Final results on airborne multipath models for dual-constellation dual-frequency aviation applications

Mihaela-Simona Circiu, Stefano Caizzone, Christoph Enneking, Friederike Fohlmeister, Markus Rippl, Michael Meurer (German Aerospace Center)
Michael Felux (ZHAW)
Ioana Gulie, David Rüegg (Airbus Defence and Space)
Joseph Griggs (Collins Aerospace)
Rémy Lazzerini, Florent Hagemann, Francois Tranchet (Airbus Operation SAS)
Pierre Bouniol (Thales Avionics)
Matteo Sgammini (Joint Research Center of the European Commision)

BIOGRAPHY (IES)

Dr. Mihaela-Simona Circiu graduated Computer Engineering at Technical University, Iasi, Romania in 2011 and a 2nd level Master in Satellite Navigation and Related Application at Politecnico di Torino, Italy in 2012. In 2020 she received her PhD Degree in Electrical Engineering and Information Technology at RWTH Aachen, Germany. Since 2013 she is working as a Navigation Research Engineer at the German Aerospace Center, in Oberpfaffenhofen near Munich. Her main area of interest include integrity for aviation application with focus on GBAS. She is participant in different working groups and since March 2020, she is leading the Augmentation Systems Group.

Dr. Stefano Caizzone received the M.Sc. in Telecommunications Engineering and the Ph.D. degree in Geoinformation from the University of Rome "Tor Vergata", Italy, in 2009 and 2015, respectively. Since 2010, he is with the Antenna group of the Institute of Communications and Navigation of the German Aerospace Center (DLR), Wessling, Germany, where he has been responsible for the development of innovative miniaturized antennas. Since July 2020, he leads the Antenna Group. His main research interests concern small antennas for satellite navigation, controlled radiation pattern antennas for robust satellite navigation and high-performance antenna design for precise satellite navigation, antenna arrays for satellite communication.

Christoph Enneking received the BSc. and the MSc. degrees in electrical engineering from the Munich University of Technology (TUM), Germany, in 2012 and 2014, respectively. In September 2014, he joined the Institute of Communications and Navigation of the German Aerospace Center (DLR), Wessling-Oberpfaffenhofen. His research interests include GNSS signal design, estimation theory, and GNSS intra- and intersystem interference.

Friederike Fohlmeister received the BSc. and the MSc. degrees in electrical engineering from Technische Universität München (TUM) in 2012 and 2014, respectively. In December 2014, she joined the Institute of Communications and Navigation of the German Aerospace Center (DLR). Her research interests include GNSS signal processing under multipath, ionospheric scintillations and other disturbances.

Markus Rippl *received his Diploma in Electrical Engineering and Information Technology from Technische Universität München* (TUM) in 2007. Since then, he has been a research associate with the Institute of Communications and Navigation (IKN) at the German Aerospace Center (DLR) in Oberpfaffenhofen near Munich. His areas of interest include GNSS integrity using receiver-side algorithms, next generation Receiver Autonomous Integrity Monitoring (RAIM) algorithms and architectures, and the development of a future integrity architecture supporting Advanced Receiver Autonomous Integrity Monitoring (ARAIM) with an Integrity Support Message (ISM).

Dr. Michael Felux graduated in technical mathematics from the Technische Universität München (TUM) in 2009 and received his Doctoral Degree in Mechanical Engineering also from the TUM in 2018. From 2009 to 2020 he worked at the German Aerospace Center where he was a group leader and program manager for the research on GBAS-based aeronautical navigation. In April 2020 he joined the Zurich University of Applied Sciences (ZHAW) as a Senior Lecturer for CNS and ATM.

Prof. Dr. Michael Meurer received the diploma in electrical engineering and the Ph.D. degree from the University of Kaiserslautern,Germany. After graduation, he joined the Research Group for Radio Communications at the Technical University of Kaiserslautern, Germany, as a senior key researcher, where he was involved in various international and national projects in the field of communications and navigation both as project coordinator and as technical contributor. From 2003 till 2013, Dr. Meurer was active as a senior lecturer and Associate Professor (PD) at the same university. Since 2006 Dr. Meurer is with the German Aerospace Center (DLR), Institute of Communications and Navigation, where he is the director of the Department of Navigation and of the center of excellence for satellite navigation. In addition, since 2013 he is a professor of electrical engineering and

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director of the Chair of Navigation at the RWTH Aachen University. His current research interests include GNSS signals, GNSS receivers, interference and spoofing mitigation and navigation for safety-critical applications

Ioana Gulie received her degree in Electronics, Telecommunications and Information Technology from University Politehnica of Bucharest, Romania in 2007. She obtained the Master of Science (MSc) in Engineering from Aalborg University, Denmark in 2014. She is working for the department of Navigation Products at Airbus Defence and Space GmbH since 2015. She is involved in research and development activities such as software receiver development projects, with focus on tracking and multipath mitigation methods, multipath channel modelling and interference localization activities.

David Rüegg David Rüegg received his M.Sc. in Electrical Engineering from the Karlsruhe Institute of Technology, Germany, in 2017. In 2018 he joined Airbus Defence and Space GmbH in Munich, where he was mainly involved in the development of navigation algorithms for GNSS receivers on various levels from tracking to PVT, as well as in activities related to SBAS and integrity. In 2020 he joined Trimble Terrasat GmbH in Munich, where his primary focus is on the development of sensor data fusion algorithms to integrate GNSS and INS navigation systems.

Joseph Griggs received a BEng Degree in Computer System Engineering from Brunel University London in 2017. In 2017, he joined Collins Aerospace as a Systems Engineer, working on various GNSS projects in areas such as integrity algorithms for aviation, spoofing detection techniques and high precision inertial and GNSS targeting systems.

