Realisation of a flexible multi-sensor-reference system for challenging GNSS reception conditions

Projektarbeit

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MS60	Multistation 60
LC	Loosely Coupled
TC	Tigthly Coupled
IMU	Inertial Measurement Unit
INS	Inertial Navigation System
FOG	Fibre Optical Gyroscope
GNSS	Global Navigation Satellite System
RINEX	Receiver Independent Exchange Format
COS	Coordinate-system
PPP	Precise Point Positioning
RTK	Real Time Kinematic
ARP	Antenna Reference Point

1 Introduction

Today, it is more important than ever, to collect informations about several sensors which are in motion. For example, a vehicle which should drive autonomously uses a wide variety of instruments to determine its orientation. Those sensors have to be calibrated and initialised. To realise that, a reference trajectory is needed to compare with the used instruments. In an open sky environment, a GNSS antenna and receiver should be enough for getting a accurate solutions. But to form an reference trajectory, proper GNSS observation and other sensors have to be used to get high precision. In addition, most of the time high buildings or extremely foliage disturb the satellite signal which makes it almost impossible to get an accurate solution. Possible error sources could be multipath.
Therefore, reference sensors cannot be realised only by a GNSS system. To get a proper solution, many devices are installed that have a complementary characteristics and are used to become more accurate and precise. The idea behind it is, when a GNSS failure is detected the navigation engine have to rely on the other sensors, for example inertial measurement unit. Furthermore, an IMU is constantly used for determining its orientation, which is nearly impossible by a GNSS receiver itself. With more than one GNSS antenna, you can measure the three orientation angles, however with a huge computation load.

In this thesis, three sensors are used to provide a high-accurate and continuous reference trajectory. Those are a GNSS antenna and receiver, IMU and a tacheometer. As mentioned before, the IMU measures orientation and takes over when a GNSS disturbance is detected. To provide informations about the orientation, the IMU have gyroscopes and accelerometer which measure independent from GNSS. After a long GNSS failure, there will be still a huge problem, because of the short time stability of the used IMU. After a long time without GNSS updates, the IMU standalone solution would become non-viable because it needs a position update. For that reason a tacheometer is also installed. This sensor is able to provide informations about the position with timestamps. Unfortunately, those timestamps are not constant and an unobstructed view between the sensor and vehicle have to be given. It seems that every sensors has its advantages and disadvantages. The goal is to fusion those sensors together to get more advantages than drawbacks. In addition, the aim of this thesis is not only creating a reference system, but making it flexible so that this setup could be used anywhere with a not time consuming construction.The main advantage of a flexible reference system is that the setup is not restricted to only one locality. This makes it possible to measure trajectories in real environments. This informations helps reconstructing car crashes and helps autonomous cars which could calibrate while driving to asses the accuracy and validate the requirement made be the law makers.

However, to make sure the described equipment can be integrated and working properly, several tests were planned. At first, the functionality of every sensor have to be tested and proved. Afterwards, all of them are installed onto a vehicle which drives multiple pattern in different locations. This should simulate a drive around in a real environment where GNSS signals reception could be difficult. At the end, all data will be collected and fused by means of a post-processing GNSS/INS software to obtain maximise precision, accuracy and minimize the standard deviation. In addition, a comparison between two IMUs from different classes are planned to show how reliable they are with a simulated artificial GNSS gap.

2 Coordinate Frames

Navigation is a big part of the current life, it describes the orientation, motion and position of an object. An Aircraft, vehicle or even a person could be that object. To describe those parameters a specific point must be define, which works as its reference point for the object and is also known as the *origin*. It can selected randomly, maybe the center of mass, the geometrical center or as in the most GNSS constellation the phase center of the antenna (APC). However, if the measurement only contains an inertial measurement unit (IMU) there will be no APC because of the missing antenna. In this example, a reference point must be chosen.
To have such information about the position and motion is meaningless unless these are related to a coordinate systems with three axes to align and orientate the object. Because it is a big different if a car has a speed of 60 m/s in respect to the sun instead to the earth. It would be also nonsense to measure the speed of a car or its position in reference to the sun. But sometimes, for example an interplanetary satellite mission, it is necessary to have a reference to the sun. To summarize, there are many different coordinate frames and systems which are there for specific measurements. In a lot of cases there are many instrument involved to calculate the position of an object. To combine or compare those solutions it is inevitable to transform their coordinate system which will be described in 6.3.1. In the following subsection there will be characterize some common coordinate frames, which some are also used for the main measurement.

2.1 Body Frame

The body frame has its origin somewhere in the object with takes place in the navigation. The forward axis is called the x-axis, which is ahead of the object. Like some other coordinate systems, the z-axis is pointing down as well. To complete the orthogonal system, the y-axis is placed on the right side of the object. These axes move and rotate along with its object, to remain fixed. As shown in figure 2.1, rotation along the axes are also know as roll, pitch and yaw. Like in the figure, roll motion is about the x-axis, pitch about the y-axis and yaw about the z-axis.

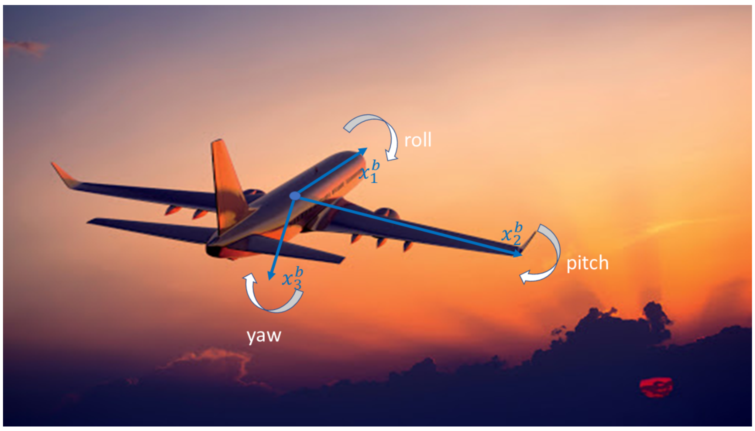


Figure 2.1: Attitude angles

> "A body frame is essential in navigation because it describes the object that the navigation solution refers to. Inertial sensors and other dead-reckoning sensors measure the motion of a body frame and most have a fixed orientation with respect to that frame"[p.29] [14]

2.2 Inertial Frame

An inertial reference system (i-frame), is a not accelerated system. It is defined to be stationary in space (fixed star) or moving with a constant velocity. Inertial sensors, like an IMU are measuring relative to an inertial frame [2]. In those coordinate systems, bodies without applied force are only moving linear in uniform motion, which is Newtons first law. However, a COS on earth experience acceleration, for example the gravity. To still form a reference system, specific force have to be considered which leads to an adjusting of the Newton laws [6]. In this case there is only a *pseudo-inertial frame* possible. For example a near-Earth environment is chosen (Earth-centered inertial frame). The origin would be the center of mass of the Earth. Z-axis is along the axis of the Earths rotation. The x-axis is pointing towards the vernal equinox and the y-axis completes the right-handed system.

2.3 Earth-Centered Earth-Fixed Frame

The origin of this coordinate frame is placed in the center of the earth, which is roughly at the center of mass [p.27][14]. The x-axis points towards the intersection of the equator with the conventional zero meridian, which defines 0° longitude. From the center of earth to the north pole proceeds the z-axis. The y-axis completes the right-handed system and is pointing to the intersection of the equator with the 90° east longitude, which makes the coordinate frame orthogonal. In contrast to the Earth-Centered Inertial Frame, this coordinate frame rotates with the earth which results that the axes are always pointing to the previous described points. The ECEF coordinate system is also known as the Conventional Terrestrial Reference System (CTRS).

> ”The Earth-centered Earth-fixed coordinate system is important in navigation because the user wants to know his or her position relative to the earth, so its realizations are commonly used as both a reference frame and a resolving frame.” [p.27] [14]

2.4 Local Navigation Frame

As its name implies, this coordinate system is for local use. Also known as geodetic, geographic or topocentric frame. The origin is a selected point from the object which is part of the navigation. Z-axis is following the gravity vector to the center of earth and the x-axis is pointing orthogonal towards the north pole. To fulfil the orthogonal right-handed system, the y-axis points to the east. This is the most common form of local navigation. This coordinate frame helps the user to locate the attitude relative to north, east and down directions.

> ”For position and velocity, it provides a convenient set of resolving axes, but is not used as a reference frame” [p.28] [14]

2.5 Local Tangent-Plane Frame

In some circumstances this coordinate system is not so different from the Local Navigation Frame. The z-axis is pointing down, the x- and y- axis may following the topographic directions north/east. But in some cases the axes may align orthogonal with environmental objects, such as a building or road. The origin of this frame is always in respect to the earth. So it appears, that this frame is earth fixed but not earth centered. It is because of its field of application, which are navigation within localized areas.

3 GNSS/INS Coupling Strategies

Both INS and GNSS solutions have many advantages, but also some disadvantages. In the next section will be described integrations of both systems to cancel out their drawbacks to make the measurement more precisely and stable. Most common integration are:

- uncoupled Integration
- loosely Coupling
- tigthly Coupling

All of the mentioned couplings are using a filter to maximise their position accuracy. The Kalman Filter is an algorithm which was developed in the 1960s to estimate the status of a linear system. This algorithm was even used for the Apollo missions and nowadays it is used for several calculations [15]. The filter is divided by two parts, estimation and propagation, which are mutually dependent. For example a car, which position (x-axis) is measured at the timestamp t=0. The first step is estimation, where all measurement data is collected and used to estimate the position of the car. However, because of the deviations which are also used for the positioning like noise, is it nearly impossible to locate the exact position. Therefore, the estimation defines a Gaussian distribution, where the position of the car is most likely. In figure 3.1 is the distribution pictured, which has a small area where the car can be. This is the estimated position at t=0 with all collected data.

Figure 3.1: Determining the position of a vehicle (one Gaus distribution)

After that, the propagation continues which takes the previous estimated values and derivations to forming a new Gaussian distribution. This one gives out the new position of the car at the time t=1. The feature of this propagation is that only previous measured data is taken to form the distribution (see 3.2 red). Furthermore, instruments measure the position at t=1 as well for the estimation step, which is marked blue.

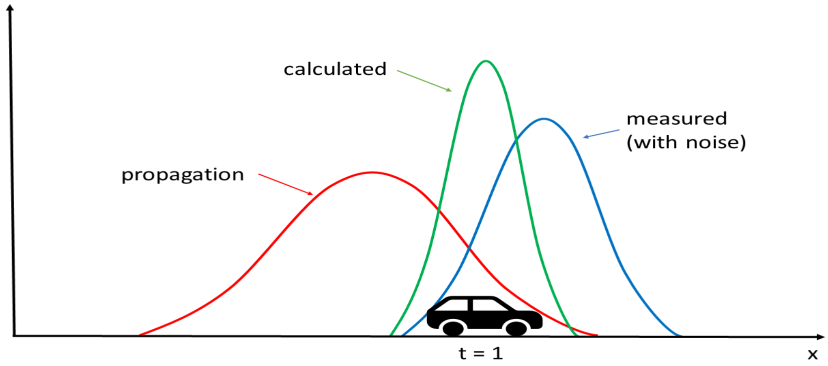


Figure 3.2: Determining the position of a vehicle (several Gaus distribution)

Those two Gaussian Distribution were multiplied by each other to get a new one (see 3.2 green, which is not bigger or more complex [15]. With this algorithm, it is possible to get the actual position by a state vector, which contains all information about the system. In addition, the filter can define its Kalman gain, which is calculated by the ratio of the developed covariances. This leads to an evaluation, which effects the influence of the measured data to propagated ones [6]. This step is important to have a convincing positioning in different environments. For example a car which drives on a road where several trees are on each side is not getting a lot of information by satellites. In this case the Kalman Gain trusts the IMU more, because of the lack of information by the GNSS.
To get more in detail, look at figure 3.3. By mean of the estimated value x_0 and thus error covariance matrix p_k, the Kalman Gain can be calculated. The noise-free matrix h_k, between measurement and state vector, and the correlation factor R_k are used as well. After that, both solution of the estimation and the real measurement z_k are combined to form x_k which is taken as the real measurement value. Moreover, x_k leads to a new correction matrix, which also create a new covariance matrix which is used for the next estimated value. For the calculation of the next estimation $P_k + 1$ and $x_k + 1$ is a transition matrix phi_k needed. The circle continued with the Kalman Gain and so on, until no more data is given to the Kalman Filter. This short paragraph should only show a quick understanding of the mathematics behind the algorithm, to go even deeper in the calculation read [1] or [16]

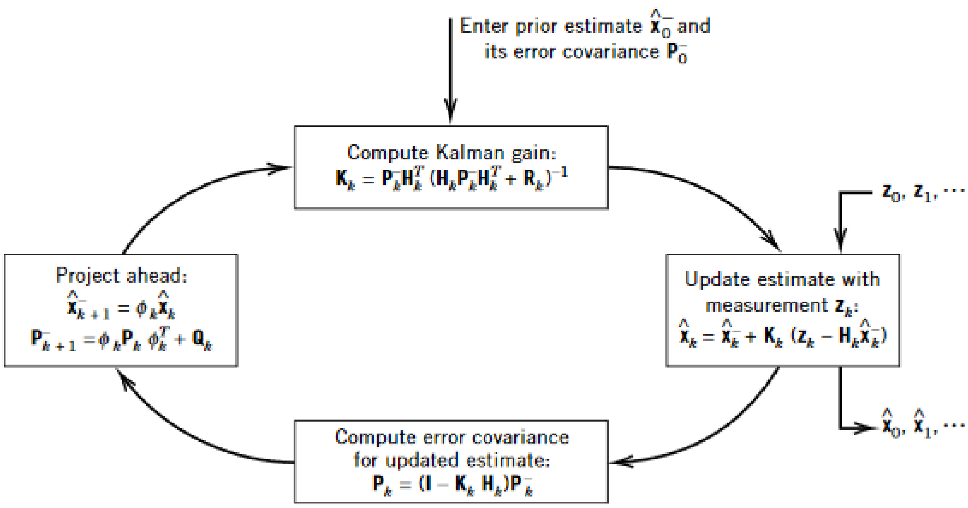


Figure 3.3: Visual display of the Kalman Filter [S.147][1]

3.1 GNSS only

The integration with no coupling is the easiest way to combine the data from different systems. Both of them evaluate their own measurement and send it to the Kalman Filter. After this process, the whole data is integrated to one solution. Position and velocity is determine by GNSS, in addition the INS calculate the alignment [S.40][6]. The Precision of the GNSS is nearly constant, whereas the IMU is not. With a longer measurement time, the IMU tends to drift with its data. This occasion leads to a higher priority of the satellite based data after a period of time. Nevertheless, the attitude is still calculated by the IMU, because it is to sophisticated to do it with satellites.

3.2 Loosely Coupling (LC)

As in the integration without coupling, both systems have their own solution. But as shown in figure 3.4 there is a repatriation of GNSS data into the Kalman Filter of the IMU [S.41][6]. The data taken with the satellites serve as supporting information for the calculation of the other system. This could help to reduce the error of the IMU sensors. However, another problem appears when there are less than four satellites visible. This leads to a navigation error [S.192][17]. Besides that, the solution is still better than without any coupling, but the system require a higher effort to set up and running.

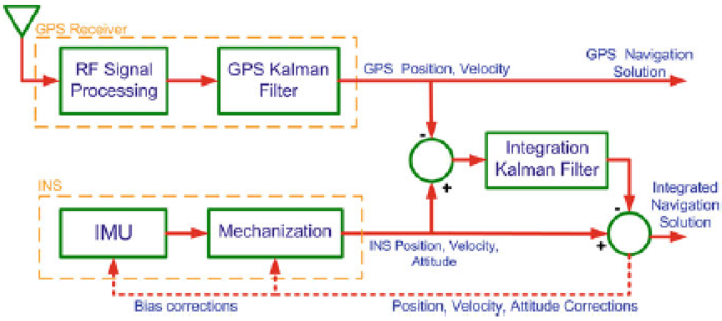


Figure 3.4: Block diagram of a loosely coupling [S.250][2]

3.3 Tightly Coupling (TC)

Despite to the other option, in this coupling there is only one Kalman Filter needed. The figure 3.5 shows the rough procedure. Raw data from both systems is send to the filter, instead of calculating its own solution [S.41][6]. This leads to a continuously error correction, because of repatriation of the bias error from the IMU. In contrast to the previous mentioned integration methods, it is now possible to get a solution even if there is less than four satellites visible. This can happen because of the raw data, which helps to determine the pseudo range and its navigation solution. Of course, the accuracy and stability increases with such integration, but it is also way more complicated to implement.

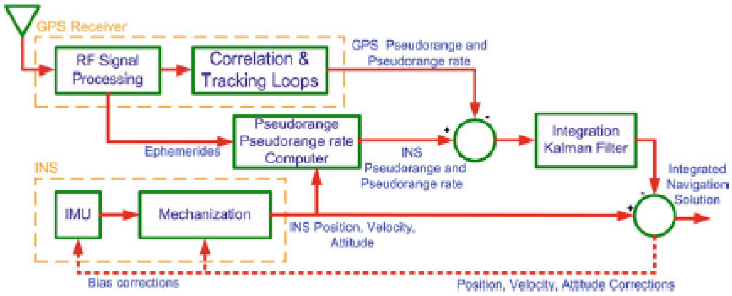


Figure 3.5: Block diagram of a tightly coupling [S.251][2]

4 Used Sensors

This thesis is about the fusion of different measurement systems, to form a integrated solution with all of them. The used sensors are a GNSS receiver, an Inertial Measurement Unit (IMU) and a target tracking tacheometer. In the following section each of the systems and their mechanics/functionality will be described.

4.1 Leica MS60 Total Station

Leica Nova Multistation 60 (MS60) is the used tachometer (shown in figure 4.1), it is a product of the *Leica Geosystem* company. A precisely description of the system, such as special gadgets and function is written down in a previous student research project [12].

