Journal of Global Positioning Systems (2007)
Vol.6, No.1: 1-12

Journal of Global Positioning Systems
2007
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On the feasibility of adding carrier phase –assistance to cellular GNSS assistance standards

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Abstract. The 3GPP (Third Generation Partnership Project) Release 7 of GSM and UMTS cellular standards as well as SUPL2.0, used in IP networks, include major modifications as to how AGNSS (Assisted GNSS) assistance data is transferred from the network (cellular or IP) to the cellular terminal. Simultaneously position accuracy improvements may be introduced. One potential option is to use carrier phase -based positioning methods. This can be achieved integrally in the cellular network or by the use of Virtual Reference Stations and an IP network. The bulk of AGNSS devices will be single-frequency due to additional cost associated with two RF front-ends. Hence, this study addresses the feasibility of single-frequency carrier phase-based positioning, making comparison with the dual-frequency case. The study shows that single-frequency carrier phase -based positioning is feasible with short baselines (<5 km) given that: 1) real-time ionospheric predictions are available and 2) there are enough satellites available. Namely, this requires hybrid-use of GPS and Galileo.

Keywords. Assisted GNSS, RTK, VRS, Ambiguity Resolution, Success Rate

1 Introduction

The annual sales of AGNSS-enabled (Assisted GNSS) handsets are estimated to rise to 400 million units by 2011 (Strategy Analysts, 2006). Currently the size of the market is approximately 100 million units annually. High growth requires developing constantly more efficient and capable methods to improve user experience in terms of availability, accuracy and short time-to-first-fix. The assistance data available from the network are a significant factor affecting the user experience. The advantages and benefits of assistance are discussed in (Wirola et al., 2007b).

As GPS/AGPS now becomes commonplace in mobile terminals, the next step in the competition will be the race for accuracy. One option to achieve this is to take advantage of carrier phase -measurements readily available in GNSS receivers integrated in mobile terminals. Methods utilizing carrier phase -measurements include Real-Time Kinematic (RTK) as well as Precise Point Positioning (PPP). The recommendation given in (Nokia, 2006) is that carrier phase -based positioning would be added to the cellular standards in such a manner that the terminal could request for carrier phase-assistance from the SMLC (Serving Mobile Location Center) and calculate the baseline vector between the base station and the terminal.

Carrier phase -based positioning was for the first time introduced in 3GPP (The Third Generation Partnership Project) in GERAN#30 (GSM/EDGE Radio Access Network with GSM being Global System for Mobile communications and EDGE being Enhanced Data rates for Global Evolution) meeting in June 2006 in Lisbon, Portugal (Nokia, 2006). When the baseline implementation for A-Galileo was agreed in GERAN#32, this feature was included in the list of items to be reviewed in the 3GPP Release 7 time frame (Alcatel et al., 2006). However, the feature was not included in the Release 7 due to the identified need to further assess the technical implementation before approving the approach. It is expected that carrier phase -based positioning will be dealt with in the Release 8 of the 3GPP standards.

This paper examines the feasibility of introducing single-frequency carrier phase -based positioning into cellular networks. The use case considered consists of a short baseline (<5 km) and a single-frequency receiver due to the cost reasons. However, the receiver may be a dual-

GNSS (GPS+Galileo) receiver. The paper includes a thorough review of the latest research in the area of carrier phase-based position. The review is complemented by simulations that are performed using a state-of-the-art open-source simulation tool developed for the analysis of carrier phase-based positioning (Verhagen, 2006b).

2 Assisted GNSS

Fig. 1 shows the high-level view of AGNSS architecture. The core of the architecture is the AGNSS server, or more precisely, server centers that are geographically distributed. These centers serve the AGNSS-subscribers in each geographical area. Assuming that the AGNSS-terminal is to receive assistance over the user plane (IP-network) the terminal takes a data connection to the pre-set server and requests for the assistance data. The assistance data is then delivered to the terminal as specified in the associated standards.

The AGNSS server may obtain its data from various sources. These may include physical GNSS-receivers distributed geographically (left hand side in Fig. 1). These receivers can provide integrity information as well as broadcast ephemeredes to the AGNSS server for distribution. On the other hand, the orbit and clock models (as well as other data) can originate from an external service providing, for instance, precise ephemeredes and orbit/clock predictions (right hand side in Fig. 1). Such services include the International GNSS Service, or IGS (Dow et al., 2006). Should predictions be available, AGNSS-enabled terminals can be provided with extended ephemeredes, in which case the terminal does not need to connect to the assistance server in the beginning of each positioning session. This improves user experience due to the time saved in not having to set up a data connection and download the assistance. With long-term ephemeredes the assistance is also available, when there is no network coverage (Lundgren et al., 2005).

Currently it is only possible to provide assistance for GPS L1 in GSM and UMTS (Universal Mobile Telecommunications System) networks. In GSM the assistance is specified in the Radio Resource LCS (Location Services) Protocol (RRLP, (3GPP-TS-44.031)) and in UMTS in the Radio Resource Control (RRC, (3GPP-TS-25.331)). Moreover, there are also user plane solutions, such as Open Mobile Alliance (OMA) Secure User Plane Location (SUPL, (OMA-ULP)) protocol.

It should be noted that there are terminological differences depending upon, which standard is in question. For instance, the mobile terminal is MS (Mobile Station) in GSM, UE (User Equipment) in UMTS and SET (SUPL-Enabled Terminal) in SUPL. Moreover, the server sending the assistance to the terminal is an SMLC in RRLP and RRC, while in SUPL the server is an SLC (SUPL Location Center).

Due the upcoming changes in the GNSS infrastructure (Wirola et al., 2007b), such as modernization of GPS and GLONASS as well as the introduction of Galileo amongst others, the 3GPP standardization body accepted a proposal which opened the way for the addition of new GPS bands as well as other GNSSs to the assistance standard in autumn 2006 (3GPP, 2006) . This decision concerned RRLP only, but the same solution was later approved into RRC (3GPP, 2007) as well as SUPL 2.0 (OMA, 2007).

