The Development of High Precision Applications with GALILEO

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Keywords: GALILEO, TCAR, MCAR, LAMBDA, WARTK-3, long rage, multi-frequency, kinematic, carrier phase.

Abstract

The support of high precision applications (centimeter level) has been a major driving requirement for the design of the GALILEO signal. This type of application will benefit of the exploitation of four carriers with their corresponding ranging codes in separate data and pilot channels. All these carriers will transmit wide-band signals, therefore providing high quality, quasi multipath-free measurements. This paper presents the performance which could be expected using this powerful signal structure when applying carrier-phase ambiguity techniques. The results are based in a number of studies sponsored by ESA during the last years on the utilization of multi-carrier signal structures for improving user accuracy using single or networked reference station sets. The major conclusion is that GALILEO, with its novel signal structure, will open a wide-range of applications that will make real-time centimeter accuracy, the new standard for reference-station supported applications.

1. Introduction

This paper presents the status of investigations of a number of studies sponsored by the European Space Agency on the field of carrier phase ambiguity resolution techniques aimed to investigate the suitability of the GALILEO signal structure to support this kind of applications. The main attractiveness of the investigations carried out is that besides theoretical analyses on the concept, emphasis has been placed on the use real hardware (laboratory signal simulator, receivers) to arrive to a proof-of-concept of the techniques.

Section 3 presents the earlier results obtained with the three-carrier signal structure which was originally proposed for GALILEO. Those results are now being revised in the light of the 4-carrier signal structure finally adopted for GALILEO. The current status is presented in section 4 and a comparison of different techniques is presented in section 5. Techniques examined so far considered a scenario of a user with a local differential station providing local differential corrections to support the carrier phase ambiguity process. Section 6 presents how this can be extended to wide-area differential networks and the effects of the ionosphere on this scenario are presented.

2. Laboratory experiment on TCAR performances

The idea of using 3 frequencies for real time carrier phase integer ambiguity fixing, the dream of any high precision GNSS user, started in ESA as early as 1996 [01] and a basic algorithm was internally refined one year later [02]. This basic algorithm was named Three Carrier Ambiguity Resolution (or TCAR in short) and was calling to have 3 adequately spaced frequencies transmitted by the then emerging GALILEO system. After these theoretical proposals, it was clear that a laboratory experiment of the concept had to be carried out to proof the concept, and in 1998 an industrial activity was placed with TerraSat and Socratec (Germany) to demonstrate the feasibility of TCAR using real signals and receiver hardware [11].

As hardware transmitter, a GPS/GLONASS simulator was upgraded with the capability of having all GLONASS satellites transmitting the same single specific frequency, modulated with GPS-like C/A and P codes, at the same position and time as the GPS satellites. This approach allows to simulate a GNSS satellite constellation in which satellites transmit a 3 frequency navigation signal, namely GPS L1, GPS L2 and a particular GLONASS channel. The frequency plan was set as close to the GALILEO one (at that time) as possible, and it is shown in Figure 1.

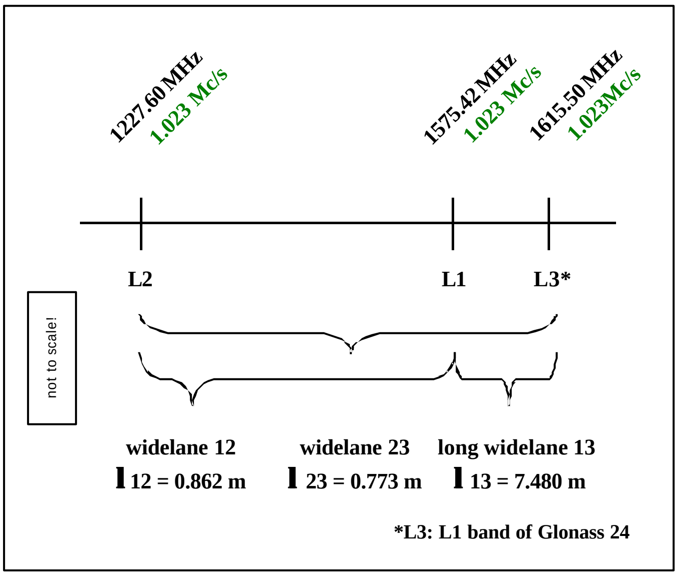

Figure 1: Frequency Plan Used in Initial TCAR Research

On the receiver side and as there were no 3-frequency GNSS receivers available at that time, the AGGA breadboard developed under a different ESA contract for other purposes but which fitted our TCAR receiver requirements was used. The AGGA breadboard is a GPS-GLONASS receiver, validated by Austrian Aerospace, that allows a flexible configuration of its channels enabling correlation with either C/A or P code.

