EXECUTIVE SUMMARY

Absolute Navigation at Sub-Centimetre Level – Phase 2

AHD-GNSS

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1. INTRODUCTION

AHD-GNSS project is carried out by DEIMOS Space S.L.U. (Spain), in collaboration with Delft University of Technology (The Netherlands). The project answers to the ITT "Absolute Navigation at Sub-Centimetre Level – Phase 2" issued by ESA in the frame of the ESA's Discovery and Preparation elements of the Discovery Preparation and Technology Development (DPTD) activities (www.esa.int/discovery).

In the Phase-2 of the study, the feasibility of having **real-time GNSS-based absolute navigation at sub-centimetre level** (error < 1 cm in the position domain) is investigated by expanding the results and the associated tools derived during the HDGNSS project (Phase-1 of the study), ESA Contract 4000118100, Absolute Navigation At Sub-Centimetre Level.

1.1. Purpose

The objective of this document is to report the executive summary of the AHD-GNSS project and summarize the most significant technical achievements. The intended readerships for this document are ESA Technical Officer and Reviewers.

1.2. Scope

The document is structured in the following chapters:

- Chapter 1: The document introduction;
- Chapter 2: The related documents, applicable and reference;
- Chapter **Error! Reference source not found.**: The project technical results;
- Chapter 4: The conclusions.

1.3. Acronyms and Abbreviations

The acronyms and abbreviations used in this document are those of Table 1-1.

Table 1-1: Description of acronyms used in the document.

Acronym	Description
AHD	Advanced High Definition
CC-R	Common Clocks (pivot) Receiver
DMS	DEIMOS Space S.L.U.
ESA	European Space Agency
GNSS	Global Navigation Satellite System
GPEF	GNSS Parameters Estimation Filter
GSP	General Studies Programme
IAR	Integer Ambiguity Resolution
ITT	Invitation To Tender
MEO	Medium Earth Orbit
PPP	Precise Point Position
RTK	Real-time Kinematics
SW	Software
TUD	Delft University of Technology

2. RELATED DOCUMENTS

2.1. Reference Documents

The following table specifies the reference documents that shall be taken into account during project development.

Table 2-1: Reference documents

Reference	Code	Title	Issue
[RD1]	-	Zanetti R., Bishop R. Kalman Filters with Uncompensated Biases. Journal of Guidance, Control, and Dynamics. Vol. 35, No. 1 (2012)	2012
[RD2]	-	Ren X., et al. Mapping topside ionospheric vertical electron content from multiple LEO satellites at different orbital altitudes	2020

3. EXECUTIVE SUMMARY

Currently GNSS Systems provide services for instantaneous absolute positioning accuracy of a few meters, assuming no local obstructions above 5-10 degrees elevation, based on the navigation signals broadcast by a MEO constellation. This positioning accuracy can be improved extraordinarily by means of GNSS evolutions, such as the augmentation of the space constellation and/or the ground network by a space network, or the definition and implementation of algorithms for generating and processing additional and more accurate information, such as integer ambiguity resolution techniques on the network and user sides.

In this evolving background, studies to demonstrate the feasibility of a system concept for high-accuracy service (HAS) for positioning are on-going. In particular in the AHDGNSS (Advanced High Definition GNSS) project, led by Deimos Space S.L.U. (DMS) in cooperation with Delft University of Technology (TUD) in the frame of ESA's General Studies Programme (GSP), it has investigated the feasibility of having real-time GNSS-based absolute navigation at sub-centimetre level by new generation of GNSS System and new generation of GNSS User Equipment. The AHD-GNSS continues the work done within the HD-GNSS.

A PPP-RTK-based high precision service for a global user has been considered, by applying state-of-the-art algorithms for both the network and the user and by investigating multi-frequency and multi-GNSS solutions. It was assumed a model based on the processing of undifferenced and uncombined code and phase observables. The PPP-RTK concept consists in providing users with precise GNSS correction data so as to enable integer ambiguity resolution and consequently fast convergence to very accurate navigation solutions.

Within the AHD-GNSS, focus has been put into the identification of enabling technologies to enhance the network corrections. To analyse the performance of identified candidate solutions, the Concept Demonstrator SW has been upgraded and used. It implements a performance model, based on covariance analyses, that permits evaluating the quality of the corrections a network can provide and the quality of positioning a user can achieve.

