Photogrammetric Week '11 Dieter Fritsch (Ed.) Wichmann/VDE Verlag, Belin & Offenbach, 2011

Online GNSS Data Processing – Status and Future Developments

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ABSTRACT

The paper presents methods for online GNSS data processing which enable users to enhance the GNSS position accuracy in real-time. This enhancement is achieved by using not only the own GNSS receiver measurements but also auxiliary data like reference station measurements or precise ephemeris. By combining the obtained auxiliary data with the GNSS measurements a user can significantly improve the general positioning performance. Due to this performance improvement it is possible to assess in real-time if an application like aerial imaging meets the requirements.

1. INTRODUCTION

Over the last 30 years satellite navigation has evolved from the pure military-use GPS system to the current multi-constellation GNSS. During this process many civil applications have been developed and the general availability and accuracy have increased significantly. The reason why GNSS measurements usually have only meter level accuracy is given by the fact that several error sources are included within the measurement process. These error sources are comprised of modeling errors like inaccurate broadcast ephemeris or measurement errors due to local multipath effects. As the calculation of the user position therefore is based on biased GNSS measurements the accuracy is degraded. Naturally, to increase the GNSS positioning performance and reliability error corrections have to be applied.

Nowadays several possibilities exist to enhance the GNSS position performance up to decimeter or even centimeter level in real-time. The paper starts with a general description of differential GNSS and continues with an overview and assessment on validated online GNSS data processing services/techniques which are easy to use and easy to be included into a specific application. Finally future developments for real-time GNSS services/applications are presented to demonstrate their potential for further enhancement of the accuracy and usability of GNSS.

2. DIFFERENTIAL GNSS

Before coming to real-time GNSS processing this paragraph is intended to give a short introduction to differential GNSS as up to now differential GNSS is the only practical way to reach very high accuracy with GNSS measurements.

In order to achieve a precise positioning result with GNSS signals there are two main enabling factors. On the one hand, by subtracting measurements taken at a reference point with known position several common error sources in the range measurement are eliminated or decreased. On the other hand the position accuracy can be brought to the centimeter level by resolving the ambiguity of the precise but ambiguous differential carrier phase measurements instead of using only code measurements.

In classical single difference positioning a differential positioning is accomplished relative to a well-known reference station (receiver difference), as depicted left hand in Figure 1. This way the satellite clock error is eliminated, since it is contained in both measurements. If one assumes further the distance between user receiver and reference station is not larger than about ten kilometers, then

an almost identical ionosphere influence can be assumed. Also the differential orbit error can be neglected due to the large distance of the receivers to the satellites. The troposphere is likewise spatially correlated and the remaining error may be neglected, if the height of both receivers is in approximately alike. With consideration of these conditions the remaining error sources are multipath and thermal noise. Ignoring the multipath errors leads to a measurement inaccuracy of the differential measurement which is twice as high as the measuring accuracy of the single measurement.
The positioning algorithm with the single difference model has nonlinear equations, which must be solved for the unknown user receiver coordinates and the combined receiver clock error. For the carrier phase measurement additionally the unknown ambiguity has to be estimated.