Figure 4.1: Leica Nova Multistation 60 [3]

The tachometer is used on construction areas and for other local measurement work. It is like a theodolite, which is also able to measure the distance and angle [12]. The total station got an electro-optical distance measure (EDM), which is used to measure the direct range between an object. The EDM sends a light wave which is reflected, for example by a prism, and is then registered by the total station. Δt is the time which is needed for the distance between two objects. By multiplying it with the velocity of light c and consider the refraction index n, the product will be the range by using this formula $d = \frac{c}{2n} \cdot \Delta t$ [12].
As described, the distance and angel measurement is simultaneously, which allow the tachometer a polar recording of the measurement data. If the vertical- and horizontal angle is measured with the distance, it leads to three dimensional coordinates. The angle is calculated by measuring two directions. If the difference of both is taken, the horizontal angle is computed. Is one of them directed to the zenith, it is possible to calculate the vertical angle by the difference [12].

An important aspect of this thesis is the accuracy, which is shown in table 4.1. For the purpose of this thesis, the accuracy of one millimetre is quite useful, because of the high GNSS and IMU

Table 4.1: Accuracy MS60 [3]

Leica Nova MS60		
Angle Measurement		
Accuracy (Hz and V)	Absolute, continuous, fourfold	1" (0.3mgon)
Distance measurement		
Range	Prism (GPR1, GPH1P)	1.5m to 10000m
	without prism	1.5m to 2000m
Accuracy/ Measure time	solo (prism)	1mm +1.5ppm /typically 1.5s
	solo (without prism)	2mm +2ppm /typically 1.5s

standards. It is obvious that the accuracy with a prism is higher than a measurement without. The reason for that is the reflectivity of such object. The range of some meters to thousand is more than enough for the performance which takes place in this thesis. With an internal application *"Measure and Stream App"*, it is possible to use a sampling rate of 20Hz, which is going to be used.

4.2 GNSS

The *Global Navigation Satellite System* (GNSS), describe the different satellite constellation, which makes it possible to define a position. There are some constellation, the most known one is the *Global Positioning System* (GPS) from the USA. This one is mistakenly known for the whole concept of GNSS, but instead there are also satellite systems from Russia (GLONASS), Europe(Galileo) and so on. For a navigation solution, it is important to have a receiver as well. It gets signals from each visible satellite and processed them. There is a big range of accuracy, which depends of the satellite signal and the sort of the receiver. To perform a navigation, there have to be a minimum of four satellites visible. Three of them are used to measure the coordinates in x-, y- and z-direction. The last one is for the time synchronisation, which appears as really important. The reason for that, are the substandard clocks in the receivers, which have an unknown offset. To synchronize the receiver clock with the high quality atomic clocks in the satellites, it is necessary to solve the fourth variable (time-offset).

In contrast to the inertial navigation, it is almost not possible to align a system by GNSS. It is only possible to measure position and velocity. What ever the case may be, with more antennas it is able to align the systems by only GNSS [18], which is far more costlier.

There are different opportunities to get a GNSS solution for position and velocity. In this thesis are described the two most common ones, carrier phase and code pseudo-range.

Code pseudo-range

A code from the satellite is sent to a receiver, which contains navigation data. These information appears on every impulse, which is every second. As mention before, the time of both systems (satellite and receiver) have to be synchronize for that. After that it is possible to get a pseudo-range with the following equation [7].

$$P = \rho + c(dt_{sv} - dt_r) + T + I + \varepsilon \tag{4.1}$$

The clock from the satellite is read by a receiver, this is why there appears a read out error ε. Furthermore, there is also an error of the satellite clock dt_{sv}. If those two variables are subtracted from the real time t, which is unknown, the time of the satellite t_{sv} comes out. To illustrate it, look at the following formula.

$$t_{sv}(t) = t - dt_{sv} - \frac{\varepsilon}{c}{}^{1} \tag{4.2}$$

This formula applies also for the receiver clock, without the read out error.

$$t_r(t) = t - dt_r \tag{4.3}$$

With those equations it is possible to calculate the difference of both clocks. When multiplying this with the velocity of light, the solution would be the pseudo-range.

$$P = c(t_r(t) - t_{sv}(t - \tau)) \tag{4.4}$$

Where τ is the time, which takes the signal from departure to arrival. After applying it to equation 4.2 the solution is $t_{sv}(t) = t - dt_{sv} - \frac{\varepsilon}{c} - \tau$. After that 4.4 forms into

$$P = c(dt_s - dt_r + \tau) + \varepsilon \tag{4.5}$$

There is a model for τ which contains the geometric distance(ρ), delay of the signal by troposphere(T) and delay by ionosphere(I)

$$\tau = \frac{\rho + T + I}{c} \tag{4.6}$$

The whole equation is reduced by the velocity of light for the units. After putting everything together, the equation 4.1 is created.

Carrier Phase

In contrast to the previous mention method, there is no need to modulate the code on a carrier phase, because now it is its own periodic signal. With this phase it is possible to determine the duration of the signal from satellite to receiver. The carrier phase is described with the following equation

$$\Phi = N\lambda + \rho + c(dt_{sv} - dt_r) + T - I + \varepsilon \tag{4.7}$$

and is almost equivalent to 4.1. Because of the small period of the signal, the accuracy of position is a lot better, which is some millimetres [7]. But this leads to an ambiguity of N multiples, which has to be multiply with the wavelength (λ). To be noted, the ionosphere effect (I) is opposed in contrast to the pseudo-range, which is why it has a negative sign.

4.2.1 Trimble NetR9

In this thesis, the *Trimble NetR9* (see fig. 4.2)receiver and *Trimble Zephyr 2* Antenna is used. This systems allows a sampling rate of 1Hz, which is used for the following accomplishment. As mentioned before, it is important to look at the accuracy, which is shown in table 4.2. It seems that the *MS60* have a better accuracy than the Trimble. This is because of the measurement conditions. *Leica* is specialized for static applications, while *Trimble* is often used for kinematic scenarios. This makes a huge different when it comes to accuracy, because it is more likely to have a "worse" solution if the measurement object is in motion. My previous thesis [12] and [19] show, how the accuracy of the *MS60* really is, when there is a dynamic measurement. There is a difference of several centimetres to the static usage. To make sure that the measurement with a GNSS system has a high accuracy, correction services are used. Those provide the user with real-time positioning via satellite or internet. The advantages of these services is availability, because there is no need for a base station. *CenterPoint RTX* is the service which is used for the GNSS setup, which is also provided by *Trimble*. The accuracy of this service is shown in table 4.2 as well. More about the Services in 5.

[1] ε is reduced by the velocity of light to have only the unit seconds

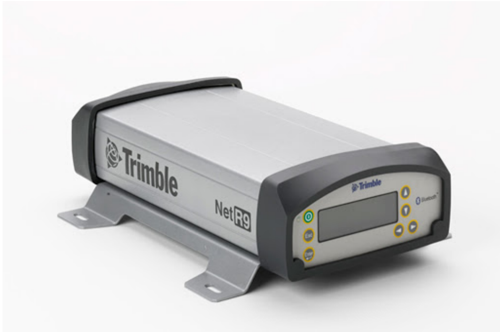


Figure 4.2: Trimble NetR9 [4]

Table 4.2: Position accuracy *NetR9* [12] [13]

	Real Time Kinematic Observation	*CenterPoint RTX*
	Single Baseline <30km	
Horizontal	8mm + 1ppm RMS	2cm RMS
Vertical	15mm + 1ppm RMS	5cm RMS

4.3 Inertial Measurment Unit (IMU)

The previous mentioned systems are for the measurement of distance and position. With timestamps it is possible to get information about the velocity as well. But with an inertial measurement unit (IMU), it allows to measure the acceleration and rotation. Using this data, a orientation and determination of its own alignment is possible. As known, acceleration is the second temporal derivation. If this value is integrated, the result is velocity. After a second integration the solution is the position. This is how an IMU could provide all those informations.
To measure the acceleration, the IMU have three Accelerometer and gyroscope. Those instruments are in orthogonal order to measure the translation and rotation. The previous mentioned integrations have some disadvantages, because every single time it creates a unknown variable. This can be solved by information which the sensor is recording, but after a long period of time an error occur. This error can rise so high, that the solution is not longer usable. To eliminate this, a fusion with GNSS and IMU could help (see 3). Another method is using a high cost IMU, which deliver stable solution for a long period of time.

4.3.1 Xsens MTi-G-710

The used IMU is defined as a low cost variant, which has the name *Xsens MTi-G-710* (see fig. 4.3). This device has an included GNSS receiver, which makes it possible to get satellite-improved three dimensional alignment. Furthermore, besides information about position and acceleration, it now uses the time to form timestamps. The measurement rate for the experiments are 200Hz[2]. In the experiment there will be two *Xsens*, one on top of the vehicle and one in the trunk.

Like the other sensors, it is important to know the errors which can occur by the measurement. Accuracy are shown in table 4.3. Like said in the last paragraph, it is a low cost IMU, which has not a real good stand alone solution over time. Therefore, it will be coupled with GNSS to updates its measurements.

[2] 400Hz could be reached

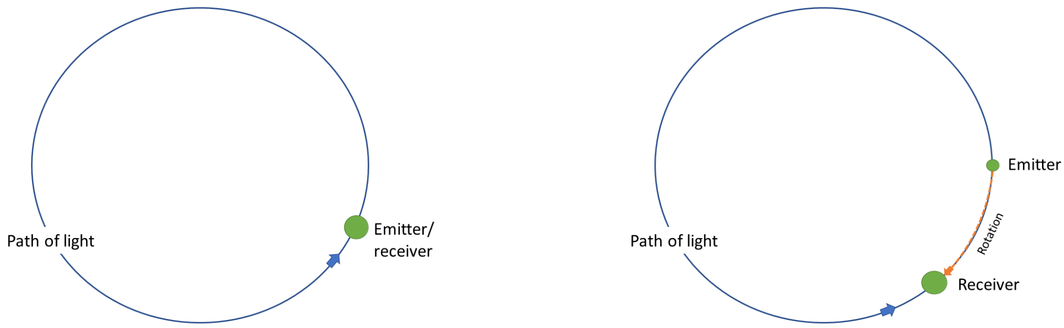
Figure 4.3: Xsens MTi-G-710 [5]

Table 4.3: Technical Data Xsens MTi-G-710[5]

Calibrated sensor data		
Roll/pitch	Static	0.2°
	Dynamic	0.3°
Yaw		0.8°
position and velocity		
Horizontal position	1 σ STD	1.0 m
Vertical position	1σ STD	2.0 m
Accuracy of the velocity	1σ RMS	0.05 $\frac{m}{s}$
Sensor specification		
	Gyroscope	Accelerometer
Initial Bias error	$0.2\frac{\circ}{s}$	5mg
Bias stability	$10\frac{\circ}{h}$	15μg

4.3.2 iFOG

In contrast to the previous mentioned IMU, the *iFOG* is a high quality IMU which is also more expansive (see fig.4.6). *FOG* stands for *Fibre Optical Gyroscope* and is primarily used to measure the rotation. Those optical gyroscopes take advantage of the *Sagnac-Effect* (see fig. 4.4). Light which is sent by an emitter follows a designated path back to its origin. The system measures time which is needed for the light to come back and the distance can be calculated with $s = c \cdot \delta t$. If the device is rotating while the measurement, the distance will be different as well as the time. With those parameters, the gyroscope can define its rotation and angles.



(a) Path of light (static system) **(b)** Path of light while rotation

Figure 4.4: Shortening the path of light due to rotations [6]

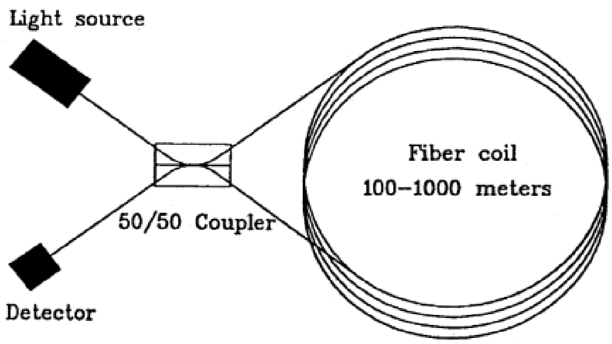


Figure 4.5: Simplified setup for a FOG [7]

Figure 4.6: iFOG IMU [8]

A problem with *FOG* based measurement are the fibres, because of its asymmetries and scattering of light. This causes problems with the *Sagnac-Effect* [7]. Due to more windings, which are seen in figure 4.5, a rotation around the sensitive axis has a bigger impact on the travelled distance. This leads to measure the intensity fluctuations instead of the interferometry phase.

The IMU is from iMAR which is a company near Frankfurt in Germany. They have experience in inertial measurement and navigation for more than 25 years [20]. Beside that, iMAR have a wide field of competence, for example submarines, drones and vehicle even for the military.
The iFOG IMU will be placed in the trunk of the vehicle (next to the *Xsens*). As the name suggest, the IMU is *FOG* based, which means it "use loops of optical fiber and measure interference in beams of light in opposite loops to detect rotation in each axis. The hardware used is more expensive, larger and typically consumes more power but its lack of moving parts makes it less sensitive to temperature changes and mechanical vibration." [21]

In table 4.4 is shown the accuracy of the used IMU and its gyros or accelerometer. Looking representative at the bias, it is clear that the *iFOG* is a lot more precise than the previous mentioned *XSens*. This can also be observed at different criteria. For example at the long time stability, in contrast to the low cost IMU, now the data should be more accurate (for a longer time) after a GNSS signal loss. It has to be mentioned that the errors which are described in formula **??** are also applying for the *iFOG*.

Table 4.4: Technical Data of iFOG-IMU[8]

	Angualar Rate	Acceleration
Sensor Range	$\pm 450 \frac{\circ}{s}$	$\pm 5g\ (option: \pm 20g)$
Bias	$< 1.0 \frac{\circ}{h}$	$1.5mg$
Bias Stability (AV)	$< 0.1 \frac{\circ}{h}$	$< 0.01mg$
Resolution	$0.1arcsec/LSB$	$0.05/2^{15} \frac{m}{s}/LSB$
Linearity / Scale error	$< 0.03\%/0.03\%$	$< 0.1\%/0.1\%$
Angular random walk	$< 0.15 \circ / \sqrt{h}$	$< 50\mu g/\sqrt{Hz}$

5 GNSS Correction Services

For making the GNSS solutions more accurate and precise several services can be used. Those can improve the positioning in real time to few millimetres. In the following section are three common services described. One of them (RTX) is used for the the ongoing experiments.

5.1 CenterPoint RTX

RTX stands for Real Time eXtendet and is a service provide by the company Trimble. This service is available via satellites or cellular delivery worldwide [22]. The accuracy should be less than two centimetres. Furthermore, there is no need of a base station or terrestrial infrastructure. It is possible to increase the accuracy anywhere with fast initializing. In selected areas the solution converges within seconds, in other areas it should not be take more than five minutes [22].
In figure 5.1 is displayed how the RTX technology works.

> "Trimble RTX real-time GNSS corrections consist of precise satellite ephemeris, along with highly accurate atmospheric models. The corrections are generated by using satellite measurements from a global network of ground based GNSS tracking stations. These corrections are broadcast to the receiver via regional geostationary satellites or over the Internet, which the GNSS receiver uses to improve the accuracy of its positions." [9]

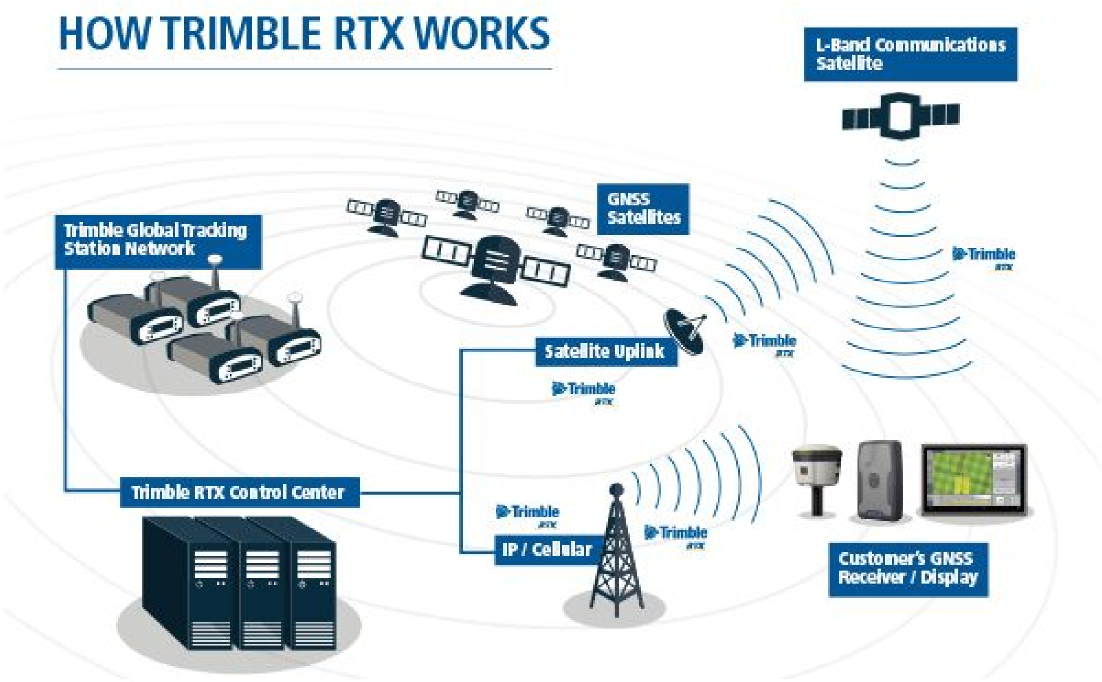


Figure 5.1: Workflow of the RTX service [9]

5.2 SAPOS

SAPOS is a satellite positioning service provided by the federal states of Germany. It is a network of several permanent reference stations [23]. With this service a complete coverage of correction parameters is possible which leads to high accuracy DGNSS measurements. Moreover, three-dimensional positions are given directly in the *ETRS89* reference frame [23]. As well as working with RTX, the user is not forced to use a second receiver for reference points.

5.3 PointPerfect

The service by *ublox* uses advanced PPP and RTX mechanism to get a fast convergence and a accuracy of few centimetres [24]. Like the company says,

> "PointPerfect is an advanced GNSS augmentation data service designed from the ground up to be accurate, reliable, and immediately available." [24]

The coverage of this service is limited to Europe and the contiguous USA.