Over 1 month, several scenarios were programmed in the simulator, to cover different conditions of signal to noise ratio, multipath, baseline length, baseline height, rover dynamics and ionospheric delay [12]. The scenarios are summarised in Figure 2: 4 fixed baslines, from a few km the shortest up to several hundreds of km the longest; 2 surface rovers at different distances from the fixed stations and 3 aircraft scenarios to probe into atmospheric effects and baseline length.

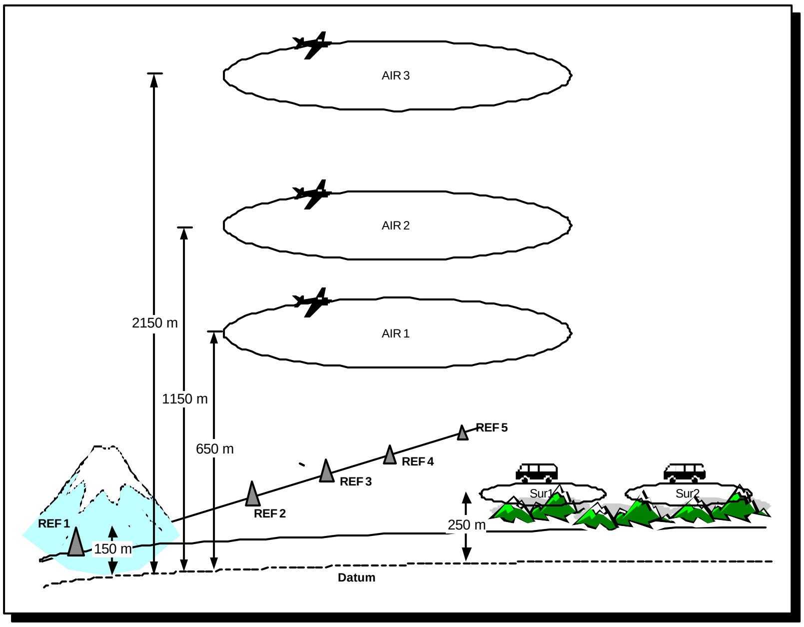

Figure 2: This figure shows the frequency plan in the TCAR lab tests. A GPS-GLONASS simulator was used on which a trick was played. All GLONASS satellites were assigned a single GLONASS frequency on which the GPS C/A code was modulated. GPS L1, L2 and the GLONASS channel presented similar frequency spacing as Galileo's E1, E2 and E5

The scenarios allowed further to compare ambiguity resolution using only 2 frequencies versus the use of the 3 frequencies. The overall outcome of the tests gave a clear advantage of using 3 frequencies with respect to only 2, in particular in the number of epochs required to fix the integer ambiguity correctly and in the robustness of the fixing versus baseline length. For distances of up to 60 km, TCAR proved very successful, with almost 100% of the cases fixing the ambiguity in no more than 3 epochs. For baselines shorter than 10 km the resolution was effectively instantaneous, achieved in 1 single epoch. Two-frequency ambiguity resolution was only achieved after more epochs in both cases.

A typical result from the tests is shown in Figure 3. It shows one of the aircraft scenarios, with respect to a fixed station. The aircraft moves in circles going close and far from the fixed station three times. The baseline changes from 25 up to 50 km (top line of the plot). The integer ambiguity algorithm tries to solve for carrier phase cycles, using an improved version of the original TCAR algorithm. The middle line on the plot shows the number of epochs (1 epoch is 1 second) that were needed to correctly solve the ambiguity. This goes from 1 (real time fixing) up to 5 epochs. The line at the bottom is the noise in the pseudorange due to simulated multipath per satellite which degrades the TCAR algorithm performance. The multipath is made to have a small amplitude and delay at the beginning of the scenario and high amplitude and delay at the end of it. The number of epochs in which TCAR solves the ambiguity increases in general with baseline length and amount of multipath noise. When the aircraft is close to the fixed station (25 km) and multipath is low (starting of the simulation) TCAR fixes the carrier cycles in 1 epoch. When the distance is larger (50 km) or the multipath high (end of the test) the number of epochs increases. Most of the times just 3 epochs were enough to solve the integer ambiguities.