Rémy Lazzerini received a Master's Degree in Computer Engineering from Conservatoire National des Arts et Métiers in 2010 and a Specialized Master in Telecommunication and Navigation from ISAE (Institut Supérieur de l'Aeronautique et de l'Espace) in 2013. After an early career in Computer and Telecommunication systems, he joins Airbus Commercial Aircraft where he currently manages Radio Navigation and Data Science projects.

Florent Hagemann received a Bachelor Degree in Electrical Engineering from Montpellier University and Master's Degree in Aeronautical Engineering and Maintenance from Bordeaux University in 2009. After a career in laboratory team for Surveillance systems, he joins the Radio Navigation and Surveillance Design Office.

Francois Tranchet received a MSc. degree in Navivation, radio and communication sytems from ISAE - ENSICA in 2008. He joined Airbus in 2012 and he is working now as a GNSS expert. He is chairing the Multi-constellations and Multi-frequencies ad-hoc group of the EUROCAE WG-62 Galileo standardization group.

Pierre Bouniol joined Thales in 2006. After managing the Navigation System Engineering team and the GNSS Products development team in Valence-France, Pierre is now in charge of the GNSS receivers product strategy. The GNSS product line is composed of four product families: GNSS receivers for military applications, civil certified GNSS receivers, anti-jamming equipment, and ground station reference/monitoring receivers. He is also the chairman of the EUROCAE WG62 "Galileo" since 2010, in charge of standardizing the use of Galileo in civil certified receivers. Pierre is also the president of the French institute of navigation, the IFN.

Matteo Sgammini is a technical officer at the Joint Research Centre (JRC) of the European Commission. He was a system and software engineer at MTU Aero Engines from 2006 to 2008. From September 2008 to April 2017 he was a research associate in the Navigation group of the Institute of Communication and Navigation at the German Aerospace Center (DLR), Germany. His research includes signal processing and estimation theory for GNSS. Currently he focuses on GNSS integrity and Galileo system performance verification

ABSTRACT

This paper proposes DFMC airborne multipath models and antenna error models derived from measurement and supported by simulations.

Based on the data evaluated, new multipath models (including the contribution from the antenna) for Galileo E1 and GPS L1 and Galileo E5a and GPS L5 are discussed. Furthermore, a model for the Ionosphere-Free combination of the signals is proposed.

1. INTRODUCTION

Aeronautical navigation is increasingly based on the use of Global Navigation Satellite Systems (GNSS). It is a cornerstone of performance based navigation and enables airspace users to ensure that their navigation capabilities meet the required level of performance. For different phases of flight, different levels of integrity, accuracy and availability are required. The requirements for position errors reach from rather generous error budgets on the order of nautical miles horizontally with a 95% probability for the en-route phase down to 10 meters vertical with an integrity risk of just 10-7 for precision approaches [1]. Different techniques and augmentation systems, such as (advanced) receiver autonomous integrity monitoring (A)RAIM and space and ground based augmentation systems (SBAS, GBAS) continue to be developed in order to be able to satisfy all performance requirements for current and future airspace usage.

On the side of the GNSS space segments, the European Galileo constellation continues to grow and has 22 operational satellites available. All the Galileo satellites offer signals on two frequencies (E1 and E5a) usable for aeronautical navigation. The US GPS constellation offers the L1/L5 dual-frequency capability on all satellites of the latest generation (Block IIF), of which 12 are in orbit and available for navigation. All new satellites from the Block IIIA generation due for launch in the coming years (the first launch took place in December 2018) will also include the L5 signals.

The ARAIM concept exploits the use of dual frequency measurements to remove the ionospheric delay, the European SBAS EGNOS will provide augmentation for the Galileo and GPS constellations and for two frequencies in its V3 phase and on the GBAS side the development of dual frequency and multi-constellation techniques to cope with challenges posed by the active ionosphere in equatorial regions is ongoing as well. All GNSS-based navigation methods need to bound any potential residual position errors. One important contribution to the positioning error is caused by multipath: in the avionics sector, during en-route signal reflections are mainly due to the airframe. The impact of multipath on the GPS L1 signal was characterized long time ago and appropriate error models are used for integrity purposes. However, no such models exist for GPS L5 and Galileo E1 and E5a signals. The GPS L5 signal, as well as the Galileo E5a signal use a 10 times higher chipping rate than the GPS L1 signal and are therefore less susceptible to multipath. The Galileo E1 signal uses a different modulation than the GPS L1 signal and may therefore also show different multipath characteristics. When combining the measurements on both frequencies to eliminate the first-order ionospheric delay, also the multipath contained in both measurements is combined and needs to be bounded accordingly.

Within the frame of the DUFMAN project funded by the European Commission new multipath models for the new signals are developed in order to be able to exploit the potential benefits for aviation users. The project has started in May 2018 and is running until beginning of 2021. The derivation of the models is based on the GNSS measurements collected during flight tests on one side, on the other side, on detailed analysis of different contributors to the multipath error, such as airframe, antenna, and receiver parameters.

Previous work presented in [2] discussed the methodology used to derive the models from measurements. The initial results obtained using measurements from dual-frequency dual-constellation avionics hardware collected within DUFMAN on A321 and A330 aircraft have been presented in previous work in [3],[4] and [5]. Additional flight campaigns took place on A350 aircraft. The flights campaign use commercially available antennas installed in the original GNSS antenna locations.