6 Measurement Campaigns Planing, Realisation and Evaluation

6.1 Planned Scenarios

The following description are the planned implementation which should take place in the test drive. This leads to information about the raw data of each instrument. To have a wide range of information, there are four scenarios planned, while each of them have a different focus.

6.1.1 Open sky (scenario 1)

With an open sky scenario, there are the best conditions for a GNSS measurement, because there is no such thing as foliation or shading. So it could be handled as a reference for the following measurement.
In figure 6.1 is the drive pictured. The green dot is the starting point, where the vehicle have to stand for approximately 10 to 30 minutes. While the bus is standing, GNSS and INS data are collected to align these instruments. After that, the vehicle will drive the shape of an eight for about five times, which works as a dynamic alignment. Next, there will be a right turn and the bus should accelerate to $80km/h$. A turn around of 180° take place after a few hundred meters, which will be continued with an acceleration of 100 to 130 km/h. At last, the vehicle will turn back to its ending position (black dot) and stands there for another minute.

Figure 6.1: Scenario 1 : Intended path of driving

6.1.2 Shadowing (scenario 2)

At the green starting point, the car will stand there for about 10 minutes. After that, it will drive the shape of an eight a few times and then head to the street. (red line, see figure 6.2) On the road are many trees which is also shown in the figure. On the way to the next building, the vehicle should drive with a velocity of 30km/h, make a turn and then follow the yellow line to the starting point, where it rests and measure for another minute.
This scenario will show the integration of the used measurement when GNSS signal, as a stand-alone solution, is quite unreliable.

Figure 6.2: Scenario 2 : intended path of driving

6.1.3 Change between open sky and shadowing (scenario 3)

As usually the measurement starts with an 10 minute alignment and stops with a resting of the bus at the destined point, which is also the starting point (green dot, see figure 6.3). After the alignment the vehicle continue to drive the shape of an eight for several times and then following the red line to the circuit. This one is marked with the blue and yellow lines. So the vehicle will start to drive in the blue direction and then turn around and follow the yellow line. This circuit should be driven three times, in the third round, the bus will drive along with the red line near the end of the yellow one.
When the vehicle is on the road, it is exposed to shading, when it drives to the starting area (which is a parking lot) it is has open sky. In this scenario, it is interesting how the integration of the systems works when the measurement environment changes a few times.

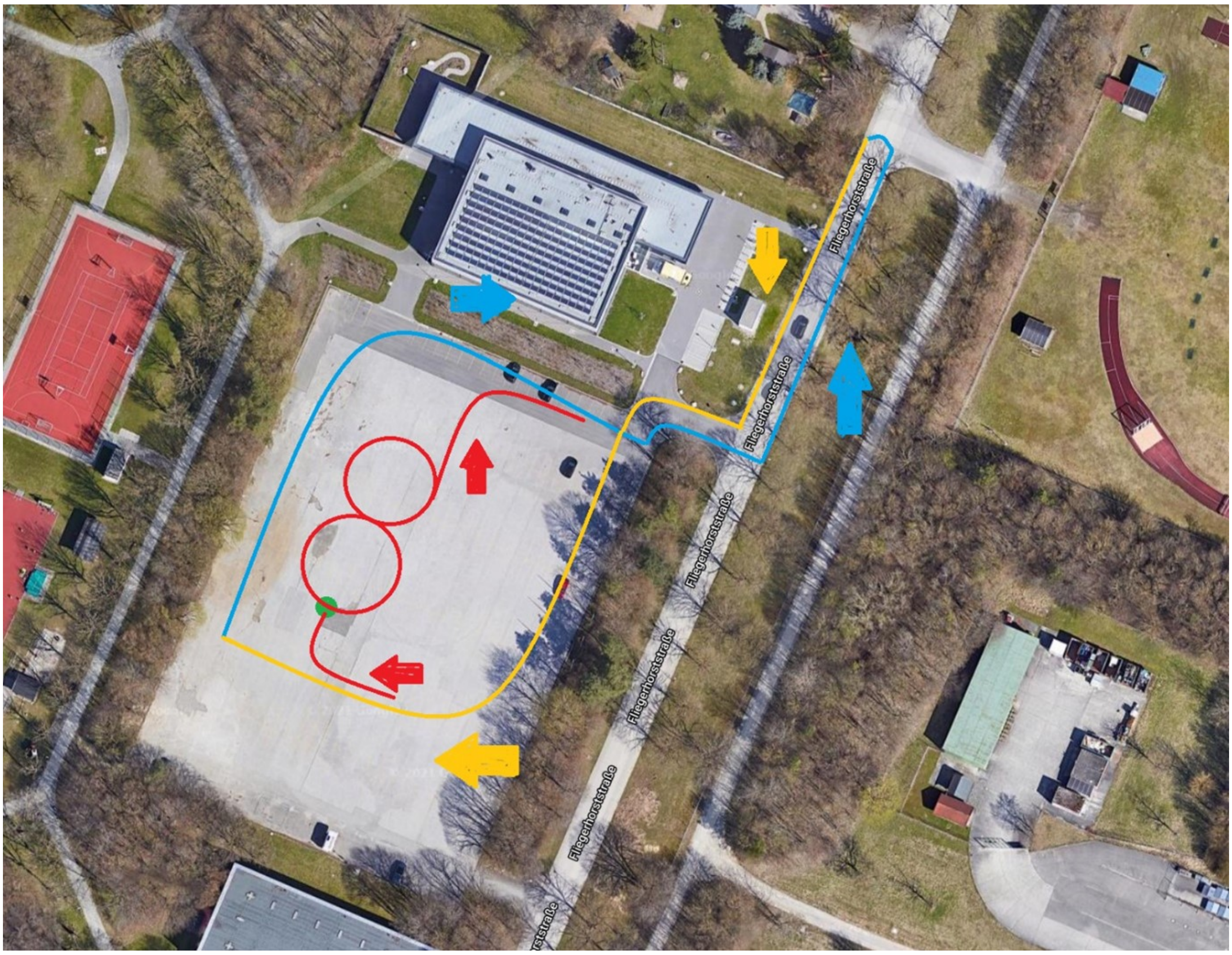


Figure 6.3: Scenario 3 : intended path of driving

6.1.4 Suburban Area (scenario 4)

The last scenario should represent the real driveway of a car which is in a little town or even in a suburb.
The green dot (as seen in figure 6.4 marks the start and finishing point, where the vehicle have to stand for 10 (start) and one (end) minutes. After the static alignment, the shape of an eight should be driven and then head to the blue line between the buildings. The yellow line represent the drive back to the starting point. The velocity is set to around 30km/h.

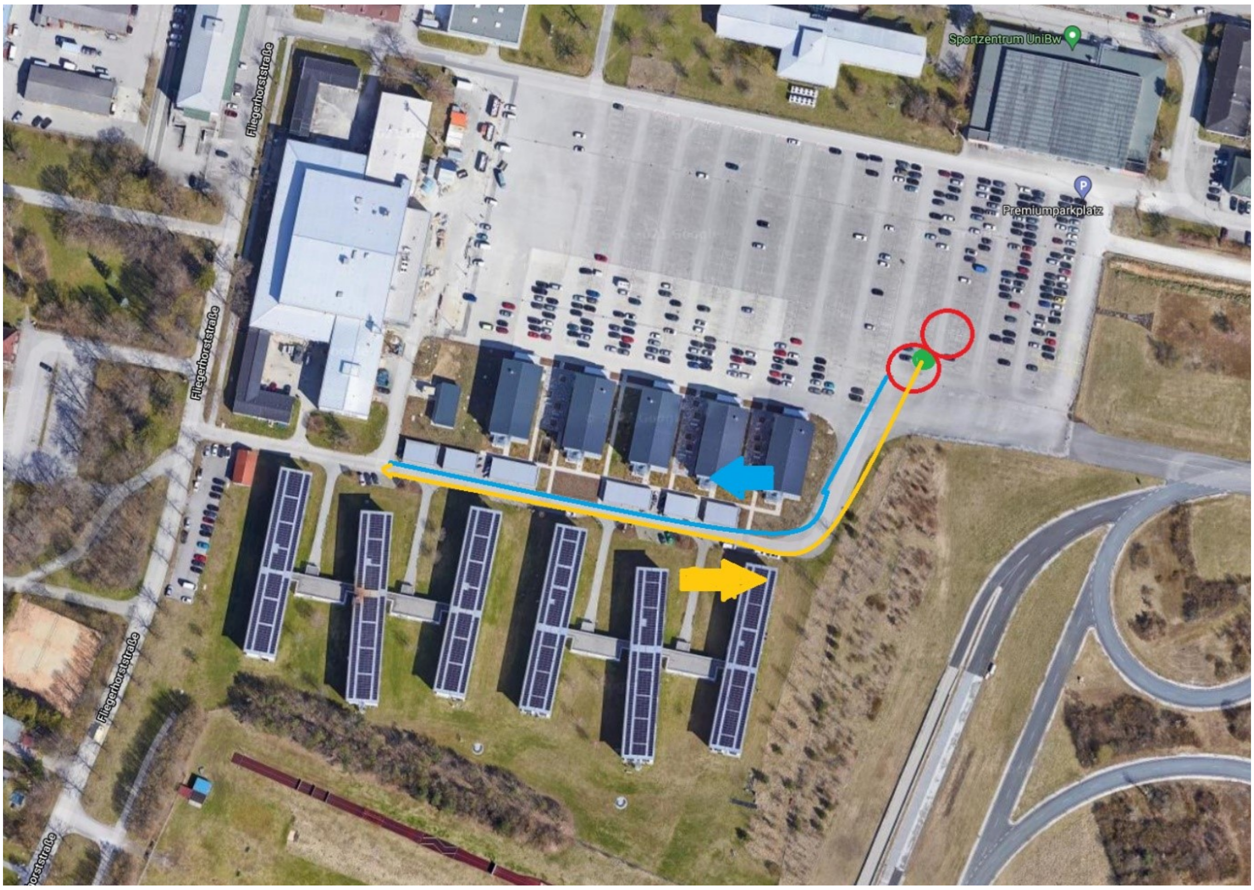


Figure 6.4: Scenario 4 : intended path of driving

6.2 Test of the Flexible Positioning Method with MS60

To make sure that the *MS60* will be working accurately in the main performance, there will be another process for only this system. In this set up, the Multistation is orientated with two reference points, afterwards the *MS60* should measure its own position and some other coordinates. Every point which is measured by the system from *Leica* will be unambiguously definite by a GNSS Antenna. The "Institute of Space Technology & Space Applications" already have some pillars which were perfectly measured. Unfortunately by continental movement these coordinates are not longer valid. For solving this problem, the position of some pillars were renewed. The measurement was realized by a *Zephyr 2* antenna and a *NetR9* receiver, both from *Trimble*. In the tables 6.1 and 8.3 (appendix) are the GNSS solutions. Everything was given by the receiver itself, except the UTM coordinates which were converted via a Matlab script. Standard deviation which occurred during the measurement are shown in table 8.4 (see appendix). The used reference frame for the GNSS was *ITRF2008*.

After determine the reference position, it was possible to orientate the *MS60* in a area which is shown in figure 6.5.

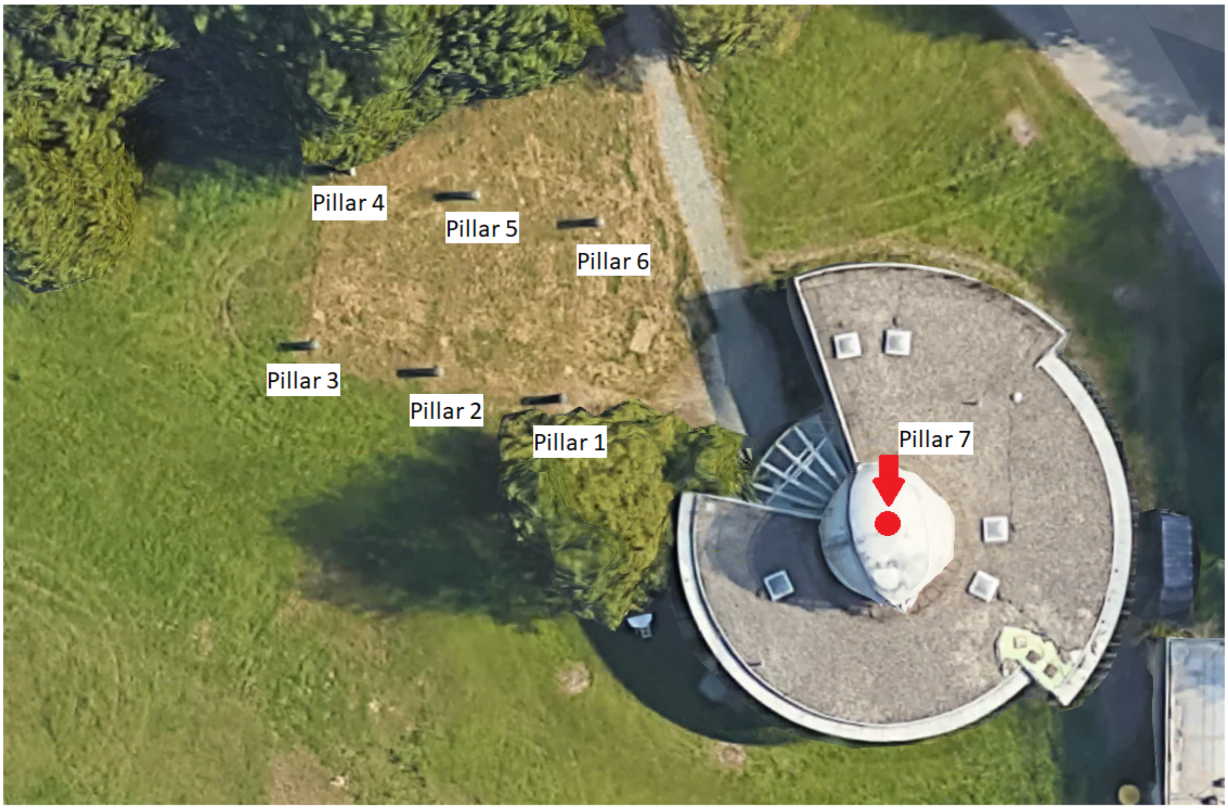


Figure 6.5: Assembly of the Pillars

The Multistation was placed on Pillar six and a circular prism was mounted on pillar two and three. With those prism, the *MS60* is able to calculate its own position and is ready to measure random points nearby. It is only necessary to provide the exact coordinates[3] of the prism to the *MS60*. For reference, the Pillar two and three were measured by the *MS60* again, despite the fact that those Pillars were already been used for orientation. In table 6.2 are the UTM coordinates, given by the *Multistation*. For the record, the value for Pillar six was not measured, it was calculated by the *MS60* trough the alignment. In table 8.1 is shown the standard deviation of the mentioned system for this assembly (see appendix).

For a second test, the Multistation was placed on Pillar five, the reference point were at two and six. The reason for that is the geometry of the orientation. Results are in appendix 8.2.

Table 6.1: Measured coordinates with *Trimble Receiver*

Pillar	Ellipsoid Coordinates		UTM		
	Latitude [deg]	Longitude [deg]	East [m]	North [m]	Height [m]
1	48.077779	11.628913	695786.165	5328287.993	594.589
2	48.077768	11.628768	695792.082	5328286.926	594.655
3	48.777572	11.628847	695797.992	5328285.929	594.693
6	48.077705	11.628666	695784.721	5328279.655	594.686

As shown in the tables, a difference of some centimetres is still noticeably. A reason for that could be the standard deviation of the *MS60*, whose amount is approximately some centimetres

[3] *MS60 will only accept UTM coordinates*

Table 6.2: Measured coordinates with *MS60*

	UTM			Difference to GNSS		
Pillar	East [m]	North [m]	Height [m]	East [cm]	North [cm]	Height [cm]
6	695784.761	5328279.580	594.663	3.98	7.55	2.29
3	695798.001	5328285.927	594.663	0.89	0.14	2.97
2	695792.073	5328286.927	594.651	0.87	0.15	0.36

in north/east (see tab. 8.1). For the next experiment, there will be as much reference points as possible to make sure the deviation will decrease.

6.2.1 Orientation with more reference Points

Like in the last positioning, the *Multistation* will be placed on pillar five. But now every single pillar, whose position is measured with GNSS, is taken to orientate the system. This means that pillar one, two, three and six were taken for the placing. With those four reference point a standard deviation below one centimetre is achieved. This value only applies to the orientation (north,east), the deviation of height is still over one centimetre. In the experiments which will described later in the thesis, it is only possible to measure two to three reference points for the whole *Multistation* orientation. But in those performances, the geometry is not limited like before. That means, the position of those points can almost be choose freely. This would lead to a higher accuracy of the *MS60*, if the reference points are around the Multistation and not only in front of it.

6.2.2 Assessment of the RTX Performance

Beside the *MS60*, solution from GNSS could also be inaccurate. The accuracy of the receiver and service was already discussed in 4.2.1. The standard deviation is quite low (see 8.4). However, it could be possible that the solution is only precise, but not accurate. For a better understanding, see figure 6.6.

