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UNIVERSITAT POLITÈCNICA DE CATALUNYA
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Feasibility study of a Wide Area High-precision Navigation Service (WARTK) for EGNOS & Galileo *(FES-WARTK)*

TN9.1: FES-WARTK Summary Report

June 2008

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Definitions, Acronyms and Abbreviations

Acronym	Meaning
AD	Applicable Document
EGNOS	European Geostationary Navigation Overlay System
ESA	European Space Agency
gAGE	Research group of Astronomy and Geomatics
IGS	International GNSS Service
PF	Processing Facility
PM	Progress Meeting
PR	Progress Report
RD	Reference Document
STEC	Slant Total Electron Content
TBC	To be confirmed
TBD	To be done
TC	Teleconference
TID	Travelling Ionospheric Disturbances
TU Delft	Technical University of Delft
WARTK	Wide Area Real Time Kinematic
WP NTRIP	Work Package Networked Transport of RTCM via Internet Protocol
RINEX	Receiver Independent Exchange format
MSTID	Medium Scale Travelling Ionospheric Disturbances
UPC	Technical University of Catalonia

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1 Introduction

The objective of this activity (FES-WARTK) is the demonstration of the feasibility of a WARTK system over Europe, based either on EGNOS or Galileo, offering in both cases a high level of accuracy as well as integrity. This feasibility study will conclude with the performance that can be achieved with a WARTK system.

The WARTK technique is able to extend the domain of local service precise positioning provision from few tens of kilometres, as for RTK classical techniques (or TCAR in Galileo), to the level of hundreds of kilometres from the nearest permanent reference GNSS station. Therefore, WARTK can make feasible the real-time GNSS positioning of roving users with accuracy below 10 centimetres in a Wide Area service region, typically in single-epoch with Galileo and Modernized GPS, and about few minutes with the current GPS signals.

2 Purpose of this document

This document is intended to provide an executive summary of the main results of the FES-WARTK project, following the requirement indicated in FES-WARTK Contract, section 4.1.2 of appendix 2: *For each Contract one Summary Report shall be produced. It shall summarize the findings of the Contract in a concise, yet instructive manner. For this reason, the technical description shall be approximately 20 pages.*

3 Scope

This document contains the main results of the FES-WARTK project, based on previous dedicated reports TN1.1, TN2.1, TN3.1, TN3.2, TN4.1a, TN4.2a, TN4.3a, TN4.4a, TN4.1b, TN4.2b, TN4.3b, TN4.4b, TN5.1, TN5.2, TN6.1, TN7.1, which are summarized in document TN8.1. This document is susceptible to future evolution since it is being released from a feasibility study and the technique itself could evolve during the course of the analysis of the feasibility of the WARTK technique for EGNOS and Galileo (FES-WARTK CCN contract).

4 References

Applicable documents:

[1]TN1.1: WARTK user group identification, FES-WARTK project documentation, January 2007.

[2]TN2.1: Assessment of the quality of EGNOS RIMS data for WARTK, FES-WARTK project documentation, March 2007.

[3]TN3.1: WARTK Algorithms and messages at PF level, FES-WARTK project documentation, March 2007.

[4]TN3.2: WARTK Algorithms at User level, FES-WARTK project documentation, June 2007.

[5]TN4.1a: WARTK PF: SW User Manual, FES-WARTK project documentation, May 2007.

[6]TN4.1b: WARTK User Modules: SW User Manual, FES-WARTK project documentation, June 2007.

[7]TN4.2a: WARTK PF: SW User Requirements Specification, FES-WARTK project documentation, May 2007.

[8]TN4.2b: WARTK User Modules: SW User Requirements Specification, FES-WARTK project documentation, June 2007.

[9]TN4.3a: WARTK PF: SW Design Report, FES-WARTK project documentation, May 2007.

[10]TN4.3b: WARTK PF: SW Design Report, FES-WARTK project documentation, June 2007.