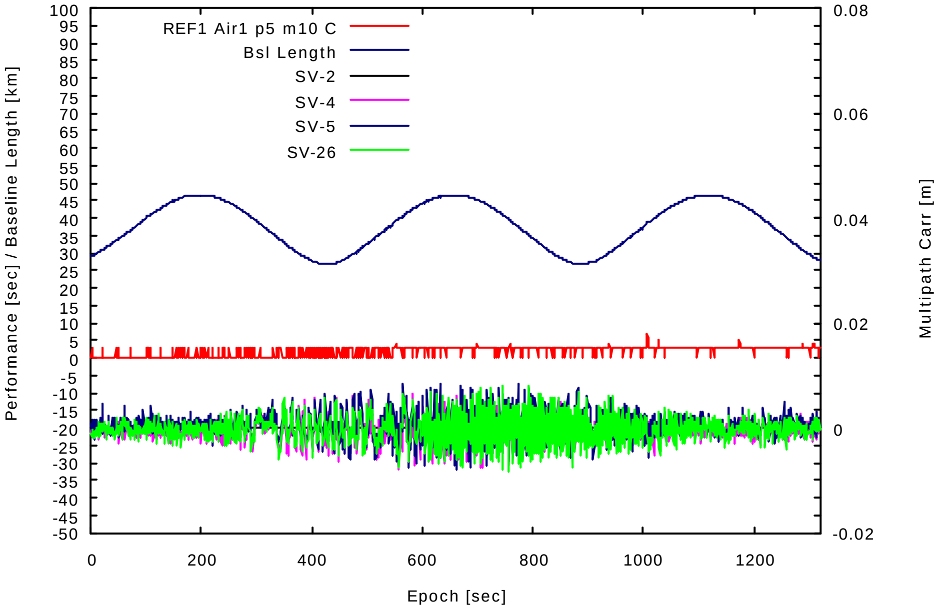

Figure 3: This figure presents one of the baseline results for an aircraft flying in circles at a changing distance of 30 to 50 km from the reference station. Noise in the carrier due to multipath is shown below for each satellite. TCAR ambiguity resolution is obtained in 1-5 seconds, mostly below 3 seconds.

A further laboratory test campaign is being carried out to reflect the finally adopted GALILEO frequency plan which introduces some changes of the center frequencies and the extension of the original three carriers to four. This is explained in the next section. There are further improvements possible in terms of analyzing ionospheric corrections in these new tests proposed, as well as in the use of wide area kinematic networks, which are reported further down in this paper.

Finally, to mention that new applications from the multi-carrier signal structure of GALILEO will certainly emerge in the future, not only for navigation but also for remote sensing of the environment. As an example ESA is studying the use of GALILEO signals for ocean mesoscale altimetry, an important step into the monitoring of oceans and their impact in long term climatology [10].

3. New research activities on MCAR-like algorithms for Galileo

Following the adoption of the new GALILEO frequency plan, illustrated in Figure 4, investigation of carrier phase ambiguity techniques were redirected towards evaluating the advantage of the additional four carrier on E6 for a Commercial Service, and to compare the performance of the GALILEO 3 and 4 carrier scenarios with the performance of the modernized GPS (GPSIII) which will also offer three carriers for civil use. The investigations were therefore generalized to Multi-Carrier Ambiguity Resolution techniques (MCAR).

