Airborne Time-Correlated GNSS Multipath Error Modeling of Carrier-phase Smoothed Code

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BIOGRAPHY

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ABSTRACT

This work analyses possible stochastic models for airborne dual-frequency, multi-constellation (DFMC) GPS and Galileo multipath errors considering their time-correlated nature. The characterization is performed based on flight data collected during the EU project DUFMAN. The potential multipath models are derived as an extension of recently proposed DFMC variance models and we analyse their potential to ensure bounding conditions over time by using frequency domain upper bounding analysis. This paper focus first on the analysis of 100-seconds carrier-phase smoothed code multipath.

I. INTRODUCTION

To ensure the safe positioning based on the Global Navigation Satellite System (GNSS), it is imperative to accurately characterize and bound residual errors in GNSS measurements, such as code-phase. In civil aviation, various augmentation systems, such as the Satellite-based Augmentation System (SBAS), Ground-based Augmentation System (GBAS), and Aircraft-based Augmentation System (ABAS), have been designed to ensure the integrity of the position solution. These systems achieve this by providing error corrections, error models, and monitoring of possible faults.

One of the critical error sources that must be properly considered is airborne multipath and noise. Current avionics standards (RTCA DO-253C, 2008)(RTCA/SC-159, 2006) offer model recommendations for GPS L1 C/A. More recently, new models have been proposed for GPS and Galileo L1/E1 and E5/E5a (Circiu et al., 2020, 2021), and these new models are being incorporated into the forthcoming dualfrequency Minimum Performance Operation Standards (MOPS) (EUROCAE, 2019). These models describe multipath and noise errors as zero-mean Gaussian distributions with variances dependent on the elevation angle of the satellite over the horizon (Booth et al., 2000; Murphy et al., 2005a,b). Additional evaluation of multipath, where the deterministic contribution of the antenna group delay variation (AGDV) has been separately modeled, has also been suggested (Caizzone et al., 2022; Circiu, 2020). These models can consider AGDV in conjunction with the multipath component, as an additional separate variance term, or as a bias (Bang et al., 2024). Since SBAS, GBAS, and Advanced Receiver Autonomous Integrity Monitoring (ARAIM) utilize snapshot estimators (e.g., least-squares), with the position computation performed independently at each epoch, the aforementioned models are sufficient. However, these models lack information about the stochastic temporal behavior of the error, such as its time correlation.

Understanding the stochastic dynamic behavior of errors is essential when using sequential estimators like the Kalman filter (KF), which are typically employed in GNSS and Inertial Navigation System (INS) integration. These estimators retain historical memory, and failing to properly model time correlation can lead to biased estimation, inconsistency, or even filter crashes (Petovello et al., 2009). Understanding the time-correlation of errors has also been important to assess the impact of the number of effective samples in translating requirements from per hour/operation to per epoch in ARAIM (Zhai et al., 2020; Bang and Milner, 2021).

Recent studies have analyzed historical data to propose potential new dynamic models for satellite orbit/clock (Gallon et al., 2022) and residual troposphere (Gallon et al., 2021). We set to analyze and model the dynamics of airborne dual-frequency dual-constellation multipath, identifying suitable models and analysing their potential to ensure bounding conditions. The methodology employed in this paper is as follows: We utilize airborne data collected and processed during the EU project DUFMAN, which includes flights from Airbus A321, A330, and A350 aircraft. Multipath and noise are isolated through the application of the code-minus-carrier technique, while the ionospheric delay is estimated by combining dual-frequency carrier-phase measurements. The AGDV, previously characterized in an anechoic chamber (Caizzone et al., 2022), is corrected in the antenna frame by utilizing information on the aircraft's attitude and heading. The contribution of integer ambiguities after ionospheric error removal is averaged out over segments of continuous tracking without cycle slips. For ARAIM, GBAS, and SBAS applications, carrier-smoothed code measurements are typically used (nominally over 100s).

