

Feasibility Study of a European Wide Area Real Time Kinematic System

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ABSTRACT

The Wide Area Real Time Kinematic is an accurate navigation technique proposed several years ago by the gAGE/UPC authors and Oscar Colombo from GSFC/NASA. It is mainly based on an optimal combination of precise real-time GNSS geodetic and ionospheric modelling, applied to the data of a permanent network of GNSS receivers. In this way, accurate WARTK corrections can be provided to the users, allowing for navigation with typically a few centimeters of error, and supported by a relatively sparse network of receivers, which could be separated many hundreds of kilometers. This is the case of the EGNOS RIMS, for example.

In this context, the FES-WARTK project was initiated at the end of 2006 with the purpose of demonstrating the feasibility of WARTK: Analysing in detail many aspects of both the Processing Facility (PF) and User algorithms: performance of corrections, robustness under difficult conditions, including permanent receiver failures, are some of the points studied for the PF. The potential contribution of optimal ambiguity fixing techniques, such as the LAMBDA method, was another point studied during this project.

Several of the main achievements fulfilled in this project were:

- 1) Successful use of actual EGNOS RIMSs carrier phase data as part of WARTK CPF.
- 2) Several points of the WARTK CPF algorithms pending of final study have been successfully consolidated: suitability of predicted precise IGS orbits, small degradation of CPF performance in the network edges, quite accurate WARTK satellite and receiver clocks and vertical tropospheric delay estimation, among others.
- 3) Full coverage over European Union by adding 4 additional RIMSs (Balkans, Scandinavia, Netherlands and Spain).
- 4) Different aspects of the technique at CPF level have been checked with Galileo simulated data, showing the consistency and accuracy of the different “products” computed in real-time by the CPF.
- 5) At the user level new experiments have confirmed previous results, in particular the capability of instantaneous (single-epoch) precise navigation with three-frequency systems, such as Galileo.
- 6) The results presented so far about application of LAMBDA method, as an add-on to WARTK user algorithm, seems to provide a certain reduction of convergence time.
- 7) Very first, but promising, results on WARTK integrity have been found with actual GPS data.

Summarizing, the experimental results confirm the feasibility of the WARTK technique in order to provide subdecimeter-error-level navigation by using GNSS reference receivers, such as the EGNOS RIMSs, providing in general better real-time performance (higher accuracy and, specially, lower convergence time) than other techniques (such as PPP). We believe that this feasibility of WARTK from the point of view of high precision navigation service at continental scale (for instance based on the present EGNOS GPS-only RIMSs or in future upgraded GPS+Galileo RIMSs) is a significant result, taking into account in particular the present and future WARTK applications: We have also shown in this project that there is an existing market for the WARTK technique, and that there exist further new applications to be exploited in a wide range of fields in which WARTK would be a leading technique.

INTRODUCTION

The ionospheric delay is the main source of error which limits the extension of the classical High Accuracy Positioning service provided by techniques like Real Time Kinematics (RTK) or Virtual Reference Station (VRS), from local to wide-area coverage. The assumption of negligible differential ionospheric delay between the dual/multi-frequency

roving user and the closer reference receiver is not valid beyond few tens of kilometers, and cannot be used in such techniques as a valuable additional condition to solve the carrier phase ambiguities in real-time, with the associated accuracy of tens or less centimeters. The Wide Area RTK technique, introduced by the authors in 1999 (Hernández-Pajares et al. 1999, Colombo et al. 1999) solves this problem by introducing a real-time technique to provide users with an accurate ionospheric estimation in the core of the precise geodetic processing. This model has two main components, firstly, the linear/larger scale electron content variations by means of a tomographic inversion based on data coming from a network of permanent GNSS receivers that can be separated up to many hundreds of kilometers (Hernández-Pajares et al. 2000, 2002). And secondly by developing a simple but efficient model to mitigate the more frequent non-linear ionospheric effect, associated to the ionospheric waves called “Medium Scale Traveling Ionospheric Disturbances” (MSTIDs, see Hernández-Pajares et al. 2006a-b). This two aspects are well integrated with an efficient approach to ensure a right ambiguity fixing, between the permanent GNSS stations, and specially between the roving user and the nearest permanent site. As a results of this technique, the feasibility of providing a High Precision Accuracy service supported by existent Wide Area GNSS networks of permanent stations (such as the EGNOS RIMSS) is open, providing to the user a typical error of about 10 centimeters, and with a certain potential integrity, as it has been confirmed in the recent FES-WARTK activity supported by the European Space Agency. The main achievements of this project are summarized in next sections, divided by the different points of the technique: Central Processing Facility (CPF), User, and implementation and application aspects.

WARTK CENTRAL PROCESSING FACILITY (CPF)

A set of permanent GNSS receivers is required to build the precise corrections needed by the WARTK user to navigate with errors of about 10 centimeters, in particular the critical ionospheric correction (see for instance Hernández-Pajares et al. 2002). In this context the actual data of the existing network of permanent EGNOS receivers RIMS, and signal-simulated Galileo datasets on other hand, have been analyzed to determine its adequacy.

Input data: RIMSS and simulated GALILEO datasets

It has been found that the RIMSS data is adequate as main information to feed the WARTK CPF (see below), excepting for an issue regarding to the non-integer character of the double differenced carrier phase ambiguities. An example of this anomalous behaviour (not affecting at the initial purpose of this permanent receivers, to support the carrier-smoothed pseudorange-based navigation under EGNOS) can be seen in Figure 1 (left-hand plot), in which the fractional part of the double differenced carrier phase widelane ambiguities of RIMS A020 and RIMS B100 regarding to VALE permanent IGS receiver are not concentrated around 0 (red and green points respectively). However the double differenced widelane ambiguities of permanent EUREF receiver MALL regarding to the same type of receiver VALE (blue points) shows the expected integer behaviour with values close to 0 cycles.

