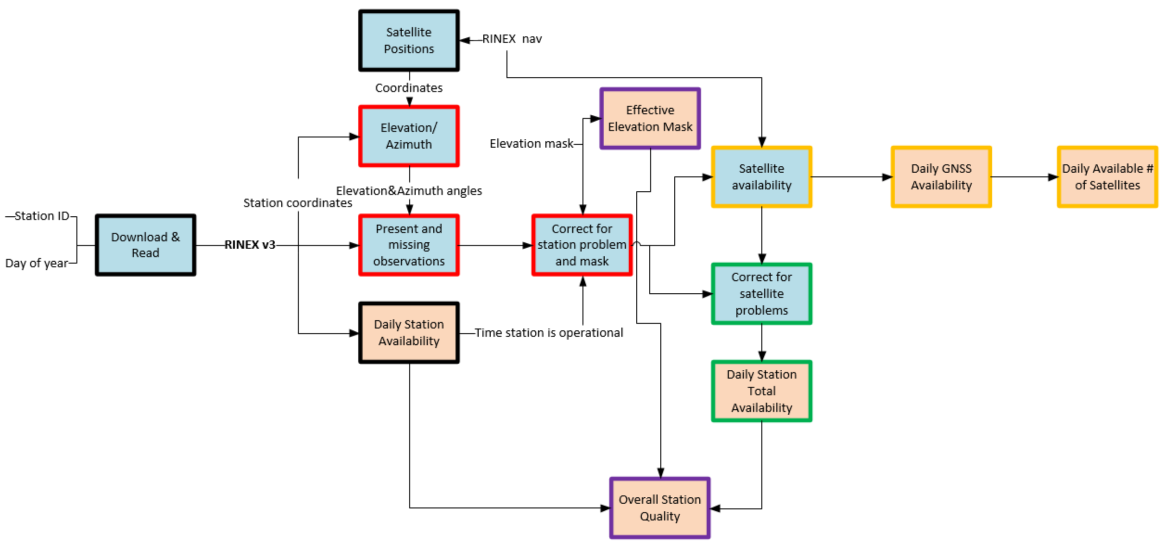


Figure A.1: Overview of the main processes

1. The first step consists of the processes shown in black in Figure A.1. For all sensor stations being part of the monitoring network, the RINEX observations files are downloaded, read into Matlab and the Daily Station Availability is directly computed. The satellite positions are computed during this first step too by using the RINEX navigation file. This is done per GNSS and done only once a day.

2. The second step is to determine which measurements are expected and which of them are present or not present. These processes are shown with a red border in Figure A.1. It's computed per sensor station for both GNSS consecutively.

3. For the Daily Station Total Availability parameter is the satellite availability needed, so that has to be computed now. It's done GNSS by GNSS, and the system performance parameters are immediately computed. The yellow bordered boxes represent the processes done in this step.

4. When the satellite availability is known, the sensor station performance parameters can be finished. It's again done station by station and for every station GNSS by GNSS. These processes are shown by a green border in Figure A.1.

5. Once every 50 days the elevation mask and elevation mask parameter is computed. Also once every 10 days the Overall Station Quality is computed. So the purple bordered boxed are not computed on a daily basis, while the rest is.

A.2.2. Step 1a: Download and read RINEX observation files

Every new day the RINEX observation files must be downloaded before being able do to any processing. This first step needs the four character station ID and the selected day of the year. The script *dwnld.mat* can handle several stations and days at the same time. Via the overview file of the Daily Station Availability it's checked if the file is already downloaded. A file containing station info can be used to link the station ID to the correct country code. The datasource can be either a stream (S) or the receiver (R). This has impact on the filename, so both options need to be searched for. The filename is defined using: *long station name _ datasource _ year day-of-year* 0000_01*D*_30*S*_*MO* for a full day of 30 second interval data. An example is *DLF*100*NLD*_*R*_20160670000_01*D*_30*S*_*MO* or *KZN*200*RUS*_*S*_20162680000_01*D*_30*S*_*MO*. All files can be found in one of the following FTP-servers, since many are stored redundantly on more FTP-servers:

- `igs.bkg.bund.de`
- `ftp.ga.gov.au`
- `igs.ign.fr`

Once downloaded, the files are extracted using *gunzip* and *crx2rnx* (Hatanaka, 2008) and moved to the correct folder, which is ordered on the day of year. The RINEX observation file is read using the script *myrnxread* (van der Marel, 2013). It reads the RINEX file line per line and stores it in a structure. The stored file consists of an header and the observations in which the satellite ID, epoch and observations are linked. After the file is read, the Daily Station Availability is immediately computed and stored in an overview file. As explained, the Daily Station Availability computes what percentage of expected unique epochs are present. Part of the output is also the epochs that are not present in the file. Figure A.2 shows the explained steps in a flow diagram.

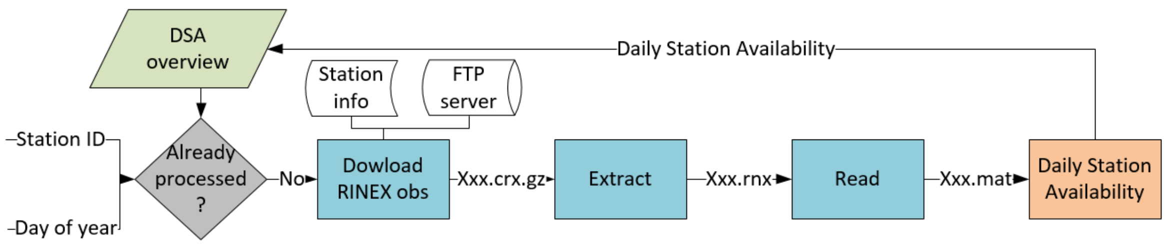


Figure A.2: The first steps in the processing is to download and read the RINEX observation files

A.2.3. Step 1b: Satellite positions

The satellite positions only have to be computed once per day, but first the RINEX navigation file is needed. Merged files of 2016 can be downloaded from CDDIS using `ftp://ftp.cddis.eosdis.nasa.gov/gnss/data/campaign/mgex/daily/rinex3/2016/brdm`. Using the Matlab function *rxnav* (van der Marel, 2013) the navigation files can be read. It results in a structure among which the ephemeris parameters can be found. The average daily clock correction per satellite is stored, as it's used for the thresholds of the code observations. Satellite positions can be computed with the use of the function *rxsatpos* (van der Marel, 2013). Investigating the algorithm used for determining the satellite coordinates is out of the scope of this thesis, but the basis of the algorithm can be found in interface control document of GPS (Fyfe and Kovach, 1994). Similar algorithms apply for Galileo. This is done based on the ephemeris parameters, satellite ID and epoch. For each GNSS, Galileo or GPS, are three arrays stored which contain the X, Y and Z coordinates of all satellites that transmit the broadcast ephemeris. This process can be seen in Figure A.3. Reading the merged RINEX navigation file and calculating the satellite positions of 31 GPS satellites for a full day using a 30 second interval takes approximately 30 seconds. Similar process for 1 second interval takes about 16 minutes. Investigating the accuracy of the orbit parameters and satellite positions is out of the scope of this research. However, since the the most recent orbit parameters are used, with an age of maximum 2 hours, it's assumed that the satellite positions are sufficiently accurate for our purposes.