GNSS measurements were collected using an airborne receiver or a RF recorder. In the first case a dual-frequency dual-constellation Collins Aerospace GLU-2100 MMR prototype receiver is used. The receiver is capable of tracking GPS and Galileo signals on L1ca/E1b and L5-I/E5a-I and is a representative airborne avionics GNSS receiver. For the second case, dual-frequency L1/E1 L5/E5a RF-samples are recorded with a Syntony bitgrabber. The availability of the RF-samples allows for a later replay to different receivers and receiver configurations in lab tests. The samples from all flight tests are initially replayed in the laboratory through the dual-frequency dual-constellation Collins Aerospace receiver prototype. In order to ensure that differences in the avionics receiver implementations are properly accounted for in the final version of the model, selected flights are replayed through a second avionics receiver prototype of Thales Avionics. Furthermore, more detailed studies of variations of receiver parameters, such as correlator spacing and receiver bandwidth are carried out with software receiver implementations. In addition to the measurement-based models, electromagnetic simulations are performed to predict the multipath model by simulation and are used to evaluate the expected multipath errors from different installations (e.g. different antenna positions or different antenna types) that are not flown within the project [6]

In this paper the results for DFMC multipath models, including the latest flight data, are presented. Moreover, one possible way of considering the antenna contribution inside the models is shown, resulting in proposed final models containing both antenna and multipath contribution. The proposed recommendations for standardization of the airborne multipath models will be discussed as well. This includes discussions of the impact of the antenna, the aircraft structure and the receiver parameters on the observed multipath error and the antenna biases.

2. PROJECT OVERVIEW

The DUFMAN project, which is funded by the European Commission under the Horizon 2020 R&D Framework Programme, has two main lines of work: one part is the development of a DFMC multipath error model based on the analysis of flight test data with a variety of different airframes; the other part is the advancement of simulation capabilities in order to be able to predict performance of a given installation (i.e. antenna, receiver with its given parameters and a specific airframe).

In an initial phase towards developing the airborne multipath models around 200 hours of experimental flight data collected with an experimental hardware installed on DLR's A320 research aircraft was analyzed. The methodology was presented in detail in and preliminary results collected with this experimental installation were shown in [2]. The previously derived versions of the models were more conservative and exceeded the existing σ_{air} models for GPS L1. However, the values were not to be considered final values as they were derived based on the experimental installation on a single aircraft and they were used to establish and validate the methodology for deriving multipath models. The antenna used in the experimental data collection was non-compliant with dual-frequency antenna MOPS [7]. In addition the antenna group delay variations, the antenna multipath rejection capability plays an important role in how much multipath is received. As the used antenna has a high axial ratio, this effect was reflected in the measurements and the obtained results. Furthermore, the antenna was not installed in its primary location, but in an experimental location further to the back of the aircraft. In this location, it was closer to other reflectors and thus the amount of multipath that is received is expected to be higher.

In order to extend the initial studies, a flight test campaign for collection of data from a variety of Airbus passenger aircraft is performed within the project. The Airbus flight test campaign uses commercially available multiband antennas in the original antenna locations on the airframe. Before the installation on the aircraft each antenna is measured and characterized in an anechoic chamber in order to ensure its compliance with current antenna MOPS in terms of group delay variations and axial ratio.

This paper presents the results obtained from all the data collected on 3 main aircraft types: Airbus A321, A330 and A350.

3. FLIGHT DATA COLLECTION

The initial multipath models presented in the [4] were derived from a single aisle Airbus A321, and one wide-body Airbus A330-900 aircraft. In this paper, additional data collected on A350 aircraft is integrated. All aircraft were equipped with a multiband antenna installed in its primary location (in all three cases the GPS 2 position). The antenna was characterized in DLR's anechoic compact test range before installation on the aircraft. The antenna is compliant with the DFMC antenna MOPS DO-373 in terms of the critical antenna parameters, i.e group delay variation (GDV) and the multipath susceptibility (specified by axial ratio) in both frequency bands [7]. The performance is good (better than MOPS limits) for the L1/E1 band and can be considered minimally compliant for the L5/E5a band in terms of GDV. Furthermore, as shown in later Sections, additional antennas were analyzed in the lab and tested according to group delay variations, such as to be able to have a broader range of performance to be expected for commercial antennas. One of the tested antennas (different from the one used in flight trials) was chosen to characterize the worst-case code errors introduced by the antenna group delay variations (referred as AGDV errors), as shown later.

For data recording in all installations a data grabber was used to record baseband samples for a later replay in the lab. The baseband samples were recorded on two different phase synchronous channels. The channels can be freely chosen within a frequency range from 1164MHz – 1610MHz. For the project data two different channels with center frequencies 1.175 GHz for GPS L5/Galileo E5a and 1.575 for GPS L1/Galileo E1 and 50 MHz bandwidth were recorded. The quantization was 16 bit.

The MMR used for replay and the analysis was a DFMC MMR prototype capable of tracking GPS L1, GPS L5, Galileo E1 and Galileo E5a signals. Chip spacing and bandwidth are compliant with the MOPS for Galileo/GPS SBAS Airborne Equipment (DO-259) [9].

4. METHODOLOGY USED TO DERIVE THE FINAL MODELS

Based on the outcome of the studies performed within DUFMAN, it was proposed to separate the multipath errors from antenna induced errors and to bound them with two separate terms.

- The multipath models are derived based on the measurements collected in flight tests where a minimum compliant antenna with respect to multipath rejection capability was used (i.e. an antenna close to the limits regarding the axial ratio requirements).

- The antenna induced errors, on the other hand, can be estimated from measurements in an anechoic antenna measurement chamber and are different for each antenna and frequency. This paper describes the methodology to derive a bounding term for the antenna errors (that are by their nature slowly varying biases) in form of a standard deviation, in order to be consistent with legacy architectures of the error budget and the error bounding concepts. The sigma term is derived from estimation of the code errors due to the antenna group delay variations (AGDV) considering flight trajectories from all flights performed within DUFMAN and additional flights conducted using DLR aircraft. The final model will be computed as

$$\sigma_{MP\&AGDV} = \sqrt{\sigma_{MP}^2 + \sigma_{AGDV}^2}$$

where σ_{MP} is the error contribution characterizing the multipath induced error, and σ_{AGDV} is the error contribution due to the AGDV.

The next two sections describe in detail the derivation of the multipath models, in Section 5 and the antenna errors development in Section 6.