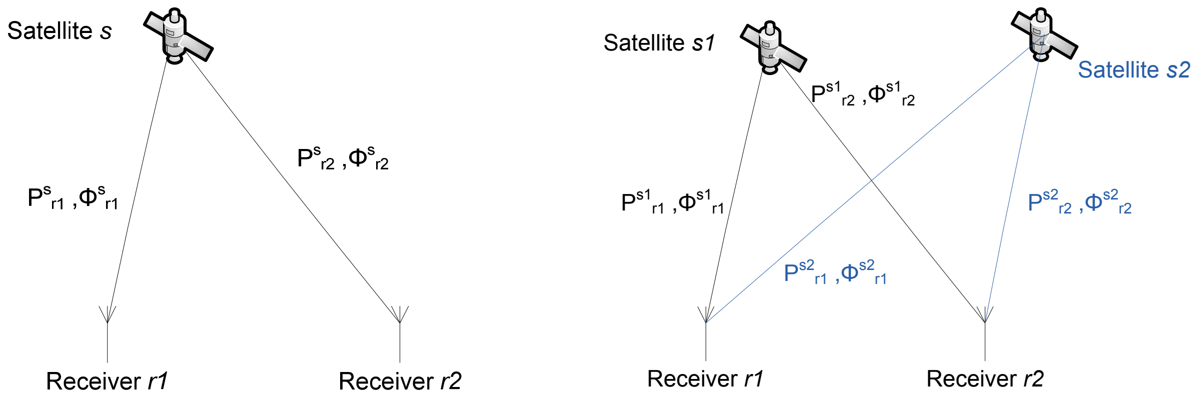


Figure 1: Visualization of single- (left) and double-differences

When using double differenced observation equations – with the difference of two single differences, as shown right hand in Figure 1 – the advantage is that the unknown combined receiver clock error is eliminated. Again a not too large distance between reference station and user receiver as well as a negligible combined clock drift were presupposed. The disadvantages of the double differenced observation equations are the reinforcement of the measuring noise and the correlation of the double differences [10]. In practice one obtains a better result over double differenced observation equations than by the positioning with single differentiation. The reason for this lies in the constantly varying combined receiver clock error of the single differences.
The fast, robust and reliable determination of the ambiguities of the carrier phase measurements forms the key in order to obtain centimeter accuracies in real time. The determination of the carrier phase ambiguities in the motion is therefore a substantial heart of the highly exact satellite navigation. If the temporally constant ambiguities are once determined, then a centimeter-level positioning is possible.
The determination of the ambiguities can in general be divided into two substantial sub-problems: finding the correct ambiguity combination, and the validation of the correct ambiguity combination. Nearly all approaches are based on the proposal of [8] and lead to the determination of the ambiguities by a search in the high-dimensional observation area, the phase space, as proposed for example by [15,5].

3. STATUS OF REAL-TIME GNSS DATA PROCESSING

The following subsections give an overview of the current major real-time capable reference-and augmentation-systems, which can be divided into network-based and satellite-based systems.

3.1. Network-based services

The market for real-time positioning has been growing fast for the last two decades. The foundation builds the introduction of real-time kinematic measurements (RTK) in the 1990s, which enabled the user to perform precise positioning on centimeter level in real-time. Other than former post-processing techniques, a base station is set up on a known point and generates correction parameters from the difference between the target coordinate and the measured coordinate. These corrections are sent via a radio link to the rover to apply the correction to the positioning solution. The user is able to carry out measurements within a distance of 5-20 km to the base station, for greater distances the ambiguity resolution is unreliable and a precise positioning solution is not achievable [16].