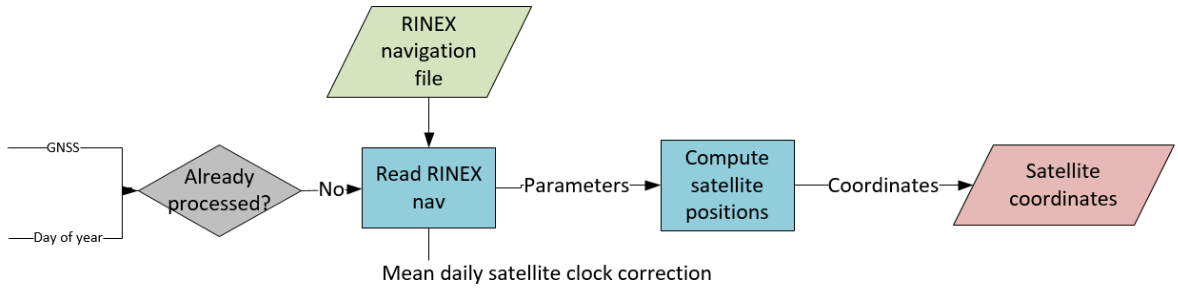


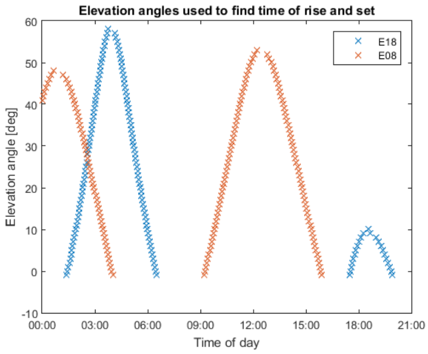
Figure A.3: Processing steps for the satellite positions, which are computed once a day

A.2.4. Step 2: Find present and not received signals

The next step is to determine per sensor station when signals are present and expected. To do so, the elevation and azimuth angles of the satellites relative to the sensor station are needed. The Matlab function $Calc\_Azimuth\_Elevation$ (Mehrtash, 2008) is used for this purpose. This process results in two matrices per GNSS, one for all elevation angles and one for all azimuth angles for the satellites. These angles in degrees are round down to the nearest integer. The derivative of the integer elevation angles is used to find the epochs when the satellite reaches a new degree of elevation. If the derivative is 1 or -1 it means that the index thereafter is a new degree of elevation. When the indices of these elevations are linked with the azimuth and time, per satellite seen by the sensor station a matrix is obtained containing the elevation, azimuth and time when a new level of elevation is reached. Data when the satellite is below -1 degrees elevation is removed from this matrix.

Figure A.4a shows an example of two satellites for which the times of rising and setting must be found. The derivative of the elevation angles are used for this purpose. If two consecutive values are more apart than 1.5 hours it's considered a break between set and rise. Since the elevation is rounded down, when rising the first elevation which is at least 0 is 0. When the satellite elevation is going down it means that 0 means an elevation between 1 and 0, since values are rounded down. So -1 is the first time the elevation drops below 0. So one epoch before the first elevation of -1 degrees is when the satellite leaves view (during the for now assumed optimal circumstances), which is shown in Figure A.4b. Several constrains need to be applied before knowing the time of rise and set. This is needed because the rising and setting have some variations: the satellite can come and leave view once or more times. It can already be visible, like E08 in Figure A.4a, or still be in view at the end of the day. For stations around the equator it may also occur that the elevation increases, decreases, increases and decreases again. So every possibility need to be taken into account for a tool that processes automatically.

When the time of rise and set of the satellite is known, it will be checked which of the signals in between rise and set are present or not present. For now it's first assumed that all signals from satellites above 0 degrees elevation are expected. This will be corrected later. All observations per satellite are retrieved using the Matlab



(a) Example of elevation over time for satellites E08 and E18. Seen from station DLF1 on doy 272

(b) Determining when a satellite comes and leaves view for the sensor station is based on the elevation

Figure A.4: Part of obtaining the time of rise and set of the satellite

function *myrnxgets* (van der Marel, 2013). Using this function results in three variables: an array of epochs, an array with observation types, and the observations itself. The observations, types and epochs can be linked by index numbers. Figure A.5a shows an example of the observations. The green array shows the epochs, which are translated to HH:MM:SS for clarity. The blue array contains the observation types and the gray matrix represents the observations. As an example does the value 37.1 in red means the C/N0 for E11 on 00:16:30. Since it's computed what periods the satellite is above 0 degrees elevation, it can easily be checked which epochs none signals are received since these epochs are not present in the epoch array of the satellite.

	'C1X'	'L1X'	'S1X'	'C5X'	'L5X'	'S5X'	'C7X'	'L7X'	'S7X'	'C8X'	'L8X'	'S8X'
00:14:00	28066068,91	147488188,8	37,9	28066071,75	110137286,4	38,9	28066069,17	113010432,2	37	28066070,66	111573862,9	43,6
00:14:30	28049850,59	147402957,7	39,1	28049852,63	110073639,8	38	28049851,64	112945125,3	38,1	28049852,07	111509386,1	43,4
00:15:00	28033641,45	147317775	40,3	28033641,74	110010029,3	36,2	28033640,9	112879855,4	37,1	28033642,31	111444945,9	42,4
00:15:30	28017441,06	147232643,1	39,9	28017441,56	109946456,8	36,7	28017441,33	112814624,5	37,6	28017442,11	111380544,2	42,7
00:16:00	28001250,34	147147563,6	40,2	28001253,04	109882923,4	38,8	28001252,2	112749433,6	38,8	28001251,92	111316182,1	44,2
00:16:30	27985071,06	147062538,6	38,7	27985072,8	109819430,7	37,1	27985072,71	112684284,7	38,9	27985072,38	111251861,3	43,9
00:17:00	27968902,31	146977570,2	41,5	27968904,06	109755980,3	39,2	27968902,61	112619179	38,9	27968903,35	111187583,3	44,7
00:17:30	27952744,39	146892660,5	40,7	27952745,96	109692573,7	39,5	27952745,11	112554118,4	39,1	27952745,7	111123349,7	45,1
00:18:00	27936598,1	146807811,3	38,7	27936599,95	109629212,4	37,3	27936599,57	112489104,1	38,3	27936599,47	111059161,9	43,5
00:18:30	27920463,63	146723025	38,1	27920466,27	109565897,9	39,1	27920463,93	112424137,9	37,5	27920465,18	110995021,5	43,9

(a) Example of observations for E11 on doy 272 by station DLF1

	'C1X'	'L1X'	'S1X'
00:14:00	28066068,91	147488188,8	37,9
00:14:30	28049850,59	147402957,7	39,1
00:15:00	28033641,45	147317775	40,3
00:15:30	28017441,06	147232643,1	39,9
00:16:00	28001250,34	147147563,6	40,2
00:16:30	27985071,06	147062538,6	38,7
00:17:00	27968902,31	146977570,2	41,5
00:17:30	27952744,39	146892660,5	40,7
00:18:00	27936598,1	146807811,3	38,7
00:18:30	27920463,63	146723025	38,1

(b) Determine when the observations are complete

Figure A.5: Part of determining which signals are present or not present

After it's known which epochs are not present it's checked per signal which observations are not received. With the use of the observation types, the correct parts of the observations are checked: C/N0, code and carrier phase observations per signal. We want to know which epochs C/N0, code and carrier phase are all present or not received per signal as shown in Figure A.5b. For an observation to be considered available, the C/N0 (S1X in the example) should be present and within thresholds, the code (C1X) should be present and within thresholds, and the phase measurement (L1X) should be present, as already explained in Chapter 3. If one is lacking, the observation is considered not received. The satellite clock drift and satellite positions are needed for the code observation threshold and the threshold parameters are needed for the C/N0 thresholds. Also the elevation of the satellites is needed to link the C/N0 with the correct threshold value. The result of this processing step is shown in Figure A.6. For every satellite tracked (black) it's stored what the times of rise and set from 0 degrees elevation is (green). First two columns represents the time of coming in view and columns three and four leaving view. So satellite E11 came and left view twice during the day. In this the first columns are the GPS weeknumbers and the second columns are the seconds of week. The observations which are not present between expected rise and set (red) show the seconds of week it occurred and the elevation (second column) and azimuth angle (third column). It shows this per observation, sat means that none signals are received and nc means that the observations are not complete, or not all signals were received simultaneously. Note that this is not yet corrected by the elevation mask and other corrections.