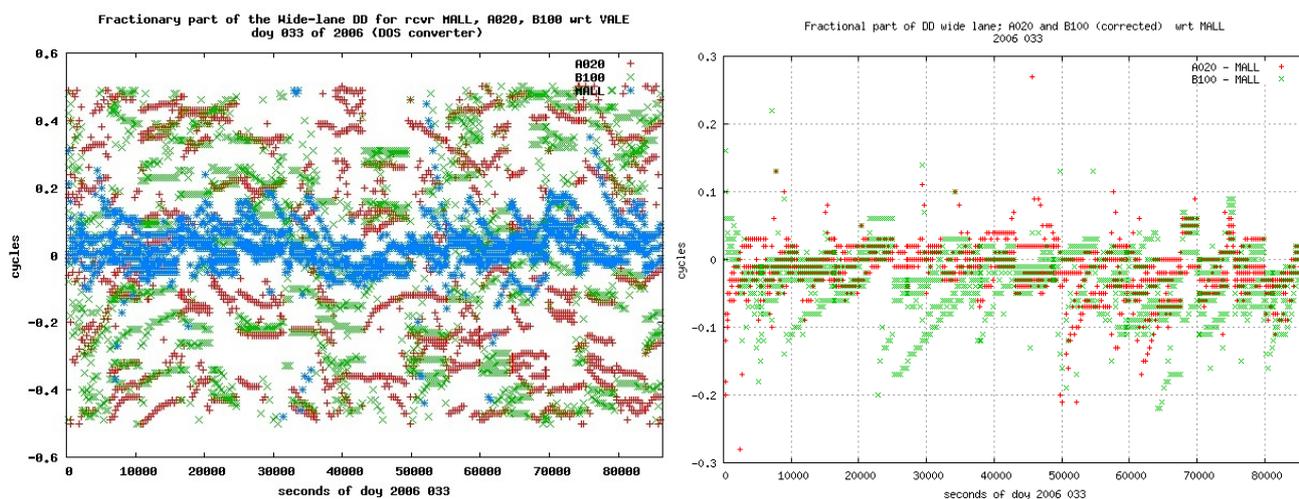


Figure 1: [Left-hand plot] Fractional part of the DD wide-lane ambiguity for the EGNOS RIMS A020 (red) and B100 (green) and the EUREF station Palma de Mallorca, MALL in blue. [Right-hand plot] Equivalent as left figure but computed for A020 and B100, using WARTK corrected ambiguity values (day 33 of year 2006).

The cause of this problem, the initialization to zero of the first carrier phase measurement, has been confirmed by the Industry. In the meantime this problem can be fixed in next RIMSS update (strongly recommended), it can be repaired for testing purposes emulating real-time conditions, by means of applying WARTK in post-processing mode with nearby permanent GPS stations, from the IGS network for example. The repaired widelane ambiguities of the RIMSS carrier phases can be seen in Figure 1 (right hand plot). This repairing process was used in this work (see below). On

the other hand we have simulated several datasets with the GSVF-2 signal-simulator and the GETR receiver at ESTEC. In order to do that the identification and fixation by software of functioning problems of the simulator and receiver, most important the synchronization of the GETR measurement files, has been performed.

Algorithms: additional checking and consolidation

Several points of the WARTK CPF algorithms pending of final study have been successfully consolidated in FES-WARTK with the help of representative datasets of actual GPS measurements. To do that the IGS permanent receivers represented in Figure 2 (left-hand plot) have been used to feed the WARTK CPF, during one week of 2006, days 346 to 352. This period includes a severe ionospheric storm, with the geomagnetic activity index (Kp) being close to the maximum value of 9 in days 348-349 (Figure 2, right-hand plot). During this strong event of Space Weather, the electron content over Europe increased up to about 50% in some parts of the day (see Figure 3, left-hand plot), with a corresponding uplift in the distribution of free electrons (see Figure 3, right-hand plot). So this data is valid for testing also the performance under high ionospheric activity.

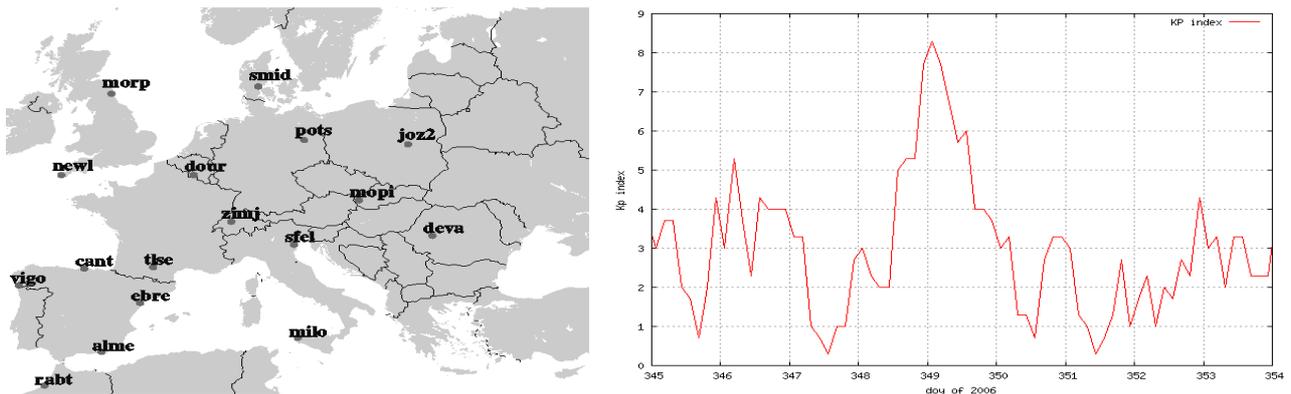


Figure 2: [Left-hand plot] Network of permanent IGS receivers used in the WARTK CPF study, having similar distribution to the EGNOS RIMs. [Right-hand plot] Geomagnetic activity index (Kp) represented during the first studied period to complete the WARTK CPF characterization.