It has been demonstrated that providing conservative Kalman filter error covariance estimates (i.e., where the KF covariance overbounds the actual KF error covariance) under uncertain time-correlated errors can be achieved by upper bounding the Power Spectral Density (PSD) of individual error components with a suitable time-correlated error model, which can then be implemented in the KF (Langel et al., 2021). This criterion has enabled the discovery of tight overbounding models for uncertain first-order Gauss-Markov Processes (García Crespillo et al., 2023) and can be readily adapted to, for example, GNSS/INS integration (García Crespillo et al., 2020; Garcia Crespillo, 2022). One requirement of the frequency upper bounding criterion is that it assumes the signal is stationary. As previously established, multipath is generally not stationary over different time frames and exhibits a strong trend depending on elevation. In this paper, we introduce a normalization step to remove the elevation dependent potential non-stationarity for detrending the data before further frequency analysis. Subsequently, we propose time-correlated error models with reduced number of required parameters by evaluating the PSDs of different flights for GPS and Galileo L1/E1 and L5/E5a.

II. STANDARD MULTIPATH MODELS

Initial multipath models were derived for GPS L1 and included in GNSS single frequency MOPS (Murphy et al., 1996; McGraw et al., 2000). More recently, in the context of the DUFMAN project funded by the European Commission new multipath models for the new signals were developed (Circiu et al., 2021). These models resulted less conservative compared to the legacy GPS L1 models due to less stringent assumptions about the antenna performance. Both models were extracted for 100-second smoothed code measurements and they are represented by a standard deviation dependent on the satellite elevation. In this work we use as a first step, the models in Circiu et al. (2021) related to the multipath component, that is, without the consideration of the AGDV contribution, which we will include in future work. The models were grouped for L1/E1 and L5/E5a as:

$$\sigma_{\text{mp, L1/E1}}(\theta) = 0.11 + 0.03 \cdot e^{-\frac{\theta}{80}}, \tag{1}$$

$$\sigma_{\text{mp, L5/E5a}}(\theta) = 0.07 + 0.06 \cdot e^{-\frac{\theta}{50}}, \tag{2}$$

where θ is the satellite elevation in degrees. On the other hand, the RTCA GNSS/INS standard DO-384 specifies that residual GNSS tropospheric, orbit, clock, and multipath errors should be modeled using a first-order Gauss-Markov process (FOGMP) (RTCA, 2020) with variance modeled as in SBAS/GBAS standards. While the standard allows for the use of different models, these models must undergo validation.

III. TIME-CORRELATED MODEL DEFINITION

Our goal in this work is to evaluate the suitability of obtaining time-correlated models that are compatible and can be considered as an extension of current (variance) multipath models. The proposed multipath model is therefore composed of two elements: one *scaling* factor based on the current standard models that captures the elevation dependency of multipath and a first-order Gauss-Markov (FOGMP) that represents the time-correlated nature. In order to avoid extra parameters, we evaluate here the suitability of using an unitarian FOGMP (i.e., one with unit variance), so that the final new models will need only one extra parameter. The multipath model ε_{mp} can be expressed mathematically as:

$$\varepsilon^j_{\text{mp},i}(\theta) = \sigma_{\text{mp},i}(\theta) \cdot \eta^j_i, \text{ with } \eta^j_i \sim FOGMP(1, \tau^j_i), \tag{3}$$

where θ is the satellite elevation, i is the frequency (i.e., either E1/L1 or E5a/L5), j is the constellation and τ is the time-correlated constant of the FOGMP.

IV. MODELING METHODOLOGY

The following steps are used to analyse and derive the time-correlated multipath error models from sample data:

- Multipath isolation: Multipath must be first isolated from the other code-phase error sources. This process starts from the computation of code-minus-carrier observables in a similar fashion as in (Circiu et al., 2020) and then the removal of the ionospheric divergence using dual-frequency carrier-phase combination. Contribution of fixed biased due to ambiguity terms are removed via averaging over continuous tracking interval after removing the AGDV induced errors considering the previously characterized antenna (Caizzone et al. (2022)) and the attitude of the aircraft. Cycle slips are also taken into account to evaluate the length of the continued tracked interval per satellite.
- In order to characterize purely the onflight multipath error and remove the contribution of possible ground multipath during taking-off, initial climbing and landing, we have only considered for the moment data from flight periods above 3 kms, we have not considered time series with only limited seconds of tracking and we have perform some screening for time series with inexplicable artifacts.
- After that, we apply a code-carrier smoothing filter with 100 second Hatch filter.
- The variance of multipath error is dependent on elevation (as shown by the existing models). This makes in principle the extracted multipath time series non-stationary by definition. Even though the change in variance might be slow or not during the continuous track of the satellite that form an independent time series, we consider here an elevation dependent variance normalization step by dividing each multipath sample by the existing standard deviation models in Eq. 1 and Eq. 2 for the code-smoothed case. In this fashion we remove the dependency of elevation and variance factor from Eq. 3 and remain with a *normalized* time-correlated time series.
- The power spectral density (PSD) of each of the multipath time series is then computed following Langel et al. (2020).
- Finally, we find suitable first order Gauss-Markov processes that best fit the PSD of the different multipath time series by grouping them per frequency and constellation in order to derive a model that provides bounding conditions for all the observed multipath realizations per group.

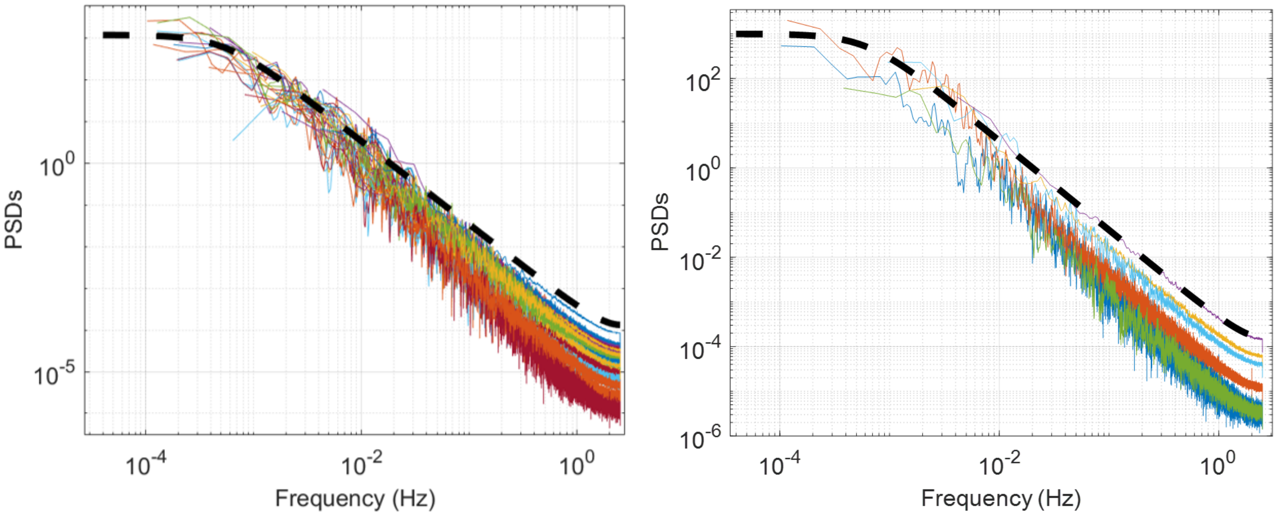
V. RESULTS

The analysis is performed over data from a total of 10 test flights with Airbus aircraft models A321, A330 and A350, each of them of a duration between 2,5 and 3 hours. Figure 1 depicts the PSD of the different time-series for Galileo E1 and E5a. Different realizations exposes slightly different frequency level, specially for higher frequencies. In Figure 1, a *best upper bound fitting* FOGMP is also represented, which has been found for a time-correlation constant of 300 seconds. Figure 2 shows similar results for GPS L1 and L5. A similar behaviour of the frequency analysis of the different multipath time-series is found and a suitable FOGMP has also been found with a time-constant of 300 seconds.