5. MULTIPATH ERROR MODELS

The initial multipath models derived from measurements collected within DUFMAN on A321 and A330 aircraft were presented during the ION ITM 2020 Meeting [5]. The proposal included a new model to be applied for GPS L1/Galileo E1, a new model for GPS L5/Galileo E5a and the Ionospheric free combination (Ifree). For each scenario, a model based on the RMS of the measurements as well as an overbounding model accounting for non-Gaussian distribution of the multipath error were presented.

Since then, additional measurements were collected on the A350 aircraft with the antenna in one the two primary antenna locations (GPS 2 Position) and included into the processing. The results show the validation of the initial proposed models, now including the A350 data. The steps taken to derive these models are as follows:

1. Obtain code-minus-carrier measurement data as basis for multipath estimates

2. Removal of ionospheric divergence using the dual-frequency carrier phase combination

3. Running the Measurement Quality Monitor (MQM) according to DO-229 and DO-253 and application of a C/N0 limit of 29dBHz for L1/E1 and 27dBHz for L5/E5a (typically performed to reduce the impact of cycle slips)

4. Removal of code errors introduced by antenna group delay variations (AGDV).
    a. The errors introduced by AGDV do have different characteristics from multipath and will be dealt with in next Section. It is important to note, that the AGDV has to be accounted for (either included in a separate error budget, as proposed above, or included inside the noise or multipath term if sufficiently small) when using these models for integrity purposes.

5. Passing data through code-carrier smoothing filter (100s Hatch filter) with re-initialization when cycle slips are detected

6. Sort the samples into elevation bins of 5° width (elevation of satellite above the horizon)

7. Removal of a receiver noise contribution from the measurements, based on estimations from lab tests and confirmed by the avionics receiver manufacturer.

The initial proposed models [4] included also an additional overbounding of the data. The overbounding was performed order to account for the heavier tails of the distribution of the experimental data with respect to a normal distribution. However, in the final derivation of the models, this step was considered by the community to be too conservative. With more data available the characteristics of the distribution might change and the derived bounds might be too large. Thus, the final multipath models are derived as root-mean square (RMS) of the measurements considering all additional flight data available without the overbounding. This approach is consistent with the methodology used to derive the existing GPS L1 model.

Figure 1 shows the RMS obtained from the measurements collected on the three different aircraft type for GPS L1 (dashed grey line) and for Galileo E1 (solid grey line) together with the new proposed bound for the multipath for GPS L1/Galileo E1 (based on RMS).

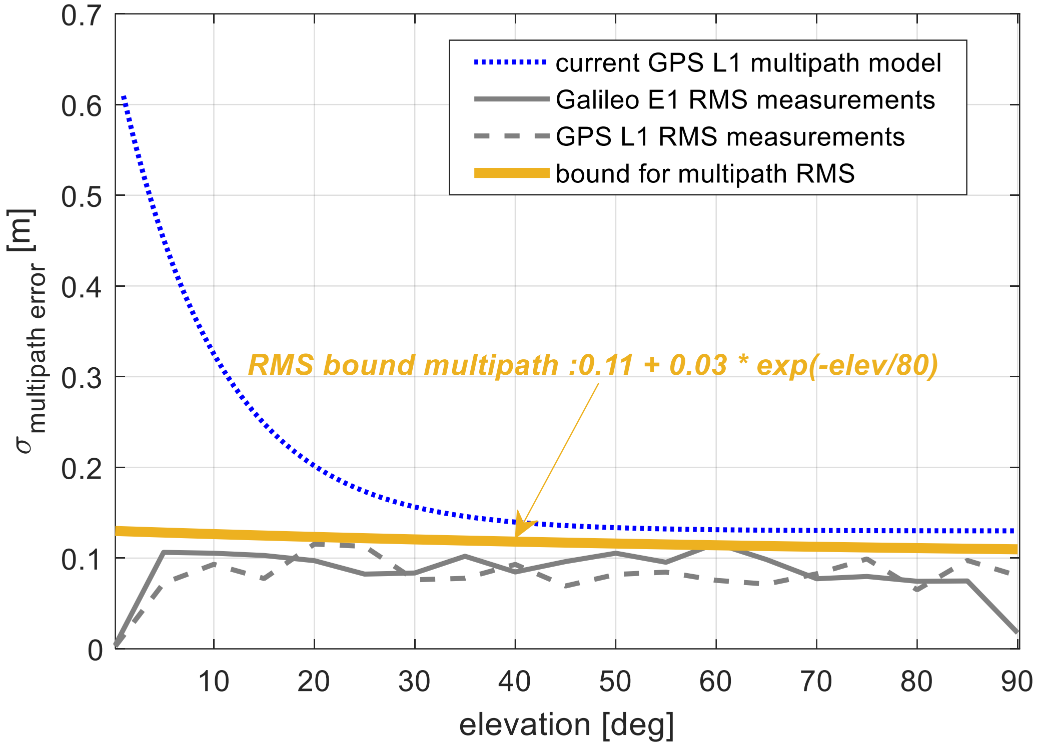

Figure 1 - RMS Multipath estimates GPS L1 (dashed line) and Galileo E1 (solid line) including data from A350 aircraft in comparison to the current multipath model (blue dashed line). The yellow line bounds the RMS of the multipath estimates

When integrating the measurements from A350 aircraft, the model was slightly modified from the previous one [4] and the following observations can be made:

- The performance of GPS L1 and Galileo E1 is similar in magnitude.
- The results show slight elevation dependency for both signals and a new model was proposed.
- For low elevations the measured errors are significantly smaller than the existing error models.

Figure 2 shows the RMS values obtained for Galileo E5a and GPS L5 together with a new proposed model (based on RMS). The following observations can be made when integrating the new data:

- The performance of Galileo E5a and GPS L5 is similar also when adding measurements from A350 aircraft.