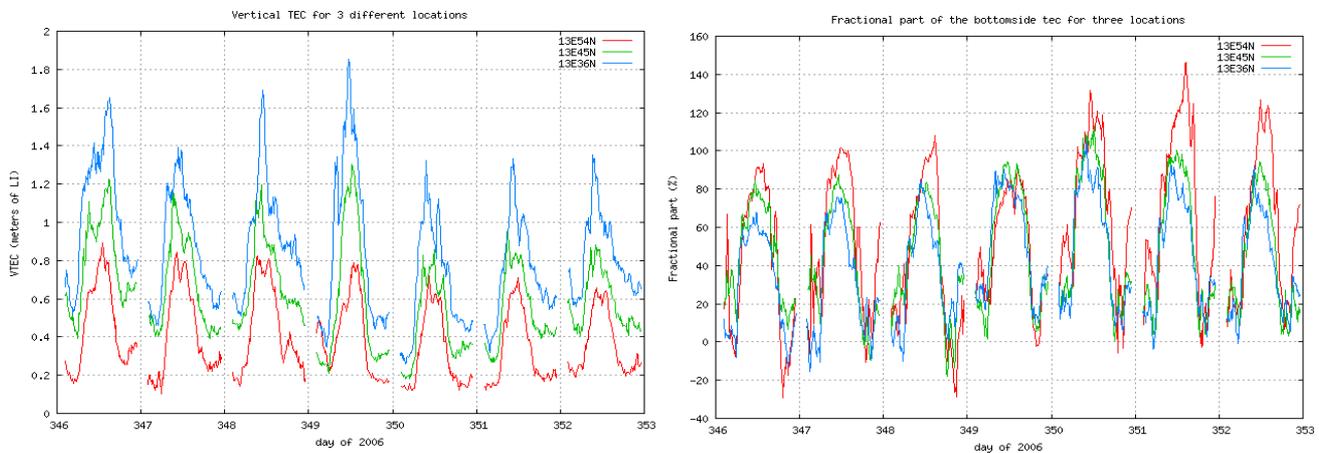


Figure 3: [Left-hand plot] Vertical Electron Content, computed by the WARTK CPF during the experiment, for three different locations in the same meridian (longitude of 13°E and latitudes of 36°N, 45°N and 54°N in red, green and blue lines respectively). [Right-hand plot] The fractional part of the bottomside electron content (computed as well in real-time by the CPF) is represented for the same period: it is evident the uplift during day 349, coinciding with the ionospheric storm shown in previous plot.

One of the points which could affect the performance of the WARTK CPF is the error in the GPS satellite orbits. It can be seen in Figure 4 left-hand side the comparison of the precise IGS predicted orbits (IGS “ultrarapid” orbits, IGU) versus the final IGS orbits. It can be seen that the 3D accuracy of the IGU orbits is at the level up to several decimeters except for some GPS satellites that can present worse accuracies (because maneuvers, eclipses, etc.). These accuracies degrade as long as the forward prediction time interval increases. The comparisons start each day at 03:00 UT because of the time needed for the PF convergence and only the data processed by the PF (with fixed ambiguities) are shown (blue points). Notice that the WARTK CPF can handle orbits with errors larger than several decimeters (see additional results below). And, despite some satellites having orbital errors of several decimeters, the WARTK PF can handle

these large errors and correctly fix the DD ambiguities (see Figure 5). This is because of the only impacting orbital error component in the error orbit is its projection on the Line of Sight (LOS), in such a way that, if this component is not very different from one LOS to another, the major part of this orbit error will be charged in the clocks estimation (see Figure 4 right-hand plot) and it is possible to fix ambiguities correctly.

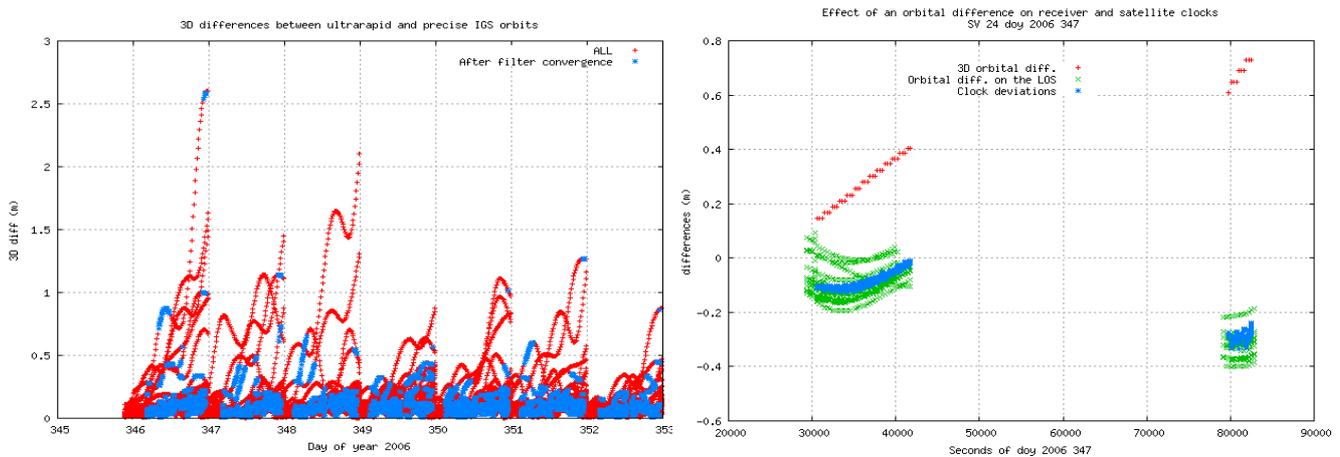


Figure 4: [Left-hand plot] Evolution of the precise predicted IGS orbits 3D error compared with the final IGS orbits during the WARTK CPF experiment. [Right-hand plot] 3D IGS orbit error (red points) compared with the LOS error projection from the different PF receivers (green points), compared with the corresponding satellite clock deviations (blue lines) – satellite SV 24, day 347 of 2006-.

The limited degradation of carrier phase ambiguity fixing with regards to distance of permanent network center can be seen in Figure 5 for both precise predicted IGS orbits (blue) and final IGS orbits (red points). The percentage with IGS orbits is a little bit better than with the IGS ones (implicit filtering in the IGS orbits computations excluding some problematic satellite orbit intervals). The ambiguity fixing percentage is always better than a 80% for receivers up to 1000km (for both IGS and IGS orbits). There is only a small degradation with the distance, i.e. the ambiguities are well solved also in the border of the network. These percentages are also maintained for days 349 and 350, during the ionospheric storm.

The nominal accuracy of IGS clocks is about 5ns (1.5m). WARTK PF computes its own system time taking the clock of the reference receiver as the reference clock. So it is possible to compare the clocks estimations for both satellites and receivers. The satellite clocks estimated by WARTK are also quite compatible with the IGS ones (left plot in Figure 6), in spite these clocks are obtained from a regional network. As sake of reference, the comparison with JPL clocks (which take part of the IGS combined clocks) is also shown in Figure 6, left plot. In particular, the WARTK satellite clocks RMS (compared with IGS ones) is 0.5 ns not so far from the JPL solution. The WARTK receiver clock estimation is still more compatible with IGS and GIPSY determinations, with discrepancies at the level of few tenths of ns (Figure 6, right hand plot).

