Collaborative calibration of MEO GNSS signal biases based on LEO satellites

GNSS-BICS

GNSS-BICS-P Executive Summary

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1. ABSTRACT

GNSSBICS is a feasibility study carried out in the frame of the ESA's General Studies Programme (GSP) by DEIMOS-Space, Deimos-Engenharia and ESA.

This activity investigated what G/S infrastructure would be necessary to develop a System, named as GNSS-BICS (GNSS Bias Calibration System), in charge of providing, under demand, the GNSS MEO S/C SISBAF (Signal-In-Space Biases Amongst Frequencies), from GNSS observations gathered by GNSS multi-frequency receivers on-board LEO satellites (potentially from different missions).
According to a complete engineer process, with several iterations, the outline of GNSSBICS system was defined, and a demonstrator of the GNSS-BICS system named as GNSS-BICS-P (GNSS Bias Calibration System Prototype), able to provide the real GPS SIS biases amongst the L1 and L2 frequencies and TEC estimations profiting from the above calibration was developed.
Finally assessment of performance, in terms of accuracy of the calibration of the GPS L1-L2 differential group delay and estimation of the ionospheric total-electron content were evaluated through experimentation.

1.1. Project objectives

GNSSBICS proposal was prepared answering ESTEC contract no. 4000105076/11/NL/AF. The main motivation for the GNSSBICS project is:

- To define a system in charge of providing, under demand, the GNSS MEO S/C SISBAF (Signal-In-Space Biases Amongst Frequencies), from GNSS observations gathered by GNSS multi-frequency receivers on-board LEO satellites (potentially from different missions), ensuring its feasibility: the GNSS-BICS (GNSS Bias Calibration System).

With this motivation in mind, the following objectives were defined:

- To investigate what G/S infrastructure would be necessary to develop such a system.
- To evaluate the achievable performance, of accuracy of the calibration of the GPS L1-L2 differential group delay and estimation of the ionospheric total-electron content, under different working conditions and configurations of the GNSS-BICS system.

2. GNSSBICS TECHNICAL RESULTS

Most important technical results obtained in the frame of GNSSBICS project can be summarized as follow:

1. Analysis of available GPS dual frequency data for LEO missions.
2. Definition of GNSS-BICS ground infrastructure.
3. Definition of GNSS-BICS functional architecture and detailed design of the system constituents.
4. Development of a system prototype, GNSS-BICS-P
5. GPS on-board antenna code biases calibration.
6. Calibration of the GPS L1-L2 differential group delay.
7. Estimation of ionosphere prediction model parameters.
8. Demonstration of GNSS-BICS concept viability.

2.1. GNSS-BICS LEO Satellites

Nowadays the estimation of the differential group delays amongst different navigation signals is performed at the different GNSS Control Centres by processing GNSS multi-frequency observables gathered by ground sensor stations. A significant improvement can be envisaged if the estimation is aided by multi-frequency observables from GNSS receivers on-board LEO (Low Earth Orbit) satellites. In fact, in case of relatively high LEO orbits, the measurements gathered by the receivers are mostly unaffected by the ionosphere, therefore representing a very especial source of information about SISBAF.

If multi-frequency measurements from these missions are available, the estimation of SISBAF and TEC (Total Electron Content) can be de-coupled. On a first step, SISBAF can be estimated from LEO measurements, achieving an accuracy of a few centimeters. On a second step, TEC values are estimated from the measurements gathered by a GNSS ground stations network, taking advantage of the SISBAF parameters estimated on the first step.

Analyses of available real data have been performed during the first phase of the study.

2.2. GNSS-BICS Architecture, Elements, Interfaces

A scheme of the GNSS-BICS architecture is shown hereafter.