[11]TN4.4a: WARTK PF: SW Test Report, FES-WARTK project documentation, May 2007.

[12]TN4.4b: WARTK PF: SW Test Report, FES-WARTK project documentation, June 2007.

[13]TN5.1: Test Plan and Test Procedures Document: using EGNOS RIMS data, May 2007.

[14]TN5.1-2: Test Plan and Test Procedures Document: using the Galileo SVF, FES-WARTK project documentation, June 2007.

[15]TN6.1: WARTK Test Results Report, FES-WARTK project documentation, March 2008.

[16]TN7.1: WARTK System Definition Document, FES-WARTK project documentation, November 2007.

[17]TN8.1: FES-WARTK Final Report, FES-WARTK project documentation, December 2007.

Reference documents:

[RD1] Consortium UPC, TUD Feasibility study of WARTK based on EGNOS and Galileo Doc. No. Ao/1-5033/06/NL/HE/030 Issue 1/30.

[RD2] B. Rols, Use of RIMS raw data for WARTK, ThalesAlenia Space, REF: EGN-ASP-TN-641, Issue: 1, Revision: A, Date: 13 December 2007.

[RD3] Feasibility study of a Wide Area High-precision Navigation Service for EGNOS and Galileo, (High level of accuracy and integrity for EGNOS and Galileo), Statement of Work, REF: TEC-ETT/2005.78/JS/js

[RD4] WARTK-EGAL project: Final Report

5 Overview of the Document

The document summarizes the main results achieved in the FES-WARTK project.

6 Summary

The main result of this project, taking into account the selected achievements listed above and the different WP summaries, 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) only requiring as main infrastructure a network of permanent GNSS receivers (to feed the WARTK Central Processing Facility), which can be separated up to more than 800 km (such as the existing ones in Europe for EGNOS, or USA for WAAS).

The WARTK feasibility has been proven, not only at algorithmic level, but also at different practical levels: 1) the adequacy of the EGNOS RIMS network (after confirming and repairing the RIMS carrier phase ambiguity issue) ensuring (with NLES RIMS) an almost complete European Union coverage, 2) the suitability of different messages definition (WARTK proprietary and also the actual RTCM v3.1 format), 3) the good response of WARTK CPF under unexpected problems in data sources in order to ensure the integrity of the system, 4) the economical and scheduling feasibility, in order to setup a first European WARTK Test BED (EWARTB) as a previous step to European WARTK Service (EWARTK), 5) the existence of groups of RTK customers very interested in the advantages of WARTK, the existence of an even larger number of potential new applications thanks to WARTK characteristics, among other points. Additionally, a first study on WARTK integrity at user positioning domain has been faced as well in the framework of this FES-WARTK project, providing very preliminary but promising results, to be statistically confirmed in future exhaustive studies (such as the one which is now starting 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.

7 FES-WARTK main selected achievements

The main achievements of the FES-WARTK, which are summarized below and detailed in previous Technical Notes (from TN1.1 to TN7.1, see applicable documents), are:

1) **Confirmation of the EGNOS RIMSs carrier phase measurement issue**, i.e. lack of integer nature of the double differenced ambiguities (between pairs of satellites and receivers) double difference ambiguities, with recent RIMSs datasets and different processing approaches. The corresponding results (WP2000, see TN2.1 and plot below) have been sent to the Industry, and as consequence a small external activity has been performed, confirming the issue of the RIMS carrier phase ambigutities (see [RD2])

