DUFMAN

DUal Frequency Multipath model for AviatioN

Final Report

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Version	Date	Changes	Author
1.0	27.02.2021	Initial Version	Rippl
1.01	06.05.2021	Updates after comments	Rippl, Caizzone
1.02	28.05.2021	Change distribution level to Public Fix formatting in Table 2	Rippl

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1. Scope and Structure of the Document

1.1. Scope

This document presents the final report to the DUFMAN project. It is accompanied by the Final Review milestone meeting, concluding the project with all its activities. Acceptance of this Final Report together with all relevant milestone deliverables (see Section 5) is reached by formal notice from the European Commission to the Contractor that the milestone is completed.

This report summarizes the project from a managerial perspective. The technical results of this project are captured in the technical report deliverables and the material provided for dissemination. The main document related to the modeling methodology developed in this project is report D2100, *"Dual Frequency Multipath Model",* in its third and final version provided with this milestone [RD09]. The main contribution towards ICAO is the NSP/5 JWGs/6 working paper 21 [RD29] detailing the final DF multipath model proposition from the project.

1.2. Structure

This document is organized as follows:

Section 2 is a summarized view on the project main achievement, problems, limitations or unexpected points encountered from the kick-off meeting until the end of the project (Final Review). It details the status of the work accomplished from the kick-of meeting until the issue date, the work performed during the period and any deviations from the work plan.

Section 4 gives a consolidated view on all dissemination activities executed in the project. The scientific publications and all contributions to standardization working groups are summarized in Sections 4.1 and 4.2.

Section 5 presents a complete list of deliverables submitted since the kick-off meeting. This section serves to summarize all deliverable documents in their respective final and accepted versions.

As a documentation to the review and acceptance process, the final version of the RIDs document [RD49] is reproduced in Section 5.1. Section 5.2 details all project meetings.

The summarized report of travel activities in relation to the DUFMAN project is given in Section 6.

Section 7 summarizes project inventory used throughout the project and references the complete and final inventory list appended to this report.

Section 8 is a final list of Intellectual Property Rights used by the project partners throughout the project.

Section 9 discusses Lessons Learned from the project.

During project execution, an issue log was kept using an online task list on the project team site to facilitate resolution of open issues. The complete issue log is presented in Section 10.

1.3. Applicable Documents

Table 1: Applicable Documents

Reference	Document ID	Title	Issue
[AD01]	Tender Specifications No 635/PP/GRO/RCH/17/9877	R&D for a GNSS Dual Frequency Multipath Model for Aviation – Tender Specifications	20.09.2017
[AD02]	No 635/PP/GRO/RCH/17/9877[1]	Invitation to tender	20.09.2017
[AD03]	Service Contract No 635/PP/GRO/RCH/17/9877	Service Contract No 635/PP/GRO/RCH/17/9877	Signed 14.04.2018
[AD04]	DUFMAN-FP-201701	Financial Proposal – DUal Frequency Multipath model for AviatioN	8.12.2017
[AD05]	DUFMAN-TP-201701	Technical Proposal and Work Plan – DUal Frequency Multipath model for AviatioN	8.12.2017
[AD06]	DUFMAN-MD-PU-PMP	Project Management Plan	1.0 21.07.2018
[AD07]	DUFMAN-MD-PU-PMP	Project Management Plan	2.0 13.12.2019
[AD08]	DUFMAN-MD-PU-PMP	Project Management Plan	3.0 21.07.2020