Next step is to use the elevation mask to correct the signals being not received (red in Figure A.6) for satellites behind the elevation mask. The azimuth angle is linked to the elevation mask, which tells what the minimum elevation is at that azimuth angle. If the elevation of the satellite is lower or similar than the elevation mask angle, the time, elevation and azimuth is added to a new variable in the blue structure of

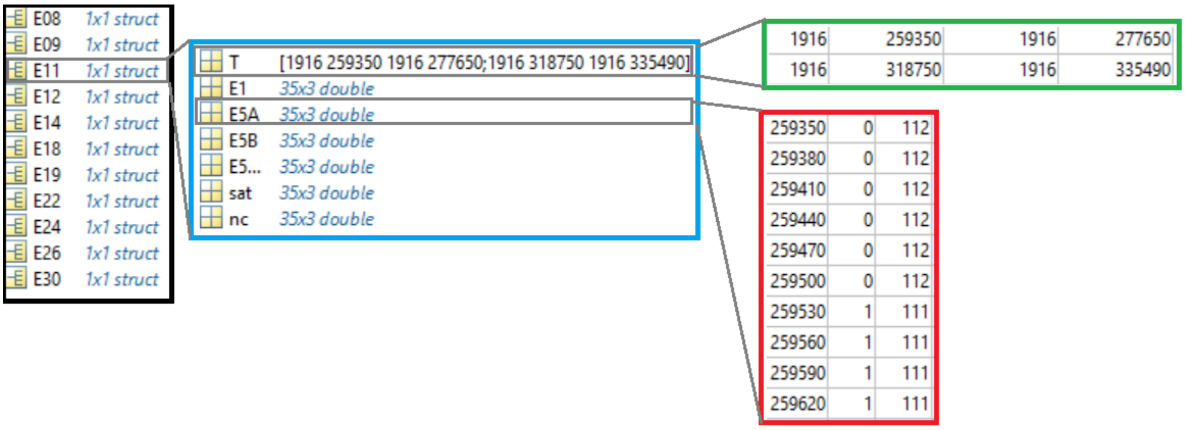


Figure A.6: Results of these processing steps. For every satellite of the black structure is a structure (blue) that contains the times of rise and set (green) and for every signal the time, elevation and azimuth (red) of expected but not received signals

Figure A.6. This tells from which signals there's no information. After that it's removed from the list of not received signals (red in Figure A.6. The next correction is that of the sensor station being not operational. For this the Daily Station Availability is loaded. If it's 100 % no correction is needed, but when it's below 100 the DSA is computed again and the times at which the station isn't receiving are returned. The red part of Figure A.6 is checked if the times are similar to the times that the station isn't receiving. When this is the case, the row is removed from the list and added to the list of no information since there's no information from the signal at that moment. Figure A.7 shows an overview of the explained processing steps.

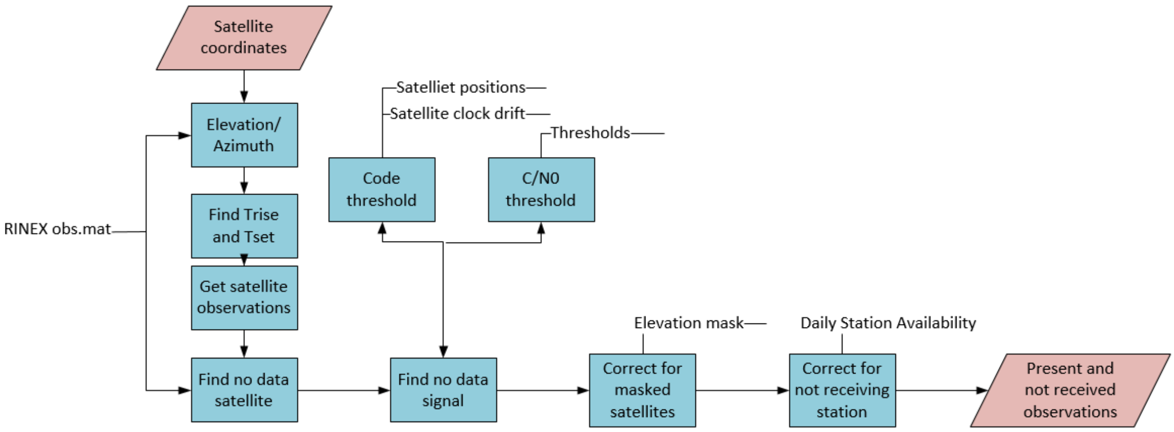
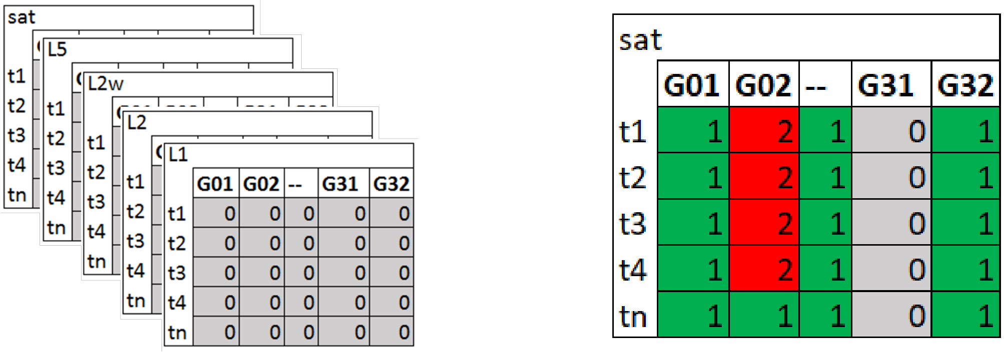


Figure A.7: Part of the explained processing steps

A.2.5. Step 4: System performance

In order to compute the Daily Station Total Availability, satellite information is needed that tells when the satellites are available or unavailable. So the computations of previous sections are done first for all stations before computing the system performance. When the system performance is known, the sensor station performance can be finished. For each signal, Galileo: E1, E5A, E5B, E5AB and GPS: L1, L2W, L2, L5, and for all signals simultaneously a matrix is created like Figure A.8a. Each box in the matrix therefore is linked to an epoch, satellite and signal. Goal is to fill each box and know if they are: available, unavailable or no info. Files like Figure A.6 are loaded one by one for all sensor stations that are selected for the monitoring network. By using the times of rise and set an array can be made with all epochs for when the satellite is above 0 degrees elevation. Epochs when there's no info because of the elevation mask or the station being not operational are already removed from this list. This leaves only epochs when the observation was received. If it's received, it's filled in in the matrix of Figure A.8a. If the signal is not present while expected it's also marked in the matrix. The box is finished when it's defined available. When a box is unavailable, the amount of times that a box is defined unavailable is counted within the box. Figure A.8b shows a matrix which is filled in. If a box is one, the satellite or signal was available based on SiS availability during that particular epoch and unavailable when the result is two. A two is only assigned if the signals are expected by at least two sensor stations and received by none. The zero means that there's no information for the satellite during the epoch. When the monitoring network consists of enough operational sensor stations, there's only no information if the satellite has no broadcast ephemeris.



(a) A matrix for each signal

(b) Each matrix is filled in

Figure A.8: A matrix is created and filled in to know the satellite availability.

Determining if signals are received by sensor stations is only halve of the satellite availability processes. Next step is to get the satellite health status. The RINEX navigation file is again read into Matlab. This process can be speed up by combining it at the step of computing the satellite positions, as the navigation file is already read in that step. Reading the navigation file results in a matrix containing the orbit parameters including the satellite health flag. The satellite health flag and epochs are retrieved for every satellite consecutively. This gives a temporary matrix for each satellite. During this research all health statuses other than zero are assumed to be unhealthy. This assumption is conservative as some flags have different meanings, like only a single signal is affected, or it can be a warning that the health status can become unhealthy. For future work this is an aspect that can be improved.

If an health flag is other than zero, the satellite was atleast partly unavailable during the day. So if the sum of the health flags is zero for the day, the satellite was fully healthy. Figure A.9 shows the health statuses of satellite G17 on doy 344. Points on top of the plot represent an unhealthy status and points at the bottom an healthy status. Since the first point, at 2 o'clock, is unhealthy, the satellite is assumed to be unhealthy from the start of the day. By taking the differential of the health flags, which are either one or zero, the begin and end of the unhealthy period can be found. The function that finds the health statuses only returns for satellites that are unhealthy the start and end time(s) of the unhealthy periods.