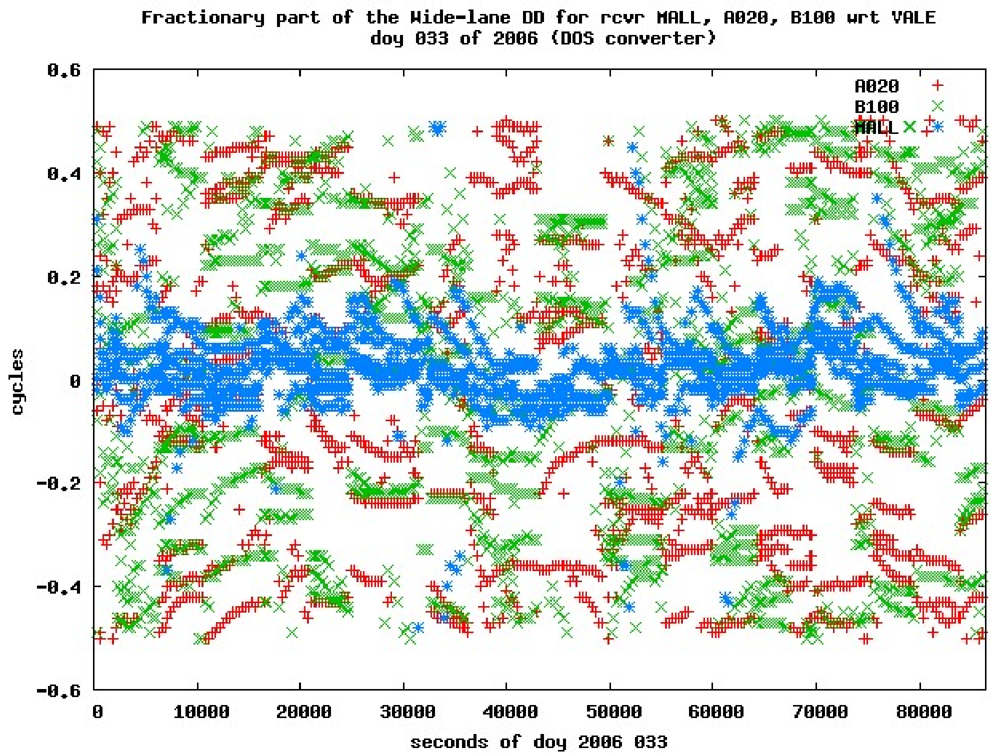

Figure 1: Fractional part of the DD wide-lane ambiguity for the EGNOS RIMS A020 (red) and B100 (green) and the EUREF station Palma de Mallorca, MALL in blue.

2) **Proposal of a procedure to repair RIMSs carrier phase measurement issue**, by using data coming from standard dual-frequency GPS receivers (close to the given RIMS). It has been successfully tested emulating real-time conditions (WP2000, see TN2.1 and plot below).