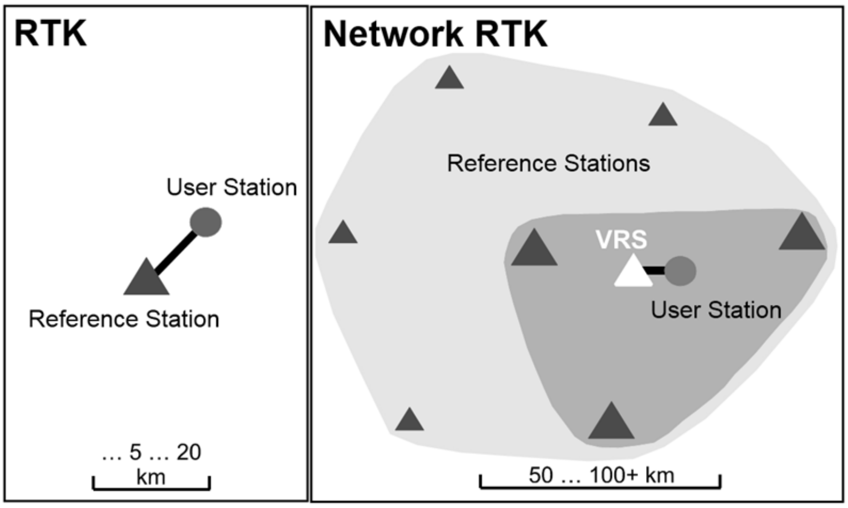


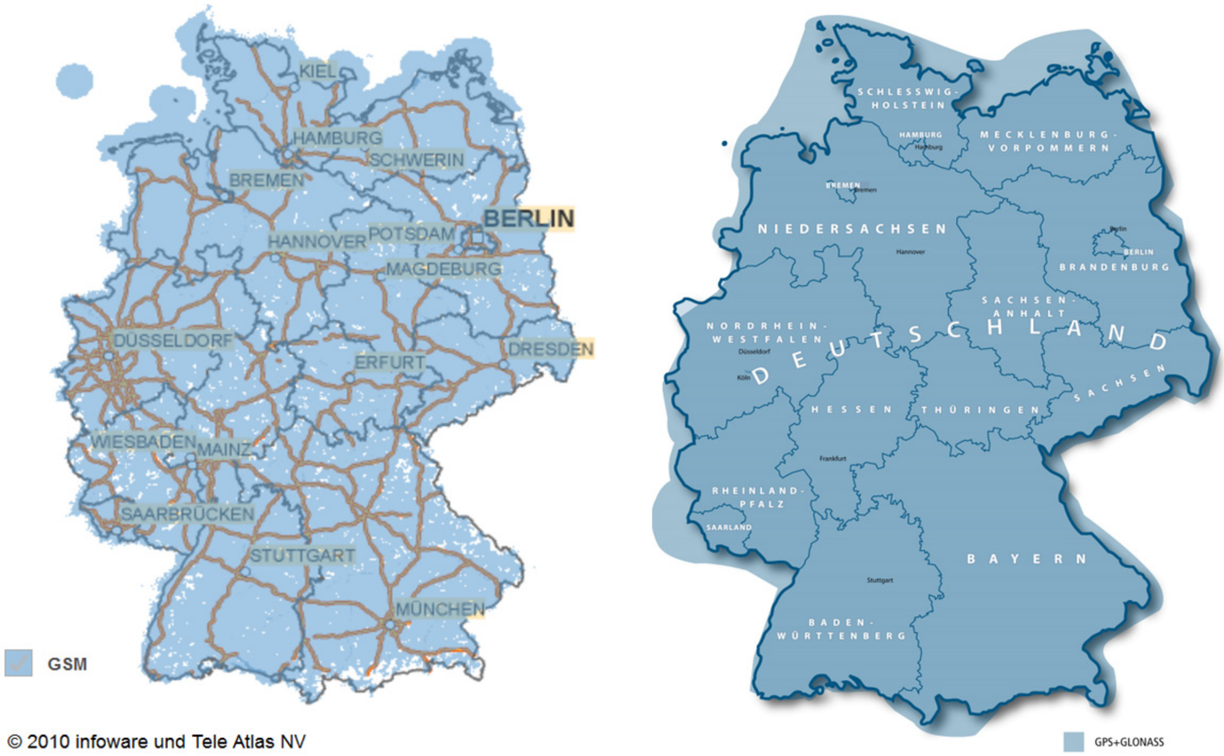
Figure 2: Principles of RTK and Network RTK from [16]

3.1.1. Network-based Approach

As the market demand increased RTK was still an option, but due to the performance limitations the development and installation of a more suitable solution was impelled. The main goal of the network-based approach is the reduction of reference stations on one hand and an area-wide availability of correction parameters on the other. The common distance between the reference stations in a RTK network is 50-70 km to ensure an area-wide coverage. In this case the correction parameters are not derived from one single reference station (as with RTK) but from a network of reference stations, which provide a combined solution (Figure 2). A common correction approach is called “Flaechen-Korrektur-Parameter” (FKP). It is used in the network services provided by SAPOS, a national German RTK network provider, consisting of more than 250 stations. Using data of a minimum of three closest reference stations around the rover, double difference satellite-specific atmospheric corrections are derived by using planar interpolation functions [18]. A similar network approach uses these correction parameters to generate a so called virtual reference station (VRS) close to the user’s position. The synthetic observations of the VRS are used to determine the short baseline between VRS and the roving receiver [17]. Furthermore, there is the master-auxiliary-concept (MAC) consisting of one master reference station, that generates complete observation corrections. The observations of the other reference stations (auxiliary stations) are expressed as correction differences to the master station to limit the amount of data [3]. For each of the concepts a mobile network (e.g. GSM) is used for the data communication.