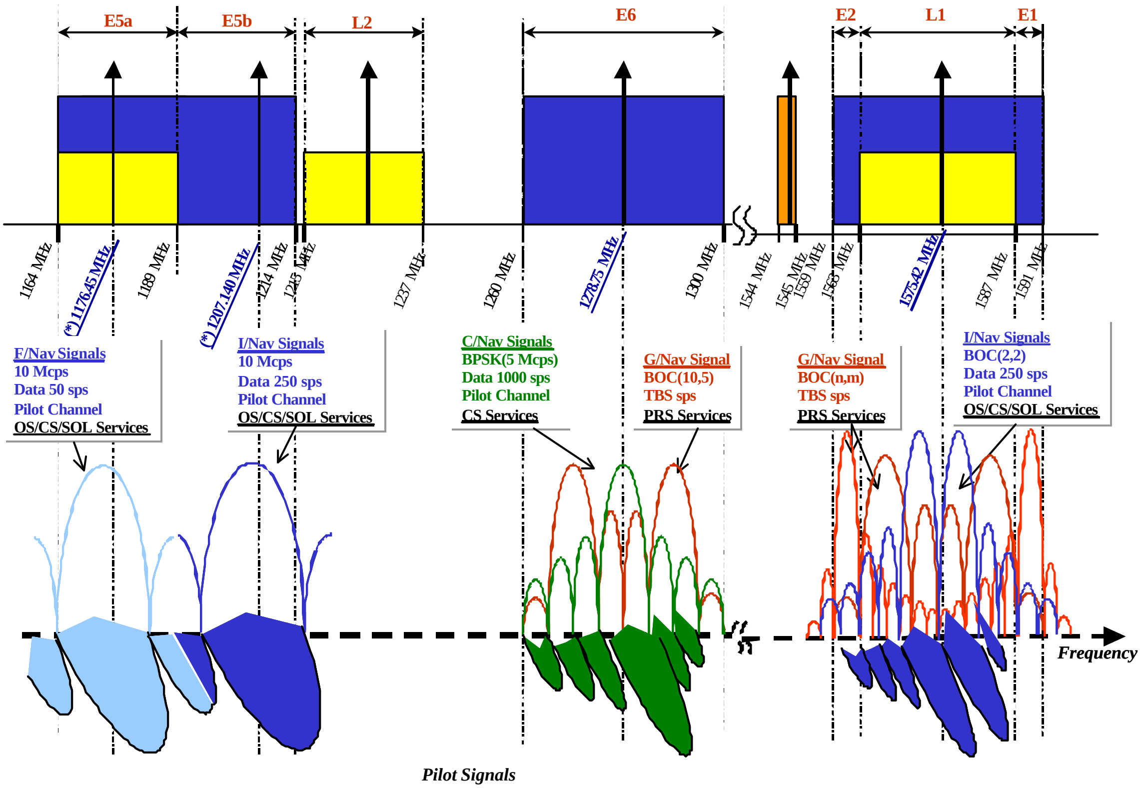

Figure 4: GALILEO Frequency Plan

The activities will tackle in detail the L1-L2-L5 GPS III, and the L1-E5b-E5a Galileo frequencies scenarios, pointing the potential advantages and drawbacks of each. The capabilities of a MCAR algorithm are result of the tracking errors, both for code-phase and carrier-phase, and the frequency shift between the navigation carriers. In terms of frequency distribution both scenarios are somewhat similar as two central carriers are shared, namely L1 and L5/E5a (1575 Mhz and 1176 Mhz respectively), and the remaining one L2/E5b is shifted approximately 20 Mhz (1227.6 Mhz and 1207 Mhz respectively). In terms of tracking errors both scenarios might differ as for each Galileo carrier they are expected to be comparable to those currently achievable with GPS-P code, while in GPS III case it is planned to transmit C/A ranging codes in both L1 and L5.

It will be analyzed as well what can be expected in terms of performances when processing all Galileo carriers, namely L1, E6 (1278 Mhz), E5b, E5a being this scenario a direct application of the MCAR algorithms under investigation.

For each of the above described frequency scenarios, different user environments are planned to be analyzed, by modifying the rover dynamics, covering those of RTK geodetic, automobile and aeronautical applications, as well as the distance between rover and reference. A specific analysis will be carried out for the static case in order to clarify the maximum baseline length, in which (assuming nominal ionospheric conditions) the technique can still succeed. The performances during landing, including unexpected levels of jerk will be carefully assessed as well. All the resultant scenarios will be generated in a fully controlled environment, laboratory conditions, by means of a Navigation System Signal Simulator and an adapted multipurpose hardware that allows tracking a wide range of navigation signals.

At time of print, data were being collected with the simulators. The results are planed to be available in October. Preliminary analyses on the concept point a potential improvement of performance for the four carriers scenarios with respect to three carriers only.

4. Comparing quality control LAMBDA to TCAR and CIR

Quality control has always been an important topic in GPS data processing. With the future introduction of new and/or modernized Global Navigation Satellite Systems (Galileo/GPS) it is of great interest to analyze the expected quality of those systems and combinations thereof. This is already possible at this stage, since no actual data is necessary in order to perform such a design and feasibility analysis. Quality control parameters to be considered include measures for internal and external reliability as well as accuracy and integrity.