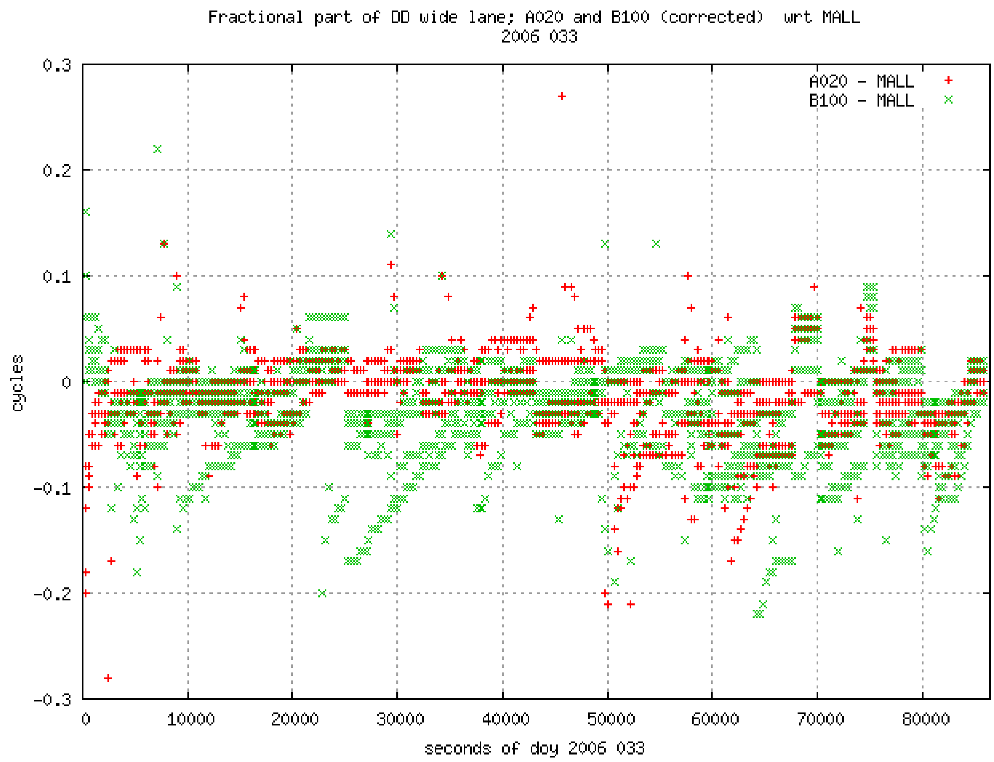

Figure 2: Equivalent as Figure 1 but computed for A020 and B100, using WARTK corrected ambiguity values.

3) **Recommendation of adding an small number of RIMS to guarantee the full WARTK coverage of the European Union: just by adding 4 additional RIMSs**, or considering 2 RIMSs associated to NLES facilities in center of Spain (Torrejon) and The Netherlands plus 2 additional RIMSs in North-West and South of Balkans (WP7000, see below and TN7.1, and next two figures),

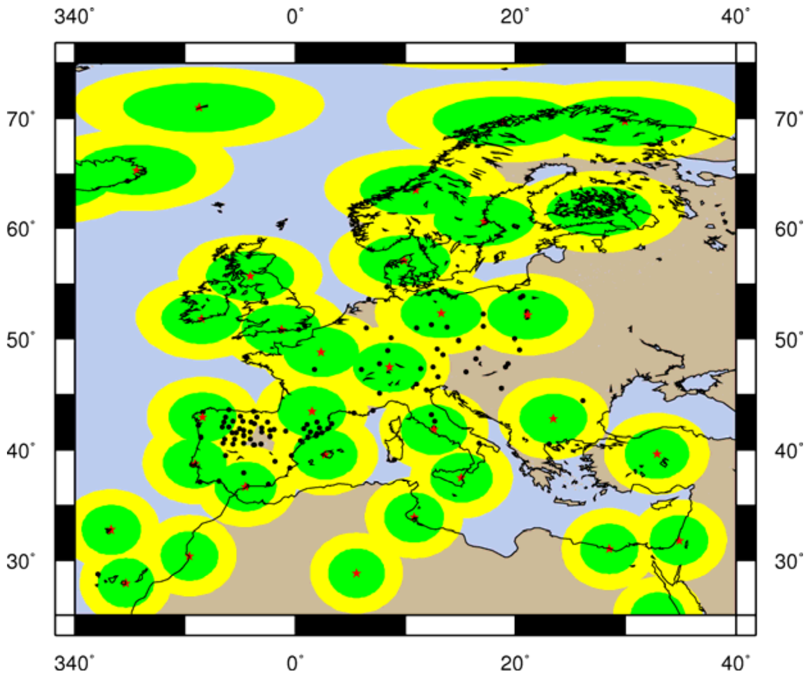

Figure 3: Distribution of EGNOS RIMS-A receivers (red stars), with the associated WARTK Service Areas in green and yellow (see details above). Additionally the available real-time GPS receivers from different European institutions are represented as black dots.

