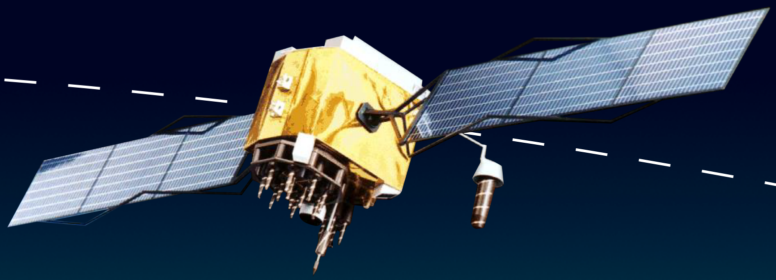
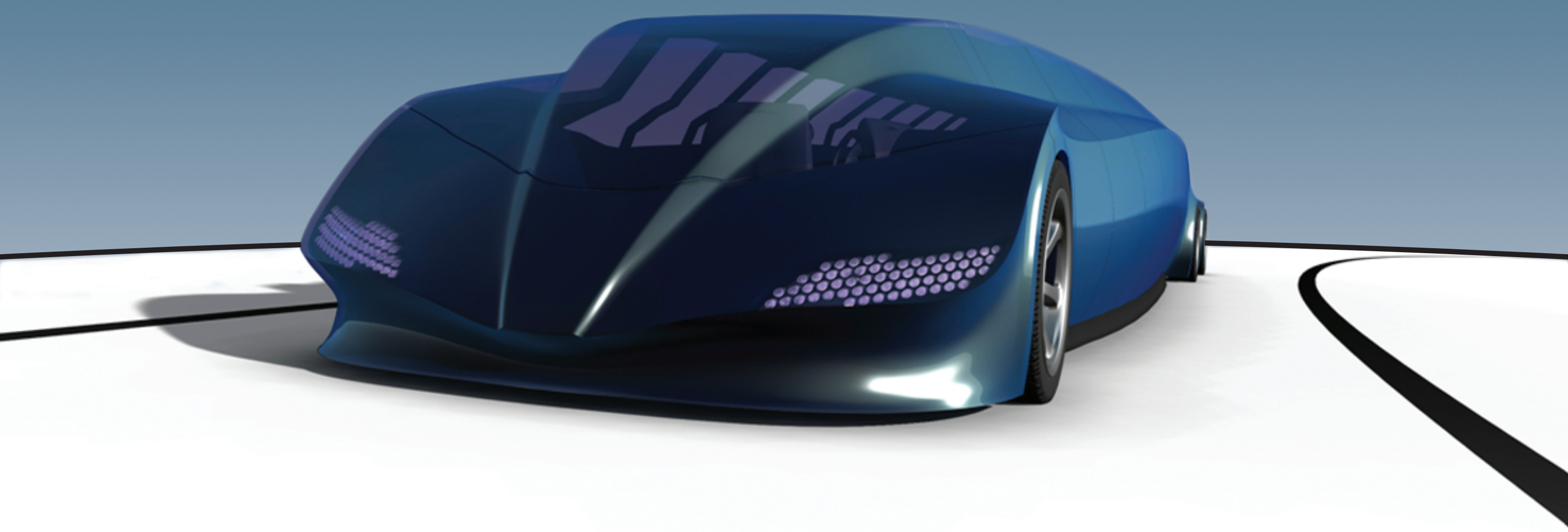


Superbus Positioning System

A High Accuracy Networked RTK GPS System

Master's Thesis



Delft, 2011

Gert-Jan Pauwels

Superbus project

TU Delft Delft University of Technology

Superbus Positioning System
A High Accuracy Networked RTK GPS System

MASTER OF SCIENCE THESIS

For obtaining the degree of Master of Science in Aerospace Engineering at Delft University of Technology

Gert-Jan Pauwels
1097407

March 8, 2011

Faculty of Aerospace Engineering · Delft University of Technology

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DELFT UNIVERSITY OF TECHNOLOGY
CHAIR OF
MATHEMATICAL GEODESY AND POSITIONING (MGP)

The undersigned hereby certify that they have read and recommend to the Faculty of Aerospace Engineering for acceptance a thesis entitled **"Superbus Positioning System"** by **Gert-Jan Pauwels** in partial fulfillment of the requirements for the degree of **Master of Science**.

Dated: March 8, 2011

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Supervisor: ______________________
Dr. Antonia Terzi

Acknowledgements

The road I took during the making of this thesis, has had me thinking frequently of the tortoise and the hare parable. I have come to the conclusion that a third creature should have entered the race. I propose a creature not necessarily as slow as a tortoise, however with a horrible sense of direction. Eventually stumbling across the finish line, having completely forgotten he had entered a race, yet having seen and learnt a lot. This would illustrate somewhat how I have come to this thesis. A lot of different things have kept me busy during the making of this thesis, sometimes losing sight of what was happening around me, but learning a great many things. Therefore, to start off, I would like to thank everybody, that has aided me during the process, and sometimes pointed me back in the right direction. It has been truly interesting, fun, and very informative.

I would like to thank Christian, of course, for his enthusiasm and helping me in such a way, that I still had to think about what it was I had to do. I have walked out of your office many times, thinking I knew the answer, only to discover, it wasn't quite as straight forward as it seemed. I would like to thank you sincerely for making this thesis an enjoyable experience. I would also like to thank the whole Superbus team, especially Antonia and Maarten, for the infrequent but highly enjoyable contact, and giving me the opportunity to help you with the Superbus. The freedom and responsibility you have given me in the making of this system, is greatly appreciated. Furthermore I would like to thank Lennard for teaching me the practical skills of "playing around" with expensive equipment. This was a lot of fun, and has been essential to turn theory into practise and the other way around. This gratitude is also directed towards Roel, who has given me a beautiful opportunity for a test campaign, and helping me a lot in the process. Frank Boon from Septentrio Satellite Navigation N.V. is also thanked, in particular for the speed and remarkable openness of the responses from him and his company.

My sincere gratitude also goes out to all my friends and family, for helping me and always being there. You have given me the confidence and perseverance to complete this study. This would not have been possible otherwise. I hesitate naming you all in person, in fear of forgetting or ranking anyone. Certainly my parents deserve an honourable mentioning. They have given me opportunities that not many people have, for which I am extremely grateful. Also specifically for helping me the last few hectic months with proofreading and logistic tasks. My brother also, for sometimes carving my path, and sometimes the pointy but truthful remarks. A special thanks also to Dennis, for helping me with the visual lay out of the report and presentation. Son, Ro, Behn, Nigel, Michiel, Matthijs, Klaas, Jelle, Geert, David, Daf, Joep, Barend, Noortje, Floor, Nathalie, Elisa, Claire, Doris, Lysanne, Vi and all the others, thanks for all the pep talks/proofreading/dinners/climbing and all the other forms of help and activities. It was great.

Gert-Jan Pauwels
Delft, March 8, 2011

Abstract

In this report a high accuracy positioning system is investigated for use in the Superbus. The Superbus project is an effort to apply a new and complete conceptual approach to public transport. It consists of a vehicle, logistics and infrastructure. The positioning system for the vehicle is to have a horizontal position error, which will not exceed 5 *cm* in 95% of the obtained solutions. Secondary requirements included large (quasi-national) deployment area. Networked RTK positioning using GPS is shown to be a valid means to adhere to these requirements. Real Time kinematic (RTK) positioning allows for the required accuracy, while a base station network will allow for the required deployment area using Pseudo Reference Stations (PRS). UMTS is shown to be potentially effective for the required wireless data transfer using the NTRIP protocol. Testing confirmed adherence of the Superbus Positioning System to the requirements in a variety of real world scenarios. Furthermore, the receiver is shown to perform to manufacturer specifications. Difficult environmental conditions, such as urban areas and multipath are confirmed to have an effect on the position estimate in certain situations. It is however demonstrated that the receiver is capable of adhering to Superbus requirements in these situations, provided the initial ambiguity resolution is correct. Temporary signal loss of all satellites (for example due to an underpass) is shown to inflict the need to reinitialise the ambiguity resolution algorithm, causing a temporary unavailability (around 20 seconds) of the precise RTK position estimate. Heading estimates are also established to be within specifications in good conditions. In high multipath conditions, or conditions with a low amount of satellites in view, the heading estimates exceed the manufacturing specifications with varying margins. This is possibly due to the fact that the ambiguities of the secondary antenna cannot be fixed in this scenario. Material testing showed that carbon fibre, the material that initially would cover the antennas in the vehicle, is highly unfit for this purpose. A thermoplastic counterpart shows no degradation of the satellite signal, and can be used for said purpose.

Preface

Writing a preface is a strangely personal affair. It is one of the last things one does, before print. A lot of things that have occupied you during the making of the report often find a way in the text. For this reason, I have decided to write this part in Dutch. Some have (rightfully) commented that the text below is quite easily translatable in English. Still, I have opted to keep it this way, since the language is closest to me, and the majority of the people that will read this. I apologise to the people who are not able to read the preface, but I hope that they will enjoy the rest of the thesis.

Tijdens mijn scriptie is mij vaak gevraagd, wat de Superbus nu precies is. Één van mijn antwoorden was vaak, dat het een demonstratie was van de stand van de wetenschap. Wat is er mogelijk met wetenschap, en waar gaat het naartoe. Techniek, zoals de Superbus, is bij uitstek een graadmeter voor de stand van de wetenschap omdat het aantoont wat voor de mens beheersbaar is geworden. Dit beheersbare element van techniek is een steunpilaar, een wetenschappelijke theorie moet falsifieerbaar zijn. Techniek is niet mogelijk zonder dat de uitkomst van een actie voorspelbaar is. Dit klinkt logisch, toch is wetenschap niet altijd verbonden geweest met falsificatie. Descartes heeft dit in 1637 als eerste opgeschreven in zijn Discours de la Méthode [8]. Dit wil niet zeggen dat er daarvoor geen nuttige dingen zijn gezegd of uitgevonden, maar wel dat sindsdien de kijk op de wereld en de wetenschap is veranderd. In de volgende paragrafen zal hier los op worden ingegaan [35].

In de vorige paragraaf zijn een aantal dingen impliciet opgenomen. Één daarvan is dat techniek klaarblijkelijk evolueert. Dit Darwinisme is een vreemd fenomeen, en het laatste -isme, dat door de moderne wetenschap zonder hakken en stoten wordt geaccepteerd. De moderne samenleving is ervan doordrenkt. Het kernpunt van het Darwinisme, van evolutie, is een *gebroken* eenheid. Het hangt aan elkaar door sterfelijkheid, vermenigvuldiging en verandering. Een nakomeling is een replicatie van zijn ouders. Deze mens is niet hetzelfde als zijn ouders, maar men spreekt wel over hetzelfde, een mens. Mijn opa is gestorven, dat zal ik ook. Wij zijn niet hetzelfde, toch dragen wij dezelfde naam. Wij delen een identiteit, die groter is dan wij als individuen. Ondanks dat een paard door de jaren heen is veranderd, blijft men spreken van een paard. Identiteit is veranderlijk, en wordt pas, juist door zijn vermenigvuldiging duidelijk. Darwinisme betekent een verandering van de kleinste gemene deler van *hetzelfde*. Deze is met het Darwinisme omgewenteld van individu naar genoom.

Als gezegd viert Darwinisme hoogtij. Dit is omdat met de ontdekking van het Darwinisme zeer veel wordt blootgelegd in taal, cultuur en techniek. Het *extended phenotype* van de mens [7]. Taal bestaat ook uit een gebroken eenheid. De betekenis wordt duidelijk door zijn vermenigvuldiging, tevens is de identiteit ervan evengoed veranderlijk. Een woord dat slechts eenmaal wordt gebruikt, is betekenisloos. Tevens kan een woord uitsterven, en kan een betekenis veranderen. Wij gaan er vaak vanuit dat taal utilitaristisch is, dat wij controle hebben over de taal. Dit kun je niet meer volhouden wanneer je het bovenstaande accepteert. Voorbeeld, een kind voegt zich in, in de heersende taal. Deze is groter dan zichzelf, en hierdoor wordt het onmogelijk om

”om het hoekje” van je eigen taal te kijken. Je bent al ingelijfd *in* de taal, voordat je er *over* wilt praten. Dit illustreert dat techniek, cultuur en taal *met* de mens leven, maar dat de mens geen controle heeft over het verloop ervan. Dit ligt aan *alle* heersende omstandigheden.

Is de mens hier niet de factor die besluit wat juist en onjuist is? Is ze niet de ratio van techniek? Een gedachte experiment. Het betreft de vraag waar ratio en betekenis op komen zetten. Wat betekent iets, en daarmee, wat *is* iets. Het kan vrij simpel worden verwoord. Stel wij hebben twee simpele en gelijkende organismen A en B. B wijkt op een cruciaal punt af van A, doordat B de mogelijkheid heeft een verandering in zuurgraad te detecteren. Hierdoor heeft B de mogelijkheid om zich uit de voeten te maken als het heersende milieu hem niet zint, waarbij A zich overlevert aan pure kans. B vergroot hiermee zijn overlevingskans en zal ter zijner tijd zege vieren in het gevecht om dezelfde, beperkte levensomgeving.

Het is belangrijk te zien dat door deze ontwikkeling een betekeniswereld wordt geopend. Het is plotsklaps zinvol geworden om over zuur en niet zuur te praten. Het beïnvloedt je overlevingskansen. Daarvoor kon je niet spreken over zuur en niet zuur. Er was geen verschil tussen, het was betekenisloos. Met de mogelijkheid tot detectie, ontstaat zuurtegraad, plaats en tijd, juist doordat er consequenties aan zijn verbonden.

Hiermee wordt duidelijk dat een replicator (genoom) een ratio heeft boven die van het individu (replicant). Je kunt niet anders dan zeggen dat het genoom van soort B (per toeval) rationeel is geweest. De ontwikkeling was het goede antwoord op de heersende omstandigheden. Soort A heeft verloren, soort B leeft voort. Zo is de ontwikkeling van de vleugel ook een juist antwoord op de heersende omstandigheden. Stukje bij beetje heeft zich dat steeds verder ontwikkeld tot iets waarmee een vogel kan vliegen. De uitkomst had ook niet iets anders kunnen zijn dan iets wat lift genereert, want een vleugel moet zich houden aan de wetten van de wereld om zich heen. Je kunt dus ook niet anders zeggen, dan dat een vleugel er is om te vliegen. Het is onlosmakelijk verbonden aan zijn functie. De natuur heeft het bij het rechte eind.

Dit kan geëxtrapoleerd worden naar techniek. Een hamer (ook een replicator) heeft zich in de geschiedenis ontwikkeld en is immer bijgebleven met de heersende omstandigheden. De botte steen is uitgestorven, en de hout met stalen constructie leeft voort, daar ze het meest passend is voor de heersende omstandigheden. Het woord hamer blijft, de fysieke verschijning ervan verandert.

Ook voor wetenschap geldt hetzelfde. Teruggrijpend op de geschiedenis: Descartes kwam zoals eerder vermeld, met de wetenschappelijke methode. Een manier voor het bedrijven van wetenschap. Falsifieerbaarheid kwam hiermee hoog in het vaandel. Dit duidde op een eerste radicale omwenteling van het wereldbeeld: de mechanisering (de tweede is het Darwinisme). Het was een omwenteling in de identiteit van dingen. Het veranderde de blik van wat iets *is* en maakte het onafhankelijk van geloof (bijvoorbeeld de Ideeënleer van Plato met een niet fysieke wereld met de essentie van álle dingen erin) en trok het naar reproduceerbaarheid. Water was niet meer een stof met een essentie. Neen, water is een stof die gaat koken bij honderd graden. De eigenschap kun je reproduceren, en gebruiken. Maar belangrijker: een tripje naar de alpen maakt het tegendeel duidelijk. Toch, de wet is niet ongeldig geworden door een tegenspraak. Ze is er tegen bestand. Ze is ingedekt om tegenstand te weerstaan, kan veranderen en variaties in zich opnemen, naar mate de wetenschap voort schrijdt. Een hypothese blijft bestaan als ze de beste resultaten oplevert. Iets *is* hiermee bij zegen van zijn reproduceerbaarheid en de potentiële gebruiken ervan. De wetten die dit beschrijven zijn ook onderhevig aan het Darwinisme. Slechts de meest passende hypotheses zullen overleven in de strijd van de wetenschap. Herinnert u zich Phlogiston nog?

Descartes zei het onopgemerkt zelf al. Hij probeerde, levend in het tweespalt tussen klassieke en wetenschappelijke wereld, nog een opening te houden voor klassieke opvattingen, maar daar faalt hij in. Hij zag de wetenschap als boom [9]. Met een dikke stronk, en uitbreidend in steeds kleiner wordende takken. De stronk was voor hem de basiswetenschap, wiskunde en fysica. Van daaruit kon elke wetenschap en kennis worden afgeleid, de steeds maar kleiner worden takken. Hij doorzag echter al dat elke wetenschappelijke hypothese uiteindelijk wordt getoetst uit de techniek die het voort brengt: de vruchten. Deze techniek dicht het gat tussen mens en natuur, met wielen, hamers, telefoons en internet. Deze vruchten zijn succesvol. De vruchten voeden daarmee de boom voor de immer voortschrijdende wetenschap. Wederom Becher met zijn Phlogiston. Zijn simpele elementen systeem was op de lange duur niet afdoende meer, de tak baarde op den duur minder vruchten dan concurrerende hypotheses, en storf af. Ze is nutteloos geworden

Descartes, in zijn tweespalt, kon zijn boom echter niet in de lucht laten zweven, en zocht naarstig naar een (naar het blijkt onnodige) grond voor de wortels. Deze grond vond hij in de religie en de filosofie (metafysica). Hiermee voert hij helaas een totaal overbodige dubbele boekhouding in. Zijn theologische en filosofische gronden voor de wetenschap zijn onnodig wanneer het succes van een wetenschap slechts beoordeeld wordt uit het resultaat.

Waar komt Superbus in dit verhaal? Dat kan alleen de toekomst vertellen. De identiteit van de superbus moet nog duidelijk worden. Duidelijk is wel dat het een mooi voorbeeld is van het resultaat van de wetenschap. Bij uitstek een voorbeeld van waarom ik techniek ben gaan studeren. Een apparaat dat ogenschijnlijk de wetenschap tart. Over enkele jaren zullen we niet meer verbaasd zijn over dit project. Dan wekken andere dingen onze interesse, oud nieuws. Dat wil niet zeggen dat de Superbus vergeten is. Dat ligt eraan of Superbus een succesvolle replicator gaat worden.

Gert-Jan Pauwels
Delft, 8 Maart, 2011

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Chapter 1

Introduction

For several decades now, the major cities in the west of the Netherlands have been growing steadily in prosperity and population, while the north of the country has seen a relatively slower growth. Especially in times of a beneficial economic climate the growth of the northern provinces has been lagging behind. In 1997 this was also the conclusion of a government commission that suggested that the profits, gained from the vast gas deposits of the north, could be used to improve infrastructure in these areas. One of the incentives involves a better and faster transportation link between the west and the north of Holland. By doing this, the hope is that the northern cities will start to see larger economic growth figures, due to much faster and easier traffic between the north and the economic heart of the west.

The Superbus project started in 2004 as a reaction to this incentive, as well as to other modern day environmental and mobility issues: pollution, congestion and safety. The Superbus project sees to tackle these issues by applying a new and complete conceptual approach to public transport. It consists of a vehicle, but also new dedicated infrastructure and new logistics.

The Superbus itself is a high tech, road going vehicle that has been designed to be fast, safe, comfortable, and flexible in order to promote its usability. Furthermore it has been designed to have as little environmental impact as possible. It is to attain a cruising speed of 250 km/h and will be powered electrically.

With the technology present in the vehicle, a demand also followed for a real time, high accuracy positioning system. Requirements were set according to which the horizontal position error of the system may not exceed 5 cm in 95% of the obtained solutions. This system will allow Superbus subsystems to function optimally and can allow for more advanced future upgrades, to the vehicle and the whole Superbus system. The purpose of this report is to investigate a positioning system, that can adhere to the requirements set by Superbus. Additionally the designed system will be tested to validate it's suitability for use in the vehicle.

The structural composition of the report is as follows. Chapter 2 will serve as an introduction to the Superbus, and the project as a whole. System requirements will be specified, and the project goals will be defined precisely. Chapter 3 will constitute a theoretical background to the project, and will explain what systems are necessary. Chapter 4 will describe the positioning system and its practicalities. Chapter 5 will serve as the main chapter wherein the obtained system is tested and validated. The last two chapters will consist of a conclusion, discussion and of recommendations.

Chapter 2

Superbus

Public transport plays an important role in modern society, it has become a backbone for both social and economic interaction. This infusion in society does however not mean that changes and improvements in public transport are not possible or desirable. This is the vision of the Superbus project, it aims to re-establish the way we look at public transport.

This chapter will function as an introduction to the Superbus project. The origin of the project will be considered shortly, and Superbus concept will be introduced. In the subsequent sections an introduction to Superbus positioning will be made, after which the requirements and positioning project will be defined.

2.1 The Superbus project

The Superbus project started in 2004 as a reaction to modern day environmental and mobility issues: pollution, congestion, time constraints and safety. These are issues that gained tremendously in importance in the last decade. The project will try to tackle these mobility issues from more than one perspective. The project really took off in November of 2005 when it received a grant from the Ministry of Transport, Public works and Water management (Ministerie van Verkeer en Waterstaat), currently the Ministry of Infrastructure and Environment. The grant was conceived for the development of a means of public transport between the north of the Netherlands and the more densely populated south-west. This means of transport should function as an economic and social catalyst to draw the historically more isolated northern part of the Netherlands and the south-west closer to each other. Superbus was one such means of transport selected that could fulfil this role.

After the grant was received, the detailed development got underway and in the beginning of 2007 construction began on a first test vehicle. Development of the detailed design continued throughout the building process, which is now nearly complete. After its completion the vehicle will undergo rigorous testing to analyse performance and ensure passenger safety. During this time Superbus will try to develop enough knowledge and momentum for the concept to make implementation of the concept a possibility.

The Superbus project is a project that tries to rethink public transport. The goal of the project to provide a fast, demand based road transportation system for medium to longer distances up to approximately 250 kilometres. It tries to address modern mobility demand with a fast, safe and environmentally friendly public transport vehicle. The vehicle is specifically designed with speed, passenger comfort and sustainability in mind. It is important to note that it is a complete conceptual approach to public transport, and as such the project does not constitute a transport vehicle alone. The Superbus project spreads over multiple disciplines:

- Vehicle
- Infrastructure
- Logistics
- Safety and Reliability
- Environmental aspects
- Exploitation and economic viability

In order to discuss the concept of Superbus, the background is enlightened first. The demand for transportation grows constantly, as does the amount of people who demand it. People have been travelling further and further over the years, caused by technological advances. Yet for daily commutes, time is a more important factor than distance. People generally do not wish to spend more than a certain amount of time each day on transportation, or travelling [29]. This situation is now aggravated by an ever growing fleet of cars dressing the nation, causing bottlenecks and traffic jams in the established road network. Conventional growing of this infrastructure, building more roads for more cars, will not be a viable, sustainable solution to the problem. Not only due to space constraints, but also due to safety issues and pollution. Superbus therefore tries to find one of the solutions to this problem. It does so by studying the reasons for people to take cars and tries to derive an feasible alternative. At the same time the solution must be sustainable, both for people and the environment.

An important element is to find the appealing and deterring factors of both private and public transport. For example: the sense of privacy one has in a private vehicle, as well as the fact that one is able to drive right to the door of your destination, are compelling factors for a automobile. On the other hand, a person driving is not able to do work, for example. Public transport can in some cases allow for this, as well as avoid many known traffic bottlenecks. If a new form of public transport is to be successful it will need to outweigh the advantages of a car and/or negate the annoyances of public transport.

It is clear that the problem has multiple facets, there is no single source that causes the problem. As mentioned, the Superbus project sees the solution in several facets as well. For example: moderating the overall road congestion by diminishing the number of vehicles on the road, increasing comfort and adding speed. The aspects mentioned in section 2.1, will all be combined to a system that is designed to provide fast, easy, comfortable and sustainable mobility to the user.

Very concisely: Superbus consists of a vehicle together with infrastructure and is designed as a more flexible yet fast alternative (mainly) to modern high speed transport. It aims to be more flexible by applying an on-demand structure, in contrast to, or together with a normal time-table. Starting points and destinations are therefore more flexible, and can be more local due to the ability of the vehicle to use normal roads in addition to its own infrastructure.

The Superbus (figure 2.1) itself is an electrical vehicle which can transport up to 23 passengers at a speed of up to 250 (Km/h). The vehicle will be powered by batteries and will make use of separate infrastructure to reach these high velocities, the Supertrack. Thanks to the low weight, low aerodynamic drag and rolling resistance the vehicle is very energy efficient. The absence of exhaust fumes and the low energy use also make the Superbus an environmental friendly way of transport.

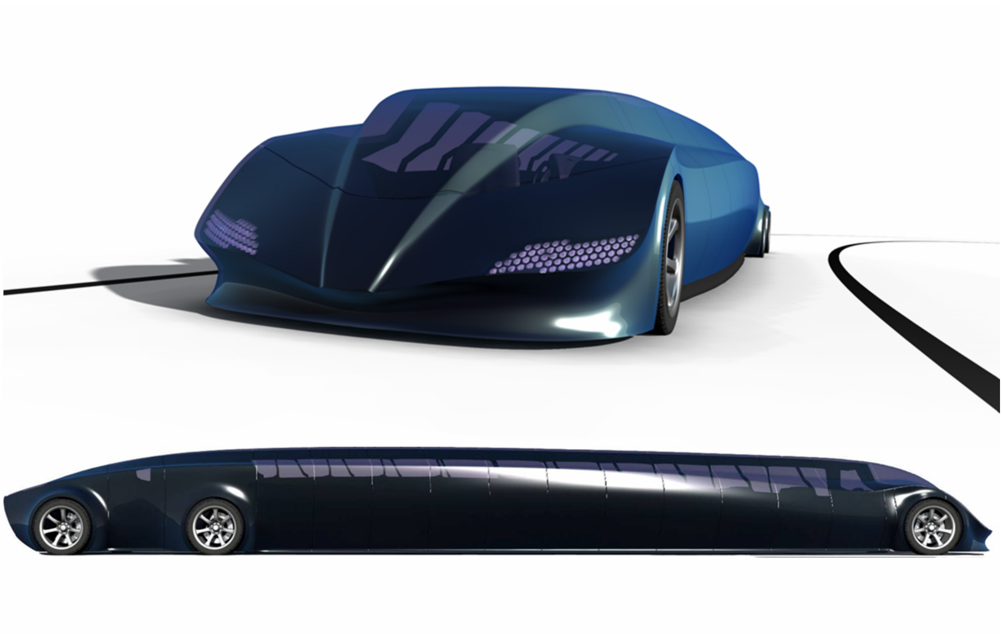


Figure 2.1: Front and side view of a Superbus vehicle. [source: Superbus]

Passengers are able to book a fare by means of internet or telephone. A central booking system combines passengers for matching destination and departure points and offers several travel options. The passenger can then book the most suitable, and has a journey with little stops or transfers. Passengers are boarded on the Superbus in urban areas on normal public roads before the vehicle goes to the Supertrack where it travels at high speed until it almost reaches destination. Here it transfers to local roads to let the passengers of close to their end destinations.

This condensed section is of course not the complete report of the Superbus system. In the section below an overview of the concept will be sketched, clarifying problems, visions and design choices in no particular order. The sections will hopefully create an insight in, and understanding of the main design philosophies of the Superbus system.

2.2 Conceptual design

A basic view of the Superbus concept has been presented in the previous section. This shows only the final result, provided the project is successful. In the following sections, a more elaborate view will be laid down in no particular order. It can create an insight into the design decisions and increase the overall understanding of the concept. Information for this section is redacted from Superbus documents [26–29, 52].

Travel times

First of all Superbus will try to reduce travel times in two ways. Not only does it increase the speed of motion compared to normal cars and trains, but it also tries to decrease transit,waiting, and initial transportation times (door-to-station). These can add up significantly in conventional public transport. The last method of reducing travel time is the use of dedicated Superbus infrastructure, Supertracks. These tracks allow the vehicle to reach its top cruising speeds, and circumvents normal traffic. In short, Superbus tries to reduce the door to door travelling times, not only the station to station times.

With a cruising speed of 250 (km/h), Superbus will be competitive with most high speed train services. The travel times are additionally reduced by altering the conventional time tables and itineraries of classic public transport systems. These mainly employ fixed line services with predetermined stops. Superbus will employ an on-demand structure. This means that they are not bound to fixed time tables. Because the vehicle is not limited to tracks as are high speed trains, this means that they are also means that the fixed itinerary and destination becomes obsolete. The Superbus will potentially be a much more flexible way of travel.

The on-demand structure can be exploited to benefit the user. The user will be able to convey base and destination points to the Superbus system, as well as departure- and or arrival times. The Superbus system is then able to pool multiple users together and devise a optimised itinerary which will minimise travel times. It will also avoid transits to a great extent, or optimise them, as to minimise the discomfort. The viability of such an on-demand system is aided by the fact the Superbus vehicle is able to carry a relatively low number of passengers for a public transportation vehicle: 20 to 30 depending on the lay-out. This allows customisation of routes and travelling times, while still reducing the number of vehicles on the road significantly: A four person passenger car is on average only occupied by 1.4 people, a much smaller number than a Superbus [28].

Logistics

Note that the Superbus will not be a pure door-to-door transportation vehicle. Collecting each passenger individually would take too much time and negate the time won by the speed of the vehicle. Yet by being fully road-going, stopping points can be much more dynamic than for example trains. These points are called concentration points. These can be created by introducing fixed stations, but they can always be dynamic as well: when- and wherever enough people are present to justify a stop, one can be created. Examples include events and conventions. Furthermore, because the Superbus can only carry 20 to 30 people (depending on configuration), these concentration points can be relatively small and local.

When the Superbus system is fully deployed and operational, it will employ a direct point to point routing system, with potentially a few local stops at the starting point and the destination. This will ensure fast travel times while maintaining a high degree of vehicle occupation and minimising the distance a user needs to travel to get onto the vehicle.

This on-demand system does however not mean that standard line services will be ignored completely. If demand is stable and large enough, such a line service can be employed with little drawbacks, or even benefits, to the passenger. This can be of particular interest to commuters seeking for a stable fast way of travel for medium to long distances. An example here, might be the Zuiderzeelijn, the original route planned for the Superbus, mentioned in section 2.1. Also in the beginning roll out phase of the system, not enough vehicles will be available to employ an effective on-demand system. Additionally, the passenger base needs to have grown sufficiently large to support the system. This is a two way system that will need time to grow.

One can see that if the concept takes off, the success will largely be dependent on modern ICT solutions. Managing many passengers individually, providing each with an efficient travel solution, but also managing an increasing Superbus fleet, including destination, route and current location, will need a new, highly optimised, highly converged, and continually up-to-date system. The old time table system is thrown out, yet it does need to be replaced with something superior to benefit the passenger. This in order to become a viable alternative to other forms of transport.

Lastly the charter market may become a lucrative market for Superbus. Since the vehicle has a relatively low number of passengers, it becomes more obtainable for a single business to acquire a high occupancy rate (or load factor). At this point it may become beneficial to charter the complete vehicle. This will allow more freedom to the business and its users to travel on desired times and to desired destinations. This will again shorten travel times since the Superbus can use a direct route to the destination. This may especially be interesting to medium to large corporations with several branches within the range of the Superbus.

Passenger comfort and safety

Benefits over other modes of transport, as already discussed in previous sections, are paramount for the success of the Superbus system. For example, the locality, and individuality of the Superbus approach mentioned above are important steps in the passenger's perceived comfort, and likely diminish the reluctance to opt for public transport. The Superbus concept tries to do this in other areas as well.

The vehicle itself will be extremely comfortable and is produced to express a certain luxury. It must offer a significant benefit over a car in order to convince people to take the Superbus. Therefore the seats are very comfortable and head- and legroom are very spacious. However, the sense of privacy in a car is not to be underestimated. The seats are spaced far apart and many individual entrances drape the vehicle for this reason. It will relieve some of the annoyances people perceive when using public transportation. People must not feel hindered while travelling, be it for privacy, comfort or the ability to work.

The ride itself must also not be overlooked. A harsh journey can issue the same feeling and discomfort, and makes any form of productivity impossible for the passenger during the trip. First of all, the suspension design is a major factor for perceived comfort. Seconly, accelerations in all directions need to be managed: Longitudinal, lateral and vertical. This is shown in table 2.1.

Table 2.1: Recommended acceleration domain. [Source: Superbus [28]]

Direction	domain (m/s^2)
Longitudinal	$\pm$ 1.0
Lateral	$\pm$ 1.0
vertical	9.31 - 10.81

After analysis of comparable modes of transport, Superbus established that accelerations need to remain in this domain in order to be perceived as comfortable. There are several ways to achieve this. First and foremost, de- and acceleration should be kept within these limits during normal operation. Superbus will not be a race car: it will take a leisurely 70 seconds to accelerate from stand still to the cruising speed of 250 (km/h) and vice versa. The vehicle is able to perform far better during emergency situations, but naturally these situations tend to be avoided.

Lateral accelerations are harder to control, they are dependent on the speed of the vehicle and the radius of the turn, see equation 2.1. With a cruising speed of almost 70 (m/s) this would leave a turn radius of 4.8 kilometres.

$$a = \frac{V^2}{R} \tag{2.1}$$

The turning radius or speed can may be altered, if necessary, by banking the road. This will convert some of the lateral accelerations to vertical accelerations. This will allow tighter turns at greater speeds. Note that banking roads would on the other hand add to the cost of the infrastructure. Since one of the main advantages of the Superbus concept is the relatively low infrastructural investment, this may need to be avoided.

Another approach to this can be taken as well. In addition to the banking roads, the same results can be achieved by banking the vehicle: the same transition of forces applies. An active suspension system is able to raise, lower, soften and stiffen the suspension of each individual wheel. This would allow the vehicle to bank into the turn by raising the suspension on the outer wheels slightly. This will reduce the bank angle, and hence reduce the cost of the road. Note that this scenario is supposing the traction of the wheels is sufficient, and the aerodynamics are not disturbed beyond acceptable limits.

The active suspension (atlhough currently not implemented) is useful for controlling vertical accelerations as well. Whenever a known coarseness in the road is encountered the suspension of the appropriate wheels can be softened moments prior, to allow the vehicle to coast over the unevenness due to the low weight of the wheel. This would significantly reduce the vertical accelerations, allowing the vehicle to remain at higher speeds while passing these variations in the road. This in turn would again reduce the cost of the infrastructure since the need for a perfectly even road is no longer there.

All the measures mentioned above combined try to relieve the reluctance to take public transport and offer genuine advantages of choosing the Superbus over a normal car. But this comfort means very little without safety and reliability. Therefore safety is a priority both in infrastructure and in the vehicle itself.

The fast Supertracks, the independent roads only accessible for Superbus, will be monitored actively. Cameras will control the entrances and fences or noise barriers will make access for wildlife and people difficult.

The vehicle too will have many active safety features embedded. Computer systems will monitor more than 750 sensors, for example in the doors and seat belts of every passenger. These will affect the passengers directly. But all other on board parts and systems will be checked continuously as well. Tire pressure, engine and battery status, etc. Also seven radars will be fitted onto the Superbus to improve situational awareness. At 250 (km/h) it will take a significant length of road to stop, some 2.5 kilometres. The radars will aid in detecting obstacles and irregularities before the pilot is able to, and can aid in taking appropriate action. Passive safety is also not forgotten. Mandatory seat belts were mentioned already but also the full carbon fibre body will, if necessary, protect the passengers.

Sustainability

Conservation of the environment has become a relevant issue in recent years, and as a result Superbus tries be as close to a environmentally neutral solution as possible. This will ideally serve as an incentive for others, and show that an *environmentally* viable solution can also be an *economically* viable solution. Naturally, the low environmental impact will increase the marketability of the Superbus as well. Yet most importantly, it will ensure the Superbus will remain a viable option in the future, as legislation on carbon emissions and general environmental impact will invariably tighten.

The vehicle itself is electrically powered and offers regenerative braking, in order to regain some of the kinetic energy of the vehicle. Electrical motors can convert energy to movement with greater efficiencies than conventional motors [28]. Also, the electrical energy can come from any number of (environmentally friendly) sources, wind, sun, etc. It is therefore less dependent on liquid fuel prices alone, in addition to being more efficient. Lastly, the aerodynamics are improved dramatically to reduce drag, and hence the power needed to attain the higher cruising speeds. The vehicle will approximately need the same power output at 250 km/h as a normal bus needs at 100 km/h [28].

To achieve the lower power requirement at speed, the frontal area is reduced in comparison with a conventional bus, and the aerodynamic properties are optimised to reduce the drag coefficient. This is can be seen in figure 2.2. By using advanced modelling and simulation software the drag coefficient has been reduced to one that is lower than a typical passenger car [28].

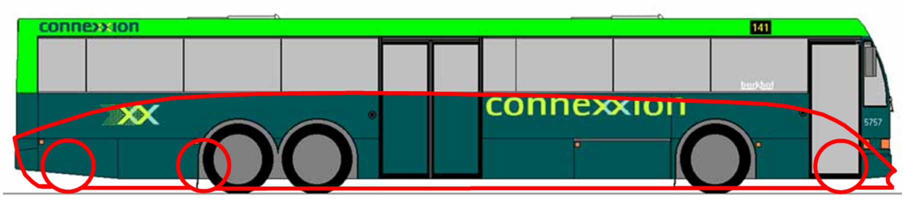


Figure 2.2: Comparison between a Superbus and a conventional bus. [source: Superbus]

The vehicle

To allow for the high speed performance of the Superbus while still managing a reasonable power requirement, a low, light weight and aerodynamically efficient design is mandatory. This has consequences for the interaction with the vehicle.

As can be seen in figure 2.2, the vehicle is obviously too low for a person to stand in. This invalidates a vehicle set up with one set of doors and an aisle. Instead each row will have two individual gull-wing doors, allowing persons up to a length of 2.10 metres to enter the vehicle in a normal manner and sit down naturally without having to bend down. This can be seen in figure 2.3. It allows you to stand while the doors are open, yet are low and flush when closed. The multiple door design however does mean a more difficult design in order to maintain an ample structural strength and stiffness for the vehicle. The doors are formed hexagonally to optimise the transition of forces in the vehicle frame. In order to incorporate this design without compromising in the weight restrictions, the vehicle will have a fully load bearing carbon fibre construction.

The hexagonal structure allows for this, and obtains sufficient torsional and longitudinal stiffness.

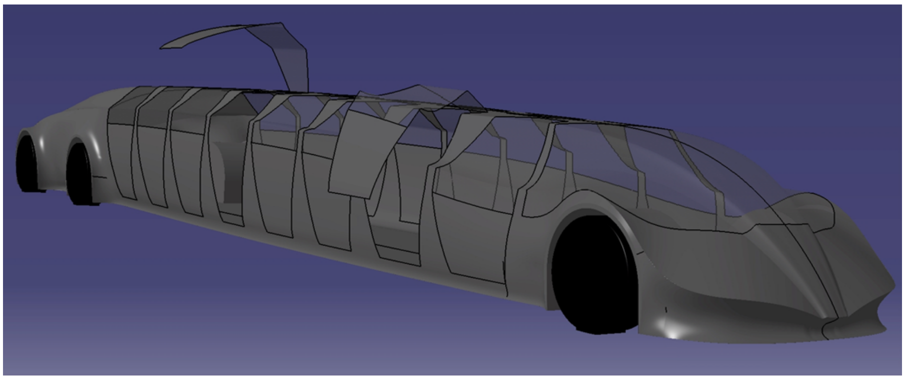


Figure 2.3: Gull-wing door design. [source: Superbus]

A problem arising from the extremely low vehicle design is a that a reduced number of roads is accessible. In order to make Superbus useful, it should at least be able to travel on all roads a normal bus is able to go. With the chassis just mere centimetres from the ground this is not possible, Speed bumps, steeper bridges, and other urban obstacles would be impossible to navigate. Therefore the complete vehicle can be lifted up or down nearly 40 centimetres. Low for high speed cruising, high for inner city flexibility, see figure 2.4.

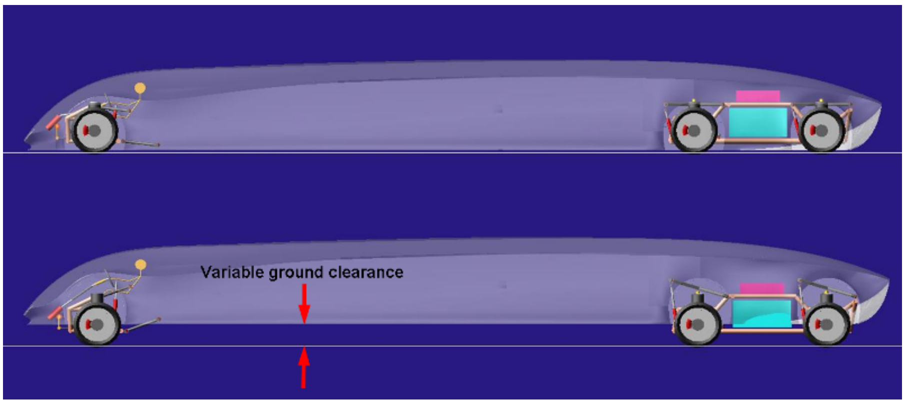


Figure 2.4: Ground clearance in high and low settings. [source: Superbus]

Now that most external design choices are clarified somewhat, it may be useful to summarise some of the vehicle specifications and performance parameters. This is done in the table below.

Table 2.2: Superbus specifications overview. [source: Superbus]

Main specifications	
Drive system	4 electric motors
Power Output	300 kW (600 kW max)
Range	$>$ 250 km
Acceleration (0-100 km/h)	36 s
Maximum cruising speed	250 km/h
Length	15 m
Width	2.5 m
Height	1.65 m
Weight	10000 kg incl. payload
Seating capacity	23

2.3 Superbus and positioning

Now that the Superbus concept has become clear, it is the appropriate time to discuss the goals of the positioning subsystem in the Superbus. Why is positioning needed in the Superbus and what are the main tasks of such a positioning system?

Simply put, the primary task of the positioning system is to aid additional Superbus (sub)systems. It will provide essential information to other Superbus systems and software. In section 2.1 it is explained that the Superbus is more than a straightforward vehicle, and encompasses many systems and sensors to ensure a comfortable and safe journey. Some of these systems need position, heading or other situational awareness information in order to function. As an example one can think of something as simple as navigation software, but the data can also used for more elaborate systems. Examples will be given below. Even more information can be found in section 4.5

Position data will also become an integral part of a planned elaborate database system, incorporating various kinds of information concerning road conditions. This can, amongst others, result in a more effective driving strategies for the Superbus. Such a database can for a example incorporate permanent road features, such as cornering strategies and locations of road imperfections. But in later stages variable conditions can be incorporated as well. Think of features such as current road temperatures, local weather conditions, and temporary road works or obstacles. All these features may prove useful in a vehicle that promotes fast, safe and smooth transportation.

Other uses may be found in the efficient fleet management system required to sustain an on demand itinerary structure. Section 2.2 shows that this system could become quite complex, resulting in the need to have up to date position information of all the vehicles. Lastly, as was mentioned in section 2.2, the vehicle is equipped with radars that provide additional situational awareness around the vehicle. Positioning information, more specifically, yaw rates, can be used for processing the raw radar data into intelligible information.