By varying the SW configuration elements an experimentation campaign has been executed according to a plan that envisages tests for the sequential assessment of first the network and then the user performances. The accuracy of network corrections, such as orbits, clocks, biases, and ionosphere delay have been assessed by changing the number of ground stations, supplementing the ground network with a LEO constellation for plasma-ionospheric estimation, augmenting the number of MEO satellites, and varying the number of frequencies. Similarly, the user solutions have been evaluated by configuring the quality of corrections and the number of frequencies. Integer ambiguity resolution techniques have been applied both on the on the network (N-IAR) and the user (U-IAR) sides.

In phase-2 of the AHD-GNSS project, several enablers and features have been studied in order to improve the estimation of accuracies of network corrections to be broadcast to the user. They are the estimation of ionospheric corrections, estimation of GNSS MEO orbits, inclusion of a LEO constellation to supplement the ground network for the estimation of the ionosphere, and integer ambiguity resolution on the network side. Furthermore, algorithms to resolve ambiguities on the user side have been also proposed.

The proposed LEO constellation is that of Iridium NEXT, formed by 66 satellites, with 11 orbital planes and 6 satellites per plane. They support the estimation of the ionosphere. The ionosphere model is divided into two layers. The lower one, called in turn ionosphere, is found at a height of 300 km, while the upper one, called plasmasphere, is found at a height of 1600 km. In the proposed concept the receivers of the LEO constellation provide the MEO to LEO geometry, with which the plasmasphere accuracy can be estimated. Then, the ground stations provide the MEO to GS geometry for estimating the accuracy of the lower layer, i.e., ionosphere, thereby complementing the plasmasphere. The spatial distribution of each of the two layers is modelled by spherical harmonics functions. The observables for extracting the ionospheric terms are those of a Precise Point Positioning (PPP) model, which eases the inclusion of multiple frequencies and constellations.

The orbit estimation is achieved by extending the already existing functional model for estimating clocks and biases. A simplified dynamic model for the covariance propagation is used.

The other network corrections considered in the processing chain are satellite clocks and satellite phase and code biases. The model to estimate them is inherited from the first phase of the project.

Two integer ambiguity resolution algorithms have been proposed. The one for the network integer ambiguity resolution (N-IAR) follows the Vector Integer Bootstrapping approach, while the one for the user IAR (U-IAR) is based on the Best Integer Equivalent (BIE) approach. Covariance propagation is made, though, following the usual non-data driven method.

The proposed network architecture is depicted in Figure 3-1.

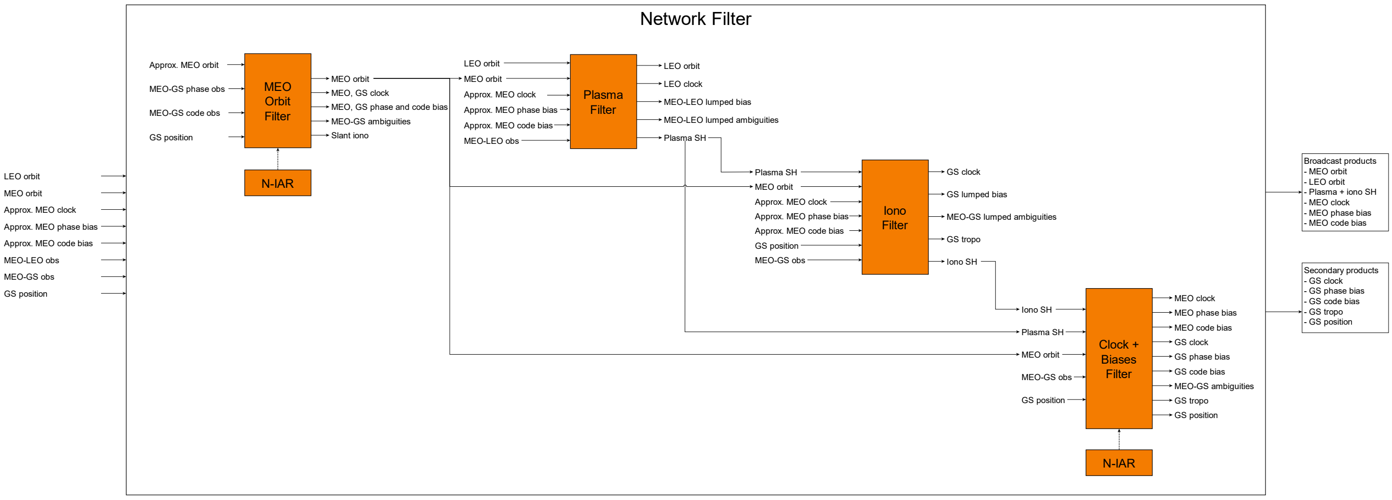


Figure 3-1. Network Filter architecture.