An additional WARTK CPF product, which is at the same time a good demonstration of the geodetic CPF performance, is the vertical tropospheric retrieval. It can be seen (Figure 7) that the zenith tropospheric delay (ZTD) differences are typically below 1 cm (RMS of 6 mm), when it is compared with the post processed solution given by GIPSY (a similar accuracy level that the nominal Near Real Time IGS ZTD computed with a latency of 2-3 hours).

Summarizing, the main conclusions about the detailed WARTK CPF performance with actual GPS data are:

- (a) The predicted precise (ultrarapid) orbits, behave “quite well” under WARTK (only few cases –less than 0.006%–generating some trouble, but they are detected in real-time).
- (b) The degradation of the CPF performance is small with respect to the distance of the corresponding RIMS to the network center.
- (c) The satellite clocks estimated by WARTK CPF are also quite compatible with the IGS ones, at the level few tenths of ns, regardless these clocks are obtained from a regional network.
- (d) The WARTK receiver clock estimation is even more compatible with IGS and GIPSY determinations, with discrepancies at the level of few tenths of ns.
- (e) A good agreement (typically better than 1cm) is found in the zenith tropospheric delay: differences are typically below 1 cm (RMS of 6 mm), compared with post processed GIPSY solution (similar accuracy level that the nominal Near Real Time IGS ZTD computed with a latency of 2-3 hours).

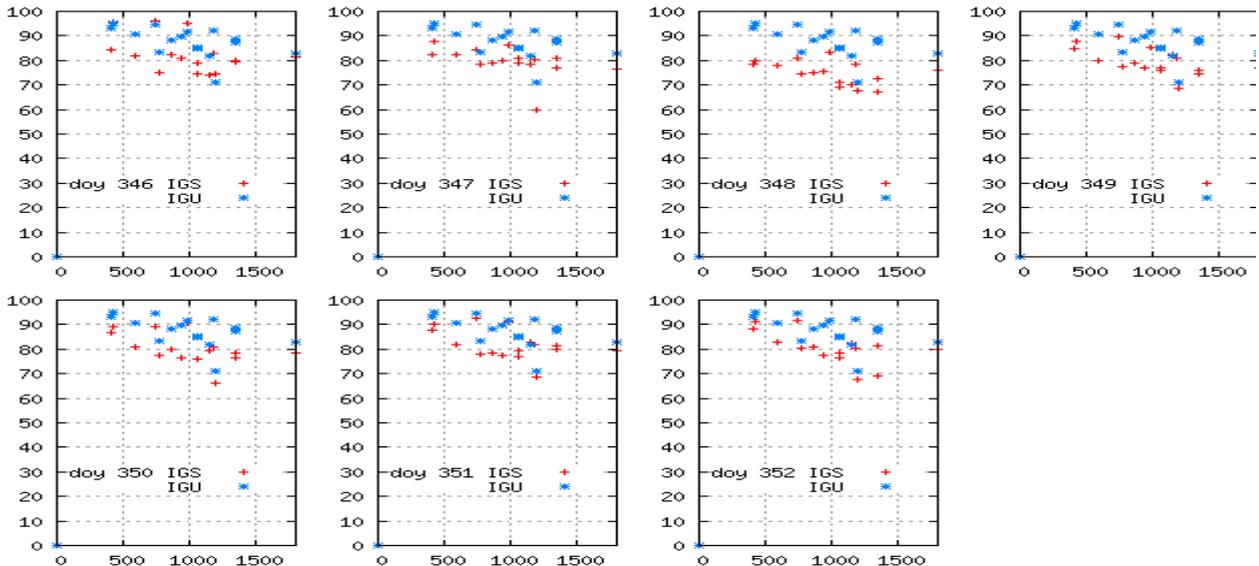


Figure 5: Comparison of the ambiguity fixing percentage regarding to the permanent receiver distance to network center (in km) for both IGU and IGS orbits (blue and red points respectively), for the analyzed experiment.

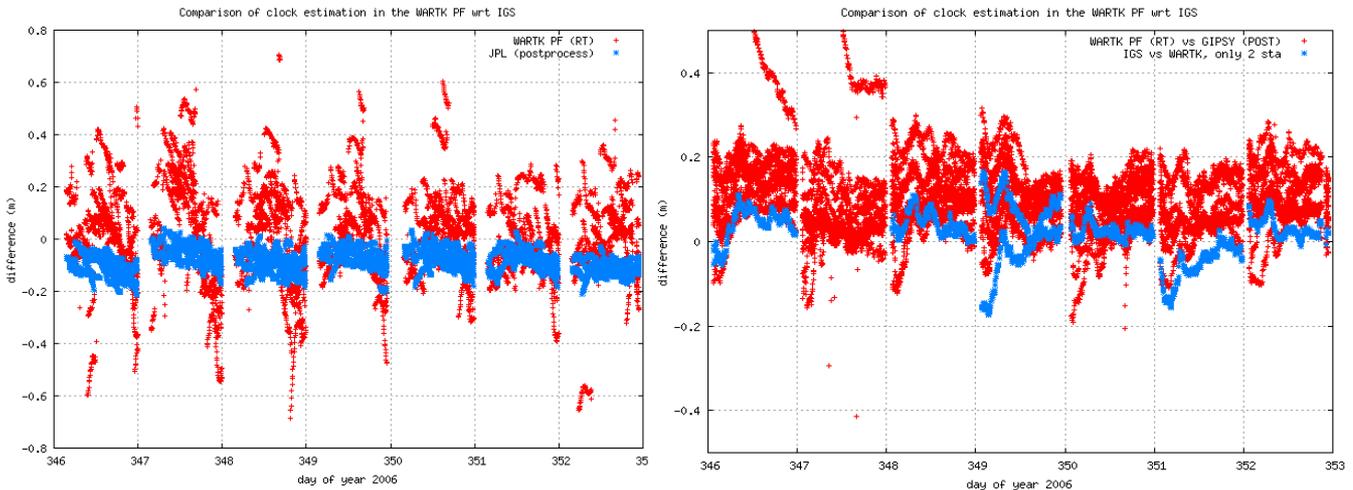


Figure 6: [Left-hand plot] Discrepancies of WARTK GPS satellite clock estimations regarding to final IGS clocks (red points), compared with the same discrepancy for JPL postprocessed satellite clocks. [Right-hand plot] A similar comparison but for receiver clocks (red points). This comparison is shown only for 2 receivers in blue points.