So in conclusion, the goal of this project is to provide precise heading, pitch, position, velocity and time information to the Superbus vehicle in order to support diverse subsystems. In addition supplemental information can be provided regarding the performance of the computed solution. These can aid in the safety issues concerning such a fast moving vehicle.

2.4 Superbus positioning requirements

Throughout this chapter it has become clear that a positioning system is a necessity for Superbus. In the previous section the essential physical quantities needed for the Superbus subsystems have become more explicit. Yet the performance for these quantities is still unclear: What is the needed precision for these quantities? And although these performance requirements of the Superbus GPS system are clarified in more detail in section 5.2, it is useful to discuss the global requirements the Superbus positioning system. It will provide a background to the next chapters, in which both the positioning system as the theory will be explained.

Together, the Mathematical Geodesy and Positioning (MGP) section and the Superbus team, set up the general requirements, discussing what information was needed for the Superbus systems and subsystems. Flexibility and precision were paramount, allowing direct use of the required data, but maintaining overhead, especially in precision, for future developments. This resulted in the following requirement:

> The Superbus Positioning System, must be able to provide *real time*, precise positioning data. Horizontal position error may not exceed more than 5 centimetres in 95% of the obtained solutions.

One notices that this requirement only mentions positioning accuracies, for the project however, speed, heading and pitch parameters with matching precisions were upheld. Additionally the dynamic nature of the project, an update rate of 10 (Hz) was upheld. As a last addition to these requirements, the deployment of the Superbus was taken into account. Superbus is a fast moving vehicle, for trans regional transportation. This means a large deployment area is an inherent character of the Superbus. In addition the Superbus system aims to be flexible in terms of destination, starting point and routing. This has led the project to the adoption of a (quasi)national deployment area for the Superbus. In other words, the requirement above, should be valid in large areas of the Netherlands.

As already mentioned, a more elaborate complete overview of the precise performance parameters is given in section 5.2. A more elaborate view on some subsystems that utilise positioning information will be given in section 4.5.

2.5 Superbus positioning project definition

Most important parts involving Superbus have now been clarified. The concept is clear, as are the uses and requirements for a Superbus positioning system on the global level. The positioning project itself however, still needs to be clearly defined. This section will outline the exact goals, boundary conditions and prerequisites for this project. This section shows what needs to be done, and in the process provides an overview of the next four chapters.

Firstly, the boundary conditions of the project are discussed. In the initial phases of the Superbus project it was decided that a practical and flexible approach to the positioning system was to be taken. This means that from a very early stage it was clear that a flexible Commercial-Of-The-Shelf (COTS) positioning solution was to be implemented. Choosing this path ensures support for the system, while keeping development costs to a minimum. Together with the MGP section it was decided that satellite navigation would be the most suitable system for the positioning demands of the Superbus. This system, more precisely the Global Positioning System (GPS), is already in use and could potentially adhere to the requirements of section 2.4. The satellite system is already available, and commercial equipment is readily available and supported. Another advantage is that GPS is globally available. For Superbus this means that this solution is independent on infrastructure and allows for (globally) flexible trajectories. The global nature of GPS can also be an advantage because the system needs to be certified only once, which is not the case for solutions dependent on the individual driving infrastructure, such as optical systems. This again makes the infrastructure cheaper and easier to obtain, not every individual Supertrack needs to be certified individually. This on the other hand also means that the proposed solution is already bounded to GPS in order to acquire a positioning information that meets the requirements. It directly places other potential solutions such as optical and inertial based positioning in second row.

Now that it is clear that the project is bounded to GPS equipment, the positioning project can be easily and sharply defined. The GPS dependency immediately sets certain circumstantial boundary conditions on the system design itself.

Literature suggests that a stand alone GPS system is theoretically not able to attain the accuracies required for the Superbus, using exclusively the currently available signals [31]. For these accuracies, additional information, available from varied sources is mandatory. Therefore it was known that some form of data communication between vehicle and main land was mandatory.

A second circumstantial boundary condition is the following. The Superbus requirements include heading, pitch and yaw rates. These are unavailable from GPS system with one antenna, at least not *directly*. In order to make these available, a secondary GPS antenna will always be a requirement.

The last boundary condition, is that the physical GPS receivers and antennas were already determined by the time the author joined the project. This predominantly affects antenna placement in the vehicle and the interface with other Superbus hardware.

The requirements, conditions and hardware combined broadly outline the design direction and determine the outline of the GPS project. This can be broadly subdivided into four sections.

Firstly the physical part: System design and physical integration. This entails determining what the capabilities and requirements of the chosen receivers are, and in what way the required information is accessible. This, together with the next section, will in its turn help to determine the method of positioning used, and how the complete system will fit together and may be implemented. But this will also determine the way the receivers will output data and interface with other hardware. It will result in a system available for physical implementation in the vehicle. The physical section also encompasses antenna placement, which can be crucial for the availability and accuracy of the calculated GPS solution. The placement therefore can play an important role in the adherence to the requirements. Lastly this section involves selection of proper front end and back end settings for the receiver. This entails setting up the receiver to obtain the best solution in the highly kinematic environment it resides. This is the back end. But establishing which information to input and output, as well as determining the output rate, and output format is also important. This is called the front end.

The second part is data communication link. As mentioned, developing a GPS system that is theoretically able to abide the stated requirements, always needs additional outside information. The second section of the GPS project involves the selection and implementation of this mandatory communications system. The Superbus properties such as deployment area and speed, but also the needed data link bandwidth are important factors in this field.

By this time, the Superbus GPS system will be physically largely determined, whereafter the focus shifts to software. The third section is therefore: software and interface. This section implicates the interface with other Superbus hardware.

In the beginning of the project it was determined that a sample C++ program was to be developed that was able to set up the receiver, as well as to receive and interpret the receiver output. The project requires some information that is not always available in the standardised output format: NMEA. The binary format developed by the receiver's manufacturer, does give access to this information. This does however complicate the way the information is accessed, hence the sample C++ code.

The last section is the verification and validation of the completed GPS system. Establishing the performance of the system and juxtapose the measurements to both the Superbus requirements and the manufacturer specifications in a series of tests.

The project sections described above loosely follow suit with the following chapters. The first and second sections will be discussed in the next chapter. After this, all theory will be available. It is then applied and the complete system will be discussed in chapter 4. This chapter will also discuss the third section, the software. Lastly the validation and verification are done in chapter 5.

Chapter 3

Theory Of High Accuracy GPS

A Global Navigation Satellite System (GNSS) is a modern navigation aid that is able to provide the Superbus with position, speed and heading data. Currently there are several such satellite systems in existence, in various stages of development. The Global Positioning System (GPS) however, is currently the only fully functional and globally available system. It is developed by the American Department of Defence (DoD), and became fully operational in April 1995.

In this chapter, the GPS system will be explained. It will become clear that the Superbus requirements, discussed in the previous chapter, are theoretically attainable using augmented positioning.

The first sections introduce the GPS system and provide a theoretical background on the Standard Positioning System that GPS employs. Subsequently the main error sources in GPS are explained, after which we will discuss augmented positioning as a way to adhere to Superbus requirements. Next, the pseudorange rates will be touched upon briefly, whereafter the communication system needed for augmented positioning will be discussed. A brief conclusion will finish the chapter.

3.1 GPS

GPS segments

The complete system architecture for the GPS system consists of three segments: A space segment, a control segment and a user segment, as can be seen in figure 3.1.

The space segment consists of a nominal figure of 24 satellites to provide global coverage, but currently constitutes 32 satellites (January, 2010). The satellites have a near circular, orbital radius of 26,560 (km) in 6 planes, with a 55° inclination, allowing a user with a clear view of the sky to always receive the minimum of 4 satellites. Each satellite has an orbital period of 718 minutes and travels at nearly 3.9 Km/s. The satellites are equipped with highly accurate atomic clocks, and every satellite continuously transmits radio signals that allow a receiver to measure and compute the distance to

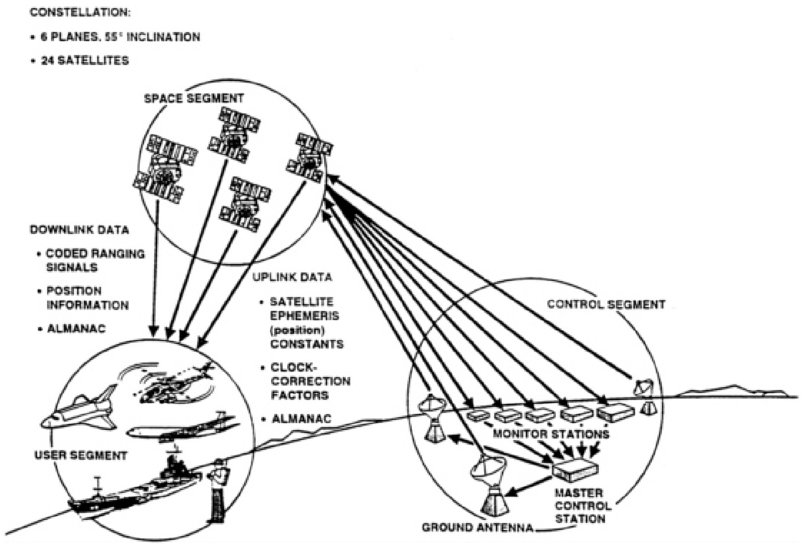


Figure 3.1: Segments of the GPS system. [source: NATIONAL ACADEMY PRESS [2]]

the satellite.

The control segment is a network of tracking stations, located around the globe, with the master control station located in Colorado, USA. The main function of the control segment is to monitor and control the space segment satellites. The control segment predicts the individual satellite orbits and the behaviour of the atomic clocks (which vary over time) and updates the broadcasted navigation message accordingly.

The user segment comprises the GPS receivers, available for both military and civilian users. These receivers are able to obtain a Position, Velocity, Time (PVT) solution by measuring the range (and range rate) to a minimum of four satellites in view.

Satellite signals

There are several possibilities to compute a receiver position by using GPS. All of these possibilities however, are dependent on the radio frequency (RF) signal originating from the satellites. For this reason the architecture of the GPS signal will be clarified.

GPS satellites currently transmit signals over two frequencies, L1 and L2. The individual properties of both signals are listed below In table 3.1.

An L1 or L2 signal leaving the satellite is a combination of three respectively four components: a carrier wave, a Coarse Acquisition code (C/A code), a precision code (P(Y) code) and finally a navigation message. L1 consist of all four, while L2 lacks the public C/A code (although new satellites are already launched with similar func-

Table 3.1: Properties of transmitted satellite signals

	L1 signal	L2 signal
Carrier Frequency (MHz)	1575.42	1227.60
Wavelength (m)	0.19029	0.24421
Code Frequency ($Mcps$)	1.023 & 10.23	10.23
PRN codes	C/A & P(Y)	P(Y)

tionality on the L2 band). These components will now be explained below.

Carrier wave

The carrier wave is the actual sinusoidal RF signal on which the other two components are modulated. It is transmitted at 1575.42 (MHz) for the L1 signal. L2 uses a 1227.60 (MHz) signal, amounting to wavelengths of 19.03 to 24.42 centimetres respectively.

Pseudo Random Noise codes

The ranging code, or the C/A and P(Y) code, is a mathematical pseudorandom binary sequence. This is a sequence which is repetitive and highly *orthogonal*. Orthogonality of a radio signal implies that a receiver is able to reject an arbitrarily strong signal when not coded in same coding scheme. Pseudo Random Noise (PRN) codes are one such coding scheme. The use of these PRN codes in the GPS system is significant for two main reasons. First, it allows all GPS satellites to broadcast over the same frequency. Each satellite has a separate unique PRN code. One such code is orthogonal to all the remaining PRN codes of the satellite system. This allows identification of the satellite by the code. It also eliminates interferences between satellite signals, allowing all satellites to broadcast on the same frequency.

In case of GPS, orthogonality of the signal is exploited by recreating the exact same code within a receiver. When two different PRN codes are multiplied, the result will always be around zero: the two signals will cancel each other. The only exception to this is when two identical codes are multiplied. When the two signals are correlated a large output will be the result. This is of great importance, and the second advantage to using PRN codes. The repetitive nature of the code and its correlation features can be exploited. As mentioned, PRN codes can be replicated in an GPS receiver. This replicated code is subsequently be shifted in the time domain (In reality they are also shifted in the frequency domain because of Doppler effects, this is however omitted for now), until it lines up with the received signal. This enables the receiver to acquire the signal travel time, and hence the range to the satellite. Note also that the satellite signals received by the receiver on earth are below the natural static noise levels, and are therefore essentially ”invisible” for radio receivers. However by shifting the replicated signals in time and multiplying these with the received signals, the satellite signal are amplified above noise levels, when -and due to the PRN codes only when-the two signals are exactly aligned.

As stated above, there are two types of PRN code used in the GPS system. The Coarse Acquisition code and the precision code. These two codes, have different characteristics and allow for different positioning precisions, however the same principle applies to both. The C/A code is a publicly accessible code, allowing users all over the world to use GPS signals for positioning purposes, the Standard Positioning Service (SPS). The precision code allows for more accurate positioning, however, this signal is encrypted to the Y code, and accessible to the United States military only.

The C/A code is 1023 bits long. A bit is also often called a *chip*. The code is repeated every millisecond. This means each chip is approximately 1 microsecond, or 300 metres long. The encrypted P code however is extremely long, about 10^{14} chips. The code is also sent at a faster pace, 10 times that of the C/A code, resulting in a chip length of about 30 metres. Modern receivers are able to synchronise the satellite code and the replicated code to approximately 1% of the length of a chip (0.1% for modern high end receivers). This gives an indication of the theoretical precision of the positioning solution, for the moment disregarding any other errors, such as ionospheric delays and multipath. For SPS this amounts to an approximate precision of about 3 metres, while the precision service will be around 30 centimetres, due to the much shorter chip length.

Navigation message

Finally, navigation data is present in the satellite signal. This is a series of messages, binary coded, modulated in the signal at 50 (bits/s). These messages contain the Time Of Week (TOW), GPS week number, satellite health information, clock bias parameters, ephemeris data and an almanac. Ephemeris data, constitutes the satellite's precise orbit information. The Almanac contains coarse ephemeris data of all the satellites, and an ionospheric model allowing receivers to correct for signal delays encountered when the satellite signal travels through the ionosphere. Because of the low data-rate of the navigation message, it takes 12.5 minutes to download all the data. The ephemeris data, needed for receiver positioning can take as much as 30 seconds to load.

Observables

In the previous section the signal side of the GPS system is examined, but it is not yet made clear how the receiver is able to use these signals. The PRN code and its correlation behaviour have been discussed briefly, the methods of positioning employed by receivers will become clear in the following sections. Here the most basic of receiver results will be introduced: the measurements, or observables. These are the basic building blocks for obtaining a PVT solution.

For now we are aware of two things: First of all, it was stated that observations are necessary to ascertain any knowledge of your position. Secondly we now know from the previous section, that GPS satellites broadcast modulated radio signals on 2 frequencies.

It is also clear from the previous section that information is present within the tracked satellite signals. But what kind of data exactly can be extracted from a tracked satellite? This data is divided into two groups:

- Pseudorange measurements, ρ
- Carrier phase measurements, ϕ

These parameters can be extracted for every individual tracked satellite, every single epoch, or unit of measurement. This information may then be used to calculate a positioning solution, for that given epoch. Doppler measurements can also be extracted but are omitted for now, see section 3.6.

The most important thing to realise is that the pseudorange measurements, essentially the range from satellite to receiver, are extracted from the C/A code by using the PRN code to it's potential. This will be discussed further in the following sections.

The small correlation window of the public PRN code ingeniously allows the receiver to calculate the distance to the satellite, providing a pseudorange. This range can be used to obtain a positioning solution. The word public in the previous sentence is quite important, since the military P(Y) code is not available for use in civilian receivers. Since the code is needed to extract pseudorange measurements, no pseudorange information can be ascertained directly from the L2 signal. Only the secret P(Y) code is transmitted on that frequency, and not the generally available C/A code.

However, using several indirect techniques [16], exploiting the fact that the P(Y) code is modulated in the same way onto both the L1 and L2 signals, pseudoranges can be extracted from the P(Y) code on both frequencies. This brings the number of observables to three, one pseudorange from the C/A code and two from the P(Y) code. Note that a modernisation of the GPS satellite constellation is underway, adding the C/A code to the L2 signal as well. This will provide greater accuracy and robustness and faster signal acquisition than the current L1 C/A-code signal [19].

Phase information can be extracted from both frequencies as well. This will become advantageous in later stages of this chapter, where the augmented positioning will be clarified (section 3.4). Details on these observables will be discussed there.

Lastly Doppler related measurements can be obtained, again from both frequencies. The use of these signals will be discussed in section 3.6. For now it is clear that in total seven observables are extractable from each satellite, each epoch. An extended overview of the observables is given in table 3.2. Note that for now we are only concerned with the pseudoranges from the C/A code and the Carrier phase measurements.

In the following sections, more emphasis will be put on how the measurements are obtained, and how a valid position estimation may be calculated from them. In

Table 3.2: Observables available from a GPS satellite. L2C signal is being rolled out, but not yet completed

	L1 signal	L2 signal
Pseudorange from C/A code	x	-/x
Pseudorange from P(Y)-signal	x	x
Carrier phase	x	x
Doppler measurements	x	x

section 3.2 we will start this by presenting a basic method using only the C/A code pseudorange measurements. In section 3.4 more precise methods will be discussed using the carrier phase measurements.

3.2 Standard Positioning Service

In the previous section the fundamental properties of the GPS system have been presented. These can now be utilised in a method for standard positioning.

The main point is that the characteristics of PRN codes may be used for positioning purposes. The PRN code generated by a satellite is linked to the atomic satellite clock. The code replicated by a GPS receiver is, in the same way, linked to a clock, however in this case, the much less accurate receiver clock. As stated before, by shifting the replicated code in time and multiplying it with the received signals from the antenna, a satellite can become accessible to the receiver when the two codes align. If the codes align, the receiver can compare the received satellite time, to the receiver time. The difference is the time it took the signal to cross the distance between satellite and receiver. By multiplying this transit time with the speed with which the radio signal propagates, i.e. the speed of light, one obtains the apparent range to the satellite, the pseudorange ρ (3.1).

$$\rho(t) = c[t_u(t) - t^s(t - \tau)] \tag{3.1}$$

Here $t^s(t-\tau)$ is the emission time imprinted in the code and $t_u(t)$ is the arrival time as measured by the receiver clock. τ is the transit time.

This pseudorange is however by no means the actual distance between the satellite and the receiver. It is the result of a measured time difference, and several errors and biases that influence this time difference are present in the signal. By rewriting (3.1), and making the most prominent of these errors and biases explicit, one obtains (3.2).

$$\rho(t) = r + c[\delta t_u - \delta t^s] + I_\rho + T_\rho + \varepsilon_\rho \tag{3.2}$$

This is the core and basic equation for the pseudorange ρ. r is the actual range to the satellite, the value one needs to calculate a worthwhile position solution. All the other terms are errors and biases that need to be handled and accounted for as much as possible.

The receiver clock for example is not nearly precise enough for sustained time-keeping, they are low cost clocks that are not synchronised with the much more precise satellite clock. A simple approximate time is used in a receiver and hence a bias is present in the measured transit time. This is δt_u. Note that the satellite clock too can have a small bias with respect to GPS time (GPST). This is the time composed by the control segment of the GPS system, used as the benchmark time to assess all GPS satellites. This satellite time bias is δt^s. To convert these time biases to a range, they are multiplied by the speed of light in vacuum, c. Other errors present in (3.2) are the ionospheric delay, I_ρ, and tropospheric delay, T_ρ. These are present due to the fact that the radio signals propagate at varying speeds in different atmospheric layers. This has an influence on the travel time. The last term ε_ρ is a generic term for all other non-explicit errors still present in the pseudorange, such as receiver noise and multipath. These will be discussed later.

Now we can begin to piece together the final parts of the Standard Positioning Service (SPS). We are now familiar with the concept of pseudoranges, but still these cannot be used for positioning. First, errors and biases from equation (3.2) need to be eliminated as much as possible. Leaving these in as unknowns would make the resulting equations unsolvable, ignoring them would result in a useless positioning solution.

Looking at section 3.1, one can already be quite successful in handling these biases and errors. δt^s is broadcast in the navigation messages, allowing it to be utilised in (3.2). Furthermore an ionospheric model is broadcast through the navigation message, allowing an approximate ionospheric delay to be calculated in the receiver. This reduces I_ρ significantly. Moreover, if the receiver is a dual frequency receiver, receiving both L1 and L2, the ionospheric delay can almost completely be removed, due to the different effect of the ionosphere on both frequencies. The tropospheric delay is much more stable, and can be approximated by a model preprogrammed in the receiver. This allows T_ρ to be significantly reduced. Measures to reduce ε_ρ can include measurement smoothing to reduce effects of multipath and measurement noise, however some residual errors will remain present.

Now the largest remaining error in the pseudorange equation is the receiver clock bias, δt_u. This bias cannot be corrected for in stand alone mode. Noting that this receiver clock bias is identical for all received satellites and hence all pseudoranges, this bias can be treated as a global variable, just like the ultimately sought after receiver position x. Realising this, we rewrite equation (3.2) to (3.3).

$$\rho_c^{(k)} = \|x^{(k)} - x\| + b + \varepsilon_\rho^{(k)} \tag{3.3}$$

$\|x^{(k)} - x\|$ is the range of satellite k in vector form, where $x^{(k)}$ is the position of satellite k and x is the position of the receiver. b is the receiver clock bias converted to metres and lastly $\varepsilon_\rho^{(k)}$ is the residual errors of the satellite, which differs for every satellite and can, for now, not be minimised any further. By tracking for example nine satellites, and extracting data from one measurement, or epoch, one acquires nine of these equations, where x and b are the same for each equation, and $x^{(k)}$ is known from the almanac for each satellite. This leaves a total of four unknown variables (excluding the $\varepsilon_\rho^{(k)}$) that need to be solved: three position values and the receiver clock bias. From linear algebra it is known that these variables can be solved if there are at least four equations, and thus if at least four tracked satellites visible.

The problem now is the fact that there are still errors present in the pseudoranges due, among others, to $\varepsilon_\rho^{(k)}$, not allowing for an exact solution of the problem. A solution must be found that fits all the measurements best. This is commonly done by minimising the sum of the squared residuals, the difference between the pseudorange of satellite k and the forthcoming calculated position. To do this we must first linearise equation (3.3) by expanding it in a Taylor series. We may then use an approximate solution for the receiver position and clock bias and let the solution converge iteratively. Let us make a first estimate of equation (3.3) using initial estimations x_0 and b_0. The equation then becomes:

$$\rho_0^{(k)} = \|x^{(k)} - x_0\| + b_0 \tag{3.4}$$

Now let the true position and bias of (3.3), x and b, be represented as $x = x_0 - \delta x$ and $b = b_0 - \delta b$ respectively:

$$\rho_c^{(k)} = \|x^{(k)} - (x_0 - \delta x)\| + (b_0 - \delta b) + \varepsilon_\rho^{(k)} \tag{3.5}$$

Here δx and δb are the unknown corrections that need to be applied to our initial estimate. Using (3.4) and (3.5) we can subsequently develop a linearised equation (using a Taylor expansion) where δx and δb need to be determined:

$$\begin{aligned} \delta\rho_c^{(k)} &= \rho_c^{(k)} - \rho_0^{(k)} \\ &= \|x^{(k)} - x_0 - \delta x\| - \|x^{(k)} - x_0\| + (b - b_0) + \varepsilon_\rho^{(k)} \\ &\approx -\frac{(x^{(k)} - x_0)}{\|x^{(k)} - x_0\|} \cdot \delta x + \delta b + \varepsilon_\rho^{(k)} \\ &= -1^{(k)} \cdot \delta x + \delta b + \varepsilon_\rho^{(k)} \end{aligned} \tag{3.6}$$

Now, considering an over-determined system, i.e. a system with more than four satellites tracked, equation (3.6) can be written in a matrix form for K satellites. We can then use the least-squares solution to find the corrections to our initial estimates. This is represented in (3.7).

$$\begin{bmatrix} \delta\hat{x} \\ \delta\hat{b} \end{bmatrix} = (G^T G)^{-1} G^T \delta\rho \tag{3.7}$$

With $\delta\rho$ the pseudorange errors of K satellites which can also be written as,

$$\delta\rho = G \begin{bmatrix} \delta x \\ \delta b \end{bmatrix} + \varepsilon_\rho \tag{3.8}$$

with G,

$$G = \begin{bmatrix} (-1^{(1)})^T & 1 \\ (-1^{(2)})^T & 1 \\ \vdots & \vdots \\ (-1^{(K)})^T & 1 \end{bmatrix} \tag{3.9}$$

These equations give the corrections $\delta\hat{x}$ and $\delta\hat{b}$ to the original estimates x_0 and b_0. We may now produce new, improved estimates using:

$$\begin{aligned} \hat{x} &= x_0 + \delta\hat{x} \\ \hat{b} &= b_0 + \delta\hat{b} \end{aligned} \tag{3.10}$$

Equation 3.3 can then be linearised again using the new estimates for x_0 and b_0, and the system can be solved again. This iteration may be continued until the change in estimates is small enough. This is usually within a few iterations, even with very poor initial estimates.

In practise, a slightly different, but related, method is employed: Weighted Least Squares. Up until now, it was assumed that every pseudorange has an equal validity and provides equally precise data: the variances of all measurements are assumed equal. This is however not the case. Therefore a weight matrix W is added to equations 3.7 and 3.8. the result then becomes:

$$\begin{bmatrix} \delta\hat{x} \\ \delta\hat{b} \end{bmatrix} = (G^T W G)^{-1} G^T W \delta\rho \tag{3.11}$$

and:

$$\delta\rho = G \begin{bmatrix} \delta x \\ \delta b \end{bmatrix} + \varepsilon_\rho \tag{3.12}$$

The composition of this new weight matrix is outside the scope of this thesis, as well as subject of research. However an indication will be given by clarifying the GPS antenna behaviour somewhat. The gain or amplification pattern of these antennas is not equal in all directions due to physical limitations and design. For example it is generally not wanted that a satellite signal is picked up by the antenna that is coming from below the horizon. This is because this signal is in all likelihood a reflection of a satellite signal bouncing of the ground. In other words a multipath signal, which will be described section 3.3. This signal can have a deteriorating effect on position estimation and it is therefore not desirable to pick up these signals. An effect of the antenna design is that the resulting gain pattern is dependent on the angle the satellite signal has relative to the GPS antenna. In appendix C the gain pattern an AeroAntenna AT2775-42 is given, this is the antenna that will be used in the Superbus system later on. One can see there, that the amplification of a satellite signal originating form near the horizon, is much less than that of one originating from the zenith. This influences the signal to noise ratio of satellites that have a low elevation angle. This in turn causes the pseudoranges extracted from these signals to have a larger standard deviation. This, as a last step, means that generally one wishes to give these measurements a lower importance in the position estimation process. Arriving to this conclusion illustrates the importance of the implementation of a weight matrix in the position estimation calculations.

3.3 Measurement error sources

Now that is explained how a SPS solution may be found, and a possibility for more precise positioning is suggested, it can be useful to comment on the error sources, the reasons why the SPS solution will not reach the theoretical range measurement precision. Some sources have already been briefly commented on, such as ionospheric and tropospheric delays, and methods for decreasing the resulting errors touched upon. Here some sources, now collected in ε_ρ, that may have consequences for Superbus will be considered. These are either modelling errors or stochastic errors. Modelling errors can be improved upon by introducing better models. This is however not the case for stochastic errors. The main error sources mentioned here are:

- Control segment errors
- Receiver noise
- Multipath

Control segment errors are errors in the broadcast information, produced by the control segment. These include the satellite ephemeris data, satellite clock bias and Ionospheric model. These parameters need to be modelled and estimated by the control segment apriori, and hence inherently have errors. Even so the prediction models are always improved, which in turn decreases the control segment error.

The signals tracked by a satellite receiver are always corrupted to a certain extent by the receiver. The noise being added to the received signals can come from a variety of sources including, cables and antennas, but also thermal noise from inside the receiver is a factor. Receivers are designed to closely follow the received signal and identify the edge of a chip. Unfortunately, due to the fact that the edge of a chip is obscured by random noise, it is difficult for the receiver to identify the edge of each chip. It is not a clear mark, forcing the receiver to make a decision on when the signal changes. This introduces an error. In general, the receiver noise is dependent on signal strength, which in turn is dependent on the satellite elevation angle.

Multipath is probably the greatest source of errors in a Superbus GPS system. Radio signals show the same behaviour as light, in the sense that they can reflect when encountered with an object. This is much like light hitting a mirror and changing direction. In figure 3.2 this is demonstrated. Here one can see that the radio signals reflect of buildings causing the antenna to receive both the original and the reflected signal, but also merely the reflections alone can be received.

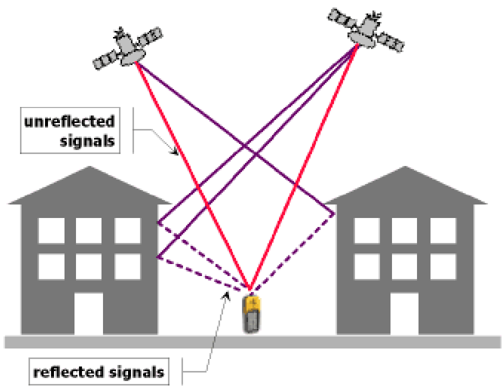


Figure 3.2: Graphical representation of a multipath situation. [source: BKG]

Signal reflections can play a major role in the Superbus due to the fact that it will routinely drive in environments prone to signal reflections. This includes urban environments, but also for example sound barrier walls, commonplace near highways.

Typical errors in the pseudoranges differ for code or carrier phase measurements, with carrier phase measurement errors being about a factor 100 smaller. They can range from several metres for code measurements to several centimetres for carrier phase measurements. Multipath can hence cause a serious effect in the positioning solution of a receiver. This may be of great importance for Superbus when a precision of a few centimetres is required, and due attention must be given to this fact.

The parameters mentioned above are also called nuisance parameters. These are parameters in the pseudorange equations that are not of direct interest (e.g. not position and time), but do need to be estimated or eliminated. As was mentioned, estimation is never error-free and the elimination of these nuisance parameters would by far be preferred. A table of typical measurement error sources and their effect on the pseudoranges is presented in table 3.3.

Table 3.3: Typical error sources and their residual error sizes. [source: [31]]

Error source	receiver type	Potential error size	
		code measurements	phase measurements
Satellite clock		2 (*m*)	2 (*m*)
Satellite ephemeris		2 (*m*)	2 (*m*)
Ionosphere	single frequency	1-5 (*m*)	1-5 (*m*)
	dual frequency	1 (*m*)	1 (*m*)
Troposphere		0.1-1 (*m*)	0.1-1 (*m*)
Multipath		0.5-1 (*m*)	0.5-1 (*cm*)
Receiver noise		0.25-0.5 (*m*)	1-2 (*mm*)

In the table the values concerning the carrier phase measurements are given as well. Although carrier phase measurements are not explained in detail as of yet. Their existence is known however, and the nuisance factors associated with the carrier phase are included as well for clarity and completeness. They will become valuable in the next section.

3.4 Augmented positioning

In the previous sections the standard method of obtaining a PVT solution have been recounted. In this section the concept of augmented positioning will be described. It will become clear that more precise solutions are attainable in this manner. It will furthermore become clear that this precision is not as easy to obtain as an SPS solution.

To begin this section, the carrier phase measurements must first be explored in more detail. The precision gains will then become more visible. In the subsequent sections, methods for using these measurements will be explained.

Carrier phase measurements

Most high end GPS receivers currently available have the ability to track the carrier signal, in addition to the conventional code tracking. The carrier signal is the physical radio signal broadcast by the satellite as explained in section 3.1. This signal can be tracked by a GPS receiver in a manner analogous to the PRN code. The receiver can replicate sinusoidal wave of the tracked L band (1,2 or both). It can then shift the signal in time, essentially shifting the phase of the replicated signal, until the received signal and replicated signal are identical.

One might currently enquire what the benefits are of tracking the phase of the carrier signal. This has to do with the tracking capabilities of the receiver. As was mentioned in section 3.1, a GPS receiver is able to track a PRN code to about 1% of a chip. For the C/A code this amounts to about 3 metres, therefore, without considering other errors, the theoretical limit of the receiver. Modern receivers are able to track the carrier frequency to about 1% of a carrier wavelength as well. A wavelength is considerably shorter than a PRN chip, 19,03 centimetres versus 300 metres. This brings a very significant precision gain, if the carrier phase could be used for positioning. The carrier phase can be tracked to about 1-2 millimetres. However some difficulties are encountered on the way to carrier phase positioning.

First we revisit the code pseudorange equations of (3.1) and (3.2). At first sight, it seems that the equation can be used for carrier phases as well. This is largely true, by tracking a carrier frequency the same problems remain as for code tracking. There are still ionospheric and tropospheric delays, there are still biases in receiver and satellite clocks, and the remaining errors are also still present. But when trying to accommodate wavelengths in the pseudorange equations, one runs into a problem. The whole point of the receiver and satellite clocks was to obtain the range to the satellite by comparing broadcast and reception times. This information is lost by only tracking the carrier phase. But fortunately this is no great obstacle since both the carrier signal and the PRN code are coupled to the same atomic clocks in the satellite. The receiver can generate the same carrier signal coupled to its own clock. The pseudoranges can then be deduced from the phase difference between the phase when it was generated, and the phase when it is received.

Yet one final thing needs clarification. When purely looking at the carrier signal one ends up with precisely knowing the phase difference of the two signals, but no idea of the range to the satellite. The wavelength is about 20 centimetres, but the range to satellite is approximately up to 26500 kilometres. This leaves the user with precise but ambiguous measurements, one does not know the number of cycles N that preceded the measured one. This indeed need to be added as an extra parameter to the pseudoranges leaving equations (3.13) and (3.14).

$$\phi(t) = \phi_u(t) - \phi^s(t - \tau) + N \tag{3.13}$$

$$\phi = \lambda^{-1}\left[r + I_\phi + T_\phi\right] + \frac{c}{\lambda}(\delta t_u - \delta t^s) + N + \varepsilon_\phi \tag{3.14}$$

Here λ is the wavelength of the tracked L band. ϕ_u and ϕ^s are respectively the phases of the receiver generated and satellite received carrier signal. N is the number of cycles preceding the measured phase cycle. The remaining parameters are analog to (3.1) and (3.2).

Introduction to augmented positioning

The building blocks for more precise PVT estimates with GPS are now becoming clear. With the help of carrier phase measurements a far more accurate estimation could be possible. However the issue of the integer ambiguity remains. Furthermore, recalling section 3.3, nuisance parameters such as ionospheric and tropospheric delays are still a factor in phase measurements as well. They need to be reduced fairly drastically to obtain the cm precision needed for the Superbus. And even then, the solution needs to be real-time to be of any value to the Superbus.

So if it is cardinal to remove nuisance factors, how can this be done? Simply put, there is one thing that all precise positioning techniques have in common. They will all use additional information to obtain solutions with a higher precision. Therefore this group of systems is also called augmented GPS, they will use information from outside sources. They depend on this information for their precision, and therefore they are no longer stand alone solutions. The extra requirement of a real time solution only increases the difficulty of obtaining a solution, it does not change the fact that additional information is needed from a separate source. It only means that real time communication between information source and GPS receiver should always be present in such a case.

In the next few sections, two options to obtain a precise PVT solution will be discussed: Precise Point positioning (PPP) and relative positioning. The relative positioning section will contain discussions on Real Time Kinematic (RTK and Flächenkorrekturparameter (FKP)).

Precise point positioning

Let us first look again to equation (3.14), repeated below. This brings back the core of the problem and serves as a suitable starting point.

$$\phi = \lambda^{-1}\left[r + I_\phi + T_\phi\right] + \frac{c}{\lambda}(\delta t_u - \delta t^s) + N + \varepsilon_\phi \qquad [3.14]$$

Here λ is the wavelength of the tracked L band, r the range to the satellite, $I_\phi + T_\phi$ the ionospheric and tropospheric delays and δt_u and δt^s represent the receiver and satellite clock errors. N is the number of cycles preceding the measured phase cycle, and finally ε_ϕ are the remaining errors such as receiver noise and multipath.

Recall the way an SPS solution is obtained. Each tracked satellite provides one pseudorange equation, and four parameters remain identical within all these equations. These are the three position parameters (x, y, z) , embedded in r and the receiver clock bias (δt_u). If we would try to solve these equations in the same way as we calculate an SPS solution, we would fail. There would always be more unknown parameters than equations, since the ambiguity N is different for each tracked satellite: the system of equations is under determined.

If we now recall the fact that once the ambiguity N has been found, it remains constant for as long as the satellite is being tracked. This in theory allows a PVT solution if those two conditions are met: the carrier phase ambiguities are known and the satellite are tracked continuously. This is the approach precise point positioning takes. However these carrier phase ambiguities cannot be solved directly. Again due to the under determined nature of the system, the carrier phase ambiguities cannot be solved instantaneously. So rather than solving the system directly, parameter estimation algorithms are used to estimate the internal states (position, receiver clock error, and carrier phase ambiguities) until the system converges to a precise solution and the carrier phase ambiguities N can be fixed.

Although this works in theory, it still does not offer an adequately precise PVT solution. As becomes clear from table 3.3, the remaining pseudorange errors are still far too large. Ionospheric and tropospheric delays still plague the pseudorange equations, as do the satellite clock and ephemeris errors. PPP therefore uses alternative ways to minimise nuisance parameters.

As was mentioned in section 3.2 the ionospheric delay can be largely negated by using a dual frequency receiver. This is however not the case for any of the other parameters. Therefore PPP uses alternative sources such as the International GNSS Service (IGS) for superior estimation of the remaining errors. IGS is an alternative and elaboration to the ground segment of the GPS system. It is a network of tracking stations with data- and analysis stations that monitor the GPS constellation and provide superior satellite clock and ephemeris data, as well as superior broadcast tropospheric delay estimates in comparison to the estimates the SPS broadcast message provides. With the aid of the IGS data, PPP can generally provide centimetre level precision on a static receiver, while decimetre level is possible on kinematic receivers [3], both in real time.

Limitations

PPP does retain certain drawbacks to SPS, making it, overall, unfit for use in the Superbus. First and foremost is the convergence period. The parameter estimation algorithms need a relatively long time to converge to a precise solution for the phase ambiguities. Furthermore the convergence time is dependent on many factors included vehicle dynamics, where convergence is typically 30 to 40 minutes [6] -though significant progress is being made [51]-, making PPP less flexible for use in the Superbus. Note that due to the presence of initial phase offsets, the phase ambiguities are not integers, but need to be estimated and subsequently kept constant as floating point numbers instead. This significantly increases the difficulty of obtaining the proper carrier phase ambiguities. Though static convergence times are significantly shorter, this is not a real scenario for Superbus, which in essence is a kinematic GPS situation. Connected to the convergence issue are losses of lock. The phase ambiguities are only fixed if the lock on the satellite remains fixed. Again this poses problems in kinematic receivers. Superbus will encounter viaducts, aqueducts and urban environment, causing a GPS signal to be interrupted regularly, causing the need for a reinitialisation of the parameter estimation filter, an hence losing precise positioning. The long convergence time is simply unacceptable in this scenario. The precise positioning will be ”out” for too long and, changes are, will never come to fruition due to the regular interruptions in the Dutch landscape. Furthermore the decimetre precision of PPP is not quite in compliance with the 5 centimetre precision requirement stated for the Superbus.

Relative positioning

Another method to eliminate some of the nuisance parameters is relative positioning. A significant amount of the nuisance parameters turn out to be correlated in time and space. This means that the errors change only slowly over time and space. By having a reference receiver, or *base station*, on a known location close to the user receiver, or *rover*, a relative position of the rover compared to the base station can be obtained with substantial precision gains. Roughly speaking horizontal precision values of 1 centimetre are attainable, depending on the distance to the base station.

The method is also called Real Time Kinematic (RTK) and computes the rover position relative to a known base station, by sending raw observations, or correction messages to the rover (depending on the type of RTK). By doing this one can exploit the temporal and spatial correlation of the ionosphere and tropospheric delays and negate several nuisance parameters, enhancing the precision of the final positioning solution to the centimetre level. The base station location is precisely known and the kinematic rover position is referenced to this location. If the base station is close to the rover, for the moment let us assume a maximum of 50 kilometres, approximately the same satellites will be visible for both receivers. Note that when both receivers are tracking the same satellite, the satellite clock error (but to a large extent also the ephemeris errors) of a satellite will be the same for both receivers. Add to this the fact that the rover position is related to the known position of the base station, and it becomes clear that the error introduced by the satellite clock and ephemeris data will cancel. Also, the ionosphere and troposphere are highly correlated between the two receivers. The received signal at both receivers travels through roughly the same atmospheric conditions introducing largely the same atmospheric delays in the signal. This again provides the possibility of essentially cancelling these nuisance factors. In total this provides the possibility of a very precise PVT solution.

As mentioned real time kinematic positioning can work by relaying time-tagged raw measurements of the reference receiver to the rover receiver, to obtain a PVT solution. Let us look at the carrier phase measurements of one satellite visible by both receivers for a certain epoch.

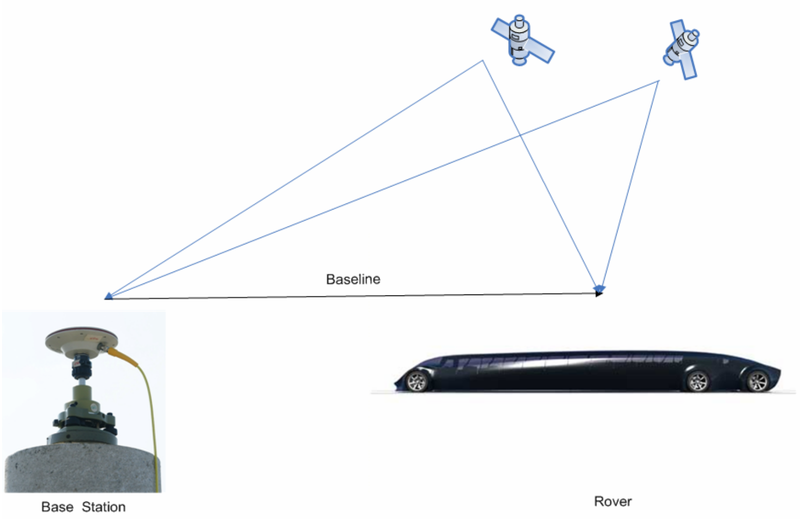


Figure 3.3: Graphical representation of an RTK set up.

$$\begin{aligned}\phi_u &= \lambda^{-1}[r_u + I_u + T_u] + f(\delta t_u - \delta t^s) + N + \varepsilon_{\phi,u} \\ \phi_r &= \lambda^{-1}[r_r + I_r + T_r] + f(\delta t_r - \delta t^s) + N + \varepsilon_{\phi,r} \end{aligned} \quad (3.15)$$

Here the subscripts u and r denote the user and reference receiver respectively. Now let the pseudorange from the reference be sent to the rover receiver u. By differencing these pseudoranges the temporal and spatial correlated parameters drop out, as well as the satellite clock error, see equation 3.16.

$$\begin{aligned}\phi_{ur} &= \phi_u - \phi_r \\ \phi_{ur} &= \lambda^{-1}[(r_u - r_r) + (I_u - I_r) + (T_u - T_r)] + f((\delta t_u - \delta t_r) - (\delta t^s - \delta t^s)) \\ &\quad + (N_u - N_r) + (\varepsilon_{\phi,u} - \varepsilon_{\phi,r}) \\ \phi_{ur} &\approx \lambda^{-1} r_{ur} + f((\delta t_u - \delta t_r) + N_{ur} + \varepsilon_{\phi,ur} \end{aligned} \quad (3.16)$$

Assuming:

$$T_u \approx T_r$$
$$I_u \approx I_r$$

It is now clear that there are substantially less nuisance factors present in the equation, only receiver noise, multipath and both receiver clock errors remain. This with the condition that the measurements received by the rover are not too old and that the reference station is not too far away. These ”too old” and ”too far away” prefixes are fuzzy, since the correlation is dependent on atmospheric effects and time. As a rule of thumb a degradation in horizontal precision of 1 centimetre every 10 kilometres distance from the base station is taken. Time constraints on the received differential corrections are harder to determine, but they could be extrapolated to match the current epoch for several minutes, again with degrading precision [25]. This degradation due to time is the result of the fact that the RTK method has to transmit real time measurements from the reference to the rover receiver. Since this transmission inevitably takes time, the measurements have to be extrapolated, which invariably leads to degradation in precision.