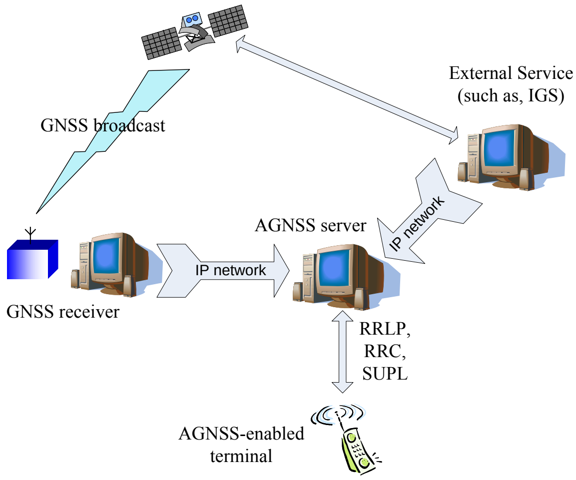

Fig. 1. The AGNSS architecture

AGNSS introduces common and per-GNSS elements into the standards. The superstructure is detailed in (Syrjärinne et al., 2006). The common elements are GNSS-independent and include, for instance, ionosphere model and reference location. In the future, for instance, troposphere models or Earth-Orientation Parameters can be added without obstacles.

The per-GNSS elements, on the other hand, are by definition GNSS-dependent (as well as signal-dependent) and include differential corrections, real-time integrity, GNSS-common time relation, data bit assistance, reference measurements as well as orbit and clock models (ephemeredes). The new multi-mode navigation model capable of supporting at least seven GNSSs is discussed in (Wirola et al., 2007a) and (Wirola et al., 2007b). The introduced generic approach significantly reduces the system complexity.

3 Carrier phase -based positioning

Real-Time Kinematic (RTK) techniques utilize carrier phase -measurements that are readily obtained from a GNSS receiver. Carrier phase measurements enable centimeter-level accurate baseline (i.e. distance and attitude between the receivers) determination between two (or more) GNSS receivers. Also, if the absolute position of one receiver is known at high accuracy, the absolute position of the other receiver can easily be deduced. The addition of carrier phase -based positioning to cellular standards, therefore, potentially enables ubiquitous cm- or dm-level positioning accuracy.

The current commercial solutions typically utilize both GPS L1 and L2 signals for high-precision surveying. Moreover, with the GLONASS modernization (Klimov et al., 2005), the utilization of multi-GNSS is becoming ever more attractive. Also, the recent studies (Wirola et al., 2006; Alanen et al., 2006a; Alanen et al., 2006b) show that single-band single-GNSS RTK is feasible under certain circumstances. In addition, all the Galileo as well as the modernized GPS signals can be utilized in the baseline determination (Eisfeller et al., 2002a; Eisfeller et al., 2002b; Tiberius et al., 2002). The more signals there are the more certain (in statistical sense) the baseline becomes (Wirola et al., 2006).

Carrier phase -based positioning may be introduced either by supporting it in the SMLC or by utilizing an external service. In the case of an SMLC-implementation (control plane solution in the cellular network), the terminal requests for carrier phase -measurements from the SMLC. The SMLC then starts sending the measurements from the LMU (Location Measurement Unit) to the terminal. Another option is to utilize Virtual Reference Stations (VRS) as a service external to the network. In this case the terminal sends the AGNSS assistance server an assistance request that contains the approximate position of the terminal. A VRS is created to this location and measurements are streamed to the terminal most likely over an IP-network. The advantage of this technology is that the baseline is always very short and no additional hardware (LMUs) is required in the network.

The key to the high-accuracy baseline determination is *integer ambiguity resolution*, for which there are many algorithms available. In addition to solving the ambiguities, another key issue is the *validation of ambiguities*. Validation refers to using statistical tools to determine, whether the ambiguities and, hence, the fixed baseline solution can be relied on. If the ambiguities cannot be solved, somewhat less accurate option is to utilize the *float solution*. In this case the ambiguities are not fixed to their integer values, but are considered as real numbers.

This study concentrates on discussing the various factors affecting the ambiguity resolution success rate and how those factors affect the feasibility of adding carrier phase-based positioning to the 3GPP standards.

4 Method and analyses

In the following the performance of the carrier phase -based positioning is analyzed under varying circumstances. Chapter V examines a situation, in which a set of individual measurements is exchanged between two receivers. This corresponds to *Measure Position Response with Multiple Sets* defined in RRLP (3GPP-TS-44.031). Chapter VI studies a situation with periodic reporting of measurements from one receiver to another as defined in RRC (3GPP-TS-23.271).

The performance is characterized in terms of the success rate for fixing the integer ambiguities successfully. Theoretical tools for this analysis are given, for instance, in (Teunissen et al., 2000). This work utilizes an open-source analysis tool called VISUAL (Verhagen, 2006b), which allows for simulating success rates in temporal or spatial dimensions.

In real-time applications ambiguity fixing success rate can be calculated on-the-fly in order to examine, whether ambiguity fixing should be attempted at all. As a general rule, the success rate must be above 99% before fixing should be attempted (Verhagen, 2006b). If the ambiguity solution is not available, the system can provide the user with a float solution. Baseline accuracy obtainable with a float solution is 0.1 - 1.0 meters.

5 Single-shot multiple-sets

The first set of simulations considers a case, in which one receiver makes three measurements with 50-s spacing corresponding to the total measurement time of 100 s. This can be considered as a situation, in which the MS sends multiple sets of carrier phase measurements to the SMLC (3GPP-TS-44.031) allowing the SMLC to calculate the baseline.

Fig. 2 shows the success rates for Galileo E1 (up) and for Galileo E1+E5a (below). The parameters and assumptions of the simulation are

- 5-km stationary baseline
- Date 1st January 2008 00:00:00 UTC
- 15-degree elevation mask
- Fixed ionosphere (i.e. external ionosphere model used to correct the observations)
- Float troposphere (i.e. troposphere delay estimated as state) with Ifadis mapping function
- 3-mm STD for carrier phase observations
- 30-cm STD for code phase observations
- 30-satellite Galileo constellation

Fig. 2 shows that single-band carrier phase -based positioning using only Galileo should be considered too unreliable for implementation. On the other hand, the addition of the second frequency (E5a) improves the performance significantly. In the dual-band case, the carrier phase -based positioning is enabled and feasible globally.

