POD AND PPP WITH MULTI-FREQUENCY PROCESSING

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1 INTRODUCTION

Precise Orbit Determination (POD) and Precise Point Positioning (PPP) are methods for estimating the orbits and clocks of GNSS satellites and the precise positions and clocks of user receivers. These methods are traditionally based on processing the ionosphere-free combination. With this combination, the delay introduced in the signal when passing through the ionosphere is removed, taking advantage of the dependency of this delay with the inverse square of the frequency. It is also possible to process the individual frequencies, but in this case it is needed to properly model the ionospheric delay. This modelling is usually very challenging, as the electron content in the ionosphere experiences important temporal and spatial variations. These two options define the two main kinds of processing: the dual-frequency ionosphere-free processing, typically used in the Orbit Determination and Time Synchronization (ODTS) and in certain applications of PPP, and the single-frequency processing with estimation or modelisation of the ionosphere, mostly used in the PPP processing.

In *magicGNSS*, a tool suite developed by GMV to offer a series of GNSS services, a hybrid approach has been implemented. This approach combines observations from any number of individual frequencies and any number of ionosphere-free combinations of these frequencies. In such a way, the observations of ionosphere-free combination allow a better estimation of positions and orbits, while the inclusion of observations from individual frequencies allows to estimate the ionospheric delay and to reduce the noise of the solution. It is also possible to include other kind of combinations, such as geometry-free combination, instead of processing individual frequencies. The joint processing of all the frequencies for all the constellations requires both the estimation or modelisation of ionospheric delay and the estimation of inter-frequency biases. The ionospheric delay can be estimated from the single-frequency or dual-frequency geometry-free observations, but it is also possible to use a-priori information based on ionospheric models, on external estimations and on the expected behavior of the ionosphere. The inter-frequency biases are due to the different HW group delays per frequency in the transmitter and the receiver. However, it is possible to include constraints in the estimator regarding these delays, assuming small variations over time.

By using different types of combinations, all the available information from GNSS systems can be included in the processing. This is especially interesting for the case of Galileo satellites, which transmit in several frequencies, and the GPS IIF satellites, which transmit in L5 in addition to the traditional L1 and L2. Several experiments have been performed, to assess the improvement on performance of ODTS and PPP when using all the constellations and all the available frequencies for each constellation. This work describes the new approach of multi-frequency processing, including the estimation of biases and ionospheric delays impacting on GNSS observations, and presents the results of the performed experimentation activities to assess the benefits in ODTS and PPP algorithms.

2 *magicGNSS* INFRASTRUCTURE

magicGNSS offline service is based on a web application which allows, among other functionalities, to run ODTS and PPP executions (Tobías et al., 2014). In the ODTS (Fig. 1), observations from a network of GNSS receivers are used to estimate orbits and satellite clocks, together with the position and clocks of the receivers. In the PPP (Fig. 2), observations from a particular receiver are processed, to estimate the position and clock of this receiver. This processing needs precise information about satellite orbits and clocks, which can be obtained from ODTS processes. In both cases, if different frequencies and combinations are included, biases between them need to be also estimated. In addition, if single frequency or geometry-free measurements are processed, ionospheric delays are also included in the estimation.

Fig. 1 Schema of POD processing in *magicGNSS*.

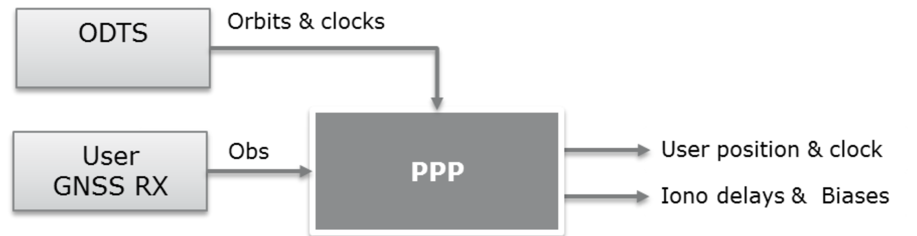

Fig. 2 Schema of PPP processing in *magicGNSS*.

Apart from the web application, *magicGNSS* implements the same algorithms on a real-time basis (Fig. 3). With this configuration, precise orbits and clocks are generated in a real-time ODTS. With these orbits and clocks, corrections to the navigation message are generated and sent to the real-time PPP, which estimates the position and clock of the user receiver in real-time.