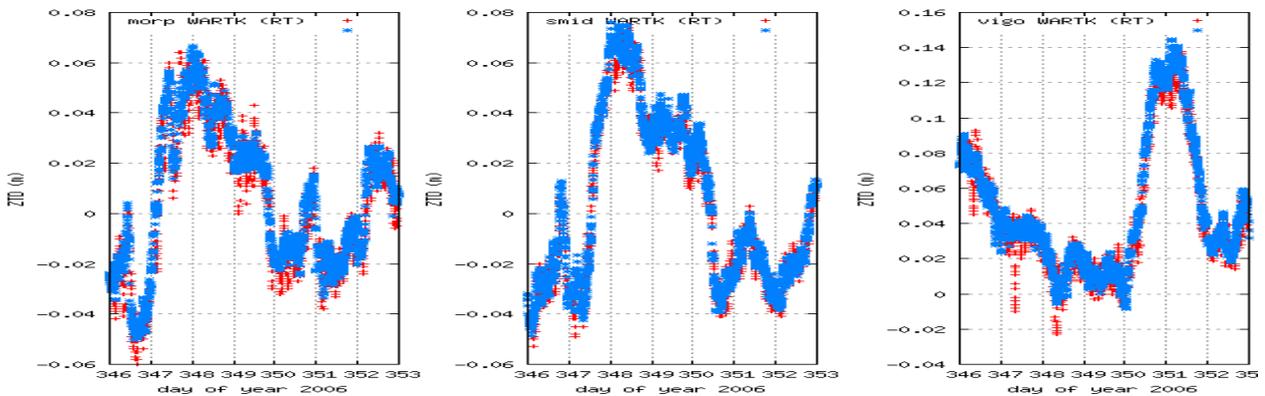


Figure 7: Zenith Tropospheric Delay estimated during the WARTK CPF experiment over three permanent receivers.

Moreover similar aspects of the technique at CPF level have been checked as well with Galileo simulated data, confirming the consistency and accuracy of the different “products” computed in real-time by the CPF. Aspects regarding CPF integrity have been also positively assessed with actual GPS data: potential failures of reference receiver, and potential satellite anomalies in predicted precise ephemeris, among other points. In the different aspects, the technique offers feasible solutions.

WARTK USER

The WARTK user navigation is based on at least dual frequency carrier phase data, combined with accurate corrections provided by the CPF, specially the most important one, the ionospheric delay. With this correction the user is disposed of an extra equation to quickly estimate and fix the carrier phase ambiguities in real-time (see for instance Hernández-Pajares et al. 2000). This process can be done in single epoch in cold start for a three (or more) frequency user (see Hernández-Pajares et al. 2003). In this section the new results on WARTK user algorithm obtained in the FES-WARTK activity are summarized, starting from the main experiment description and ending by the first results on integrity.

Newly analyzed experiment with actual GPS data

An experiment on boat navigation was carried out around the city of Delft, The Netherlands, on 12 October 2006, within the context of the FIX8 project. The closest RIMS to the experiment region is “A021” (in Paris) about 400 km far away (Figure 8). High Travelling Ionospheric Disturbance activity was detected during the experiment, making the interpolation of ionospheric corrections more difficult. The IGS receiver data (Figure 8, right hand plot), with the same topology as the EGNOS RIMSs (Figure 8, left hand plot), has been used as input for the CPF, resembling its geometry, and also to provide external data to repair the RIMS carrier phases.

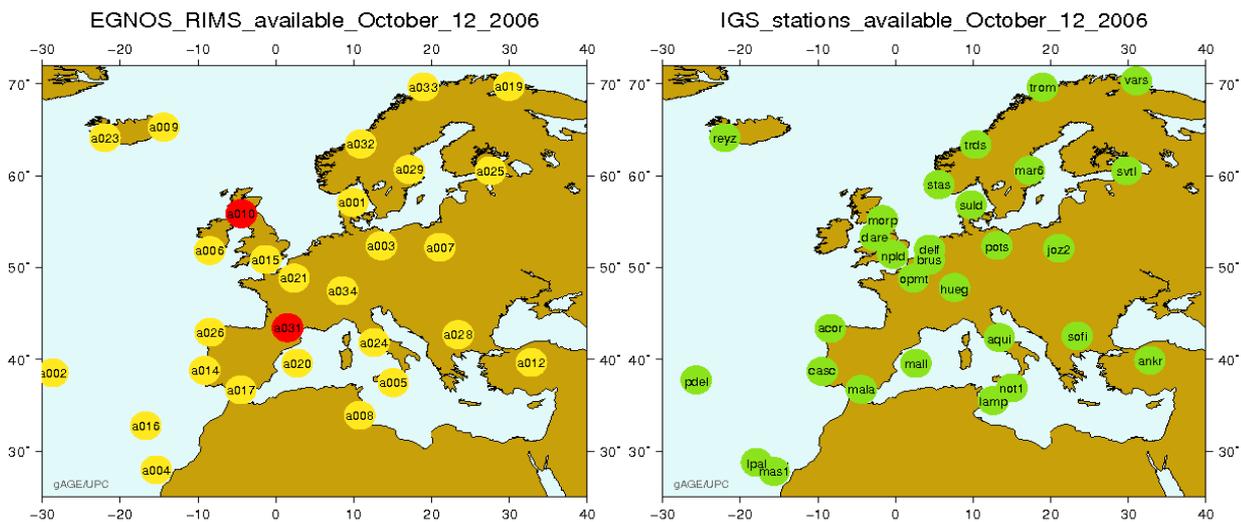


Figure 8: [Left-hand plot] EGNOS RIMS available during the boat experiment (yellow circles). [Right-hand plot] Selected network of IGS receivers resembling the RIMS spatial distribution.