Consider then temporal changes in the success rates. Fig. 3 shows the success rate as a function of time in Paris for Galileo E1 (up) and Galileo E1+E5a (below). The date and other assumptions are the same as before.

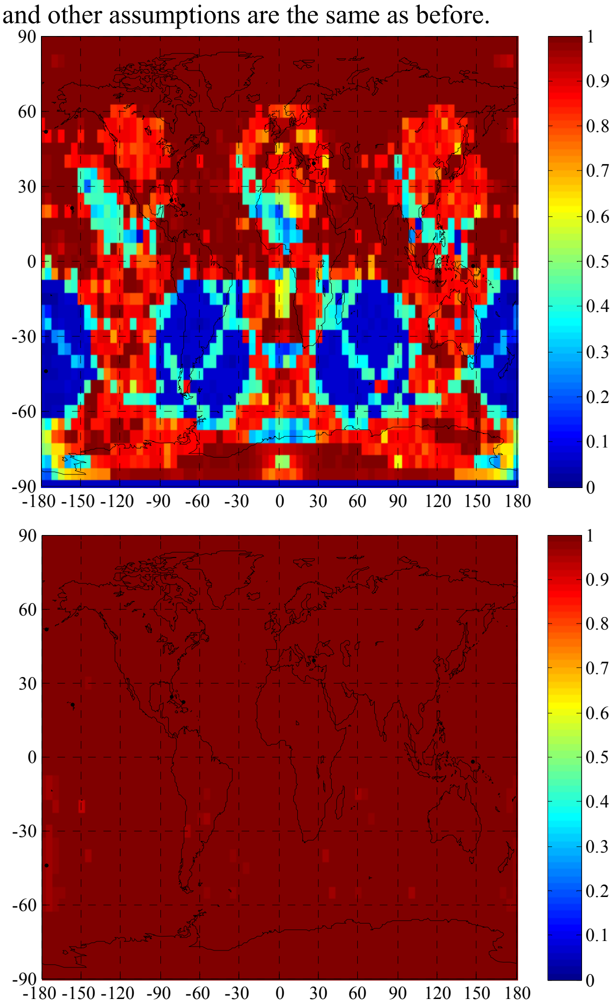

Fig. 2. Ambiguity fixing success rate for single-shot multiple-sets. Up: Galileo E1, Below: Galileo E1+E5a.

The simulation shows that in a single-frequency case the success rate is highly dependent upon the number of satellites available. In general, it seems that carrier phase -based positioning is feasible, when there are at least 10 satellites visible. However, there are only short periods, when this takes place. On the other hand, dual-band positioning does not suffer from the lack of satellites. Only if the number of satellites is below seven the success rate drops below the threshold. The dual-band case clearly outperforms the single-band case.

The literature supports the conclusions drawn from the simulations. Tiberius et al. (Tiberius et al., 1995) report 100% ambiguity fixing rate, when using GPS L1+L2 code and carrier phase measurement and only one set of measurements (one instant). In the study seven or more satellites were used all the time and the baseline was in the order of one km. However, the authors reported problems with validating the calculated ambiguities.

Finally, if GPS and Galileo are used in hybrid, the situation improves significantly. This is shown in Fig. 4, in which the simulation shown up in Fig. 3 has been rerun adding the GPS L1 signal. The results show that the redundancy from additional satellites (29-satellite GPS constellation) contributes significantly to the success rate. There are only few short periods during which there might be problems with fixing the ambiguities. The finding is also supported by the literature. For instance, Verhagen (Verhagen, 2006a) reports that combined dual-band GPS+Galileo yields a constant success rate of >99.9%. In that case the success rate becomes almost independent of time and location. Increased number of satellites is identified as the single most important factor for high success rate. However, there is no information, how the ambiguity validation success rate behaves in a combined GPS L1 + Galileo E1 situation.

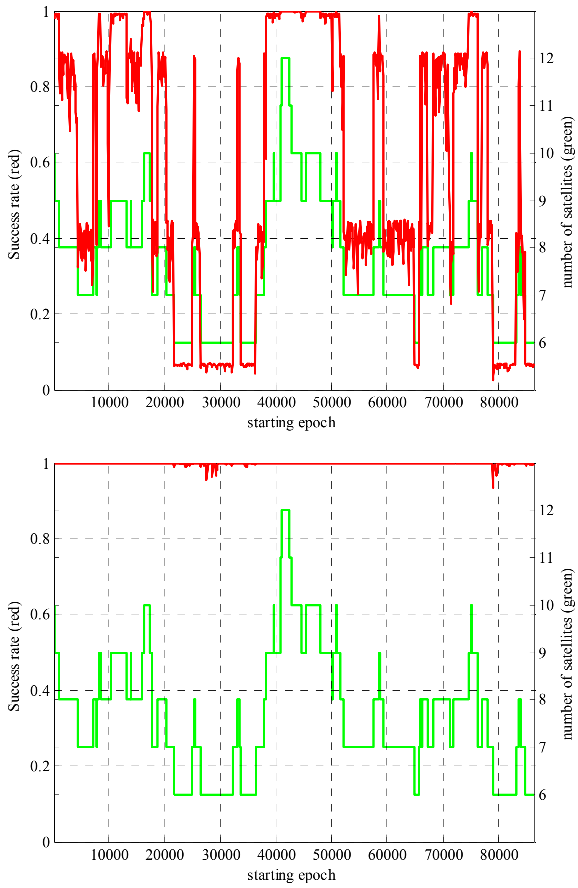

Fig. 3. Ambiguity fixing success rate for single-shot multiple-sets over one day in Paris (48.5° N, 2.2° E). Red denotes success rate and green the number of satellites above the elevation mask. It is assumed that all the satellites above the mask can be used in the ambiguity resolution. Up: Galileo E1, Below: Galileo E1+E5a.