3.1.2. Service Performance

All concepts are in use by different providers at the moment. In Germany for example, there is the national provider SAPOS and the Ascos service, who use FKP and VRS. And there are also Leica (MAC) and Trimble (VRS), who provide correction data. This constellation shows that the differences between the concepts are rather small for the users. All providers claim an accuracy level of just a few centimeters (horizontal) and an age of data of approximately one second. The age of data may differ depending on the mobile network which is in use and the amount of data, which is to be sent. Where the VRS solution only broadcasts a very small amount of data, FKP and MAC need more bandwidth (and therefore possibly more time) to share information between processing center and rover. The correction data of network-based services are continuously available around the clock, except of maintenance issues such as software updates or hardware changes which are realized during nighttime or weekends.
Figure 3 shows the availability of the Trimble network (right) as an example and the coverage of the Vodafone mobile network (GSM), which is used as a communication link between rover and processing center. It is visible, that the correction service provider claims a complete coverage of Germany, while the mobile network contains some gaps. As the user needs both for a precise positioning solution, a provision of correction parameters as well as their submission to the rover, the coverage is not necessarily area-wide. Nevertheless, network-based services provide a convenient way to perform precise positioning on centimeter level with reduced equipment – only a GNSS receiver with a GSM connection is needed – and effort.



Source: vodafone.de Source: trimble.com

Figure 3: Coverage of the Vodafone Germany GSM network (left) and the Trimble network (right)

3.2. EGNOS

One important data source for GPS corrections in the European area is EGNOS (European Geostationary navigation overlay service) which is a Satellite Based Augmentation System (SBAS).

Further possible sources for precise orbit and satellite clock parameters are the SISNeT technology and the precise ephemeris delivered by IGS.
SBAS are satellite-based support systems, which send correction signals in real time, so that the GPS users can achieve improved position accuracy. The SBAS conveys these correction signals via satellite. The SBAS Service is standardized and available in several regions around the world other than Europe: US (WAAS), Japan (MSAS), India (GAGAN, planned), Russia (SDCM, planned), China (SNAS, planned). EGNOS is the European SBAS and is developed by the European space agency ESA, the European organization for the protection of aviation EUROCONTROL and by the European commission (EC). The goal of EGNOS is not only to improve the position accuracy for GPS receivers, but also an improved continuity and integrity. For this EGNOS is divided into three segments:

- Space segment: The space segment consists of three geostationary satellites, which radiate the EGNOS signal.
- Ground segment: The ground segment consists of different reference stations (Ranging and Integrity monitoring station, RIMS), main control stations (master control centers, MCC) and ground stations (navigation land earth station, NLES). As can be seen in Figure 4, these stations are mainly distributed over Europe, but there are also some stations in other continents. The reference stations receive the GPS signals and pass the measurements on to the main control stations. The main control stations process the data and compute the corrections. The corrections are then sent by means of the ground stations to the geostationary satellites.
- Support segment: The support segment is a mechanism for the support of the system support (performance assessment and check out facility, PACF) and a mechanism for the assistance of the EGNOS user (Application Specific Qualification Facility, ASQF)

Space segment:
- reference stations (RIMS)
- main control station (MCC)
- ground stations (NLES)

Support segment:
- system support (PACF)
- user support (ASQF)