- There is only a slight dependency on satellite elevation.

- The new results exceeded slightly the previous proposed model and thus the GPS L5/Galileo E5a multipath model has been slightly modified to bound these results.

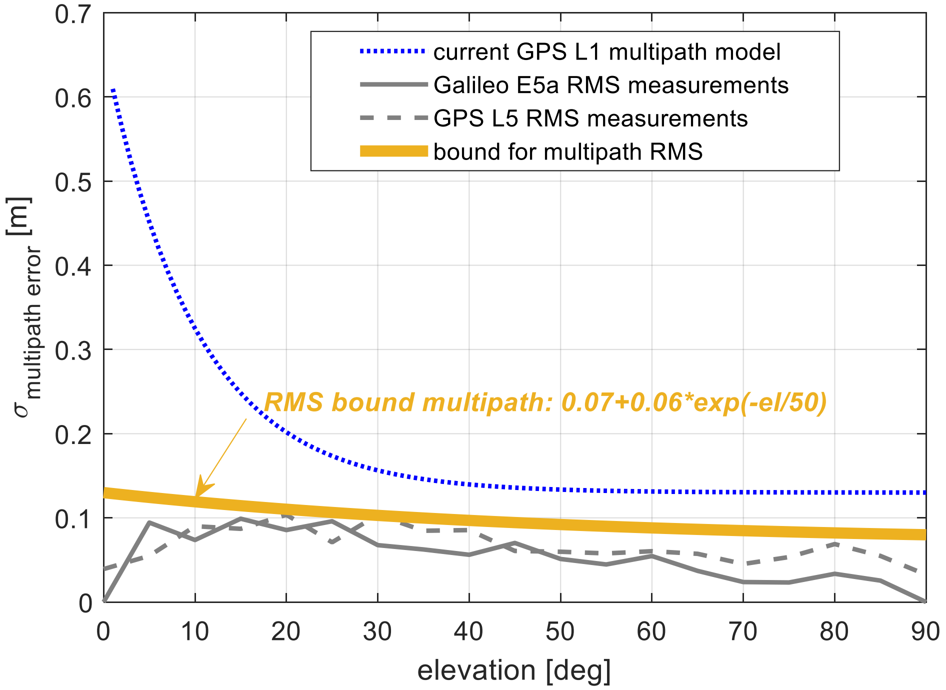

Figure 2 - RMS Multipath estimates GPS L5 (dashed line) and Galileo E5a (solid line) including data from A350 aircraft in comparison to the current multipath model (blue dashed line). The yellow line bounds the RMS of the multipath estimates

Finally, Figure 3 shows the RMS results obtained for the Ifree combination with a new proposed model for the multipath based on RMS. The following observations can be made:

- The data suggests a small elevation dependency
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- The performance of Galileo and GPS is comparable, thus one common model is proposed

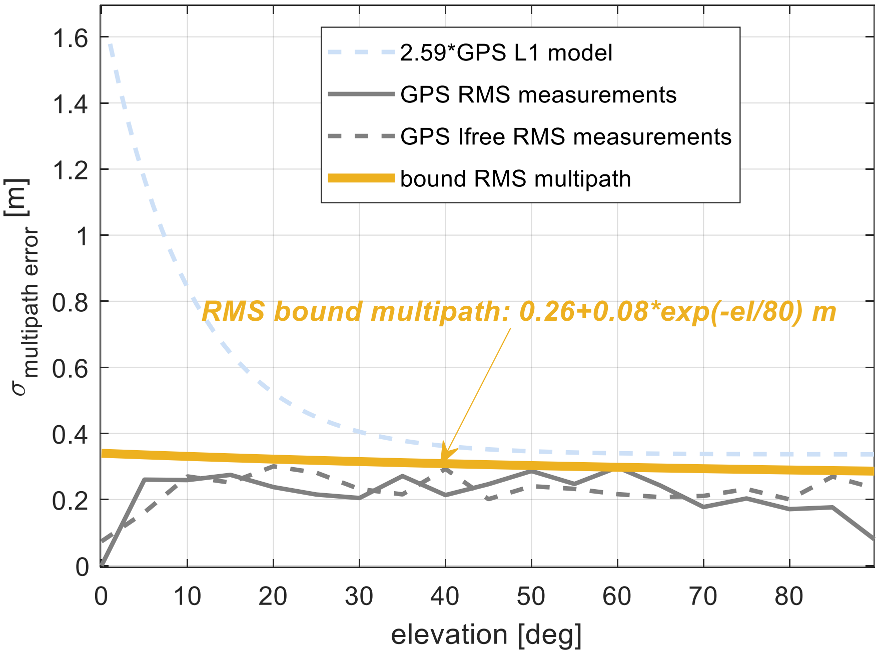

Figure 3 - RMS Multipath estimates GPS Ifree (dashed line) and Galileo Ifree (solid line) including data from A350 aircraft. The clue dashed line shows often theoretical model used based on the existing GPS L1 model and assumption of equal error distributions for L1/E1 and L5/E5a. The yellow line bounds the RMS of the multipath estimates

6. DEVELOPMENT OF ANTENNA ERRORS

This section describes the methodology and the error models obtained for the AGDV errors.

6.1 Antenna measurements

The error contribution due to the antenna, caused by the antenna group delay variations (AGDV), has been demonstrated to be relevant and actually comparable in magnitude with multipath in terms of pseudorange error [6].

The results shown in previous section have been targeting the modelling of the multipath contribution alone and therefore the antenna contribution has been explicitly removed in step 4 of the procedure shown before. The removal of the errors was performed because otherwise the process of the multipath estimation (which includes the mean removal per satellite for estimating the carrier phase ambiguities) would eliminate also part of the AGDV. In order to properly account for such errors, an additional term in the models has to be introduced. In order to establish realistic values for such a term, the following steps were executed: among the various avionic antennas measurements and analyzed in DUFMAN, it was chosen to analyze the one that had the largest group delay variations, i.e. those closest to the limits specified in DO-373 for both frequency bands, such as to be representative of a minimally MOPS-compliant commercial antenna and provide conservative values at both bands and in the Ifree combination.