If a satellite is (partly) unhealthy during the day, the matrix of Figure A.8b is adapted for the unhealthy period. This overrules the already filled in available values. Since the columns of Figure A.8b represents all epochs of the day, daily percentages can easily be computed. This process returns and stores an array containing all Daily GNSS Availabilities. If a value is bigger than zero and smaller than 100, an extra array is stored containing all epochs that the satellite is unavailable. The next step is to compute the Daily Available # of Satellites. As already explained, this is done by summing up the satellite availabilities of the GNSS and dividing it by 100. The diagram of Figure A.10 shows the steps that have been done.

A.2.6. Step 5: Daily Station Total Availability

Now the satellite availability is known, it's possible to finish the computations of the Daily Station Total Availability. The start is again the file of Figure A.6. Epochs of expected but not received signals, which are in blue of Figure A.6, and also occur in the array of epochs that the satellite is unavailable, are removed from the blue array and moved to the array containing epochs that there's no information from the satellite by the sensor station.

Per GNSS are two tables created as shown in Table A.2 and A.3. Table A.2 is filled with the amount of observations based again on the blue info of Figure A.6. The total amount of possible observations during ideal circumstances is retrieved just by T. Equation A.1 is used for this purpose, in which cycles is the amount of times the satellite comes and leaves view. T_1 and T_2 are the times of coming and leaving view. No_info of

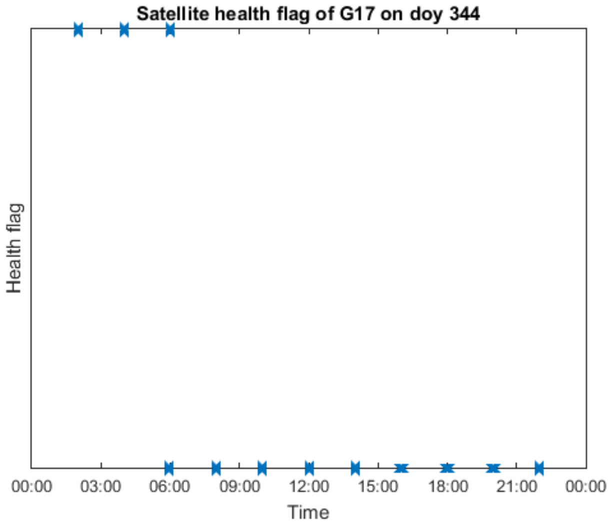


Figure A.9: Figure showing satellite health statuses. Points on top are unhealthy statuses, while the points at the bottom represent healthy statuses. This satellite is considered unhealthy from 00:00:00 - 06:00:00

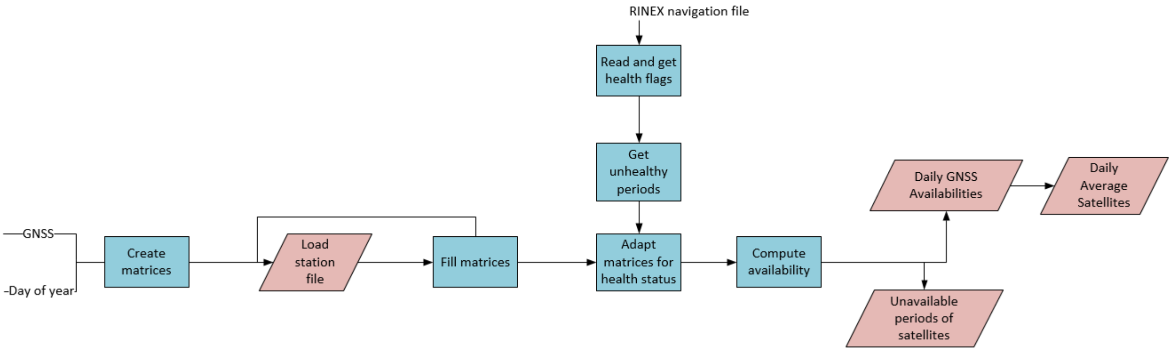


Figure A.10: Part of the explained processing steps for the system performance parameters

the left table represents the amount of observations out of the total that there's no information of the satellite. This is the length of the array containing epochs in which the satellite is not tracked, while the station is not operational, the satellite is behind the elevation mask or the satellite is unavailable. The columns of *sat* to *E5ab* is filled based on the amount of epochs that the observation is not received during the expected period. So the values in Table A.2 are all numbers of (possible) observations.

$$\text{Total} = \sum_{\text{cycles}} \left(\frac{\text{T}_2 - \text{T}_1 + \text{interval}}{\text{interval}} \right) \tag{A.1}$$

Table A.2: First a table is filled in with the amount of epochs that the satellite is above the horizon (total), amount of epochs that there's no information of the signal due to the satellite or sensor station being no operation or the satellite is behind the elevation mask (no_info). Sat to E5ab are the amount of epochs that the signal is not received while expected

Satellite	total	no_info	sat	E1	E5a	E5b	E5ab
E01	x	x	x	x	x	x	x
E02	x	x	x	x	x	x	x
Enn	x	x	x	x	x	x	x

Using the information of Table A.2, Table A.3 can be filled in. It gives the percentages that each signal of each satellite is received by the sensor station. Equation A.2 shows how it's done. The variable *mis* is the amount of observations from the Table A.2 arrays (*sat, E1, E5a, E5b or E5ab*). The variable *sat* means the amount of epochs that not all signals are received for Table A.2 and the percentage of epochs that all signals are received simultaneously in Table A.3.

Table A.3: Second table that shows the amount of epochs that the satellite is expected to be observed (total) and the percentage of those epochs that all signals are received (sat) or that a single signal is received

Satellite	total	sat	E1	E5a	E5b	E5ab
E01	x	%	%	%	%	%
E02	x	%	%	%	%	%
Enn	x	%	%	%	%	%

$$\begin{aligned} \text{pct} &= \frac{\text{total} - \text{no\_info} - \text{mis}}{\text{total} - \text{no\_info}} \cdot 100\% \\ \text{total}_{\text{new}} &= \text{total} - \text{no\_info} \end{aligned} \tag{A.2}$$

Not a Number (NaN) is assigned to the variable *total* of satellites which are unavailable during the full day. So by using the Matlab function *nansum* of the multiplication of the total and sat array of Table A.3 and divide it by the *nansum* of the total array, the Daily Station Total Availability is obtained. The steps described in this paragraph are given in Figure A.11.

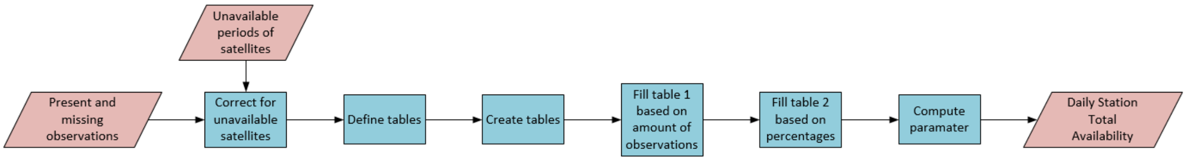


Figure A.11: Processing steps for the Daily Station Total Availability

B

Results Daily Station Availability 13 days

The Daily Station Availability, as explained in Section 4.1, is computed for all IGS MGEX sensor stations for 13 days during 2016. This gives a first insight in the performance of all stations. A result of -2 means that only RINEX version 2 was available during the day. Other results are between 0 and 100 %, in which the value tells what part of the day the station was operational. Figure B.1 and Figure B.2 show the daily results and Figure B.3 gives the average result over the 13 days per station.