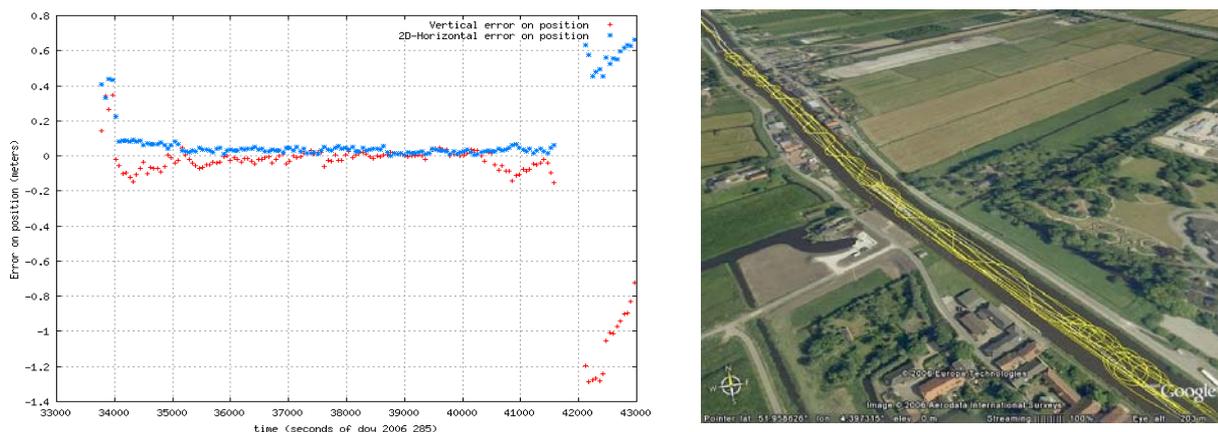


Figure 9: [Left-hand plot] Boat navigation error for vertical and horizontal coordinates (blue and red lines) by using the WARTK user technique. [Right-hand plot] Boat trajectory representation during the experiment.

In Figure 9 (left-hand plot) the vertical and horizontal boat positioning errors (in meters) are depicted as a function of time of day in seconds, taking as reference the IGS permanent receiver of BRUS, about 130 kilometers far from the boat experiment area (a post-processing RTK solution regarding to a permanent receiver place few kilometers far, has been taken as reference solution). You can see that most of part of the time, when there are not significant cycle-slips, the error is well maintained, typically below 10 cm. On the other hand, notice that in the experiment several turns were

performed by the boat (Figure 9, right-hand plot). And the WARTK technique is able to offer other useful information to the user beyond the main one, the high accuracy real-time positioning. In Hernández-Pajares et al. 2004 was demonstrated that the availability of zero-difference accurate ionospheric corrections makes possible to dispose of a real-time estimate of the user orientation with its single antenna and dual/multi frequency receiver, with typical unbiased errors of few degrees (Hernández-Pajares et al. 2004). In Figure 10 the orientation estimation with the single antenna (real-time WARTK yaw/wind-up user estimation) can be seen, being compatible with the maneuvers reflected in the reference solution (see for instance the green and blue parts, with the corresponding u-turns and full rotations).

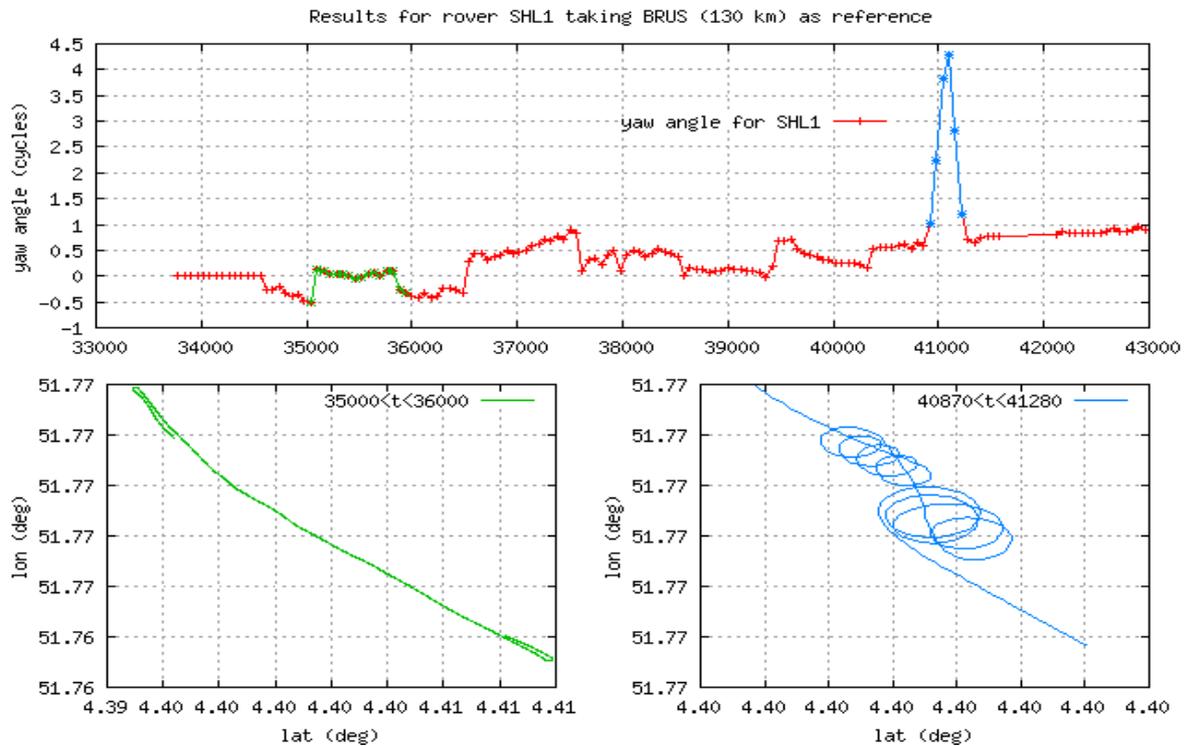


Figure 10: [Top plot] Boat yaw angle estimated in function of the time for the boat thanks to the WARTK user algorithm. [Bottom plots] The boat trajectory (left) and a zoom corresponding to the boat turns are represented.

The study was extended by using the RIMS A015 -at UK- as reference and closer receiver, at 410 km from the permanent IGS receiver DELF treated this time as roving user to have more statistics, with two main objectives: (1) To test the feasibility of the repaired RIMS data to be used to obtain WARTK corrections, and (2), to provide very first results on WARTK user integrity. Indeed, the RIMS carrier phase issue of lack of integer feature was repaired for RIMS A015 by using NPLD receiver 89 km far. A similar result to Figure 1 (right-hand plot), was obtained. In Figure 11 the horizontal and vertical errors are represented (green and red points respectively), as far as the corresponding protection levels (blue and magenta points) and the number of fixed ambiguities (divided by ten for scaling purposes, the widelane fixings in light blue and L1 fixing in brown). Despite there is a worsening in the accuracy of the solution related with the imperfect repairing process, the conclusions obtained in previous studies are basically confirmed. Indeed, the main advantage of using ionospheric corrections and fixing ambiguities is in the convergence time to a precise (decimeter error-level) solution. This convergence time is only of several minutes when the ionospheric corrections are used, compared with, typically, more than half an hour without the ionospheric corrections.