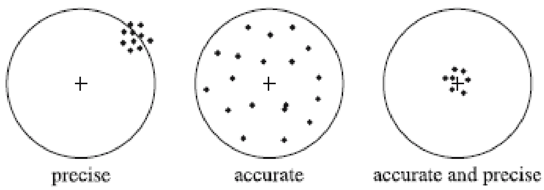


Figure 6.6: Accuracy and precision of measurement [10]

If the data do not spread wide around the mean value, the standard deviation is low and it leads to a precise measurement. However the whole data could have a big offset to the real position. A accurate measurement means that the mean value compares to the real position. In this scenario, the standard deviation is higher because of the wide spread of the data points. If both, precision and accuracy is combined, a valid measurement is ongoing. At this moment, it is only known that the previous GNSS data is precise. To make sure that the GNSS solution is valid, there will be a new test for it. Now, no longer the position and their coordinates are interesting. Instead the distance(d_6i) between each point will be calculate. If both systems works accurately, there should be no difference between the GNSS and *MS60* solution. The coordinates from the pillars

Table 6.3: Distance in relation to Pillar six

Pillar	MS60 [m]	NetR9 [m]	difference [mm]
1	8.4719	8.4631	0.88
2	10.3667	10.3604	0.63
3	14.6828	14.6813	0.15

are already measured with the *Trimble NetR9*, those values could be calculated with the following formula.

$$d_{6i} = \sqrt{(x_6 - x_i)^2 + (y_6 - y_i)^2 + (z_6 - z_i)^2} \tag{6.1}$$

The Multistation was placed on pillar five with a local orientation. Pillar six and one were used for it, where six served as the point of origin. The connecting line to pillar one is in local *north* direction. East is orthogonal of it, beginning in the origin. Now a local coordinate system is created where the distance could also calculated with the formula 6.1. Because the point of origin from the *MS60* is pillar six, all distances will be in reference to this position. In table 6.3 is shown the distance measurement of both systems. The difference is not more then some millimetres which means that the GNSS solution is accurate and precise. The deviation can be a consequence of all errors from both systems combined, such as the prism, *RTX* and so on.

6.2.3 Validation of the Proposed Method

After knowing all specifics from the mentioned systems, a short experiment was build. The prism and the GNSS antenna were mounted on the measurement bus. The antenna was on top of the Prism, which means that there should be only a offset in height. After about twelve minutes the GNSS solution was used to compared with the *MS60*. In table 6.4 are the measured coordinates with the standard deviation from both systems. Like in the previous measurements, the standard deviation of the Multistation is still higher than the one from GNSS, except for the height component. A difference of under two centimetres in north and east is acceptable under those circumstances. By reducing the offset between the prism and antenna there is still a difference of 3.49 centimetre. This value is still high but satisfactory for the following experiments.

Table 6.4: Coordinates and deviation between *MS60* and *NetR9*

	MS60		*NetR9*		Difference [cm]
	Position [m]	std dev [cm]	Position [m]	std dev [cm]	
North	5328285.3610	1.37	5328285.3781	0.4	1.71
East	695794.2139	1.09	695794.1957	0.3	1.82
Height	595.5414	1.15	595.651	2.4	10.96

6.3 Evaluation

In the previous mentioned experiments many data points of different sensors were collected. Those instruments should be integrated into each other to get a high quality solution. To perform such fusion, a special program was used. It shows how reliable a GNSS only solution is, when there is such things as shading and foliation. This will be compared with the solutions were IMU and later the *MS60* are integrated.

6.3.1 Post-processing GNSS/INS Software TerraPos

For the integration of multiple sensor and information the program *TerraPos*[4] was used. This platform allows a high accuracy data analysis, including the position or alignment [25]. In *TerraPos* it is possible to integrated as much sensors as required. At first, a GNSS solution is created, with that it is possible to create a Loosely coupling with an IMU. However, it is also a Tightly coupling with pure raw data from the sensors achievable. Additional instruments could be an odometer or magnetometer. A *post-processing* also allows using reference station and error correction data for the GNSS. More information about the used program see [26].

For the analysis, data from GNSS, IMU and *Multistation* were fused. This procedure is not trivial, because of the different data types with have to be integrated into the program. An instruction of the workflow with *TerraPos* is written down in [19].

Lever-arm

As seen in figure 6.7, reference point of sensors and the antenna phase centre are not placed in the same location. This leads to an offset, which makes it almost impossible to integrate all data together. The distance between those sensors are called *lever arm* and have to be defined. With the help of the *MS60*, it is possible to create a local coordinate system[5]. At first, a line was measured which is defined as north direction. East is 90° turned in mathematical positive

[4] Version 2.5.7
[5] by the setting *orientate to line*

direction. Now all the measured data is placed in this local coordinate system. With the *Leica*

(a) Rooftop of the measurment bus

(b) top view from the IMU plattform in the trunk of the meansurement bus

Figure 6.7: Antenna (blue), Xsens (green), iFOG with GNSS time stamping module (yellow), Prism (red)

Mini 360° *Prism* it was possible to measure the distance of the GNSS antenna towards the IMU by placing the prism on top of the reference centre. Lever arm between the used *MS60 Prism* and GNSS antenna is in north- and east direction negligible because of the concentric placement. Only in height is a difference of those two sensors.

However, there is still a measurement uncertainty, since the little prism which was on top of the systems were held and placed by co-workers. To minimize this, each measurement was taken three times and the mean amount was used. All lever-arms are displaced in tab 6.5

Table 6.5: Lever-arm in relation to GNSS Antenna, expressed in body-frame

Sensor	Position [m]		
	X	Y	Z
Xsens top	-1.552	-0.4252	0.2777
Xsens trunk	-0.6419	-0.1999	1.7695
MS60(prism)	0	0	0.1445
iFOG	0.159	0.009	1.698

Coordinate transformation

Through the installation of the sensor, which is seen in 6.7, appeared several different coordinate systems (COS) (see fig. 6.8). For a valid analysis, each COS have to match the body frame. Those settings are done in *TerraPos*, were the coordinate systems can be rotate with the Matrix of rotation. For an example there will be write down the transformation of the *Xsens* which is placed on top of the measurement bus.

The COS have to rotate 180° around x-axis and −90° around z-axis. After this, the mentioned *Xsens* is now transformed in body frame. For understanding the mathematical aspect, the rotation matrix is divided into three components:

$$R_x(\alpha) = \begin{bmatrix} 1 & 0 & 0 \\ 0 & cos\alpha & -sin\alpha \\ 0 & sin\alpha & cos\alpha \end{bmatrix} \quad R_y(\beta) = \begin{bmatrix} cos\beta & 0 & sin\beta \\ 0 & 1 & 0 \\ -sin\beta & 0 & cos\beta \end{bmatrix} \quad R_z(\gamma) = \begin{bmatrix} cos\gamma & -sin\gamma & 0 \\ sin\gamma & cos\gamma & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

Which are multiplied as seen below

$$R = R_x(\alpha) \cdot R_y(\beta) \cdot R_z(\gamma) = \begin{bmatrix} 1 & 0 & 0 \\ 0 & cos\alpha & -sin\alpha \\ 0 & sin\alpha & cos\alpha \end{bmatrix} \begin{bmatrix} cos\beta & 0 & sin\beta \\ 0 & 1 & 0 \\ -sin\beta & 0 & cos\beta \end{bmatrix} \begin{bmatrix} cos\gamma & -sin\gamma & 0 \\ sin\gamma & cos\gamma & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$R = \begin{bmatrix} cos\alpha cos\beta & cos\alpha sin\beta sin\gamma - sin\alpha cos\gamma & cos\alpha sin\beta cos\gamma + sin\alpha sin\gamma \\ sin\alpha cos\beta & sin\alpha sin\beta sin\gamma + cos\alpha cos\gamma & sin\alpha sin\beta cos\gamma - cos\alpha sin\gamma \\ -sin\beta & cos\beta sin\gamma & cos\beta cos\gamma \end{bmatrix}$$

with the angles

$$\alpha = 180° \ \beta = 0° \ \gamma = -90°$$

the matrix simplified to

$$R = \begin{bmatrix} -1 & 0 & 0 \\ 0 & 0 & -1 \\ 0 & -1 & 0 \end{bmatrix}$$

For the GNSS and *MS60* it is not so complicated, it automatically transform into body frame by changing the direction of the z-axis. The second *Xsens*, which is located in the trunk, have been placed in the body frame position. So it does not need any rotation matrix, unlike the *iFOG*. Its x-axis has to rotate 180° and y-axis 90°.

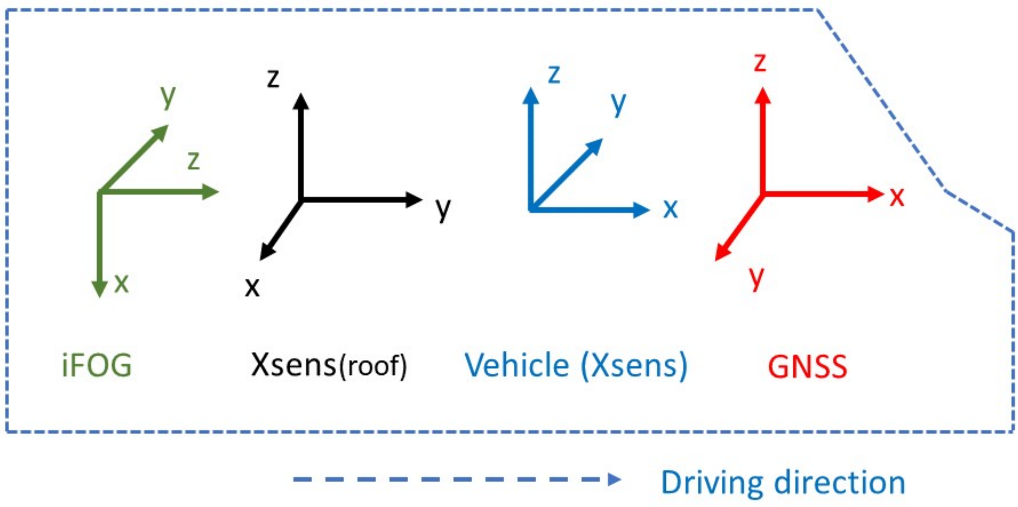


Figure 6.8: Trajectory of the vehicle (GNSS only solution)

Coordinate Update

With the previous mentioned software (*TerraPos*), it is possible to perform an coordinate update (CUPT). For that, the data from *MS60* are taken to support the GNSS + IMU solution.

6.3.2 Scenario n°1

Like described in section 6.1, the first drive around was for gaining information about the sensors in ideal circumstances. Because of a spontaneous timeslot, it was possible to use the whole area for the drive. This is the reason for a different pattern which is plotted in figure 6.9, but which supply more information for the settings and following measurements of those sensors. In the previous mentioned figure, a red circle shows the reference station which is used to correct the GNSS data. This is not a common station which is available for everyone, it is primarily used by the University of German armed forces.

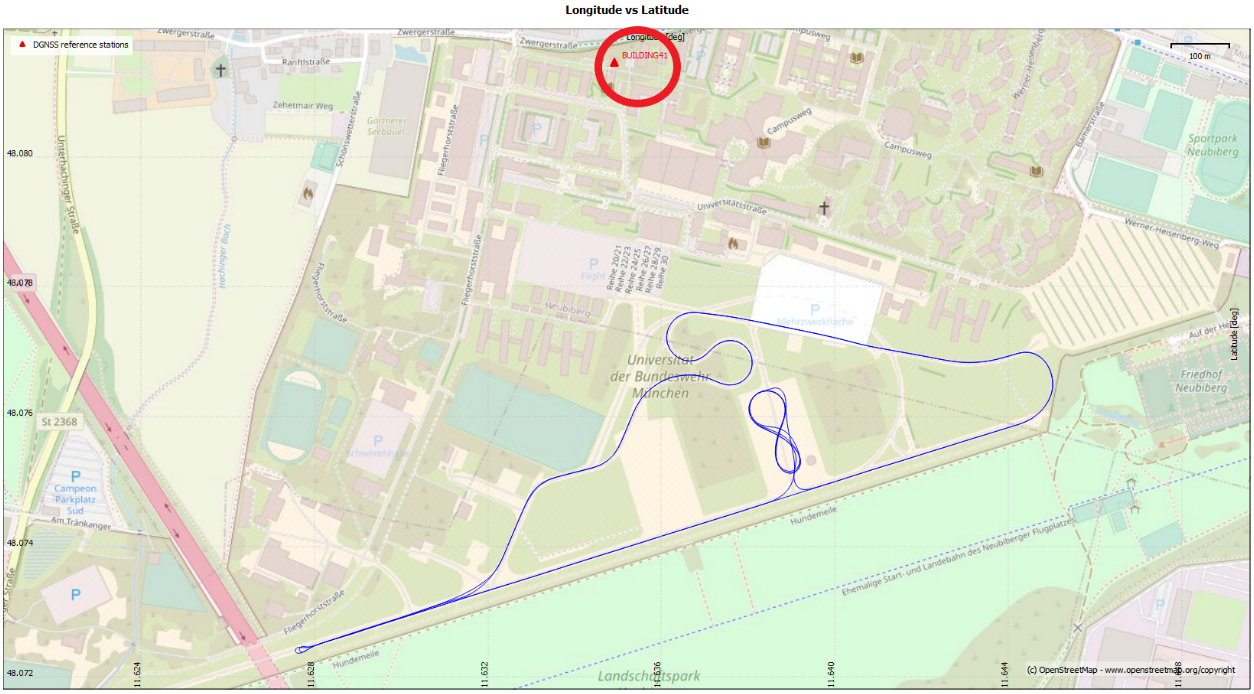


Figure 6.9: Trajectory of the vehicle (GNSS only solution)

Looking on the standard deviation of the open sky measurement (see fig. 6.10), it shows how accurate the GNSS only solution is. The deviation in height direction is the biggest compared to east and north. Nevertheless, it is only 1-2 millimetres, which is due to the sensor noise. This means that it is unnecessary to fusion another sensors for a more precise solution. It proves that in open sky a GNSS only system is more than enough.

However, this measurement showed that there was a problem with the second used IMU (*iFOG*), because the sampling rate was not constant, which makes it a lot more complicated to use this data. It was the first attempt of measuring data with this IMU. Afterwards it was discovered that some of the settings in soft- and hardware did not work out. With help from the *TerraPos* support and Dipl.-Ing. Mohamed Bochkati it was possible to solve the problems and initialise those data to the using program. Like described in 4.3.1 the IMUs have different lifetime stability, which could impair the integrated solution while there is no GNSS signal. For a quick comparison, a GNSS failure is simulated. For that, a total of 3x60 seconds is deleted in the GNSS data. In 6.11 is displayed where and how long the GNSS breakdown was. The failure took place on three different drive styles, while the dynamic alignment (driving the shape of an eight), around curves and while driving straight ahead. To be noted, all north and east coordinates were subtracted with the starting one. This leads to a local perspective, were the origin is also the starting point of each measurement. This procedure has happened to all plots which shows the trajectory of the vehicle.

To continue, the GNSS data is coupled (loosely) with each IMU. Looking at the standard de-

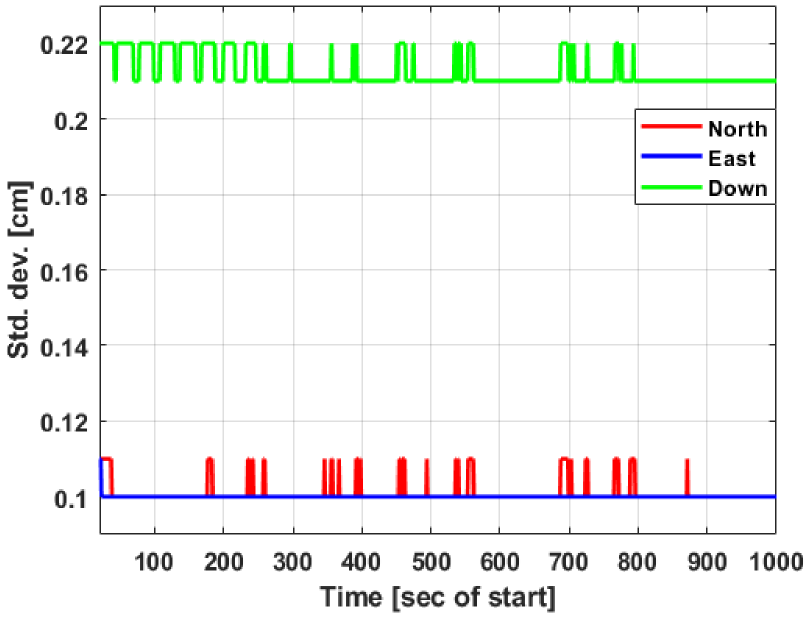


Figure 6.10: Standard deviation GNSS only

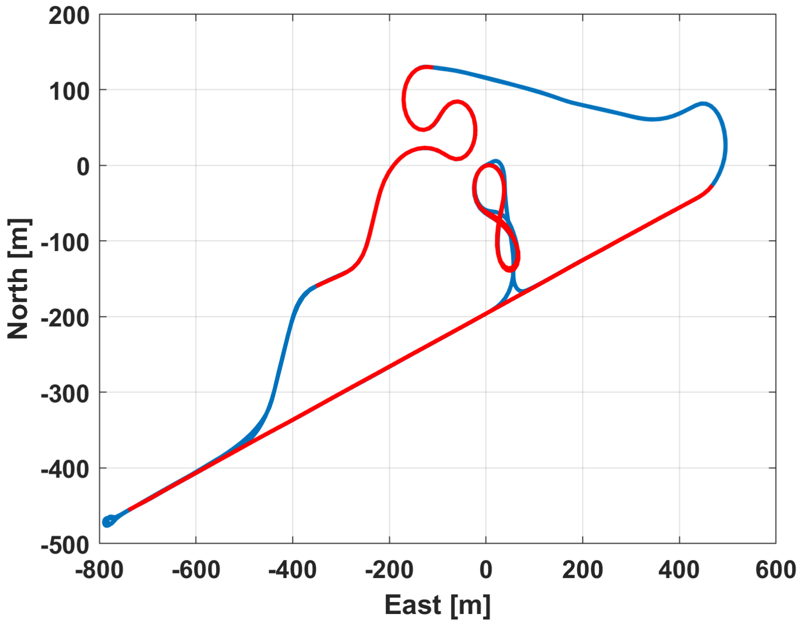
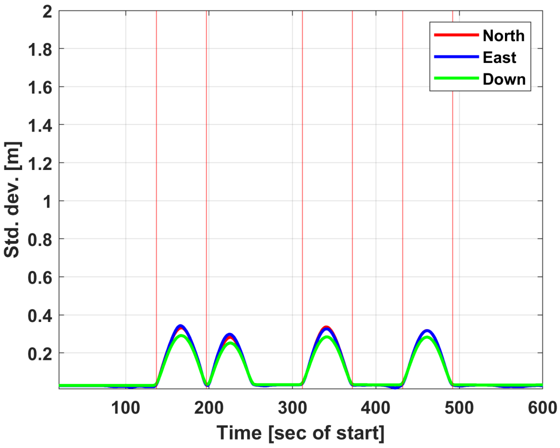


Figure 6.11: Trajectory, red marked sections indicates the artificial introduced GNSS gap, GNSS only

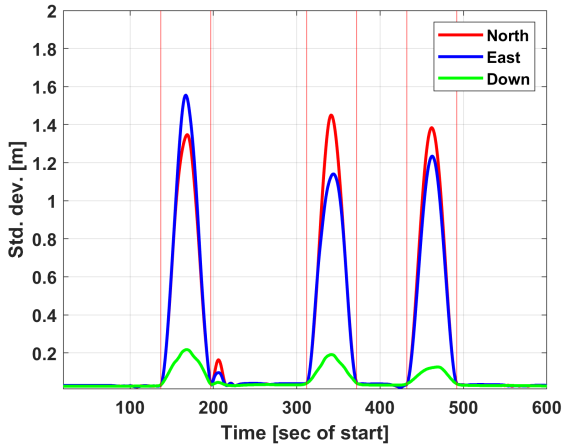
viation (fig.6.12) of both, it is obviously that the values of the *iFOG* are quite lower than the *Xsens*. While the low cost IMU has a std.dev. above one metre, the high cost one is around 30 centimetre, which is not even a quarter[6]. In those figures the GNSS failure is marked with two red lines.