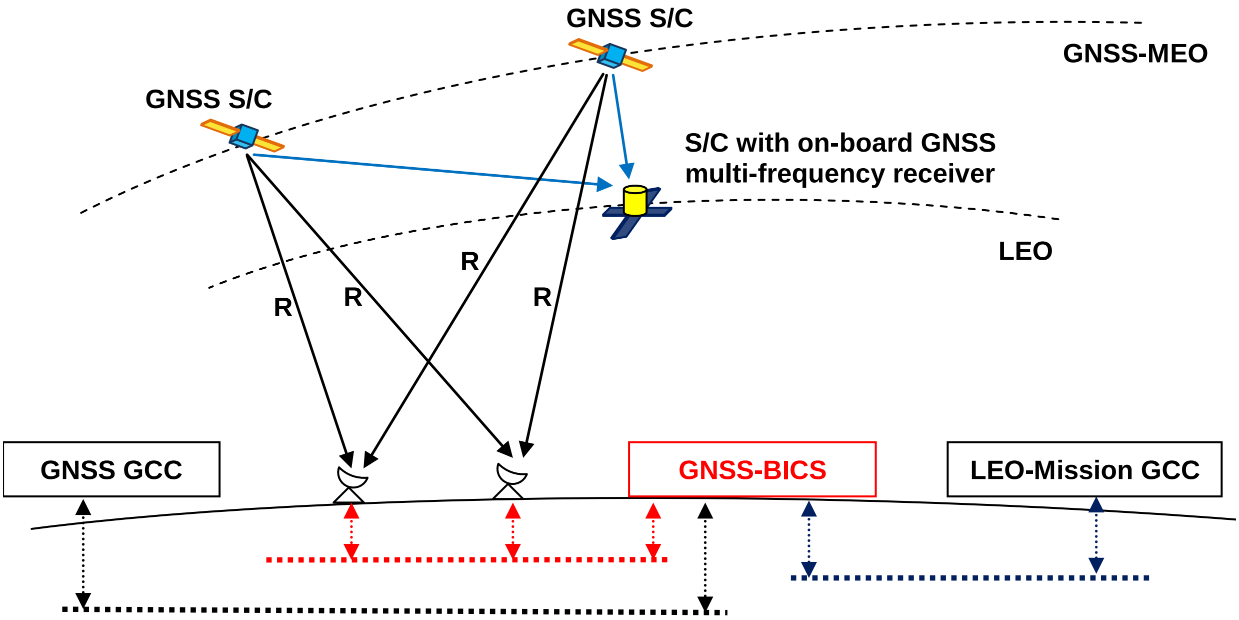

Table 1: Schematic view of GNSS-BICS

The GNSS-BICS system would establish a passive, transparent and indirect collaboration between two or more independent space systems (see Table 1); namely

- a GNSS system, based on MEO satellites,
- and other or others system(s) based on LEO satellites (potentially from different missions) equipped with multi frequency receiver.

This collaboration would not require the modification of any of the individual space systems, but the development of a complementary, independent and limited ground infrastructure, estimating in pseudo-real-time the GNSS MEO S/C SISBAF.

2.3. GNSS-BICS-P Main Functions and Performances

2.3.1. A-priori calibration of the transmitting MEO antennas

The MEO antenna calibration is devoted to the evaluation of antenna code bias off-axis angle dependency. It is based on the use of the multipath linear combination of basic code and phase measurements gathered by a network of ground stations, equipped with receivers not applying smoothing and characterized by identical model and settings, in this way avoiding to smooth the MEO antenna bias off-axis dependency, and ensuring consistency.

2.3.2. SISBAF estimation

The GNSS-BICS SISBAF calibration function is in charge of processing the measurement data coming from the LEO S/C, estimating the SISBAF values, and predicting their evolution in the near future.

As already explained in [1], the SISBAF calibration process is carried out in two sequential stages:

- *Pre-processing*. First, the LEO measurements are pre-processed in order to discard the ones with undesired effects (e.g., ionospheric delay, outliers), correct the valid ones with pre-calibrated corrections (e.g., antenna code bias calibration), reduce the noise level through smoothing, and finally obtain the observables useful for estimating the SISBAF, that is, the geometry-free combinations of smoothed codes.

- *Filtering*. Second, the pre-processed measurements are combined and their combinations enter the estimation filter in order to estimate the SISBAF parameters. Single difference geometry free observables $P_{i,i',j,1}(t,t')=P_{i,j,1}(t)-P_{i',j,1}(t')$ (see [1]) enter an EKF (Extended Kalman Filter) that produces an estimate of the state at each observation epoch as new measurements become available.