It is worth noting that separating the multipath and AGDV contribution not only it is a rigorous approach for the characterization of the total error budget, but also has the benefit that in case tighter constraints on the DO-373 limits will be specified, the corresponding σ_{AGDV} can be easily obtained, without the need of performing new flight campaign and extensive analysis.

The measurement results obtained by such antenna are shown in Figure 4. It can be seen that the antenna is close to the MOPS limit at both bands.

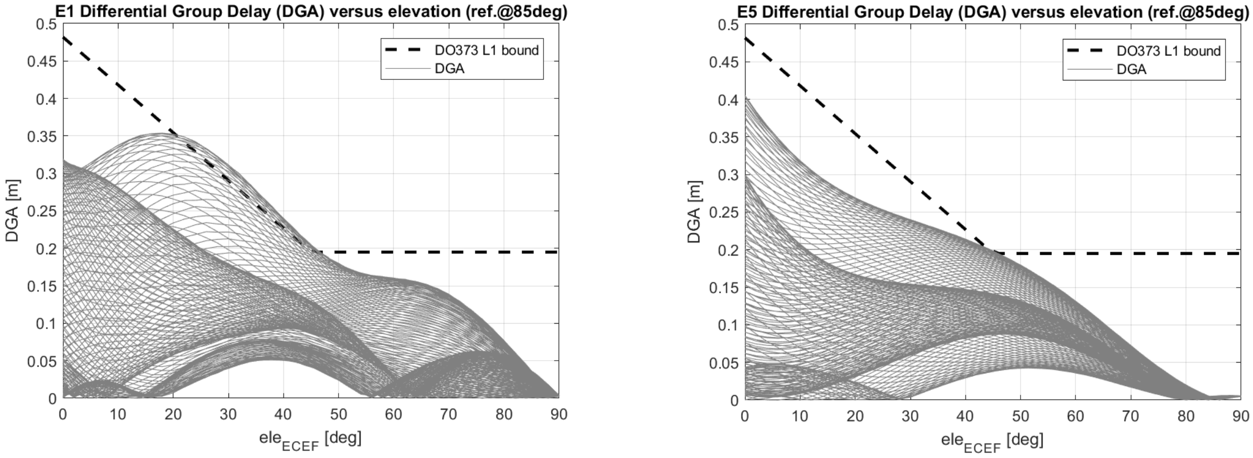

Figure 4 - Differential Group Delay versus elevation for the antenna under consideration: E1 band (left) and E5a band (right). The dotted line is the DO373 L1 bound.

The values from this antenna have then been used (in form of a lookup table) to obtain an estimation of the expected antenna-related pseudorange errors during flight. This has been accomplished by considering the flight trajectories as obtained by actual flight data and evaluating the residual errors due to the antenna according to the azimuth and elevation of visible satellites at each time step.

A mean removal of all satellites in view at each time step has been considered, such as to estimate the actual error affecting the position solution. More details about the methodology are given in the next section.

6.2 Methodology to bound the antenna-induced errors (AGDV)

The methodology used to derive the models for the antenna errors makes use of AGDV estimates from the anechoic chamber and flight trajectories from over 200 hours flights with the actual satellite geometry. The steps taken to derive the models are:

1. Use of the flight trajectories from all the flights available within DUFMAN and from DLR flight tests
2. Calculation of the AGDV errors for each satellite visible during the flight tests based on the satellite elevation and azimuth. These values are derived from the AGDV error maps available for the entire hemisphere from anechoic chamber characterization. The errors are estimated based on the satellite angles in body frame and transformed in level frame (ECEF)
3. Removal of the mean over all satellites in view. This step is needed to derive the errors that will affect the position solution and remove the common bias that will contribute to the receiver clock estimation. The removal is performed independent for GPS and Galileo constellation.
4. Sorting of the AGDV residual into elevation bins and computation of the RMS and mean for each bin

The process is performed for each constellation and frequency independently. For the Ifree combination, the linear combination is performed from the single frequency absolute biases.

Finally, Figure 5 shows the RMS results obtained for the antenna group delay code errors. The following observations can be made:

- The data suggests a dependence on elevation, in particular for low elevations
- The same performance was observed for GPS L1 and Galileo E1
- The performance of L1/E1 and L5/E5a is comparable

Based on these results, new models for σ_{AGDV} can be proposed for antenna AGDV contribution in Figure 5 One model is suggested for single frequency L1/E1 and L5/E5a (shown in black dot line) and one model for the Ifree combination shown with red dot line and are expressed as:

$$\sigma_{AGDV,SF} = 0.065 + 0.2 * e^{-\frac{\theta}{14}}$$

$$\sigma_{AGDV,Ifree} = 0.17 + 0.5 * e^{-\frac{\theta}{15}}$$

with θ being the satellite elevation angle (above horizon). The single frequency model was derived to bound both L1/E1 and L5/E5a results.