With the envisioned introduction of three-carrier GNSS systems, being modernized GPS and Galileo, new methods of ambiguity resolution have been developed. In a project of ESA with the Technical University of Delft, Faculty of Geodesy, two important candidate methods for triple-frequency ambiguity resolution, being ITCAR (Integrated Three-Carrier Ambiguity Resolution) [02] and CIR (Cascading Integer Resolution) [11], are compared with the already existing LAMBDA for three frequencies (Least-squares Ambiguity Decorrelation Adjustment) [05] method.

The TCAR, CIR and LAMBDA methods for GNSS ambiguity estimation are compared at three different levels. First, the three methods are compared at the conceptual level. This reveals the basic assumptions involved in either method and shows conceptual similarities and differences. The consequences and significance of the differences are also described. Next the three methods are compared numerically. This involves the complexity and the computational load of either method. Finally the performance of the methods is compared in terms of the probability of correct integer ambiguity estimation [06]. In order to compare the methods on those aspects, the three methods will be applied to various GNSS data processing models and the differences in performance will be explained.

This comparison is of importance in order to understand the strengths and weaknesses of these three methods. It will help developers, users and practitioners alike in making their choice between the different methods for their particular application at hand.

At the time of print, only the conceptual comparison has been concluded. Results are reported below.

4.1. Conceptual comparison

The three methods differ essentially in the following aspects. First, the ambiguity resolution in case of TCAR and CIR is always based on the geometry-free model, whereas in case of the LAMBDA method ambiguity resolution is based on whatever model the user believes is suitable for his/her problem. This implies that in case of the LAMBDA method all available information in the model is actually used. This is important, since in most cases the user is finally interested in geometric information (baseline coordinates), and using the relative satellite-receiver geometry can greatly enhance the performance of ambiguity resolution.

All three methods perform a decorrelation step, although the reason to do this is different. In TCAR and CIR, the decorrelation is necessary to increase the probability of obtaining the correct result. LAMBDA, since it is based on the integer least squares estimator, will always find the most likely candidate. Here the decorrelation step is necessary to optimize on computational efficiency. In general the LAMBDA decorrelation will achieve (much) better decorrelation than the pre-defined decorrelations as used in TCAR and CIR. This also means that LAMBDA is suitable for any integer estimation problem, independent of the number of frequencies as well as independent of the actual frequencies, which means that LAMBDA can also be applied to possible hybrid Galileo/GPS systems.

5. Wide Real Time Kinematics with three-carrier phases (WARTK-3)

5.1. Introduction. WARTK-3 Algorithm

The planned three-carrier satellite navigation systems, Modernised GPS and GALILEO, offer the potential advantages of high success and integrity in instantaneous ambiguity resolution. However, The ionospheric differential refraction, at distances of tens of kilometers or more, is one of the main problems affecting the capability of instantaneous carrier phase ambiguity resolution, and hence the feasibility of centimeter-accuracy navigation at long distances from the reference station.

Techniques proposed so far to improve the instantaneous positioning by using three-frequency systems, such as Three-Carrier Ambiguity Resolution, or TCAR, and Cascade Integer Resolution, CIR [11], share a similar basic approach: the double differenced integer ambiguities are successively solved from the longest to the shortest beat-wavelength, including "extra-widelane" and "widelane" combinations of carrier phases, and the first carrier L1. In particular, TCAR is one simple approach that tries to instantaneously solve (single-epoch) the full set of ambiguities. But TCAR performance is strongly affected by the ionospheric refraction decorrelation with the distance. As a consequence, an Integrated TCAR approach (ITCAR) has been developed by several authors [11], including search algorithms and a navigation filter in which the ambiguities are part of the outputs and the ionospheric residual errors are coarsely estimated. But the ITCAR algorithm is still affected by the lack of knowledge of the double differenced ionospheric refraction, limiting the ambiguity success for distances greater than tens of kilometer [12]. The conclusions are still applicable to MCAR algorithms operating on the basis of four carriers, as they would be available for GALILEO.