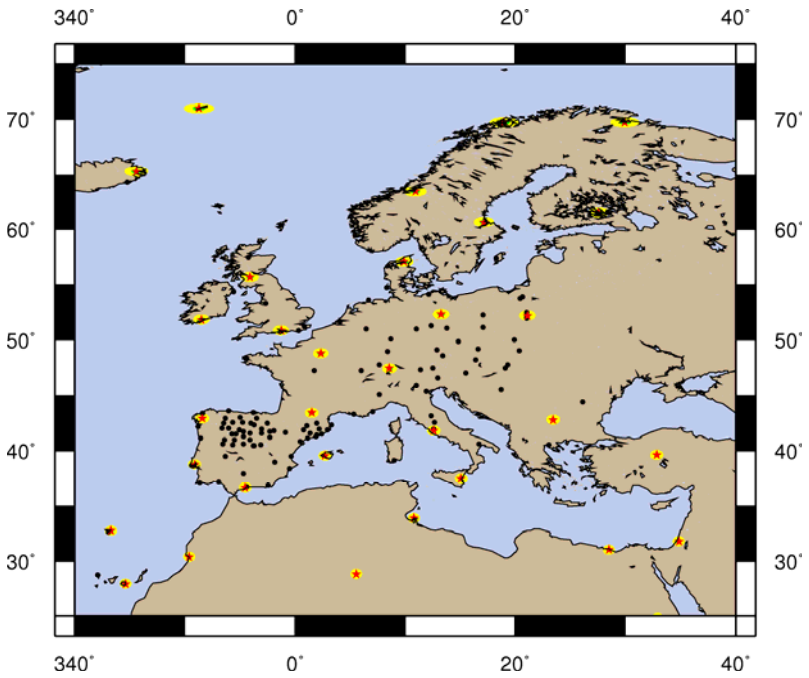

Figure 4: Distribution of EGNOS RIMS-A receivers (red stars), with the associated RTK and VRS

Service Areas in green and yellow (see details above). Additionally the available real-time GPS receivers from different European institutions are represented as black dots.

4) **Several points of the WARTK CPF algorithms pending of final study (regarding to results in previous activities) have been successfully consolidated** in this FES-WARTK project (WP3100, see below and TN3.1) with the help of representative datasets of actual GPS measurements. In particular:
    a. Regarding to **predicted precise (ultrarapid) orbits, it is shown they behave "quite well" under WARTK**, and even in some few cases (5 over 129000) in which they produced a problem in the CPF computation, this problem was quickly detected (their ambiguities cannot be fixed) and the responsible satellite was correspondingly flagged (this flag is added to the corresponding orbit message to the users, see below).
    b. Regarding to **the degradation of the CPF performance with respect to the distance of the corresponding RIMS to the network center, it is small**, with high real-time ambiguity fixings (better than a 80%) for receivers up to 1000km. There is only a small degradation with distance which indicates that the ambiguities are well solved even for receivers on the edge of the network. These percentages are also maintained for days under ionospheric storm conditions.
    c. Regarding to the **satellite clocks estimated by WARTK CPF, it has been found that they are also quite compatible with the IGS ones**, at few tenths of ns, regardless these clocks are obtained from a regional network. This result strongly suggest its feasibility for global usage in PPP-like approaches (in combination, for instance, with the predicted accurate orbits of IGS).
    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 is found in the zenith tropospheric delay**, a

sensitive –and hence, interesting- parameter regarding to the quality of the geodetic adjustment. It can be seen that the zenith tropospheric delay (ZTD) differences are typically below 1 cm (RMS of 6 mm), when compared with the postprocessed solution provided by GIPSY. In other words, the WARTK real-time (instantaneous) ZTD estimation has a similar accuracy level that the nominal Near Real Time IGS ZTD (computed with a latency of 2-3 hours).

5) **Identification and software reparation of functioning problems of the GSVF-2 signal-simulator and GETR receiver, most important the synchronization of the GETR measurement files** (WP5200, see below and TN5.1-2). These issues were a direct result of the limitations of the simulation hardware, in particular, the GETR. **To overcome this problems two relevant upgrades of the ESTEC laboratory equipment are ongoing**:
   a. An integrated GPS and Galileo simulator from Spirent
   b. The firmware of the IfEN GNSS receiver will be updated to be compatible with the current Galileo OS SIS ICD.