The result is that we now have quite a precise carrier phase measurement, allowing for positioning at the centimetre level. Yet now we once again have the problem that the whole system is under determined. Looking at equation (3.16) we can investigate the number of unknown in the system. First of all we have the position vector, bringing 3 unknowns (x, y, z). But now instead of one clock that needs estimation in SPS, we have two, one for the base and one for the rover receiver. Luckily, these can be combined into one unknown. Lastly we have an integer ambiguity. Note that the position vector and clock errors remain the same for each tracked satellite, yet the integer ambiguity is different for each satellite. So expanding this for a system with K satellites, we observe that there are $4+K$ unknowns in the system. Supposing we have a way to find out the K ambiguities they will stay constant as long as the satellites remain tracked. This would leave 4 unknowns in the system, which would bring the minimal number of satellites needed for a solution, provided that the phase ambiguities are fixed, to 4 as well.

Note that the Septentrio receiver used in the Superbus upholds a minimum of 5 satellites for an RTK solution. 4 Satellites would mean that there is no redundancy in the system. It is opted by Septentrio that this is not desirable, and only enables RTK with a minimum of 5 tracked satellites. Secondly, Septentrio uses double differencing, where base and rover clock errors together would cancel out completely, however this is at the expensive of one visible satellite, again bringing the minimum number of available satellites back up to 4 once ambiguities have been set.

This once again brings us back to the problem that the total system to compute a PVT solution is under determined. The ambiguities are still there, just like in section 3.4. The problem does however get somewhat simpler. This is because the unwanted noise in the carrier phase measurements is lessened considerably. This is significant not only for the accuracy of the final solution, but this also means that the ambiguities are now actually integers.

This brings us to the next step, The actual resolution of the ambiguities. Up until now it has become clear that the system of equations is under determined, but becomes determined, and hence directly solvable (epoch per epoch, with 5 or more satellites are visible), once ambiguities have been fixed. For now we have an under determined system of equations. In order to get to this next step, we therefore first have to resolve these ambiguities. This can be done using the code measurements, or search algorithms (or both). These techniques however need multiple epochs to solve the ambiguities [31]. This means that this method for precise positioning too (w.r.t. PPP) has its drawbacks for use in the Superbus. Yet ambiguity resolution is attainable much faster (practically, within about 30 seconds), with a greater final accuracy after initialisation. Additionally these initialisation times are also possible in kinematic conditions. This fast calculation of the phase ambiguities, together with the centimetre accuracy obtained once they are fixed, considerably enhances the usability of GPS for high precision kinematic navigation.

To conclude, the drawbacks of PPP are largely negated by using relative positioning. The initialisation time is reduced to a great extent, to far under a minute in practise. Furthermore, no convergence is present. Once the integers are obtained, centimetre level precision is possible. The fast initialisation also allows for more flexibility in the urban landscape, where some satellite lock may be lost momentarily.

Limitations

Though RTK is a promising candidate for the Superbus, able to deliver centimetre accuracy at fast intervals (10 Hz), some problems remain. First of all note that no algorithm for ambiguity resolution is 100% full proof, and an incorrect ambiguity can, in some cases, be fixed. In this case a bias will appear in the solution. Modern algorithms, such as the LAMBDA method [48], however do attain high success rates of 99.9% when using L1 and L2, for so-called short baselines.

Secondly the ambiguity resolution is (practically) not instantaneous and problems can arise from this. The Dutch landscape, open as it seems, has a considerable amount of constructions, blocking a clear view of the sky. Especially in urban areas, but also on highways in the form of viaducts, underpasses and noise barriers. These can momentarily block all or enough satellites to lose an RTK solution. In other words, ambiguities are lost and need to be recalculated. Depending on the amount of satellites that can still be tracked, this takes from a few seconds to a minute, during which only a SPS solution is present (which usually reestablishes within a couple of seconds after reacquisition). This SPS solution is by far insufficient in terms of precision, and hence leaves the Superbus vehicle somewhat ”blind” during RTK reinitialising. This is a problem, especially in areas where blockages occur faster than reinitialisation is completed, leaving the Superbus lacking proper positioning for more extended periods. This problem can be alleviated to a certain extent. First of all accurate velocity measurements are usually independent of positioning mode (RTK or stand alone), see section 3.6. Heading information can be independent of positioning mode as well (see chapter 5). Furthermore, additional methods of positioning could be employed, for example by the incorporation of a Inertial Navigation System (INS), allowing the vehicle to be precisely tracked during GPS outages.

Another problem arising from the use of RTK for the Superbus is the roaming area of the vehicle. As rover GPS receivers travel further away from a base station the relative position accuracy diminishes due to spatial decorrelation. Atmospheric delays as well as constellation geometry start to deviate from the conditions present at the reference station. For current generation carrier phase GPS receivers this is about

1 part per million (PPM) in horizontal direction, double that for the vertical. This means that the standard deviation of horizontal position (σ) degrades 1 centimetre, every kilometre of distance (l) from the base station.

$$\sigma_{total} = \sigma_{system} + \frac{l}{10^6} \tag{3.17}$$

In addition the correction data from the receiver must not be too old. If RTK is to be used on the Superbus, two new requirements need to be addressed:

- The need for constant data transmission to the vehicle
- The need for suitable corrections, able to accommodate the accuracy requirements

These two items will be discussed in sections 3.4 and 3.7.

The mobility problem, FKP and VRS

As was mentioned in section 3.4, the precision of the calculated PVT solution degrades with increasing distance from a base station. With the positioning requirement for Superbus set at 5 centimetres, let us assume that a base station must be present within 20 kilometres at any one time in order to make this possible. This 20 km limit is not a strict limit, and depends on atmospheric conditions, but is nonetheless recommended by receiver manufacturers [42]. With the Netherlands being the initial platform for the Superbus, this means that a significant number of base stations need to be present, in order to get total national coverage. This is cumbersome and expensive from a infrastructural point of view. Stations and data centres need to be developed and maintained. The cost of such a network and its upkeep would be large, though, if necessary, theoretically well possible. In addition there are problems from the operational standpoint. Whenever the switch is made from one base station to another, the RTK algorithm needs to be reinitialised. This causes a gap in precise positioning of about half a minute, as was discussed in the previous section. If the Superbus is to cruise at 250 Km/h this means switching stations every 12 minutes, in a best case scenario. Theoretically a soft handover scenario could be possible, where the receiver will initialise using corrections from the second station, before discarding the first station. This would however most likely require custom firmware from the receiver manufacturer.

Luckily there are options to reduce the size of the base station network, while increasing the flexibility. This reduces the costs of the Superbus infrastructure while maintaining the 5 centimetre accuracy requirement. Two such options are using Flächenkorrekturparameter (FKP) or Virtual Reference Stations (VRS). FKP and VRS are two approaches to the same problem: minimising the distance dependent nuisance errors over larger distances than conventionally possible. This is the largest problem for relative positioning.

The systems work by modelling the distance dependent parameters and relaying these to the rover receiver. Consider an already existent network of reference stations. The exact positions of these stations are known, and they continuously receive satellite measurements. If enough of these stations are present, and enough measurements are obtained, one can model the complete state space representation of the complete GNSS system, and estimate all the parameters by using continuously updated Kalman filters. This parameter estimation can be very good, and can allow for millimetre accurate carrier phase positioning if enough states are implemented [56]. The states of such a system can include:

- Ionospheric delays
- Tropospheric delays
- Carrier phase ambiguities
- Satellite clock errors
- Satellite orbit errors
- Receiver clock errors

This basically means that every aspect of the pseudorange equations is contained and estimated, for each individual satellite, in the state space model. A complete representation of the GNSS system is present and estimated in real time, with great accuracy. These factors can then be interpolated for every point contained within this network. Two ways to let the rover receiver benefit from this model will be discussed below.

FKP

The first way to better exploit the spatial correlation in a reduced base station network is called Flächenkorrekturparameter [17, 56–58]. Figure 3.4 is a graphical representation of the situation. Here two reference stations and a rover are represented, each at a certain distance from each other. The vertical axis is a representation of the error size between the three receivers. One can see that in normal use of relative positioning a base station just sends out raw measurements of one point, ε_1 or ε_2. These corrections will become less adequate with increasing distance from the actual reference site, as can be seen in the difference between ε_1, ε_2 and the rover. FKP on the other hand produces more information. It does send raw measurements of one single base station, but in addition it calculates a linear approximation of the spatial correlation of the errors between multiple reference stations, the purple line in figure 3.4. Basically this allows the spatial variation approximation to be significantly better at a certain distance and hence produce a better solution than possible with the single base station RTK solution. The RTK algorithm at the rover receiver uses the additional information and it's own approximate position to calculate better error corrections.

The main advantage of FKP is that in principle no two way communication is necessary. This means that it can be broadcast, and rovers can operate while only receiving data. However, looking ahead in the Superbus design, two-way communication will be present in the Superbus. FKP *can* use this feedback of rough position estimation to optimise the FKP corrections sent to the rover. However, originally to conserve the required bit throughput, this technique only sends out a simplified correction model to the rover. Since ample bit throughput and two-way communication will be available, the following technique may be better suited for Superbus applications.

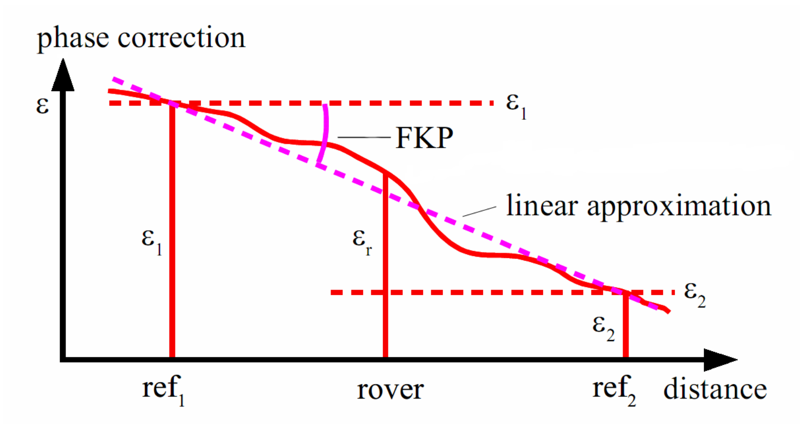


Figure 3.4: Graphical representation of relative positioning errors. [Source: 06-GPS]

VRS and PRS

This method can make more extensive use of the state space model, and is called the Virtual Reference Station (VRS) or Pseudo Reference Station (PRS) [12, 17, 54, 56]. Virtual Reference Stations do not provide extra correction data in addition to the observation data of the reference receiver. However, the state space model of the base station network is used to calculate the prevailing nuisance errors near the rover and consequently produce simulated observation data. This is then sent to the rover as if it were a normal reference station. For this system to work two-way communication is mandatory since the network must know an approximate location in order calculate the errors and feign observation data. For various reasons, discussed in chapter 2 and section 4.5, this will be the case for Superbus.

With this method, correction data for any location within the network can be calculated and sent out. This effectively means that distance errors due to the kinematic nature of Superbus can be circumvented, the VRS can just move along with the vehicle, as long as the vehicle remains in range of the reference station network.

Unfortunately, due to current practical limitations of the RTK algorithms, this is not the case, the virtual station still needs to be fixed on one location, making a ”hard switch” when relocating the VRS. This forces a reinitialisation of the RTK algorithm. This situation brings back the distance dependent error when the vehicle moves away from the VRS, but more importantly it brings back the gap in the RTK solution for about 30 seconds, when the VRS is relocated.

There is however a way to circumvent this. Instead of moving the VRS along with the rover receiver, one can place a VRS on an arbitrary location. Now instead of sending observations from this location to the rover, the station sends out observations calculated from the approximate position solution from the rover. In other words: the station is static but the measurements it sends out are optimised for the position of the rover and not dependent on the actual location of the base station. Another word for such a station is a Pseudo Reference Station, or PRS. This means that kinematic and distance related problems do no longer exist, The corrections are always updated to the last known rover position. In addition the base station switch can occur far less often, if ever. It is only limited to the maximum baseline length the rover receiver software prescribes.

The flexibility generated for kinematic applications by using VRS or PRS, in combination with the precision of the state space approach for the base station network, makes this an ideal solution for Superbus. Larger areas such as the Netherlands, can be covered with greater precision, with less reference stations, than a network of individual base stations. Also the problems arising from the frequent switching of base stations can be avoided. A last benefit from this approach is that commercial base station networks are already operational. This completely eliminates the need for any additional infrastructure on the Superbus side, instead relying on an established network, and hence reducing costs.

3.5 The LAMBDA method and future enhancements

The LAMBDA method

In the previous section, the details of the method to resolve the carrier phase ambiguities have been omitted. Many current high grade receivers use the LAMBDA method to solve the integer ambiguities. Although the method will not be explained in full detail here, since enough information exists on the subject [48], it will be explored further to allow some additional details to come to light. For a simple double-difference example the parameter estimation problem would be as follows [48]:

$$y = Bb + Aa + \varepsilon \tag{3.18}$$

where y is the observation vector, B and b the matrix and vector relating to the real valued unknown parameters (e.g. position coordinates etc.). A and a are the matrix and vector relating to the double difference integer ambiguities.

The key concept of the LAMBDA method is to decorrelate, as much as possible, the usually highly correlated ambiguities of the n tracked satellite carrier signals, in order to make it easier to estimate the integers correctly [53] [31].

The method is comprised of 4 basic steps. In the first step one disregards the fact that the ambiguities are integers and one estimates float solutions for the problem, $\hat{b}$

and $\hat{a}$. This is done using a least squares approach.

The second step is the decorrelation and integer estimation step. Because the float ambiguity estimators, $\hat{a}$, are highly correlated, a simple rounding of the float solution would often times be wrong. In a 2D example, one may imagine the constant cost ellipsoid as very elongated (the ellipsoid where all a produce the same error from the calculated float solution $\hat{a}$). This is illustrated in figure 3.5. Here one can see in (a) that simple rounding to the nearest integers would produce an incorrect result. Hence Teunissen [48] proposed a transformation of the search space to a more decorrelated one, in order to minimise the search space for the integer least squares estimator. For this to work the transformation matrix Z has to satisfy the following conditions:

- Z must have integer entries
- Z must volume preserving
- Z must aim to reduce the product of all ambiguity variances

By satisfying these conditions it is guaranteed the transformed ambiguities are again integers, and that the variance-covariance matrix of the transformed ambiguities is more diagonal than the original [47] one.

A 2D example is given in figure 3.5 (b). Here the transformed search space is visible, where a simple rounding would already produce the correct integers. The LAMBDA method however normally uses the integer least squares estimator. This method has been shown to be superior to other options, such as simple rounding or bootstrapping [46].

Step 3 involves the decision whether or not to accept the integers obtained from step 2. Several methods to decide to accept the integers are currently in use. The popular ratio test will be discussed in the next section.

If the integers are accepted step 4 is simply to take the obtained integer ambiguities from step 2 and use these to correct the float estimates $\delta\hat{b}$ of step 1.

From a theoretical standpoint, the estimation method described here is optimal. Of course, in practise, optimality is dependent on the method of validation used for step 3. This will be discussed below. From a computational standpoint, it is more intensive than simpler methods, although in practise this has not been much of an issue, nor will it be likely to become one. High kinematic applications will certainly benefit from faster ambiguity resolution, but advances in the GPS constellation, or in integer validation tests, are perhaps a better way to minimise the resolution time while maintaining a high success rate.

For example, both the modernised GPS, as the newly developed Galileo constellations, will feature 3 broadcast frequencies. The added third frequency will finally allow for reliable *single* epoch ambiguity resolution (for short baselines) [33]. Also,

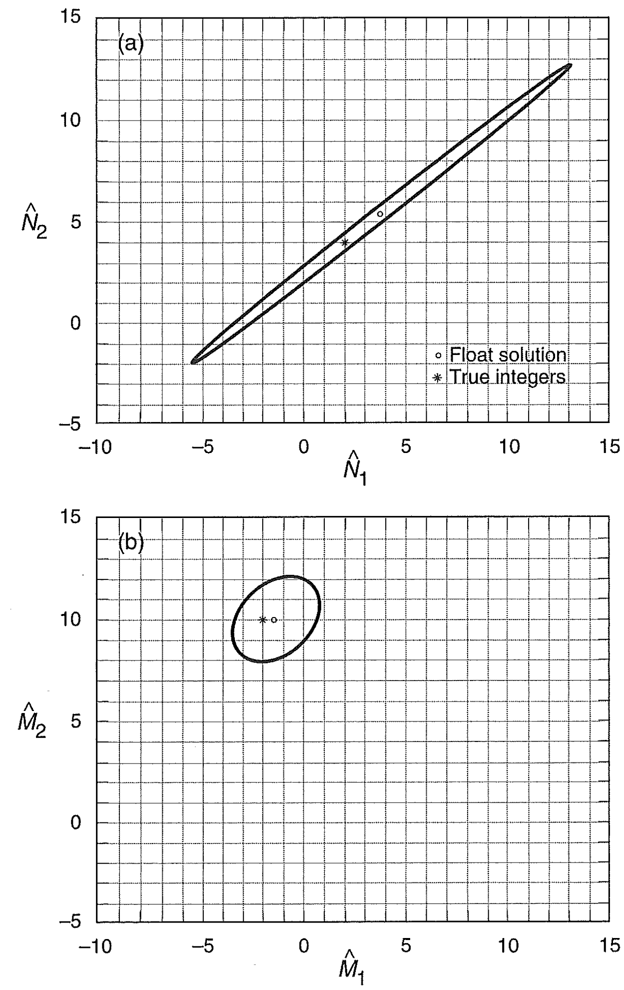


Figure 3.5: 2D example constant cost ellipsoids before (a) and after (b) the decorrelation step. Rounding in the first scenario would produce incorrect integers of $(4,5)$, while rounding in the second scenario produces the correct $(-2,10)$. [Source: [31]]

using multiple GNSS combined will have much potential in reducing ambiguity resolution times. Working on these solutions will be more effective than using another ambiguity resolution algorithm.

The ratio test

It is clear that the results obtained from step 4 are most accurate if the integers found in step 2 are actually correct. Remember that no integer estimation method has a 100% succes rate, as the measurements are inherently noisy. For this reason many

GPS receivers use an acceptance- or validation test to maximise the chance that the calculated integers are correct. An often used test is the ratio test. The test is defined as follows [49]:

$$\text{Accept } \breve{a} \text{ if: } \frac{q(\breve{a}')}{q(\breve{a})} \geq c \tag{3.19}$$

Here $\breve{a}$ and $\breve{a}'$ are the integer vectors of the best and second best solutions of the integer minimiser q respectively (see [49]), i.e the closest to the float vector $\hat{a}$. c is a tolerance value to be selected by the user.

This means that if the second best solution for q is larger by a certain amount, controlled by c, $\breve{a}$ will be accepted as the final integer ambiguity solution. If this is not the case the float solution will continue to be used until a solution is found for which equation (3.19) is satisfied.

The method for accepting the calculated integer described here, is usable for minimising the risk of accepting an incorrect ambiguity fix. There are however some problems with this way of working, mainly due to poor implementation of the method.

Many people wrongly assume that equation (3.19) establishes a direct measure for the correctness of the ambiguity vector $\breve{a}$. If the ratio test holds, the solution will be correct. This is however not true as the test only controls the *chance* (by choosing c) a wrong integer solution is accepted, i.e. it controls the failure rate of the ambiguity resolution algorithm.

Many receivers utilise a fixed value for c. Hereby they neglect the fact that the ratio test itself is dependent on the prevailing GNSS model. In other words, a fixed value for c does not mean a fixed chance of an incorrect ambiguity resolution. This means that, with a fixed c, the end user has little control over what failure rate he or she finds acceptable.

So rather than using this fixed c, [49] proposes a variable number, in order to obtain a true fixed failure rate. For now this is not used in receivers and it obscures the view on the failure rate of the algorithm. Additionally the value for c is not agreed upon in literature. The result of this can be that the algorithm failure rate is unnecessarily low, causing unnecessary rejections of integer vectors by the test. This in turn causes the time to first fix to rise. The suggested variable value for c truly enables an end user to select a acceptable risk of a incorrect ambiguity fix, by (effectively) trading it against the time to first fix. It turns out that current receivers, with a fixed c are often on the conservative side with regard to the failure rate. This causes correct integer resultions to be disregarded by the ratio test and the system to stay with a float solution. The variable c can result in a more accurate failure rate, and therefore accept a integer resolution sooner, and hence improve the time to fixed ambiguities. This may be of value for future GPS applications, not the least of which the Superbus, where it will be shown that losses of lock will occur in normal operating conditions. Here effective and fast ambiguity resolution algorithms are paramount.

The future for RTK

As is mentioned in section 3.4, the baselines of RTK may not become too large. This in order to minimise the distance related errors, as well as to enable ambiguity resolution with a sufficiently high success rate. This is the main background for the FKP or VRS debate above. When spatial decorralation become a factor, the ambiguity resolution success rate and the position estimation precision will drop below useful values.

In the previous section 3.5, is was stated that future developments may improve and simplify matters for Superbus. The onset of multiple GNSS and the addition of a third carrier frequency, will allow for reliable instantaneous integer ambiguity resolution. But again, this is only true for short baselines, much like it is now. The onset of wide area RTK might be interesting in this regard.

[33] and [13] describe a method for RTK that greatly increases the maximum baseline distance of current RTK. This Wide-Area RTK (WARTK) uses phase observations from a network of permanent base stations to model the ionospheric delays for a large area. This model can then generate precise and real time ionospheric corrections for a rover receiver anywhere within its network. The benefit is that this modelling of the ionosphere can occur using a base station network with large spacing (several hundreds to over a thousand kilometres). This can enable fast ambiguity resolution on a continental level. It will increase the operational theatre of the Superbus significantly while reducing the cost of the RTK network. Simulated Galileo data proved that an instantaneous ambiguity resolution success rate of 99.9% is possible at baselines of 114 kilometres, while at 257 kilometres the time to first fix was 5 seconds. This compared to a 0% success rate and a 75 seconds time to first fix respectively, when ionospheric corrections were not used. Rover position estimates also remained below Superbus requirements with 95% of estimates withing 0.8 centimetres horizontally and 1.6 centimetres vertically (ionosphere weighted with moderate signal strenght).

One can conclude from this that although RTK can adhere to Superbus requirements using present day technology, the future will truly enable high precision kinematic positioning in a large geographical deployment field. Instantaneous ambiguity resolution will become possible, while the baseline requirements for RTK will become more relaxed. Added GNSS constellations will make the RTK more robust as well. GPS is interoperable with Galileo. This will make for more robust position estimation since the loss of low elevation satellites due to signal blockage will be far less important due to the overall increase of the number of satellites. This increase in range measurements will also increase integrity of the whole system since integrity monitoring systems such as RAIM (see section 5.1) benefit from these extra measurements. Indeed research is already available on the subject and shows promising results [14, 15, 32]. More information on RAIM is available in section 5.1.

3.6 Pseudorange rates

One last subject that is of interest when using GPS for kinematic purposes are the pseudorange rates, or $\dot{\rho}$. These allow the vehicle speed be tracked at considerable accuracy, even in absence of an ambiguity fixed RTK solution. This can be of importance to the Superbus project, for example when an RTK solution is unattainable. Therefore the pseudorange rates will now be discussed.

Recall the small remark in section 3.1 concerning the shift of the receiver replicated satellite signal. It was said that due to the PRN encoding, the satellite signal would only become measurable if it was multiplied with an aligning replicated signal. Only changes in time where hitherto considered, but due to the relative motion between a GPS satellite and a user, the observed frequency also changes, the Doppler shift. This means that in order to obtain a fix on a satellite, the receiver needs to shift the replicated signal in both the time and the frequency domain.

This Doppler shift however can in turn be used by the receiver to estimate velocities directly, and not by differentiating between two position estimates. Indeed this method is used regularly within receivers, with good results.

The pseudorange rate, or relative speed between user and satellite is usually obtained from carrier phase measurements, and can be obtained by differentiating equation (3.2), resulting in:

$$\begin{aligned}\dot{\rho}^{(k)} &= \dot{r}^{(k)} + (\dot{b} - \dot{b}^{(k)}) + \dot{I}^{(k)} + \dot{T}^{(k)} + \varepsilon_{\dot{\phi}}^{(k)} \\ &= (v^{(k)} - v) \cdot 1^{(k)} + \dot{b} + \varepsilon_{\dot{\phi}}^{(k)} \end{aligned} \tag{3.20}$$

One can see that the receiver and satellite clock biases, now become the rates of change of these clocks, the clock drifts $\dot{b}$ and $\dot{b}^{(k)}$ This has a much smaller effect on the solution and so $\dot{b}$ becomes a nuisance factor, rather than an unknown. Furthermore one can see that ionosphere and troposphere errors equally become subject to the rate of change. The rate of change of the ionospheric and tropospheric errors is usually quite small, minimising $\dot{T}^{(k)}$ and $\dot{I}^{(k)}$, justifying them to be incorporated in $\varepsilon_{\dot{\phi}}^{(k)}$. Furthermore $\dot{r}^{(k)}$ becomes dependent of the satellite velocity vector $v^{(k)}$, sent in the satellite broadcast message, and the user velocity vector v, which has to be estimated. Lastly $1^{(k)}$ is the user-to-satellite line of sight vector, available through a user position estimate, or approximate position.

The user velocity can now be calculated in exactly the same way as a SPS solution as described in section 3.2. First the the equation is rewritten to:

$$(\dot{\rho}^{(k)} - v^{(k)} \cdot 1^{(k)}) = -1^{(k)} \cdot v + \dot{b} + \varepsilon_{\dot{\phi}}^{(k)} \tag{3.21}$$

If we now simplify $(\dot{\rho}^{(k)} - v^{(k)} \cdot 1^{(k)})$ to $\dot{\tilde{\rho}}^{(k)}$ we can write (3.21) for all the tracked satellites as a system, in much the same way as section 3.2, to:

$$\dot{\tilde{\rho}} = G \begin{bmatrix} v \\ \dot{b} \end{bmatrix} + \tilde{\varepsilon}_{\dot{\phi}} \tag{3.22}$$

Here G is the same (3.9), and v is the velocity vector of the user. Now in the same way, using a least-squares method, a solution for the problem can be found.

The beauty of the method is that it produces quite precise results, since ionosphere and troposphere do not play a major role any more. Tests revealed a standard deviation of 0.015 m/s in horizontal direction and about double that in vertical direction.

3.7 Communication

In the previous sections it has become clear that a GNSS can in theory be used for Superbus navigation, while adhering to the specified requirements. From section 3.4 however it has become clear that in order to obtain a precise PVT solution, one last obstacle remains in place: Additional information from outside sources is always needed. This in turn means that in order to make precise GPS positioning work in a Superbus environment, the vehicle should have a permanent communications link. This might not be as straight forward as it seems in this culture of pan-communication. The vehicles speed of 250 km/h is an important factor in this. In addition, the Superbus team is planning a (quasi)national deployment, which dramatically changes the way to approach the communication system. This however will be the subject of this section.

Let us review consequences of RTK positioning for communication to and from the vehicle. RTK relies on a network of base stations to provide corrections for a large geographic area. These observations need to be transferred to the vehicle. Consider the VRS solution proposed in section 3.4. This solution requires observation data from only one reference station. This data is sent in a format set up by the Radio Technical Commission for Maritime services (RTCM), called RTCM 2.3 [37]. Relaying the observation data of 12 satellites in RTCM 2.3 requires a data rate of 6845 bps, or 6.8 kb/s [50]. This figure is independent of the number of base stations present, and hence quite a stable bandwidth estimate.

Although this bandwidth requirement seems quite low, one must keep in mind that the data stream needs to be stable and constant. Recall the remarks of section 3.4 concerning the RTK algorithm. If observation data is too old, for example due to an outage, the algorithm will have to reinitialise, causing a temporary loss of RTK positioning. For the communication this has several consequences. Data relay must be constant, or at least so fast that no RTK time out will occur. System delays must be kept within acceptable levels for the same reason. Also, the envisioned vehicle speed of 250 km/h is not insignificant, and can render certain relay solutions, possible for static rovers uses, useless.

Although not the main subject of this thesis, a pragmatic solution must be found for data relay. Therefore some possibilities for mobile data transfer will be considered here. Main advantages and drawback will be covered, and reflected against the communications requirements given below:

- Bitrate equal or exceeding 10 kb/s

- Able to relay data at speeds to a minimum of 250 km/h
- Latencies not greater than 2 seconds
- Uninterrupted data relay greatly preferred

Note that only two systems are regarded here. The section consists of a pragmatic approach to the communications problem. This means that currently unavailable commercial systems are of limited interest. Although the Superbus concept is in search of top-end solution, this does not mean that it should be a theoretical solution outside the capacities of the project. When technologies mature this can always be reconsidered for the concept. For now however, only systems within reach of the Superbus project are considered, with information gathered from various sources [5, 20–22, 39].

Networked VHF radio

The first system that was proposed for Superbus data relay was a specifically designed system by the Koning & Hartman Company. During the initial phase of the Superbus project Koning & Hartman was involved in the voice communication of the Superbus. A system was designed where a basic VHF system was used, which could in theory be upgraded to include data-relay.

The system architecture involves an elaborate network of VHF stations placed adjacent to Superbus routes. A station would need to be placed every 20 kilometres, due to radio range constraints. This is an expensive and not very practical from an infrastructural point of view. On the other hand, the need of a station every 20 kilometres, would open the possibility of placing a GPS reference station at the same location. This would decrease the dependence from third parties, such as commercial GPS base station networks.

However the collaboration with Koning & Hartman was ended prematurely, and detailed plans never became a reality. That said, the system never showed great promise for data relay. First of all the VHF system was designed from an analog standpoint. It was initially designed for voice, and therefore the radios were not capable of multiplexing. Voice was not converted to a digital signal before being sent. This means that at one point in time only voice or only data could be transferred, with voice always gaining priority. For RTK positioning, this is not acceptable. The problem could be overcome by adding a dedicated channel for data, but this would again raise costs, on both the vehicle and base station sides.

Yet this is not the only problem. Consider the system with a radio and reference station every 20 kilometres. This can never be a viable operational system. In section 3.4 it was clarified that the carrier phase ambiguity remains constant as long as a satellite remains in view. Similarly, the observations from the reference station need to remain as well. If observations from a new reference station are received, the phase ambiguities change as well. This means the RTK algorithm needs to recalculate them, which can take up to a minute. With the Superbus obtaining velocities of up to 250 km/h, this could mean the algorithm needs to be reset every 5 minutes. One can see that the lack of an RTK solution for approximately 20% of the time, due purely to system architecture, is not a preferred situation.

Solving the above situation by using PRS or FKP could work, but then data centres are needed to compute the state space. Still the last problem, the handover between radio stations, remains. The radio receivers in the vehicle would only be able to be connected to one radio station at any one time. If a switch is needed, the radio first needs to cut the connection from the first source, search for the second source and handshake, before data relay can be resumed. The time this process takes was somewhat unknown due to the speeds of the vehicle, but estimated to about 2 or 3 seconds. Though this should be fast enough, the loss of communication could again cause the RTK algorithm to reinitialise, losing an RTK solution for some time. This was however never tested.

Considering all the potential problems and difficulties of the Koning & Hartman radio system, it is dismissed for use as data relay system, though in theory it does adhere to the requirements. The drawbacks of the system are too large. Development, construction and maintenance costs of such a system would be far to great to be of any economical interest.

GPRS and UMTS

The conclusion of the previous subsection essentially forces us to search for third party solutions for mobile communications. The cost of a (quasi)national private system would be considerable and, due to the very limited bandwidth to be used, simply not economically viable. In addition it would be a tremendous undertaking, which would take years to complete. This realistically leaves commercial systems the only option for a cost effective national data relay system. This considerably narrows down the options and basically leaves GSM or the newly rolled out UMTS as candidates. Satellite communication is disregarded due to poor transfer speeds and high latencies. It remains to be determined whether these commercially available systems are suitable, and satisfy the criteria stated in the beginning of the section.

General Packet Radio Service (GPRS) is an elaboration on the Global System for Mobile Communication (GSM). GPRS and GSM are designated a second generation mobile communication technology, while Universal Mobile Telecommunications System (UMTS) is deemed a third generation technology, currently taken into service.

Both systems operate in the Ultra High Frequency (UHF) band, with GSM mainly on the 900 and 1800 MHz bands, and UMTS operating on a slightly higher frequencies, ranging from 1900 to about 2200 MHz. Both systems are cellular, meaning that static cell stations are placed within an area, this is demonstrated in figure 3.6. When a user roams across the network, the mobile device connects to one of these cells depending on signal strength, so in reality cells overlap. There are different sizes of cells, ranging from large base stations installed on masts, to small cells, placed on rooftops in urban areas or even inside buildings. The size of these cells depends on different factors, including geography, transceiver power and user density.

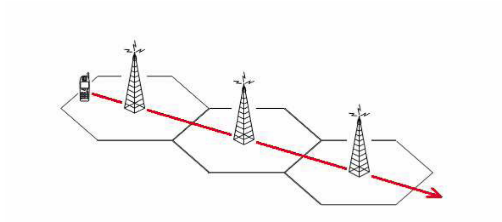


Figure 3.6: Cell structure of cellular networks. [source: [5]]

At this point the GSM and UMTS technologies start to diverge. GSM uses Gaussian Minimum shift keying (GMSK) for the modulation of data onto the carrier signal. This is represented in figure 3.7. This technology shifts the frequency of the carrier signal to accommodate the digital data signal. The frequency range of a cell is divided into smaller individual frequencies ranges of 200 kHz, allocated to individual users. As an indirect result of modulation and the overlapping nature of the cells, each adjoining cell in a network must use a slightly different frequency, in order to avoid interference. This brings to light an inherent property of the GSM network. When a user is roaming, and moves away from the cell station, the signal strength decreases rapidly, this in turn causes a switch to another cell. But since this cell operates in a different frequency range, the handover cannot be gradual. In other words, the switch to another base station causes a momentary loss of communication at the moment the communication transfers from one cell to another.

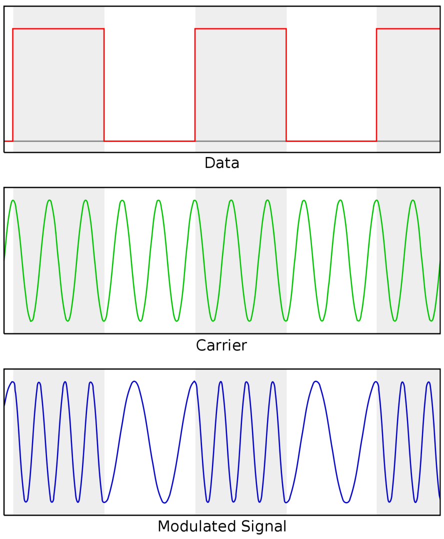


Figure 3.7: Representation of frequency shift modulation. [source: wikipedia]

UMTS on the other hand uses Code Division Multiple Access (CDMA) for modulation. This technology does not allocate each user a dedicated frequency, but instead uses a larger frequency domain to transfer the data. CDMA is a form of spread spectrum. The data is sent simply direct, spread across the entire bandwidth using a Pseudo random noise code. In this way multiple users can utilise the full bandwidth a certain frequency spectrum allocation allows. Diligent readers will now become alert, as this is the same modulation method as used in the GPS satellite signal, discussed in section 3.1.

Allowing multiple users to use a single communication channel without interfering with each other is called multiplexing. This can be done in several ways. For example, a certain frequency domain can be subdivided into smaller frequency bandwidth segments, much in the way GSM uses the bandwidth of a cell, called Frequency-division multiple access (FDMA). Another way is to divide the bandwidth into time slots, and allow multiple users to use the bandwidth by accessing the signal at a certain sequence of time intervals, called Time division multiple access (TDMA). CDMA on the other hand, uses PRN codes to allow multiple user on one communication channel. Let us recall the GPS satellite segment. In the constellation over 30 satellites send signals at the same frequency while never interfering with each other. This is because of the PRN codes. The satellites send information to earth modulated in a certain code. The receiver replicates this code and multiplies it with the signals it receives. The interesting aspect of these PRN codes is that they are auto-correlating. In other words if the signal replicated in the receiver and exactly aligned with the signal being sent out, the data present within the signal can be extracted. In any other situation, where the two signal are not synchronised, the two signals will cancel each other out. Please refer to section 3.1 for more information on the subject.

In the case of mobile communication it works as follows. When a user enters a cell, he will be assigned a specific PRN sequence. Whenever data is sent to the user, it is done modulated with this specific sequence, the PRN code. The receiver replicates this PRN code and multiplies it with the received signal. Remember that now only the matching received and replicated signals will correlate. All other codes will cancel out and therefore only the information destined for this specific user remains. In this way the available bandwidth of a cell is used more efficiently. Multiple PRN signals can be sent over the same frequency band and still every individual user is only able to extract the correct signal without interference from other data being sent. One can loosely use the analogy where a person is still able to comprehend and distinguish different languages while in a airport lounge. It becomes a matter of tuning into the right reference frame.

One might now enquire why this UMTS is deemed third generation technology, while it seems only a arbitrary step in modulation schemes. To explain this, it is first important to uncover three inherent properties of mobile communication.

- Users are not bound to one geographical location
- Users can be on the move, e.g. have a non-zero speed
- Users solicit bandwidth

All these properties give rise to interconnected problems in mobile communication. The bit rate of any transmitted radio signal diminishes with increasing distance from the transmission station.

This means that a mobile carrier must always have a network of cells to allow the users to be truly mobile. The carrier must find a balance between bit rate and cell density. It is evident that an increasing cell network density increases costs, and a reduced data rate decreases usability. Furthermore, when using multiple cells, the user should be able to switch between cells. This should cause no interruptions or dropped calls. These properties are also dependent on cell size. Lastly the user can have a non-zero speed. This can in its own right cause problems in communication due to Doppler effects. This again drops the data rate significantly with increasing speeds.

Now the differences between GPRS and UMTS can be explained. Firstly due to the spread spectrum CDMA has a much higher native data rate than GPRS. The modulation technique used in GSM, GMSK, is optimised for speech and low power consumption on the receiver end, and is therefore not ideal for the transmission of data. Also the GSM network will always prefer speech before data, meaning reduced or no data transmission on busy cells as well as increasing latencies. Enhanced Data Rates for GSM Evolution (EDGE) has partly solved the low native bit throughput problem by using an alternate form of frequency shift keying, but it still relies on the GSM network. The static bandwidth of the different systems depend on several parameters, such as the amount of fault correction used, but a general overview is given in table 3.4. Note that the speeds of GPRS and EDGE can be improved by making use of multiple slots, this on the other hand directly reduces the number of users a cell can manage.

Table 3.4: Theoretical data rates of mobile communication systems. [source: wikipedia]

Communication System	Data Rate (kb/s)
GPRS	9 - 21,4
EDGE	8.8 - 59.2
UMTS	144 - 2000

One can see that all these systems can obtain the required data rate set for Superbus, 10 kb/s. UMTS however, does this with a large margin, giving it more robustness at speed. As mentioned, Doppler shifts can cause problems when a receiver is on the move. The frequency picked up by a receiver will become higher or lower than the transmitted signal, when the receiver moves to or away from the source respectively.

Although the frequency shifts caused by a moving receiver are reasonably small, due to the high speed the signal has, it can have a pronounced effect on communication. Especially GSM suffers from this due to the frequency modulation it employs. This modulation is by nature dependent on shifts in frequencies, and therefore has trouble dealing with velocities exceeding approximately 160 km/h, due to Doppler effects. The number of bits that is incorrectly received (0 instead of 1 and vice versa) after transmission rises due to these problems, causing the need for the bit sequence to be resent. This in turn causes the total data rate to drop. Furthermore, the frequency channels can start to interfere with each other. GSM networks therefore employ guard bands between channels to reduce the chance of interference, but this in turn reduces the total data rate of the cell.

UMTS and its CDMA modulation offers important benefits in this regard. The PRN Codes are not dependent on frequency shifts and therefore the Doppler shift become a less prominent problem and is more easily handled. UMTS hence supports higher receiver velocities, and in theory should support a data rate of 144 kb/s at 500 km/h.

A further benefit of CDMA, and the independence of individual frequency channels is the possibility for soft handovers. When a cell switch is needed, a hard 'handover' is performed. The receiver must jump from one frequency to another. This can cause problems, such as dropped calls and a interruption of data flow. Since CDMA cells all broadcast over the same frequency, a hard switch is no longer required, smoothly transferring the data flow from one cell to another. This eliminates the data interruption (important for sustaining an RTK solution), and reduces the probability of a dropped call (depending on the cell overlap).

The pseudo random nature of the CMDA modulation also provides a better resistance to multipath than GSM. Multipath is the reflection of radio signals off objects, causing the signal to be received twice or more. This was introduced in section 3.3. Since the bounced signal will be slightly delayed it will have a bad correlation with the receiver produced code, and hence become far less dominant or even cancel completely. As an additional benefit the PRN codes are more private. Clandestine tapping of the signal is far more difficult, since prior knowledge of the used PRN code is needed in order to pick up the right signal.

As a conclusion of this section, it is now possible to say that a permanent data connection with the Superbus is, in theory, possible. UMTS supports the required bandwidth, and more importantly, supports it up to the required speed of 250 km/h. UMTS is able to provide an uninterrupted connection across the complete network with acceptable latencies. Although the system is presently still not completely rolled out, it is in such a mature stage, that it will be usable, and will only get better. GSM in theory supports most of the requirements for use in the Superbus, and can be used in absence of an UMTS but problems are expected above certain speeds, and possibly when switching cells.

3.8 Concluding remarks

In this chapter the basics of GPS positioning have been explained. The basic signals, measurements and calculation methods have been clarified for practical use. The

Standard Positioning Service is clear, in addition to the more accurate methods of augmented positioning. It has become clear that the Superbus requirements, discussed in the previous chapter, are theoretically attainable. It is now also transparent that augmented positioning is mandatory for the desired precision. With augmented positioning comes the additional requirement of a wireless data connection, in order to transfer additional or correction data to the vehicle. UMTS is for now seems the most practical solution to this derived requirement.