Furthermore, the gap between those IMUs are also shown in figures 6.13, where both solution are compared to the GNSS only data. Note that because of the low std. dev. and open sky condition, the GNSS only solution will be handled as the reference. After looking at those figures, it seems that only at the beginning, where the dynamic alignment took place, the deviations are increasing.

[6]comparing to the *Xsens* solution



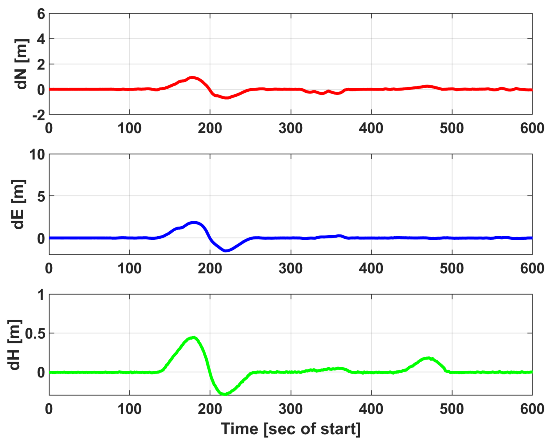
(a) iFOG



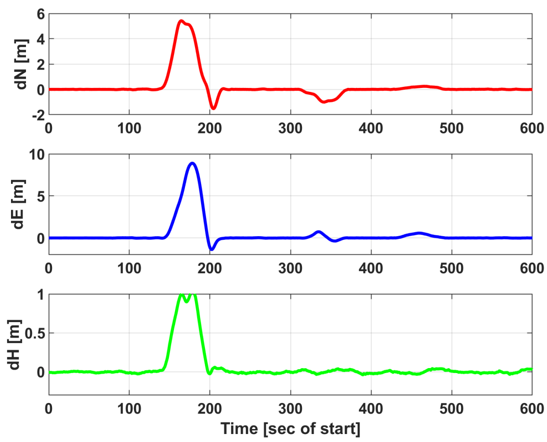
(b) Xsens

Figure 6.12: Comparison of the standard deviation (loosely coupling)

Like previously, the *iFOG* is still more accurate but have a deviation up to two metres. On the other hand, several metres (more than eight!) of difference are recorded with the *Xsens*. However, both of them decreases the deviation to not more than one metre.



(a) iFOG



(b) Xsens

Figure 6.13: Comparison of GNSS/IMU (LC) to GNSS only

To makes things clear, the comparison between those IMUs are special. Because it is not common for such a long GNSS failure[7]. This should only show how different IMUs could be and how the data is effective by that. For a proper analysis, the sensor should have a functional alignment without any disturbance. It is also mentionable, that the standard deviation do not match up the difference to the GNSS only solution. Like seen in figure 6.13, after a certain time, the deviation will not increase in act to 6.12. Anyway, std. dev. is still a valid argument for evaluate the accuracy, because it shows how reliable the collected data is. It has to be noted, that the settings of the *iFOG* are not perfectly done, there is still some work to do for a proper initialisation in *TerraPOS*. This could mean, that the solution with an integrated *iFOG* in the future will be more precise and accurate.

[7]except for tunnels, parking garage and so on

6.3.3 Scenario n°2

From now on, every following scenario is processed as a tightly coupling solution where GNSS, Xsens and the total station are integrated. Like said, it applies to the continuous measurement, where not otherwise stated.
In the second scenario, there was a part were the GNSS signal should be loss, which is on the street between the trees (see fig. 6.14). But at first, the measurement bus stayed in the parking lot for the

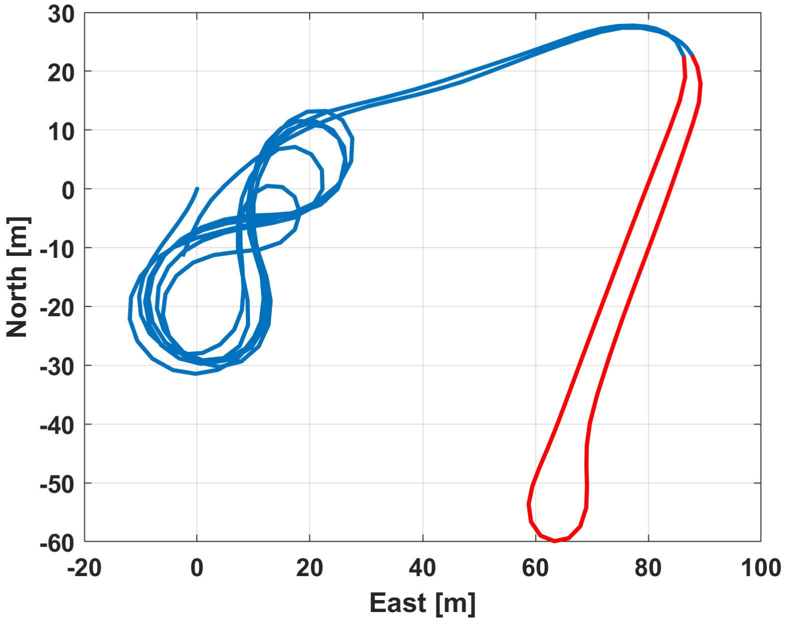


Figure 6.14: Course of the vehicle with high foliage (red), tightly-coupling (GNSS/Xsens/MS60)

GNSS and IMU initialisation. Unlike the description in 6.1, the bus never rested for ten minutes straight at the beginning. In all scenarios the time of each static alignment was about four to seven minutes. The reason for that are on one hand, that the GNSS does not needed so much time to locate its position, and on the other hand the *XSens* need a dynamic alignment for its orientation. This is shown in figure 6.14 by the shape of an eight, which is used for the alignment. The reason for that is constant change of the acceleration in x- and y-direction (bodyframe) and the rate of angle in yaw orientation. This criteria leads to a proper alignment for the used IMU. After finishing this procedure, the vehicle drove along the street which is covered with high trees around it. Last but not least, the measurement bus drives back to the parking lot which simulate the open sky area.

Looking at the standard deviation of the GNSS only solution (fig.6.15), it is obviously that until the first red vertical line the data is constant. After it, which indicate the cruise on the street, deviation increase up to several centimetres. For a more precise analysis see following table (6.6).

Table 6.6: Data from the part of *GNSS loss*, GNSS only

	North [cm]	East [cm]	Height [cm]
max	9.8	6.4	84.1
min	1.1	1.1	2.4
RMS	4.06	2.71	22.99
mean	2.99	2.17	11.76

It is clear that the most deviation is seen in height, no matter whether it is the mean or maximum value. The second most disturbance is in north direction, the cause of that could be the orientation of the street. While driving along, the vehicle was heading to north which explains the higher deviation. In overall, the measurement would be more drifting if the GNSS loss would be longer.

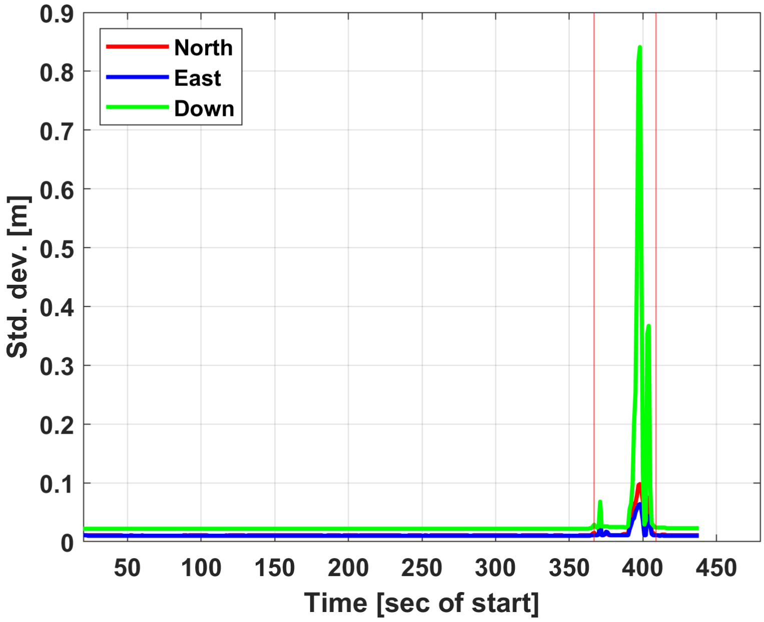


Figure 6.15: Standard deviation of the GNSS only solution

Now it is time to fusion the sensors with the GNSS to see if the solution would be more accurate and precise. The first thing which stands out in figure 6.16 are the high start values. As mentioned before, the IMU needs a initialisation which happens during the measurement[8]. So at the begin, the deviation is higher as in the GNSS solution, but after a certain time, the deviation will fall to a lower value. Looking once again at the same part, but now with the integration of the *Xsens* and *MS60* it shows that the deviation is in overall obviously lower (see tab. 6.7).

Table 6.7: Data from the part of GNSS Signal loss (TC solution)

	North[cm]	East[cm]	Height[cm]
max	1.7	1.5	2.0
min	0.7	0.7	1.6
RMS	1.08	1.03	1.75
mean	1.06	1.02	1.74

There is a massive decrease of all values when the GNSS system is coupled with additional sensors. The most obviously reduction is in height. The mean value is reduced from twelve centimetres to two. Moreover, the other directions benefits from the integration too. It may looks like there is only a improvement by some centimetres, but it was only a signal loss situation of 40s. If the drive would continue with this foliage, the data between GNSS only and the coupling would differ more and more.

To illustrate the difference of each data, the tightly coupling solution is subtracted from the GNSS. A plot of this arrangement is in figure 6.17. When the measurement bus is in rest, a offset is only seen in north and height. The amount in north is about one centimetre, whereas height is

[8]By this is meant the driving of circles

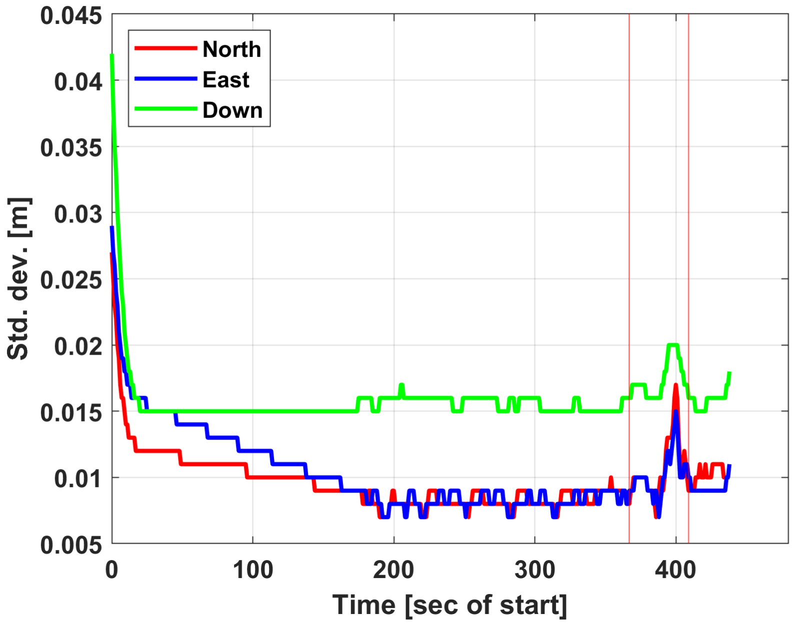


Figure 6.16: Standard deviation, tightly-coupling (GNSS/Xsens/MS60)

commonly a little bit higher. After the resting phase, it can be an oscillation perceived. The pattern is due to the dynamic alignment, where the vehicle drove severe times the shape of an eight. So besides that, it is more interesting how big the deviations are while the GNSS is loss. The data is in table 6.8 clearly arranged. The mean value might be low, but compared to the figure 6.17, there is almost anytime a difference which is not constant. This can be observed by the RMS value which is slightly higher. The cause of that, is the accumulation of deviates around the zero line which lower the mean value.

Table 6.8: Comparison of tightly-coupling (GNSS/Xsens/MS60) and GNSS only

	North[cm]	East[cm]	Height[cm]
max	6,79	4,47	12,42
min	0,13	0,02	0,44
RMS	4,11	2,0	5,48
mean	3,76	1,56	4,69

After looking into the tables and figures it seems, that the integration of several sensors helps to make the solution more valid. Like said before, the vehicle drove not even a minute in this kind of foliage. If the time would be much longer the deviations would be more clearly. However, this scenario should show how important it is to use all instruments even if there is only a small period of critical GNSS receiving.

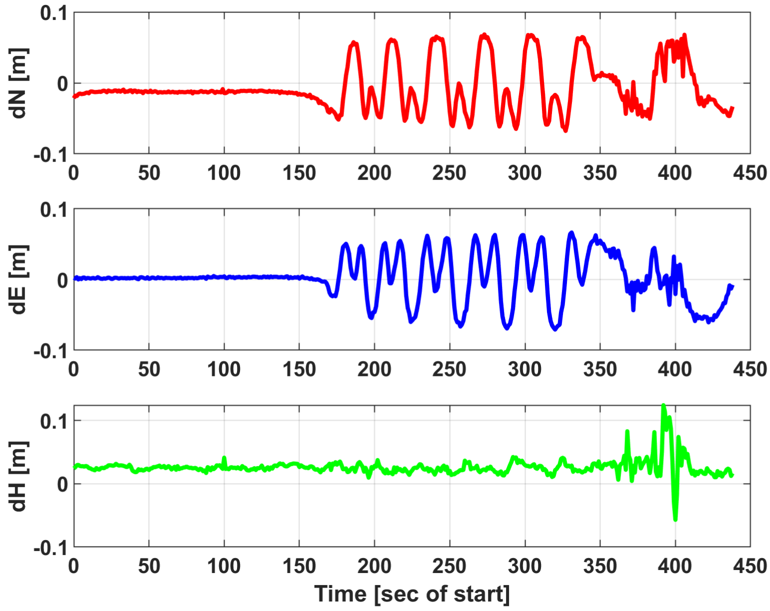


Figure 6.17: Difference between tightly-coupling (GNSS/Xsens/MS60) and GNSS only

6.3.4 Scenario n°3

For the next scenario, the vehicle drove to a certain place where the GNSS signal should be lost and then back to the open sky area. Here it was important to know how the integration would work when the GNSS signal get lost several times, because the previous mentioned drive were performed three times.

To make thinks clear, the foliage which is seen in figure 6.3 (section 6.1) might be very low. But actually there are standing big trees on each side of the road. This can be observed in figure 6.18. In this figure is also shown how a *MS60* setup would look like. The red circle indicates the tacheometer with a GNSS antenna for the time synchronisation. On each side (blue marked) is a reference point, which was used to orientate the *MS60* (left reference point is cut out due to picture format). Those reference points have at first a GNSS antenna mounted (measuring its position) and afterwards a prism which was targeted by the *Multistation*. Besides the *MS60* setup, it is detectable that the foliage on the right side is very high. This is also the place were the measurement bus turned around and a GNSS failure was forced. The foliage across the street should interfere the GNSS signal at the driveway which is on the right side of the red line in figure 6.19.

At first, the figure 6.20 shows, if the GNSS Signal is actually disturbed by the foliage. There a three distinctive peaks located in this plot, which happens to be the part where the vehicle drove on the street. Although it is shown that the GNSS signal were interrupted, but the standard deviation increases only by few centimetres. For the most applications the deviation would be more than enough. However, in this case the aim is to lower the deviation as low as possible with the right instruments.