Single-shot data delivery means that the baseline may be solved once (when the set of measurements arrives), but not updated after that. The receiving terminal/server may extrapolate the measurements for 20-30 s without losing accuracy significantly (Schüler, 2006). However, the baseline is lost after this in the case the receivers (or one of the receivers) are moving. Therefore, the single-shot multiple-set method is useful only for stationary receivers. Moreover, since there is no possibility for rigorous solution quality and integrity monitoring in time, baselines should be limited to short ones. The exact length depends on the bands and GNSSs used as well as on the atmospheric conditions and also on whether ionosphere or troposphere models are available.

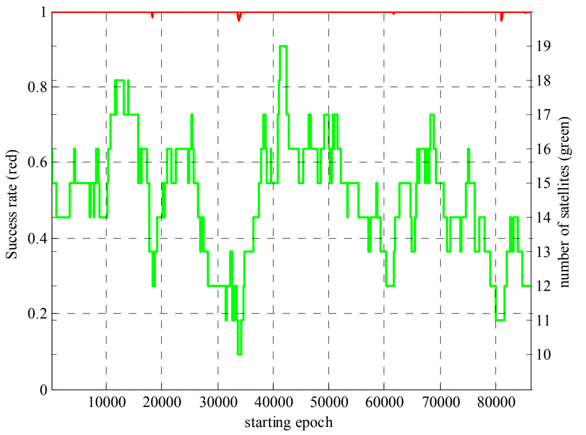

Fig. 4. Ambiguity fixing success rate for single-shot multiple-sets over one day in Paris (48.5° N, 2.2° E), when GPS L1 + Galileo E1 are used.

6 Periodic measurements

Periodic measurements refer to a case, in which one receiver periodically sends its signal measurements to the other receiver. This enables, for example, monitoring the solved parameters in time and, therefore, quality control. Also, with multi-band receivers, filtering of ionosphere advance (as well as troposphere delay) becomes possible. Finally, longer observation periods assist the validation process. Periodic reporting is enabled in UMTS networks over RRC.

Fig. 5 shows the success rates for Galileo E1 (up) and for Galileo E1+E5a (below), when one receiver streams measurements to the other receiver - in this case 1 signal measurement every 10 s for 100 s (in total 11 measurements). Note that by a signal measurement one understands a set of measurements consisting of code and carrier phases for all the observable satellites and signals. The other parameters and assumptions of the simulation are as given in chapter V.

Fig. 5 shows a major improvement in the single-band case. It appears that the single-frequency carrier phase -based positioning becomes feasible in many locations, when several epochs are utilized in the solution. However, the analysis made for Paris for the same situation running over one day (Fig. 6) shows that although there is an improvement as compared to the results shown in Fig. 3, windows for successful carrier phase -based positioning are still few. The promising periods are now longer (for instance, between epochs 40000 - 50000 s), but it can be assumed that the high variation in the success rate in time makes single-band positioning still very challenging even if more measurements are now available.

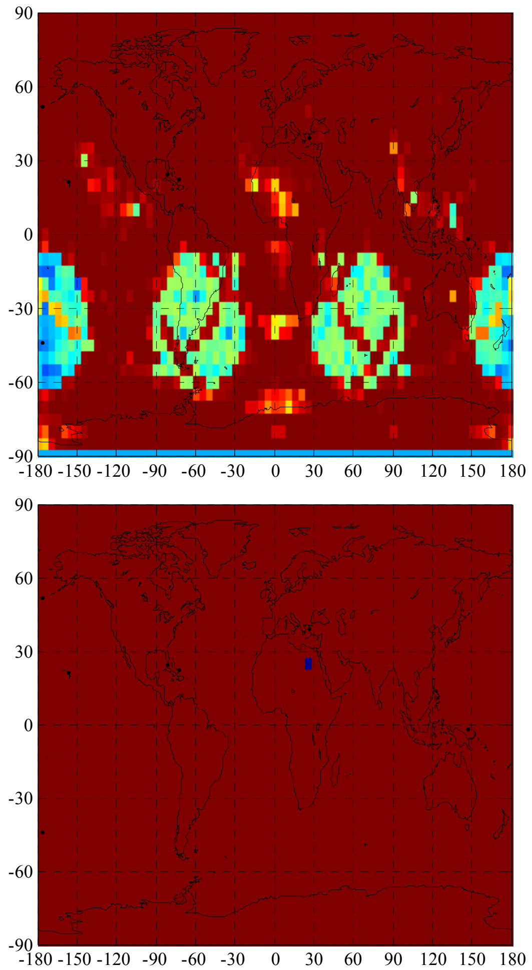

Fig. 5. Periodic reporting. Success rate for Galileo E1 (up) and for Galileo E1+E5a (below).

The dual band case continues to demonstrate excellent performance globally independent of time. This can be verified from the lower graphs in Figs. 5 and 6, respectively.

Finally, in Fig. 4 it was shown that the combined GPS L1 + Galileo E1 shows major improvement over the single-GNSSs case in the single-shot situation. Repeating the same analysis for streaming shows that increasing the number of available observations yields high success rate (above 99.9%) independent of time. The finding is supported by the literature (Verhagen, 2006b). Once again, the increased availability of signals is identified as the single most important factor.