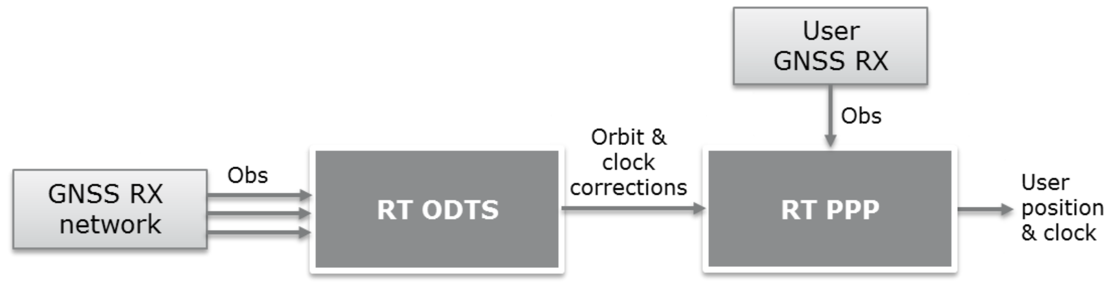

Fig. 3 Schema of Real-Time infrastructure of *magicGNSS*.

3 MULTI-FREQUENCY PROCESSING

The traditional ODTS and PPP solutions are based on processing ionosphere-free measurements to estimate the satellites orbits and clocks in the ODTS or the precise position of the user in the PPP, according to the following equations:

$$l_p = \rho + c(b_{Rx} - b_{sat}) + Tr + HW_p + \varepsilon_p$$
$$l_\phi = \rho + c(b_{Rx} - b_{sat}) + Tr + HW_\phi + N\lambda + \varepsilon_\phi$$

Where:

- l_P is the ionosphere-free combination of pseudoranges from two different frequencies.
- l_ϕ is the ionosphere-free combination of carrier phases from two different frequencies.
- b_{Rx} is the receiver clock offset from the reference time.
- b_{Sat} is the satellite clock offset from the reference time.
- c is the vacuum speed of light.
- Tr is the signal path delay due to the troposphere.
- HW_P and HW_ϕ are the hardware biases of satellites and stations.
- λ is the carrier combination wavelength.
- N is the ambiguity of the carrier-phase ionosphere-free combination (it is not an integer number).
- ε_P and ε_ϕ are the measurement noise components, including multipath and other effects.
- ρ is the geometrical range between the satellite and the receiver.

The same can be done with different pairs of frequencies. In that case, all the observations are processed together in the estimator.

However, it could be also interesting to process individual frequencies without any kind of combination. For PPP applications, it could happen that the receiver is only able to provide measurements for some particular frequency and the single-frequency processing is strictly needed. In ODTS, single-frequency processing would allow the estimation of ionospheric delays and the biases between frequencies and codes, which could be interesting for certain applications.

In these cases, the observations of ionosphere-free combination should be replaced by the observations for the selected frequencies, according to the following equations:

$$l_{1p} = \rho + c(b_{Rx} - b_{sat}) + Tr + I + HW_p + \varepsilon_{1p}$$
$$l_{1\phi} = \rho + c(b_{Rx} - b_{sat}) + Tr - I + HW_\phi + N_1\lambda + \varepsilon_{1\phi}$$

Where:

- l_{1P} is the pseudorange for a particular frequency.
- $l_{1\phi}$ is the carrier phase for a particular frequency.
- I is the signal path delay due to the ionosphere.
- N_1 is the ambiguity of the carrier-phase observation for a particular frequency.
- ε_{1P} and $\varepsilon_{1\phi}$ are the measurement noise components for a particular frequency.

For the processing of single-frequency observations, the assessment of ionospheric delays and biases is required. The ionospheric delays can be taken from external sources, such as Global Ionospheric Maps (GIMs) or ionospheric models, such as Klobuchar and NeQuick. They can be also estimated together with orbits, positions and clocks.

Regarding the biases, when mixing different frequencies in the same estimator biases appears both in satellites and receivers. In general, the absolute value of these biases is unknown and the solutions are referred to some particular combination. In that case, for this combination there is no need to include any kind of bias, but for the rest of combinations and individual frequencies included in the processing, one needs to introduce a relative bias. This bias can be obtained from external sources or estimated together with orbits, positions, clocks and ionospheric delays.