[1] https://etendering.ted.europa.eu/cft/cft-display.html?cftId=2640

1.4. Reference Documents

Table 2: Reference Documents

Reference	Document ID	Title	Issue
[RD01]	DUFMAN-MD-DLR-CO-PR1 D1201	Progress Report 1	1.01 20.11.2018
[RD02]	DUFMAN-MD-DLR-CO-PR2 D1202	Progress Report 2	1.03 19.02.2019
[RD03]	DUFMAN-MD-DLR-CO-PR3 D1203	Progress Report 3	1.01 17.05.2019
[RD04]	DUFM AN-MD-DLR-CO-PR4 D1204	Progress Report 4	1.02 27.08.2019
[RD05]	DUFMAN-MD-DLR-CO-PR5 D1205	Progress Report 5	1.0 18.10.2019
[RD06]	DUFMAN-MD-DLR-CO-PR7 D1207	Progress Report 7	1.0 28.07.2020
[RD07]	DUFMAN-TN-DLR-PU-D2100	Dual Frequency Multipath Model	1.01 05.11.2018
[RD08]	DUFMAN-TN-DLR-PU-D2100	Dual Frequency Multipath Model	2.01 14.08.2020
[RD09]	DUFMAN-TN-DLR-PU-D2100	Dual Frequency Multipath Model	3.00 20.01.2021
[RD10]	DUFMAN-TN-DLR-PU-D3100	DFMM Test Plan	1.01
[RD11]	DUFMAN-TN-DLR-PU-D3100	DFMM Test Plan	2.00
[RD12]	DUFMAN-TN-DLR-PU-D3100	DFMM Test Plan	2.10
[RD13]	DUFMAN-TN-DLR-PU-D3100	DFMM Test Plan	2.20
[RD14]	DUFMAN-TN-DLR-PU-D3200	DFMM Test Specifications	1.00
[RD15]	DUFMAN-TN-DLR-PU-D3200	DFMM Test Specifications	2.02

Reference	Document ID	Title	Issue
[RD16]	DUFMAN-TN-DLR-PU-D3200	DFMM Test Specifications	2.11
[RD17]	DUFMAN-TN-DLR-PU-D3200	DFMM Test Specifications	2.20
[RD18]	DUFMAN-TN-DLR-PU-D3300	DFMM Test Results	1.02
[RD19]	DUFMAN-TN-DLR-PU-D3300	DFMM Test Results	2.01
[RD20]	DUFMAN-TN-DLR-PU-D3300	DFMM Test Results	3.00
[RD21]	DUFMAN-TN-DLR-PU-D3300	DFMM Test Results	4.00
[RD22]	DUFMAN-TN-DLR-PU-D3300	DFMM Test Results	5.01
[RD23]	DUFMAN-TN-DLR-PU-D3400	Galileo Database of Aviation Multipath	1.00
[RD24]	DUFMAN-TN-DLR-PU-D3400	Galileo Database of Aviation Multipath	5.00
[RD25]	DUFMAN-TN-DLR-PU-D3400	Galileo Database of Aviation Multipath	6.00
[RD26]	NSP/5 IP/25	"Development of airborne multipath models for dual frequency and multi constellation applications ". Information paper 25 for ICAO Navigation System Panel 5th meeting, November 2018 (NSP/5 IP/25)	11/2018
[RD27]	NSP/5 JWGs/4 IP/6	"Update on the development of airborne multipath models for dual frequency and multi constellation applications in the DUFMAN project".	04/2019

Reference	Document ID	Title	Issue
		Information paper 6 for ICAO Navigation System Panel 5th meeting, Joint WGs 4th meeting, April 2019 (NSP/5 JWGs/4 IP/6)	
[RD28]	NSP/5 JWGs/5 WP/35	"Initial DFMC airborne multipath models from DUFMAN project". Working paper 35 for Navigation System Panel 5th meeting, Joint WGs 5th meeting, October 2019 (NSP/5 JWGs/5 WP/35)	10/2019
[RD29]	NSP/5 JWGs/6 WP/21	"Airborne Multipath And Antenna Error Models From The DUFMAN Project ". Working paper 21 for Navigation System Panel 5th meeting, Joint WGs 6th meeting, June 2020 (NSP/5 JWGs/6 WP/21)	06/2020
[RD30]	NSP/6 WP/16	"Airborne Multipath And Antenna Error Models From The DUFMAN Project ". Working paper 16 for Navigation System Panel 6th meeting, November 2020 (NSP/6 WP/16)	11/2020
[RD31]	DUFMAN-TN-MODDEV-1.0	Technical Note Model Development	16.07.2019
[RD32]	DUFMAN-TN-DLR-PU-PositionPaper_MP_Model_for_standardization-0.1	Aspects of Multipath Model Standardization	21.02.2020