Moreover a first study on integrity has been performed in the same experiment. The very first results of integrity in WARTK are summarized in the Stanford plots included in Figure 12, vertically scaled for an approximate probability of Miss of Integrity (MI) event of 10^{-4} . These first results suggest the potential fulfillment of the more exigent requirements of integrity and accuracy, in spite of using repaired observables. A deeper study on WARTK integrity is in progress in the context of the ESA funded MRS activity.

Also at the user level new experiments for both signal-simulated and actual data have been gathered and processed, emulating real-time conditions, confirming the previous results with actual GPS data, in particular single-antenna orientation information and the capability of instantaneous (single-epoch) precise navigation with three-frequency systems, such as Galileo. This can be seen in Figure 13, where the availability of precise ionospheric corrections speeds up very significantly the precise positioning convergence also when only GPS constellations is used. The use of combined GPS+Galileo constellation speeds up very significantly the precise convergence time (near half time)

regarding to GPS only in the absence in both cases of the precise WARTK ionospheric corrections. This results obtained from simulated datasets are very significant, specially relatively, between different studied approaches.

An additional aspect studied in the WARTK user algorithmic is the potential advantage of fixing carrier phase ambiguities: once its double differences -which are integer numbers- are well known they are removed as unknowns (instead of constraining them as in the most part of previous results). The potential advantages of fixing instead of constraining double-differenced carrier phase ambiguities by a WARTK user have been shown when the optimal integer estimation performed by the LAMBDA method (Teunissen, 1993, 1994) is applied on simulated Galileo data and actual GPS data, being able of reducing the positioning error from about 10 to few centimeters.

Finally, taking into account the experiments performed so far during previous activities, and in particular in this FES-WARTK project, a summary of expected preliminary performance of WARTK can be found in Table 1. The performance is described in terms of “convergence time”, “accuracy”, “integrity (HPL, VPL)” for different configurations: GPS-only and (medium baseline), GPS + Galileo (medium baseline), GPS-only (worst case baseline) and GPS+Galileo (worst case baseline). It is very important to emphasize that this is the first time we are looking at integrity aspects of the technique. These results in integrity, at the contrary that in accuracy, are very preliminary, just reflecting the results of the first experiments analyzed under this perspective, in this FES-WARTK activity.

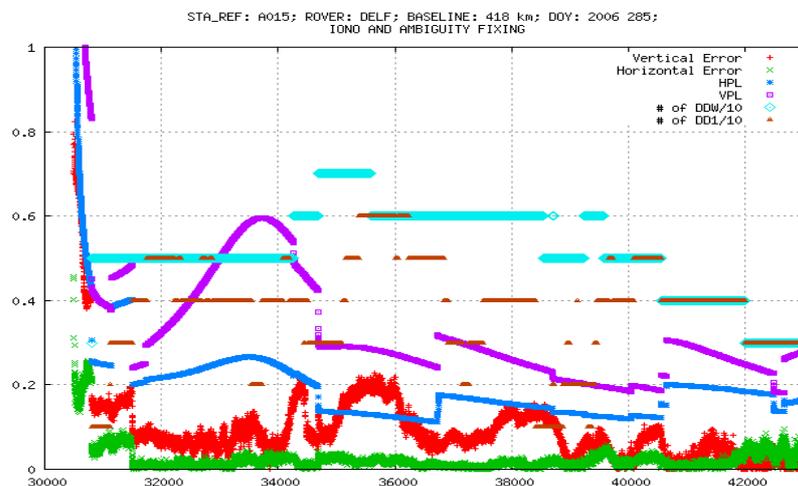


Figure 11: Vertical and Horizontal WARTK user positioning errors (red and green points, in meters) in function of GPS time of day 12 October 2006 (seconds) for permanent receiver DELF treated as roving user. Moreover the corresponding protection levels (magenta and blue points), and the number of constrained double differenced wideband and L1 ambiguities (divided by 10, for scaling purposed, light blue and brown points) are represented.

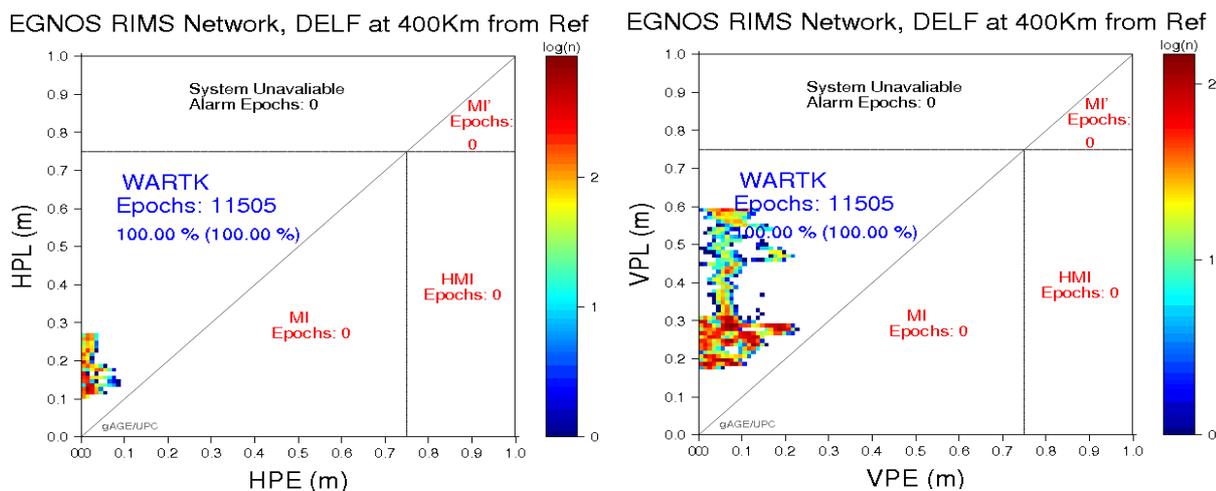


Figure 12: [Left-hand plot] Horizontal Protection level versus actual error for WARTK navigation of station DELF treated as rover, regarding to RIMS A015 as closer reference site, at about 400 km far (12 October 2006). 100% of points fulfill alarm limits requirements for APV-II and CAT-I (limits are out of plot range). [Right-hand plot] Similar plot for vertical coordinate.