In compare, the solution with all used sensors flatten those peaks. It is shown figure 6.21. The data in 6.20 is, besides the peaks nearly constant, whereas in 6.21 the solution varies. This could be

Figure 6.18: Multistation setup for scenario 3

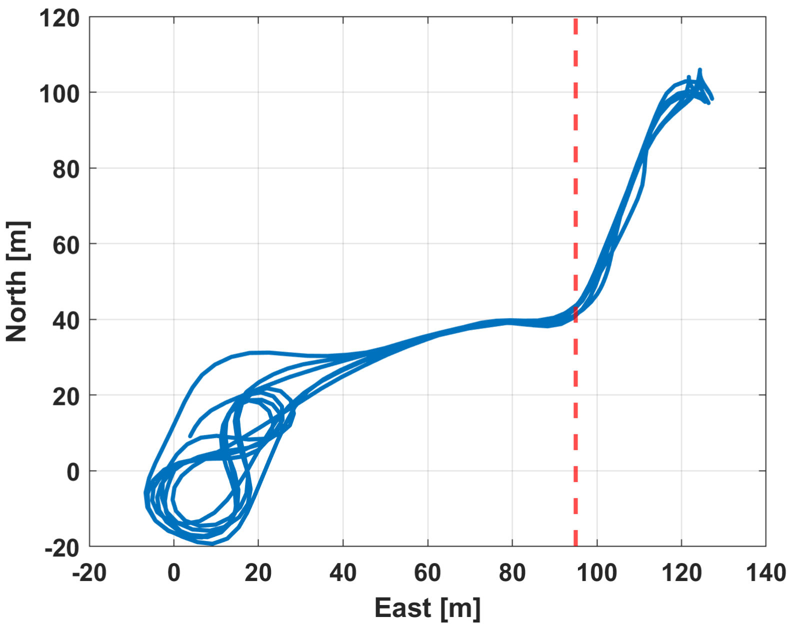


Figure 6.19: Course of the vehicle with a possible GNSS loss (right side of red line), GNSS only

due to the integration of several sensors, which have different *Kalman Gains* (see 3). That means, every instrument has a particular value for its measurement data. The Kalman filter decides,

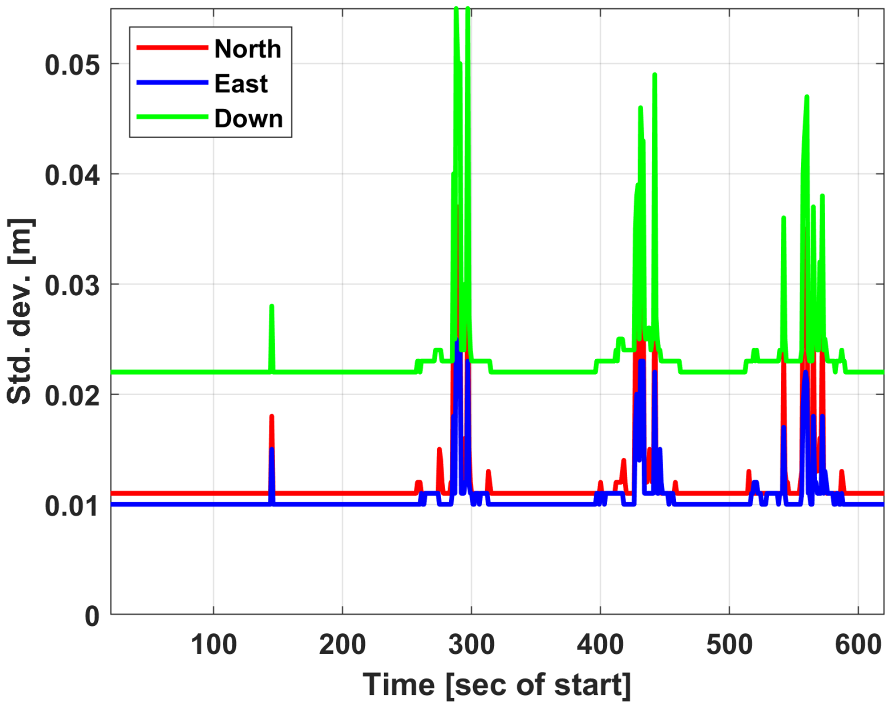


Figure 6.20: Standard deviation of GNSS only solution

based on their standard deviation, which data will be *trusted*. This selected data will be used to define position and orientation[9]. Therefore, through any disturbance of a sensors for a certain measurement, the solution is based on the more reliable data. However the out-coming data is still more precise than the GNSS standalone. So in the end, an integration of different sensors would offer a more valuable solution.

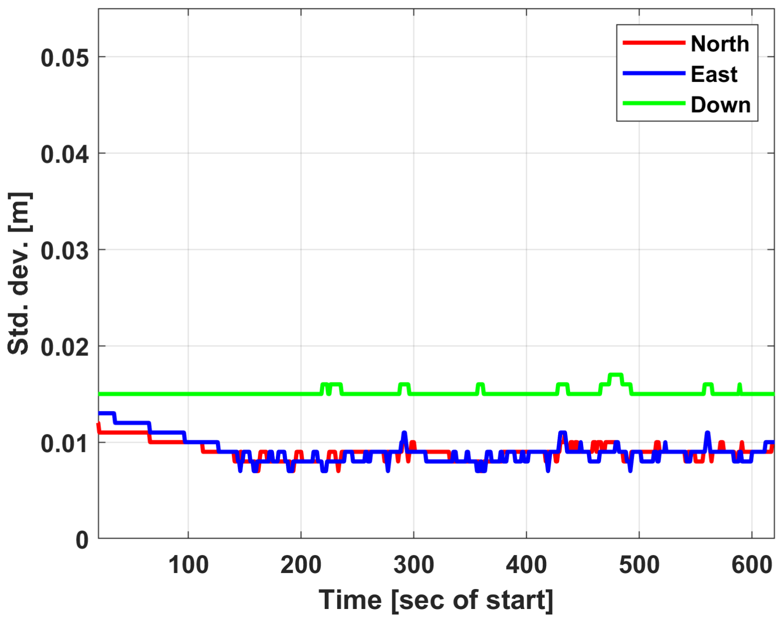


Figure 6.21: Standard deviation of tightly-coupling (GNSS/Xsens/MS60) solution

To clear this up, the time of GNSS loss was shorter than in scenario two, so the deviations are not

[9]in this case only the *Xsens* has an outcome for the orientation

so big. It was only the intention to make sure the integration works properly if the GNSS signal would be lost frequently.

6.3.5 Scenario n°4

The last scenario should show how effective a multi-sensor-systems works in a suburban area. As seen in figure 6.4 there are multiple buildings besides the street. Each of them are a three storey building, which should lead to a GNSS signal shadowing. Nevertheless, in figure 6.22 is shown, that there has not been any critical GNSS loss. The solution has a low standard deviation which indicates a proper function of the GNSS system.

However, after integrate the two other sensors (*MS60, XSens*), the std. dev. still lower its val-

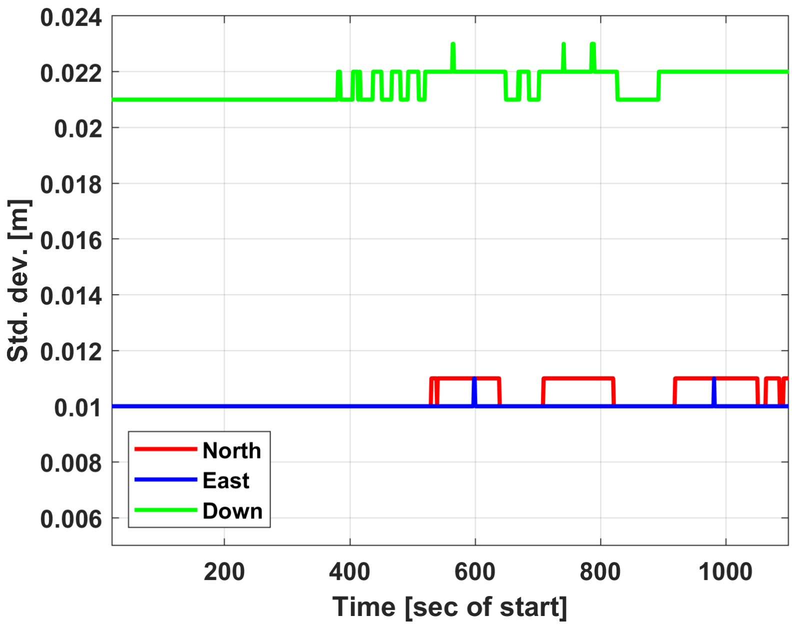


Figure 6.22: Standard deviation (GNSS only)

ues (see fig.6.23). The average decrease almost over one centimetre, which means that it is still helpful to use more sensors for a more precise and accurate solution. However, this applies for a reference trajectory which this thesis is aiming for. To locate and navigate in a common scenario a GNSS solution would be enough. An integration of more sensors always mean a higher development effort and increasing costs. The price performance ratio is in this case not satisfactorily.

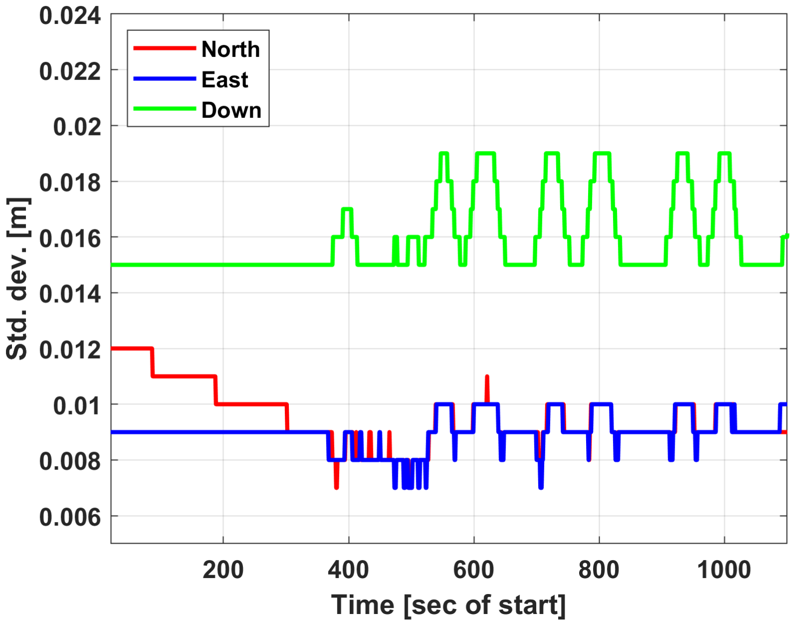


Figure 6.23: Standard deviation, tightly-coupling (GNSS/Xsens/MS60)

6.3.6 Scenario n°5

After finishing all the scenario, there is still a lack of informations which is needed to form a conclusion. In this thesis was already spoken about how the deviation decrease when more instrument are taken for the measurement. But the interval of GNSS loss was not so long as expected. To fulfil this void, a measurement is taken which origin was to test the tool chain of the used sensors. In this scenario, the measurement bus drove between a really close and high foliage. The real driveway is shown in figure 6.24, the red dot below the building *162* was the starting point, where the initialisation took place too. It is obvious that the area is almost completely covered with trees and a constant GNSS signal is impossible.

This can be seen in figure 6.25. The standard deviation has multiple peaks which reaches almost one metre. There are also two big peaks which have a value of one to three metres (north and east). Sometimes the std. dev. decrease to some centimetres, which means that the GNSS signal still come through this particulate thick foliage. The number of satellites[10] represent the solution. Whenever a high amount of satellites (12-16) are *visible* the std. dev. decrease, at those specific high peaks only four to six were useable.

In addition, in figure 6.26 is shown how the drive pattern would look like if only the GNSS solution would be used. Comparing this figure with the one in 6.24 it is obviously that a GNSS only solution would be incorrect due to poor signal connection. Especially the right side or the offset on middle of the road shows, where a proper GNSS signal is loss. Those sections are also seen in figure 6.25 by the increasing standard deviation. It is a difference of several meters between those solutions. This makes it almost impossible to get a proper GNSS solution without any other integrated sensors.

To show how import it is to combine multiple instruments for a high quality solution, the *MS60* is integrated in figure 6.27 It is shown that the driveway is more precise and is almost looking like 6.24. This can also be observed in the std. dev., which is also way more lower than the GNSS only solution. The deviations are decreasing from meters to centimetres, which is a big improvement (see fig. 8.15 in appendix). However, on the right side of figure 6.27 there is

[10] It has to be noted, that only GPS, Galileo and GLONASS satellite were tracked

Longitude vs Latitude

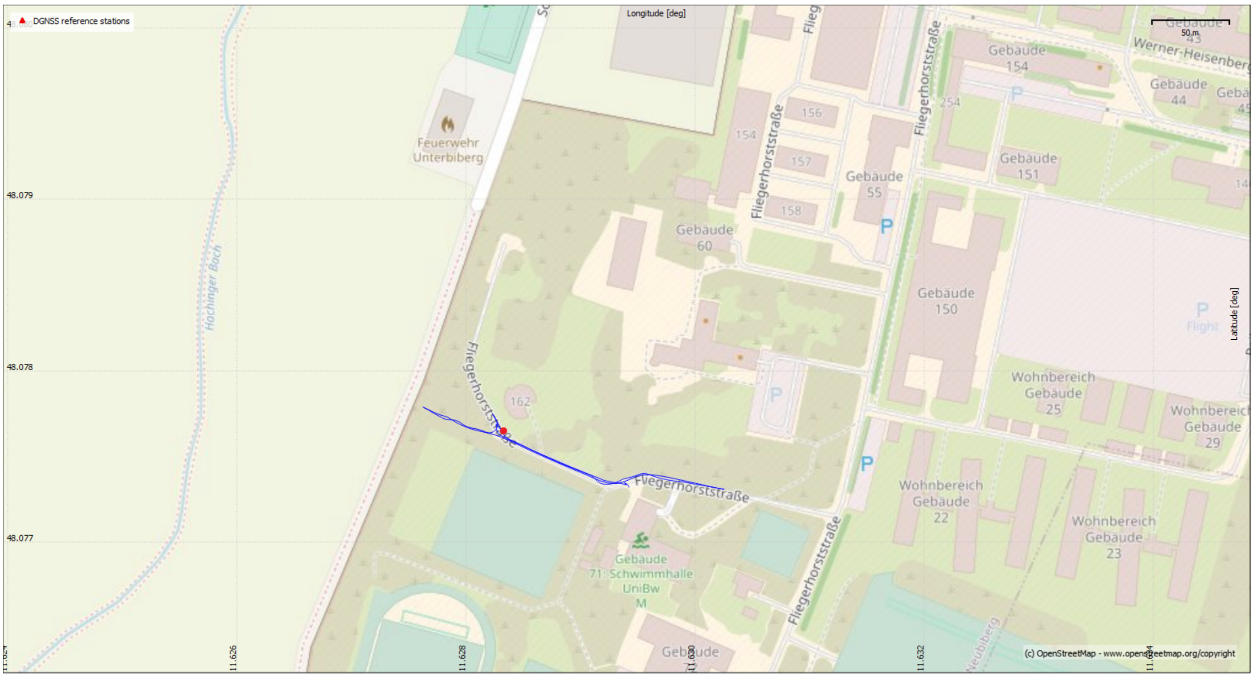


Figure 6.24: Driveway of the measurement bus with tightly-coupling (GNSS/Xsens/MS60) solution

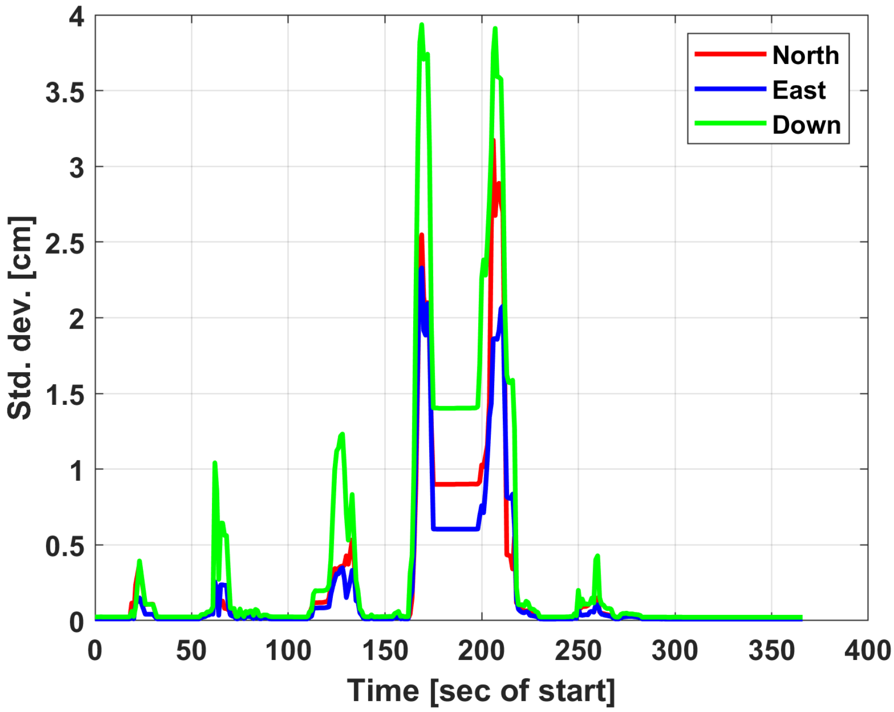


Figure 6.25: Standard deviation of the GNSS only solution while signal loss

still a false path noticeable (red circle). This has to do with the line of sight of the *MS60* and its prism. After a disturbance by following the prism, for example when the sight is blocked by leafs or streets signs, the Kalman Gain decrease and the solution gets worse. This has happened in this particular case, the sight was blocked which courses the Kalman Filter to *trust* the GNSS data which are not correct. For a better solution, it should be a continuously measurement by both instruments. But it can be really hard to fulfil this, which is why there was another sensor added.