Future practical implementations

With kinematic high accuracy positioning becoming easier and more accessible with the onset of mobile broadband and base station networks, it has become a subject of research to develop practical applications for road use. The accuracy obtained using RTK is sufficient to start development of guided driver aids, or even autopilot functionalities in road vehicles. RTK is coming out of the laboratory phase.

Certainly this is of interest for Superbus, as it undoubtedly has a need for such systems, in order to make the vehicle safer, faster and more useful. Perhaps, people are not yet ready for high speed driverless transportation, but systems as lane assist, automated emergency stops and active vehicle control in difficult situations are desirable, if only to improve safety. Several research programs in this area have been carried out already, and provide an insight in the possibilities for Superbus in the not so distant future.

One such program is the development of a driver-assist system to enable bus drivers to use the narrow road shoulder as an additional lane for high traffic roads [43]. The narrowness of the shoulder in combination with the width of the bus, provide a challenging situation for any bus driver. The use of a base station network, an accurate geo-spatial database, and several on board sensors, are shown to make this kind of use of the road a safe effective possibility. An accurate road model provides a comparison for the real time position estimates, while several interfaces (head up display, haptic and tactile feedback) provide a way for the driver to keep the bus on the shoulder easily and accurately, even in bad weather situations.

Of course, the scenario of an RTK outage as mentioned in section 3.4 cannot be ignored. Underpasses or other unforeseen circumstances might interrupt the reception of satellite signals momentarily, causing the integer ambiguities to be lost. In [43], a simple system using a commercial velocity and a yaw-rate sensor, or two velocity sensors, proved accurate enough (20 centimetres tolerable error) to allow the system to continue to work for 15 seconds in the event of an RTK outage. Although this set up might not suffice for Superbus use, it does show, that such a system to cope with RTK outages can be developed at a reasonable cost.

Another article focuses on a more rigorous form of driver aid, building a system to autonomously drive up a curvy road on order to study the vehicle behaviour at the limits of handling [4]. In the end it might provide a system that is able to react and keep the vehicle in control when the driver makes an error. Where this system deviates from stability control systems currently available in vehicles, is the fact that it can keep the vehicle on a predetermined path.

The system is inspired by skilled racecar drivers, who have two major advantages over a typical driver. Firstly they have an ability to predict vehicle grip more accurately and secondly they are able to use *all* vehicle actuators (including counter intuitive use of throttle and braking) more accurately to keep the vehicle in control in difficult situations.

The system controls the vehicle into corners by estimating speed and steering commands, based on grip friction estimates and the desired path. When the vehicle has entered the corner, the system uses the actuators (steering, throttle, brake) to cope with modelling errors (for example initial friction estimates), and disturbances (deviations in grip) to keep the car in control an on the desired path.

Again this may be an important safety feature for the Superbus. With an accurate road model (already mentioned above), it may become possible to use this system in various ways. It may for example be able to step in and override the driver in situations where the driver is about to lose control of the vehicle.

These two examples are only a way to introduce the possibilities that wide area RTK enables in future vehicle and infrastructure design. For Superbus these technologies may be very important, both with respect to safety and as its role as a technology demonstrator. Section 4.5 will elaborate more on GPS related possibilities for the Superbus. This section only shows some direct research that is being done in the field.

In the next chapter a GPS system will be proposed for the Superbus. This system will adhere to Superbus requirements as much as possible. In subsequent chapters the performance of said system will be evaluated.

Chapter 4

Superbus Positioning System

With the theory from chapter 3, and the requirements from section 2.4, all information needed to construct a GPS based navigation system for the Superbus is clear and available. This is the goal of this chapter.

First a small recapitulation of the previous chapter will be given. Subsequently the NTRIP protocol, needed for the augmented positioning, will be discussed. The next section will cover the Positioning System, and how it is set up for use. Subsequently the Position module is discussed, this program allows for easy access of the GPS receiver data to other Superbus systems. Lastly applications of the Superbus Positioning System are discussed.

4.1 Introduction to the Superbus Positioning System

In this section an introduction to this GPS system will be given. It is a small recapitulation of the possibilities and impossibilities, in order to clarify why the specific system in section 4.3 is developed.

Starting with the requirements stated in section 2.4, it is immediately clear that they exclude standard stand alone positioning. It is simply not precise enough. That said, SPS still can be useful as a back up to the precise system, but also for velocity measurements, as they are obtained through the pseudorange rates and therefore are already more precise than the differentiation of two or more individual positioning solutions. This would allow some Superbus systems to remain functional when losing a precise position fix.

This however only leaves augmented positioning as a possibility for the Superbus. This is in itself not a problem, but it does put extra strain on the additional requirement of (quasi)national deployment. The communications channel, needed for all types of real time augmented positioning, must be robust enough to be able to maintain the required bit rate at the appropriate speeds, but it must also be able to do so for large areas. This has been discussed in section 3.7. The conclusion there was that currently

UMTS is the best solution for this problem. The network, although not thoroughly complete, is large enough for practical use and the bit rate exceeds the requirements. This could allow other subsystems and applications to use the data connection simultaneously. This opens up a larger range of subsystems and applications that can make use of GPS, for example a networked database or other location based services. An elaboration on this is found in section 4.5. It is also important to note that UMTS provides the possibility of seamless transmission throughout the complete network, and should support speeds, up to and exceeding that of the Superbus.

This leaves the decision of what specific augmented positioning system will be used for the system. Again looking at the requirements and the theory of section 3.4, one possibility is greatly preferred: relative positioning. At the time of writing, Precise Point Positioning is not robust and fast enough for practical use in the vehicle. RTK, with the use of base stations allows the precision requirement to be met, however only if close enough to a base station. This would mean the Superbus would only have a deployment area of roughly 10 to 20 kilometres around the base station. This might be sufficient for basic testing purposes, but will become less and less acceptable, as the project matures. The solution to this can be the use of virtual or pseudo reference stations (VRS and PRS), that use a network of reference stations to compute local base station observation values, which in turn can be sent to the vehicle. This has been clarified in section 3.4

The very last hurdle is the mode of transmission of this observation data. This can be done through the internet, using the NTRIP protocol, which would allow Superbus easy access to base station information. More information of the protocol can be found in section 4.2.

4.2 NTRIP

Network Transport of RTCM via Internet Protocol, NTRIP, is a standardised and easy method of exchanging RTCM data, correction data for augmented positioning, over the internet, making the system far more flexible than systems using direct data connections such as mobile radio transceivers [10, 40, 55].

NTRIP is based on the Hypertext Transfer Protocol HTTP/1.1. This means it is a stateless generic protocol, which makes it very simple to use. Each request for RTCM data is independent from previous connections, and therefore all relevant information is transmitted in the request. This makes it a simple and lean protocol, relatively easy to implement on systems with limited resources.

The generic set-up of an NTRIP system is available in figure 4.1. Here one can see that the basic correction or observation data is managed in RTCM, again a standardised protocol, but now for correction data itself. This protocol is flexible and allows for various methods of relative positioning, including the one prospected for the Superbus, RTK. These RTCM messages are available directly from an appropriate GPS receiver and sent to a managing computer. This computer runs the NTRIP Server software.

The NTRIP Server then forwards the RTCM corrections it receives from the GPS receiver to the NTRIP Caster via the NTRIP HTTP protocol.

The NTRIP Caster is the main body of the system. It is the program that organises, manages and maintains all aspects of the system. It compiles a list containing all necessary information on the available NTRIP Servers and manages what information is sent to an NTRIP client and if a client is authorised to receive this data.

The NTRIP Client is the end user part of the system. It acquires access to NTRIP Servers through the NTRIP Caster. It also handles the user's security aspects between Caster and Client, as well as the configuration of the desired corrections. The NTRIP Client delivers the correction data directly to the rover (user) GPS receiver depicted at the bottom of figure 4.1.

With the NTRIP protocol one acquires a system which is independent of direct data connections, as was standard until recently. The system is more flexible as it allows multiple users on one reference station, and it is easily accessible as long as an internet connection is present. This is an ideal solution for Superbus granted a permanent internet connection is available.

4.3 Superbus Positioning System

The building blocks for precision GPS are now completely reviewed and explained. This section will contain the layout of the GPS system for the Superbus. This system will in theory be able to adhere to the requirements set by the Superbus team in section 2.4. The overview provided here is a proof of concept. This is the system set up that will be tested in order to provide quantitative measures to establish usability in the Superbus. An evolved version of this GPS system, more fit for quasi national roaming will be discussed concisely, however no tests were carried out to support claims of usability. In theory this system should adhere to the requirements of section 2.4 as well, since no major changes are implemented.

In figure 4.2 it becomes clear that the system consists of two parts, a base station section and the Superbus section. The base station in the figure is placed preferably on a accurately known location, in order to obtain the most precise results. It is consequently setup to output the necessary correction data for RTK positioning.

The communications between these two parts are standardised by use of the NTRIP protocol. This protocol allows exchange of RTCM correction data through the internet as explained in section 4.2. This in turn means that the first part of the system as visible in figure 4.2 is interchangeable with any other source that transmits RTCM correction data with the NTRIP protocol. This will become important during later stages of the Superbus development, where the use of a single reference station might become insufficient. In this case a single base station can be substituted by a national network of reference stations. This network will allow the use of Virtual Reference Stations (VRS) as discussed in section 3.4. An overview of this system is provided in figure 4.3. It is

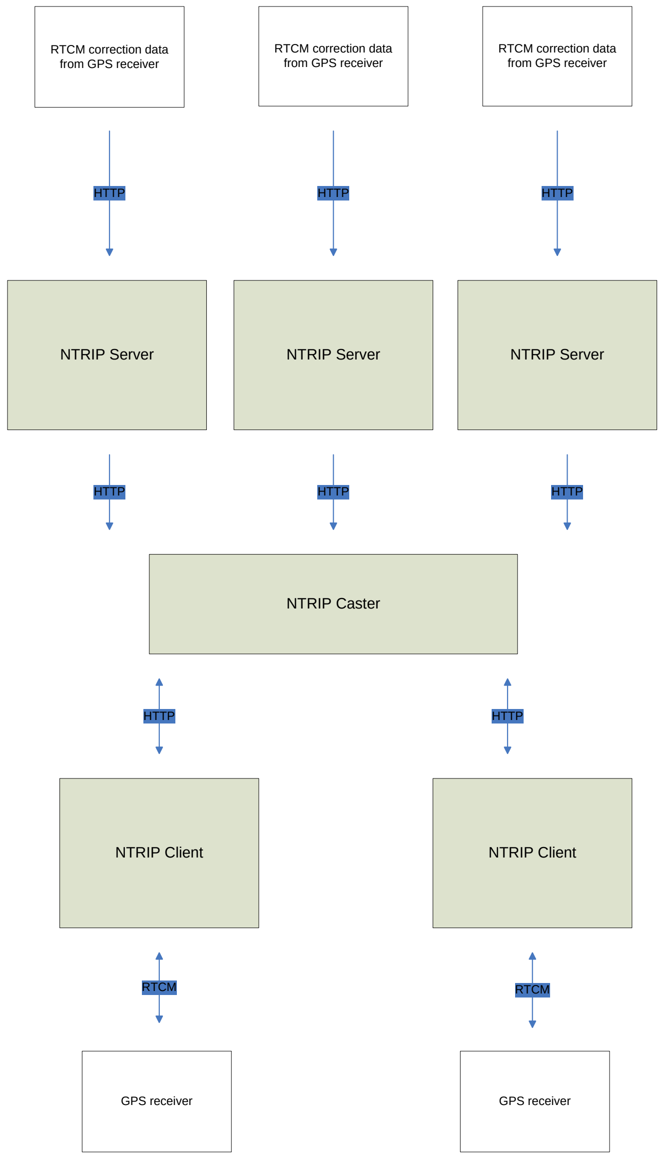


Figure 4.1: Generic NTRIP set up.

worth to stipulate that this switch to a networked base station system does not constitute any major changes at the Superbus side of the system as can be seen in the figure, as long as the data is available to the Superbus via the internet and the NTRIP protocol.

The second part of the system, the Superbus itself, is equal for both lay outs and works as follows. The vehicle is equipped with a computer that has access to the internet via an UMTS connection. This computer is running several programs, int. al. the NTRIP Client software. This software either requests the RTCM data directly from a base station, as in figure 4.2, or it can request data from an appropriate base station, or a VRS station in a network, by sending the approximate (stand alone) position of the rover receiver. This is the case in figure 4.3. The applicable RTCM data is sent to the vehicle and relayed to the GPS Receiver e.g. via RS232 where it is handled as standard correction data. The receiver is now able to acquire an RTK positioning solution and output this solution via TCP/IP. The output can either be in NMEA, sent onto the Superbus network ring directly, or the output can be in the Septentrio Binary Format (SBF), a proprietary binary format, which can encompass more and more precise data. Although the receiver can output NMEA with the same high precision, the SBF output is preferred because the (standardised) maximum number of characters per NMEA sentence (82) may be exceeded when high precision is selected. This will corrupt the NMEA sentence, rendering the valid PVT solution unreadable. Another benefit of using the SBF messages, is the additional information one can obtain. NMEA does not have standardised messages for all information; roll and pitch values are not represented for example, and only very basic heading information is available. The receiver solves this by adding a proprietary NMEA sentence. This logically negates the advantage of NMEA, namely the standardised nature of the protocol.

If the receiver is instructed to output information in SBF it must first be parsed to extract the required information before this information is sent onto the main network ring. The network ring is the main life line for many subsystems, problems in the ring will upset all communication between subsystems. This obviously has large consequences for the vehicle and especially safety. Therefore access to the ring should be regulated and stressed as little as possible. Although the data throughput capacity of the ring would be large enough for a raw dump of all the SBF data, the fact remains that SBF is a proprietary format and hence should be decoded and parsed before the required information is presented. Rather than dumping the SBF data onto the network and letting each subsystem to extract the necessary information, another approach is taken. The SBF data is sent to a managing computer which is running the application that will parse information output by the receiver, repack it, and only then redistribute it to the main network ring in the Superbus. This limits the amount of information being released onto the network, and once the information is on the main network ring, it is freely accessible to every device and subsystem connected to the network.

Receivers and settings

Up until now the type of receivers and especially their output have been reasonably implicit. All information concerning this has been cloaked in amorphous terms: ap-

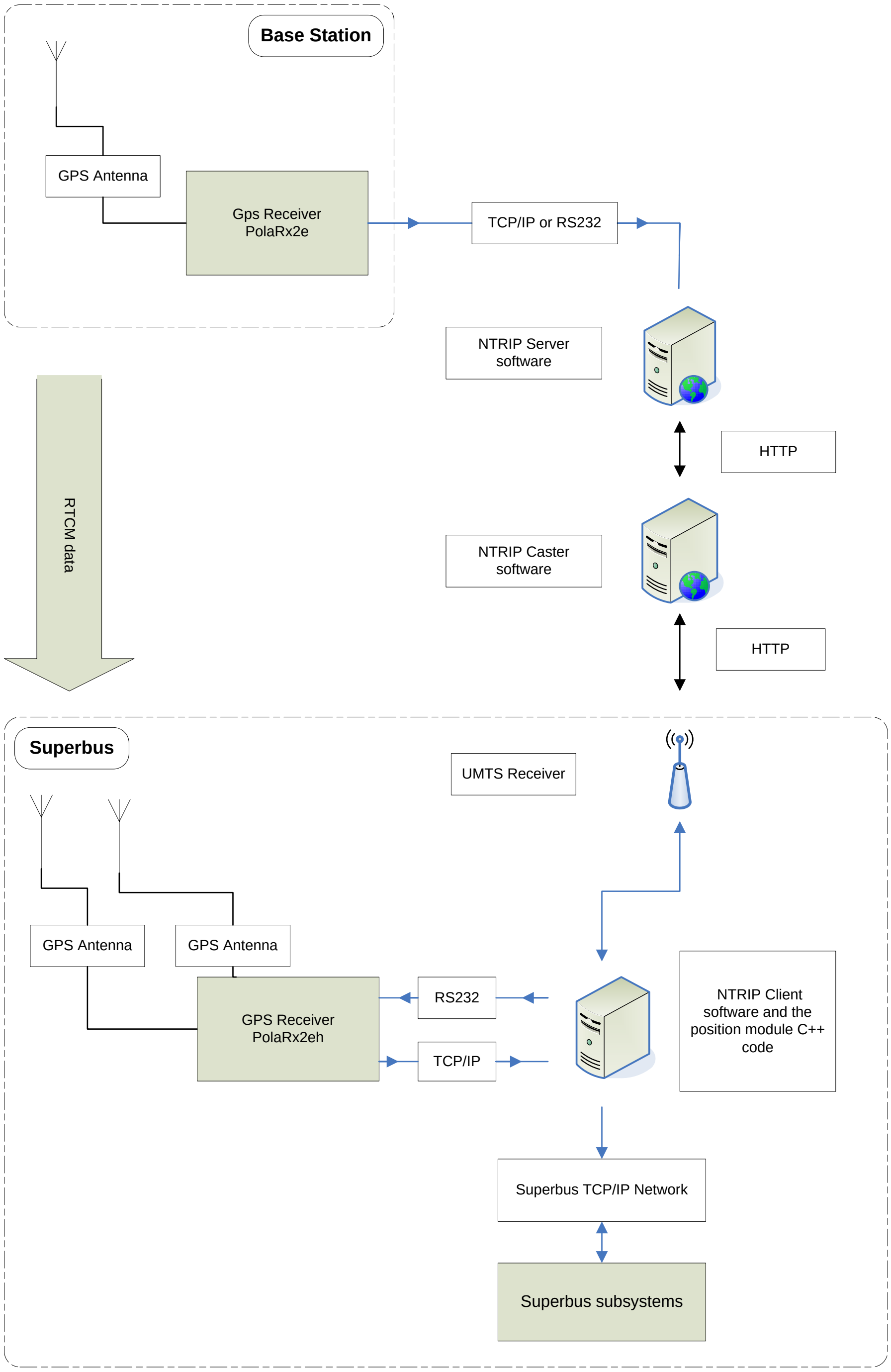


Figure 4.2: Superbus GPS system lay out with dedicated base station.

propriate, required, beneficial. This section will briefly discuss the receivers, and provide more insight into the settings and output of these devices. Note that these settings are only an initial starting point, and may need adjustments during testing to obtain the best results with the complete system.

The receivers selected to power the GPS system for the Superbus, are developed by Septentrio. This is a relatively new company based in Leuven, Belgium. It is quite an open attitude company with close ties to the TU Delft. This allows us to interact more easily with the company which makes it markedly easier to obtain information and solve problems in this relatively new use of RTK positioning. Such relationships with other manufacturers have proven more difficult by the group of MGP. Key technical details remain hidden from end users, which, for MGP, can be awkward at best. Septentrio has a more open dialogue, whilst offering a state of the art approach to GPS receiver development [44].

The PolaRx2e is selected as the base station receiver, for the initial stages of development. This is a 32 channel, single antenna, dual frequency receiver capable of providing correction data in both RTCM 2.3 and RTCM 3.0. The antennas also stem from Septentrio, the PolaNt, though they are rebranded dual frequency antennas from AeroAntenna.

The output settings of the reference receiver are predominantly kept on default base station settings. However to obtain the best results the position of the phase centre of the antenna must be input into the receiver. All testing to validate the GPS system in the next chapter has been done with one base station, RTCM 2.3 and the AeroAntenna AT-2775 antenna.

For the vehicle, the PolaRx2eH is selected. This is largely the same receiver with the exception that it serves two antennas, again from the type AT-2775. This allows the receiver to set up a short baseline between the main and the auxiliary antenna, and hence provide accurate heading and pitch information. The receiver can accept a multitude of correction data over various ports, and subsequently output an accurate RTK PVT solution, using the LAMBDA method for ambiguity resolution. Full specifications of the receivers can be found in appendix A. The PolaRx2 series receiver and the antenna are represented in figure 4.4.

The settings of the receiver can be found in table 4.1. The elevation mask has been set at 10 degrees due to the installation of the antennas in the Superbus. They are placed in carbon fibre, e.g. highly reflective compartments, and care should be taken to adjust this setting once installed. The antennas should have a view of the sky that is as large as possible, while the multipath resulting from the reflections of the compartment should be limited. Note however that the elevation mask should not be smaller than the 10 degrees currently set because low elevation satellites are far more prone to multipath and losses of lock. This influences the robustness of the RTK solution greatly. The placement of the antennas in the vehicle is quite important as well. Since the auxiliary antenna position is calculated using a small baseline, the antennas should have largely the same aerial view, so that the same satellites are tracked. Also the

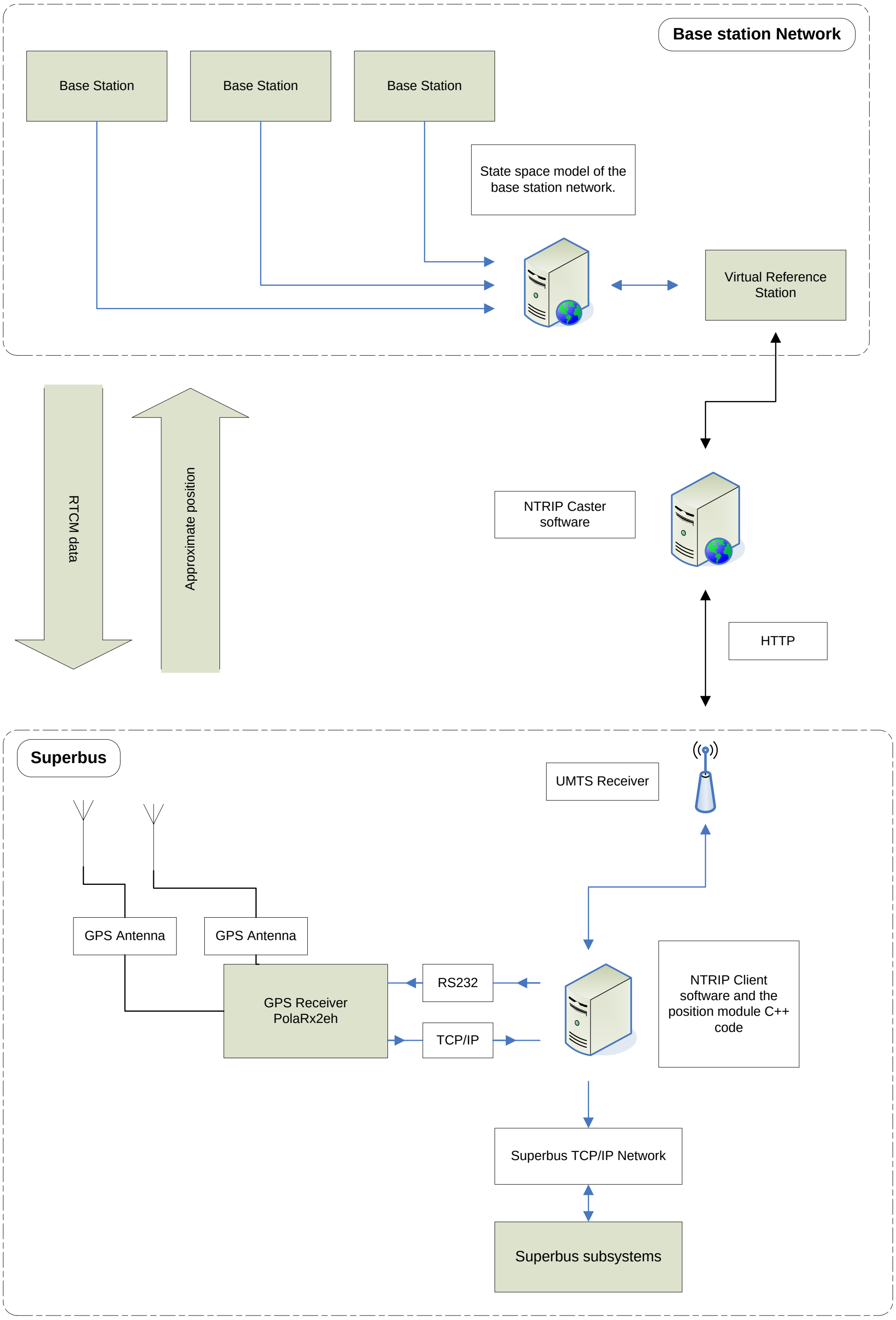


Figure 4.3: Superbus GPS system lay out with network based VRS.

Figure 4.4: Septentrio PolaNt antenna and the PolaRx2eH receiver. [source: Septentrio]

Receiver Settings	
PVT Output	10 (Hz)
Measurement Interval	0.1 (s)
PVT Mode	RTK and Stand alone
RTCM Input	RTCM 2.3
Input Port	Com 2
Satellite Tracking	GPS only
Tracking mode	Dynamic
Receiver Dynamics	High
Elevation Mask	10°
Measurement Fit	off
Smoothing Interval	100 (s), 10 (s) Initialisation
Remaining Settings	Default

Table 4.1: Provisional Set up of the PolaRx2eh receiver

longer they are placed apart, the more precise the heading precision will become. In the Superbus the antennas are placed centrally in the roof along the longitudinal axis of the vehicle, and are placed 8.19 metres apart. This was the farthest apart they could be placed, while maintaining a similar view of the sky. A situational sketch is provided in figure 4.5.

The tracking sensitivity is set on medium, as a trade off between precision and robustness of the solution. To accommodate the dynamic nature of the vehicle, the tracking mode is set to dynamic. On the PVT calculation side, the receiver dynamics are set to high. This is done to help the Kalman filter to filter out measurement errors adequately. Furthermore the PVT interval is set to 10 Hz.

Code smoothing is used to reduce pseudorange noise and multipath. Carrier phase and Doppler measurements are unaffected by this. The smoothing interval is 100 seconds, with a 10 second alignment. During this alignment the smoothed code is not used for the PVT calculations. In the Septentrio receiver *dual* frequency carrier phase measurements are used to smooth the code measurement. This allows long smoothing intervals to be used without any negative side effects.

A measurement fit is not used. Normally the measurement interval of the receiver is greater than the output interval. The measurement fit would fit a quadratic polynomial over all the measurements within the output interval and evaluate these with the measurement interval of the output epoch. This will reduce multipath, but at the expense of a latency. This is not desirable in this highly dynamic application of GPS, furthermore the measurement interval is chosen equal to the output rate of the PVT solution.

To conclude the list, Satellite Based Augmentation System (SBAS) satellites are not tracked, due to the fact that two dual frequency antennas are fitted. The tracking of SBAS satellites would use up valuable receiver channels. Without tracking SBAS Satellites, the receiver can track up to 8 satellites on two frequencies, on each antenna. This number should not be reduced, since the receiver will only start the initialisation of an RTK solution when tracking 6 satellites, on two frequencies. Additionally, tracking these satellites would not benefit the Superbus. The accuracy of the SPS solutions using SBAS is not sufficient for use on the Superbus.

The set up that was used during testing, figure 4.2, serves as an initial starting point for further testing in the Superbus itself. Additional settings could be needed, and some settings might become obsolete. For example, one setting is for now omitted, but can become very useful once the receiver and antennas are permanently fixed into the vehicle. The location of both antennas can namely be fed into the receiver. If the antenna geometry is known, the receiver can use this information to validate the calculated integer ambiguities. This can accelerate time to first fix values, and the decrease the probability of a wrong ambiguity fix, especially in single frequency operation [41]. The settings of table 4.1 however should give a solid starting point for further testing and tweaking in the vehicle itself.

4.4 The Position Module

In section 4.3, it has become clear that the GPS receiver in the Superbus vehicle is not directly connected to the main network, but instead is routed to a computer first. This allows a computer program to act as a buffer and controller between the network and the GPS receiver. This program, the Position Module, has two main tasks:

- Set up communications and initialise the receiver

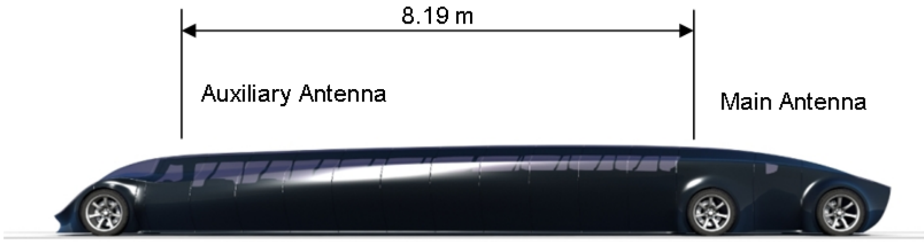


Figure 4.5: Placement of the two GPS antennas in the Superbus.

- Process the output SBF data before sending it to the main network

One advantage of the system set up as shown in figures 4.2 and 4.3 has already been mentioned in section 4.3: it limits the amount of data on the main network ring by extracting all the desired information from the SBF messages, and repacking it in one simple message, before sending it out on the main network. This will simplify the way all the subsystems must access GPS data as well.

However several more benefits are present. Most importantly: the program controls the in- and output to and from the receiver, as well as the output to the main network. The Position Module stops all the data of the main network from reaching the receiver. This is desirable since it eliminates the chance of an accidental input in the receiver. The receiver listens to everything coming in over the TCP/IP port and will respond accordingly if a correct input argument is presented. Although the chances are small, an accidental string of characters from another subsystem could cause an unintended reaction from the GPS receiver. Since the computer that runs the Position Module has two TCP/IP ports, one for the GPS receiver and one for the network ring, data from the network ring does not reach the receiver automatically, eliminating the accidental input problem.

The Position Module also controls the settings of the receiver. Although they can be saved internally, the program re-initialises the settings every time the program is run. This makes it a more robust solution, in the initial stages of testing. In the event of a problem with the network ring, GPS receiver or any other subsystem in the vehicle, a simple restart of the Position Module could allow the GPS receiver to connect to the network again while outputting the correct data. Cutting power to the receiver and then letting the system reboot can achieve the same result, however with a significant time loss.

The final task of the Position Module is the processing of the SBF block, extracting the appropriate data, and redistributing it through the main network. This is an infinite process and will continue as long as the receiver is operational.

Program structure

In this subsection the general lay-out of the code will be presented. The Position Module has two main tasks as already mentioned above. First it is to set up a communications channel with the receiver. When the channel is opened successfully, the program initialises the receiver by sending all the necessary settings to the receiver. This includes the general settings mentioned above, but also the SBF blocks to be output. When this has been successful, the Position Module switches to the other task at hand, to interpret the SBF output, extract the relevant information, and package this into a single package. This package can then be sent onto the main network ring.

In figure 4.6 a schematic overview of the program is given. This will now be explained in more detail. The program starts by declaring all dependencies, subroutines

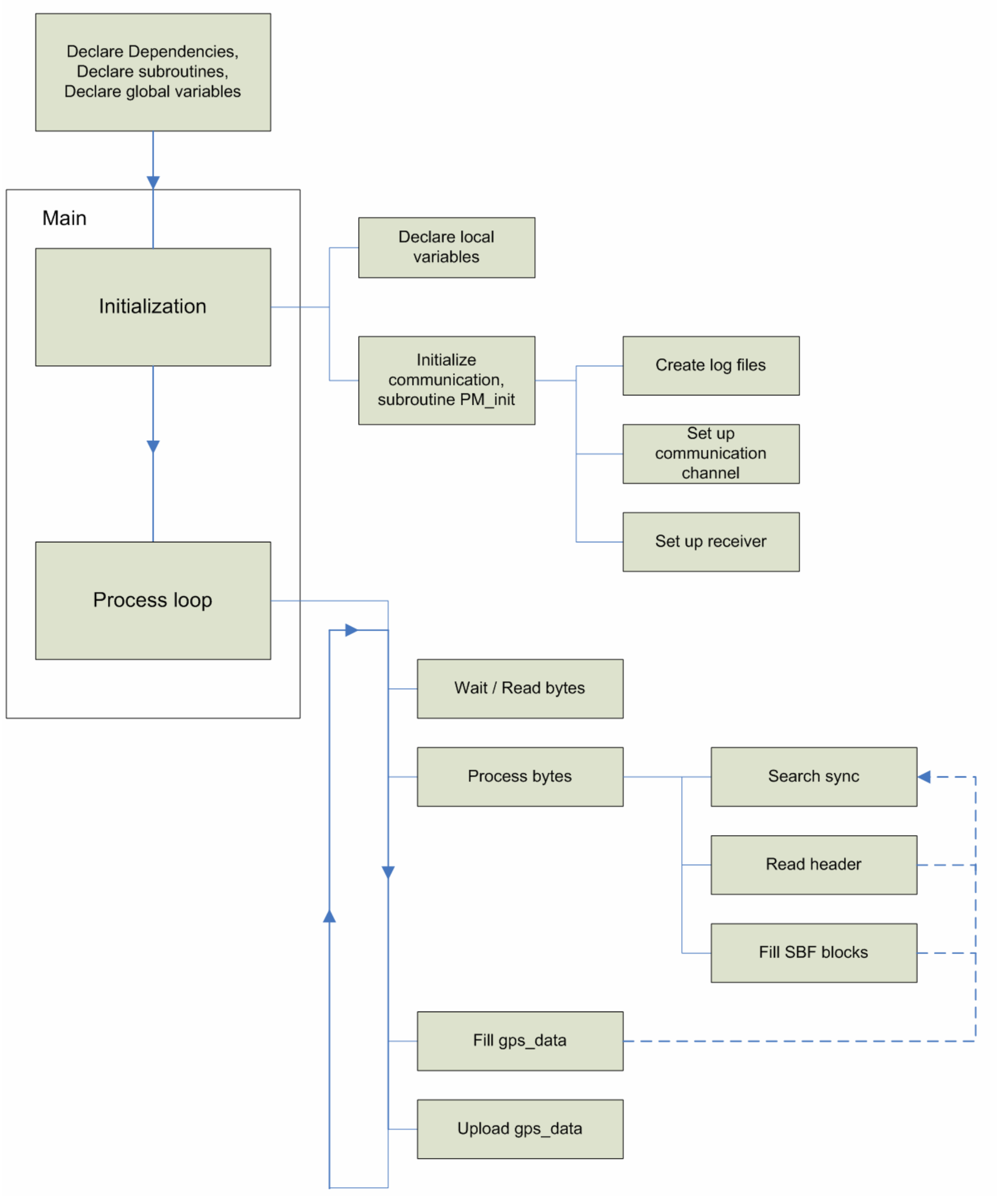


Figure 4.6: Position Module, high level lay out.

and global variables. This is standard practise and needs little explanation. The Position Module then enters the main routine, where it will first perform the initialisation of the receiver. Local variables are declared and the initialisation subroutine is called. This subroutine will itself perform several tasks. It will first open log files that will save all the information that is output by the receiver. This is mainly done for debugging and could be removed if deemed necessary. A serial connection with the receiver is subsequently established. The connection is set to its maximum speed to obtain enough throughput for the output: 115200 baud, 8 bytes, no parity and 1 stop bit. If the connection with the receiver is successful, the proper settings, as discussed in table 4.1 are sent to the receiver. In addition the command is issued to output several SBF blocks. These blocks will in total contain all relevant parameters necessary to operate the GPS system in the Superbus. A list of these parameters can be found in table 4.2.

When the initialisation has been completed, the program enters the process loop. Here all the incoming SBF blocks will be read and parsed for the relevant parameters. Each SBF block is composed in the same fashion by the receiver. It is a binary sequence which will always be composed of a multiple of 4 bytes. The message itself opens with a header followed by the body. Padding bytes are potentially used as filling to complete the message. The header commences with a synchronisation field, ”$@”, used to identify the start of an SBF block. The header then contains a cyclic redundancy check (CRC) to detect any errors resulting from the data transfer. Then message identification is given, a unique number discerning each type of SBF block. Lastly the message length is contained within the header.

The information contained in the header is used in the processing of the SBF blocks as follows. The incoming bytes are stored in a buffer which is searched for the synchronisation, ”$@”. When this is found the subsequent 6 bytes are read as well. If the synchronisation characters were not random and the message was convoyed correctly, these 8 bytes must constitute the header of an SBF block. A first check for this is carried out by checking the last two bytes of the header. If all is well this will be the length of the SBF block. This must always be a multiple of 4 bytes, always positive and always less than 4096. If this is not the case, the message is discarded, and the search continues for the ”$@” synchronisation. If the last 2 bytes do uphold the previous requirements, the program moves to the next stage. The program runs number expressed in the 5^{th} and 6^{th} bytes of the alleged header through a list of SBF blocks that contain relevant information for the Superbus. If the number does not pair up with one of the preprogrammed blocks, the program will again return to the search for the sync. If the number is contained in the list of relevant SBF blocks, another scenario unfolds.

The length and information contained in an SBF block is well documented, and available in the manual [41]. The program will compare the length of the SBF block contained in the header, with a hard coded length, the length the block should be. If these numbers do not coincide, the search for sync is again initiated. If they do coincide however, the Position Module will read out said number of bytes and fill the parameters contained in the SBF block, preprogrammed in the Position Module, with the values provided by the received bytes.

An example: the first four bytes of the message body of an SBF block usually comprise the time of week. The data contained in these four received bytes are now assigned to the time of week parameter of the SBF block in question. The next two bytes are usually the week number, these bytes are assigned to the week number of the SBF block. This reading and assigning of values continues for all parameters in the SBF block. If the block parameters are filled with values, a CRC check is performed and the data is output to the log files. Within the program itself, a flag is also set to show that the SBF block has been filled. If enough blocks are filled with data from the same epoch, the module continues with the next step. If this is not the case it will again move to the beginning of the process loop, the search for ”$@”.

The next step is simply to fill a new structure, GPS_data. This structure contains only parameters relevant for the Superbus, and this is filled with values obtained from the collected SBF blocks from the previous step. The parameters of GPS_data are represented in table 4.2. Once it is filled, the GPS_data block can be sent onto the network where the data is easily accessible for all Superbus subsystems. This part of the program is not functional yet, and needs to be completed before the Position Module can be used in the vehicle. The end of the loop is now reached and the program will again start the search for the synchronisation. The process repeats, the stored SBF blocks will be overwritten with new data until GPS_data can again be occupied with new data.

Output

The last subject of this section will involve the output of the receiver. What are the parameters in the assembled structure, GPS_data, and why are they selected? As mentioned in the previous section, the selected parameters can be found in table 4.2.

Position Module Output Parameters		
Position	Latitude Longitude Altitude	
Velocity	Groundspeed V_n V_e V_u	
Time	Time of Week Current Date Current Time in UTC	
Attitude	Heading Pitch Course over Ground	
Integrity and Safety	PVT Mode Integrity Flag PDOP HDOP HERL Position HERL Velocity Distance to Base Station	NrSV PVT Error Flag TDOP VDOP VERL Position VERL Velocity Age of Last Correction

Table 4.2: Provisional output for the PolaRx2eh receiver

The parameters output by the Position Module are basically divided into five parts: Position, Velocity, Time, Attitude and Integrity and safety. An example output can be found in appendix D. Most of the parameters contained in these sections are quite straight forward and need little justification, but all will be covered shortly.

Latitude, Longitude and Altitude (above ellipsoid) in the Position section are given in WGS-84 while in stand alone mode, in RTK mode, the reference frame of the base station coordinates is used. However, the WGS-84 is still used for calculation of the baseline, since the satellite orbits are given in WGS-84. The velocity outputs, V_n, V_e, V_u, are those in the north, east and up direction. A ground speed is also provided, a simple resultant vector of the three directional velocities. The time is given in Time of week (TOW) and in UTC Time. The current date is also presented. Attitude aspects of the GPS_data structure are the heading, pitch and course over ground. The first and third respectively may occasionally not coincide, with heading being the true attitude of the two antennas, while the course over ground (COG) is the track heading of the vehicle.

The last part of the output consists of the Integrity and Safety information and might need some more explanation. The PVT Mode parameter provides information about, logically, the PVT mode in situ. This is important information as it gives an easy and direct indication of the maximum precision that can be expected from the receiver. While in stand alone mode, certain subsystems in the Superbus may want to decide not to use certain PVT information due for example to lacking precision. Subsequently there are two parameters that are flagged only if the system is not working as intended. These parameters are the PVT Error Flag and the Integrity Flag. The PVT Error flag is raised when a PVT solution can not be attained. The flag can differentiate 9 different scenarios, as can be seen in table 4.3.

Table 4.3: differentiations in the PVT error flag

	PVT error scenarios
1	Not enough measurements
2	Not enough ephemerides available
3	DOP values too large (15)
4	Sum of squared residuals too large
5	No convergence
6	Not enough measurements after outlier rejection
7	Height greater then 18km and speed greater than 515 (m/s)
8	Not enough differential corrections available
9	Base station coordinates unavailable

This can be very useful for debugging, or again for subsystems to decide whether or not to use certain information being output. The Integrity Flag is produced by the RAIM algorithm, discussed in section 5.1. The settings for the RAIM are configurable, so the user can influence the circumstances in which a flag will be raised. Needless to say, integrity is compromised when the flag is raised, in which case PVT data should not be used or with extreme care. For certain applications, more stringent criteria then a simple flag might be appropriate, This can be programmed into the software at the subsystem side, by using the External Reliability Levels (ERL's). These parameters give a quantitative measure of reliability of position or velocity solutions. A position or velocity solution passes if the value is lower than a preprogrammed alarm level at the subsystem side.

The Dilution Of Precision (DOP) values output, are another way to interpret the GPS solution. More precisely, it provides information about the effects of the current satellite constellation geometry. Although not very comprehensive, the DOP values can be useful to quickly overview the current GPS situation. Generally PVT solutions with values over 6 for the Position DOP, PDOP are considered not usable. Extensive elaboration on DOP's is outside the scope of the thesis. However, a good introductory article is available in the bibliography [18].

The last three parameters are the number of satellites in view (NrSV), the distance to the base station and the age of the last correction. The NrSV is always a quick but coarse way to assess the robustness an precision of your PVT solution. The more satellites available the more robust your solution will be: the system will more likely be able to cope with variations in operating environment without loss of functionality or failure. The Distance to Base Station can be an important parameter as well. As indicated in section 3.4, the precision of relative positioning decreases with increasing distance to the base station. This parameter therefore can provide an extra indication of the state of the RTK solution. Note however that while using VRS for correction data, this may not be the case. These stations might be placed at considerable distance from the vehicle. The corrections received are however calculated for distances much closer to the Superbus. The Age of Last Correction is provided for somewhat the same reasons as the Distance to Base Station. In the same section 3.4 it has become clear that correction data may not be too old, or it will become useless. For the system in the Superbus, the maximum age of the correction data is left at the default value of the Septentrio receiver, 20 seconds. Under normal circumstances the latency will never become this large and therefore this parameter can provide circumstantial information about the robustness of the radio connection and hence your RTK solution.

4.5 GPS applications and future developments

In this chapter the Superbus GPS system has been clarified. The system, the settings, and the output are now clear. It is now time to take a closer look at the purpose of the system.

The intended use of the GPS system is to provide information to other Superbus (sub)systems. These systems exceed straight forward uses such as simple navigation software. The data can also used for more elaborate systems. In this section the possibilities of the Superbus GPS system will be explored in more detail. This includes hardware systems and software systems, for both immediate use as for future development.

Hardware

In the early design phases of the Superbus project a precise positioning system was to be used by at least two hardware subsystems, the active suspension system and the radar system. These will be considered in more detail below. In the process a validation for the GPS requirements will come to light.