Reference	Document ID	Title	Issue
[RD33]	RD33_DUFMAN_MD_DLR_Dissemination Activities	Dissemination activities	20.01.2021
[RD34]	ION_GNSS_2018_Caizzone	Caizzone, S., Circiu, M.-S., Elmarissi, W., Enneking, C., Felux, M., Yinusa, K., "Multipath Rejection Capability Analysis of GNSS Antennas," Proceedings of the 31st International Technical Meeting of the Satellite Division of The Institute of Navigation (ION GNSS+ 2018), Miami, Florida, September 2018, pp. 3478-3489. https://doi.org/10.33012/2018.16109	
[RD35]	ION_GNSS_2018_Circiu	Circiu, Mihaela-Simona, Caizzone, Stefano, Felux, Michael, Enneking, Christoph, Meurer, Michael, "Improved Airborne Multipath Modelling," Proceedings of the 31st International Technical Meeting of the Satellite Division of The Institute of Navigation (ION GNSS+ 2018), Miami, Florida, September 2018, pp. 2195-2209. https://doi.org/10.33012/2018.15855	
[RD36]	ION_ITM_2019_Felux	Felux, Michael, Circiu, Mihaela-Simona, Caizzone, Stefano, Enneking, Christoph, Fohlmeister, Friederike, Rippl, Markus, "Towards Airborne	

Reference	Document ID	Title	Issue
		Multipath Models for Dual Constellation and Dual-frequency GNSS," Proceedings of the 2019 International Technical Meeting of The Institute of Navigation, Reston, Virginia, January 2019, pp. 62-68. https://doi.org/10.33012/2019.16683	
[RD37]	ION_GNSS_2019_Caizzone	Caizzone, Stefano, Circiu, Mihaela-Simona, Elmarissi, Wahid, Enneking, Christoph, Winterstein, Andreas, "Airborne Antenna and Multipath Error Characterization for DFMC Error Standardization," Proceedings of the 32nd International Technical Meeting of the Satellite Division of The Institute of Navigation (ION GNSS+ 2019), Miami, Florida, September 2019, pp. 1453-1463. https://doi.org/10.33012/2019.16908	
[RD38]	ION_GNSS_2019_Circiu	Circiu, Mihaela-Simona, Felux, Michael, Caizzone, Stefano, Enneking, Christoph, Fohlmeister, Friederike, Rippl, Markus, Gulie, Ioana, Rueegg, David, Griggs, Joseph, Lazzerini, Rémy, Hagemann, Florent, Tranchet, Francois, Bouniol, Pierre, Sgammini, Matteo,	

Reference	Document ID	Title	Issue
		"Initial Results for Dual Constellation Dual-frequency Multipath Models," Proceedings of the 32nd International Technical Meeting of the Satellite Division of The Institute of Navigation (ION GNSS+ 2019), Miami, Florida, September 2019, pp. 1401-1417; https://doi.org/10.33012/2019.16906	
[RD39]	ION_ITM_2020_Felux	Felux, Michael, Circiu, Mihaela-Simona, Caizzone, Stefano, Rippl, Markus, Sgammini, Matteo, Durel, Pierre, "Standardization of New Airborne Multipath Models," Proceedings of the 2020 International Technical Meeting of The Institute of Navigation, San Diego, California, January 2020, pp. 146-153. https://doi.org/10.33012/2020.17133	
[RD40]	ION_ITM_2020_Caizzone	Caizzone, S., Circiu, M.-S., Elmarissi, W., Enneking, C., Winterstein, A., "Multipath Suppression Capability and Indicators for Airborne Dual Frequency GNSS Antennas," Proceedings of the 2020 International Technical Meeting of The Institute of Navigation, San Diego, California, January 2020, pp. 154-161.	