Figure 4: Ground- and Support Segment of EGNOS

According to specifications, horizontal position accuracy should be better than seven meters. In practice, the horizontal position accuracy is at the meter level. The EGNOS system consists of three geostationary satellites and a network of ground stations. The system started its initial operations in July 2005, showing outstanding performances in terms of accuracy (better than two meters) and

availability (above 99%), see [6] for example, and it was certified for use in safety of life applications in March 2011. A commercial service is under test and will also be made available in 2011. EGNOS is operational and available for use with both an open service and a Safety-of-Life service for aviation.
EGNOS delivers fast and long term corrections for satellite orbits and clocks, ionospheric corrections which can be computed from a measurement grid over Europe and degradation factors. This information is widely used nowadays, even for handheld consumer receivers, in order to get a less biased position result. For precise positioning applications the EGNOS integrity information can be used to exclude measurements which suffer from too large errors due to satellite errors or strong ionospheric activity.

3.3. OmniSTAR

OmniSTAR is a global real-time differential GPS broadcast system providing corrections based on a worldwide network of reference stations. OmniSTAR uses the network of reference stations to measure errors inherent to the GPS system and additionally precise orbit and clock information for every satellite are utilized. The data is up-linked to geostationary satellites, which distribute them over their respective footprints. In April 2011 Trimble has acquired certain OmniSTAR assets from Fuegro N.V.. The acquisition includes agriculture, construction, mapping and Geographic Information Systems (GIS) and survey applications. Within the following the basic properties of the OmniSTAR system are described shortly.

3.3.1. OmniSTAR data link

As already stated OmniSTAR corrections are broadcasted via several geostationary satellites which are located about 36.000 km above the equatorial plane. The geostationary satellites covering 8 regions including most of the landmass of each inhabited continent. Fig. 5 shows the footprint and the included region where corrections are provided within Europe and Africa. The red dots are reference stations used within the current network.

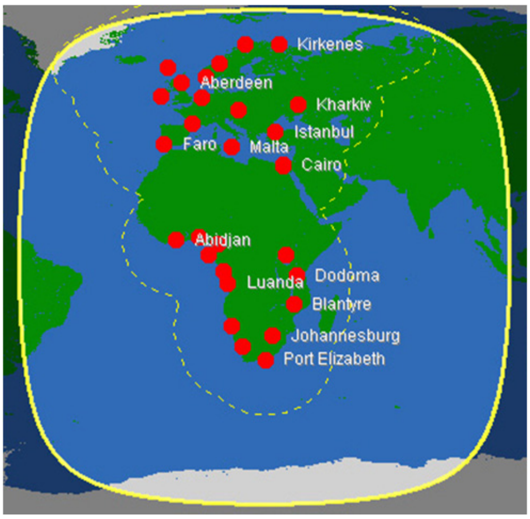


Fig. 5: OmniSTAR coverage map for EUSAT/AFSAT [12]

The correction data is down-linked within the L-Band near below to the GPS L1 center frequency but the distinct frequency is depending on the individual OmniSTAR satellite, e.g. the down-link frequency for the EUSAT is 1537.440 MHz with a data rate of 1200 bps. The near proximity to the GPS L1 signals allows the usage of (appropriately designed) L-Band antennas and therefore avoids the need for additional reception hardware. The general OmniSTAR data link concept is based on a one way communication from the satellites to the user. This passive system design enables an infinite number of users at the same instant of time.

3.3.2. OmniSTAR services

The OmniSTAR VBS (Virtual Base Station) service is based on GPS L1 Code measurements of reference stations that are used to calculate optimized GPS corrections for the location of the user. These + corrections are passed to the GPS receiver to create an optimized DGPS solution. Accuracy is better than 1m (2DRMS) horizontal at mid-latitudes inside the reference network.

OmniSTAR HP (High Performance) is a dual frequency DGPS service. The OmniSTAR HP broadcast consists of phase and code measurements from the reference station network. Due to the fact that dual frequency measurements are used, the information is already free of ionosphere signal delay errors. After receiving the phase and code measurements from the OmniSTAR satellite broadcast, these information are applied to the raw GPS measurements gathered by the user GPS receiver. The accuracy of this service is in the decimeter level domain.