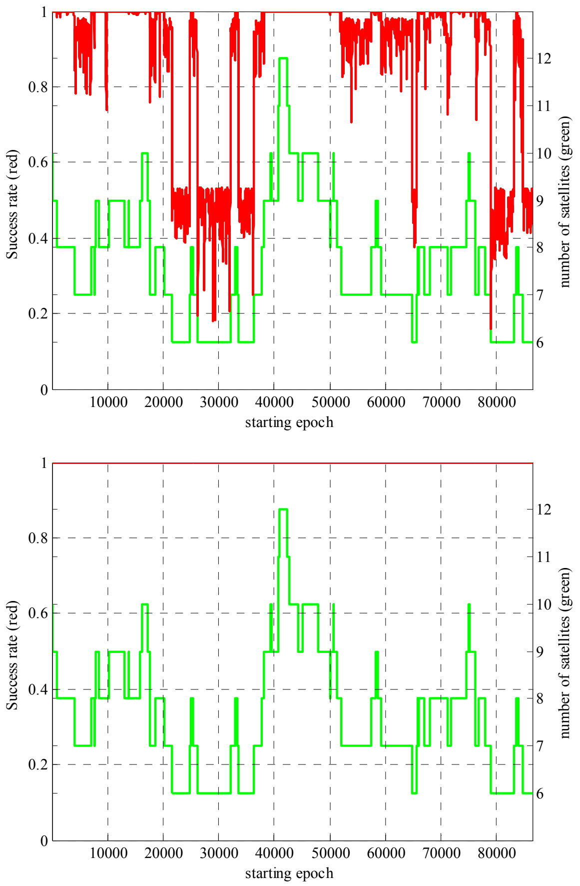

Fig. 6. Periodic reporting. Success rate for Galileo E1 (up) and for Galileo E1+E5a (below).

7 Measurement update rate

From the bit consumption point of view the most important issue is the measurement update rate, i.e. how often the terminal is required to report the signal measurement to the other receiver or server (or vice versa). This is analyzed by fixing the measurement period to 100 s and varying the measurement interval. The parameters and the assumptions of the analysis are as before, signals used are Galileo E1+E5a and the measurement rates in Fig. 7 a-d are

Fig 7a: a signal measurement every 100 s for 100 s (in total 2 measurements)

Fig 7b: a signal measurement every 50 s for 100 s (in total 3 measurements)

Fig 7c: a signal measurement every 20 s for 100 s (in total 6 measurements)

Fig 7d: a signal measurement every 10 s for 100 s (in total 11 measurements)

The simulations show that the 20-s measurement spacing yields a constant >99% success rate. Therefore, it is deduced that the measurement interval shall not exceed 20 seconds in periodic reporting.

There is also another issue supporting this view. Once the ambiguities have been fixed, the baseline will be tracked using the solved ambiguities. The 20-s measurement spacing requires that in order to be able to update the baseline continuously, the measurements from the sending receiver must be extrapolated for 20 seconds. Note, however, that this is possible only if the sending receiver is stationary. This is the case if the sending receiver is, for example, an LMU.

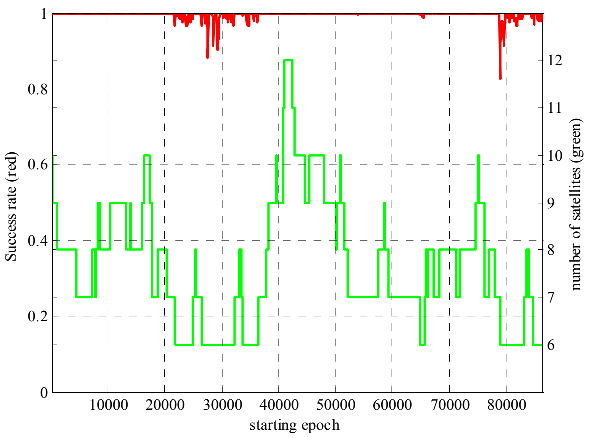

Figure 7a. 100-s spacing between measurements.

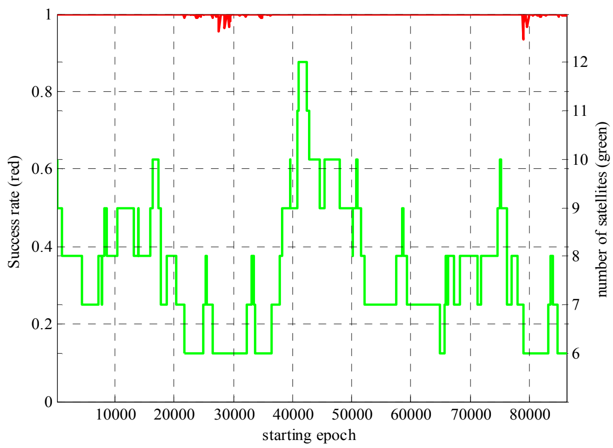

Fig. 7b. 50-s spacing between measurements.

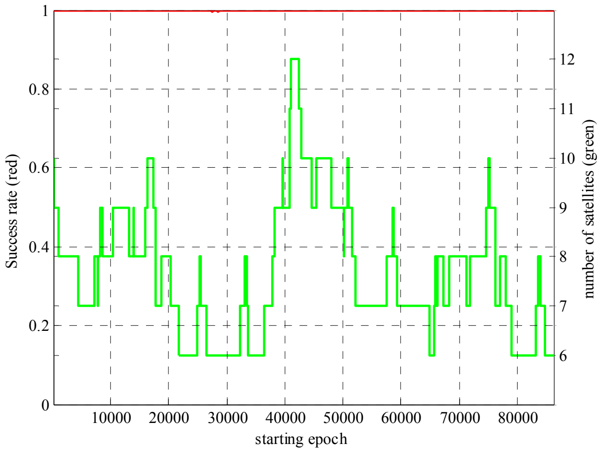

Fig. 7c. 20-s spacing between measurements.

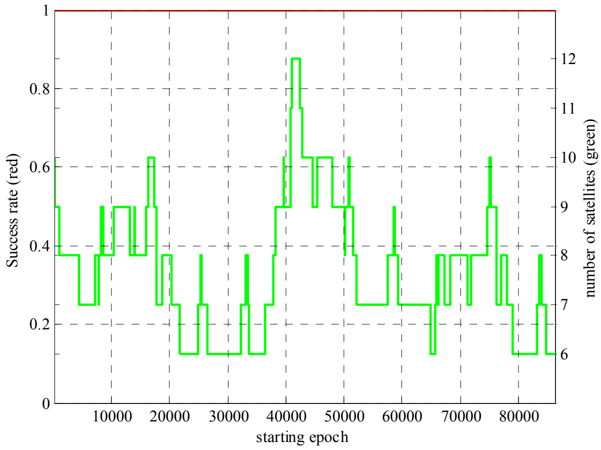

Fig. 7d. 10-s spacing between measurements.