Reference	Document ID	Title	Issue
		https://doi.org/10.33012/2020.17134	
[RD41]	ION_ITM_2020_Circiu	Circiu, Mihaela-Simona, Felux, Michael, Caizzone, Stefano, Enneking, Christoph, Fohlmeister, Friederike, Rippl, Markus, Gulie, Ioana, Rüegg, David, Griggs, Joseph, Lazzerini, Rémy, Hagemann, Florent, Tranchet, Francois, Bouniol, Pierre, Sgammini, Matteo, "Airborne Multipath Models for Dual-constellation Dual-Frequency Aviation Applications," Proceedings of the 2020 International Technical Meeting of The Institute of Navigation, San Diego, California, January 2020, pp. 162-173. https://doi.org/10.33012/2020.17135	
[RD42]	ION_ITM_2020_Griggs	Griggs, Joseph, Rippl, Markus, Caizzone, Stefano, Circiu, Mihaela-Simona, "Effects of Preliminary DFMC Multipath Models on ARAIM Performance," Proceedings of the 2020 International Technical Meeting of The Institute of Navigation, San Diego, California, January 2020, pp. 174-188. https://doi.org/10.33012/2020.17136	

Reference	Document ID	Title	Issue
[RD43]	ION_ITM_2021_Bang	Bang Eugene, Circiu Mihaela-Simona, Caizzone Stefano and Rippl Markus "Antenna Group Delay Variation Bias Effect on Advanced RAIM", ION ITM 2021	
[RD44]	ION_ITM_2021_Circiu	Circiu, Mihaela-Simona, Felux, Michael, Caizzone, Stefano, Enneking, Christoph, Fohlmeister, Friederike, Rippl, Markus, Gulie, Ioana, Rüegg, David, Griggs, Joseph, Lazzerini, Rémy, Hagemann, Florent, Tranchet, Francois, Bouniol, Pierre, Sgammini, Matteo, "Final Results on Airborne Multipath Models for Dual-constellation Dual-frequency Aviation Applications," ITM 2021, San Diego, California, Jan 2021.	
[RD45]	ION_NAVI_2020_67_Circiu	Circiu, M-S, Caizzone, S, Felux, M, Enneking, C, Rippl, M, Meurer, M. Development of the dual-frequency dual-constellation airborne multipath models. *NAVIGATION*. 2020; 67: 61– 81. https://doi.org/10.1002/navi.344	
[RD46]	20ITM-Onsite	ITM 2021 Technical Programme	09.01.2020
[RD47]	DUFMAN-MD-DLR-CO-TaskList	Final issue log/action item list	20.01.2019
[RD48]	DUFMAN_Inventory_20210127.pdf	Inventory list	22.10.2019

Reference	Document ID	Title	Issue
[RD49]	RD49_RID_FR_20210227	Consolidated RID list (all previous milestones)	
[RD50]	DUFMAN_MoM_KickOffTelecon_20180503_final	Minutes of Meeting – Kick-Off Meeting (Telecon)	03.05.2018
[RD51]	DUFMAN_MoM_TKOM_20180615_final_revision1.pdf	Minutes of Meeting – Technical Kick-Off Meeting (Face-to-face)	15.06.2018 Revision 1
[RD52]	DUFMAN_MD_DLR_CO_CP1-MinutesOfMeeting_1.0	Minutes of Meeting – Checkpoint 1	21.09.2018
[RD53]	DUFMAN_MD_DLR_CO_PM1-MinutesOfMeeting_1.0	Minutes of Meeting – Progress Meeting 1	19.12.2018
[RD54]	DUFMAN_MD_DLR_CO_PM2-MinutesOfMeeting_v1.0	Minutes of Meeting – Progress Meeting 2	15.03.2019
[RD55]	DUFMAN_MD_DLR_CO_PM3-MinutesOfMeeting-1.0	Minutes of Meeting – Progress Meeting 3	18.07.2019
[RD56]	DUFMAN_MD_DLR_CO_PM4_MinutesOfMeeting_v1.00	Minutes of Meeting – Progress Meeting 4	03.09.2019
[RD57]	DUFMAN_MD_DLR_CO_PM5-MinutesOfMeeting_v1.0	Minutes of Meeting – Progress Meeting 5	28.11.2019
[RD58]	DUFMAN_CP2_Notes_v1.00	Notes on Checkpoint 2 meeting	13.02.2020
[RD59]	DUFMAN_MD_DLR_CO_PM7-MinutesOfMeeting_1.00	Minutes of Meeting – Progress Meeting 7	29.09.2020
[RD60]	DUFMAN_MD_DLR_CO_CP3-MinutesOfMeeting_1.00	Minutes of Meeting – Checkpoint 3	11.12.2020