Active suspension would allow a vehicle to stiffen and soften the individual wheel suspension to alter the vehicle behaviour in different circumstances. An example can be seen in figure 4.7, where the (driver-) right side suspension is stiffened to counteract body roll in a turn. One can clearly see that the vehicle with active suspension (right) is much more level while cornering. This improves handling and passenger comfort. For Superbus this system of actively controlling all wheels can be of particular interest. Consider a scenario where the suspension would be significantly softened when passing a small identified bump in the road. The vehicle would then easily glide over the imperfect piece of infrastructure due to the relatively low weight of the wheels, without the need to slow down to the extent normally required. This alleviates the requirement for a high cost, perfect and smooth highway, and so reduce the overall cost of the Superbus infrastructure. The active suspension also increases passenger comfort in the same process.

The system can be expanded to different scenarios as well. For example while cornering and in city traffic. During corners the ride can be smoother by reducing body roll. City traffic can be made more comfortable by reacting to speed bumps and other city obstacles. When the chassis is raised during city travel, the centre of gravity is also raised. This aggravates the body roll in turns and as well as the reaction to speed bumps. An active suspension can react to this change of vehicle dynamics. This train of thought can be continued to overall handling as well, improvement in this section improves overall safety of the vehicle.

Figure 4.7: Vehicle behaviour during cornering. Active suspension is enabled on the right. [source: Bose]

For the active suspension to work properly, two main points are important. The first would be a flexible, and highly up-to-date database of the Superbus infrastructure wherein all locations of road imperfections could be stored, adapted, and accessed. The second would be a reliable and accurate positioning system, that could facilitate the possibility of a fast and accurate alteration of the suspension. Hence the decision for the 5(cm) accuracy, and 10 Hz output rate. The first Superbus has however been built without active suspension due to reliability and safety concerns. A system failure in the higher speed regions could potentially lead to a hazardous situation. For this reason the integrity and availability of the GPS system PVT solution needs to be as high as possible. The active suspension was deemed not mature enough for immediate use, but remains of interest. The requirements for the GPS system remain standing for this reason, the system may still be evaluated for further development of the Superbus.

The second subsystem that was to benefit from an accurate positioning system is the radar system of the Superbus. Radar image processing is heavily dependent on the angular velocities of the vehicle. High accuracy, high frequency angular velocities are needed in order to properly extract data from the collected radar reflections. With a dual antenna GPS set-up as is now built in the vehicle, these angular velocities could theoretically yield sufficiently accurate results. Unfortunately two factors discouraged Superbus to implement this approach. Firstly, the PolaRx2eH receiver currently does not output angular velocities directly, resulting in the need to differentiate numerically between multiple epochs to obtain the required speeds. This would inevitably lower the accuracy of the solution, it would result in the average speed of the time between epochs. Secondly the output frequency of the receiver (10 Hz) is lower than frequency needed for the radar system (50 Hz).

Both problems might not be the end of it however. Septentrio has already reserved space in the appropriate message blocks for angular velocities. To obtain the most accurate results, the relative speed between the two or three antennas will probably be used for these messages. This will give results with a theoretical precision of 2.12 (mm/s) based on the preliminary calculations in appendix E. This would result in a theoretical standard deviation of the angular velocity of approximately 0.03 ($\circ/s$). Interpolation to 50 (Hz) might obtain acceptable results, on the basis that Superbus will be a high speed vehicle, but will not endure large accelerations. For passenger comfort and safety, these need to be kept to levels comparable to high speed trains, smooth and aptly dampened.

Software

Although GPS data is initially not needed for the hardware in the first Superbus vehicle, this does not make high precision GPS obsolete. A range of software can still use the positioning solutions provided by the receiver. These software applications will now be explored in more detail.

As an example of software applications vehicle routing will be discussed first. This will clarify the direction the development of the Superbus software may take. Although no high precision GPS is needed for this application, it may be of importance. Initially only static routing will be used, similar to the simple navigation devices found in most modern cars. But remember one of the key philosophies of the Superbus concept: flexibility. Superbus will try to cater on an on-demand basis. This means that most routes and driving times are not set in stone and change frequently. Because of this an active or online routing system may be of great interest.

Envision this scenario as an example. The Superbus is on a trip to Amsterdam and the normal highway is blocked due to high traffic. Although the Superbus will initially experience no hinder of this on the supertrack, it will need to drive trough the same access routes to the highways as normal traffic. These might be congested as well. It may then become useful, to take an alternative route with less traffic on the local roads.

Online routing can aid in this situation to minimise delays. But it will also have the advantage of estimating arrival times. It will give passengers more detailed information about delays and will allow them to adapt to them more easily.

Online route planning can in the long run also aid in areas that are less obvious. The Superbus is an electrical vehicle. This has benefits, but also drawbacks. Charging a vehicle takes a lot longer than the refuelling of a conventional bus, several hours instead of a few minutes. It is therefore important to optimise the use of the available energy. Efficient driving speeds and especially accelerations can extend the range of the vehicle significantly. Although this may not always be possible, a system providing online route and traffic information can select more suitable routes depending on range and remaining charge. This can for example mean a slower or longer route, but one that will provide the Superbus a road on which it can drive at a constant speed, using energy more efficiently.

The next example is an example of a Location Based Service (LBS). A service that is able to provide or manipulate information on the basis of the user's geographical location. The example previous example illustrates this. The intended route of the vehicle can change on the basis of up to date traffic information, and the location of the vehicle itself. Usually the information provided is volatile and is therefore unfit to be stored in a local database. Online databases are more fit as they can be updated frequently and accessed by multiple users at the same time. An online database however requires the user to have access to some form of mobile communication. For Superbus this is the case, providing the Superbus with interesting and important opportunities.

One of these opportunities has already briefly been discussed in section 2.4. There, an online database was suggested to record several parameters concerning road conditions, which could be redistributed to the vehicles. Up to 7 radars will be used in the Superbus in order to gain information of objects around the car. This will help the Superbus to cope with unforeseen objects on the road ahead at high speeds. This is however, the last line of safety precautions. This means that the vehicle must react immediately to any event that might be hazardous. This includes braking for wildlife, but also for unwanted objects on the road. In this last case, it is important that the situation does not repeat itself. Emergency braking is dangerous, and at best uncomfortable for the passengers. Therefore a continuously updated database of the routes the Superbus travels may be desirable. It can store information about the state of the track, location of bumps and holes, location of foreign objects, or any other information that is necessary to keep the vehicle safe. The radars or drivers could make tags for positions where problems have arisen. Other vehicles can then be informed with ample time to avoid emergency braking situations or other uncomfortable manoeuvres. If the problem is resolved, this can then be updated in the database. Such a system may be a desired extra measure of safety. The driver will be offloaded, either because there is ample time to react, or because non critical information can be suppressed from the driver in the case a potential hazard is being approached. Also the database will always be up to date. This is a big advantage in contrast with a more conservative on-board version of this system. Pondering this for a second can reveal the potential of these types of location based services, especially if these types of systems are combined and integrated.

In section 2.1 the basic principles of the Superbus system have been explained. Now consider the Supertrack and the online reservation system stem from these principles for the next example. Take these systems and combine them with the location based service approach shown above. A large fleet management system (FMS) that combines many of these elements can now be contemplated. Online routing, Supertrack states and schedules, passenger reservations and pick up, traffic information can all be combined. An example of such an FMS system is shown in figure 4.8. This system will try to combine all these factors with vehicle locations and schedules and search for a more optimum solution compared to a preplanned static route and schedule.

Below the system of figure 4.8 will be examined. Note that this is a hypothetical system and by no means complete or final. It serves as an example to demonstrate the benefits of an LBS approach. Plans for a less elaborate LBS system exist and involve only a database for road conditions. This example may be used to expand the planned system over time.

This example of the FMS uses information from seven sources to optimise the solution for three parameters:

- Routing and driving strategies
- Pick up/deliver and vehicle scheduling
- Supertrack scheduling

The seven information sources are:

- Routing and driving strategies
- Pick up and vehicle scheduling
- Supertrack schedule

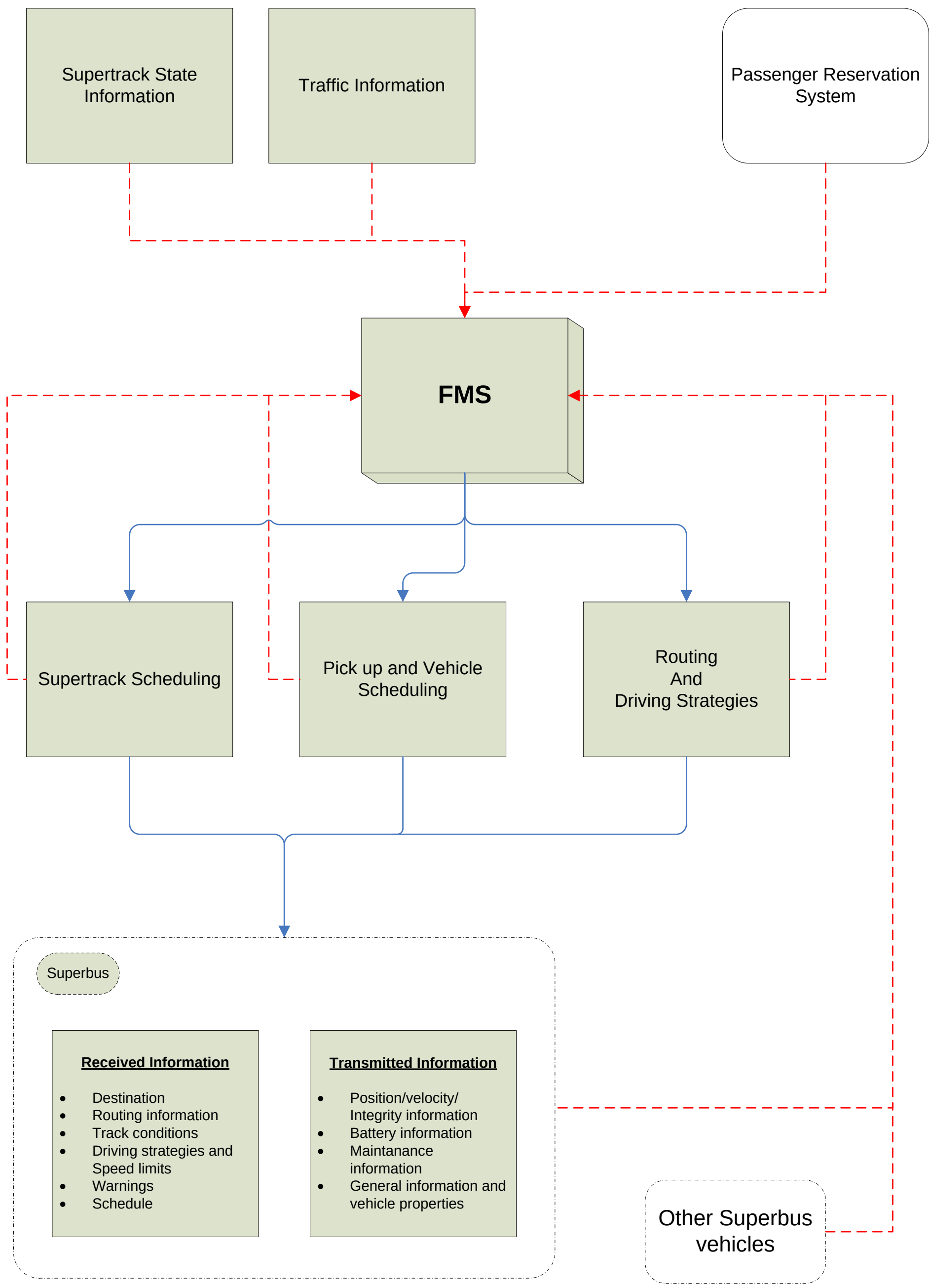


Figure 4.8: Superbus FMS example.

- track conditions and traffic information
- Reservation information
- Other Superbus vehicles

The FMS computer is the main component in the system. It will compute a pick up schedule, schedules for the vehicles, routes, Supertrack schedules, and driving strategies (maximum speeds, etc.) based on information collected from all the sources stated above. The computed information including designated information from the other information sources will then be sent through to the appropriate vehicles. It is important to notice the multiple feedback loops present in the figure. The whole system is dynamic and each of the calculable parameters mentioned above can have their own optimum. Local situations change continuously, as do reservations and the other parameters. The FMS will attempt to find a global optimum solution for the whole system, with the help of these feedback loops.

Looking at the vehicle side of the system, it is easy to see the benefits. The vehicle supplies all current and applicable information to the FMS: position information, battery information, but this may also include velocity and GPS integrity data, updates in track conditions and maintenance information. In return it collects up to date information: routing, driving strategies, speed limits, scheduling, passenger information, track information, traffic information etc.

GPS integrity data might appear redundant, but consider the vehicle with an active suspension. If integrity is low, the FMS might decide to lower speed limits, or change the driving strategy to accommodate the lowered situational awareness. Battery information can be used in conjunction with the passenger reservations to optimise the driving schedule of each individual vehicle. The real-time nature of the system can be of other interests as well. Information from other Superbusses can be used to quickly update other vehicles. This might be in the area of track and traffic information, but this may also include maintenance information for example. This could improve down time of vehicles and increase safety.

Lastly a note on receiver benefits of an LBS system. In the next chapter it will become clear that urban environment and multipath are challenging scenarios for the Superbus Positioning System. Wrong ambiguity resolutions do indeed occur and the receiver can struggle to adhere to Superbus requirements in these situations. Here as well, an LBS may be beneficial. As an added measure to minimise wrong ambiguity resolution and multipath, one can in the future investigate the use of a database of visibility levels or useful elevation angles on much travelled routes and urban areas. Such a database is relatively easy to obtain [45]. The database can warn drivers to adverse conditions depending on location, or perhaps eventually, the use of the information can be integrated in the GPS receiver itself, filtering out or weighting satellites depending on elevation angle, azimuth and vehicle location.

Current situation, concluding remarks

With GPS -for the moment- being omitted for use in two critical Superbus hardware systems, one could argue that the requirements set forth, have been compromised. This is not true however. The sections above have shown that the inclusion of centimetre level GPS positioning will greatly enhance the flexibility of the Superbus development in the future. As the project matures, operational aspects of the vehicle will be better explored, and a multitude of enhancements can be thought of. Not the least of which, an FMS as was explored in the previous section. Indeed a basic FMS is already planned in the concept discussed section 2.1. Though initially it will not require the degree of precision currently offered by the GPS system, it will begin to offer some of the aspects discussed above. It will provide an online routing service. Not autonomous as hinted in the previous section, but via a system controller, overlooking the complete Superbus fleet. Nonetheless in will allow the Superbus to adapt to prevailing conditions faster and more easily. The routing also implements the possibility to take the vehicle size into account and exclude certain infrastructural situations.

The planned FMS is basic, but offers a starting point on which extensions, including the ones discussed in the previous section, can be build. The potential of online FMS systems is great and might even evolve to some rudimentary autopilot aspects that could regulate the allowed maximum speed of the vehicle, by position. This controller could quite easily be implemented, given an accurate, high integrity, positioning solution and a proper database.

One last aspect which justifies the realisation of the accurate GPS system in the Superbus is vehicle testing. The vehicle will initially be used for testing purposes, both for the vehicle behaviour itself as well as a testbed for TNO (Toegepast Natuurwetenschappelijk Onderzoek) research. Vehicle dynamics for example will be studied in detail. It is of no surprise that an accurate GPS solution is not only valuable but mandatory. With the help of GPS data the vehicle track can be recreated accurately and behaviour to exposed situations can be analysed in detail. This will prove very important in order to assure the Superbus is safe not only in intended situations (high speed, cornering, braking), but also unintended situations such as skidding. The Superbus vehicle does not qualify as one of the vehicle categories currently employed by Rijksdienst voor het wegverkeer (RDW), hence there is no fixed legislation to which the vehicle has to comply. For admission to the open road network, Superbus needs to validate the vehicle is safe for use. An extensive test campaign is necessary for this purpose, in which the gathered GPS data can play an important role.

Chapter 5

Validation of Superbus Positioning System

In the previous chapters, the potential merits and significance of the proposed Superbus Positioning System have been reviewed. It has become clear that augmented GPS is in theory able to provide Superbus with the necessary data. Now, after acquiring a functional system, it is time to review it in real world conditions, and establish its performance and behaviour. This vital step in the development of the Superbus Positioning system is the goal of this chapter. It is famously summarised by a Dutch computer scientist: In theory, there is no real difference between theory and practise. But, in practise, there is.

This chapter will start with an insight in the validation process, and certain concepts will be clarified. Then, a precise review will be presented of the performance requirements. The following sections will involve actual testing. First the experiments are explained and the set up of the tests will become clear. The last section will review the results of the tests and will conclude whether they adhere to the requirements and the stated specifications.

5.1 Introduction to validation

This section serves as a general introduction to the verification and validation of the performance of the positioning and heading system for the Superbus. The system will now be scrutinised under various conditions in order to obtain field data. With this test data available, the system will then undergo the verification and validation process. Definitions of these concepts are given below. Validation and verification will be covered mainly in section 5.4.

- Verification: The task of determining whether a system performs to its specifications.
- Validation: The process of determining whether a system fulfils the purpose for which is was intended.

To be able to review the performance of the GPS system with the processes discussed, parameters must be established in order to quantify the positioning performance. Yet there is no standard present for this type of vehicle, or GPS system. However, since the Superbus clearly falls in the category of professional use, its GPS system will be reviewed with an adapted version of the aviation performance parameters [1]. These parameters are, by using stringent requirements, used to verify navigation solutions, and establish if a system is fit for use in safety-critical applications, such as aviation and maritime navigation.

For the system as installed in the Superbus, performance parameters are categorised into three main components: Accuracy, integrity and availability [16, 36]. The fourth component used in aviation, continuity, is omitted in the Superbus assessment. Continuity involves the ability of a navigation solution to complete an action, such as a landing, without accuracy or integrity problems. The navigation in the Superbus needs to be continuous, hence there is no specific action to complete. The remaining three are discussed in more detail below.

Accuracy: Measure of navigation output deviation from truth, usually expressed as 1σ or 95% (approximately 2σ) error limits.

In less technical terms: How close is the calculated position solution to the true position? An example. As was previously addressed in chapter 3, the accuracy of a standard stand alone GPS receiver is usually several meters in favourable conditions. The estimated position can be several meters away from the antenna with which you are measuring.

This has consequences for the application of the system. If the required position accuracy is on the meter level, a position error of several centimetres, is of lesser importance. And indeed, a system which provides a better accuracy will most likely be unnecessarily large and expensive. Hence care should be taken into properly assessing the requirements of the position accuracy as well as other performance parameters.

There is however more to say about the subject. The definition noted above is taken from ICAO annexes, but is actually not the complete story. Notably there is a difference between accuracy and precision, which is hidden in the definition above. Both are distinct and will be addressed separately in section 5.4. Precision is defined as the deviation of a single solution from the *mean* of the complete data set. The summation of all these solutions results in a probability density function for the complete data set. The mean of this set is however not necessarily the actual or "true" mean. This is why we also introduce accuracy, which involves the mean of the complete data set and how much it deviates from the *truth*, see also figure 5.1. The accuracy of a data point can be defined as the precision plus a bias, as systematic error. An example: the position estimates of a data set are all within a few centimetres from each other. However, the complete data set, is several meters away from the target, or in GPS terms, the ground truth. In this scenario the precision of the data set is very high, the accuracy on the other hand isn't.

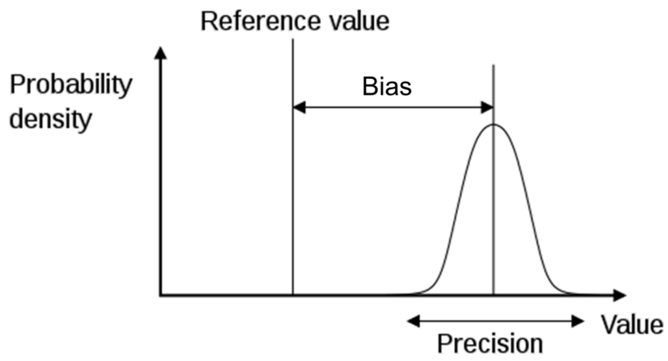


Figure 5.1: Bias and precision graphically represented, accuracy = precision + bias. [source: wikipedia]

The results in section 5.4 will discuss accuracy and precision separately. We will also discuss bias: the difference between the mean of the measurements and the reference value, or ground truth. The precision of the GPS system will be quantified as the 1σ values, or empirical standard deviation of the data set. This is represented in equation 5.1, where N is the number of measurements, x_i the solution of a measurement and $\bar{x}$ the mean of the data set.

$$\hat{\sigma} = \sqrt{\frac{1}{N}\sum_{i=1}^{n}(x_i - \bar{x})^2} \tag{5.1}$$

Note that the standard deviation values will be listed with intervals. Since the obtained data sets are empirical, the results might be slightly different, if the test is repeated. In other words, the standard deviation has its own standard deviation, $\sigma_{\hat{\sigma}}$. For this reason the standard deviation is given accompanied by the extreme values between which the standard deviation will lie with a 95% confidence level.

The last item listed, will be the 95th percentiles. These percentiles indicate the value below which, 95% of the recorded solutions can be found. The reference value for this figure is the ground truth, and hence it is a measure of accuracy.

Integrity: A measure of trust which can be placed in the correctness of the information supplied by the total system. Integrity includes the ability of a system to provide timely warnings when the system should not be used for it intended operation.

For safety-critical applications in practise this means that a system should be able to autonomously assess whether it exceeds specified tolerance levels, and act accordingly. An operator requires a warning when the accuracy of the estimated position solution from the receiver is not within a certain guaranteed limit, due to anomalous measurements (outliers, etc). For this reason the Septentrio receiver used in the Superbus GPS-system, makes use of Receiver Autonomous Integrity Monitoring (RAIM). This system uses statistical tests to evaluate the integrity of the computed position solution. It uses surplus measurements of GPS satellites, to assess the consistency of the measurements. To be able to do this, certain quantifiable performance requirements are needed: maximum probability of missed detections (Pmd), maximum probability of false alarms (Pfa) and alert limits.

As can be seen in figure 5.2 there are four possible outcomes when detecting outliers in the measurements (e.g. due to a failing satellite, a malfunctioning receiver channel, or multipath). Two are correct: a detected outlier, when an outlier is present (D), and the inverse, no outlier is detected, when no outlier is present (B). Two outcomes on the other hand are erroneous: a false alarm due to outlier detection when no outlier is present (A), or an undetected error, no outlier detected when an outlier *is* present (C). The statistical tests are based on assumptions that the residuals of the satellite measurements, the difference between the measured and estimated distance to a satellite, are normally distributed, and the mean is equal to zero for all correct measurements (blue curve, in figure 5.2). When, for example, a satellite is not performing properly or multipath is present, the residuals will form a distribution with a mean unequal to zero (red curve, in figure 5.2). Naturally these two distributions will intersect. allowing the occurrence of missed detections (C).

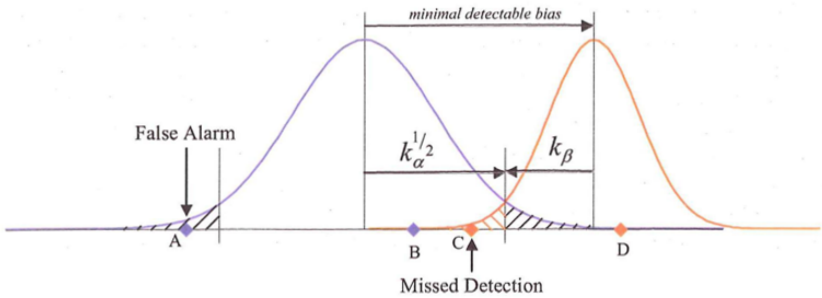


Figure 5.2: Outlier detection. [source: Septentrio]

The procedure to monitor integrity used in the Septentrio receiver is based on a test procedure developed at the TU Delft [34, 48] and follows three steps:

- Detection: Assess whether some anomalous behaviour has taken place.
- Identification: Assess which measurement constitutes as an anomaly.
- Adaptation: Remove measurement from position computation to restore integrity.

To detect whether an (unspecified) anomaly or outlier has occurred, an overall model test is used. If this overall model test statistic is larger than the *predetermined* threshold of the probability of a false alarm (A), the procedure performs a statistical test (w-test) to evaluate from what satellite the detected outlier is coming from. This satellite is then removed from the position computation and a new solution is computed.

To evaluate the impact of *missed* outlier detections, the minimal detectable biases (MDB) of the satellite pseudoranges are computed: The MDB's show the minimum range error for each satellite pseudorange measurement that can be discerned by the w-test described above with the predefined Pmd. The receiver can then calculate the impact that these MDB's have on the position estimate, resulting in reliability levels (RL's). In other words: suppose an undetected outlier introduces an error in the range measurement of a satellite, with the size of the MDB. The effect that this *undetected* outlier has on the position estimate, can be compared with the estimate where this outlier is present. The results of this comparison are the reliability levels (RL's), or errors in position estimates which cannot be detected by this integrity monitoring. RL's thus give a radius within which the accuracy of the position is ensured. The user then evaluates whether or not, this reliability level is sufficient to use the GPS system. This is commonly done by setting horizontal and vertical alert limits (HAL and VAL). When the horizontal or vertical RL's exceed this limit, the calculated position should *not* be used for navigation purposes.

As becomes clear from the above, the calculation of the integrity of a GPS system is rather complex and also dependent on user requirements: the maximum probability of missed detections, maximum probability of false alarms and alert limits. To ensure integrity it is essential that these values are properly defined. Only then it becomes clear whether or not the position estimates meet the requirements and may be used for critical applications.

Availability: Fraction of the time the navigation system is usable (as determined by compliance with accuracy and integrity requirements).

Availability is the percentage of continuous time, during which the system is able to deliver position solutions that fall within certain requirements of accuracy and integrity. These are often HAL and VAL values determined by the user. For example, consider a certain GPS system, which is able to deliver centimetre accurate position solutions for 6 hours every day, and meter accuracy during the remaining 18. If the accuracy requirement is 10 centimetres, the availability of the system will only be 25%. If however, the requirement is 10 meters, the availability jumps to 100%. So the concept of availability is not only dependent on the space segment, but also on the requirements of the user.

In this thesis, Availability will not be assessed in great detail, only the observed results will be specified and commented upon. Statistically significant availability testing would entail controlled long duration testing, both static and dynamic. This was not done, and would for now be of lesser importance, due to the tendency of UMTS disconnections during dynamic testing, currently clearly the weakest link in the system. This is largely uncontrollable in real world testing, and dependent on prevailing conditions of the mandatory 3G network. This is dependent on geography and service provider. One might argue that availability entails the whole system and hence also the availability of the 3G network. This is correct and therefore the values are discussed in section 5.4. However UMTS service is, on the moment of writing, still being rolled out, the UMTS network will only expand, and national coverage, and therefore availability, will only become important in later stages of Superbus development.

5.2 Performance requirements

For Superbus accuracy and availability requirements were set to ”best possible solution attainable”. This has been so from the start of the project, and is partly due to the nature of the Superbus project. The vehicle is a prototype, an attempt to launch a new way of thinking in public transport, and as a result a high profile technology demonstrator. The nature of the project is to be on the very top end of current technology as the project progresses into maturity. ”Best possible”, of course, has its own set of boundary conditions as funds and time frame are limited, immediately narrowing the positioning solution options considerably. In conjunction with the Mathematical Geodesy and Positioning group (MGP) a base requirement was therefore set: 95% of the obtained solutions should fall within 5(cm) of the ground truth.

But even without the direct need of the requirements set conjointly by Superbus and MGP, the system can still be evaluated to it merits. The system can be verified by comparing the actual system performance to the performance figures given by the manufacturer. Septentrio has provided these figures and they are presented in table 5.1 and table 5.2. The first represents the heading and pitch precision for different baseline lengths. The second table shows the horizontal and vertical precision. Note that for the RTK solution, the precision is supplemented with another value in part per million (ppm). This signifies that an RTK solutions degrades in precision, with increasing distances from the base station. For the horizontal solution 1 part per million, or 1 cm every million centimetres, or 10 (*km*). The full specifications of the PolaRx2eH receiver are available in appendix A. These provided values, along with the requirements set by Superbus, will be used in the verification and validation of the receiver performance.

The requirements for integrity are more difficult to define. These requirements are largely determined by the accuracy requirements. Notifications must be given, when the system can not be guaranteed to adhere to certain performance values. However, the vehicle is a technology demonstrator, and no legislation exists stating the integrity requirements of a positioning system used as a primary navigation system. For aviation application, legislations and requirements are well documented [11, 23], and need to be met, before any system is certified for primary navigation. Such legislation is not in place for road vehicles, and indeed the whole Superbus vehicle itself falls outside any category road vehicle as defined by the dutch government.

Table 5.1: Heading and pitch precision (1σ) specification, provided by receiver manufacturer.

baseline length (m)	heading precision (deg)	pitch precision (deg)
1	0.30	0.60
3	0.10	0.20
10	0.03	0.06

Table 5.2: Positioning precision parameters (1σ) specification, provided by receiver manufacturer.

precision	horizontal (m)	vertical (m)
Stand Alone	1.1	1.9
RTK	0.01 + 1ppm	0.02 + 2ppm

For now the Superbus vehicle runs as a test vehicle, and legislation procedures to accommodate such an unusual vehicle as the Superbus are underway. It will become the task of the government to determine HAL, VAL and failure rate values, acceptable for critical GPS use on the public road. For this reason, no HAL and VAL values are determined as of yet, nor any failure rates. The integrity monitoring, RAIM, integrated within the receiver can, at any point in time, be adapted to future requirements. Evaluation of the RAIM system and its availability is however outside the scope of this thesis and has been done extensively [16]. Therefore the RAIM system is, for purpose of this rapport, deemed fit for use in the Superbus.

However an indication of the necessary integrity requirements can be suggested, originating from the aforementioned aviation requirements. First of all it is important for Superbus to assess what the critical systems are that will use GPS, and what the requirements for these systems are. For example, in the case of active suspension (section 4.5), the requirements for GPS, counter intuitively, may actually be less stringent at high speed than at low speed. Since the active suspension idea depends on timing, a one meter error will only cause a 0.014 second timing error at 250 km/h, while at 50 km/h it will be 5 times as high. This illustrates the importance of a precise set of requirements. Once these are available, one can start to set the HAL and VAL values in the RAIM algorithm, perhaps as a function of speed. The maximum probability of missed detection can as a start be set identical to the recommendation for a CAT-I ILS landing at 10−7.

In conclusion the test results will be used for verification and validation of the Superbus navigation system. Firstly the compliance to Superbus requirements will be assessed. Furthermore the performance claims of the receiver will be verified, more precisely for position and heading precision. Lastly the results section will comment on the availability of the system.

5.3 Experiments

In the previous section it has become clear what aspects of the receiver need to be evaluated. By using three main performance parameters, accuracy, integrity and availability, we are able to make qualitative remarks about the performance of the Septentrio PolaRx2eH receiver, in conjunction with the complete GPS system, as developed in 4.3.

A crucial aspect of performance testing is a reference, a ”true” position, to which to compare the real time solutions output by the receiver. Only by comparing the receiver to this ground truth are we able obtain figures regarding the performance of the receiver. In practise it is impossible to obtain a perfect ground truth, since this ground truth is obtained by measurements as well. We must therefore suffice with the ”best possible” ground truth that can be obtained, depending on test set up and conditions. This aspect of testing will be discussed in more detail in the following sections.

The data for this performance evaluation was gathered by three test campaigns, two static and one kinematic, consisting of several individual experiments. The goals of each experiment was different, or at least overlapping, and together provide enough data to assess the quality of the receiver and its navigation output. First a general set-up and the goals of each is provided. Then the technical set-up of each campaign will be given, to provide a better understanding to how the data was gathered. Furthermore, general remarks will be presented which are important during the processing of the results. Although the kinematic test was performed prior to the static test, the static test will be reported first as the kinematic results will be discussed with reference to the static results.

Materials testing

In December 2007, a general equipment test was performed. This test was combined with a materials test. In section 2.5 it has briefly been suggested that the placement of the two GPS antennas is quite important. This is, amongst others, supported by table 5.1, where the manufacturer supplied heading and pitch accuracies are represented. One can see that the accuracy is proportional to the baseline length.

Yet the Superbus design is relevant as well, and provides it's own consequences to antenna placement. Superbus is a meticulously shaped vehicle, designed in order to reduce drag to a practical minimum. Therefore, on the outside of the vehicle, no obstructions in the airflow were to be created. Since the (already) acquired antennas are relatively large professional grade antennas, this meant that they were to be installed internally. This has several consequences. Antenna placement flexibility is reduced significantly due to shape, size and placement of the internal bays of the vehicle. These dictate where and how the antenna's can be placed.

More importantly risk of obstructed aerial view and multipath are increased. The main problem is that the internal bays wherein the antennas are installed are covered with sheet material in order to satisfy aerodynamic and esthetic demands. The antenna will therefore be covered at all times, when the vehicle (and thus the GPS system) is in operation. It is therefore of importance to have an apprehension of the effects the used material will have on the GPS signals the antenna is trying to receive. Some materials reflect or absorb Radio Frequency signals. This behaviour could, in this case, prohibit the satellite signals to arrive at the antenna that is covered and hence make the complete GPS system useless.

Since the antennas would always be covered, and the consequences possibly very large, it was decided that a materials test would be conducted. To cover the antennas in the available antenna bays, two material possibilities were available.

The first and original possibility was a 2 millimetre thick carbon fibre sheet. Since carbon is a conductive material as well, it would potentially prohibit radio signals to reach the antennas in much the same way as steel. The performance is dependent on the thickness and the weave of the carbon sheet.

The second possibility was an equally thick advanced thermoplastic: High Performance thermoPlastic Composite (HPPC). Since this material was quite new, the exact effect on radio signals was unknown. The material is based on a thermo-moldable resin reinforced with a glass fibre filler. Glass fibre is normally non conductive, and will usually not interfere with radio signals. Therefore it is potentially a better candidate for the cover sheet. However, the absence of exact material specifications still demanded further testing.

Experimental set-up materials test

The test took place on December 4th 2007 in a field near the faculty of Aerospace engineering in Delft (see figure 5.3). The field was selected due to its proximity to the faculty, but more importantly because of the unobstructed aerial view the low multi-path environment. This will help the solution to be as accurate as possible, and eliminate these factors from the obtained result as much as possible. The day was overcast and there was a slight drizzle, the afternoon test period was centred around a window where no less than 11 satellites would be visible at any one time. This is demonstrated in figure 5.4.

Figure 5.3: Location of the material test. [source: Google Earth]

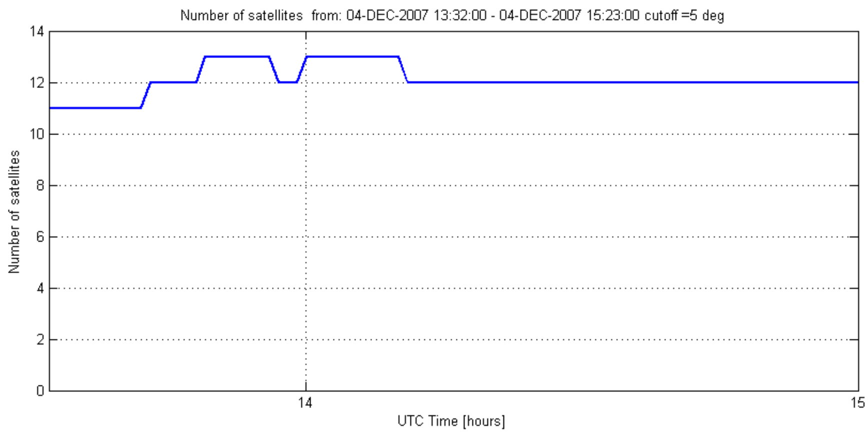


Figure 5.4: Number of satellites visible during materials test (cut-off angle 5°).

The material set-up was as follows. The base station, the PolaRx2e, was set up with AeroAntenna AT-2775 antenna on a tripod and allowed to measure undisturbed for the complete test. The receiver was set to default values, but set to track only GPS satellites with a cut off angle of 5 degrees, and record the resulting Rinex files.

The other receiver, the PolaRx2eH, was equipped with the same antenna, and was set up approximately 10 metres away from the base station. This receiver was set-up to approach the Superbus settings. These are available in table 4.1. The exception to these settings is the cut-off angle, which was set to the same 5 degrees as the base station and the output rate, set to 1 Hz. Again the receiver was allowed to log Rinex files.

The experiment itself was set up as follows. The Base antenna was allowed to log the raw measurements for the complete duration of the experiment. The measurements were then processed in Trimble geomatic office version 1.63 to obtain a static solution. These coordinates consequently served as the base station coordinates. Subsequently a baseline could be set up between this receiver and the secondary, or rover receiver.

The rover receiver was also allowed to log during the same time period without physical disturbance. However each of the two selected materials would each cover the antenna for approximately 30 minutes. A construction of 3 wooden poles would ensure that the material sheets would completely cover the antenna, but not come into contact with it. The construction can be seen in figure 5.5. The first 30 minutes of raw measurements where recorded without any material, though the wooden poles were already present. These measurements would provide a base solution, to which the performance of the two materials could be compared. For the second 30 minute time frame the rover antenna was covered with the HPPC material. The receiver did not move, nor did it stop logging the raw measurements. This procedure was repeated for the third 30 minute time period with the carbon fibre material.

To obtain a solution, a baseline was set up in Trimble geomatic office, between the base station and the rover. This baseline was computed both statically and dynamically. This was done for all three measurement periods. In this way the static solution can be compared to the remaining two solutions. This is done in section 5.4.

Static testing

The static testing was done on march 31st 2009, on the rooftop of the NMI (Nederlands Meet Instituut) building in Delft. This location was chosen because of the availability of a highly accurate ground truth. The building is a stable platform. The main column on which the testing is done, is constructed upon its own separate foundation, free from the remainder of the building. This allows for steady measurements for longer periods of time and therefore a more accurate ground truth. Position accuracy of the antenna mount points, or markers, are within a single millimetre from each other (see *http://gnss1.tudelft.nl/dpga/station/Delft.html*), and therefore very suitable for static testing.

Figure 5.5: Rover antenna covered with carbon fibre material,supported by the wooden construction.

In figure 5.7 a schematic overview of the roof is given. As can be seen, several fixed points are marked, and represent markers on the building of which the positions are precisely known. By setting up a base station on point 21, and configuring the Superbus segment on points 13 and 14, a suitable platform for static testing is created. Though not identical in set-up as the Superbus itself, the Superbus set-up, as described in 4.3, will confidently provide equal results in similar conditions.

The goal of the static tests performed, was to evaluate the static behaviour of the GPS system in normal circumstances. Furthermore, after initial kinematic testing, it became clear that more data was needed to assess the reacquisition behaviour of the receiver. Therefore two tests were scheduled. The first was a standard static test, where the receiver was set-up in the way it will initially be set up in the Superbus, see table 4.1. Approximately 30 minutes of data was collected and stored.

Figure 5.6: NMIbuilding and test set up.

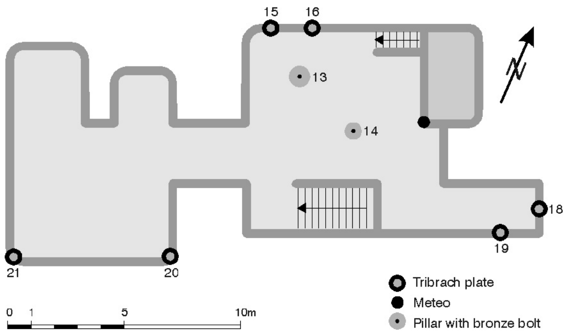


Figure 5.7: Overview of the top of the NMI building.

The second test required loss of lock situations, encountered by the Superbus for example by passing under a bridge, or travelling through a tunnel. This needed to be simulated repeatedly and under controlled conditions, to ensure clean and reliable data. The need for a controlled situation, had emerged during a previous kinematic test, where it proved difficult to obtain enough data under similar condition, to reliably formulate propositions regarding the reacquisition time of the GPS system. This resulted in a static experiment where both receiver antennas where covered repeatedly by metal objects to simulate loss situations. Both the main antenna on point 13, and the auxiliary antenna on point 14, where covered for 5 seconds, ensuring a proper signal loss for all satellites and both antennas. Then the receiver was allowed to regain a RTK fixed solution, before repeating the process. This was done a total of 56 times.

Experimental set-up static test

As can be seen in the figure 5.7, placing the main antenna of the Superbus segment on point 13, and the auxiliary antenna on point 14 yields the characteristics presented in table 5.3. The antennas used for the Superbus segment were Leica AT502, while for the base station a Leica AT504 without radome was used. Because two antennas of differing types have unequal phase centres, this must be corrected during post processing. The test set up will be largely the same as Superbus setup, it will however deviate from the actual Superbus configuration in 4 areas: utilised antenna, logging speed, transmission of the correction data and base station location.

Firstly, the antennas used for the Superbus segment were two Leica AT502 antennas, while for the base station a Leica AT504 without radome was used. These are not three identical AT2775 antennas (rebranded to PolaNt), as is the case in the Superbus. The use of different antennas can introduce a slight difference in performance. These differences will be small though, due to the fairly similar performance of both antenna types.
Secondly, because these base station and rover antennas differ, they will also have unequal phase centres, which has to be corrected during post processing.

Table 5.3: Antenna positions and baseline lengths.

Type	Antenna Type	Marker	Baseline	Baseline length (m)
Base station	Leica AT504	point 21	Point 21 to 13	14.984
Main antenna	Leica AT502	point 13	Point 13 to 14	3.002
Auxiliary antenna	Leica AT502	point 14		

The phase of the centre of a GPS antenna is not a single point [24]. It varies, depending on where the satellite signal comes from. Given these variations, using different antennas for a single test setup is undesirable. The unequal antennas and consequently differing phase centres will typically introduce a vertical error that can be difficult to handle. Nonetheless, point 21, with its AT504 antenna, was still selected for use as a base station. This was due to renovations on the NMI building, which prohibited certain markers from being utilised; hence no suitable point was available for a third AT502 antenna as a base station. Point 21, therefore, provided the best signal, with manageable multipath. The vertical separation of the phase centres is subsequently handled in post processing by incorporating the calibrated phase centre for the two different antenna types, and adding the resulting difference to the antenna height of the base station. These calibrated phase centres are acquired by and available from the United states National Geodetic Survey (NGS). Note that the phase centres provided by the NGS are only in the vertical direction, caused by satellite elevation. Azimuthal changes are neglected as they are caused by the local antenna environment, and are therefore hard to correct.

The receiver settings were nearly identical to those anticipated for the Superbus, available in table 4.1. This permits a direct comparison to the results that can be expected for the vehicle in a static position. The single exception is that the output interval was set to $1(Hz)$, in favour of $10(Hz)$, due to logging constraints.
The proximity of the base station, and the resulting short baseline, is not expected to interfere with this comparison, but should be noted. The operational Superbus can use virtual base stations, as was revealed in section 3.4 which will typically mimic base

stations at a distance of 5 to 10 kilometres. The results obtained here should therefore be slightly better (approximately 1 centimetre) than can be expected for the Superbus.