In order to remove the antenna code bias from observations an a-priori calibration of the transmitting MEO antennas has been performed; multipath linear combination has been used to evaluate the antenna effect variation with transmission angle and to generate the corresponding code correction.

2.3.3. VTEC estimation

The broadcast group delay (BGD) is directly computed from the inter-frequency biases (IFB). The standard IFB estimation process is based on the implementation of dual-frequency ionospheric combinations in which only the ionospheric contribution and the IFB remain as unknowns. In this way the estimation filter returns the IFB corresponding to each dual-frequency combination for all satellites and stations. As a by-product, it also returns the vertical TEC, which is used for the ionospheric model parameters computation.

Concerning the TEC evaluation, there is also the option to use NeQuick model for computing the ionospheric information (Slant TEC for each station satellite link). This is done using the standard reference ionosphere or the information from the navigation message Az parameter if available.

The same TEC evaluation can be obtained from a third option, using IONEX data, containing maps with the vertical Tec values as an input. However, the main use of these files is foreseen in Verification and Validation activities.

If NeQuick or using IONEX as input are selected for ionospheric modelling, only the IFB (for stations and satellites) is estimated in the filter.

2.3.4. Ionosphere broadcast model fitting

Ionosphere model parameters, to be included in the navigation message, have been predicted interpolating with a parabolic model the Az values (being Az the effective ionisation level) obtained by the NeQuick model that best fit the estimated VTEC profiles over time and per network station.

2.3.5. System Performances

The experimentation has been performed to quantitatively evaluate the achievable performance, in terms of accuracy of the calibration of the GPS L1-L2 differential group delay and estimation of the ionospheric total-electron content.

3. CONCLUSIONS

GNSS-BICS is a system in charge of providing, under demand, the GNSS MEO S/C SISBAF (Signal-In-Space Biases Amongst Frequencies), from GNSS observations gathered by GNSS multi-frequency receivers on-board LEO satellites (potentially from different missions).

The emphasis of the study has been in analysing the feasibility of this system, in terms of a realisable solution.

Analyses of available real data have been performed during the first phase of the study resulting in:

1. evidence of the presence of the ionosphere between the LEO and GPSs., which justifies the need of having an Ionospheric detection algorithm to screen the arcs for ionosphere and allow a precise SISBAF estimation.
2. symptom that a geometry dependent behaviour, such as an elevation dependent bias, is present in the single difference geometry free observables, and should be corrected in the pre-processing. A specific calibration was performed to allow such a correction, since these antenna code bias calibrations were not found in the literature.

Definition of functional architecture has been postulated, describing the functional elements and their candidate implementations.

The performances achievable by the system main function have been evaluated through execution of simulations in different scenarios. Experimentation on GPS L1C-L2P SISBAF, from GNSS observables gathered by Jason-2 & MetOp-A indicates that the overall methodology works in line with expectations.

The summary of final experimentation conclusions follows:

- **[Real data based] Satellite antenna code-phase bias variation over DoT (Direction of Transmission)**: 48 mm RMS over all satellites.
    - This is considered an excellent result. Therefore this technique is proposed for further assessment in the frame of G2G (Galileo 2nd Generation, EGEP-ID68).
    - Note: improvements on the estimation accuracy may still be possible, and are addressed in other ESA activity (EGEP-ID68).

- **[Real data based] SF-IONO analysis**: very promising results provided per station in intense ionospheric condition (F10,7 = 171 [W/(m2 Hz)]).
    - These results are translated into navigation message error for a both nominal and reduced GSS network (fitting error component below 10 TECu).
    - Results and algorthms for the derivation of the navigation message are relevant in the frame of G2G activities (EGEP-ID68), especially those for the reduced GSS network.

- **[Real data based] SISBAF estimation**: 11.7 cm RMS over all satellites.
    - This is considered an excellent result, given the limited amount of data available (24 hours ranging data from MetOp A and Jason-2). The achieved performance are comparable with those by GNSS Ground Segments (based on global ground receiver networks) processing a much larger amount of data.
    - This technique shows great potential considering that many future ESA missions plan to embark dual frequency GNSS RX. Therefore further research on this is proposed, especially in combination with current techniques.

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