The Technical University of Catalonia (gACE/UPC) has shown in previous works that a real-time tomographic model of the ionosphere, obtained from dual-frequency data from a network of fixed sites, in combination with a geodetic program, is accurate enough to allow GPS real-time carrier phase ambiguity resolution for a rover at hundreds of kilometers from the nearest reference site. gACE/UPC has now, under ESA contract, extended the technique to three frequencies, allowing to use the TCAR technique at medium and long distances (from tens to hundreds of kilometers), and with a minimum of geodetic computation. The techniques developed by gACE/UPC as part of that study is the Wide Area Real Time Kinematics with three carrier (WARTK-3). The main improvement of the WARTK-3 is in the 3rd TCAR step, where the critical problem is the ionospheric refraction that could introduce errors greater than .5 cycles. This limitation is solved by using the real-time ionospheric corrections provided by the ionospheric model running continuously in a central processing facility.

$$\nabla\Delta\hat{N}_1 = \frac{1}{l_1}\nabla\Delta\left(L_1 - L_w + l_w N_w\right) = \nabla\Delta N_1 - \frac{1}{l_1}\nabla\Delta(e_w + m_w - m_1) + \frac{1}{l_1}\left(a_1 - a_w\right)\nabla\Delta I + \ldots \quad (6)$$

TCAR 3rd step.

In addition, an ambiguity integrity real-time test, as far as a simple pseudorange multipath mitigation approach, have been incorporated in the algorithm, improving the performance.

5.2. WARTK-3 System

The WARTK-3 System would be base on a network of reference stations collecting a minimum of three frequency data, computing real-time ionospheric corrections in an ionospheric filter feed with the reference stations data and received and used successfully by the users for solving the ambiguities in real-time in 3-frequency systems such as Modernised GPS and GALILEO (see Figure 5). These accurate ionospheric corrections are broadcasted to the users who incorporate them to the original and simple TCAR algorithm. WARTK-3 is in this way a quite simple algorithm, in particular with a low computation load for the user, compared with ITCAR and also with WARTK, algorithm developed for the two frequencies GPS.

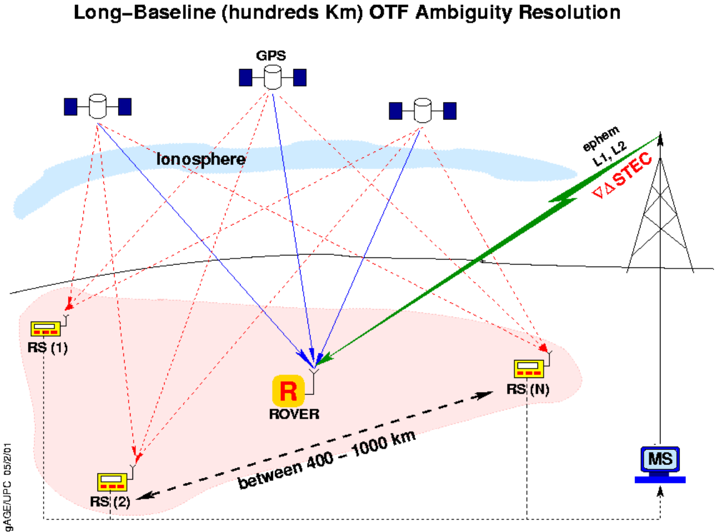

Figure 5: The Wide Area Real-Time Kinematics System (WARTK-3)

This approach fills a gap in the typical accuracy versus baseline length plot (see Figure 6) between the Local Area DGPS (or GBAS) systems, which provides such centimeter accuracy, but limited to distances below 20 km, and the Wide Area Augmentations systems (WAAS, EGNOS, MSAS), with meters accuracy extended to thousands of kilometers. The WARTK-3 technique would provide subdecimeter errors at hundreds of kilometers baselines.