Schüler (Schüler, 2006) reports that 30-s extrapolation leads to 35-mm RMS error in the baseline as compared to a case without extrapolation. However, the article recommends using 5-s - 10-s spacing for the best balance between bandwidth consumption and performance. Accepting errors of few tens of millimeters allows for extending the spacing to 20-s, which was considered maximum interval from the success rate point of view.

8 Analysis of different systems

Fig. 8 shows an analysis of ambiguity fixing success rates over one day for single-epoch fixing attempts (i.e. only one instant of time used). The height of the bar indicates the span of the success rate over the day and the black dot the average success rate. The blue bars on the left are for GPS, the red bars in the middle for Galileo and the green bars for GPS+Galileo hybrid. The method of analysis is detailed in (Verhagen et al., 2007). The assumptions for baseline, time and other parameters are as before.

Firstly, comparing the blue and red bars in Fig. 8 shows that Galileo outperforms GPS in single- and multi-band cases. This is attributable to a greater number of satellites in the Galileo constellation as well as to higher orbit altitude. Both these contribute to a greater number of visible satellites and, therefore, receivable signals.

In the literature it is often stated that selecting frequencies close to each other yields a longer widelane and, hence, improved ambiguity resolution. This is evident, for instance, in results for GPS L1+L2 and L1+L5, in which L2 is closer to L1 in frequency than L5. Consequently, GPS L1+L2 outperforms L1+L5. However, there is a limit to which this effect can be exploited. In all the widelane combinations noise is amplified by a factor that is dependent upon the frequencies. Now, if the frequency separation becomes sufficiently small, the noise amplification becomes dominant over the effect that a longer widelane has on the resolution. This is shown, for instance, in results for Galileo E5a+E5b. Moreover, when using widelane combinations, one must ensure that [1)]real advantage can be gained by using them and that [2)]wide- and narrowlane ambiguities can be decorrelated to such extent that they can be solved. For more discussion see (Teunissen, 1997).

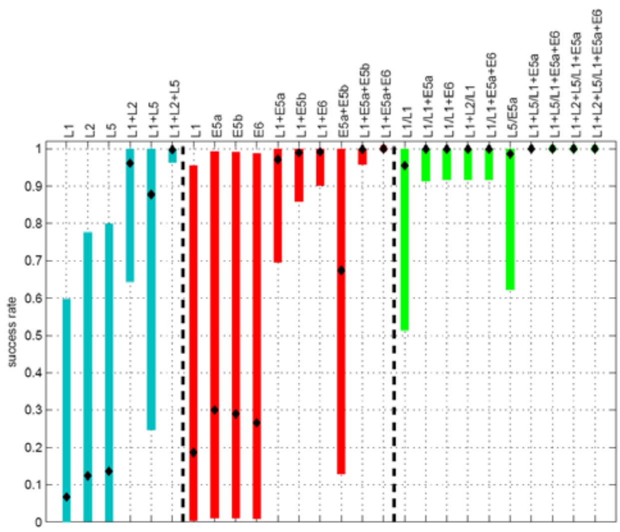

Fig. 8. Single-epoch success rates over one day. Black dot denotes the mean value and the bar the span of success rates over the day. Blue GPS, red Galileo, green hybrid.

Another finding is that the dual-GNSS cases clearly outperform the single-GNSS cases. This is true across all the signal combinations. The main benefit from Galileo is in fact the increase in the number of satellites/signals available for carrier phase -based positioning. However, considering the Galileo-only situation, (Verhagen, 2006a) shows that due to constellation differences, Galileo E1+E5a or E1+E6 performs substantially better at low latitudes than GPS L1+L5 or L1+L2, but at other latitudes no significant differences are observable.

Yet another result visible in Fig. 8 is that adding a third frequency to the solution does not have significant impact on the average success rate, but its span decreases (minimum success rate increases). Hence, a triple-frequency solution has impact on quality-of-service as well as service availability although the average success rate is not affected. Moreover, Richert (Richert et al., 2005) states that the success rate for validation improves significantly as the third frequency is taken into account.

9 Single-frequency field measurement results

Fig. 9 shows field test results for GPS L1 taken 8th January 2007 in Tampere, Finland (61.5° N, 23.7°E) for 300-m and 3600-m baselines, respectively. The number of satellites used varied from 8 to 10.

The code and carrier phase measurements from two GPS measurement engines were double differenced and fed to an extended Kalman filter. Integer ambiguities were solved using the LAMBDA-algorithm using discriminator as the validator with a threshold value of 3 (Tiberius, 1995). Neither ionosphere nor troposphere was modeled and no a-priori model of atmosphere was used.

In the example given the measurement rate was 1 Hz and the time is counted from the beginning of the session. In the beginning of the session the receivers have all the visible satellite stably in track.

It should be noted that if a success rate analysis was made for the current case, the success rate would be very high due to great number of measurements (1 Hz rate). In fact, in the current field tests the ambiguity solution converged relatively quickly, but the solution was validated at 53 and 25 seconds, respectively. As pointed out earlier, the small number of signals (frequencies) makes the validation of the ambiguities challenging (Richert, 2005). This was also confirmed in the reported field tests.

The results show that, when feasible, single-band carrier phase -based positioning is capable of producing cm-level baseline accuracy. On the other hand, the results also show that since with single-frequency measurements it is not possible to compensate for atmosphere without an externally supplied model, there is a cm-level drift in the baseline coordinates. It is assumed that this is due to tropospheric conditions, because the changes are quite slow.

Consider then the accuracy of the baseline, when the integer ambiguities are not or cannot be fixed or validated. In such a case the float solution can be utilized as opposed to the fixed solution. Fig. 10 shows data from the 300-m baseline, which is the same case as in the upper graph in Fig. 9. Only the time span is shorter.