	66	67	68	69	206	207	208	209	210	211	212	239	240
ABMF	100	100	100	100	0	0	0	0	0	0	0	0	0
AIRA	-2	-2	-2	-2	0	-2	0	0	0	0	0	100	-2
AJAC	0	0	0	0	100	100	100	100	100	100	100	100	100
ALIC	100	100	100	100	100	100	100	100	100	100	100	99,7	100
ANMG	0	0	0	0	99,7	99,9	100	99,8	99,5	99,8	100	99,8	99,9
AREG	100	100	100	100	100	100	99,7	100	100	100	100	-2	-2
ASCG	100	0	0	0	100	100	100	100	100	100	100	-2	-2
AUCK	-2	-2	-2	-2	100	100	100	100	96,5	100	100	4,17	100
BIK0	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2
BOR1	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2
BRST	100	100	100	100	0	0	0	0	0	0	0	100	100
BRUN	0	0	0	0	88,5	73,8	82,5	83,4	94,2	96,2	99,3	0	0
BRUX	100	100	100	100	100	100	100	100	100	100	100	100	100
CAS1	100	100	100	100	100	100	100	100	100	100	100	100	100
CCJ2	-2	-2	-2	-2	0	-2	0	0	0	0	0	100	-2
CEBR	100	100	100	100	100	100	100	100	100	100	100	100	100
CEDU	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2
CHOF	0	0	0	0	99,9	100	99,9	99,8	99,8	99,2	99,9	99,8	99,8
CHPG	100	100	100	100	100	100	100	100	100	100	100	-2	-2
CHTI	-2	-2	-2	-2	100	100	100	100	100	100	100	100	4,17
CKIS	100	100	100	100	100	100	100	100	100	100	100	100	100
CMUM	0	0	0	0	99,9	99,9	99,8	100	96	100	99,8	0	0
CPNM	0	0	0	0	99,3	100	99,7	99,1	98,5	96,8	94	100	100
CPVG	100	100	100	100	0	0	0	99,9	100	100	100	-2	-2
CUT0	0	0	0	0	100	100	100	100	100	100	100	100	100
CUUT	100	100	100	100	100	100	100	100	100	100	100	100	100
CZTG	0	-2	0	-2	98	98,9	98,2	97	98,7	95,9	53,3	0	0
DAE2	0	0	0	0	92,1	88,8	84,6	94,4	93,5	88,3	93,3	100	100
DARW	0	0	0	0	-2	-2	-2	-2	-2	-2	-2	-2	-2
DJIG	100	99,6	0	100	0	5,45	0	0	100	6,88	0	-2	-2
DLF1	100	100	100	100	100	100	100	100	19,7	100	100	100	100
DLTV	0	0	0	0	100	100	98,5	99,3	99,7	99	100	100	99,5
DUND	-2	-2	-2	-2	100	100	100	100	100	100	100	100	100
DYNG	100	100	100	100	100	100	100	100	100	100	100	-2	-2
EBRE	100	100	100	100	100	100	100	100	-2	100	100	100	100
EUSM	0	0	0	0	100	100	100	100	99,7	100	99,3	99,7	100
FAA1	0	0	0	0	100	100	99,9	100	100	100	100	99,9	100
FTNA	100	100	100	100	100	100	100	100	100	100	100	-2	-2
GAMB	0	0	0	0	-2	-2	-2	-2	-2	-2	-2	-2	-2
GAMG	0	0	0	0	0	0	0	0	0	0	0	0	0
GANP	100	100	100	100	100	100	100	100	100	100	100	100	100
GMSD	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2

(a) Part one

	66	67	68	69	206	207	208	209	210	211	212	239	240
GOP6	0	0	0	0	0	0	0	0	0	0	0	0	0
GOP7	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2
GRAC	100	100	100	100	100	100	100	100	100	100	100	100	100
HARB	100	100	100	100	100	100	99,2	99,5	100	99,6	99,7	-2	-2
HKSL	-2	-2	-2	-2	0	0	0	0	0	0	0	0	0
HKWS	-2	-2	-2	-2	0	0	0	0	0	0	0	0	0
HOFN	100	100	100	100	100	100	100	100	100	100	100	95,8	95,8
HRAG	0	0	0	0	99,9	99,3	99,9	99,9	100	99,2	99,9	99,8	100
ISTA	-2	-2	-2	-2	100	100	100	100	100	100	100	100	100
JCTW	0	0	0	0	99,2	99	99	99,3	99,2	99,6	99,6	99,2	99,6
JFNG	0	100	0	0	100	100	100	100	100	100	100	-2	-2
JNAV	0	0	0	0	100	99,4	97,6	98,4	70,4	100	100	100	100
JOG2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2
JPRE	0	0	0	0	100	99,8	99,7	100	99,7	100	100	99,9	99,8
KARR	100	100	100	100	100	100	100	78,6	100	100	100	100	100
KAT1	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2
KIR8	-2	-2	-2	-2	100	99,9	99,8	100	100	100	100	-2	100
KIRI	100	100	100	100	100	100	100	100	100	100	100	100	100
KIRU	100	100	100	100	100	100	100	100	100	100	100	100	100
KIT3	-2	-2	-2	-2	-2	-2	-2	-2	0	0	-2	0	0
KITG	0	0	0	0	100	100	100	100	100	100	100	-2	-2
KOUG	100	100	100	100	100	100	100	100	100	100	100	-2	-2
KOUR	100	100	100	100	100	100	100	100	100	100	100	100	100
KRGG	100	100	100	58,3	100	100	100	100	100	100	100	-2	-2
KZN2	0	0	0	0	99,9	100	100	99,9	100	99,2	99,9	99,8	100
LAUT	100	100	100	100	100	40,2	100	100	9,03	100	100	100	100
LHAZ	-2	-2	-2	-2	100	-2	-2	-2	100	100	100	100	-2
LLAG	0	0	0	0	99,9	100	99,9	99,9	100	99,2	99,9	99,9	100
LMMF	0	100	100	100	100	100	100	100	100	100	100	0	0
LPGS	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2
M0SE	0	0	0	0	0	0	0	0	0	0	0	0	0
MAJU	100	100	100	100	100	100	100	100	100	100	-2	99,9	100
MAL2	100	99,6	100	100	99,4	99,7	100	100	100	100	100	100	100
MAR7	-2	-2	-2	-2	100	100	100	100	100	100	100	-2	100
MARS	0	0	0	0	0	0	0	0	0	0	0	100	100
MAS1	100	100	100	100	100	100	100	100	100	100	100	100	100
MATG	99,9	99,9	100	100	71,8	71,4	100	100	100	100	100	100	85,6
MAYG	100	100	100	100	100	100	-2	99,8	100	100	100	100	100
MCHL	100	100	100	-2	100	100	100	100	100	100	100	100	100
MEDI	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2
METG	100	100	100	100	0	0	100	100	100	100	100	-2	-2
MGUE	100	100	100	100	100	99,9	100	100	100	100	100	100	100

(b) Part two

Figure B.1: Results from 13 days of the Daily Station Availability for all IGS MGEX stations