   The **benefits of these upgrades (more realistic and better quality of the Galileo-like measurements, and larger number of satellites in view, including the possibility of combined Galileo and GPS constellations) will be shortly exploited** in an extension of two months of this FES-WARTK activity .

6) **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** (the ionospheric voxel model in different conditions, the satellite and receiver clock errors, the tropospheric delay among others). **Aspects regarding CPF integrity have been also positively assessed**: From the point of view of distance regarding to the Network center, 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 (WP6000, see below and TN6.1).
7) **At the user level new experiments** for both signal-simulated and actual data

have been gathered and processed, emulating real-time conditions, **confirming previous results, in particular the capability of instantaneous (single-epoch) precise navigation with three-frequency systems, such as Galileo**, and single-antenna orientation estimation. Additionally, a **promising very first result of integrity** is provided with actual data (WP6000, see below and TN6.1).

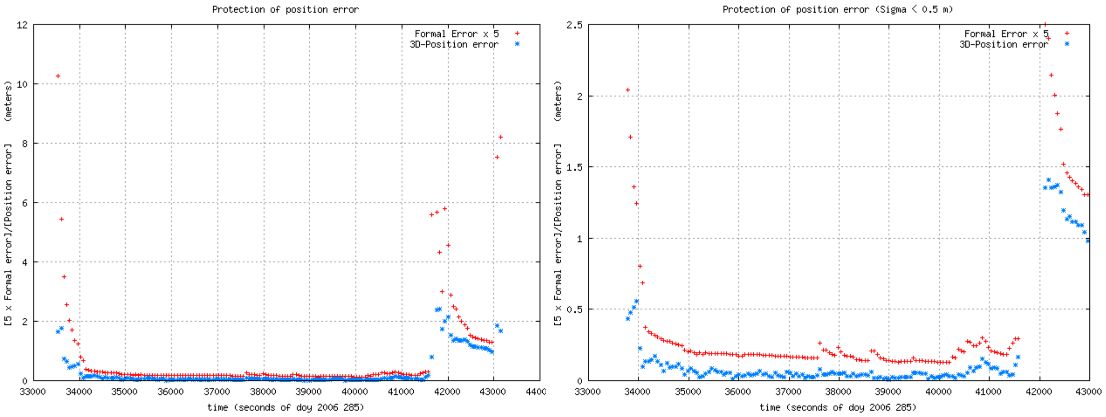

Figure 5: 3D positioning error (blue) vs. corresponding protection level (red) for the boat experiment, emulating real-time conditions with WARTK (12 October 2006).