Finally, it is also possible to combine the observations of single-frequency together with the ionosphere-free combinations, or even include other kind of combinations such as the geometry-free combination, which could be more adequate for the estimation of ionospheric delays.

4 USAGE OF GPS L5

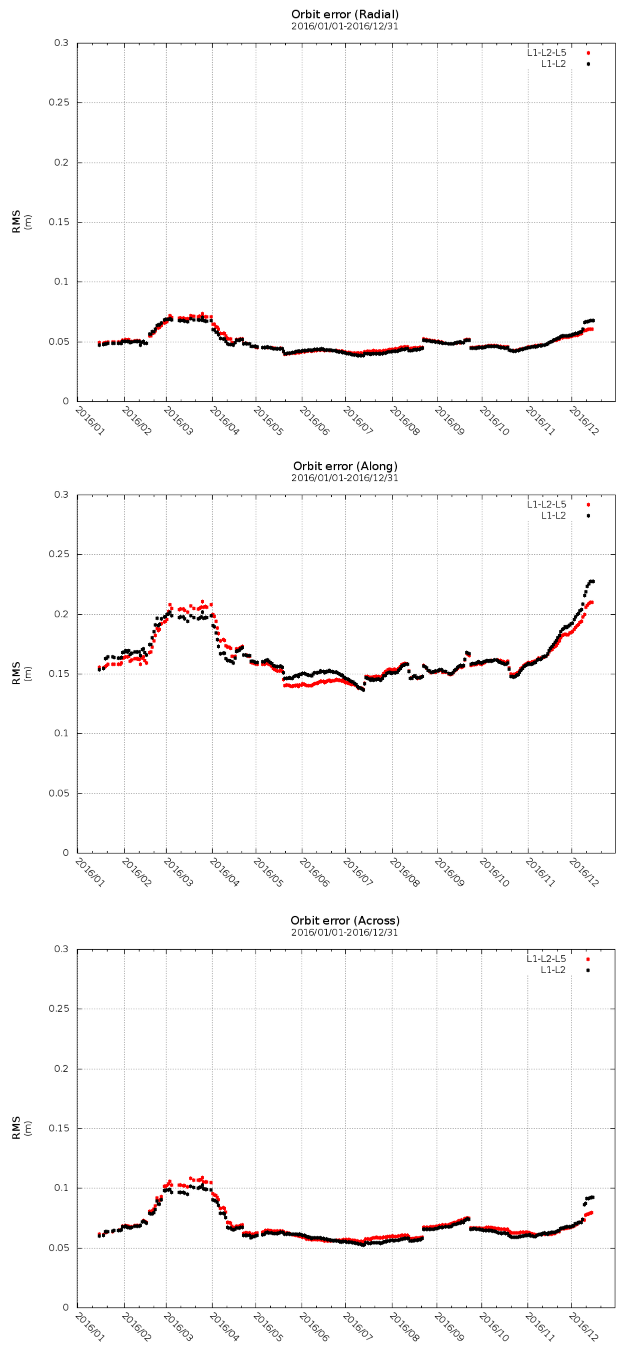

Fig. 4 Radial, along and across errors in the estimated orbits of GPS satellites obtained with a 20-stations GPS-only ODTS (vs reference configuration based on 50-stations), both with L1-L2 and with L1-L2-L5

With the new approach for multi-frequency processing, several experiments have been performed. In particular, the potential improvement in orbit determination when using L5 frequency in GPS block IIF satellites has been analyzed.

For this analysis, one year of data has been processed with ODTS, in batches of one day, to generate orbits and clocks for GPS satellites.

The same has been done with different configurations:

Configuration 1:	20 stations GPS-only L1 and L2
Configuration 2:	20 stations GPS-only L1, L2 and L5
Reference:	50 stations GPS+GLONASS+Galileo L1 and L2

The last configuration is used as reference to assess the error of the orbits estimated with the other configurations.

Fig. 4 shows these errors. It can be observed that the impact of including L5 is not significant. However, these results could be different in the future if more GPS satellites start to use L5.