OmniSTAR XP (Extended Performance) positioning is based on precise orbit and clock information for GPS satellites. Precise satellite orbit information is broadcasted every minute and precise clock information every ten seconds. With a provided satellite position accuracy within 20-30 cm and a satellite clock error within a nanosecond, it is possible to estimate positions up to the decimeter level without the need for a user to work close to one of the OmniSTAR reference stations. This technique is also referred to as “Precise Point Positioning” (PPP).

The OmniSTAR G2 (GPS & Glonass) broadcast additionally contains the orbit and clock corrections for the Russian Glonass system as well as for GPS. OmniSTAR G2 uses Glonass orbit and clock corrections derived from a separate independent network of reference station.

OmniSTAR can combine HP & XP or HP, XP & G2 into a robust positioning solution with a high availability. When a user is working far away from any of the OmniSTAR reference stations the solution relies on precise orbits and clocks information (XP/G2). When working close to the reference stations the solution is improved using the HP network solution (HP/XP/G2). The combination of OmniSTAR HP & XP is referred to as OmniSTAR HP^{+}. The pricing for the different services are dependent of the application and the geographical region. Standard North American subscription pricing for GIS/Mapping applications are:

- OmniSTAR VBS - $800.00 per year per receiver
- OmniSTAR XP - $1,500 per year per receiver
- OmniSTAR HP - $2,500 per year per receiver

3.3.3. OmniSTAR performance

Within [13] one can see the development of the standard deviation for a position solution for two OmniSTAR services over time, where the picture is taken from an official OmniSTAR reference [13]. It is clearly visible that it needs some convergence time to obtain good position solution accuracy.

Figure 6: Standard deviation of horizontal accuracy after start-up for HP^+ (HPXP) and XP only [13]

An evaluation of the OmniSTAR XP service for airborne applications in [2] shows similar results. This paper states that one major drawback of OmniSTAR XP is the static initialization time which is needed to get the best result because in case of high (airplane) dynamics the convergence period is prolonged.

3.4. Further Systems

Beside the described RTK, EGNOS and OmniSTAR systems there are more services which also provide improved real-time positioning capabilities but shall only be described shortly.

For maritime users IALA standard conform DGPS corrections are broadcasted via medium wave and as this service is intended for ships the reference/broadcast station are mostly located at the coast. Due to the medium wave transmission a user needs dedicated equipment to make use of this data. Ground Based Augmentation System (GBAS) consist of reference receivers located around a central location which normally is an airport. The measurements of the reference receivers are used to derive corrections which are sent via VHF data broadcast to the user receiver. The main drawback of this system for general purpose users is the very local character of the corrections and simultaneously these systems are only installed near to big airports. StarFire is a commercial satellite based augmentation system comparable to the OmniSTAR system. According to [11] the real-time accuracy is on the decimeter level on a worldwide basis. The corrections are broadcast at L-Band frequencies via geostationary satellites.

4. FUTURE DEVELOPMENTS AND CHALLENGES

4.1. GNSS System of Systems

The near future of satellite navigation will bring a whole bunch of new satellite systems and signals, as can be seen in Figure 7. GPS is modernized with the signals L1C and L5, Glonass is adding CDMA signals to the legacy L1/L2 FDMA signals and has already a test signal on L3 with CDMA modulation transmitting since April 2011. Galileo is on the way with the very promising E5 AltBOC signal, as well as the Chinese Compass. Also India and Japan are eager to bring their navigation payloads in orbit.

A combined use of the signals in space of the modernized GNSS will drastically reduce the instantaneous ambiguity fail rate on short baselines. The increased success-rate of fixed ambiguity is caused by a higher number of satellites and the resulting improved satellite geometry. By the availability of additional modernized signals the RTK positioning will be more robust and will have a shorter time to first ambiguity fix. Depending on the environment the RTK positioning may be even more precise due to the improved geometry.