VI. DISCUSSIONS

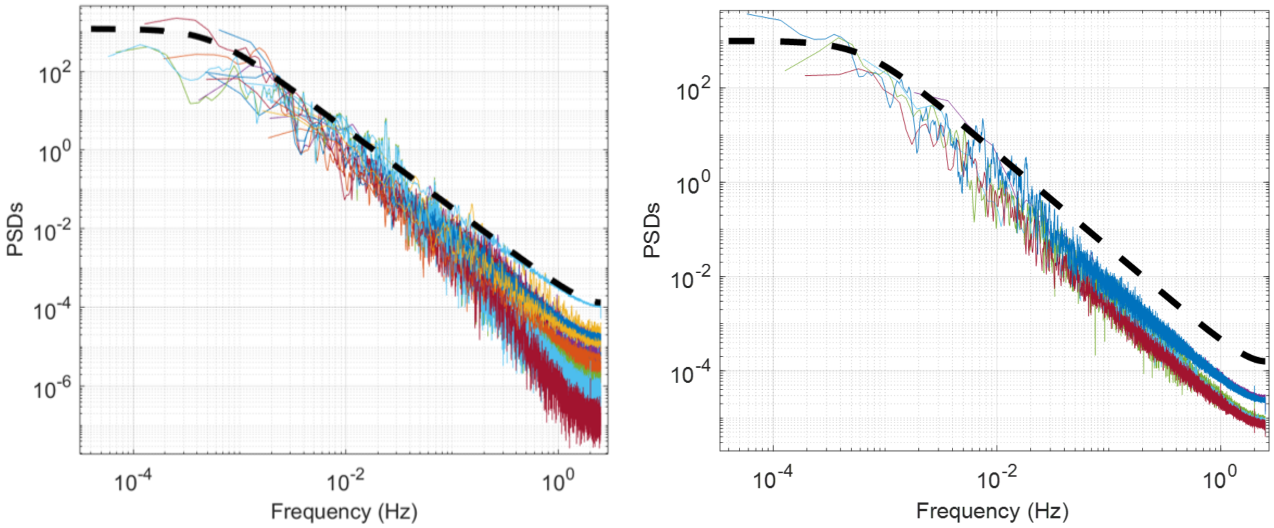
The results in Figure 1 and Figure 2 shows the suitability of the methodology and the proposed general model approach in Eq.3. It is possible to find a suitable time-constant for the FOGMP that provides an appropriate upper bounding representation of the underlying multipath time-series, which has been found to fit remarkably well. We have also found that for this best fit, the sensitivity to the time correlation constant was not big and values of a few seconds didn't seem to impact dramatically the upper fit. A closer determination of the time-constant will be consolidated in future work. For safety critical applications an upper bounding is desirable, some possible explanations and further investigations why the obtained normalized FOGMP are not strictly bounding all the time-series PSD are:

- Uncertainty of PSD estimate for lower frequencies may depend on the amount of data in that specific time series.
- Some residual noise may not be accounted for when normalizing the samples.
- The multipath variance models were derived as Root-Mean-Square (RMS) of the error, which provided good overbounding on the overall multipath and AGDV model Circiu et al. (2021). However, this may provide slight differences in the analysis when considering it separately from AGDV.
- The variance models were derived with respect to elevation in a navigation frame, however, some physical differences may appear due to manoeuvres of the aircraft in the analysed data due to multipath dependency on aircraft structure (in the aircraft frame).
- The choice of an specific PSD estimator may have an impact and may present some differences with respect to the FOGMP curves which are extracted from the theoretical equations in discrete sense (Joerger et al. (2023)).



(a) Galileo E1 **(b)** Galileo E5a

Figure 1: Power Spectral Density of Normalized Galileo Airborne Multipath Time-Series and associated unitarian First-Order Gauss-Markov (black dashed)



(a) GPS L1 **(b)** GPS L5

Figure 2: Power Spectral Density of Normalized GPS Airborne Multipath Time-Series and associated unitarian First-Order Gauss-Markov (black dashed)

VII. CONCLUSIONS

This work presents the analysis and dynamic error modeling of airborne multipath and noise for dual-frequency GPS and Galileo of carrier-phase smoothed code based on real flight data. The proposed models are derived in a way that can be considered an extension of current (variance) standard models. These findings could support various ARAIM activities, the use of augmentations like GBAS/SBAS with sequential estimators, and contribute to the development of future GNSS/INS dual-frequency dual-constellation MOPS.

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