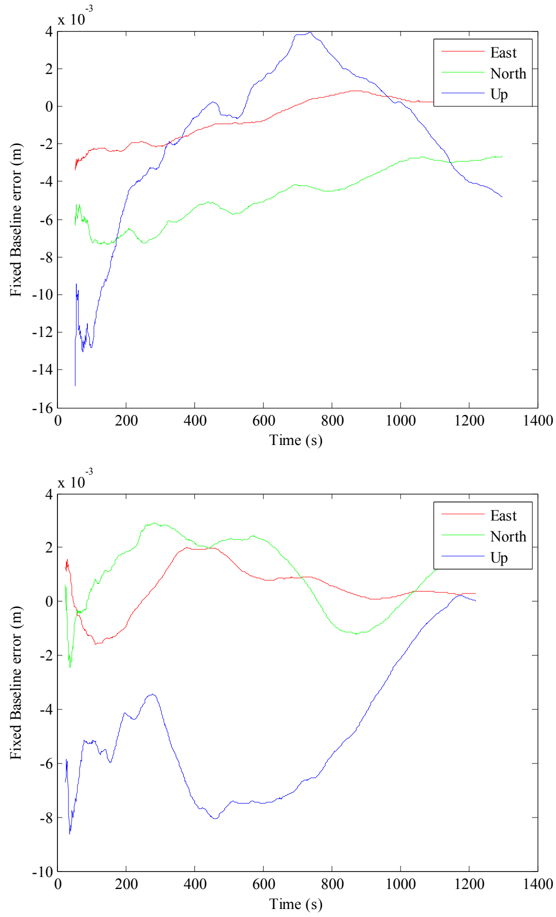

Fig. 9. GPS L1 field test results for 300-m (up) and 3600-m (below) baselines. Time is counted from the beginning of the session. Validation of the solutions took 53 and 25 seconds, respectively.

The upper graph in Fig. 10 represents the baseline obtained by differencing the standalone receiver positions. The error is in the order of several meters in all the baseline coordinates. As expected, the largest error occurs in the up-direction (approximately 5 meters). The lower graph shows the float solution. The float solution is always available (given that there are no cycle slips) and as shown, the error in the float baseline is significantly smaller than in the baseline obtained by differencing the two positions. After 30 seconds from the beginning of the session the errors in the float baseline coordinates are already in the order of 20 cm. Hence, although ambiguity fixing is not nearly always possible in the single-frequency case, the float solution, which is readily available, can improve accuracy significantly.

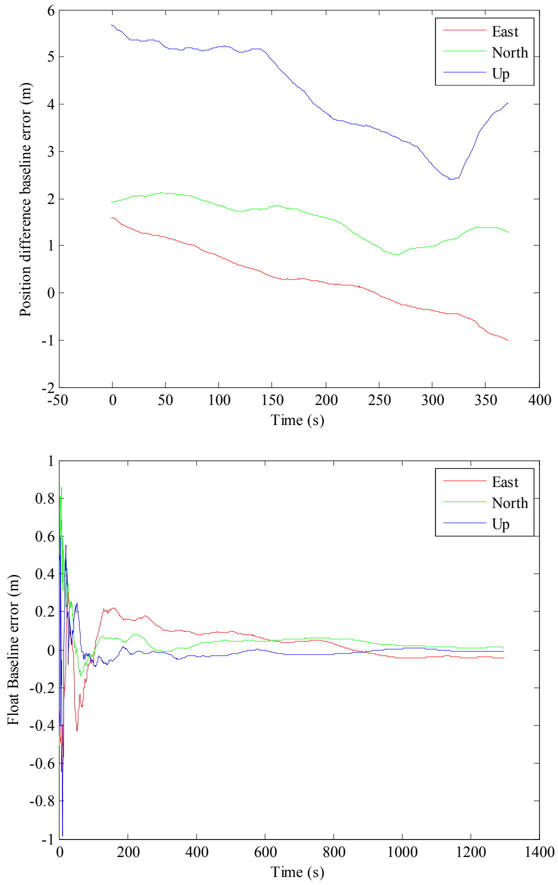

Fig. 10. GPS L1 results for the 300-m baseline. Up: Accuracy obtained using the difference of the receiver positions. Below: Accuracy of the float solution.

10 Bandwidth requirements

The data required for carrier phase -based positioning include

- Time of measurements
- Reference location for the measurements
- Code phase measurements and uncertainties
- ADR measurements, uncertainties and continuities

In the current 3GPP standard releases there are fields for transferring time of measurement, reference location as well as code phase measurements from the AGNSS assistance server to the terminal. The missing fields are ADR (Accumulated Delta Range, or Integrated Doppler), ADR uncertainty and ADR continuity indication.

ADR measurements differ from other measurements in a respect that the range required for the measurement depends upon the reporting interval. This is because of the cumulative nature of the ADR measurement. The requirement for the range is that it must be greater than four times the maximum increase (or decrease) in ADR over the maximum measurement interval. The condition arises from the need to identify the ADR roll-overs and as the condition is fulfilled, the receiving end is capable of detecting the ADR roll-overs. Therefore, the receiver is capable of reconstructing the original measurement by examining the two upper bits of the previous and current ADR measurements. Hence, the number of bits (*b*) required for representing the ADR measurement fulfilling the range requirement can be given by

$$4\cdot\max_t\left|\partial_t ADR(t)\right|\cdot T<2^b \Rightarrow$$
$$b=\left\lceil \frac{\ln\left(4\cdot\max_t\left|\partial_t ADR(t)\right|\cdot T\right)}{\ln 2}\right\rceil \qquad (1),$$

where *ADR(t)* the time-varying ADR measurement in meters and *T* the measurement interval in seconds. Moreover, the resolution of the measurement must be (at least) 1 mm resulting in a requirement to have additional 10 bits (2^{-10} m < 1 mm) for the decimal part.