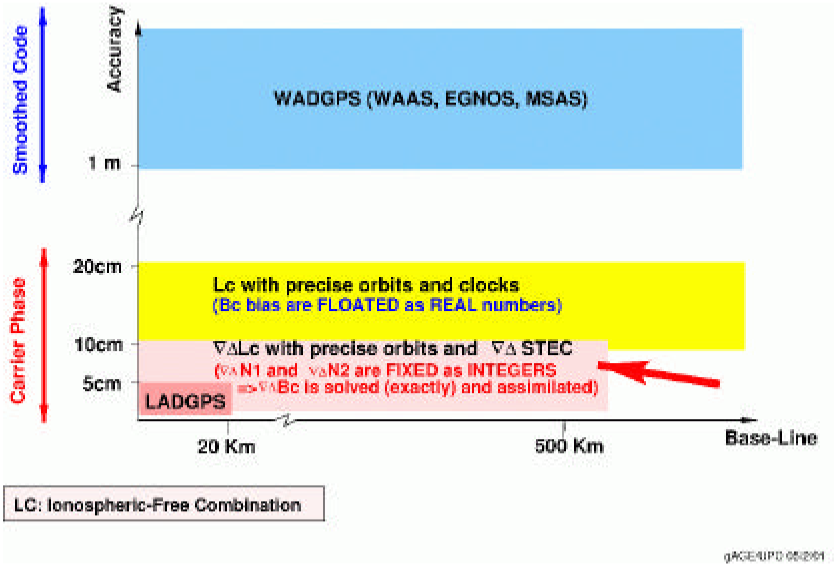

Figure 6: Accuracy versus baseline length (from the nearest reference site) plot for different GPS differential systems.

5.3. WARTK-3 Performances

The performance assessment was done based on several datasets, with simulated airplanes, surface roving users, and fixed sites. The datasets were generated with a modified GNSS satellite signal generator, provided by ESA in the context of a previous funded study. The two GPS carriers (at 1575.42 and 1227.60 MHz), and the GLONASS channel 24 carrier (at 1615.50 MHz) were the three frequencies adopted by the GNSS simulator for 4 satellites in view for 20 minutes at 1Hz, using the available 12 channels of an AGGA validation receiver. These data being adequate for real-time ambiguity determination studies is very limited (just 4 satellites) for navigation purposes.

Several scenarios were used with different environmental conditions in terms of signal power, multipath, user dynamics, ionosphere and distances between reference stations (up to 129 km baseline).

A summary of the main ambiguity resolution results is shown in the next Table, for atotal number of 3834 trials, where the success in the three TCAR steps is indicated in three cases: (a) without ionospheric corrections, (b) with the corresponding Klobuchar model ionospheric corrections broadcast by the GPS system and (c) with the real-time tomographic ionospheric corrections.

P5-M0 / SUR2-REF5 (≈129km)	Success $\nabla\Delta N_{ew}$	Success $\nabla\Delta N_{w}$	Success $\nabla\Delta N_{1}$
Without ionospheric corrections	100%	100%	0%
Klobuchar corrections	100%	100%	33%
Real-time tomographic correct.	100%	100%	92%

Table 1: Ambiguity resolution success relative to the total number of trials on resolving On-The-Fly the extrawidelane, widelane and L1 ambiguities (respectively $\nabla\Delta N_{ew}$, $\nabla\Delta N_{w}$ and $\nabla\Delta N_{1}$)

The datasets available for this study, in spite of being adequate to work out the instantaneous ambiguity resolution, are very limited to determine the single epoch position (4 satellites in visibility). With another dataset containing a realistic set of 6 or more available satellites (available in the near future), this hard limitations to positioning will disappear, providing better geometry (smaller DOP) and the possibility to detect and filter out the satellites (typically none, or sometimes one) presenting ambiguity errors (using a navigation filter or Receiver Autonomous Monitoring Algorithms, RAIM).

The corresponding results to the 4 satellites are illustrated in the figure below, containing from top to bottom the prefit residuals, and the East, North and Vertical components of the instantaneous positioning error (all in meters) after using WARTK-3. The corresponding navigation, in spite of the limited number of 4 satellites available in the datasets can be done instantaneously, in single-epoch mode, with RMS of 3, 5 and 2 cm in East, North and Vertical components.