5 USAGE OF GALILEO E1/E5a/E5b

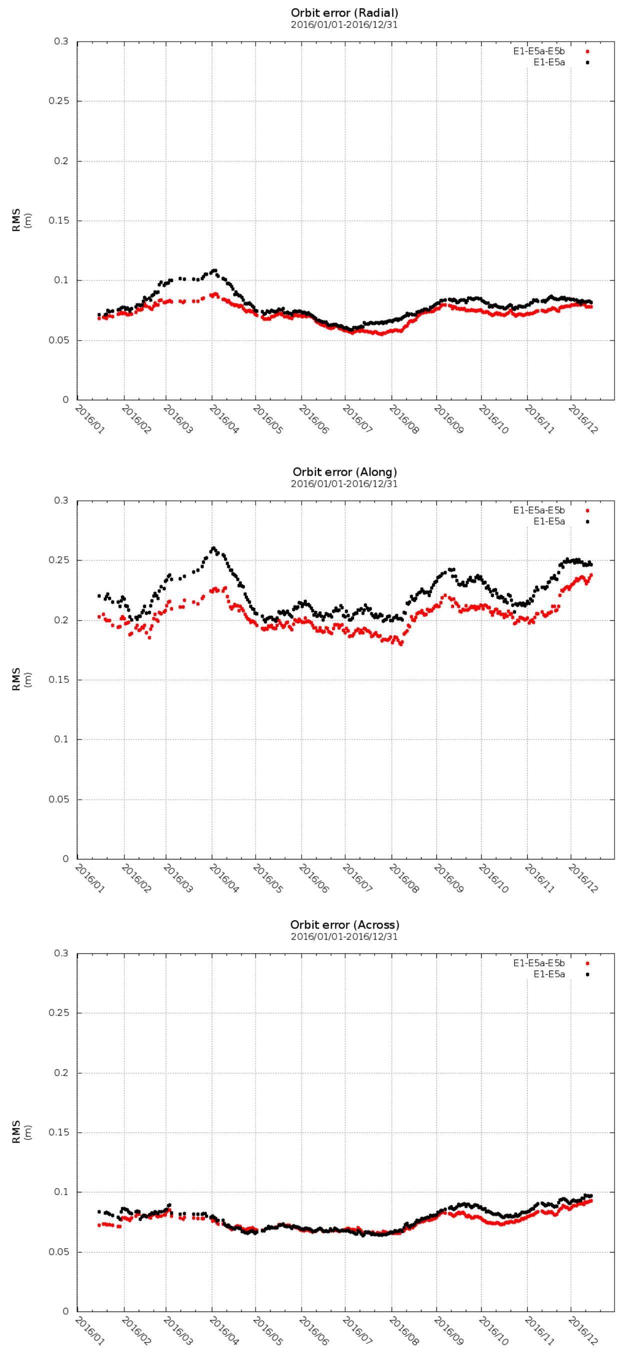

Fig. 5 Radial, along and across errors in the estimated orbits of Galileo satellites obtained with a 20-stations GPS+Galileo ODTS (vs reference configuration based on 50-stations), both with E1-E5a and with E1-E5a-E5b.

For the case of Galileo satellites, several frequencies are available. With the multi-frequency approach described in previous sections, it is possible to include all these frequencies in ODTS processing. To assess the impact of using several frequencies in the estimation of Galileo orbits, an additional experimentation has been performed.

Again, one year of data in batches of one day has been processed. For this experiment, the following configurations has been used:

Configuration 1:	20 stations GPS+Galileo E1 and E5a
Configuration 2:	20 stations GPS+Galileo E1, E5a and E5b
Reference:	50 stations GPS+GLONASS+Galileo E1 and E5a

The last configuration is used as reference to assess the error of the orbits estimated with the other configurations.

Fig. 5 shows these errors. It can be observed that the inclusion of E1, E5a and E5b in the processing can significantly improve the estimation of orbits and clocks.

6 ESTIMATION OF BIASES AND IONOSPHERIC DELAYS

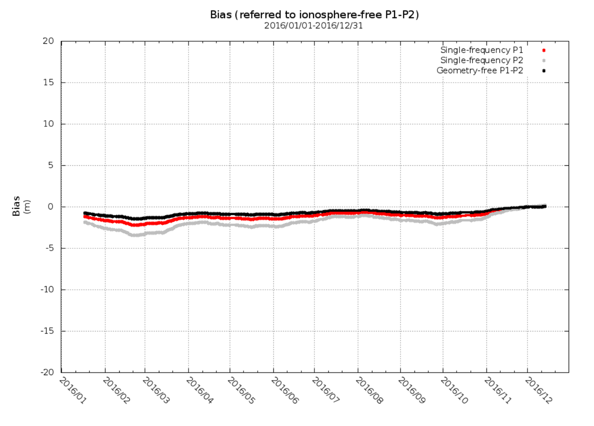

Fig. 6 Biases of MAS1 for single-frequency P1 and P2 and for geometry-free P1-P2 relative to the bias of ionosphere-free P1-P2.