The correction data, needed for an RTK solution, consisted of RTCM 2.3 messages sent every second. The messages where transferred directly from the base receiver to the rover receiver, using a RS232 com cable and a null modem. Note that UMTS was not utilised during this test, as it was already derived from testing that the system as seen in section 4.3 works well under normal circumstances. Lastly note that the auxiliary antenna is only utilised to obtain heading and pitch values, the position solution originates from the main antenna.

The loss of lock for the reacquisition test was obtained by blocking both antennas for 5 seconds by hovering a frying pan over them. The receivers were then allowed to re-establish a RTK fixed position and heading solution. The blocking interval was selected to be 30 seconds, meaning that if the re-acquisition time, after the initial 5 second signal blockage, was 20 seconds, 5 seconds of RTK fixed data would be recorded. If the reacquisition time exceeded the 30 second mark, the next 30 second interval would be used completely before instigating the succeeding loss of lock.

Kinematic testing

Kinematic testing was performed on the 23rd of May 2008, and involved a vehicle equipped with copious, near excessive amounts of GPS receivers. The testing for the Superbus system was part of a larger experiment, involving other professional grade receivers. This allowed the vehicle path to be reconstructed in the greatest possible precision, while still maintaining a fully functional vehicle in real world conditions, relatively unrestricted in motion.

The vehicle was a standard, road legal, van equipped with a carefully measured platform, on which the receivers where mounted. In figure 5.8 an overview is given of the platform, and the receivers mounted relevant for the Superbus testing. The experiment was generally set-up in the following manner. The Septentrio receiver, was set-up in RTK rover mode, with settings matching those used in the Superbus scenario. RTK corrections from a base station on the NMI building were collected in the vehicle up to 7 kilometres away, via UMTS receiver. Corrections were transferred using the NTRIP protocol, as explained in section 4.2. The receiver was allowed to acquire its own real time solutions, and were only logged for analysis. The two other antennas on the platform were connected to two industrial grade Trimble R7 receivers, logging measurements. These measurements could then be post-processed to a ambiguity fixed carrier phase solution using a reference antenna situated on the NMI building. This allows the vehicle path to be accurately recreated. Values obtained from the Trimble receivers where used as a ground truth for the real-time solutions of the Septentrio receivers. The ambiguity fixed carrier phase ground truth was the best possible reference that could be obtained in this real time kinematic experiment, while still maintaining a relatively free roaming vehicle. The Trimble track is hence not perfect, with a standard deviation of a few centimetres, depending on conditions and distance to the base

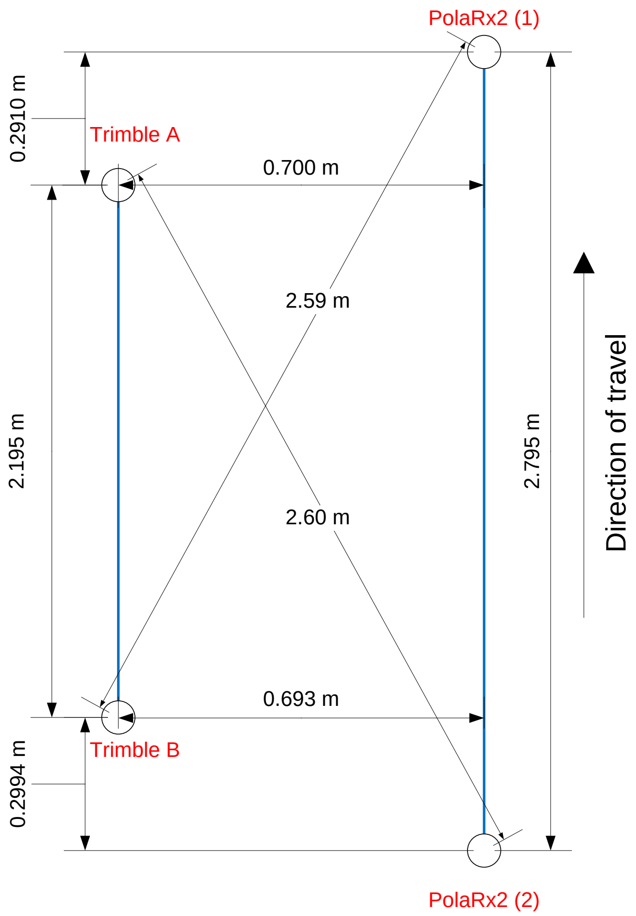


Figure 5.8: Vehicle frame overview, dimensions and antenna placement. Vehicle front is top of figure.

station. For the results the post processed Trimble track was however assumed as the ground truth.

The goal of the campaign was to obtain data to be able to comment on the real world performance of the Superbus. A total of three experiments where carried out that day that will henceforth be known as: (1) Duifpolder experiment, (2) A4 experiment, (3) Emerald experiment.

The Duifpolder experiment involved repeatedly driving along a long straight road in a flat, open countryside environment. Almost no objects were present, which could block or reflect GPS signals (see figure 5.23). Several round trips were made, at different speeds. The main goal was to obtain data under optimal circumstances, however, due to the lack of UMTS reception, a stable connection could not be achieved. Although some runs where successful with an RTK fixed solution, the bulk of the data contained only a stand alone solution. Therefore, in this test the main focus will lie in the stand alone performance of the GPS receiver. The baseline length of the experiment was approximately between 6 and 7 kilometres.

The A4 experiment took place on the final stretch of the A4 highway near Delft-Zuid. The goal here was to see how the receiver behaved in sub-optimal conditions, and to evaluate the reacquisition behaviour of the receiver. The section of highway contained 2 viaducts, causing a short loss of lock for all satellites. The receiver then reinitialises a lock, subsequently a stand alone position, RTK float solution and lastly an RTK fixed solution. Since the Superbus will drive on, or next to normal highways, it is imperative to know the behaviour of the receiver in these conditions. It will happen on a regular basis that an object blocks satellite signals, causing a loss of RTK or even a loss of stand alone solution. The data link conditions of the second experiment were better than the Duifpolder, although problems with the UMTS reception were still present. The baseline length of this experiment was approximately between 4 and 5 kilometres.

The Emerald experiment was a test in light to medium urban environment as can be seen in figure 5.29. It is a track through suburbs which diminish the view of the sky. Due to the more urban environment, the UMTS reception improved dramatically, and in no instance was the connection for the correction data lost or dropped. This allows for a proper evaluation of performance when the GPS system is working as it should, in a real world environment. Please note though that this were by no means perfect conditions, and results will show that multipath has played a role in positioning precision. In addition, most of the time the receiver-set cut-off angle of 10 degrees, was exceeded by buildings and other infrastructure, diminishing the amount of satellites visible. This scenario might be seen as a absolute worst case scenario for a highway situation, the scenario where precise positioning is most important. It might be seen as a simulation of an environment the Superbus might encounter on urban highways, for example near The Hague or Amsterdam. The baseline length of this experiment was approximately between 1.5 and 2 kilometres.

Experimental set-up kinematic test

As was discussed earlier, the experimental set-up involved installing a platform on top of the test vehicle. This platform was carefully measured, and the position of each antenna documented, as shown in figure 5.8. For the purposes of the experiment, it was assumed that the platform was rigid. This is a reasonable assumption, due to the thickness of the beams, used in the platform, the way it was connected to the roof, and visual assessment during the experiment. The equipment on board relevant for the Superbus testing included two laptops, two Trimble R7 receivers, two Zephyr geodetic antennas, a Septentrio PolaRx2eH receiver and two AeroAntenna AT-2775 antennas.

Figure 5.9: Vehicle with installed frame.

The experiment was set up as follows. The raw measurements of the two Trimble antennas, A and B, where logged by the two R7 receivers every second. These measurements were later post processed using a reference station, located on the NMI building, resulting in two individual sets ambiguity fixed carrier phase positioning solutions, one for Trimble A and one for Trimble B. These sets were calculated using Trimble Business Centre version 1.12.

With the platform of the antennas assumed rigid, carefully measured and local level at all time, it is possible to obtain a ground truth for the main Septentrio antenna. For this, the Trimble B track was translated and rotated for every epoch in the test data set, in order to obtain a virtual Septentrio ground truth. The translation was equal to the measurements given in figure 5.8. The rotations where obtained by comparing the Trimble A and B solutions and so deducing the heading between both receivers. Since the relation between the heading of the Trimble receivers, and the main Septentrio antenna was fixed, it is now easy to calculate the virtual Septentrio ground truth for every epoch in the data set. This ground truth is used to as a reference in order to assess the performance of the real time Septentrio solution in all the dynamic test described in the previous section.

The Septentrio receiver in the test vehicle, received correction data in RTCM 2.3

from a PolaRx2e receiver, the Superbus base station receiver, which was installed on the NMI building as well, several kilometres away. The data transfer was conducted with the NTRIP protocol as explained in 4.2. The UMTS receiver in the test vehicle was connected to a laptop running an NTRIP client. This client collected the correction data and rerouted it via RS232 cable, to the com 2 port of the receiver. This was now able to calculate an RTK solution, logging it at 10 (Hz), both on an internal logger and on a secondary laptop, running a basic program, designed for use in the Superbus. Once again the Septentrio receiver was set analogous to Superbus settings, keeping the test variables down to a minimum. The settings of the PolaRx2eH are available in table 4.1.

5.4 Test results

In the following, the results of the staged experiments will be transcribed. Compliance to requirements and manufacturer claims will be verified, a concise evaluation will be given and a conclusion will be formulated.

Materials test

The goal of this experiment is to judge the effects of a sheet of material covering the antenna, as discussed in section 5.3. Two materials are to be compared: HPPC and carbon fibre. Three baseline solutions were computed, both static and dynamic. One 30 minute period without material covering the antenna, one with HPPC covering the antenna and one with carbon fibre.

As mentioned the Rinex files from resulting from the experiment were processed in Trimble geomatic office version 1.63. The results consisted of three static solutions for the rover antenna, and three sets of dynamic solutions, consisting of 1771, 1741 and 640 solutions for the no-plate, HPPC and carbon fibre periods respectively. A sky-plot of Delft during the experiment is presented in figure 5.10.

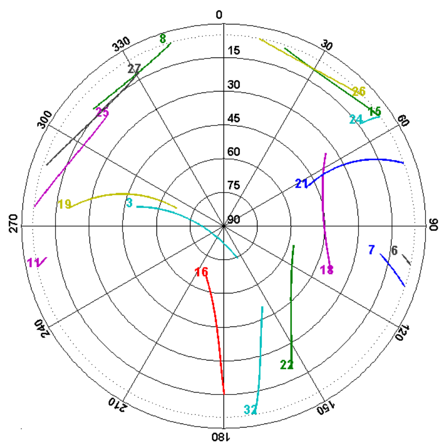


Figure 5.10: Skyplot over Delft, during the materials experiment.

The results of the materials experiment will be presented in relation to the no-plate static solution. In other words, the 30 minute no-plate static solution will be considered the ground truth of the rover station. All other solutions will be given in relation to this point.

Table 5.4 and figure 5.11 shows a comparison of the 3 static solutions. One can clearly see that the HPPC material has no significant effect on the static solution, both the no-plate and the HPPC solution are nearly identical. The carbon fibre solution however, differs significantly, showing that indeed carbon fibre is unfit to be used as a top sheet material. The carbon fibre static position is calculated a full 3.70 metres from the no-plate static ground truth, while the HPPC Static solution differs no more than

2 millimetres. Note that figure 5.11 only shows the position errors in the horizontal plane.

Table 5.4: Static solution performance results.

Position error from ground truth		
	HPPC	Carbon fibre
North position error (m)	0	2.063
East position error (m)	0	0.766
Up position error (m)	0.002	2.973

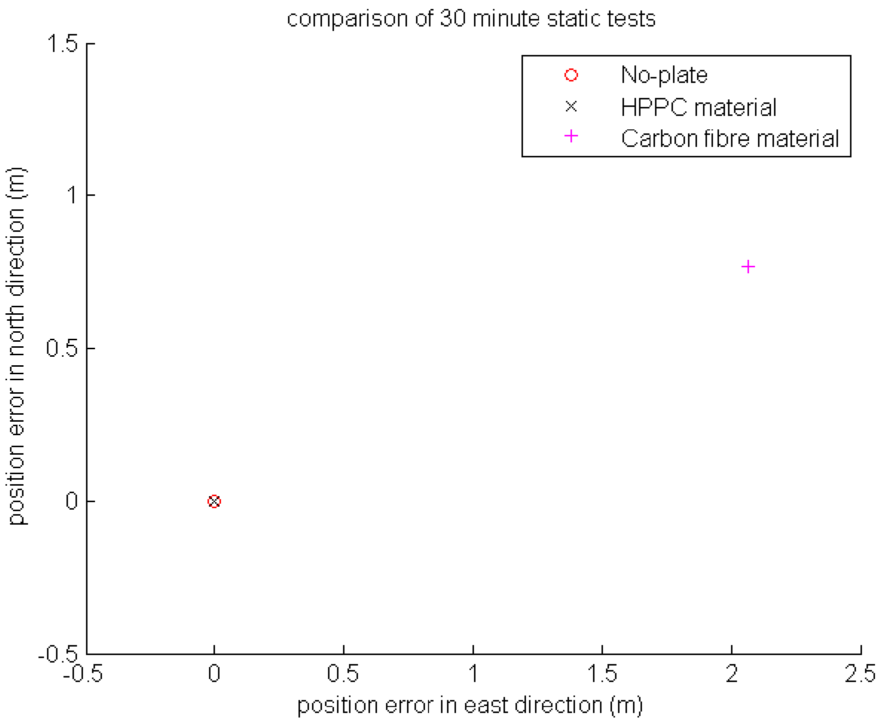


Figure 5.11: Comparison of three, 30 minute, static solutions.

The dynamic solutions predominantly show the same scenario. Figure 5.12a and 5.12b show the point clouds of the dynamic no-plate and HPPC solutions. Once again, these show nearly identical behaviour. This is supported by the standard deviations and 95th percentile values presented in tables 5.5 and 5.6. These values nigh on correspond. This is also supported by a two sample F-test of the two data sets. The test cannot reject the hypothesis that both sets have the same variance at a 5% significance level, for all directions. Please note that the output resolution of the Septentrio receiver is limited to 1 millimetre.

The carbon fibre figures however are again substantially worse, and it is clearly visible that the dynamic solution is influenced by the carbon sheet (figure 5.12c, table 5.5 and 5.6). It is also important to note that only 640 position solutions could be calculated of the approximately 1800 measured epochs. This means that only about 38% of the measurements was good enough to obtain a solution, but generally still far off from the ground truth.

Table 5.5: Dynamic solution performance results, standard deviations.

Standard Deviation			
	North (m)	East (m)	up (m)
No-plate	0.0015	0.0023	0.0046
HPPC	0.0016	0.0024	0.0046
Carbon fibre	1.4485	2.2025	2.2854

Table 5.6: Dynamic solution performance results, 95^{th} percentiles.

95^{th} percentile			
	North (m)	East (m)	up (m)
No-plate	0.0030	0.0040	0.0110
HPPC	0.0030	0.0040	0.0120
Carbon fibre	2.3475	1.6210	2.5580

As a last illustration of the unfitness of the carbon fibre top sheet, two figures are presented for two individual satellites, visible during the complete experiment. The first figure, figure 5.13a, shows the carrier to noise ratio of a high elevation satellite. The second, figure 5.13b, shows the ratio for a descending satellite. The red vertical lines show the three measurement intervals, no-plate, HPPC and carbon fibre. One can clearly see that the behaviour of the carrier to noise ratio does not alter when the HPPC sheet is installed over the antenna. The ratio however, falls dramatically, when the carbon fibre plate is installed. Although some peaks can still be observed during the carbon fibre intervals, the signals remain very weak, furthermore, the peaks can probably be attributed to multipath.

As a conclusion it can be stated that the use of the carbon fibre cover plates is not recommended for use on bays in which GPS antennas are placed. The carbon fibre sheet degrades or blocks the satellite signal to such an extent, that positioning is impossible, or not adhering to the accuracy requirements set in section 5.2. The sheet material would render the GPS system unusable for any practical application in the Superbus. The HPPC material performs much better, and performance results shows almost no deterioration when the antenna is covered by the HPPC sheet. Therefore the use of the HPPC material would be recommended over the carbon fibre top sheet. As a secondary recommendation, after observing the effects of the carbon fibre plate, it is advised that proper static GPS performance testing should be done when the GPS system is installed in the vehicle. This to evaluate the effects of the carbon fibre bays, in which the antennas are installed. These can still inhibit the system to adhere to the performance requirements due to deteriorated signal reception or the high multipath environment (due to the reflection properties of the carbon fibre) within the bays.

Static test, performance

The goal of this experiment is to assess the static performance parameters of the GPS system, as described in 5.3. The parameters relevant for GPS performance are explained in section 5.1, the experimental set-up in section 5.3. Conditions were very good with a normal amount of satellites visible, see figure 5.14

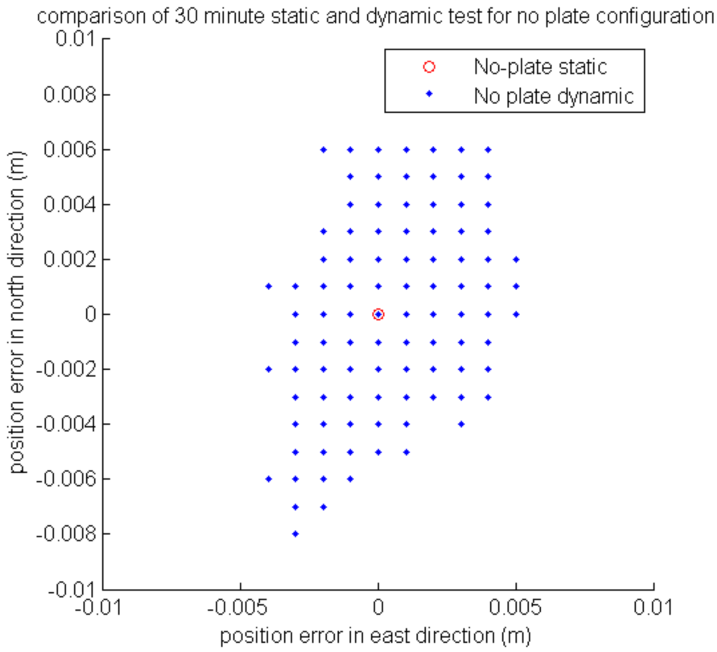
The data consisted of almost 25 minutes of position, heading and pitch solutions, recorded every second. RTK was available and maintained during the complete test of 1490 RTK epochs, resulting in an unsurprising 100% availability. Do note that UMTS, and NTRIP where not used. The 1490 epochs were converted and compared to the known values of the designated points on the NMI building. These known values were gathered in a 1997 measuring campaign. Final results of the raw position data are presented in ETRS89, however relative deviations from the ground truth will be presented here. Also take care in noticing that the results are given in x, y, z coordinates and not in north, east and up.

In the static test the phase difference of the two different Leica antennas was set to $0.0628(m)$. This value was obtained using antenna calibration information available from the National Geodetic Survey at *http://www.ngs.noaa.gov/ANTCAL/*. The phase difference of the L2 signal was used, in preference to the L1 signal due to the fact that Septentrio has indicated that their receivers only initiate an RTK ambiguity resolution in the case a L2 signal is available. However most likely Septentrio uses both L1 and L2 in an integral way for the final position estimate. This has been neglected in this evaluation.

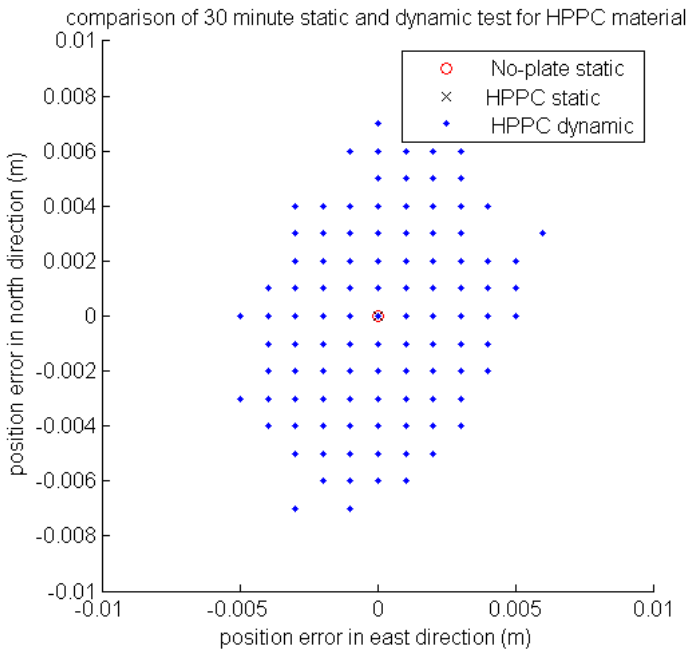
Table 5.7: Static performance results.

position, heading and pitch error RTK fixed			
	Bias	Standard Deviation (1σ)	95th percentile
X position error (m)	-0.0053	0.0043	0.0108
Y position error (m)	-0.0015	0.0018	0.0047
Z position error (m)	-0.0054	0.0035	0.0110
Heading error (deg)	-0.0447	0.0425	0.1105
Pitch error (deg)	-0.0852	0.0660	0.1896

In the table 5.7 basic statistical data of the RTK fixed position error is presented. Bias is obtained by comparing the mean of the data set to the marker point positions, and are supplemented by confidence intervals, marking the region within which the

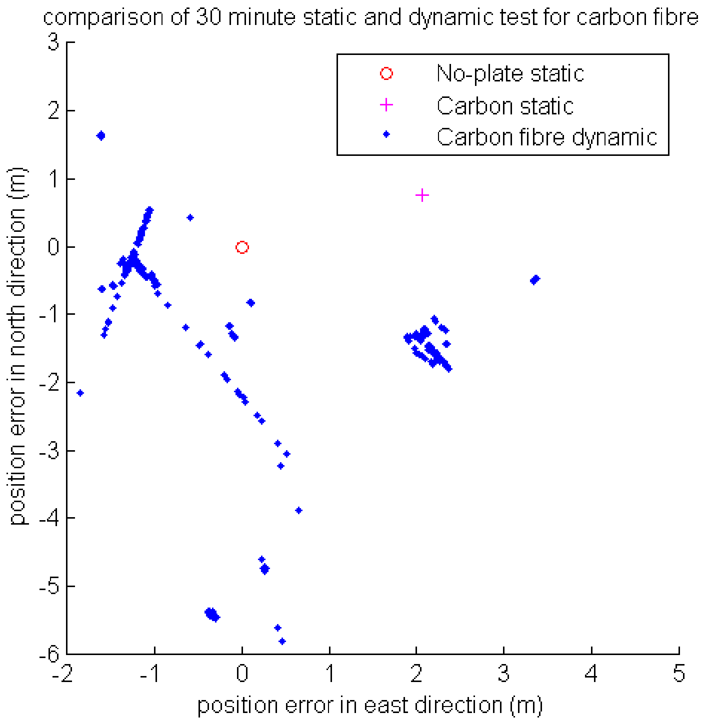


(a) No-plate dynamic solution



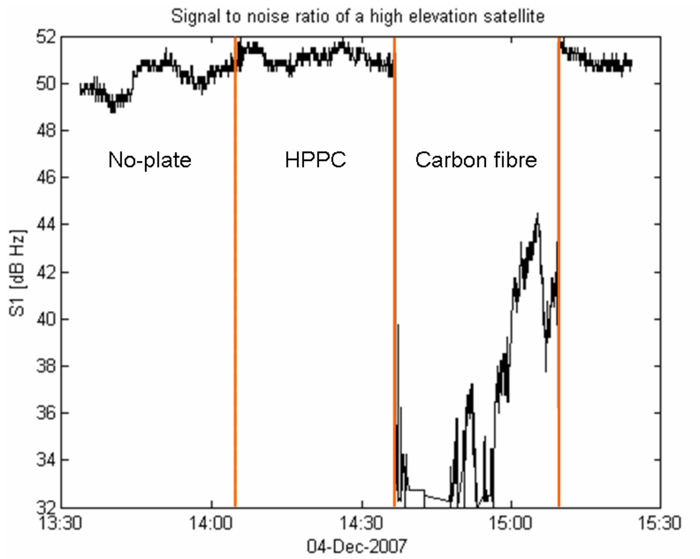
(b) HPPC dynamic solution

Figure 5.12: Comparison of the dynamic solutions.

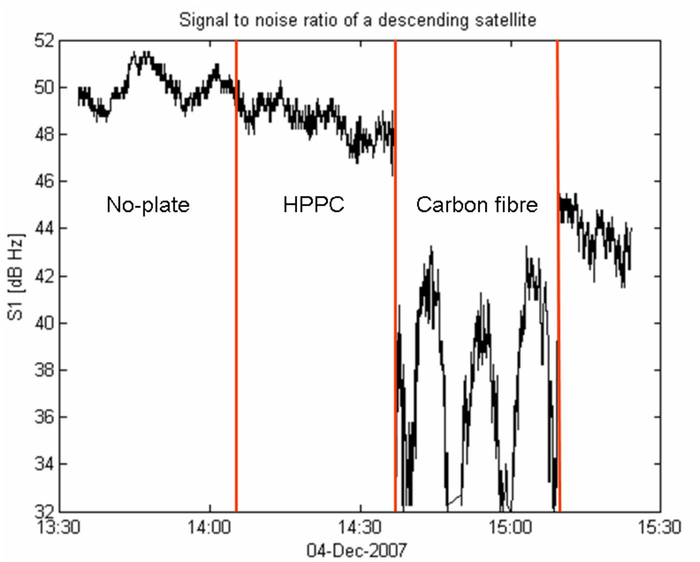


(c) Carbon fibre dynamic solution

Figure 5.12: Comparison of the dynamic solutions.



(a) High elevation satellite



(b) descending satellite

Figure 5.13: C/N_0 (signal strength) ratios of two satellites under three circumstances.

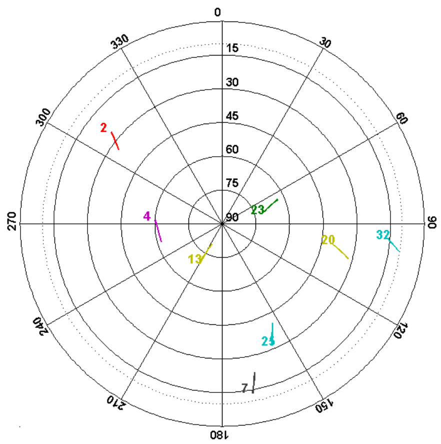


Figure 5.14: Skyplot over Delft, during the static experiment.

true bias falls with 95% certainty. Standard deviations are given as well and are again accompanied by confidence intervals. Finally the 95th percentiles are also given and represent the distance to the median within which 95 percent of position estimations are represented.

The results show complete compliance with both the requirements set by the Superbus, as the information provided by the manufacturer, as provided in section 5.2. The 1σ accuracy values are far smaller the mandatory minimum, showing that the system is theoretically able to provide the necessary precision to be used for applications such as an active suspension, described in section 5.2. The static nature of this test, as well as the close proximity to the base station and the omission of the UMTS connection do provide a basis for optimum results. It does however show the potential of the current set-up.

A t-test of the data revealed that the hypothesis of a zero mean could be rejected at the 5% significance level for both the single antenna position, as for the dual antenna heading and pitch. These biases can be categorised small, as the bias and standard deviation values combined still comply to the requirements. That said, the biases are most likely a result of satellite geometry, for they are not constant in time, as can be seen in figure 5.15. Atmospheric effects should not be present in this very short baseline.

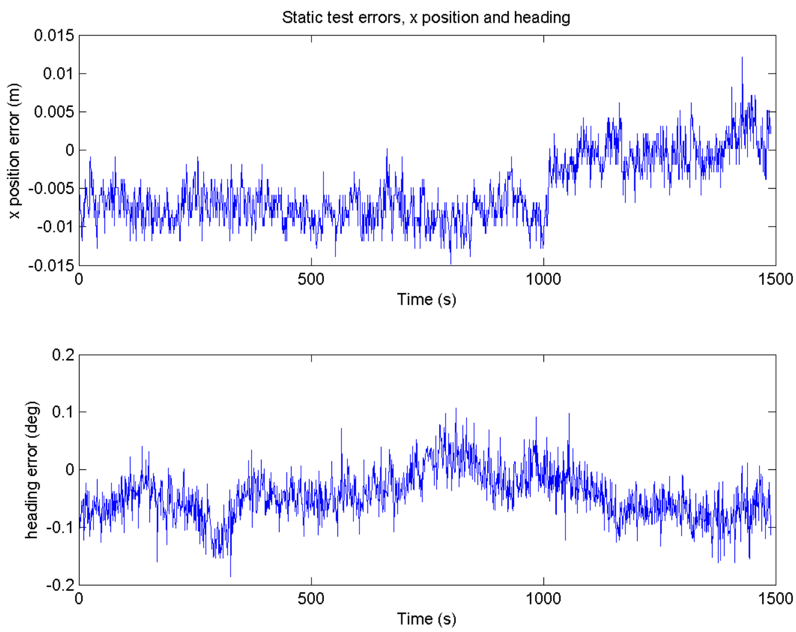


Figure 5.15: X position and heading error over time.

Lastly, a short note is given on the 3D speed estimates of the Septentrio receiver in static condition. As became clear from section 3.6 it can be expected that these estimations are very good under normal circumstances. Indeed this is the case in the static test. A standard deviation of 0.0156 m/s is calculated, and the 95th percentile is 0.0608 m/s. Figure 5.16 shows the errors in speed estimation during the test.

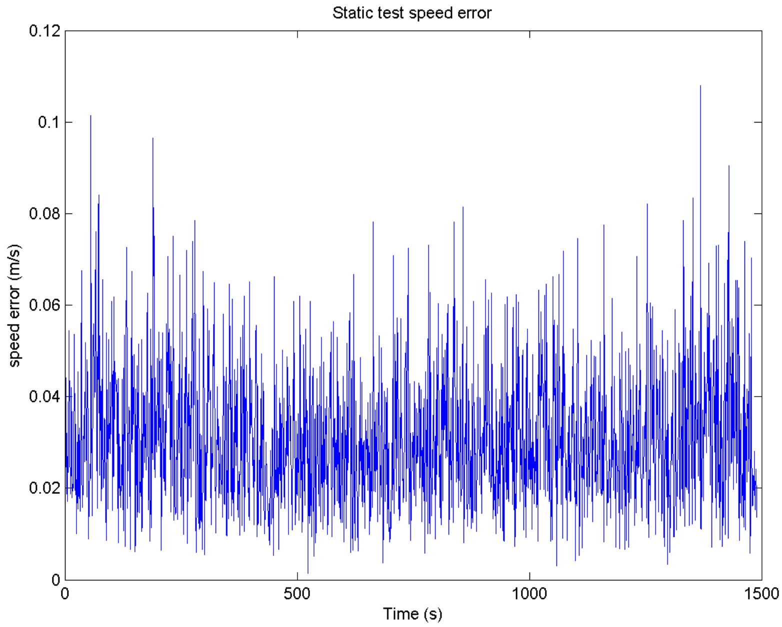


Figure 5.16: Speed error over time.

From this test it can be concluded that in optimal conditions, the GPS system designed for the Superbus will conform to the necessary requirements.

Static test, reacquisition

The goal of this experiment was to gain an understanding of the reacquisition behaviour of the GPS receiver, after a loss of lock of all, or at least a significant number of tracked satellites has occurred. This has been described in 5.3. The parameters relevant for GPS performance are explained in section 5.1, the experimental set-up in section 5.3

The data constitutes 2223 epochs, measured every second, with 56 losses of lock during the test. Availability is not applicable here, since satellites were intentionally blocked. However during the test, the receiver locked up twice, refusing to reacquire an RTK solution, both float or fixed. The receiver was reset and the test was resumed in the same fashion.

The results provided, in table 5.8, are subdivided in the three solution possibilities, stand alone, RTK float and RTK fixed. For all types of solution, the bias, standard

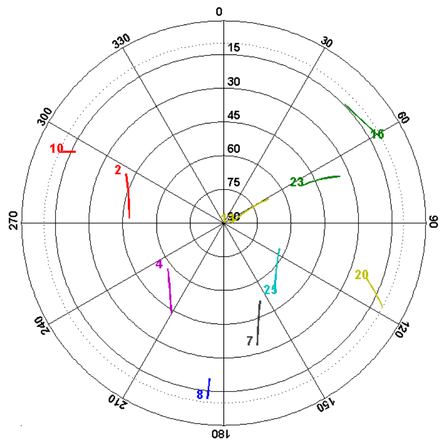


Figure 5.17: Skyplot over Delft, during the reacquisition experiment

deviation and 95 percentile are given. Confidence intervals are supplied where applicable.

During the processing of the test data, it became apparent that the receiver had estimated and fixed the ambiguities incorrectly during one reacquisition cycle. This can be seen clearly in figure 5.18 with a RTK fixed position approximately 2.7 (m) off in x position and about 2.0 (m) in y position. Because of the rather large role this wrong ambiguity fix plays in the statistical variables, the relevant reacquisition iteration has been omitted from the data set to acquire the values in table 5.8.

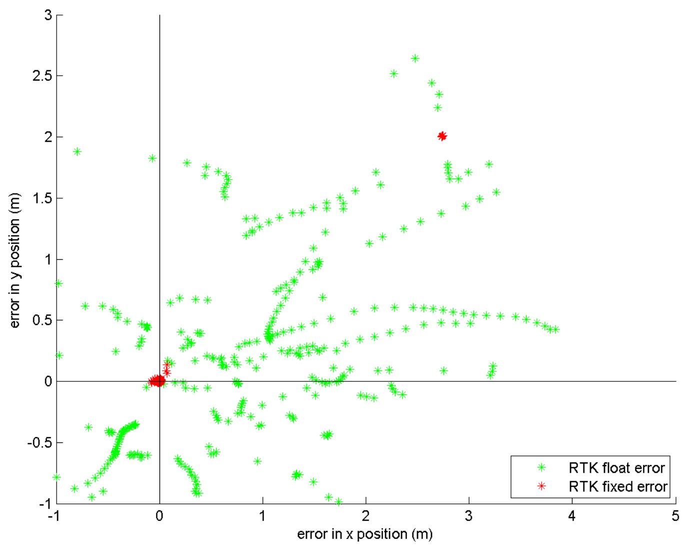


Figure 5.18: Demonstration of incorrect RTK ambiguity fix.

Note that the position solutions are worse than the pure static test, but when an

RTK fixed solution is available, the results are still very good, and compliant to the requirements. The difference is partly misleading and can be partly explained. A deteriorating RTK fix solution is still given, in the few seconds after the signal is being blocked. This is clearly visible in figure 5.20 around the 1900 epoch, where a divergent RTK fixed trail is present before the RTK fix is ultimately lost. For the stand alone and RTK float solutions it can be mentioned that the conditions are the worst possible during the reacquisition procedure, with the receiver trying to reacquire signals whilst simultaneous computing solutions, and shifting to a higher graded solution type, the first moment this is possible. Therefore care should be taken in judging these results, only limited epochs are present, and those present have a higher variance. Confidence intervals are therefore typically larger then in the previous static case.

Table 5.8: Static performance results of the reacquisition test

	Mode	Std dev (1σ)	95th percentile
X position error (m)	stand alone	1.8788	3.5828
	RTK float	1.8714	3.4171
	RTK fixed	0.0097	0.0178
Y position error (m)	stand alone	1.5080	3.1272
	RTK float	0.8030	1.6260
	RTK fixed	0.0074	0.0083
Z position error (m)	stand alone	3.5447	6.9813
	RTK float	2.4743	4.4189
	RTK fixed	0.0139	0.0240
Heading error (deg)	stand alone	10.3119	8.0225
	RTK float	19.0006	40.0303
	RTK fixed	9.3275	30.2785
Pitch error (deg)	stand alone	6.5096	23.7425
	RTK float	35.3474	66.2149
	RTK fixed	16.2679	51.1518

Heading and pitch solutions fare worse, this can be explained twofold. Again the signal reacquisition plays a role, also it is found that the second antenna may not yet have an RTK fixed solution, when the (global) fixed flag is raised within the receiver, see figure 5.19. Note the convergent trails at the 1700 and 1800 epochs (The trail at the 1900 epoch is due to signal blockage). This is invisible for the end user, and gravely influences the statistical results.

The fixing success rate can be calculated in two ways, either scoring the two lock-ups as failures or discarding them from the calculation. In the first case the success rate yields 94.8% $\pm$ 5.7% in the latter 98.2% $\pm$ 3.45%. The 95% confidence intervals accompanying these figures are calculated by equation 5.2, where p is the ratio of failures and N the sample size. Both fixing success rate results have intervals upholding the Septentrio claim of 99%. Note that a 100% fixing success rate will not be possible, measurements are always imperfect, and therefore a small chance of an incorrect fix will always remain.

$$ci = 1.96\sqrt{\frac{p(1-p)}{N}} \tag{5.2}$$

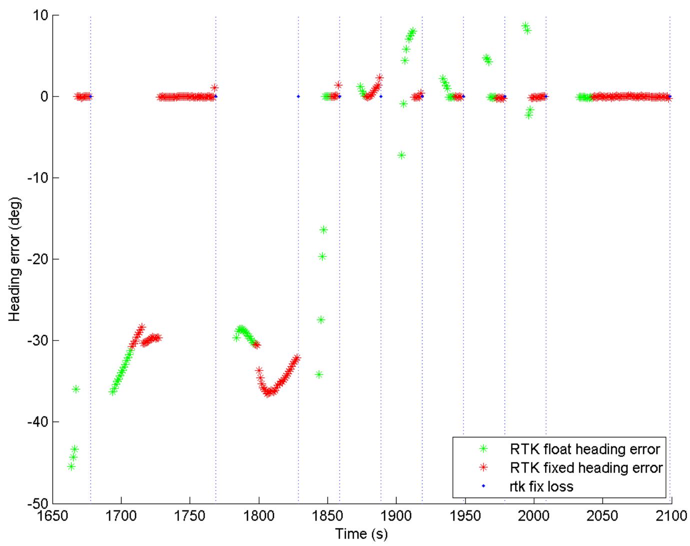


Figure 5.19: Heading error due to unfixed secondary antenna.

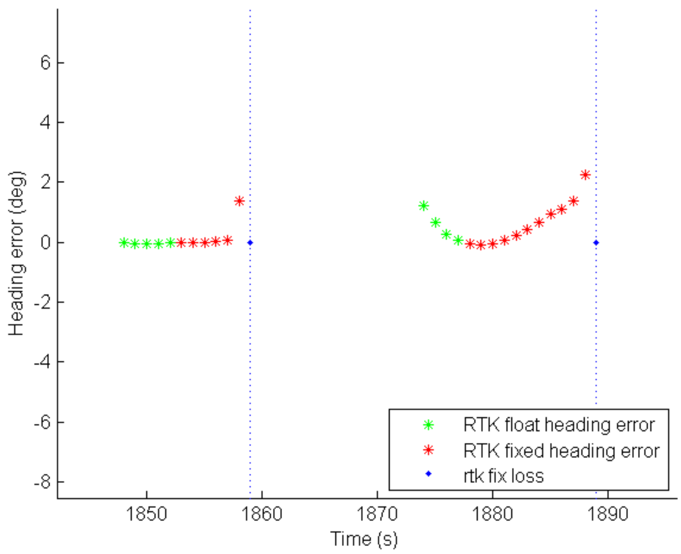


Figure 5.20: Detail: Divergent heading error before loss of RTK.

The results of the reacquisition times are shown in figure 5.21. Here one can see a clear minimum of 19 seconds. A second peak is visible at 24 seconds and a third at 29, which supports the theory that an interval of 5 seconds is maintained to attempt a RTK initialisation. Additionally a clear decreasing trend can be seen in reacquisition times. With such a clear distinction of 5 second intervals, the smaller peaks adjoining the larger ones could be presumed to have the same reacquisition length as the large peak. Figure 5.22 shows the same information, but represented in cumulative percentages. Here one can see that nearly 95% of reacquisitions are within 30 seconds, the mean being 22.73 seconds.

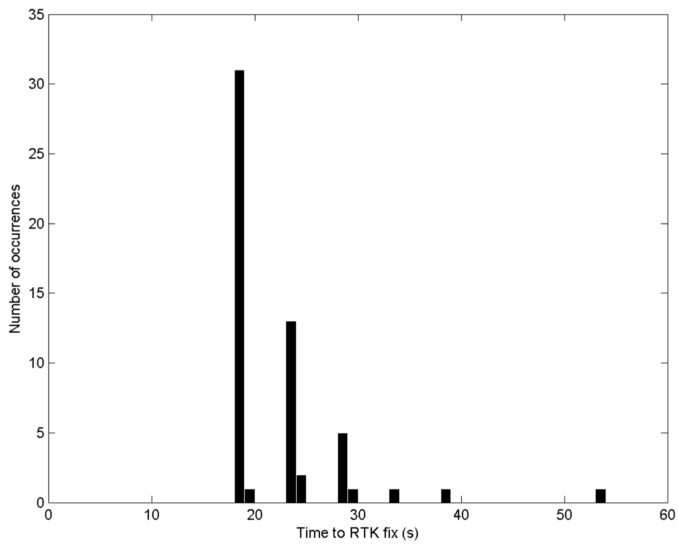


Figure 5.21: Histogram of the reacquisition times. A total of 56 trials

Dynamic test, Duifpolder

The goal of the Duifpolder test was to assess receiver performance in preferred conditions. A large open area with little multipath and ample satellites in view. This test could be used to validate the system performance, additionally it functions as a baseline for the subsequent tests in more challenging environments. This goal could be completed with the obtained data, albeit with some adversities.

Since the Duifpolder is located in the centre of a large rural part between Delft and Rotterdam, UMTS service was erratic. The connection was lost several times during the experiment. In total 3061 epochs were recorded, of which 1333 were RTK fixed. 1701 were stand alone while 27 were RTK float. Float solutions were only used for initialisation, after radio failures. Under normal operation the receiver could maintain an RTK fix solution. Conditions were good and sunny, while the number of satellites in view ranged from 5 to 8. Note that only 15.8 percent of the epochs feature less than 8 satellites, while only 1 percent features less than 7.

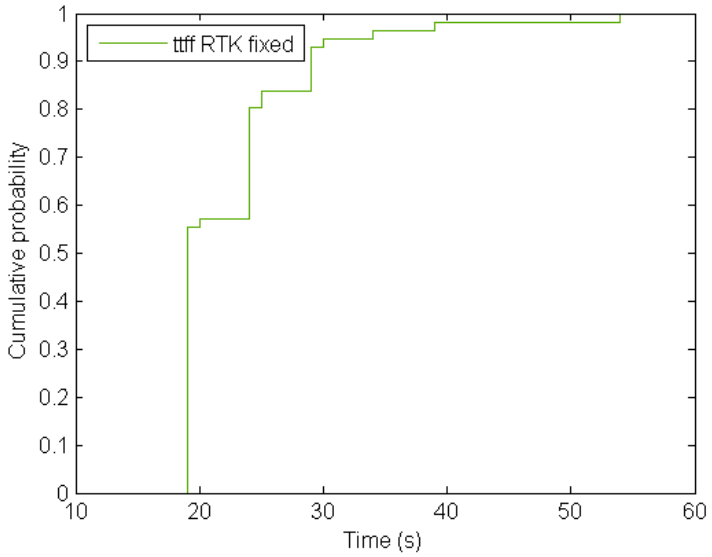


Figure 5.22: Cumulative representation of reacquisition times.