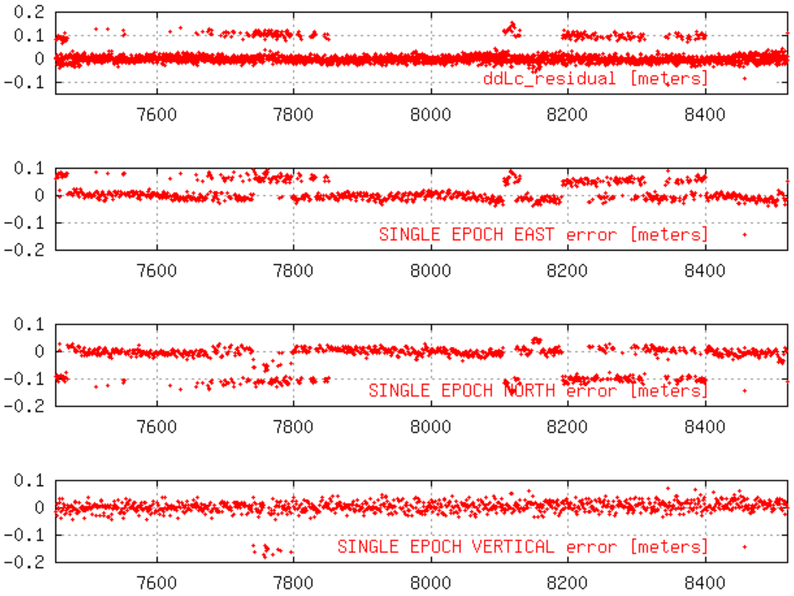

Figure 7: Prefit double differenced Lc residual (top plot), and instantaneous (single epoch) navigation errors in East, North and Vertical (up) components (2nd to 4th plots) obtained with WARTK-3 for the rover trajectory at about 130 km from the reference site

In order to characterize the impact of latencies in the ionospheric correction (due for instance to potential problems in communications), we have considered delays from 1 to 30 seconds (30 epochs) in the ionospheric correction computations within the fixed sites network. For each of these delays, the success percentage on achieving successful ambiguity resolution have been computed. It can be seen that after 5 minutes the success decreases from 90 to 85%. After 10 minutes, the success decreases to 75%. These numbers can worsen in scenarios with still higher differential ionospheric delay variation. Then it can be seen that at mid-latitude the latency is not an issue for WARTK-3, that can support in the ionospheric model up to about 5 minutes of latency.

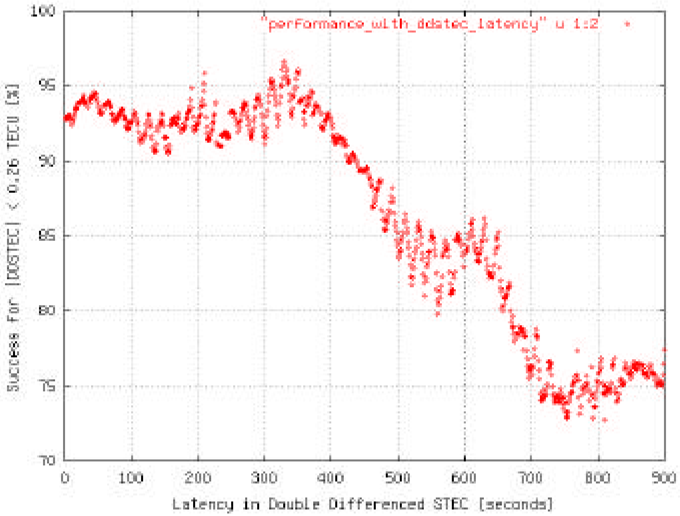

Figure 8: Percentage of success on instantaneous double difference ionospheric determination is accurate enough to solve the full ambiguities

The WARTK-3 performance has been also checked in other difficult scenarios such as lower latitude (35 degrees instead of 48 degrees) with higher ionospheric values, extreme conditions in the tropic, below the Northern Equatorial Anomaly of the Ionosphere, and high dynamics.

5.4. WARTK-3 Conclusions and Future Work

As the main conclusion, the results of this study, applying the real-time ionospheric corrections with a minimum of geodetic computation load, suggest the feasibility of instantaneous full ambiguity resolution, that allow the centimeter-accuracy navigation, at distances of more than 100 km, with future systems such as GALILEO and modernized GPS. This conclusion is supported by an exhaustive study performed under the ESA study.

Additional improvements in the presented technique WARTK-3 is being achieved under a new ESA activity with the gACE/UPC regarding the following points: Gathering a more realistic and higher number of satellites in the signal simulator, than the four available in this dataset, Adding more reference stations in the perimeter of the network, running the user its own ionospheric filter, combining its ionospheric observations and the ionospheric corrections broadcast by the reference network, using a navigation filter approach, instead of a single-epoch approach.

6. Conclusions

The multi-carrier signal structure of GALILEO will translate into an unprecedented capability, namely real-time centimeter accuracy over long baselines. The theoretical and experimental work summarised in this paper shows such a potential. This will come in addition to a more robust operation of integer ambiguity fixing with respect to multipath, interference and atmospheric effects, thanks to the number of frequencies used, higher transmitted signal power and the support of ground kinematic networks.

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