This is suggested also because the AGDV requirements in DO-373 are the same for both signals

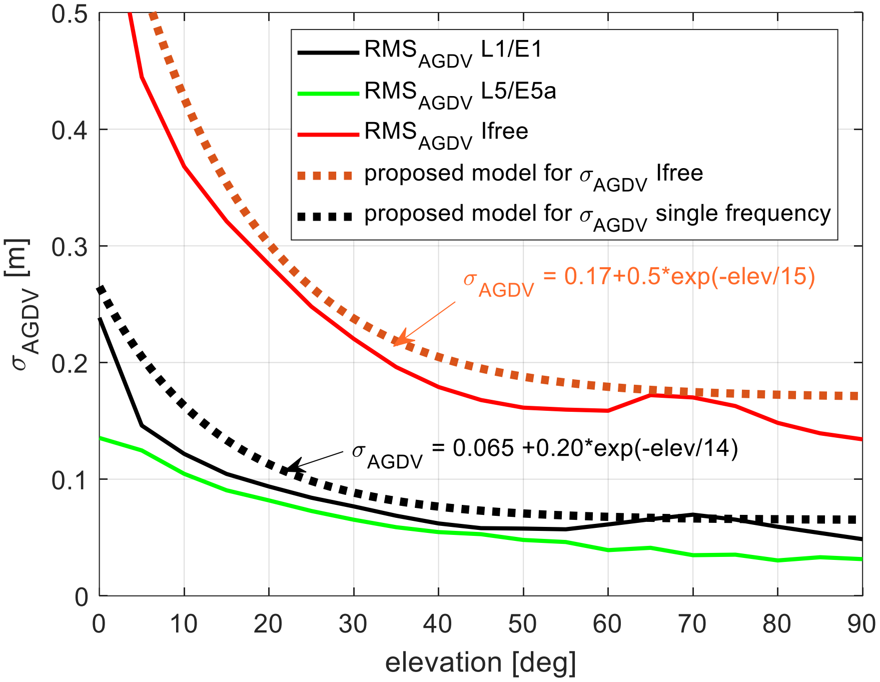

Figure 5 - RMS of the AGDV from measurements for L1/E1 (black curve), L5/E5a (green curve) and Ifree (red curve) using an antenna minimally compliant at both bands and the derived models for $\boldsymbol{\sigma_{AGDV}}$

Section 5 and 6 presented the definition of the multipath and antenna errors separately. The final models would combine the two contributions as:

$$\sigma_{MP\&AGDV} = \sqrt{\sigma_{MP}^2 + \sigma_{AGDV}^2}$$

with the σ_{MP} being the multipath error model introduced in Section and σ_{AGDV} the antenna error model derived in Section 6. This section presents and discussed the proposed models for each signal.

Based on the results obtained from the two error sources, a common model is proposed for bounding the multipath and the airborne antenna errors for GPS L1 and Galileo E1. The model is derived from combining the multipath model based on RMS of the measurements (in Figure 1) and single frequency model of the AGDV shown in Figure 5. Such approach will allow to be compliant with the legacy error architecture, i.e. will not add additional error terms in the error budget to be considered by the receivers. The proposed model is shown in Figure 6. The black curve shows the resulting curve from the combination of the multipath model and the antenna model. Based on these results, a new model can be proposed for GPS L1/Galileo E1 shown with orange line and expressed as:

$$\sigma_{MP\&AGDV,L1/E1} = 0.13 + 0.17 * e^{-\frac{\theta}{13}}$$

with θ being the satellite elevation angle (above horizon). The following observations can be made:

1. The proposed model follows a similar methodology to the existing GPS L1 model (considering only the RMS of the measurements).

2. The proposed model is lower than the existing GPS L1 model for low elevations and converges to the same values for elevations above 40 degrees

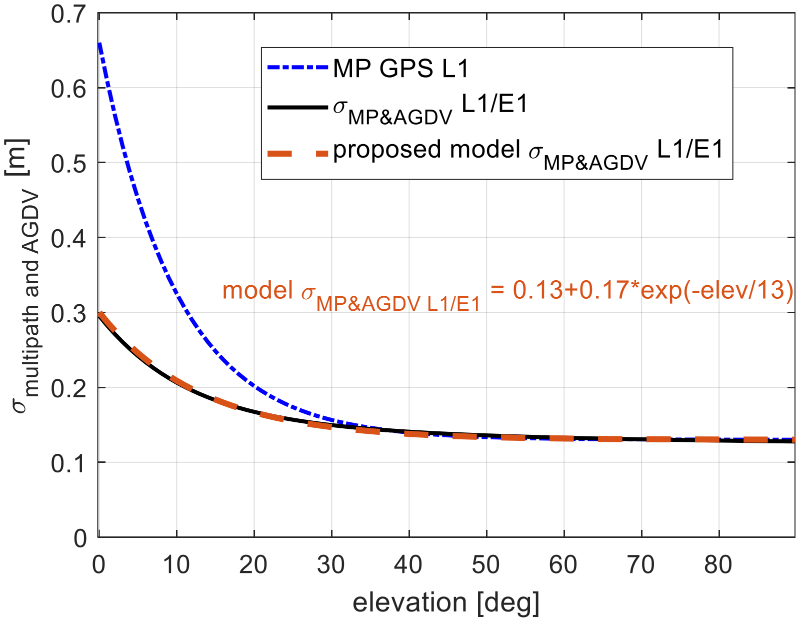

Figure 6 - RSS of the multipath and antenna error models (black line) and the proposed model for $\boldsymbol{\sigma_{MP\&AGDV}}$ for L1/E1. The dashed blue line shows the existing GPS L1 model

In a similar manner, shows the combination of the models for the multipath and AGDV errors (in black curve) for GPS L5/Galileo E5a. The black curve shows the curve obtained when combining the multipath model for L5/E5a (based on RMS) and the antenna error model derived for single frequency. Even if the actual RMS of the AGDV errors derived for the L5/E5a are lower, the same bounding model as for L1/E1 was used (black dashed curve in Figure 7) in order to be conservative. This is because the antenna requirements are defined in the same way for both frequency bands. The orange dashed curve shows the proposed model for the combined multipath and antenna errors results and is expressed as:

$$\sigma_{MP\&AGDV,L5/E5a} = 0.11 + 0.18 * e^{-\frac{\theta}{15}}$$

with θ being the satellite elevation angle (above horizon).
The following observations can be made:

1. The proposed model accounting for the multipath and AGDV errors on L5/E5a is lower than the existing GPS L1 model, especially at low elevations. At elevations above 40 degrees, it is slightly lower than the existing GPS L1 model.