Longitude vs Latitude

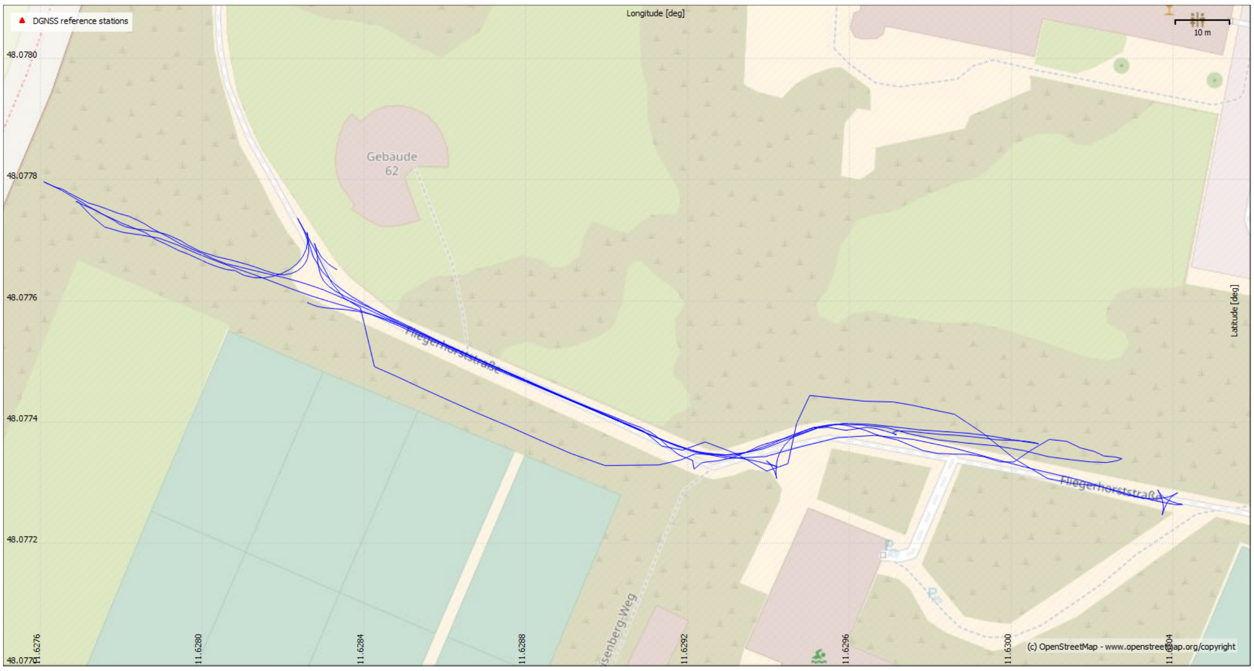


Figure 6.26: Driveway of the measurement bus with GNSS only solution

Longitude vs Latitude

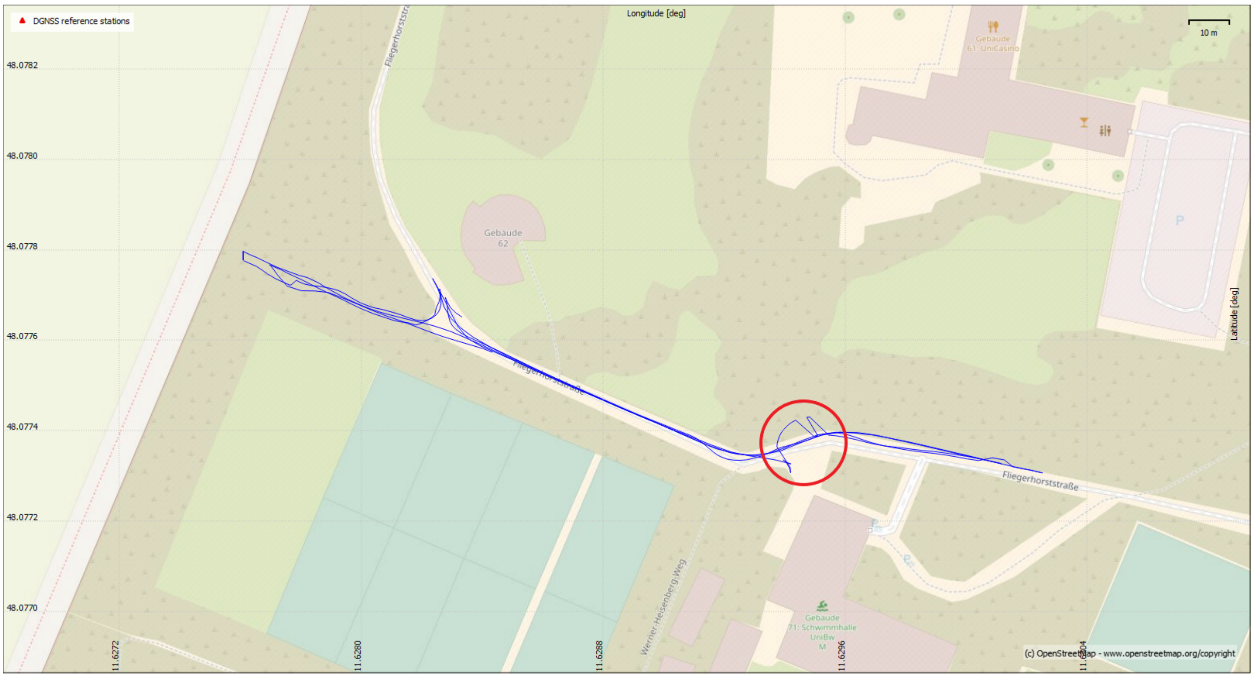


Figure 6.27: Driveway of the measurement bus with the GNSS+MS60 solution

Figure 6.28 shows the standard deviation when all three sensors are integrated. Those peaks have flattened and become more smother, almost every value is below five centimetres. At the end it seems that the solution is drifting upwards, this could be explained by the poor sight of the *MS60* which was mentioned earlier. In figure 6.24 is shown the driveway which is based on the integrated solution. This path looks like the real pattern which was driven by the vehicle.

However, maybe a GNSS and IMU integration could be enough for this purpose. Thinking about

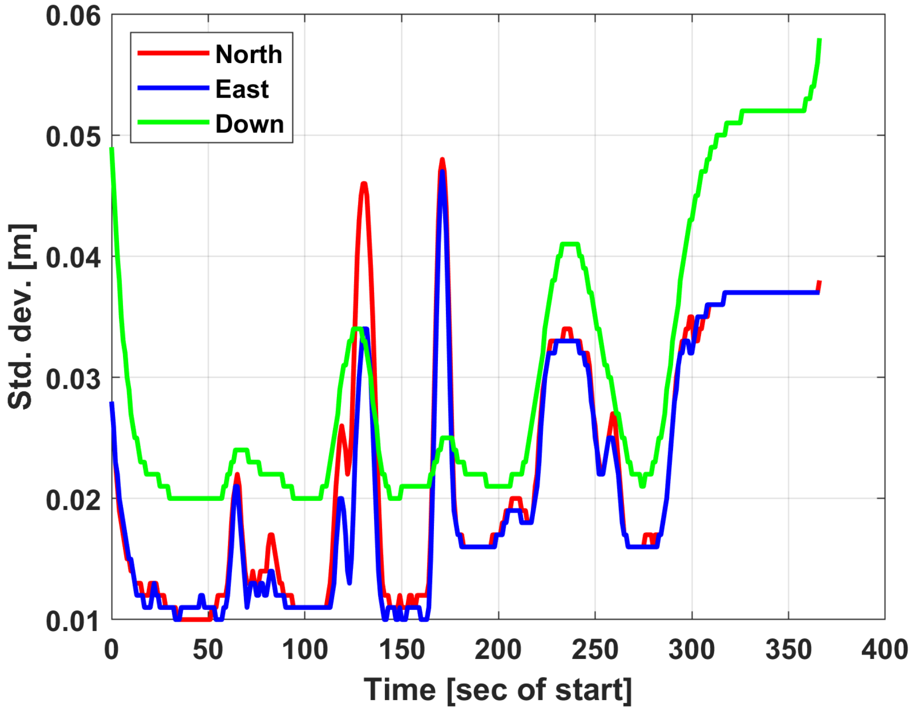


Figure 6.28: Standard deviation of complete tightly-coupling (GNSS/Xsens/MS60) data

what was said in 4.3.1, the *Xsens* has only a short time stability. This means after a long period without any GNSS signal, the IMU would drift and the solution is not longer valid. Looking into the std. dev. of the GNSS and IMU solution in figure 6.29 it seems quite identical to 6.27. Nevertheless, one big difference is the last peak which is drastically flatten from decimetre to centimetre. Even that there was a big foliage the GNSS signal never been down for a long period of time, but it was still enough for the IMU to drift. What happen when the signal loss is longer than in this scenario are described in the bachelor thesis [19]. The drift would increase with time and the solution is not longer acceptable. In this case the advantage of the *MS60* would be more obviously.

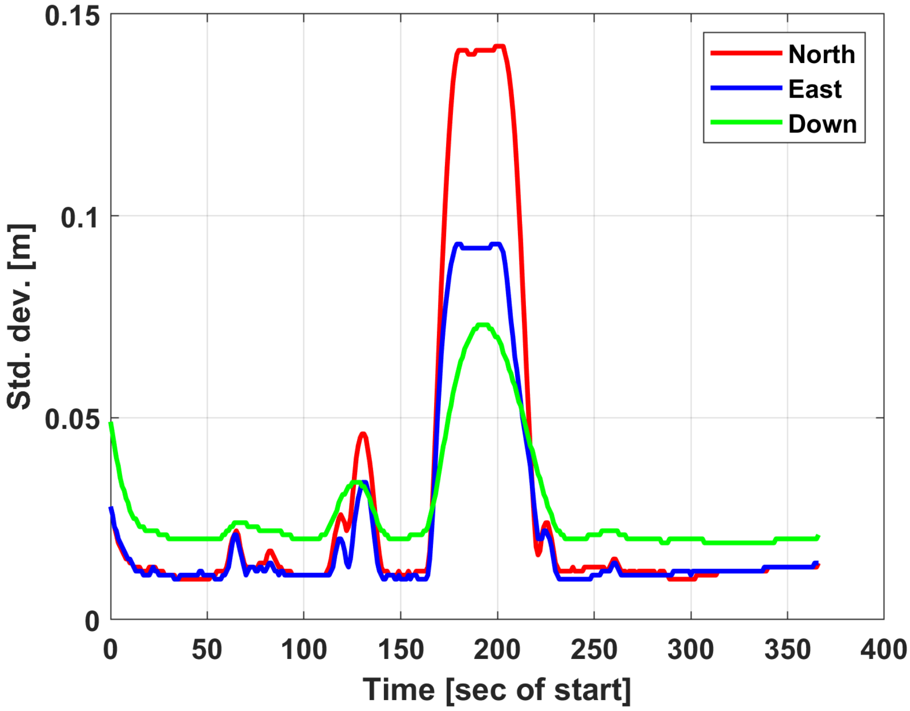


Figure 6.29: Standard deviation of IMU (Xsens) and GNSS integration (without *MS60*)

7 Conclusion

Realisation of flexible reference system was the aim of this thesis. After finishing all those scenarios and analysing them, it may be successful. But at first everything that happened will be summarized. At first, before trying to mount anything on the measurement bus, the systems should work properly. For that, both instruments (*MS60 & Trimble*) were operated separately. After adjusting the settings of them, they were compared to each others. In addition to that, the pillars in front of the *Messkuppel* were measured with *RTX* so the institute has new reference coordinates. With those, it could be shown that the GNSS system works properly with a low standard deviation. On the other hand, in this case the tacheometer had a poor geometry of reference points, which effected the accuracy and precision.
To prepare for the following scenarios, there was a short measurement with all three devices to ensure the integration and test the tool chain. This has helped to get ready for the upcoming measurements, so it was known how to fusion all those sensors. In addition, it turns out that this little experiment was useful at the end of all scenarios, more about this later.
After getting everything ready, the described scenarios could be fulfilled. The first one delivered useful information about the instruments when there is a nearly perfect condition. This data was used to create a reference and to initialise those sensors to the used program *TerraPos*. Furthermore, due to a open sky, a comparison between the IMUs could take place. It shows that the low cost IMU (*Xsens*) has a significant higher deviation as its high cost variant (*iFOG*). However, the time interval of a total GNSS failure was really high (60s), it should only clarify the difference between those IMUs. As mention previously, some data for the *iFOG* setup are still missing. When those adjustments, like knowing the true lever arm, the solution will become more accurate and precise. However, in the followed scenarios the GNSS signals should be compromised by foliage or buildings. In the fourth scenario, which took place between students residential, no impair of GNSS was recorded. It seem that those high buildings does not disturbed the satellite connection. So in this case a integration of multiple sensors is not necessary. On the other hand, in the second and third scenario, an improvement was made by fusion all instruments together. The standard deviations as well as the accuracy improve with a multi- integrated solution. However, a critical GNSS failure was not achieved, although the vehicle drove between a lot of foliage. Due to that, the test drive for the tool chain was analysed too. There was a remarkable GNSS break-in recorded, which was used to check if the setup is still suitable. It shows a higher precision and accuracy when the GNSS is integrated with only one another sensor. But there were still some discrepancies. Sometimes the prism was covered by leafs/signs[11], or the period of GNSS disturbance was to long to be handled by the *Xsens* itself. After integrate a second additional sensor, the solution gets more and more precise.
So, as seen in the analysis, an improvement by integrating more equipment is made, but is that enough for the required reference system? Well, it depends on how flexible is defined. If someone needs a reference trajectory anywhere within two days, the answer is yes. When the trajectory should be known right after the measurement, the previous setup would not work. One reason for that is *TerroPos*, it is a program which is working for a *PostProccesing* solution. That means after the measurement, several information are gathered and used which are not available in real time. The integration of those sensors takes also time and happen, in this specific program, afterwards. However, like discussed in [12] and [19], the *MS60* is not mentioned to measure dynamic object, it is used for static applications. Furthermore, a continuously visual connection between the sensor and the prism have to be maintained. If the sight is blocked, the measurement will stop immediately. It was also mentioned that the *Xsens* has a short time stability while there is no satellite signal. So maybe the solution gets out of hand when the vehicle drive in a tunnel or in areas with a big foliage. Of course, by using a high cost variate, the long time stability would be reached, but only to a certain point.

[11]this would not effect IMUs, only the *MS60*

However, every sensor has its disadvantages, but with a fusion those could get cancelled and only the advantages stays. Moreover, when different systems, like a *LiDAR* would also be integrated, the solution would be more precise and accurate. This could be a good way to equip a vehicle which should record such reference trajectory. It can be said, that every additional sensor is an advantage for a better solution, which should be the aim of it. Integrate more sensors means also increasing the cost of the measurement, which should not be an obstacle when a reference is required.

8 Appendix

8.1 Instruction for a flexible reference trajectory

In this section will be explained how to set up a reference trajectory with following instruments: GNSS receiver and antenna, IMU[12] and a tacheometer (*MS60*).

8.1.1 IMU

For a proper use, the IMU have to be mounted on the vehicle. It is recommended to use a strap down variant, so it would be easier to process the data in *TerraPos*. Make sure to write down the alignment direction, because it is necessary to transform its coordinate system to body frame. Before starting the measurement it is also important to pair the IMU with a GNSS clock device, so the timestamps will be accurate and more important, constant.
After adjust those criteria, the IMU could be run by an application when its connected to a computer. For example, *Xsens MT Manager* is used for this particular IMU. When this is finished, the IMU is ready to use. To sum it up:

– mount IMU on the vehicle (use the COS carefully)

– connect with GNSS for timestamps

– connect with a laptop and run its program

– start the measurement

8.1.2 GNSS

To settle a GNSS system, it requires a rover and an antenna. Place the antenna on top of the vehicle for a better GNSS function. Connect it to the receiver which record and collect the data. Now use a laptop which is paired with the GNSS receiver to adjust the settings of it.
At first, by connecting the laptop with the receiver, a LAN cable is needed. Secondly, type the IP address of the receiver[13] into any given browser. After a certain time the starting site will be on screen. It could be that the site requires a login with username and password. This is only a short instruction, for more details look into [11]S.22
When the site is loaded, the actual position and general information about the measurement are given under *Receiver Status* -> *Position* (see fig. 8.1).

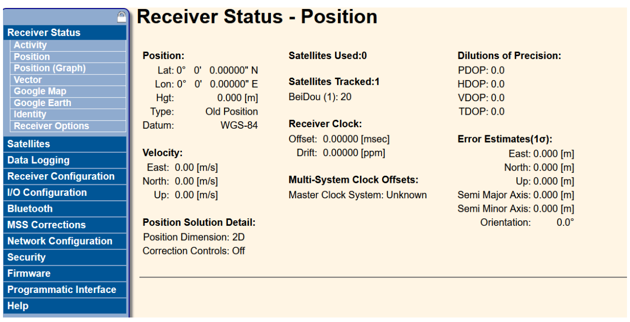


Figure 8.1: Position of the receiver

[12]in this thesis *Xsens* and *iFOG* have been used
[13]which is depicted on the receiver itself by scrolling the settings

There it can be ensured which coordinate system is used, the position and which value the deviations have. To make sure every satellite is enable for the tracking, go to *Satellite -> Satellite Enable/Disable* (fig. 8.2).

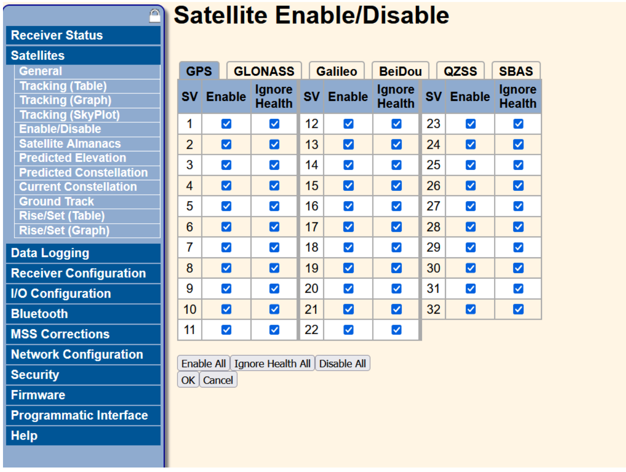


Figure 8.2: Path for enable/disable a variety of satellites

As seen in the figure, different types of satellites can be chosen for the measurement. It could be interesting, maybe for a special occasion when only *GPS* satellites should be part of the tracking. On the other hand, this site should be checked before any measurement to make sure the indented satellite are not disabled by a recent measurement. Which satellite are already tracked and *visible*, is shown in figure 8.3 (*Satellite –> General*)

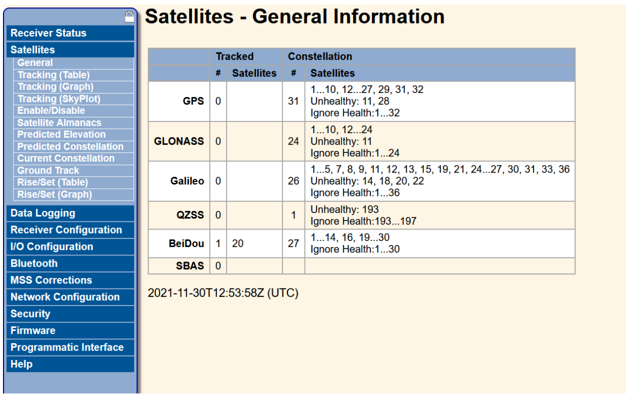


Figure 8.3: Satellites which are already tracked

Continue with figure 8.4, which can be reached by going to *Receiver Configuration -> Tracking*.