	66	67	68	69	206	207	208	209	210	211	212	239	240
MIZU	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2
MOBS	100	100	100	100	100	100	100	100	100	100	100	100	100
MQZG	-2	-2	-2	-2	100	100	100	100	100	100	100	4,17	100
MRO1	100	100	100	100	100	100	100	100	100	100	100	100	100
NAUR	100	100	100	100	99,9	100	-2	99,9	100	100	-2	100	100
NCKU	0	0	0	0	100	99,3	98,2	93,3	96	94,1	100	100	100
NICO	100	100	100	100	-2	-2	-2	-2	-2	-2	-2	-2	-2
NIUM	100	100	100	100	100	100	100	100	100	100	100	100	100
NKLG	100	100	100	0	100	100	99,5	100	100	100	100	-2	-2
NNOR	100	100	100	100	100	100	100	100	99,9	100	99,9	99,9	100
NURK	0	0	0	0	0	0	0	0	0	0	0	0	0
NYA2	0	0	0	0	0	0	0	0	0	0	0	0	0
OBE4	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2
OHI2	99,1	100	100	100	99,7	98,8	100	100	100	100	100	100	100
OHI3	100	100	100	100	100	100	100	100	100	100	100	100	100
ONS1	-2	-2	-2	-2	100	100	100	100	100	100	100	-2	100
OUS2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2
OWMG	0	0	0	0	0	0	0	0	0	0	0	-2	-2
PADO	100	100	100	100	100	100	100	100	100	100	100	100	100
PARK	-2	-2	-2	-2	100	100	100	100	8,99	100	100	100	100
PEN2	-2	-2	-2	-2	100	99,9	99,1	99,9	99,2	99,3	99,9	99,9	100
PERT	100	100	100	100	100	100	100	100	97,8	100	100	100	100
PNGM	100	100	100	100	100	100	100	47,5	100	100	100	100	100
POHN	100	100	100	100	100	100	100	100	100	100	100	100	100
POTS	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2
PTGG	100	0	0	0	0	0	0	0	0	0	0	-2	-2
PTVL	100	100	100	100	100	100	100	100	8,99	100	100	12,2	100
REDU	100	100	100	100	100	100	100	100	100	100	100	100	100
REUN	0	0	0	0	0	0	0	0	0	0	0	0	0
REYK	100	65,1	0	-2	100	100	100	100	100	100	100	100	100
RGDG	100	100	100	100	100	100	100	100	100	100	100	-2	-2
RIO2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2
ROAP	-2	-2	-2	-2	100	100	100	100	99,7	100	100	100	100
SAMO	100	100	100	100	100	100	100	100	100	100	100	100	100
SCRZ	-2	-2	-2	-2	-2	0	0	0	-2	100	100	100	100
SCTB	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	0	0
SCUB	0	0	0	0	0	0	0	0	0	0	0	0	0
SEYG	100	100	100	100	0	0	100	99,8	0	100	0	-2	-2
SGOC	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2
SIN1	0	0	0	0	99,9	100	99,5	99,9	100	99,2	98,2	0	0
SOLO	100	100	100	100	100	40,2	100	100	8,99	100	100	12,2	100
SPTU	0	0	0	99,8	100	100	100	100	100	100	100	100	100

(a) Part three

	66	67	68	69	206	207	208	209	210	211	212	239	240
STFU	0	0	0	0	99,9	100	99,9	99,8	100	99,2	99,9	99	99,9
STJ3	100	100	100	100	100	100	100	100	100	100	100	-2	-2
STK2	-2	-2	-2	-2	0	-2	0	0	0	0	0	100	-2
STR1	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2
SUTM	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2
SYDN	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2
TASH	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	0	-2	-2
THTG	100	100	100	100	100	100	100	100	100	100	100	-2	-2
TLSE	100	100	100	100	100	100	100	100	100	100	100	-2	-2
TLSG	100	100	100	100	100	100	100	100	100	100	100	-2	-2
TONG	100	100	100	100	100	-2	-2	100	100	-2	100	-2	100
TOW2	100	100	64,6	-2	100	100	100	100	100	100	100	100	100
TSK2	-2	-2	-2	-2	0	-2	0	0	0	0	0	100	0
TUVA	100	100	100	100	100	100	-2	100	100	100	100	100	100
TWTF	-2	-2	-2	74,1	100	100	100	100	100	100	100	100	100
UCAL	0	0	0	0	99,8	100	100	100	100	99,2	99,9	95,7	100
ULAB	-2	-2	-2	-2	0	0	0	0	-2	0	0	0	0
UNB3	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2
UNBD	0	0	0	0	98,6	99	99,1	98,2	97,5	98,4	98,4	98,9	99,1
UNBN	100	100	100	100	100	100	100	100	100	100	100	100	100
UNSA	0	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2
UNX2	0	0	0	0	99,9	100	100	99,9	99,9	99,2	99,9	99,8	99,9
UNX3	0	0	0	0	0	0	0	0	0	20,4	99,9	99,8	100
USN8	100	100	100	100	100	100	100	100	100	100	100	100	100
USN9	100	100	100	100	100	100	100	100	100	100	100	100	100
VILL	100	100	100	100	100	100	100	100	100	100	100	100	100
VOIM	0	0	0	0	-2	-2	-2	-2	-2	-2	-2	-2	-2
WARK	-2	-2	-2	-2	100	100	100	100	100	100	100	100	100
WGTN	-2	-2	-2	-2	100	40,2	100	100	100	100	100	100	8,33
WIND	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2
WROC	-2	-2	0	0	-2	-2	-2	-2	-2	-2	-2	-2	-2
WTZ3	0	0	0	0	99,9	100	100	99,4	99,2	99,2	99,9	99,8	100
WTZR	100	76,1	0	-2	100	100	100	100	100	100	100	100	100
WTZS	-2	-2	-2	-2	100	100	100	100	100	100	100	100	100
WTZZ	99,5	100	100	100	99,5	100	100	100	100	100	100	100	100
WUH2	0	0	0	0	0	0	0	0	0	0	0	0	0
XMIS	96,5	98	100	100	100	100	100	100	100	100	100	100	-2
YAR2	-2	-2	-2	-2	100	100	100	100	100	100	100	100	100
YEL2	100	100	100	100	97,9	98,3	100	100	100	100	100	-2	-2
ZIM2	-2	-2	-2	-2	-2	100	100	100	100	100	100	100	100
ZIM3	0	0	0	0	0	100	100	100	95,6	100	100	100	100
ZIMJ	-2	-2	-2	-2	0	0	0	0	0	0	0	100	100

(b) Part four

Figure B.2: Results from 13 days of the Daily Station Availability for all IGS MGEX stations

Station	DSA
ABMF	30.77
AIRA	7.69
AJAC	69.23
ALIC	99.98
ANMG	69.11
AREG	84.59
ASCG	61.54
AUCK	61.59
BIK0	0.00
BOR1	0.00
BRST	46.15
BRUN	47.53
BRUX	100.00
CAS1	100.00
CCJ2	7.69
CEBR	100.00
CEDU	0.00
CHOF	69.08
CHPG	84.62
CHTI	61.86
CKIS	100.00
CMUM	53.49
CPNM	68.26
CPVG	61.53
CUT0	69.23
CUUT	100.00
CZTG	49.23
DAE2	64.23
DARW	0.00
DJIG	31.68
DLF1	93.82
DLTV	68.92
DUND	69.23
DYNG	84.62
EBRE	92.31
EUSM	69.13
FAA1	69.22
FTNA	84.62
GAMB	0.00
GAMG	0.00
GANP	100.00
GMSD	0.00

Station	DSA
GOP6	0.00
GOP7	0.00
GRAC	100.00
HARB	84.46
HKSL	0.00
HKWS	0.00
HOFN	99.36
HRAG	69.08
ISTA	69.23
JCTW	68.73
JFNG	61.54
JNAV	66.59
JOG2	0.00
JPRE	69.13
KARR	98.35
KAT1	0.00
KIR8	61.51
KIRI	100.00
KIRU	100.00
KIT3	0.00
KITG	53.85
KOUG	84.62
KOUR	100.00
KRGG	81.40
KZN2	69.13
LAUT	88.41
LHAZ	38.46
LLAG	69.14
LMMF	76.92
LPGS	0.00
M0SE	0.00
MAJU	92.30
MAL2	99.89
MAR7	61.54
MARS	15.38
MAS1	100.00
MATG	94.50
MAYG	92.29
MCHL	92.31
MEDI	0.00
METG	69.23
MGUE	99.99

Station	DSA
MIZU	0.00
MOBS	100.00
MQZG	61.86
MRO1	100.00
NAUR	84.60
NCKU	67.75
NICO	30.77
NIUM	100.00
NKLG	76.89
NNOR	99.97
NURK	0.00
NYA2	0.00
OBE4	0.00
OHI2	99.81
OHI3	100.00
ONS1	61.54
OUS2	0.00
OWMG	0.00
PADO	100.00
PARK	62.23
PEN2	69.01
PERT	99.83
PNGM	95.96
POHN	100.00
POTS	0.00
PTGG	7.69
PTVL	86.25
REDU	100.00
REUN	0.00
REYK	81.93
RGDG	84.62
RIO2	0.00
ROAP	69.20
SAMO	100.00
SCRZ	30.77
SCTB	0.00
SCUB	0.00
SEYG	53.83
SGOC	0.00
SIN1	53.59
SOLO	81.65
SPTU	76.91