2. The proposed model shows a significant elevation dependency, mainly driven by the antenna error model.

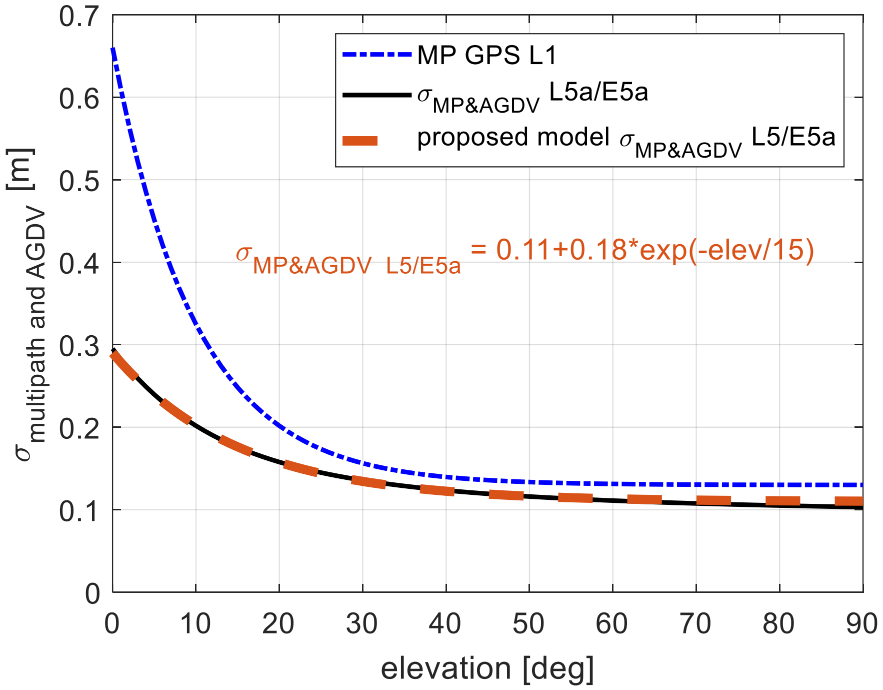

Figure 7 - RSS of the multipath and antenna error models (black line) and the proposed model for $\boldsymbol{\sigma_{MP\&AGDV}}$ for L5/E5a. The dashed blue line shows the existing GPS L1 model

Finally, Figure 8 shows the proposed models for the Ifree combination. The black curve shows the result obtained from combing the multipath model and AGDV errors model for the Ifree combination and the blue dashed curve show the theoretical model obtained from the existing multipath GPS L1 model multiplied by the 2.59 factor. The suggested model is shown in orange curve and is described as:

$$\sigma_{MP\&AGDV,Ifree} = 0.34 + 0.4 * e^{-\frac{\theta}{14}}$$

The following remarks can be made for the new model:

1. The elevation dependency is introduced by the AGDV errors

The proposed model is significantly lower at low elevations compared to the theoretical model and converges to the theoretical values for elevations above 40 degrees.

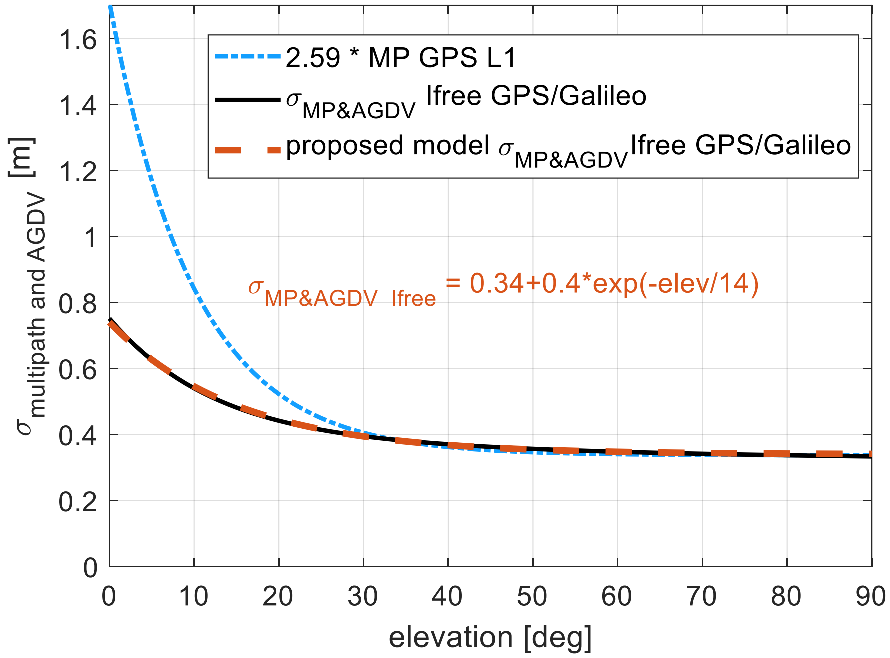

Figure 8 - RSS of the multipath and antenna error models (black line) and the proposed model for $\boldsymbol{\sigma_{MP\&AGDV}}$ for Ifree combination. The dashed blue line shows the theoretical Ifree model (2.59* GPS L1)

7. CONCLUSION

In this paper we presented the final models developed within the DUFMAN project resulting from a detailed analysis of the flight data collected with three aircraft types Airbus A321, A330, A350.
The most important results in terms of developing a DFMC multipath model were:

- Models combining multipath and antenna AGDV errors have been proposed which suggest a separation of multipath and antenna errors in two different terms.
- The proposed models are valid for 100 seconds smoothing time constant
- The proposed models do not exceed the existing GPS model. Different commercial antennas have been analyzed and the results are similar

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