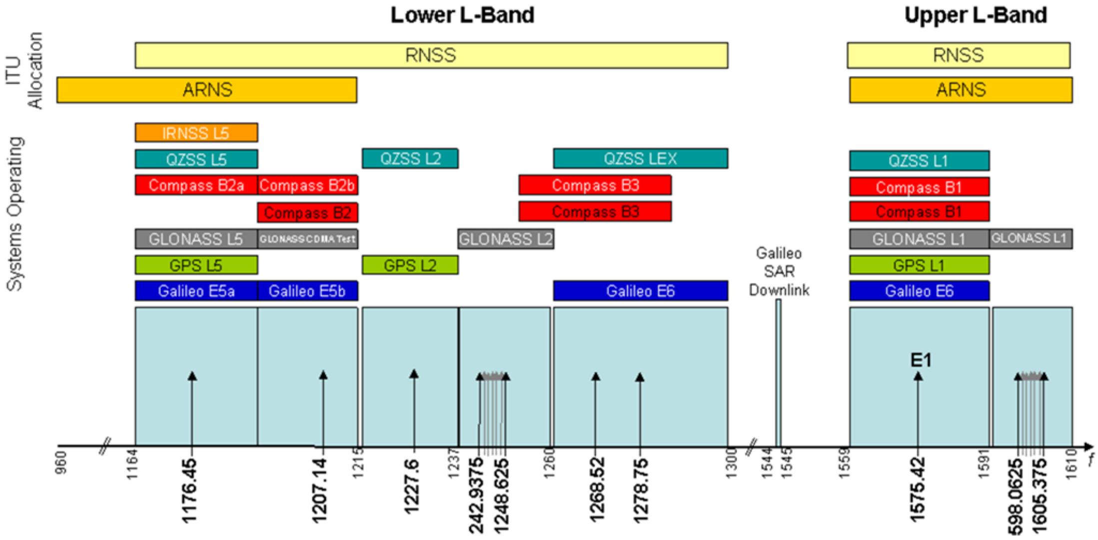


Figure 7: Frequency plan for all existing and upcoming regional and global navigation systems

4.2. Jamming

One weak point for applications which need precise positioning solutions in low altitudes or on the road is the threat of jammers. Due to the low power levels of the received GNSS signals they are vulnerable to interference. In this case it is intentionally through jamming attempts which is the most serious threat. Jammers are relatively easy to purchase from abroad over the internet and operate them by plugging them into the cigarette lighter of a vehicle. The result is the partial or complete destruction of GNSS signals not only in the vehicle it is operated in, but also within vehicles in the vicinity of about a kilometer.

An analysis of InCar-Jammers shows that the primary InCar-Jammer interference types are brute force jammers, transmitting a high power wideband chirp signal [1]. Also narrowband continuous wave jammers are available. The modernization of GPS and the upcoming of new satellite navigation systems like Galileo include the introduction of new frequency bands for open GNSS

Figure 8: Examples for commercial InCar Jammers [1]

services. Some of the upcoming open signals like the additional L5 band for GPS cover wider bands and are therefore not so prone to interference, but also the development of more sophisticated jammers for all used frequency bands and signal types are foreseeable and mitigation techniqes might only bring marginal attenuation of the interference effects.

4.3. New GNSS Signals

Despite the numerous advantages of a multi-system positioning approach a few of the new signals have some interesting properties, first and foremost the Galileo E5 broadband signal. It will feature an ultimately low range noise in the centimeter range and an impact of multipath, which is on centimeter level in benign environments and by far smaller than the multipath errors on all other signals in all other environments as well. This development will have important consequences for precise positioning in the future. The drastically increased range precision due to the very low E5 range noise will allow high accuracy measurements for combined code-and-carrier positioning. Unlike current GNSS signals (e.g. GPS L1, L2) only a single-frequency Galileo receiver will be needed in the future rather than a (significantly more expensive) multi-frequency device. Therefore, carrier phase and range measurements – in contrast to present GNSS signals – will almost become comparable in terms of accuracy. Such a single-frequency system will additionally be able to eliminate the ionospheric propagation delay, which is a major point in enhancing positional accuracy over long distances by the code-plus-carrier principle. Furthermore, integer ambiguity recovery – often said to be a key issue in precise positioning – will become feasible.