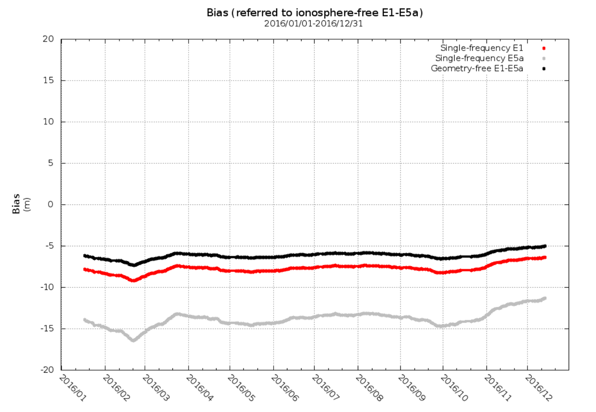

Fig. 7 Biases of MAS1 for single-frequency E1 and E5a and for geometry-free E1-E5a relative to the bias of ionosphere-free E1-E5a.

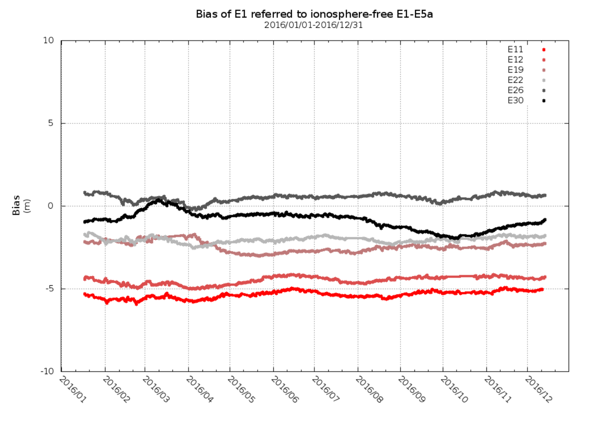

Fig. 8 Biases of some Galileo satellites for single-frequency E1 relative to the bias of ionosphere-free E1-E5a.

If several individual frequencies and combinations of frequencies are included in the ODTS or PPP process, it is possible to estimate satellite and station biases between them. In particular, one of the combinations can be selected as a reference, and relative biases are estimated for the rest of frequencies and combinations.

An additional experimentation has been performed to estimate biases for satellites and stations. In particular, one year of data for a particular station (MAS1) has been processed with PPP in batches of one day. For this experimentation, the following configuration has been used:

PPP Config.:	1 station (MAS1) GPS+GLONASS+Galileo L1-L2, E1-E5a

As a result, both station (Fig.6 and Fig.7) and satellite (Fig.8) biases have been obtained. As expected, satellite and station biases are quite stable over the year, although small variations can be observed.

With the same processing, it is possible to obtain the ionospheric delays for this particular station. This can be done by directly estimating the delays, or improving this estimation with a-priori ionospheric information. This information can be obtained from models (e.g. Klobuchar or NeQuick) or based on corrections (Carbonell et al., 2016).

7 CONCLUSIONS

The multi-frequency processing in the estimation of satellite orbits and clocks and in the estimation of station positions and clocks seems to be a potential way of improving the performance of such estimates. With this strategy, any number of individual frequencies from all the constellations and any number of combinations of these frequencies are included together in the processing. Typically, ionosphere-free combinations are combined with single-frequency measurements or geometry-free combinations.

With this approach, it is possible to use all the available information coming from the satellites. The increase in the amount of information expectedly leads to an improvement in the quality of the estimated parameters. This is clearer for the case of Galileo frequencies, as the amount of new information is very large. For the case of GPS L5, no clear improvement is observed, because only some satellites are transmitting with this frequency and the amount of L1 and L2 observations is enough to obtain a precise determination.

Apart from increasing the amount of information used in the processing, the multi-frequency approach also allows the estimation of satellite and station biases and the estimation of ionospheric delays without degrading the estimation of positions, orbits and clocks.

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