Station	DSA
STFU	69.05
STJ3	84.62
STK2	7.69
STR1	0.00
SUTM	0.00
SYDN	0.00
TASH	0.00
THTG	84.62
TLSE	84.62
TLSG	84.62
TONG	69.23
TOW2	89.58
TSK2	7.69
TUVA	92.31
TWTF	74.93
UCAL	68.81
ULAB	0.00
UNB3	0.00
UNBD	68.24
UNBN	100.00
UNSA	0.00
UNX2	69.11
UNX3	24.61
USN8	100.00
USN9	100.00
VILL	100.00
VOIM	0.00
WARK	69.23
WGTN	57.58
WIND	0.00
WROC	0.00
WTZ3	69.03
WTZR	82.78
WTZS	69.23
WTZZ	99.92
WUH2	0.00
XMIS	91.88
YAR2	69.23
YEL2	84.33
ZIM2	61.54
ZIM3	61.20
ZIMJ	15.38

Figure B.3: Average of the Daily Station Availability of 13 days

C

Details Daily Station Availability 100 days

Dynamic features, like showing extra information by using a mouseover aren't possible on paper. So more detailed information of the Daily Station Availability can be found in the tables of Figure C.1, Figure C.2, Figure C.3 and Figure C.4. The legend of the color codes is similar as Section 6.2.1. Results are shown in two digits to be able to show even the effect of an event of a single epoch.

	Day of year																								
Stations	**267**	**268**	**269**	**270**	**271**	**272**	**273**	**274**	**275**	**276**	**277**	**278**	**279**	**280**	**281**	**282**	**283**	**284**	**285**	**286**	**287**	**288**	**289**	**290**	**291**
FAA1	99.97	100.00	100.00	99.97	100.00	100.00	99.93	100.00	100.00	99.93	100.00	99.93	100.00	100.00	99.93	99.97	99.97	100.00	100.00	99.97	100.00	99.97	99.97	100.00	100.00
DLF1	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	68.51	0.00	72.26	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
MAL2	99.97	99.97	100.00	99.97	99.93	100.00	99.97	99.90	99.97	99.90	100.00	99.97	100.00	100.00	100.00	99.97	100.00	98.92	98.96	99.90	99.97	100.00	100.00	100.00	100.00
KOUR	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
AREG	100.00	100.00	99.10	99.51	100.00	100.00	100.00	100.00	100.00	100.00	100.00	0.00	100.00	0.00	0.00	0.00	0.00	100.00	100.00	100.00	100.00	99.48	100.00	100.00	100.00
NKLG	100.00	100.00	99.58	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	0.00	100.00	0.00	0.00	0.00	0.00	100.00	100.00	100.00	100.00	99.44	100.00	100.00	70.49
XMIS	100.00	100.00	100.00	100.00	100.00	44.03	100.00	100.00	70.52	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	0.00	100.00	100.00	100.00	100.00	100.00
WARK	100.00	65.07	95.83	2.00	4.17	4.17	4.17	4.17	4.17	82.99	4.17	4.17	4.17	97.08	4.17	4.17	4.17	4.17	4.17	100.00	45.56	100.00	4.17	4.17	4.17
YEL2	100.00	100.00	100.00	100.00	100.00	100.00	100.00	99.83	100.00	100.00	100.00	100.00	99.90	99.20	0.00	0.00	0.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
KRGG	100.00	100.00	100.00	0.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	0.00	0.00	0.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
JFNG	0.00	100.00	100.00	0.00	100.00	99.93	100.00	100.00	100.00	100.00	0.00	0.00	0.00	100.00	0.00	0.00	0.00	96.98	99.97	100.00	100.00	99.65	100.00	100.00	98.72
STFU	99.90	100.00	99.97	99.97	100.00	100.00	99.97	99.93	100.00	99.97	100.00	100.00	99.90	99.93	100.00	99.97	99.86	99.97	99.90	99.93	99.86	99.90	100.00	99.58	99.93
KZN2	99.93	100.00	100.00	99.97	100.00	100.00	99.93	99.69	100.00	99.97	99.55	100.00	99.86	99.93	99.97	99.79	72.43	73.40	99.97	99.90	99.58	99.93	98.96	99.58	99.97
TOW2	99.97	100.00	99.97	100.00	100.00	100.00	99.97	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
RGDG	0.00	0.00	0.00	0.00	0.00	0.00	0.00	100.00	100.00	0.00	100.00	0.00	0.00	0.00	0.00	0.00	0.00	100.00	0.00	100.00	100.00	100.00	100.00	100.00	100.00
MAJU	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	99.72	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
DUND	95.83	95.83	100.00	100.00	95.83	100.00	100.00	91.67	100.00	100.00	95.83	95.83	95.83	91.67	100.00	100.00	95.83	91.67	87.50	95.83	100.00	95.83	95.83	95.83	83.33
OHI3	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
CAS1	100.00	72.50	100.00	100.00	100.00	44.03	100.00	2.40	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
SUTM	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	99.97	100.00	100.00	100.00	100.00	100.00	99.97	100.00

Figure C.1: Results of the first 25 days for the Daily Station Availability

	Day of year																								
Stations	**292**	**293**	**294**	**295**	**296**	**297**	**298**	**299**	**300**	**301**	**302**	**303**	**304**	**305**	**306**	**307**	**308**	**309**	**310**	**311**	**312**	**313**	**314**	**315**	**316**
FAA1	99.72	99.93	99.97	99.97	99.97	100.00	66.88	99.93	100.00	99.93	100.00	99.97	100.00	100.00	100.00	100.00	99.93	100.00	99.93	100.00	99.97	99.97	100.00	99.97	100.00
DLF1	100.00	100.00	100.00	100.00	100.00	100.00	100.00	93.92	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
MAL2	99.65	97.92	99.97	100.00	99.97	99.97	98.96	99.97	97.92	99.97	100.00	99.97	82.22	0.00	99.97	99.97	99.97	99.97	100.00	99.97	99.97	98.96	100.00	99.93	100.00
KOUR	100.00	100.00	100.00	99.69	100.00	100.00	100.00	100.00	100.00	98.96	100.00	100.00	100.00	100.00	100.00	100.00	98.96	100.00	100.00	100.00	98.96	98.96	100.00	100.00	100.00
AREG	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
NKLG	0.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
XMIS	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	17.15	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
WARK	4.17	4.17	4.17	4.17	100.00	4.17	4.17	4.17	96.81	100.00	4.17	4.17	4.17	4.17	4.17	4.17	4.17	100.00	4.17	4.17	8.33	100.00	4.17	100.00	4.17
YEL2	99.79	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	98.96	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	97.92	87.50	100.00	99.27	100.00
KRGG	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
JFNG	100.00	100.00	16.74	100.00	100.00	97.88	99.83	99.97	100.00	100.00	98.16	97.50	97.88	99.93	98.26	99.69	98.44	100.00	99.79	99.72	99.13	99.97	99.48	0.00	99.38
STFU	99.65	99.97	98.09	99.93	98.37	99.97	99.79	100.00	99.83	99.76	99.97	99.93	99.76	99.79	99.86	99.97	99.79	99.69	100.00	99.24	99.62	97.95	95.45	90.69	100.00
KZN2	99.97	99.97	98.40	100.00	98.33	99.97	99.93	99.79	99.97	99.69	99.93	100.00	99.86	99.97	99.97	99.97	99.93	99.79	99.58	100.00	99.65	97.88	95.42	90.59	100.00
TOW2	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
RGDG	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
MAJU	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
DUND	91.67	100.00	95.83	95.83	100.00	100.00	100.00	100.00	100.00	91.67	95.83	87.50	100.00	87.50	95.83	100.00	91.67	100.00	95.83	95.83	4.17	95.83	91.67	91.67	100.00
OHI3	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	97.36
CAS1	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	45.83	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
SUTM	100.00	100.00	100.00	100.00	100.00	100.00	100.00	98.37	100.00	99.97	100.00	100.00	100.00	100.00	100.00	100.00	99.97	100.00	100.00	99.97	100.00	100.00	100.00	99.97	100.00