4.4. Future Methods for Precise Positioning in Real-Time

The state of the art positioning technique is without doubt network RTK. It provides the best positioning accuracy currently available and is extensively used in a wide range of applications with significant economic benefits. The main disadvantage of this approach is the need to build up and maintain an extensive reference station network as well as the necessity of a communication link between the processing centre and the roving receiver. In industrialized areas like Europe and most of Northern America a network of reference stations is proficient and mobile communication is almost area-wide available. But the number of areas where a precise positioning solution in real-time is inquired is increasing and either a reference station network or a mobile network is not in sight. The costs for building up and maintaining such networks are out of all proportion for the providers in most undeveloped or rural areas like in Africa or even in parts of Northern America. An option to avoid a reference station network is the precise point positioning (PPP) method. There have been extensive investigations in the past couple of years to analyze the potential and the performance of this method. PPP works without any differential approach to mitigate common errors like atmospheric delays, receiver and satellite clock errors or ambiguity resolution for carrier phase measurements, but it uses precise GNSS satellite clock and orbit information to achieve an accurate positioning solution. In kinematic post processing mode accuracies on cm-level have been achieved [9] by using the clock and orbit information from the International GNSS Service (IGS), but for most applications, as visible by the success of RTK and network RTK, real-time positioning is desired or even necessary. There are three main challenges for real-time PPP: firstly the precise satellite clock and orbit information are predicted (IGS product: ultra-rapid), which reduces the accuracy compared to the post processing method where observed satellite data are used, secondly the large convergence time of the PPP method (> 30 min) are to be minimized and thirdly the broadcast of the satellite clock and orbit information to the roving receiver in unconnected rural areas has to be assured.

A couple of promising approaches will be presented in the near future. PPP and network RTK methods are connected in [14] and [7] to solve the convergence time issues as well as the dependence of a mobile network. In [4] the network RTK approach has been analyzed and its performance has been improved for industrial applications, enabling a correction data service in the problem areas mentioned above.

5. CONCLUSIONS

Modern GNSS augmentation services provide real-time accuracy on the decimeter or even centimeter level as depicted in Table 1. The real-time solution therefore enables an application to estimate the minimum performance for the final position solution. By using post processing techniques the final accuracy might be further increased. For an aerial flight operation this means for example that already during the flight time the minimum final performance is available and therefore an operator can immediately assess if the requirements are met.
The best accuracy can be obtained by using network RTK solutions but the major drawback of this technique is the prerequisite for an operational reference receiver network within the area of interest. Satellite based systems like OmniSTAR and StarFire have slightly worse accuracy but on the other hand they are available on a nearly world-wide basis. The drawback is given by the eventually long initialization time to reach the best positioning accuracy. EGNOS or comparable SBAS systems deliver results in the meter level for single frequency users and the corrections are mostly free of charge. One also has to keep in mind that SBAS systems include integrity information and therefore deliver a trustworthy position solution.

Service/Type	Accuracy	Areal availability	Fee	Additional equipment	Initialization time
RTK	few centimeter	local	no	reference station	few minutes
Network RTK	few centimeter	regional	yes	communication link (e.g. GSM)	few seconds
EGNOS	few meter	Europe	no	none	few minutes
OmniSTAR	one meter to few centimeter	nearly worldwide	yes	suited L-band antenna	depending on mode and operation
StarFire	few meter to few centimeter	nearly worldwide	yes	suited L-band antenna	depending on operation
GBAS	few meter	local	no	VHF link	few minutes
IALA DGPS	few meter	regional coastal area	no	medium wave link	few minutes

Table 1: Overview of real-time GNSS correction services

Upcoming new signals like the Galileo AltBOC will deliver superior performance and might, depending on the user requirements, even lead to scenarios where very high real-time GNSS positioning performance can be reached without the need for auxiliary correction data.

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