The performance budgets have been obtained by means of covariance analyses. The concept demonstrator SW tool implements covariance propagation with the above-mentioned plasma-ionospheric and orbit models, on top of the models inherited from the previous phase. The concept demonstrator SW consists of two main components. The GNSS Parameters Estimation Filter (GPEF), which allows to estimate orbits, clocks, and biases accuracy; and the I-LEO, which estimates the plasma-ionospheric accuracy. The GPEF component is based on a Kalman filter; it can be configured as in Figure 3-2. The I-LEO component is based on a batch least squares; it can be configured as in Figure 3-3.

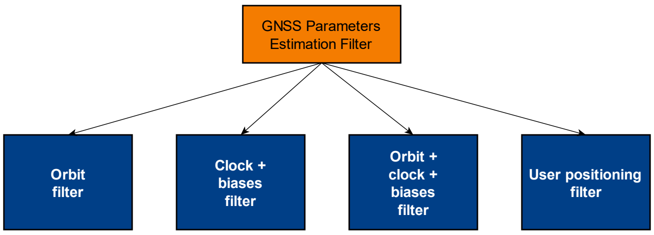


Figure 3-2. GPEF configuration possibilities

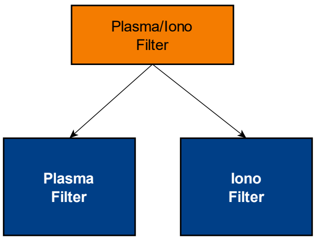


Figure 3-3. I-LEO configuration possibilities.

Both tools have been setup so as to implement the proposed Network Filter architecture.

Regarding the experimentation results, the estimation of the accuracy of MEO orbits and both layers of the ionosphere has revealed to be quite optimistic. To compensate for this effect, both the orbit and iono have been scaled to more realistic values, so that they can be further used in the subsequent processing stages. However, one possible reason to explain the optimistic accuracies is that there are constant or quasi-constant biases which are being disregarded in the implemented models. In this case, a more rigorous method to achieve more realistic values is to account for those biases in the model. One way of including them in the Kalman filter is explained in [RD1].

On the other hand, the accuracy satellite clocks and biases, as well as user positioning are quite realistic.

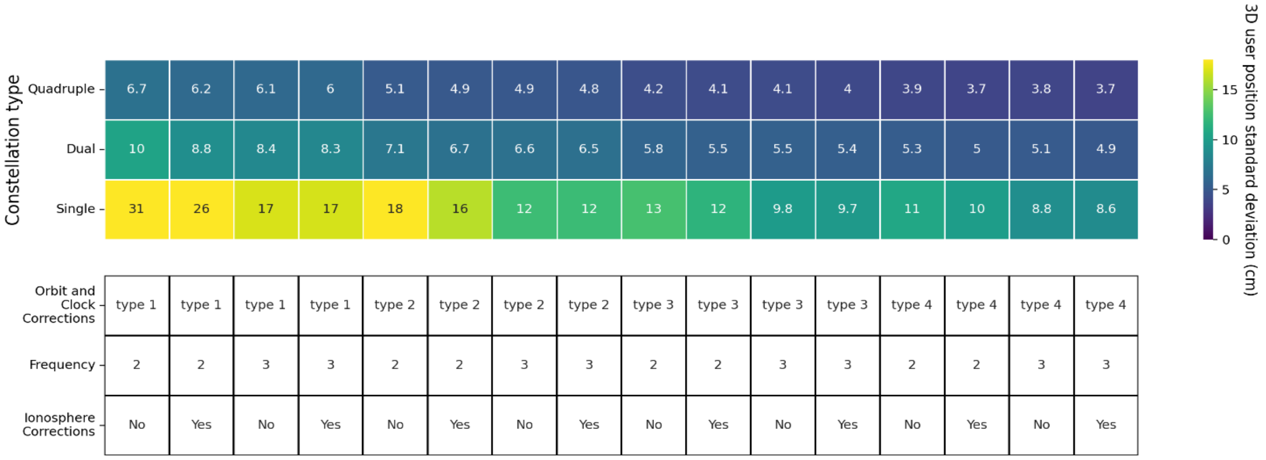
The following observations can be made about the network corrections and user positioning:

- The quality of the ionosphere module is greatly affected by the number of ground stations, resulting in higher quality results for a greater number of stations.
- The inclusion of high-quality orbit corrections doesn't provide any additional advantage to the plasma-ionospheric corrections, since their impact is almost not visible.
- The orbit corrections act with a clear influence on the clock accuracies. Phase and code can be said to be invariant to this parameter.
- The increased number of stations results directly in an improvement of the quality of satellite clocks and biases.
- The quality of the orbits and clocks is clearly one the main parameters that improve the accuracy of the user.
- An increasing number of constellations also presents an enormous advantage to the user, as it proves to augment the accuracies in a large scale.
- The use of three frequencies as an alternative to two, improves the user accuracy, but with high quality corrections and the use of multi-constellations, this parameter becomes lesser significant.

Further, it has been seen that the accuracy of orbit, satellite clocks, and satellite biases improve with an increasing number of ground stations. The accuracy of those states reaches a ground floor when the number of stations is 120, which is maintained when more stations are increased. According to these results, it is not worth for those corrections to add more than 120 stations.

Concerning the integer ambiguity resolution, it had been already observed in phase-1 that it has a significant effect on the user positioning. In phase-2 focus has been put on the network side. Enabling IAR when estimating the satellite clocks and biases has an effect on auxiliary parameters in the estimation, which are mainly receiver-related; they are the receiver position, troposphere, and receiver clocks. However, the accuracy of phase and code biases remains identical for both the fixed and float solutions.

A graphical summary of the achieved user accuracies is illustrated in Figure 3-4.



Quadruple	6.7	6.2	6.1	6	5.1	4.9	4.9	4.8	4.2	4.1	4.1	4	3.9	3.7	3.8	3.7
Dual	10	8.8	8.4	8.3	7.1	6.7	6.6	6.5	5.8	5.5	5.5	5.4	5.3	5	5.1	4.9
Single	31	26	17	17	18	16	12	12	13	12	9.8	9.7	11	10	8.8	8.6
Orbit and Clock Corrections	type 1	type 1	type 1	type 1	type 2	type 2	type 2	type 2	type 3	type 3	type 3	type 3	type 4	type 4	type 4	type 4
Frequency	2	2	3	3	2	2	3	3	2	2	3	3	2	2	3	3
Ionosphere Corrections	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes

Figure 3-4. User positioning accuracy results. Corrections of Type 1 are the least accurate, those of Type 4 are the most accurate.

4. CONCLUSIONS

In phase-2 of the AHD-GNSS project, several enablers have been studied in order to improve the estimation of accuracies of network corrections to be broadcast to the user. They are the estimation of GNSS MEO orbits, estimation of ionospheric corrections based on a dual-layer assumption, the inclusion of a LEO constellation to supplement the ground network for the estimation of the ionosphere, and the integer ambiguity resolution on the network side.

The performance budgets have been obtained by means of covariance analyses. The estimation of the accuracy of MEO orbits and both layers of the ionosphere has revealed to be quite optimistic. To compensate for this effect, both the orbit and iono have been scaled to more realistic values. However, one possible reason to explain the optimistic accuracies is that there are constant or quasi-constant biases which are being disregarded in the implemented models. In this case, a more rigorous method to achieve more realistic values is to account for those biases in the model. One way of including them in the Kalman filter is explained in [RD1].

On the other hand, the accuracy satellite clocks and biases, as well as user positioning are realistic. They could be injected as corrections to the user as they were obtained.

Further, it has been seen that the accuracy of orbit, satellite clocks, and satellite biases improve with an increasing number of ground stations. The accuracy of those states reaches a ground floor when the number of stations is 120, which is maintained when more stations are increased.

Concerning the integer ambiguity resolution, it had been already observed in phase-1 that it has a significant effect on the user positioning. In phase-2 focus has been put on the network side. Enabling IAR when estimating the satellite clocks and biases has an effect on auxiliary parameters in the estimation, which are mainly receiver-related; they are the receiver position, troposphere, and receiver clocks.

Besides the analysis done throughout the project, a further relevant output is a concept demonstrator SW tool which is capable of predicting end-to-end performances of a GNSS system in terms of formal accuracies by including new GNSS concepts, such as complementing the ground infrastructure with a LEO constellation.

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