Here can be adjust some general parameter like the elevation mask or which signal should be used. Furthermore, for the measurements in this thesis, the multipath estimation was disabled (*Tracking -> Everest*) as well as the *Clock Steering*. When *RTX* should be used, it is important to make sure that it is enabled under *Receiver Configuration -> Correction control*. An additional advice is to bring the receiver up to date. Because while working with the system for this thesis, the correction satellite was not found. The reason for that was the change of its frequency. To continue using the *RTX* it was required to manual updated it by creating a custom frequency for the mentioned satellite (see fig.8.5).
Like seen in figure 8.6[14], it is also possible to adjust the specific GNSS transmission like *PPP* and *RTK*. After adjusting those settings, the measurement can start.

[14]this are the setting which are used for the measurements

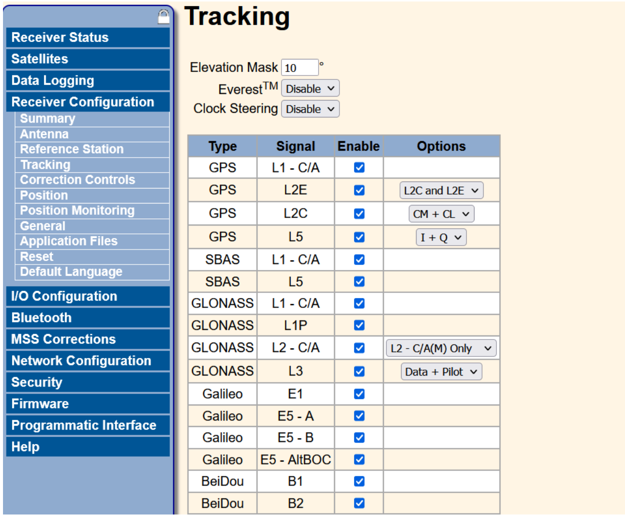


Figure 8.4: Path for changing the satellite signals

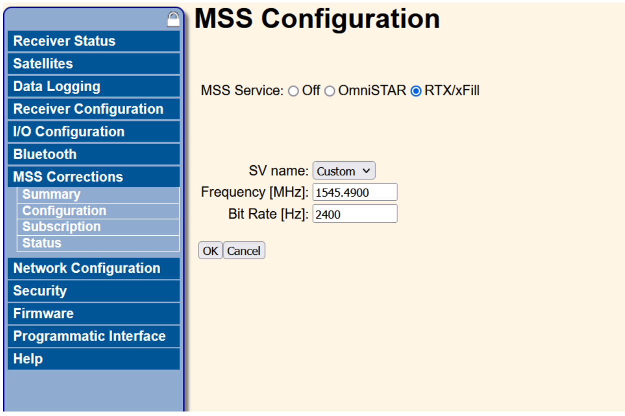


Figure 8.5: Adjusting a custom signal

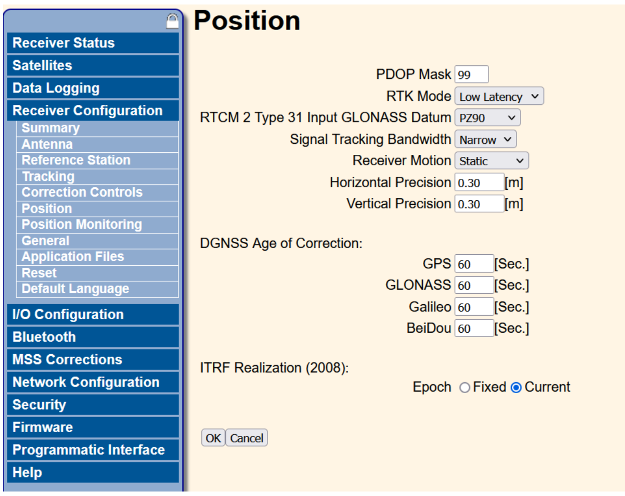


Figure 8.6: Settings for the receiver configuration

It is also possible to see where the reference station is placed and transform its position as well as the antennas in Cartesian or Geographical (fig. 8.7).

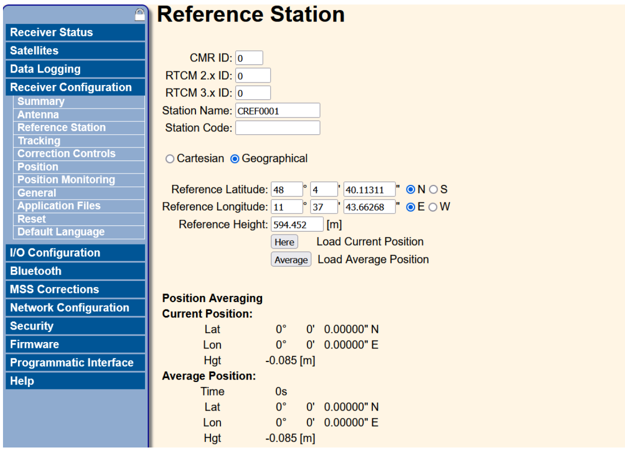


Figure 8.7: Information about the reference station

To log the data which is currently measured, go to *Data Logging*, create a new session if needed, but make sure that *Doppler* is included. After that, click enable to log the data (see fig. 8.8). To make sure everything is working properly, look at the receiver, it has to display that it is currently logging. After finishing the measurement, stop the logging and download the data. To be noted, while the receiver is logging the data, a connection between the laptop and receiver is not longer necessary. The laptop is used for the setting and to start/stop the logging. In this thesis, the laptop was used for the IMU data logging after everything was settled for the GNSS.

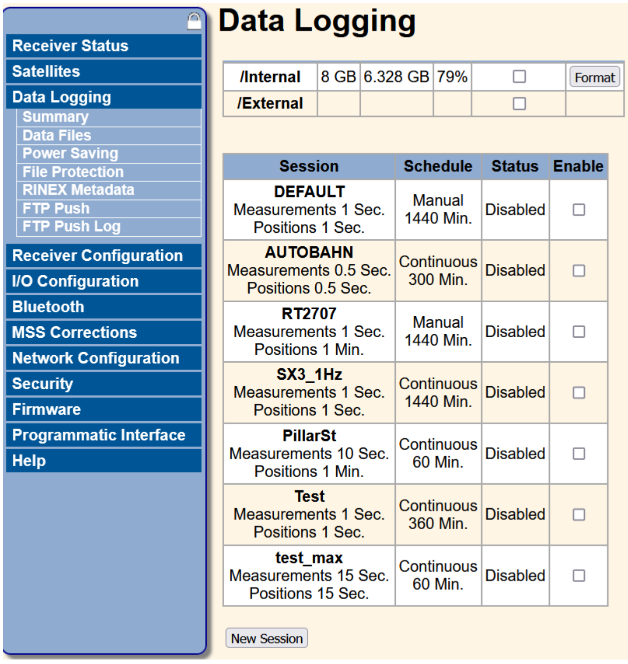


Figure 8.8: Profiles for data logging

8.1.3 Multistation 60

To measure with the *MS60*, it is necessary to create a project, which can include such information as description and photo. In this project their will be saved all data points which are measured[15]. After creating a project, it is necessary to orientate the whole system. There are many possibilities to do

[15]Data measured by Meas&Stream are not saved here, it requires a terminal program

it so, but in this thesis it will be *"free stationary"* which means the *MS60* can be placed anywhere to start the measurement. Before orientating, it is really important to set up an coordinate system where all of the measurement take place. To edit or change the current one, go to the *Job*(or creating a new one) and select *Coordinate system* as seen in the figure 8.9. Moreover, change

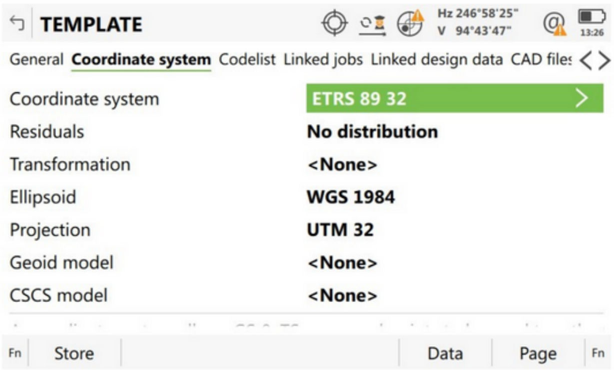


Figure 8.9: path for changing the COS [11]

the type of the prism (see 8.10), which will increase the precision of the measurement. This path can be reached by selecting the second symbol (middle one) above the jobs. There can be adjust some other function as well, for example *Meas continuous*, which is also needed for the following measurement. After adjusting those factors, the orientation can be started. For that, go to your job and select *Setup* (see fig. 8.11), then choose a an orientation (fig. 8.12). For the mobile reference trajectory a *Resection* orientation is used, which is the same as the mentioned *free stationing*.

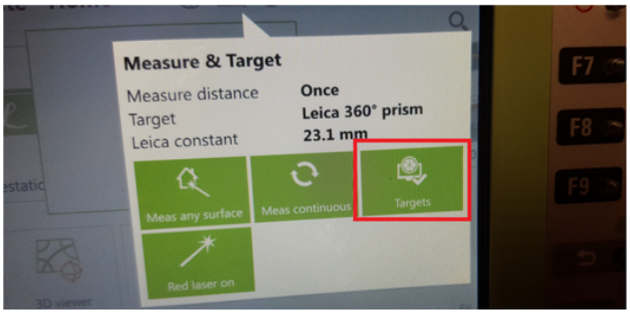


Figure 8.10: option to change the type of the prism [11]

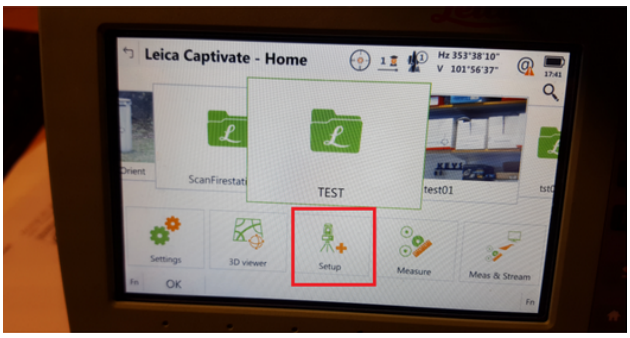


Figure 8.11: Setup the *MS60* for its orientation [11]

When the orientation is chosen, enter the instrument height in the system (it is not necessary to do it, only when the origin should be above the ground) as shown in figure 8.13. Here, it is also possible to import data from another job which are already measured or integrated. Secondly,

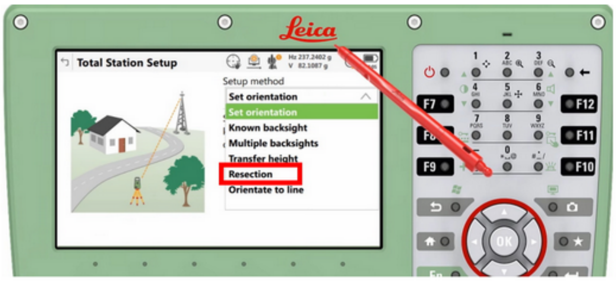


Figure 8.12: Choose a orientation [11]

Figure 8.13: Setup details of the *MS60* [11]

when no reference point were imported, create them and insert the UTM coordinates. Those will be targeted by the *MS60*. In addition, it is possible to enter a target height as well (see fig. 8.14). Afterwards the points have to be targeting and measured, it may helps when the Multistation aims close to prism. This is strongly recommended, but is not necessary because of the *PowerSearch* option from the *Leica* device. With this feature the *MS60* will automatically search in a specific area for their prism. After finishing the measurement of at least two points, the system is able to calculate its own position and identify random coordinates which are aimed for.

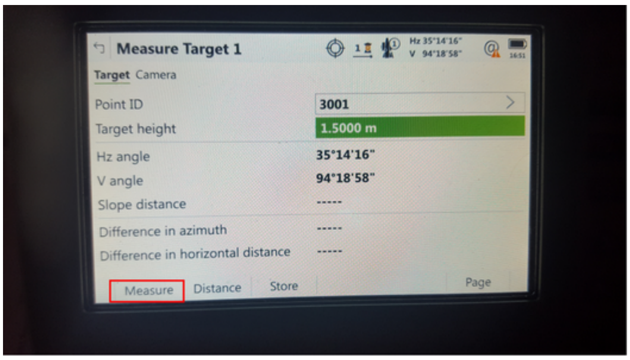


Figure 8.14: Entering the target height *MS60* [11]

However, to get those UTM coordinates, a GNSS setup is needed. Follow the steps which are described in 8.1.2, except for the data logging. If *RTX* is enabled and the standard deviation is converged (takes 10-15 min.) write down the Latitude and Longitude from the receiver which is projective in the browser of the laptop. Convert those to North, East and Heigh which is the preferred coordinate system from the *MS60*. It appears a higher accuracy when the position of the tacheometer is between the reference points. In this thesis there were only taken two reference point, but those should also be in a great geometry. This means, there should not be both reference points on the same side of the *MS60*. Moreover, those points have to place in a open sky circumstances, because of the GNSS setup.

This steps were only for the stationing and takes the most time. After that is finished, go to the project and start the measurement by clicking *Measure&Stream*. Make sure the *MS60* is connected to a laptop and a terminal program to records the data. For more information about the application *Measure&Stream* and how to connect it with a laptop read [12].

8.1.4 Processing the data

After the measurement is finished and every data is collected, the analysis can begin. For this purpose *TerraPos* was used. Make sure every file has the proper format, so the program can use it. In this thesis, the IMU raw data have to convert via *MATLAB* to a *.dat file which is needed for the processing. Data from the *MS60* have to rearranged as well and a proper import format had to define in *TerraPos*. More information about the process via *TerraPos* and how to place each file for a proper solution see [19].

8.2 Additional tables and figures

8.2.1 NetR9 Pillars

Table 8.1: Standard deviation *MS60*, first alignment

	East	North	Height
std.dev. [cm]	2.24	3.22	1.31

Table 8.2: Values from *MS60*, Second alignment

	UTM			difference to GNSS		
Pillar	East [m]	North [m]	Height [m]	East [cm]	North [cm]	Height [cm]
5	695790.583	5328278.567	594.662	/	/	/
2	695792.089	5328286.933	594.650	0.72	0.74	0.5
6	695784.714	5328279.648	594.658	0.74	0.71	2.82
Std. Dev.	0.014	0.011	0.012	/	/	/

Table 8.3: Measured Cartesian coordinates with *Trimble*

Pillar	Cartesian [m]		
	X	Y	Z
1	4182046.616	860633.377	4723101.248
2	4182046.359	860639.325	4723100.433
3	4182046.088	860645.266	4723099.649
6	4182053.027	860632.932	4723095.742

8.2.2 Scenario 5

Table 8.4: standard deviation *Trimble*

Pillar	Standard deviation [m]		
	East	Noth	Up
1	0.004	0.005	0.039
2	0.003	0.004	0.025
3	0.004	0.007	0.030
6	0.004	0.005	0.039

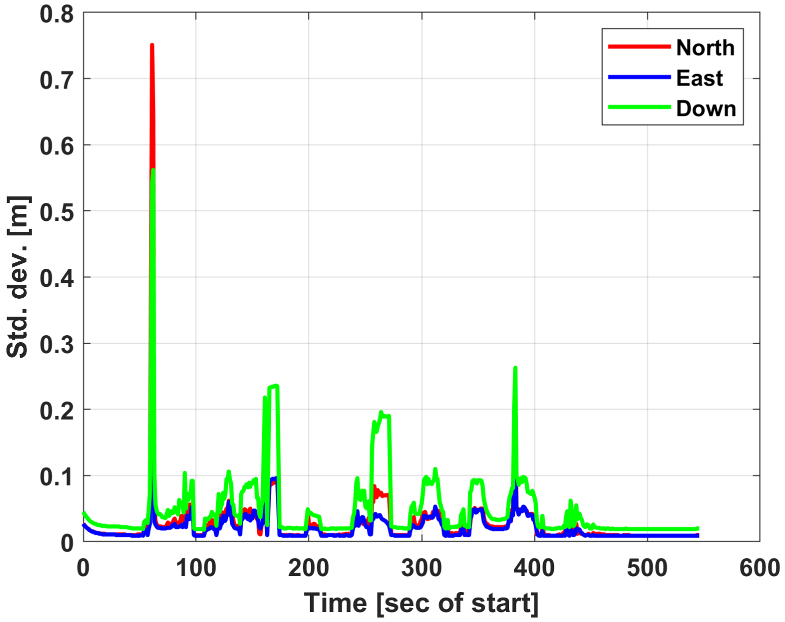


Figure 8.15: Standard deviation of the GNSS only solution while signal loss

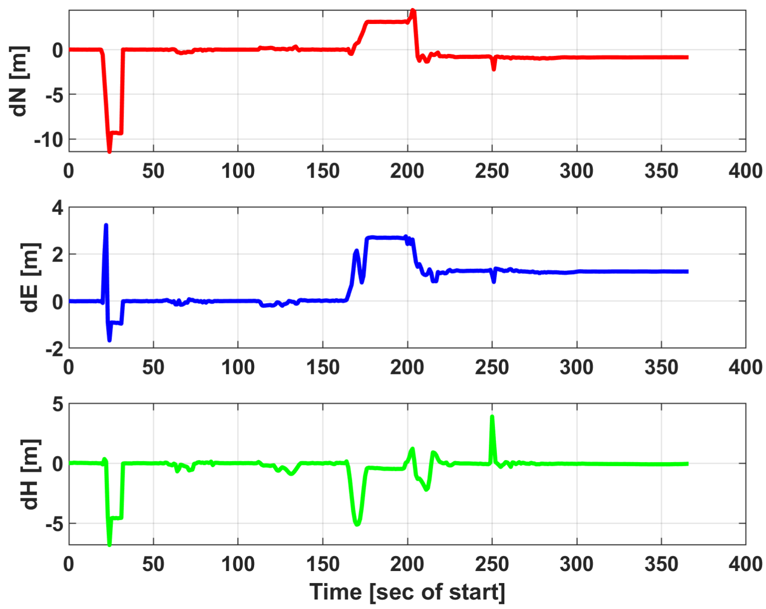


Figure 8.16: Difference between TC (three sensors) and GNSS only solution

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