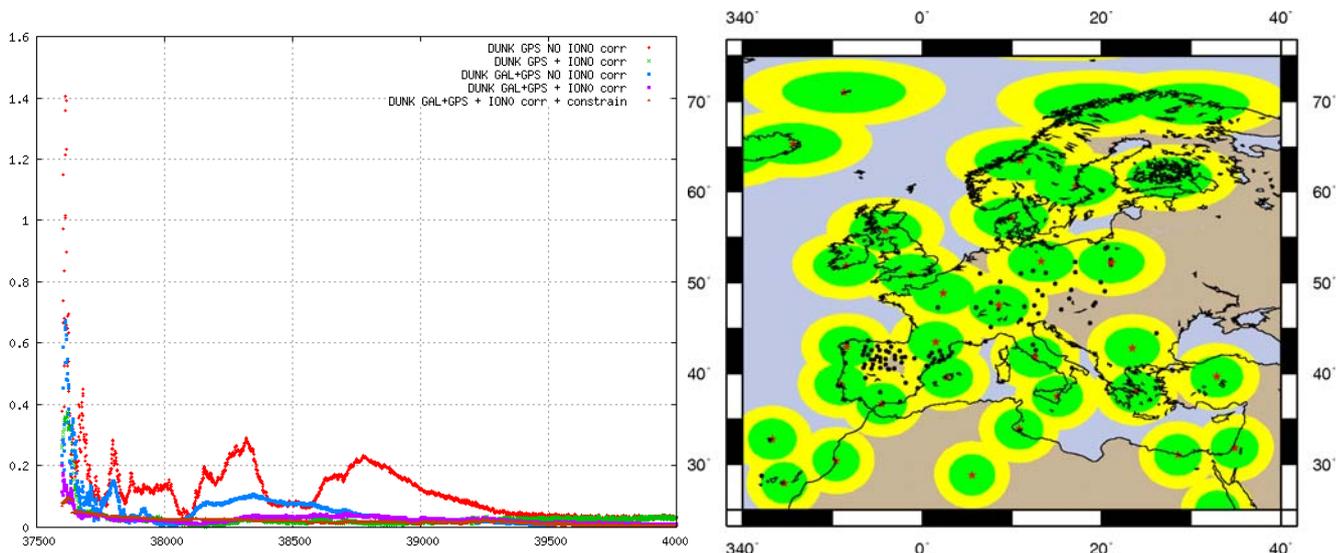


Figure 13: [Left-hand plot] 3D WARTK positioning error by using dual Galileo+GPS constellation signal simulated experiment: with and without iono corrections, and by constraining the L1, L2 double differenced ambiguities to integer values, and also for GPS only data. The results correspond to permanent IGS receiver DUNK treated as roving user, at about 250 km from the reference site. [Right hand plot] WARTK coverage (yellow circles) based on EGNOS permanent RIMS stations (red points).

TOWARDS A POTENTIAL WARTK DEPLOYMENT: ADDITIONAL ASPECTS

Additionally to the WARTK System Overview, one of the additional aspects on WARTK deployment studied in FES-WARTK activity is the recommendation of adding an small number of RIMS to guarantee the full WARTK coverage of the European Union: just by adding 4 additional RIMSs, 2 RIMSs in center of Spain and the Netherlands plus 2 additional RIMSs in North-West of Balkans and frontier between Finland and Sweden, close to the gulf of Bothnia (it is based on previous experiments indicating a WARTK coverage of about 400 km from the nearest reference site, see Figure 14, right-hand plot).

Regarding to the present and future WARTK applications there is an existing market for the WARTK technique within current applications of RTK and VRS networks, offering: (1) To diminish the distance dependencies by means of permanent stations that can be separated up to more than 800 km. (2) Consequently, to reduce costs in fixed receivers and local network deployments. (3) To improve precision and integrity of the observations. (4) To improve the performance also for 3-frequencies systems (i.e. Galileo) providing single-epoch accurate long-baseline navigation capabilities. Moreover there exist further new applications to be exploited in a wide range of fields (instantaneous GPS meteorology -Hernández-Pajares et al. 2001-, orientation sensor -Hernández-Pajares et al. 2004-, precise navigation and Tsunami detection in deep sees -Colombo et al. 2005-,...) in which WARTK would be a leading technique due to its high accuracy at long distances.

	Positioning Convergence Time	Horizontal Accuracy / meters	Vertical Accuracy / meters	Horizontal Level integrity	Protection guarantying	Vertical Level integrity	Protection guarantying
GPS-only (medium baseline: ~250 km)	< 10 min	< 5 cm	< 10 cm	~20 cm ⁽²⁾		~40 cm ⁽²⁾	
GPS+GAL (medium baseline: ~250 km)	< 30 sec ⁽¹⁾	< 5 cm	< 10 cm	~20 cm ⁽²⁾		~40 cm ⁽²⁾	
GPS-only (worst-case baseline: ~410 km)	< 10 min	10 cm	15 cm	~40 cm ⁽²⁾		~60 cm ⁽²⁾	
GPS+GAL (worst-case baseline: ~410 km)	< 30 sec ⁽¹⁾	10 cm	15 cm	~40 cm ⁽²⁾		~60 cm ⁽²⁾	

Table 1: Summary of expected preliminary performance of WARTK. Notes: (1): Convergence Time mostly due to the full initialization of the filter states, including zenith residual tropospheric delay. (2): These results are based only on the very first experiments performed in this FES-WARTK activity, and are not necessarily representatives of future consolidated results.

CONCLUSIONS

The main result of this project is the confirmation of the maturity of the Wide Area Real Time Kinematics technique, in order to provide high accuracy (subdecimeter-error-level) GNSS navigation service (instantaneously with future 3-frequency GNSS data), by means of computing and providing accurate real-time ionospheric correction in the CPF for the users. WARTK is only requiring as main infrastructure a network of permanent GNSS receivers (to feed the WARTK Central Processing Facility), which can be separated up to about 800 km (such as the existing ones in Europe for EGNOS). Additionally a first study on WARTK integrity at user positioning domain has been presented providing very preliminary but promising results (to be statistically confirmed in future studies such as the one which is now running in the framework of ESA GNSS modernization, MRS project).

Regarding to the future, and taking into account the FES-WARTK results, we believe that a logical step to move ahead is: (1) The establishment of a European WARTK Test Bed (EWARTB) on one hand, and simultaneously, (2) the development of a first specific WARTK receiver to start using the new high precision navigation system in actual conditions.

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