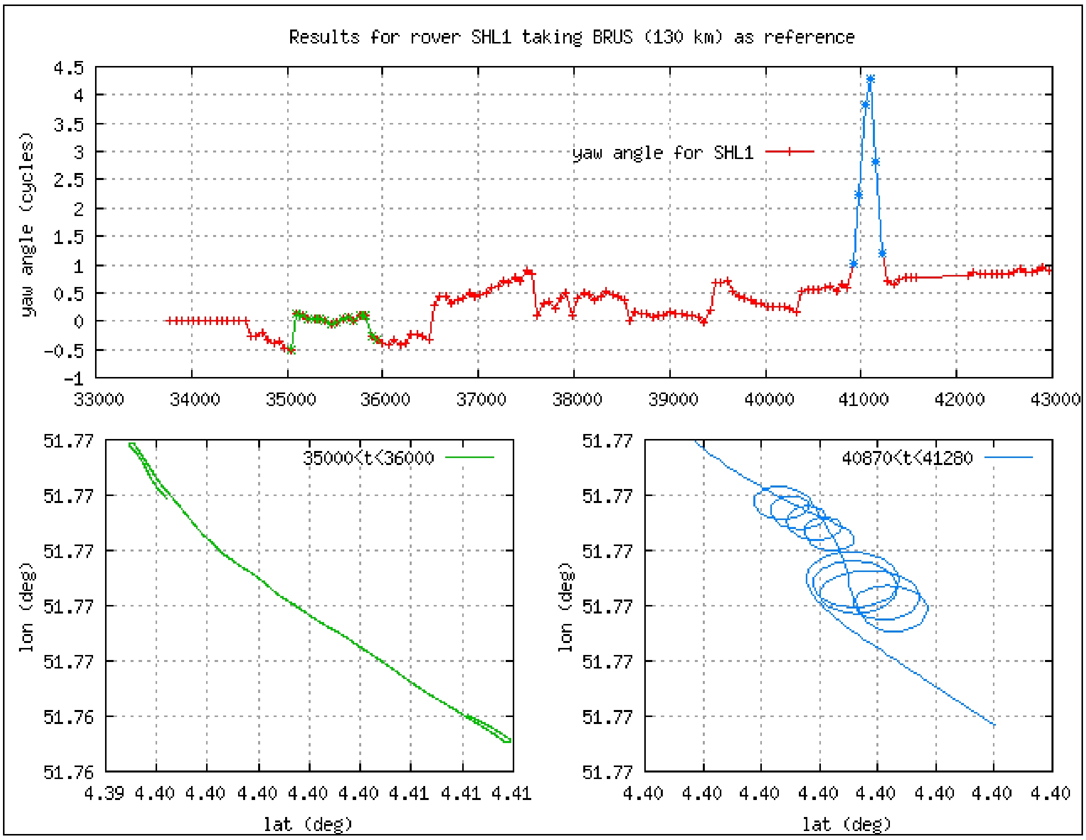

Figure 6: Boat orientation estimation (yaw angle) with one single antenna by using WARTK (nearest reference site: BRUS, at about 130 km far, day 12 October 2006).

8) **The main conclusion provided by the experimental results is the confirmation of 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 lower convergence time) than other techniques**, such as PPP using rapid IGS orbits and clocks, only available after several hours (WP6000, see below and TN6.1).

9) For the simulated GSVF data, obtained after mitigating measurement problems and the corresponding coloured noise, it was shown that the application of the LAMBDA method, as an add-on to WARTK user algorithm can improve the performance significantly. However, this improvement depends strongly on the used stochastic model. If the stochastic

model is not accurate enough, this can lead to long initialization times and even incorrect ambiguity fixing. The LAMBDA method has also been applied to the processing of the boat navigation data and one 410 km baseline. The position errors after ambiguity fixing were more or less the same as obtained with the previous processing (thus without the LAMBDA method). However, in case of the boat data, a significant reduction of the convergence time can be recognized when the LAMBDA method is applied.

10) Moreover several key points on potential WARTK deployment have been studied in this project: **the WARTK definition of addressed users and service provided, the Consolidation and definition of WARTK PF and User processing techniques, WARTK System Overview, the Consolidation of Message Definition (including the potential use of RTCM), the Consolidation and definition of the interface with EGNOS/Galileo system, and, finally the Cost estimates of the WARTK system. All the obtained results (see details in WP7000, below and TN7.1) strongly suggest the feasibility of the technique**, also from a future potential deployment point of view.

11) Regarding to the **present and future WARTK applications** (WP1000 and TN1.1):
    a. **There is an existing market for the WARTK technique** within current applications of RTK and RTK networks, offering:
        i. To diminish the distance dependencies by means of permanent stations that can be separated up to more than 500 km.
        ii. Consequently, to reduce costs in fixed receivers and local network deployments.
        iii. To improve precision and integrity of the observations.
        iv. To improve the performance also for 3-frequencies systems (i.e. Galileo) providing single-epoch accurate long-baseline navigation capabilities.
    b. **There exist further new applications to be exploited in a wide range of fields in which WARTK would be a leading technique** due to its high accuracy at long distances.

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 **Error! Reference source not found.**. 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.

	Positioning Convergence Time	Horizontal Accuracy / meters	Vertical Accuracy / meters	Horizontal Protection Level guarantying integrity	Vertical Protection Level guarantying integrity
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.