Figure 5.23: Track of the Duifpolder experiment. [source: Google earth]

Although the circumstances were not ideal from the UMTS perspective, the experiment was a success. In part, even *due* to the erratic UMTS reception. In addition to the normal performance figures, obtained with RTK, some additional information could be extracted from the data. Section 5.3 made it clear that it is nigh impossible to obtain a faultless ground truth for a dynamic test, while still maintaining unrestricted mobility. The ground truth is obtained using post processing, and provides precision figures in the order of centimetres. The performance of the Septentrio RTK solution however is judged by comparing post processed observations to the Septentrio obtained RTK solution. Therefore, the performance figures provided in these dynamic test are depen-

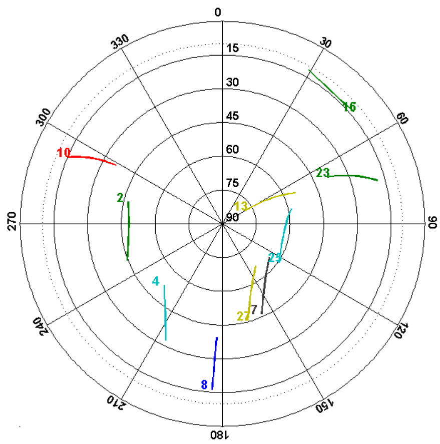


Figure 5.24: Skyplot over Delft, during the Duifpolder experiment.

dent upon the precision of both receivers.

The issue now for the dynamic test is the following: due to the method of performance calculations, it is not possible to quantify the standard deviations of each part of the system individually. In other words, only the effective error between the solutions and the combined standard deviation are available, and we are therefore unable to comment on performance of the Septentrio receiver individually. To clarify: in order simplify calculations, a fixed point on the vehicle was taken as a reference for a local North, East, Up, reference frame conversion. This point, the rear Trimble receiver (Trimble B), was always deemed $[0\,0\,0]$. This allows for an easier creation of the virtual Septentrio position from both Trimble receivers for a moving vehicle, and allows an easier comparison between the two solutions to obtain the effective error. The downside is now that no comments can be given on the individual Trimble and Septentrio standard deviations, since these two are already linked a priori.

Fortunately static observations were a byproduct of the Duifpolder test. The static intermissions between up and down legs *can* provide us with information regarding the individual receivers, and hence can help us to comment on the quality of the obtained results. Below the results of a 100 second static measurement is given for three cases. These three cases will serve as an example to indicate the quality of the results obtained during the kinematic tests.

Table 5.9: Static standard deviations (1σ) for the solutions on the dynamic platform

Standard deviation	North (m)	East (m)	Up (m)
Trimble A	0.0039	0.0035	0.0078
Trimble B	0.0033	0.0030	0.0055
Trimble combined observations	0.0018	0.0013	0.0044

In table 5.9 three sets of standard deviations are given of the 100 second static measurement. For both the first and the second Trimble receivers individually and in addition also the combined standard deviations of the two Trimbles are given. The observations for the latter are obtained by subtracting the difference to the (data set) mean of both Trimble receivers for every epoch, and taking the difference. This is represented in equation 5.3.

$$\underline{z}_i = (\underline{x}_{A,i} - \underline{\hat{\mu}}_A) - (\underline{x}_{B,i} - \underline{\hat{\mu}}_B) \tag{5.3}$$

Now observe that the results of the individual Trimble receivers and the combined observation standard deviation following from 5.3 do not coincide. The standard deviation of the combined observations is actually *smaller* than that of an individual receiver. This is an important result. It shows that the precision of combined observations is better than an individual solution. Now remember that the performance observations for the Septentrio receiver are similarly dependent upon multiple receivers, and the significance becomes apparent. It may well be that the obtained Septentrio performance results may appear better than they actually are.

This in itself is not a problem as long as the results can be explained, and that is indeed the case. If the results from table 5.9 are correct, this means that observations from both Trimble receivers, although independent, are positively correlated. To verify this, we will assess the variance and covariance propagation for linear functions [30]. If the results are indeed correlated, we can comment on the results of the Septentrio as well. The combined Trimble observations are obtained in a simplified but largely analogous way as the Septentrio observations, as explained in 5.3.

Rewriting the right half of equation 5.3 to:

$$\underline{z}_i = \underline{X}_A - \underline{X}_B \tag{5.4}$$

for the north, east and up directions respectively , one can set up the linear system as follows:

$$\underline{z} = M\underline{u} = \begin{bmatrix} 1 & 0 & 0 & -1 & 0 & 0 \\ 0 & 1 & 0 & 0 & -1 & 0 \\ 0 & 0 & 1 & 0 & 0 & -1 \end{bmatrix} \begin{bmatrix} \underline{N}_A \\ \underline{E}_A \\ \underline{U}_A \\ \underline{N}_B \\ \underline{E}_B \\ \underline{U}_B \end{bmatrix} \tag{5.5}$$

Using this, the (a posteriori estimated) covariance matrix for the combined Trimble observations, $\hat{Q}_{zz}$, can be found using the a posteriori estimated covariance matrix of the individual Trimble observations, $\hat{Q}_{uu}$:

$$\hat{Q}_{zz} = M\hat{Q}_{uu}M^T \tag{5.6}$$

$\hat{Q}_{uu}$, is easily estimated by many computational programs from the 100 static observations used for this example. And as expected, it shows a correlation between observations of the two receivers. This is shown below:

$$\hat{Q}_{uu} = \begin{bmatrix} 15.1 & -7.5 & 14.1 & 11.4 & -5.4 & 11.7 \\ -7.5 & 12.2 & -2.3 & -4.5 & 9.6 & -15.4 \\ 14.1 & -22.8 & 60.9 & 8.3 & -17.2 & 35.7 \\ 11.4 & -4.2 & 8.3 & 10.9 & -3.4 & 8.4 \\ -5.4 & 9.6 & -17.2 & -3.4 & 8.7 & -12.2 \\ 11.7 & -15.4 & 35.7 & 8.4 & -12.2 & 30.2 \end{bmatrix} \cdot 10^{-6} \tag{5.7}$$

Consequently obtaining $\hat{Q}_{zz}$ and extracting the standard deviations, one acquires the following results:

It becomes clear that there is indeed a positive correlation between both Trimble receivers that causes the joint observations to be more precise than a single solution. This can be explained by the fact that both solutions are relative solutions and use

Table 5.10: propagated standard deviations of both Trimble receivers

standard devation	North (*m*)	East (*m*)	Up (*m*)
	0.0018	0.0013	0.0044

a base station on top of the NMI building to obtain the centimetre accurate results. Recall the fact that baseline solutions use the temporal and spatial correlation of the ionosphere and tropospheric delays between rover and base station. Now recall that both Trimble receivers use the same base station and are placed close to each other in the field. This means that both Trimble receivers are affected by atmospheric differences between rover and base station in nearly the same way. Both receivers use the same measurements from the base stations, and receive practically the same signals because of their close proximity to each other. Therefore it becomes easy to understand that both baseline solutions are correlated, and hence that the combined observations can be more precise than a single solution: the analogous errors of the both baseline solutions are cancelled out.

Now let's look at the behaviour of the individual Septentrio receiver during this 100 second static period, and to the combined Septentrio-Trimble observations. The standard deviations of both are represented in table 5.11. Once again we see the behaviour that the combined solution is better than the individual solution. Luckily this can be explained now.

Table 5.11: static standard deviations (1σ) for Septentrio and Septentrio-Trimble solutions.

Standard deviation	North (*m*)	East (*m*)	Up (*m*)
Septentrio solution	0.0037	0.0050	0.0072
Septentrio-Trimble combined solution	0.0032	0.0037	0.0065

Now that this behaviour is known we can cautiously comment on the quality of the results of this dynamic test. It is safe to say that the baselines between the vehicle and the NMI building are definitely correlated. The result of this is that a combination of observations, as used to calculate the Septentrio performance, is affected by this. How much this combination of observations is affected is difficult to say because of the static nature of this deduction and the short sample period. It will be dependent, amongst others, on baseline length, atmospheric conditions and receiver type. It seems safe to say that the performance results provided in this section are equal of slightly better in comparison to the individual Septentrio results. Although this might seem a weak deduction, it actually does provide a good qualitative measure considering the stochastic nature of the provided ground truth.

A qualitative base for the dynamic test is now established. But before the actual results are presented it is important to know how these are represented. Although up until now, figures were always represented to 10^{-4} metres, all the following dynamic test results will be presented to 10^{-3}. The main reason for this, is the vehicle antenna platform of section 5.3. This was measured to the millimetre level. Furthermore, although this platform is assumed rigid and flat, the dynamic forces and vibrations during the test, makes precisions to the tenth of a millimetre useless. Additionally the antenna height of the Septentrio base station was only measured to 10^{-3}. Note that this has no influence on the standard deviation figures, yet the 95th percentile results will be influenced.

Another comment on the performance figures involves the height. One might notice these figures are often worse than the other performance figures. This has in part to do with the GPS system in general, which usually has more difficulty providing precise heights. But more importantly the platform did not provide any method of calculating roll angles. Therefore it was assumed flat and local level in the general case: steadily driving on a flat road. Yet this is not always the case, for example at higher speed turns, potholes and road shoulders. Although up-direction performance figures are presented for the dynamic test, it is important to note that these figures are less informative than the remainder of the parameters. This is especially notable in the Duifpolder where the static RTK results mentioned above were obtained on the road shoulder, resulting in a 2 centimetre bias in up direction.

Continuing with a note on the actual figures that are and are not presented in the table. First, the standard deviation figures are 1σ values and are presented accompanied with an interval. This interval represents the 95% confidence interval of the solution. The intervals are obtained by carrying out a variance test on the data. If this interval falls outside the registered precision of the table (below 0.0005), it is represented by 0.000. Secondly the 95th percentile figures are presented. This is usually done for all three solutions types, stand alone, RTK float and RTK fixed. It is decided that biases are not represented in the table. Under normal RTK fix circumstances all these values were very small (10^{-3}), indicating no systemic or methodical errors. This has already been assessed in section 5.4. Any deviation from this norm indication for example a wrong ambiguity fix or high multipath environments will be treated individually, providing more background information.

Lastly note that speed is mentioned nowhere in this table. This is due to the Trimble baseline solution. This solution provides a position solution with a reasonably restrictive 1 Hz update rate. More importantly, velocity is not computed in post processing, resulting in the need to numerically differentiate two separate position solutions to obtain velocity information. This differentiation over a relatively long interval in turn leads to an inevitable decrease in precision with higher accelerations. The slow update rate is less of an issue for heading information since instantaneous information of the two Trimble receivers can be used. Note that specific information on speed accuracy will be given below, but providing the dry figures in the main performance table would paint a misleading picture of the performance.

In Table 5.12 the results for the Duifpolder experiment are given. Consider that RTK was never lost unless the UMTS failed, and that the few available float solutions are only during static initialisation. They are therefore discarded in the table. They do not represent any real aspect of the dynamic precision test.

The table reveals some interesting data. It is easy to see that while in stand alone mode, the position performance goals of section 5.2 are logically not met. A general representation of the position error in relation to PVT Mode can be found in figure 5.25. Yet looking more at the heading yields a more interesting perspective. One can see that the Septentrio receiver provides a heading precision that is far more precise than can be expected from two stand alone positions, and one that is in line with an RTK solution. This is confirmed when looking at the RTK heading figures. These nigh on coincide. Figure 5.26 shows the heading error of the receiver over the entire Duifpolder experiment. Below it, the PVT mode is presented. One can see that the heading error of the Septentrio is irrespective of the PVT mode, precision never decreases when RTK is lost. This is interesting and is caused by the calculation method Septentrio has implemented for the secondary antenna. A small baseline is set up, between the main and the secondary antenna, where the observations of the main antenna are used for an RTK solution of the secondary antenna. This allows for precise heading and pitch data even while in stand alone mode. Note that heading figures do not suffer the same standard deviation uncertainties, as discussed above. Both headings can be compared directly without the need of additional calculations.

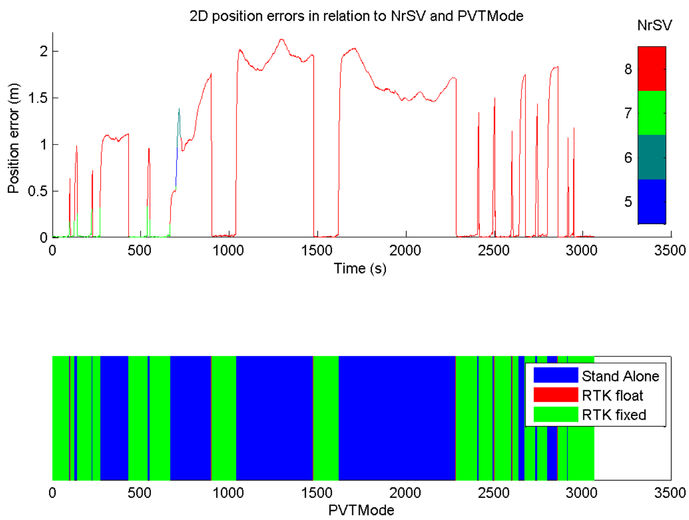


Figure 5.25: Position error in relation to PVT Mode.

The same conservation of precision holds for the speed information. It does not degrade while in stand alone mode. Although this is to be expected in light of section 3.6, confirmation of this is still of importance for Superbus. Looking at figure 5.27 more closely also reveals the reason why speeds are not integrated in table 5.12. This figure shows the difference between the numerically differentiated Trimble velocity,

Table 5.12: Duifpolder Dynamic test results.

Solution	Parameter	North (m)	East (m)	Up (m)	Heading (deg)
Stand Alone	Standard deviation (1σ)	0.449 ± 0.015	0.145 ± 0.005	0.964 ± 0.032	0.097 ± 0.003
	95th percentile	1.995	0.519	2.378	0.217
RTK Fixed	Standard deviation (1σ)	0.010 ± 0.000	0.008 ± 0.000	0.034 ± 0.001	0.095 ± 0.003
	95th percentile	0.020	0.019	0.085	0.181

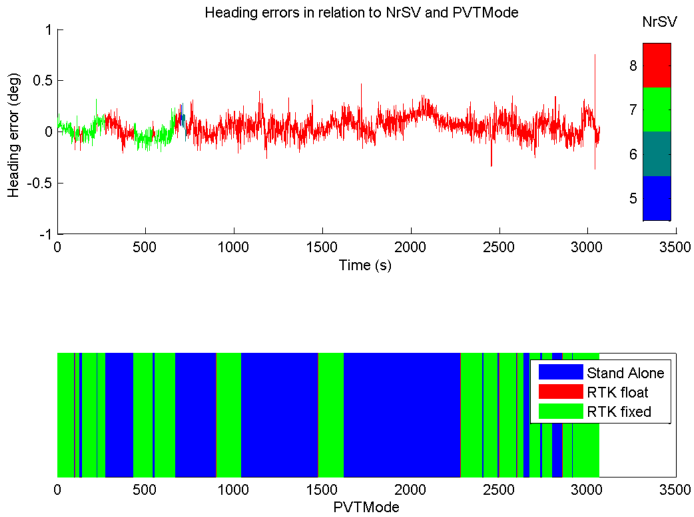


Figure 5.26: Heading error in relation to PVTMode and NrSV.

and the Septentrio velocity output directly. In the figure one can see no obvious discontinuities signalling a precision change when changing PVT Modes, shown in the figure 5.27. Note also the static periods at the 1500 and 2000 second epochs. They show no obvious difference in noise. This is in line with expectations. More interesting to see is the clear sinusoidal nature of the speed error. This is caused by the numerical differentiation introducing a fault in the comparison. The vehicle's continuous acceleration and deceleration show up as errors in opposite directions.

Another observation is presented in figure 5.28. Here one can see an apparent independence between heading error and speed. This again can be explained through the different ways the receiver obtains these figures. The same observation holds between speed and position error, but this is not shown here.

Now that most observations regarding this experiment are made, it is time to return to the core table of 5.12 and comment on how these figures fare against the requirements and manufacturer claims. Logically Stand alone figures do not comply with Superbus requirements. Yet heading performance is excellent and complies completely with the Septentrio claim of 0.10 degrees standard deviation on a baseline of 3 metres. Since the test vehicle baseline was 2.795 metres, performance is in line with manufacturer claims, even when in stand alone mode. Looking at the RTK fixed figures, shows complete compliance with Superbus requirements, even when reserving some uncertainty due to correlation issues.

Although not all epochs of the Duifpolder test were RTK fixed solutions, this is only due to technical issues not related to the GPS receiver. The receiver was able to keep RTK fixed solutions whenever possible and therefore one can conclude that RTK

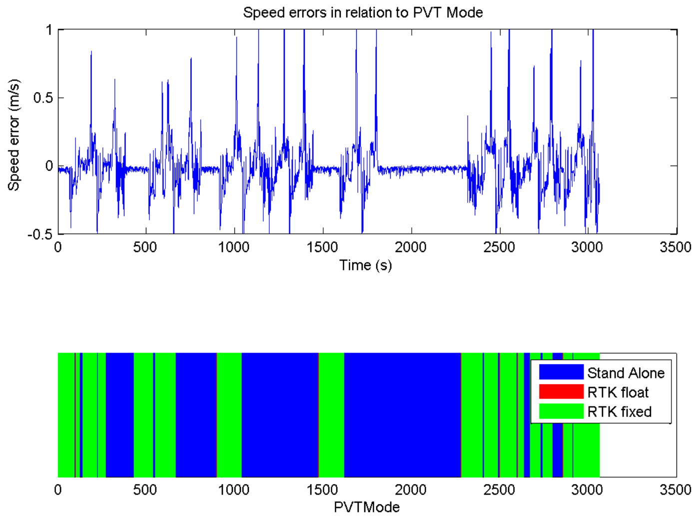


Figure 5.27: Receiver speed comparison of the Duifpolder experiment.

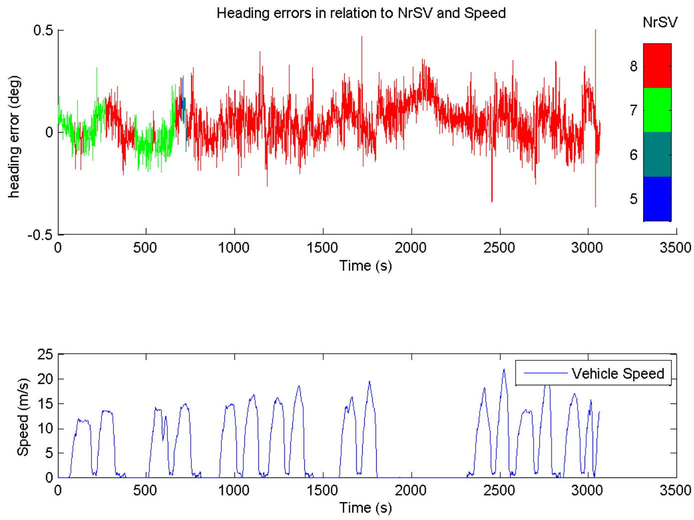


Figure 5.28: Septentrio speed in relation to heading errors.

availability was 100%, when not hindered by technical difficulties. When in RTK fixed mode it becomes clear that 95th percentile figures are very good, and comply with the requirements. Furthermore the standard deviations are in line with manufacturer claims, keeping in mind that the baseline was nearly 7 kilometres. Note that the test conditions, except for UMTS reception, were realistically very good conditions for the Superbus: Straight road, good satellite reception and low multipath conditions. Yet it is an important conclusion that the complete GPS system is able to provide the required performance with ease.

From this section it is easy to conclude that the GPS system as presented in this thesis, is practically capable to provide performance in line or exceeding Superbus requirements in all performance fields. Additionally it is shown that performance is in line with manufacturer specifications. However care should be taken to ensure a functioning data connection. This was visibly the weakest point of the positioning system during this rural test. Heading and speed solutions output by the receiver were observed to have the same precision in both stand alone and RTK fixed solutions. No correlations were found between vehicle speed and heading or position precision. Lastly a positive correlation between the two independent receiver solutions was observed (Trimble and Septentrio). It is shown that it influences the performance figures presented here. The presented results are however approximately in line with the observed performance of the individual Septentrio receiver.

Dynamic test, Emerald

The goal of the Emerald experiment was to evaluate GPS performance in less then ideal circumstances. This urban environment poses worst case conditions during high way travel. This high speed scenario has the most to gain from an high accuracy GPS system, since urban uses will mainly entail standard satellite navigation that can still function properly with decreased accuracy. UMTS conditions were good during the experiment, and the connection remained in operation. The receiver had access to correction data throughout the test. This eliminates an important mitigating factor in the other experiments, where UMTS connections were prone to fail. The receiver could therefore work under the intended conditions from the technical side. This allows for a proper evaluation of the intended GPS system in less then ideal real-world conditions.

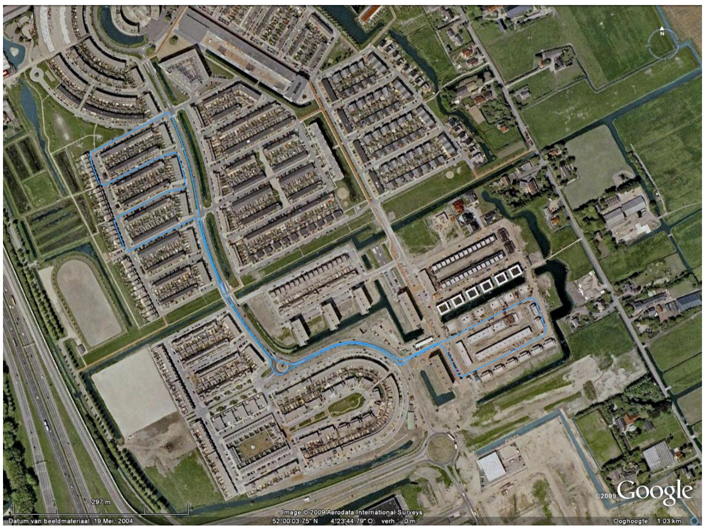


Figure 5.29: Track of the Emerald experiment. [source:Google Earth]

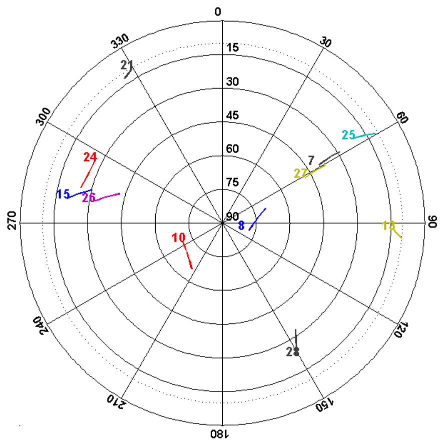


Figure 5.30: Skyplot over Delft, during the Emerald experiment.

Conditions were good and sunny, while the local environment posed normal to high urban multipath conditions. This can be illustrated by the driven track, visible in figure 5.29. The track was chosen to obtain a mix with closed streets, and reasonably open main road. The closed streets inhibit a full aerial view, reducing the number of satellites in view, and introduce large flat surfaces and objects, which can instigate multipath. The main roads have a larger aerial view, although still less than the selected 10 degree cut-off angle, and are less prone to multipath, although some large areas could still interfere. A skyplot of the Emerald during the experiment can be found in figure 5.30.

The obtained data set contains 1438 epochs, with a maximum of 8 satellites in view. 9 epochs in 3 situations did not result in a PVT solution, 81 resulted in a stand alone solution, 99 in a RTK float solution, and finally 1249 resulted in a RTK fixed solution. Note that epochs for which no solution was found, also register that no satellites where in view and occurred in the 'closed street' sections of the track, in the north-west section and the south-east section (while passing a large flat).

The performance figures obtained during the test are interesting, considering the difficult multipath environment and the fact that one third of the epochs (490) have only 6 or less satellites in view, while 174 epochs only have 5 satellites in view. Looking at the first plot (figure 5.31), where the 3D position error is given, the error between the ground truth and the Septentrio track, one notices the relatively poor performance of the solution during the first 1000 seconds of the test even when an RTK fixed solution is available. Initially this is a little over 50 centimetres. It can also be seen that there are 2 distinct breaks in trends, one around 470 seconds where the error drops to about 15 centimetres and one can also be observed around 1130 seconds to nearly zero. The final epochs of the test show a divergence again. The vehicle and system setup remained unchanged during the entire test.

All the observations above give rise to the possibility that the ambiguities were

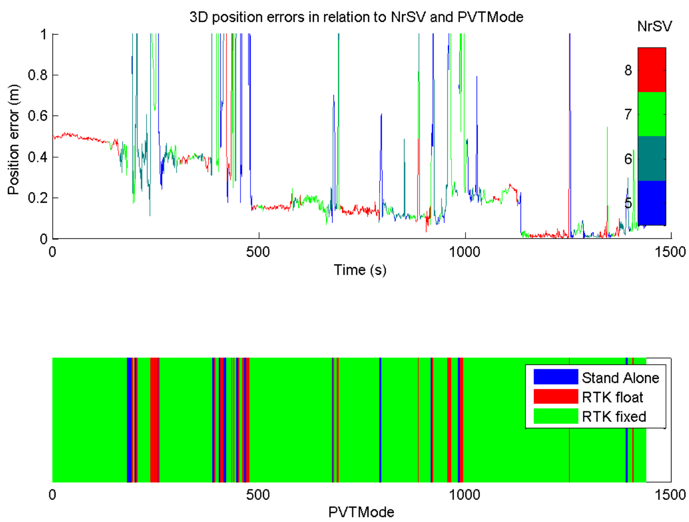


Figure 5.31: Septentrio error to ground truth in relation to the PVT Mode.

fixed incorrectly during the initialisation of the experiment. The Trimble ground truth did not show any discontinuities. The fact that the initialisation was performed statically on a parking adjacent to two large buildings supplies some credibility to this hypothesis of wrong ambiguity fixing. In addition in the final epochs of the test, where the solution starts to diverge again, the vehicle was parked on the same location. Assuming the ambiguities were incorrectly fixed, some interesting behaviour can be deduced from the data. Although it cannot be conclusively stated that the ambiguities were not correct, looking at the distinct convergent behaviour of the data set towards a correct solution, does strongly suggest this.

The data shows that the receiver is quite effective in keeping the satellite ambiguities fixed as long as not all satellites are lost, or just for a very brief time. This can be seen in figure 5.32 where the PVT solution is completely lost, and zero satellites were indicated as in view for 2 epochs. The receiver was able to regain the RTK fixed very quickly, within 5 seconds, without resorting to a complete re-initialisation, and losing precision in only two epochs. Even in the few instants the receiver could not compute a solution, the receiver likely continued tracking several satellites and retained their ambiguities. This behaviour is beneficial for Superbus use, since it will increase the robustness of the RTK solution as well as increase the availability of RTK.

The consequence of this behaviour is that the ambiguities will remain incorrect for a longer period of time in difficult environments, just as can be observed in this test. However, the benefits of a robust RTK algorithm far outweighs the re-initialisation scenario, which has become clear in section 5.4. To alleviate this ambiguity fixing behaviour the RTK algorithm employed by Septentrio clearly does maintain a running

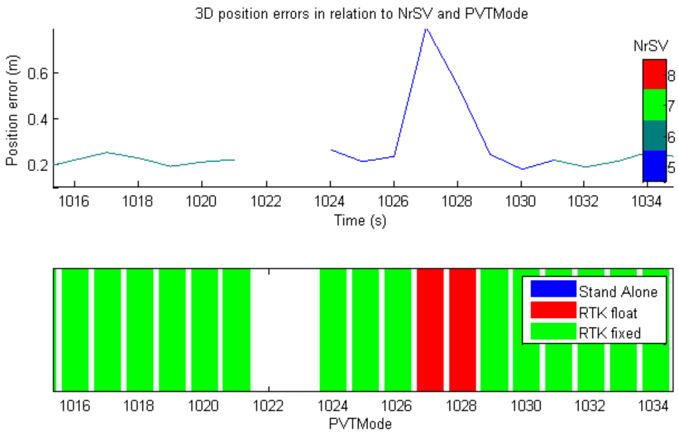


Figure 5.32: Septentrio loss of solution behaviour.

Kalman filter even when ambiguities are fixed, since the solution eventually converges to the right ambiguities, as observed in figure 5.31. If we assume initially incorrect fixed ambiguities, we must then also observe the behaviour where the solution converges, to the correct ambiguities.

The heading error graph of figure 5.33 is also interesting. Even if the ambiguities are incorrect, the heading error resulting from this fact, should be constant. This however is not traceable in the figure. The receiver clearly struggles with the combination of multipath and incorrectly fixed ambiguities, be it from one or both antennas. The error is not constant, and shows quite a large amplitude, unfamiliar for an RTK fixed solution. In some cases when RTK is lost, for example in the 900 to 1000 second interval, the heading errors aggravates even more. This leads to the hypothesis that the receiver has some trouble with the ambiguities for both antennas, due to the multipath. In section 5.4, it has been found that a RTK fixed flag is raised, even if the secondary antenna is not yet fixed. At the same time section 5.4 showed that under proper conditions, the heading error is independent to the PVT Mode. An unfixed secondary antenna could explain the larger noise than usual for an RTK fixed solution (see figure 5.35 when only 5 satellites are visible).

When the receiver has converged to the most accurate solution, from about 1100 seconds into the experiment, it is clear that the heading error values are far better than the previous sections. Here the adverse conditions of the test track are undeniably of significantly less influence. Heading errors stay within expectations, and are far less prone to multipath and reduced satellite visibility, see figure 5.36.

In light of the previous paragraphs it is decided that two sets of performance results are formed. One for the complete duration of the test, and one for the last 300 seconds of the experiment. Indeed the last section of the test shows significantly better results in all aspects, while the test conditions remained the same. The receiver was

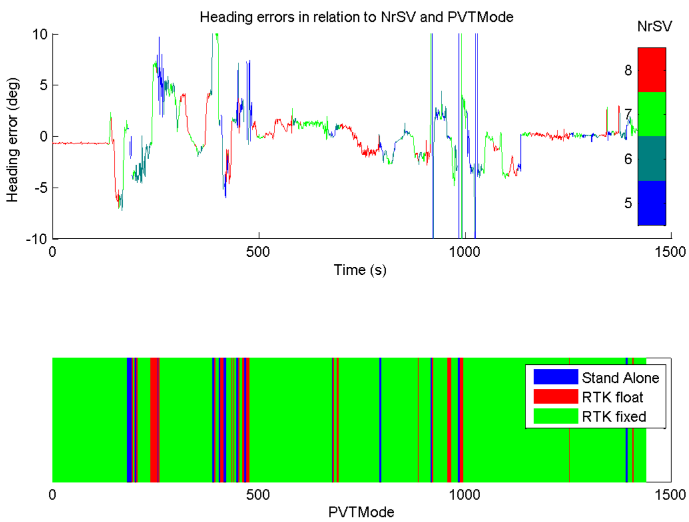


Figure 5.33: Heading error in relation to the NrSV and PVT Mode.

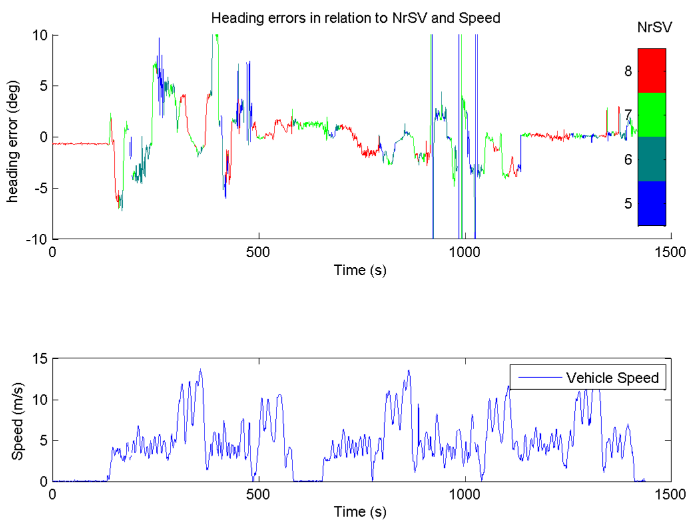


Figure 5.34: Heading error in relation to the NrSV and Velocity.

far less prone to lose RTK fixed, position and heading errors were far better, and especially heading errors were far less susceptible to multipath. Significant performance gains are visible, while: the satellite geometry remains largely the same, the test track remains identical, and the drive speeds are comparable (see figure 5.34). The last 300 seconds are therefore deemed an example of a correctly functioning RTK system in an adverse environment and included in the results. Results of the this 'High Accuracy' section will be given twofold. Once for only the RTK fixed solutions of this sec-

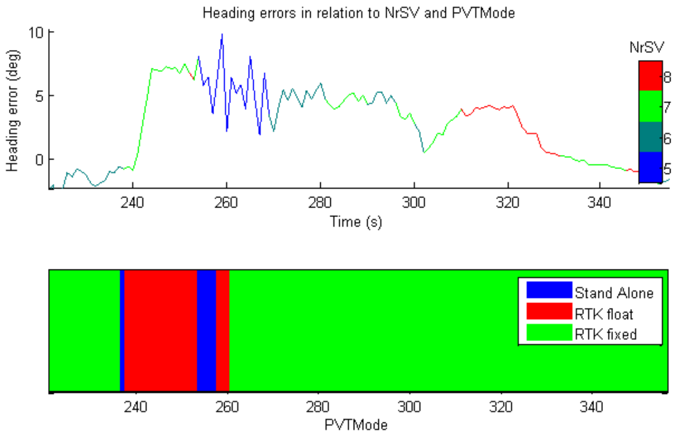


Figure 5.35: Heading error detail, showing dependence to the NrSV.

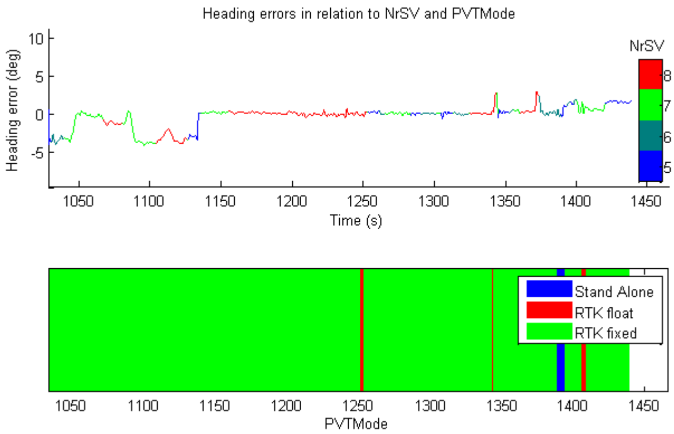


Figure 5.36: Heading error detail, showing dependence to the NrSV.

tion and once for the all solutions combined, Stand Alone, RTK float and RTK fixed. These last results concern the complete technically functioning positioning system, in adverse conditions, without distinction between solutions types. The availability of the RTK fixed solution therefore plays a role in the results. They are therefore included as a benchmark to establish if the system is fit for use in the Superbus.

In tables 5.13 the results of the 2 scenarios are given: the complete test, and the last 300 seconds. One can clearly see that the results are improved for the High Accuracy case. Clearly the high accuracy results comply to the 5 centimetre 95th percentile requirement, with an exception for the height in the total high accuracy scenario. Yet a lower performance can always be expected in the vertical direction. The 95th percentile values of the complete test are certainly worse than the high accuracy part, but when RTK is fixed they are still within decimetre range. This still makes the system useful for high precision navigation at low speeds. It is therefore still fit for use for inner city navigation. This is exactly the scenario where these high multipath conditions present themselves. Yet it may be clear that they are not in compliance to the requirements. The heading figures do not fit the manufacturer claims. Even when ambiguities are fixed, they are approximately a factor 10 higher. This is due to the high multipath situation, looking at the skyplot of the Delft during the test (figure 5.30) reveals rather disastrous conditions, with only 2 satellites above a 45 degree angle. This makes direct contact with most of the satellites difficult in narrow streets, resulting in the potential use of the reflected signals.

Concluding this section, one can confirm that the proposed positioning system still works in though, high multipath, low sky visibility conditions. It has become clear that initialisation of the system should be done with care, in low multipath conditions, to avoid incorrect ambiguity fixing as much as possible. Yet the system showed a relatively good robustness in keeping an RTK fixed position in adverse conditions. Even when RTK was lost, it was regained very quickly without complete reinitialisation. In addition it has been shown that even if ambiguities were not correct, the receiver shows auto correcting behaviour, jumping to ambiguities that better fit the observations. Even though RTK was less precise than the Duifpolder experiment, it still satisfied requirements. Especially interesting to note is the total high accuracy condition. This denotes the last 300 seconds of the test, irrespective of PVT mode. This situation somewhat surprisingly complies to the requirements for north and east directions, and shows the total behaviour during adverse conditions. This is deemed very good. It is noted that system performance in all fields improved once the correct ambiguities were fixed, be it position and heading precisions, or robustness of the RTK fixed solution.

Dynamic test, A4

The goal of the A4 test was to evaluate the receiver performance during short blackouts caused by viaducts and the like. While driving under these underpasses, locks with all available satellites may be lost, causing the need for the reacquisition procedure of the RTK solution. Since the Superbus concept leans on flexibility, a wide range

Table 5.13: Emerald dynamic test results.

Solution	Parameter	North (m)	East (m)	Up (m)	Heading (deg)
Stand Alone	Standard deviation (1σ)	2.140 ± 0.339	0.533 ± 0.084	1.946 ± 0.038	9.356 ± 0.003
	95th percentile	4.800	1.316	4.305	19.568
RTK Float	Standard deviation (1σ)	0.928 ± 0.132	0.344 ± 0.049	1.427 ± 0.204	24.751 ± 3.548
	95th percentile	2.300	0.822	2.059	10.277
RTK Fixed	Standard deviation (1σ)	0,142 ± 0.006	0.038 ± 0.002	0.152 ± 0.006	2.174 ± 0.085
	95th percentile	0.348	0.074	0.347	3.795
High Accuracy, RTK Fixed	Standard deviation (1σ)	0.014 ± 0.001	0.013 ± 0.001	0.031 ± 0.003	0.554 ± 0.046
	95th percentile	0.030	0.036	0.071	1.632
High Accuracy, Total	Standard deviation (1σ)	0.071 ± 0.006	0.044 ± 0.004	0.096 ± 0.008	0.573 ± 0.046
	95th percentile	0.046	0.047	0.081	1.635

of operational theatres may be encountered. Underpasses are omnipresent in Dutch infrastructure and therefore the behaviour in such conditions must be established.

Figure 5.37: Track of the A4 experiment. A Viaduct is present at the bottom of the track, an aqueduct crosses the halfway point of the track. [source: Google earth]

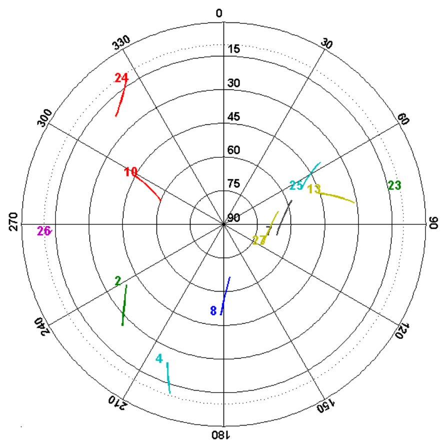


Figure 5.38: Skyplot over Delft, during the A4 experiment.

Although the experiment was successfully concluded, conditions were far from optimal during the test. The UMTS connection failed numerous times and the conditions near the 2 passed viaducts block precious satellites and cause multipath. The test yielded 1983 data points, with a maximum of 8 satellites in view. 1166 epochs were RTK fixed, while 77 were float solutions. 698 epochs were stand alone, although most of these are due to a failing UMTS connection. In addition, not all passes yielded useful data because the lack of corrections prohibited the receiver to return to the RTK fixed solution. 15 reacquisition procedures could be reconstructed from the data, while some failed due to UMTS failure.

One curious anomaly presented itself during the test. At around 1200 seconds the receiver diverted to different ambiguities, while maintaining an RTK fixed solution. This behaviour occurred, not while driving under an underpass, but rather on top of a viaduct, while changing to the southerly leg of the highway track. This resulted in about 45 seconds of PVT solutions with incorrect fixed ambiguities, whereafter the receiver corrected its mistake. The correction itself took 3 seconds, during which the receiver indicated an RTK float solution (See figure 5.39). This behaviour was earlier encountered in section 5.4, yet here unfortunately ambiguities change from correct to incorrect. Note that no epochs noted a loss of all satellites, and no underpass was passed. It is possible that the behaviour is caused by the sidewall of the viaduct, in the 10 to 15 seconds prior to the jump in ambiguities. This wall provides an reasonably homogenous multipath environment during that time. The behaviour again shows that the receiver does not stop searching for better ambiguity fits, even when these ambiguities are fixed to integers. In unfortunate instances, in this case probably the combination of multipath with an emerging satellite, this can lead to a wrong decision. No further unexpected receiver behaviour was found.

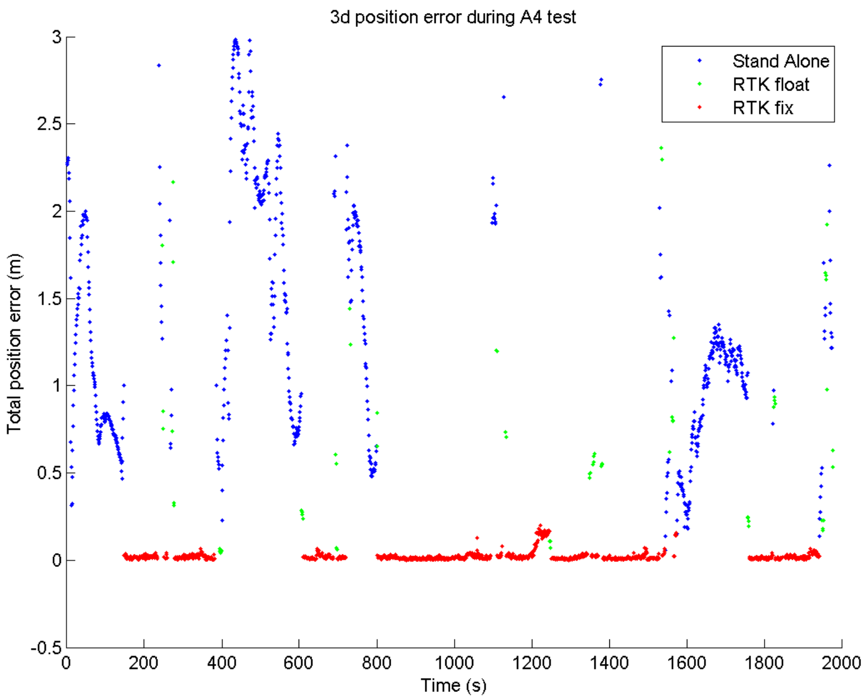


Figure 5.39: Total Position error during A4 with respect to PVT Mode.

Returning to the test results, it once again becomes clear in table 5.14 that the requirements are met for north and east directions, when an RTK fixed solution is present. In up direction is the result approaches requirements very closely. Stand alone and RTK float results are expectedly much worse due to the adverse conditions. That RTK float solutions are worse than in the Emerald experiment can be explained by the fact that needs to recover from a complete satellite black out in a multipath environment, while the receiver could mostly keep track of at least some satellites. This allows the receiver to keep the ambiguities fixed for these satellites and regain an RTK fixed solution faster. In the A4 situation, (almost) all satellites are lost and all ambiguities must be recalculated. Section 5.4 shows that RTK float solutions need to converge coming from a pure stand alone solution. This explains the high standard deviations.