Now, if the increase (decrease) rate of the ADR would depend solely on the movement of the satellite, one would have for a static GPS-receiver on the surface of the Earth (Parkinson, 1996)

$$\max_t\left|\partial_t ADR(t)\right|<930\,{}^{m}\!/_{s}\,. \qquad (2)$$

Galileo (3000 km higher orbit than GPS - slower orbital velocity) and QZSS (geostationary) have smaller Doppler frequencies than GPS. On the other hand, GLONASS (~1050 km lower orbit than GPS) has 30 m/s greater maximum Doppler than GPS. Hence, 970 m/s is taken as the maximum rate of increase (decrease). However, one must also consider 1)the receiver movement and 2)the receiver oscillator frequency error. The receiver movement can be assumed to contribute at maximum 50 m/s. The receiver oscillator stability is assumed to be better than 1 ppm. Hence, the maximum (apparent) Doppler resulting from this is 2·1ppm·c < 600 m/s. Therefore, the maximum absolute ADR rate of increase (decrease) is set to (970 + 50 + 600) m/s < 1620 m/s. The bit consumption based on equation 1 as a function of *T* taking the decimal part (10 bits) into account is summarized in table I.

In addition to the ADR measurement, carrier phase -based position also requires indication of the measurement continuity as well as on the quality (variance of the measurement). The ADR measurement continuity is defined by 1 bit, which indicates, whether the ADR measurement has been continuous between the current and the previous measurement messages. One bit is sufficient, since the protocols used guarantee that packets arrive in the correct order and that no packets are lost in the transmission channel.

The measurement quality is coded according to the RTCM standard (RTCM, 1998) using a three-bit field and a table mapping the values to ADR measurement uncertainty.

Note that it is also implicitly assumed that the ADR measurement has been corrected for the data bit polarity. Hence, there is no need to transfer the data bit polarity flag between the receivers. Moreover, although there is a field for code phase measurements, it has a resolution of approximately 300 m. This is not sufficient for carrier phase -based positioning. Hence, additional 10 bits are required to increase its resolution down to approximately 0.3 m ($\approx 300 \cdot 2^{-10}$ m).

Therefore, from the bandwidth point of view ADR measurements add some load to the network, but the load can be optimized as shown. The study shows that the reporting interval should be at maximum 20 s, which results in 27+1+3+10=41 additional bits per each signal. Considering an extreme case of 2 bands, 2 GNSSs and 8 satellites per GNSS (corresponding to 32 signals) the average bit rate is 32·41 b / 20 s = 66 bps.

Table I. Bits required for a single ADR measurement for different reporting intervals.

T (s)	bits
1	23
5	25
10	26
20	27

11 About ionosphere modelling

Carrier phase -based positioning benefits significantly from ionospheric modelling. Due to the dispersive nature of ionosphere, phase advance may be estimated, if there are measurements on more than one frequency. However, Richert (Richert et al., 2005) reports that even in a multi-band case it is still advantageous to have a-priori estimate for the advance from an external source. If there is no a-priori information available, the solution is potentially unstable. Moreover, Odjik (Odijk, 2000) reports that ionosphere modelling is essential for long-baseline applications, even if using dual-band GPS measurements.

The common element in the new AGNSS standard provides an opportunity to provide the terminal with an ionospheric model (Syrjärinne et al., 2006). Moreover, the architecture shown in Fig. 1 enables such a service by providing an interface to external services generating such ionospheric predictions. Such a source is, for instance, DLR (Deutsches Zentrum für Luft- ünd Raumfahrt), which can provide space weather forecasts (Jakowski et al., 2002). Providing an accurate ionosphere model contributes significantly on the feasibility of the single-band carrier phase -based positioning.

12 Challenges

The specific challenges to be addressed before carrier phase-based positioning can be added to the cellular standards include, amongst others, the handovers from one serving base station to the other. The carrier phase -measurement need to be continuous over the hand-over, which introduces additional book-keeping exercise to the network. However, if a Virtual Reference Station is used, the terminal can change the VRS without losing the baseline. This can be achieved by subscribing two VRS data streams to the terminal, solving the three baselines (VRS-VRS and 2x VRS-terminal) and discarding the old VRS once the baseline between the new VRS and the terminal has been established. While such an approach is feasible in the user plane, it is difficult to implement in the control plane of the cellular network.

Another concern is the definition of the quality-of-service. The *minimum performance requirements* for Assisted GPS (3GPP-TS-34.171) guide the design and implementation of the terminal. When introducing carrier phase -based positioning to the standards, it must be introduced as a new *positioning method* and similar minimum performance requirements may be required for the new method. Such work requires deep understanding of the use cases as well as the full potential of the technology and extensive field testing. There is currently no work towards such performance requirements.

13 Conclusions

The carrier phase-based positioning has the potential to bring the positioning accuracy down to centimetres. Therefore, it is tempting to consider adding the support for carrier phase-based positioning to the cellular standards.

The analyses presented in this paper show that the most significant problem with single-frequency carrier phase-based positioning is the uncertainty about its performance. The simulations show that during a day there are brief periods during which the carrier phase-based positioning is feasible, but at other times the performance can be expected to be very poor. The lack of measurements (satellites) is the most significant factor contributing to the lack of performance. In conclusion, single-frequency carrier phase-based positioning is not feasible, if there is only one GNSS available and if ambiguities need to be fixed. However, already the float solution, which is always available given that there are no undetected cycle slips, was shown to be a major improvement over traditional point positioning. It was also shown that the single-frequency case becomes very interesting with the introduction of additional GNSSs (Galileo, GLONASS) to complement GPS.

The study also shows that the full potential of Galileo lies in the use of the various available signals. If future terminals are capable of utilizing, for instance, both GPS L1 + Galileo E1 as well as GPS L5 + Galileo E5a (since they are in the same band, respectively) carrier phase -based positioning is no doubt an attractive addition to the current set of positioning methods. However, this requires that the terminals are capable of multi-GNSS multi-band reception and that the cellular standards/protocols support the periodic reporting of ADR measurements from the network to the terminal and/or vice versa.

It was also shown that the capability can be achieved with small additions to the current standards. The average additional data transfer load was shown to be in the order of 66 bps even when there are several GNSSs and signals available. The resulting accuracy is in the order of centimetres in the best case and, hence, it is believed that the implementation task and additional network load is justified.

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