Figure C.2: Results of the second 25 days for the Daily Station Availability

Day of year

Stations	317	318	319	320	321	322	323	324	325	326	327	328
FAA1	99.93	100.00	99.97	99.93	99.93	100.00	100.00	100.00	99.97	100.00	99.97	100.00
DLF1	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
MAL2	46.08	0.00	0.00	100.00	99.97	99.97	93.65	100.00	99.97	99.93	99.97	64.06
KOUR	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
AREG	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	0.00	100.00	100.00
NKLG	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	0.00	100.00	100.00
XMIS	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
WARK	4.17	100.00	100.00	4.17	4.17	4.17	100.00	4.17	100.00	100.00	100.00	4.17
YEL2	100.00	100.00	100.00	44.79	0.00	100.00	100.00	100.00	100.00	100.00	100.00	96.88
KRGG	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	0.00	100.00	100.00
JFNG	98.51	100.00	99.58	98.78	100.00	97.71	100.00	99.65	100.00	97.22	92.40	99.62
STFU	93.19	99.97	100.00	99.97	99.41	100.00	94.17	99.97	100.00	99.97	99.93	99.90
KZN2	100.00	99.97	100.00	100.00	99.97	99.93	99.86	99.97	100.00	100.00	99.97	99.90
TOW2	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
RGDG	100.00	100.00	100.00	100.00	100.00	100.00	100.00	0.00	100.00	0.00	0.00	100.00
MAJU	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
DUND	95.83	91.67	100.00	100.00	95.83	95.83	100.00	95.83	100.00	100.00	100.00	95.83
OHI3	100.00	100.00	99.97	99.86	100.00	99.97	100.00	100.00	100.00	100.00	100.00	100.00
CAS1	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
SUTM	100.00	99.97	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00

Stations	329	330	331	332	333	334	335	336	337	338	339	340	341
FAA1	100.00	99.90	99.97	99.93	100.00	99.93	99.97	100.00	99.93	99.93	100.00	99.97	100.00
DLF1	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
MAL2	0.00	100.00	99.97	100.00	99.93	99.97	99.97	99.97	99.97	99.97	100.00	99.97	100.00
KOUR	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
AREG	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
NKLG	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	0.00	100.00	100.00	100.00
XMIS	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
WARK	4.17	4.17	100.00	100.00	100.00	95.83	0.00	0.00	0.00	0.00	0.00	0.00	0.00
YEL2	95.83	100.00	100.00	100.00	100.00	100.00	99.17	100.00	100.00	100.00	100.00	100.00	100.00
KRGG	100.00	100.00	100.00	99.97	100.00	100.00	0.00	100.00	39.20	100.00	100.00	100.00	100.00
JFNG	100.00	100.00	100.00	100.00	99.06	96.22	98.82	99.93	99.72	100.00	96.91	97.99	97.95
STFU	97.67	100.00	100.00	99.97	99.79	99.97	94.62	99.83	99.83	39.24	45.94	65.66	99.93
KZN2	99.90	98.58	99.97	100.00	92.12	100.00	98.92	100.00	99.83	99.79	99.97	98.33	99.34
TOW2	100.00	100.00	100.00	100.00	100.00	10.66	87.26	100.00	99.97	100.00	100.00	100.00	100.00
RGDG	100.00	100.00	100.00	100.00	100.00	100.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
MAJU	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
DUND	100.00	100.00	100.00	95.83	100.00	100.00	95.83	100.00	95.83	95.83	100.00	100.00	95.83
OHI3	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
CAS1	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
SUTM	100.00	100.00	100.00	100.00	100.00	100.00	100.00	99.97	100.00	100.00	100.00	100.00	100.00

Figure C.3: Results of the third 25 days for the Daily Station Availability

Day of year

Stations	342	343	344	345	346	347	348	349	350	351	352	353
FAA1	100.00	99.97	100.00	99.97	100.00	100.00	100.00	100.00	99.93	99.93	99.97	99.97
DLF1	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
MAL2	99.97	100.00	85.03	99.97	20.24	0.00	99.97	99.97	99.97	100.00	100.00	99.93
KOUR	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
AREG	100.00	99.48	100.00	99.51	100.00	100.00	96.91	100.00	100.00	100.00	100.00	100.00
NKLG	100.00	100.00	100.00	99.31	100.00	0.00	100.00	100.00	0.00	100.00	100.00	100.00
XMIS	100.00	100.00	66.46	100.00	100.00	67.36	100.00	100.00	99.51	100.00	100.00	100.00
WARK	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
YEL2	95.63	98.96	100.00	100.00	100.00	100.00	99.72	98.37	99.10	100.00	100.00	100.00
KRGG	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
JFNG	99.31	99.58	99.58	100.00	96.15	0.00	98.33	99.38	99.97	100.00	99.93	96.08
STFU	99.90	99.97	95.59	100.00	100.00	99.97	99.97	99.83	82.43	95.31	99.97	100.00
KZN2	98.65	97.78	96.08	99.76	100.00	99.97	99.93	99.90	82.47	99.72	98.51	95.00
TOW2	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
RGDG	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
MAJU	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
DUND	91.67	0.00	0.00	0.00	0.00	95.83	100.00	100.00	0.00	95.83	95.83	95.83
OHI3	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	99.97	100.00	100.00	100.00
CAS1	100.00	100.00	100.00	100.00	100.00	74.24	100.00	99.58	100.00	100.00	100.00	100.00
SUTM	100.00	99.27	100.00	100.00	99.97	100.00	100.00	100.00	100.00	100.00	100.00	100.00
LAUT	100.00	100.00	100.00	100.00	100.00	83.33	100.00	100.00	99.24	100.00	100.00	45.63

Stations	354	355	356	357	358	359	360	361	362	363	364	365	366
FAA1	98.96	99.97	99.97	100.00	99.97	99.93	100.00	99.97	99.93	99.72	100.00	100.00	0.00
DLF1	100.00	100.00	99.62	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
MAL2	98.96	99.97	78.58	99.97	100.00	100.00	99.93	99.93	99.97	96.11	99.90	100.00	0.00
KOUR	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	99.72	100.00	0.00
AREG	100.00	100.00	100.00	100.00	0.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
NKLG	100.00	100.00	100.00	100.00	0.00	100.00	100.00	100.00	99.41	100.00	100.00	100.00	100.00
XMIS	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	65.52	100.00	100.00	100.00	100.00
WARK	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
YEL2	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	98.96	100.00	100.00
KRGG	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
JFNG	97.08	99.31	99.90	99.38	100.00	100.00	98.72	98.85	99.69	99.93	99.51	100.00	98.82
STFU	99.86	100.00	41.56	93.96	99.90	93.13	76.94	27.99	85.31	99.86	99.97	29.86	29.69
KZN2	97.53	99.65	98.23	100.00	95.31	99.86	100.00	99.48	99.93	98.92	99.86	99.93	99.90
TOW2	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	0.00
RGDG	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	100.00	0.00	0.00	0.00	0.00
MAJU	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	0.00	0.00	0.00	0.00	0.00
DUND	100.00	99.24	100.00	95.83	100.00	100.00	87.50	100.00	100.00	100.00	100.00	100.00	100.00
OHI3	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
CAS1	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
SUTM	100.00	100.00	100.00	100.00	86.46	73.96	100.00	100.00	100.00	100.00	100.00	100.00	100.00
LAUT	0.00	81.98	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00

Figure C.4: Results of the fourth 25 days for the Daily Station Availability