The results of passing the viaducts paint a mixed picture. 40 percent of underpasses were passed without a complete loss of PVT solution. This means that the solution of the next epoch was stand alone, or in one case even RTK float. If the PVT solution was lost, it was restored, on average, within 3.44 seconds. On average it took 11.85 seconds before RTK fixed was restored. This is significantly less than the 22.73 seconds of the static test. This is quite impressive, and possibly due to the fact that not all satellite signals are completely lost in this scenario.

Commenting on the reacquisition behaviour of the receiver during the underpass is difficult. The fact that two underpasses were present relatively close to one another poses additional difficulties for the receiver. The loss of the data connection while driving under these viaducts influences the test even more. This caused some measurements to fail. In total 15 successful results were obtained. The cumulative time to first fix probability figures of the time it takes the receiver to reacquire a fix are presented in figure 5.40.

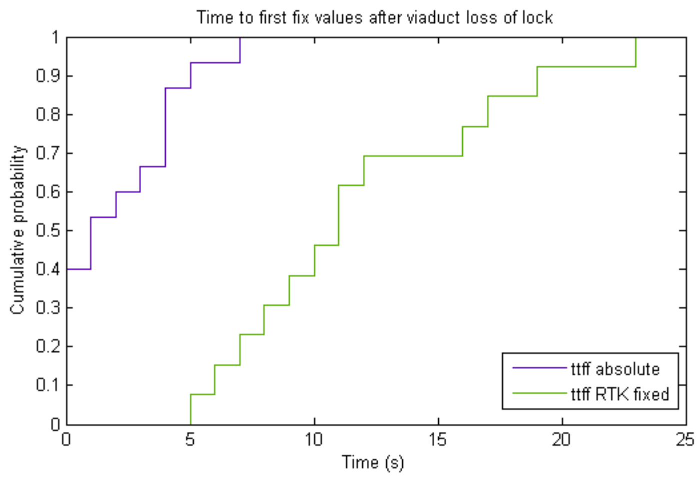


Figure 5.40: Cumulative time to first fix probabilities, absolute and RTK fixed.

Concluding this section is a little more difficult than the previous cases. It can be stated that Superbus performance requirements are met for both horizontal directions. The vertical direction error is only slightly greater than allowed. Standard deviations of the RTK fixed solution are also in compliance with manufacturer specifications.

Table 5.14: A4 dynamic test results.

Solution	Parameter	North (m)	East (m)	Up (m)	Heading (deg)
Stand Alone	Standard deviation (1σ)	0.577 ± 0.030	0.391 ± 0.021	1.254 ± 0.066	43.511 ± 2.372
	95th percentile	1.138	0.827	2.563	13.181
RTK Float	Standard deviation (1σ)	1.592 ± 0.259	0.448 ± 0.073	1.672 ± 0.272	56.195 ± 9.480
	95th percentile	1.137	0.932	4.183	12.668
RTK Fixed	Standard deviation (1σ)	0.013 ± 0.000	0.008 ± 0.000	0.031 ± 0.001	2.674 ± 0.109
	95th percentile	0.020	0.019	0.052	0.238

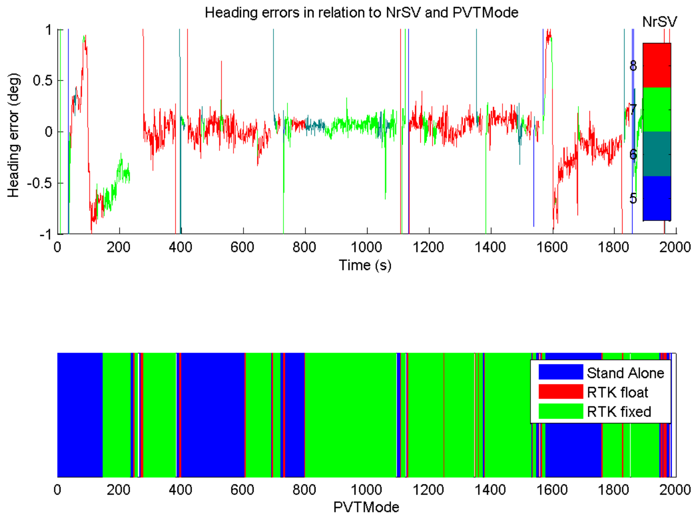


Figure 5.41: Heading errors versus PVT Mode and Number of satellites in view.

Heading figures are much worse and one may question the usefulness. Several large outliers are present in the data, which severely influence the results. Perhaps this is again due to the behaviour of the secondary antenna. A filter applied to the heading estimates may improve the usefulness the results in these conditions, because generally, as figure 5.41 shows, figures are still quite good. This is confirmed by the 95th percentile result for RTK fixed. Reacquisition heading performance after a black out however is unusable and should probably be discarded for some duration after an underpass is encountered. They do not comply with specifications. Again the robustness of the RTK solution is shown around the 1200 second mark (see figure 5.39), albeit this time in a negative way.

Chapter 6

Conclusion

In this report a high accuracy positioning system is investigated, designed and evaluated for use in the Superbus. Requirements for the system were limited but rigid:

> The Superbus Positioning System, must be able to provide *real time*, precise positioning data. Horizontal position error may not exceed more than 5 centimetres in 95% of the obtained solutions.

These requirements only leave augmented positioning as a possibility for the Superbus. This is in itself not a problem, but it does put extra strain on the additional requirement of (quasi)national deployment. Real Time Kinematic (RTK) relative positioning was selected as a valid means to obtain the performance requirements. At the time of writing the alternative, Precise Point Positioning was not robust and fast enough for practical use in the vehicle. The effective area of deployment of RTK can be enlarged sufficiently by using networked base stations and Pseudo Reference Stations PRS. Network Transport of RTCM via Internet Protocol (NTRIP) was the selected method of exchanging the RTCM data, correction data for augmented positioning, over the internet, making the system far more flexible than systems using direct data connections such as mobile radio transceivers. UMTS was selected as the communication system for the correction data. UMTS will allow for soft hand-overs between the land based cells as the vehicle moves, allowing for an uninterrupted data stream to the Superbus. In addition, UMTS is able to accommodate the high cruising speed of the Superbus vehicle.

The GPS system in the vehicle consists of two Antennas, spaced 8.19 metres apart, coupled to one Septentrio PolaRx2eh GPS receiver. The receiver is coupled to a computer receiving the required correction data from any appropriate base station or base station network. Using this set up, manufacturer specified performance figures should be within the Superbus requirements.

Several tests were carried out to evaluate real world performance and to verify the manufacturer specifications, and validate that the system fulfils Superbus requirements.

A materials test was carried out to investigate the effects of cover plating over the antennas. Results showed that Carbon Fibre plating is highly unfit for this purpose, while the alternative, a thermoplastic composite HPPC has no noticeable effect on position estimation.

A static test evaluates the Superbus RTK system, both for static performance, and position reacquisition behaviour after a black out situation. The performance results show complete compliance with both the requirements set by the Superbus, as well as to the information provided by the manufacturer. The reacquisition test was carried out 56 times. During the test the receiver locked up twice, and once estimated the incorrect ambiguities, although the 99% success rate stated by the manufacturer can be upheld. From the observations it can be concluded that the secondary antenna used for pitch and heading, is not necessarily fixed yet, when the receiver indicates a RTK fix solution. 95% of the reacquisition times were shown to be within 30 seconds, with a 19 second minimum, a 54 second maximum and an average of 22.73 seconds.

Three kinematic tests were carried out, assessing real world behaviour on a moving vehicle. The Duifpolder experiment, provided preferred conditions with ample satellites an a low multipath environment. Results showed that Superbus requirements were (logically) not met while in stand alone mode. It must however be noted that heading and speed estimates remained equally precise regardless PVT mode, and compliant to manufacturer specification. In RTK fixed mode, both Superbus requirements, as manufacturer claims were upheld and exceeded by the system.

The goal of the Emerald experiment was to evaluate GPS performance in less then ideal, urban circumstances. The local environment posed normal to high urban multipath conditions. Results showed that the system was able to satisfy requirements and specifications in these conditions as well, although only in the last 300 seconds of the test. The first part showed a large and fluctuating bias (approx. 20 to 50 cm) in the position estimates as well as poor heading solutions, giving rise to the assumption that the system had initialised with incorrect ambiguity estimates. Environmental conditions at the initialisation area may have allowed for this. The test showed that as a consequence the receiver had more difficulty maintaining an RTK fixed solution in the first part of the test, while conditions and track remained the same. Yet the system showed a relatively good robustness in keeping an RTK fixed position in adverse urban conditions when ambiguities are estimated correctly. Even when RTK was lost, it was regained quickly without complete reinitialisation.

Note that conditions were difficult with 46% of the epochs tracking 6 or less satellites, and only 2 or 3 satellite above 45 degrees elevation. It was shown that even if ambiguities were not correct, the receiver showed auto-correcting behaviour, jumping to ambiguities that better fit the observations.

The goal of the last A4 test was to evaluate the receiver performance during short black-outs in real world conditions, caused infrastructure such as underpasses. Conditions were far from optimal during the test. The UMTS connection failed numerous times and the conditions (large noise barrier) near the 2 passed viaducts block precious satellites and cause multipath. 15 scenarios could be reconstructed from the data. In 40 percent of these cases, underpasses were passed without a complete loss of PVT solution. This means that the solution of the next epoch was stand alone, or in one case even RTK float. If the PVT solution was lost, it was restored, on average, within 3.44 seconds. On average it took 11.85 seconds before RTK fixed was restored

Concluding the A4 test is difficult because of the difficult testing conditions, but it can be stated that Superbus performance requirements are met for both horizontal directions in RTK fixed mode. The vertical position error is only slightly larger than allowed. Standard deviations of the RTK fixed solution are also in compliance with manufacturer specifications. This a surprising, but good result. Heading figures are not in accordance to the specifications. Yet 95th percentile figures are still low at 0.238 degrees with RTK fixed, showing that this performance may be improved by applying a filter to the results. Reacquisition heading results are however best avoided for some time after a black out.

As a result of the testcampaigns, it can be concluded that the Superbus GPS system, as it is described it this report, can fulfil all Superbus requirements. Additionally, specifications of the manufacturer are deemed realistic and attainable. It can be concluded that the results are good when UMTS is available, even in adverse conditions, making it potentially fit for use in real world conditions.

Chapter 7

Discussion and Recommendations

The conclusion showed that the Superbus GPS system, designed in this report, is able adhere to all Superbus requirements. This does however not mean that this is unconditionally so. This, together with other observations and recommendations, will be discussed here.

First the boundary conditions of the GPS system will be clarified:

- The Superbus GPS System only fulfils all requirements with an RTK fixed solution
- A loss of RTK fixed solution can occur in adverse conditions
- Reinitialisation will take time, and incorrect ambiguity fixing can occur (in adverse conditions)
- UMTS reception is crucial for the Superbus GPS System
- Antenna placement can have a great impact on performance and system robustness

Since the availability of the necessary high accuracy RTK estimates is completely dependent on the UMTS connection, it is crucial that this connection is operational. In any other case, the estimates from the receiver will not be meaningfully better than any low-cost receiver, and hence not adhere to Superbus requirements, except for speed and heading estimates.

UMTS reception however has been an issue during testing. Connection issues were observed and should therefore be investigated further. Although low cost UMTS equipment was used, and antenna placement was not optimal, it remains an important issue. Additional testing should verify connection availability and functionality in high speed conditions and poor reception areas. Additionally, some form or auto-reconnect scheme should be employed in the case of a lost connection.

During (high accuracy) operation, care should be taken in using the computed estimates in critical situations as multipath (both urban and large homogeneous multipath conditions such as sounds walls) has been shown to impact estimates. It can be recommended that alarm limit (HAL and VAL) values are defined depending on the actual positioning requirements in various situations. The receiver supports RAIM and the use of these alarm limits, and can give timely warning when the accuracy of the computed solutions cannot be guaranteed to be within these limits.

RTK robustness, and position estimate integrity are very important when using the GPS system for critical systems. Therefore, as a precaution, it can be recommended that RTK initialisation is performed in low multipath conditions as much as possible. It is shown in testing that in the event of incorrect ambiguity fixes, the position estimates *will* slowly converge to the ground truth, indicating a movement to the correct integer ambiguities. It is also made plausible that the robustness of the system and system performance is worse in these conditions, hence the recommendation for a low multipath RTK initialisation. Although difficult to test unambiguously, it may be recommended to further test the receiver during high multipath conditions and establish if the receiver indeed performs worse if ambiguities are incorrectly fixed, and to evaluate the convergent behaviour that was observed during the Emerald test. As an added measure to minimise wrong ambiguity resolution and multipath, one might in the future investigate the use of a database of visibility levels or useful elevation angles on much travelled routes and urban areas. Such a database is relatively easy to obtain [45]. The database can warn drivers to adverse conditions depending on location, or perhaps eventually, the use of the information can be integrated in the GPS receiver itself, filtering out or weighting satellites depending on elevation angle, azimuth and vehicle location.

Further recommendations regarding the receiver, aimed more directly to the manufacturer, include a warning flag, indicating an unfixed secondary or tertiary antenna. The behaviour which is found now, where it is unknown to the user whether or not the heading and pitch estimates are RTK fixed, float or stand alone, may be dangerous and undesirable. Furthermore, a locked up receiver as witnessed during the reacquisition test, is not acceptable for Superbus use, as it takes several minutes to reboot the receiver and reestablish a RTK fixed estimate. Although the lock ups occurred during torture testing, and were not observed during the kinematic tests, it may be advisable to test the underpass interruption scenario more thoroughly to evaluate and understand the behaviour of the receiver better under these conditions. Perhaps a clear strategy can be devised on what receiver information may and may not be used in the moments after an interruption.

Lastly some general recommendations. It may be important to stress the potential benefits of the GPS system during initial testing. The high performance nature of the GPS system and the controlled conditions available at a test track give the possibility of detailed and precise vehicle path reconstruction and can help to observe and establish the behaviour of the vehicle in both normal and abnormal conditions. The availability of attitude information at 10 Hz (course over ground, heading and pitch) can also be valuable information. Braking and suspension behaviour may be assessed using pitch data and it may be advantageous to explore the limits of the vehicle grip and assess behaviour during emergency situations.

It is also good to realise that possibilities of the UMTS system in the Superbus exceeds that of the GPS system alone. It enables the development of other systems such as fleet management systems or other online location based services.

Finally some practical notes regarding the use of the GPS system as it is installed in the Superbest now. First it is important to feed the antenna position of the secondary antenna (w.r.t. the main antenna) in the receiver. This can aid time to first fix values, and decrease the probability of a wrong ambiguity fix for this antenna. Secondly it is important to evaluate the elevation cut-off angle. It can be important to change this value, depending on the conditions that are present in the roof sections where the antennas are installed. Lastly it is important to note that the use of the standard NMEA messages may prohibit the use of centimetre accurate output. It can be beneficial to use the SBF format instead, which can provide additional information as well.

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Acronyms

C/A	Coarse Acquisition code
CDMA	Code division multiple access
COTS	Commercial-Of-The-Shelf
CRC	Cyclic Redundancy Check
DoD	Department of Defense
EDGE	Enhanced Data Rates for GSM Evolution
FDMA	Frequency Division Multiple Access
FMS	Fleet Management System
GMSK	Gaussian minimum-shift keying
GNSS	Global Navigation Satellite System
GPRS	General Packet Radio Service
GPS	Global Positionint System
GPST	GPS Time
GSM	Global System for Mobile Communication
HAL	Horizontal Alarm Limit
HDOP	Horizontal Dilution of Precision
HERL	Horizontal External Reliability Level
HPPC	High Performance thermoPlastic Composite
ICAO	International Civil Aviation Organization
IGS	International GNSS Service
INS	Inertial Navigation System
L1	1575.42 MHz GPS satellite signal
L2	1227.60 MHz GPS satellite signal
LAMBDA	Least-squares AMBiguity Decorrelation Adjustment method

LBS	Location Based Services
MDB	Minimal Detectable Bias
MGP	Mathematical Geodesy and Positioning group
NGS	National Geodetic Survey
NMEA	The National Marine Electronics Association
NMI	Nederlands MeetInstituut
NrSV	Number of Satellites in View
NTRIP	Networked Transport of RTCM via Internet Protocol
P(Y)	Encrypted precision code
PDOP	Position Dilution of Precision
Pfa	Probability of false alarm
Pmd	Probability of missed detection
ppm	Parts per million
PPP	Precise Point Positioning
PRN	Pseudo Random Noise
PRS	Pseudo Reference Station
PVT	Position, Velocity, Time
RAIM	Receiver Autonomous Integrity Monitoring
RDW	RijksDienst Wegverkeer
RF	Radio Frequency
RINEX	Receiver Independent Exchange Format
RL	Reliability Level
RTCM	Radio Technical Commission for Maritime services
RTK	Real Time Kinematic
SBAS	Satellite Based Augmentation System
SBF	Septentrio Binary Format
SPS	Standard Positioning Service
TDMA	Time division multiple access
TDOP	Time Dilution of Precision
TNO	Nederlandse organisatie voor Toegepast-Natuurwetenschappelijk Onderzoek
TOW	Time Of Week
UHF	Ultra High Frequency
UMTS	Universal Mobile Telecommunications System
UTC	Universal Time, Coordinated
VAL	Vertical Alarm Limit
VERL	Vertical External Reliability Level

VHF	Very High Frequency
VRS	Virtual Reference Station

Appendices

Appendix A

Septentrio PolaRx2e Specifications

Septentrio
satellite navigation

PolaRx2e@ / PolaRx2eH

The PolaRx2eH and PolaRx2e@ are the new generation Heading and Multi-antenna receivers in the PolaRx2 platform. Implemented on a single Euro-card size board, the receivers address a wide range of precise heading or attitude positioning and navigation applications in fields like machine guidance, marine surveying and photogrammetry. Designed for tough field conditions, the PolaRx2eH and PolaRx2e@ are built around Septentrio's advanced GNSS chipset and offer high quality, high update rate positioning, heading, pitch and role information.

Precise Heading and Attitude at 10 Hz

The PolaRx2eH and PolaRx2e@ receivers bring the quality and flexibility of the PolaRx2 platform, and output with high accuracy, the position and velocity at update rates of up to 10 Hz to the field of heading and attitude based applications.
The PolaRx2eH heading receiver is the latest variant in the PolaRx2e family and can be connected to 2 dual-frequency antennas to output accurate heading & pitch or heading & roll information. Its high precision and compact form design make the PolaRx2eH perfectly suitable for machine guidance solutions in agriculture and construction, as well as in marine surveying.
The PolaRx2e@ on the other hand, collects and outputs GPS data from up to 3 antennas simultaneously (heading, pitch and roll). It can also output relative positioning of 2 or 3 antennas, which can be used for steering an independently moving part, such as for agricultural and towed equipment. As such, the PolaRx2e@ forms a perfect solution for attitude determination and other multi-antenna applications

Unique Single-Board platform

PolaRx2eH and PolaRx2e@ are implemented on a single Euro-card size board. This lightweight and compact form design, together with flexibility and affordability bring important improvements to traditional GNSS-based heading and attitude applications, whilst conjunctively opening the door for new types of applications. They can be combined with RTK positioning on the same board, offering a unique combination of high precision positioning and attitude solutions.

PolaRx2eH can be connected to 2 dual-frequency antennas whereas PolaRx2e@ can be connected to up to 3 antennas, of which the main antenna can be dual-frequency while the auxiliary antennas are single-frequency. Both receiver types have 48 hardware channels, which can be flexibly assigned to track satellites in single or dual-frequency on 1, 2 or 3 antennas in parallel (i.e. without antenna multiplexing).
One or more channels can also track the L1 signal of up to 6 SBAS satellites. Next to rigid antenna set-ups, the receivers can also be used in situations where the relative positions of the antennas are not fixed. The receiver will then calculate and output relative positions precisely.

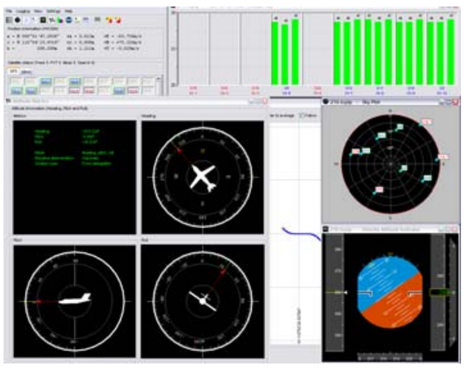
Superior GNSS technology platform

The precise accuracies and update rates available in PolaRx2eH and PolaRx2e@ receiver are made possible through the same high quality architecture used in all products of the PolaRx2 platform: it is built around Septentrio's GreFE front-end and GreCo GPS/SBAS baseband processor chips. Very low-noise Doppler measurements are the key to exceptionally precise velocities and position accuracies.

Both variants have the high tracking sensitivity and stability of phase tracking of all Septentrio receivers, allowing users to track more satellites for a longer period of time, even under adverse conditions. The receivers also incorporate Septentrio's mitigation technique APME, unique in its ability to tackle short-delay multipath.

Flexible Integration Options

The PolaRx2e Heading and Attitude variants are available as a standard Euro - card size board, ensuring easy integration. For ready-to-use solutions, they come in a waterproof IP65 rugged enclosure with sturdy connectors, allowing usage in tough and remote environments. The enclosed receiver offers 4 serial ports, a possibility of 256MB non-removable Compact Flash memory card and Ethernet access. New features include logging control via push button or external signals and programmable LEDs.
The intuitive Graphical User Interface program, RxControl, accompanies the variants. RxControl can be used with the receivers for configuration, for logging and remote control and includes advanced visualization possibilities. Possible data output formats are the industry standard NMEA format as well as a compact Septentrio owned binary format.



PolaRx2eH/@ Technical Specifications

Features

- 48 hardware channels for "all in view" GPS+SBAS parallel tracking
- All channels configurable to track satellites in single or dual-frequency on 1, 2 or 3 antennas in parallel (i.e. without antenna multiplexing)
- Dual frequency L1/L2 code/carrier tracking
- Includes SBAS channels (EGNOS, WAAS, other)
- Raw data output (code, carrier, SBAS navigation data)
- Up to 10 Hz raw measurement, position and attitude output rate (user selectable)
- Automatic or manual antenna calibration
- A Posteriori Multipath Estimator technique (APME)
- Differential GPS (rover)
- x PPS output (x = 1, 2, 5, 10)
- 10 MHz reference input / output
- RAIM module included
- Four bi-directional serial ports (RS232), baudrate up to 115 kbps
- NMEA v2.30 output
- Highly compact and detailed Septentrio Binary Format (SBF) output
- 6 LEDs for power, logging, LAN link, Multi-purpose, tracking status and position fix identification
- Start and stop Data output/Logging on Event
- Compact single-board Euro card solution
- OEM board or mounted in IP65 waterproof enclosure
- Sturdy connectors
- Includes intuitive GUI (RxControl) and detailed operating and installation manual

Options

- Differential GPS base station
- RTK (main antenna)
    - RTCM v2.2, 2.3 or 3.0 input/output
    - Reference Network compatible (FKP)
    - CMR 2.0
- 2 Event markers
- On Board Logging (non removable Compact Flash Memory Card)
- Programmable LEDs
- TCP/IP over Ethernet

Performance

Position accuracy[1,2]

	Horizontal[3]	Vertical[3]
Standalone	1.1 m	1.9 m
SBAS	0.7 m	1.2 m
DGPS	0.6 m	1.1 m
RTK[4,5]	1 cm + 1 ppm	2 cm + 2 ppm

Velocity Accuracy[1,2]

	Horizontal[3]	Vertical[3]
Standalone	1.5 mm/sec	1,9 mm/sec

Attitude Accuracy[1,2,14,16]

1 m antenna separation	
Heading	0.3°
Pitch/Roll	0.6°
3 m antenna separation	
Heading	0.1°
Pitch/Roll	0.2°
10 m antenna separation	
Heading	0.03°
Pitch/Roll	0.06°

Auxiliary Antenna positions[15]	0.6 mm
Maximum Update rate	10 Hz
Latency	< 50 msec
1 PPS accuracy[1,2]	10 nsec

Measurement precision[1,3,6]

C/A pseudoranges[7]	0.15 m (GPS)[8]
	0.30 m (GPS)[9]
	0.35 m (SBAS)
P1/P2 pseudoranges[7]	0.1 m
L1 carrier phase	0.2 mm
L2 carrier phase	1 mm
L1/L2 doppler	2.5 mHz (0.5 mm/sec)

Time to first fix

Cold start[10]		< 90 sec
Warm start[11]	After power-on	< 55 sec
	After reset	< 20 sec
Re-acquisition		< 2 sec
Time to first heading/attitude output		45 sec

Tracking performance (C/N_0 threshold)[12,13]

Code phase tracking	19 dB-Hz
Carrier phase tracking	26 dB-Hz
Acquisition	33 dB-Hz
Acceleration	4 g
Jerk	3 g/sec

1 1 Hz measurement rate
2 Performance depends on environmental conditions
3 1σ level
4 Fixed ambiguities
5 Baseline < 20 km
6 C/N_0 = 45 dB-Hz
7 non-smoothed
8 Multipath mitigation disabled
9 Multipath mitigation enabled
10 No information available (no almanacs, no approximate position)
11 Almanacs and approximate position known, no ephemeris known
12 95%
13 Max speed 515 m/sec, max altitude 18 000 m
14 Attitude accuracy increases linearly with antenna separation
15 No multipath
16 PolaRx2eH only Heading and Pitch

Physical and Environmental

Size	160 x 100 x 13 mm (OEM board)
	285 x 140 x 37 mm (In housing)
Weight	120 g (OEM board)
	930 g (In housing)
Input voltage	5 VDC ± 5% (OEM board)
	9-30 VDC (In housing)
Antenna LNA Power Output	
Output voltage	+ 5VDC
Maximum current	200 mA
Power consumption	5 W typical, 7W max
Operating temperature	-30 to +70 °C
Storage temperature	-40 to +85 °C
Humidity	5% to 95% (non condensing)
Connectors	
Antenna	TNC female
10 MHz in	BNC female
PPS out	BNC female
OEM board	
Backplane	DIN 41612 type B, 64 pins male
Extension	(consult Septentrio)
Housing	
Power	ODU 3 pins female
COM1	ODU 7 pins female
COM2	ODU 7 pins female
OUT/COM3&4	ODU 5 pins female
IN	ODU 7 pins female
Ethernet	ODU 4 pins female

PolaRx2e Family : Other Products

PolaRx2e and PolaRx2e_OEM – PolaRx2e is a versatile dual-frequency GNSS receiver platform for high-end applications. Based on code and carrier tracking of the L1 and L2 signals, it provides the user with satellite range measurements and position, velocity and time.

PolaRx2e_SBAS – The single-frequency variant tracks up to 6 SBAS augmentation satellites (such as EGNOS and WAAS) in addition to GPS satellites, offering vital integrity information for application in safety-critical environments.

PolaRx2C – The PolaRx2C can track up to 4 satellites in L2C mode. For these satellites, the CA, P1, P2 and L2C measurements are available simultaneously.

PolaNt – A lightweight precise positioning and survey single or dual-frequency antenna for use with PolaRx family.

RxControl - RxControl is an intuitive user interface to configure and control all types of PolaRx receivers and monitor, log and post data remotely.

RxMobile - A unique intuitive, portable GUI field controller for the PolaRx receivers. RxMobile allows controlling the receiver, monitoring the navigation solution and accessing its functions in the field in the same intuitive way as with RxControl.

SSNDS 03/2006/2

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Appendix B

Septentrio PolaNt Specifications

Septentrio
satellite navigation

PolaNt

PolaNt is a lightweight high precision geodetic dual-frequency antenna for use with the PolaRx2 family of high performance dual-frequency GNSS receivers. This high-gain antenna incorporates low-noise amplifiers, and is built into a rugged and environmentally sealed housing.

Performance

Frequency		1227 ± 10 MHz
		1575 ± 10 MHz
Polarization		RHCP
Axial Ratio		3dB max
Radiation Coverage		
	4.0 dBic	$\theta = 0^\circ$
	-1.0 dBic	$0^\circ < \theta < 75^\circ$
	-2.5 dBic	$75^\circ \leq \theta < 80^\circ$
	-4.5 dBic	$80^\circ \leq \theta < 85^\circ$
	-7.5 dBic	$\theta = 90^\circ$
Amplifier		
Gain		38 ± 2 dB
Noise Figure		2.5 dB max
Input Voltage		+ 5 to +18 VDC
Current		50 mA (typ)
Impedance		50 Ω
VSWR		≤ 2.0:1
Band Rejection		35 dB @ 1675 MHz

Physical and Environmental

Finish	Weatherable polymer
Weight	≈ 425 gr
Diameter	178 mm
Connector	TNCF
Altitude	≤ 6 000 m (20 000 ft)
Temperature	-40°C to +70°C

PolaRx2 Family : Other Products

PolaRx2 and PolaRx2OEM - PolaRx2 is a versatile dual frequency GNSS receiver platform for high-end applications. Based on code and carrier tracking of the L1 and L2 signals, it provides the user with satellite range measurements and position, velocity and time.

PolaRx2 SBAS - PolaRx2 SBAS can track up to 6 SBAS augmentation satellites (such as EGNOS and WAAS) in addition to GPS satellites, increasing the accuracy of the position and offering your application vital integrity information increasing the confidence in the position solution for application in safety-critical environments.

PolaRx2@ - PolaRx2@ is a unique single-board dual frequency receiver that can be connected to up to 3 antennas, bringing heading/attitude and other multi-antenna applications within economic and practical reach.

PolaRx2TR - PolaRx2TR (Timing/Reference) combines world-class performance in terms of measurement noise, sensitivity and tracking stability with user-oriented features such as Ethernet communication. PolaRx2TR also provides specific GPS timing functions (1PPS in and out).

RxControl - RxControl is an intuitive user interface to configure and control all types of PolaRx2 receivers and monitor, log and post data remotely.

Appendix C

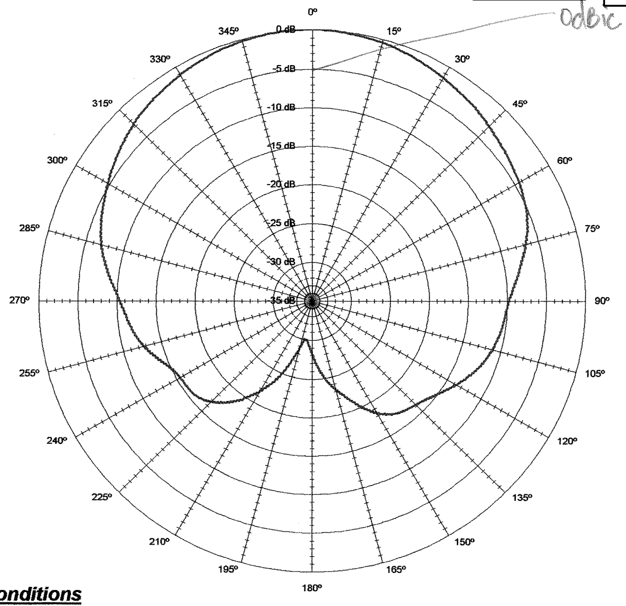
Antenna radiation pattern

AAT Antenna Performance Report

Test Information

Date	2/16/2007
Tested By	D.B.
Antenna	At2775-42

AeroAntenna Technology, Inc.



AeroAntenna Technology, Inc.

Test Conditions

Test Frequency	1575.42 MHz
Variable Angle	Elevation
Constant Angle	Azimuth

Discussion

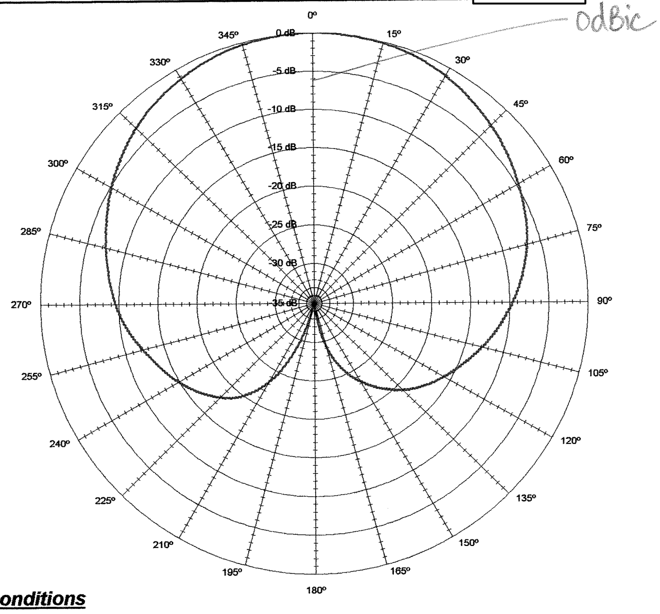
Gain @ Boresight = + 5.0dBic

AAT Antenna Performance Report

Test Information

Date	2/16/2007
Tested By	D.B.
Antenna	At2775-42

AeroAntenna Technology, Inc.



AeroAntenna Technology, Inc.

Test Conditions

Test Frequency	1227.6 MHz
Variable Angle	Elevation
Constant Angle	Azimuth

Discussion

Gain @ Boresight = + 6.0dBic

Appendix D

Example output Position Module

lat	lon	alt	vn	ve	vu	gndspd	cog
52.05846169	4.36053914	-7.056	0.001	0.043	-0.045	0.222	-20000000000
52.05846173	4.36053918	-7.067	0.061	0.028	-0.041	0.283	-20000000000
52.05846177	4.36053919	-7.07	0.038	-0.026	-0.002	0.164	-20000000000
52.05846179	4.36053921	-7.064	0.017	0.021	0.054	0.215	-20000000000
52.05846179	4.36053921	-7.064	0.017	0.021	0.054	0.215	-20000000000
52.05846207	4.36053922	-7.16	0.028	0.044	0.104	0.419	-20000000000
52.05846207	4.36053934	-7.143	-0.015	0.09	0.149	0.63	12.05
52.05846206	4.36053942	-7.131	-0.006	0.018	0.16	0.581	-20000000000
52.05846205	4.36053938	-7.143	-0.045	-0.01	-0.031	0.2	-20000000000
52.05846203	4.36053935	-7.142	0.001	-0.046	0.025	0.189	-20000000000
52.05846203	4.36053939	-7.12	0.039	0.033	0.169	0.635	-20000000000
52.05846206	4.36053931	-7.135	-0.007	-0.07	-0.031	0.276	-20000000000
52.05846205	4.36053927	-7.137	-0.02	-0.004	-0.016	0.093	-20000000000
52.05846201	4.36053924	-7.15	-0.083	-0.036	-0.091	0.463	350.086
52.05846195	4.36053922	-7.157	-0.033	-0.01	-0.053	0.228	-20000000000
52.05846194	4.3605393	-7.14	0.042	0.046	0.128	0.511	-20000000000
52.05846196	4.36053933	-7.134	-0.002	-0.004	0.118	0.424	-20000000000
52.05846196	4.36053926	-7.15	-0.049	-0.026	-0.068	0.316	-20000000000
52.05846194	4.36053931	-7.135	0.049	0.017	0.09	0.373	-20000000000
52.05846196	4.36053929	-7.143	-0.026	-0.016	0.022	0.137	-20000000000
52.05846193	4.36053932	-7.14	-0.045	0.049	0.088	0.398	-20000000000
52.05846188	4.36053935	-7.125	-0.013	-0.047	0.105	0.417	-20000000000
52.05846188	4.3605393	-7.119	0.02	-0.027	0.098	0.371	-20000000000
52.05846191	4.36053928	-7.111	0.034	-0.01	0.138	0.514	-20000000000
52.05846191	4.36053923	-7.127	-0.079	-0.007	-0.066	0.373	200.489

NrSv	PVTer	PVTMo	av corr-age	pdop	tdop	hdop	vdop
6	0	1	65535	534	399	184	501
6	0	1	65535	534	399	184	501
6	0	1	65535	534	399	184	501
6	0	1	65535	534	399	184	501
6	0	1	65535	534	399	184	501
6	0	1	65535	534	400	184	501
6	0	1	65535	534	400	184	501
6	0	1	65535	534	400	184	501
6	0	1	65535	534	400	184	501
6	0	1	65535	534	400	184	501
6	0	1	65535	534	400	184	501
6	0	1	65535	534	400	184	501
6	0	1	65535	534	400	184	501
6	0	1	65535	534	400	184	501
6	0	1	65535	534	400	184	501
6	0	1	65535	534	400	184	502
6	0	1	65535	534	400	184	502
6	0	1	65535	534	400	184	502
6	0	1	65535	534	400	184	502
6	0	1	65535	534	400	184	502
6	0	1	65535	534	400	184	502
6	0	1	65535	535	400	184	502
6	0	1	65535	535	400	184	502
6	0	1	65535	535	400	184	502
6	0	1	65535	535	400	184	502

TOW	year	month	day	hour	min	sec	Int
243752100	9	8	11	19	42	17	0
243752200	9	8	11	19	42	17	0
243752300	9	8	11	19	42	17	0
243752400	9	8	11	19	42	17	0
243752400	9	8	11	19	42	17	0
243753400	9	8	11	19	42	17	0
243753500	9	8	11	19	42	17	0
243753600	9	8	11	19	42	17	0
243753700	9	8	11	19	42	17	0
243753800	9	8	11	19	42	17	0
243753900	9	8	11	19	42	17	0
243754000	9	8	11	19	42	17	0
243754100	9	8	11	19	42	19	0
243754200	9	8	11	19	42	19	0
243754300	9	8	11	19	42	19	0
243754400	9	8	11	19	42	19	0
243754500	9	8	11	19	42	19	0
243754600	9	8	11	19	42	19	0
243754700	9	8	11	19	42	19	0
243754800	9	8	11	19	42	19	0
243754900	9	8	11	19	42	19	0
243755100	9	8	11	19	42	20	0
243755200	9	8	11	19	42	20	0
243755300	9	8	11	19	42	20	0
243755400	9	8	11	19	42	20	0

herl-p	verl-p	herl-v	verl-p	disbase	heading	pitch	ageoflastcorr
0.278393	0.236439	0.528551	0.799737	-20000000000	-20000000000	-20000000000	0
0.278428	0.236447	0.52855	0.799731	-20000000000	-20000000000	-20000000000	-20000000000
0.278443	0.236459	0.528548	0.799725	-20000000000	-20000000000	-20000000000	-20000000000
0.278469	0.236469	0.528547	0.799718	-20000000000	-20000000000	-20000000000	-20000000000
0.278469	0.236469	0.528547	0.799718	-20000000000	-20000000000	-20000000000	-20000000000
0.277942	0.236397	0.528534	0.799655	-20000000000	-20000000000	-20000000000	-20000000000
0.277901	0.236376	0.528532	0.799648	-20000000000	-20000000000	-20000000000	-20000000000
0.277858	0.236355	0.528531	0.799642	-20000000000	-20000000000	-20000000000	-20000000000
0.277876	0.236339	0.52853	0.799635	-20000000000	-20000000000	-20000000000	-20000000000
0.277858	0.23632	0.528528	0.799629	-20000000000	-20000000000	-20000000000	-20000000000
0.277772	0.236299	0.528527	0.799622	-20000000000	-20000000000	-20000000000	-20000000000
0.277696	0.236276	0.528526	0.799616	-20000000000	-20000000000	-20000000000	-20000000000
0.277699	0.236252	0.528524	0.799609	-20000000000	-20000000000	-20000000000	0
0.277715	0.236234	0.528523	0.799603	-20000000000	-20000000000	-20000000000	-20000000000
0.277834	0.236221	0.528522	0.799596	-20000000000	-20000000000	-20000000000	-20000000000
0.277921	0.236206	0.52852	0.79959	-20000000000	-20000000000	-20000000000	-20000000000
0.277856	0.236187	0.528519	0.799583	-20000000000	-20000000000	-20000000000	-20000000000
0.27789	0.236164	0.528518	0.799577	-20000000000	-20000000000	-20000000000	-20000000000
0.277906	0.23615	0.528516	0.79957	-20000000000	-20000000000	-20000000000	-20000000000
0.277931	0.236145	0.528515	0.799564	-20000000000	-20000000000	-20000000000	-20000000000
0.277884	0.23613	0.528514	0.799557	-20000000000	-20000000000	-20000000000	-20000000000
0.277788	0.236105	0.528511	0.799544	-20000000000	-20000000000	-20000000000	0
0.277653	0.236078	0.52851	0.799538	-20000000000	-20000000000	-20000000000	-20000000000
0.277684	0.236052	0.528508	0.799531	-20000000000	-20000000000	-20000000000	-20000000000
0.277656	0.236027	0.528507	0.799524	-20000000000	-20000000000	-20000000000	-20000000000

Appendix E

Angular velocity precision estimation

To obtain angular velocities from the Doppler speed calculations of a two antenna receiver, one would get a situation as in figure E.1. The following assumptions are made in the scenario. First the receiver is able to output Doppler speeds for both antennas and secondly, the centre of rotation is assumed on an arbitrary point between the 2 antennas. In this way, since the baseline of the two antennas is fixed, the angular velocities can be calculated by establishing the relative speed between the two.

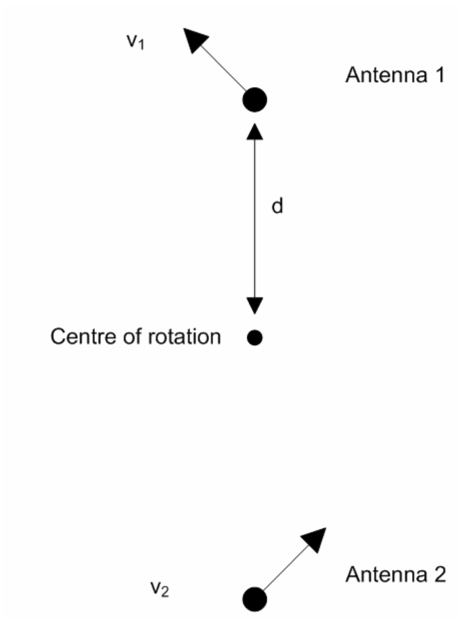


Figure E.1: Angular velocities as experienced by the Superbus.

Septentrio supplies horizontal velocity accuracy values of 1.5 (mm/s) in horizontal direction (1σ at $1Hz$ output rate). To get the rotational speed around the centre of rotation, when the vehicle endures both translational as rotational speeds, one must subtract the two velocity vectors from each other. Since the antenna baseline is fixed, this will only leave the rotational velocity. However, both velocity vectors have a standard deviation. If we assume no correlation between the two standard deviations, the resulting combined standard deviation (1σ) of the angular velocities will be approximately 2.12(mm/s). This is shown in equation (E.1).

$$\sigma_c = \sqrt{(\sigma_1)^2 + (\sigma_2)^2} = 2.12(mm/s) \tag{E.1}$$

With the distance from antenna to centre of rotation estimated at 4.1 metres, this will give a standard deviation for rotational velocity of 0.0304 (deg/s). One can see in equation (E.2) that the distance to the antenna (d), is a variable, and can be adapted to prevailing conditions.

$$\sigma_{\dot{\Psi}} = \frac{\sigma_c}{d} = \frac{0.00212}{4.1} = 5.2 \cdot 10^{-4}(rad/s) \tag{E.2}$$