1.5. Acronyms

Table 3: List of Acronyms

Acronym	Description
A/C	Aircraft
AAD	Airborne Accuracy Designator
ADS	Airbus Defence and Space
ARAIM	Advanced Receiver Autonomous Integrity Monitoring
ASAS	Airbus SAS
CAD	Computer Aided Design
CfT	Call for Tender
CMC	Code Minus Carrier
CSV	Comma-separated values
DFMC	Dual Frequency Multi Constellation
DFMM	Dual Frequency Multipath Model
DLR	Deutsches Zentrum fuer Luft- und Raumfahrt (German Aerospace Center)
DUFMAN	DUal Frequency Multipath Model for AviatioN
EC	European Commission
EM	Electromagnetic
EUROCAE	European Organization for Civil Aviation Equipment
FAA	Federal Aviation Administration
FR	Final Review
FTI	Flight Test Instrumentation
GNSS	Global Navigation Satellite Systems
GPS	Global Positioning System

GUI	Graphical User Interface
ICAO	International Civil Aviation Organization
IPR	Intellectual Property Rights
ISM	Integrity Support Messages
IWG	Interoperability Working Group
KOM	Kick-off Meeting
M	Months
MCMF	Multi Constellation Multi Frequency
MMR	Multi-Mode Receiver
MoM	Minutes of Meetings
MOPS	Minimum Operational Performance Standards
NAS	Network Attached Storage
NSP	Navigation Systems Panel of the ICAO
OS	Open Service
PIPE	Positioning and Integrity Performance Evaluator
PM	Progress Meeting
PMT	Project Management Team
PTF	Permit To Fly
R&D	Research and development
RAIM	Receiver Autonomous Integrity Monitoring
RC	Rockwell Collins
RID	Review Item Discrepancy
RF	Radio Frequency

RINEX	Receiver Independent Exchange Format
RTCA	Radio Technical Commission for Aeronautics
SARPS	Standards and Recommended Practices
SNIPE	Scenarios for Navigation and Integrity Performance Evaluation
THAV	Thales Avionics
WP	Work package

2. Final status of the project

This section presents a final status report of the entire project. The objective of this section is to summarize what the high-level objectives of the project were, how they were reached, and what changes to the project management plan have been agreed on and implemented.

2.1. Key project objectives

The first objective of the project was to build and validate a dual-frequency multipath model for aviation for ARAIM and SBAS dual-frequency for Galileo E1/E5a and GPS L1/L5 frequency. In addition, single frequency cases GPS L5, Galileo E1 and Galileo E5a had to be considered.

The derivation of the multipath models was performed following two lines of work. On one side, flight test data from a variety of airframes was collected and analyzed to develop a measurements-based model. In parallel simulation capabilities were advanced in order to be able to predict the multipath errors for a given installation (with a specific antenna and receiver setup).

For the measurements model, flight data on Airbus A321, A330 and A350 aircraft were collected. For each of the installations, a multiband antenna was installed in its primary location (in all cases the GPS 2 position). The antenna was characterized in the anechoic compact test range in order to ensure it is compliant with the DFMC antenna MOPS DO-373 in terms of the antenna group delay and axial ratio. The GNSS measurements were collected using a dual-frequency dual-constellation Collins Aerospace GLU-2100 MMR prototype or an RF recorder. For the second case, dual-frequency L1/E1 L5/E5a RF samples were recorded which allowed for a later replay to different receivers and receiver configurations in the laboratory tests. These tests allowed a detailed investigation of the impact of the receiver and validation of the model for the entire receiver design space defined in standards.

For the simulations-based model, a very good match with the measurements has been obtained. This allowed for the investigation of expected error for other installations that were not flown within the project, i.e. the impact of using different antennas with different performance, impact of the location of the antenna. Furthermore, the simulation capability allowed for verification of the applicability of the model to other airframes.

Based on the outcome of the studies performed within DUFMAN, it was proposed to separate the multipath errors from antenna induced error and to bound them with two separate terms. The multipath models were derived based on the measurements collected in flight tests. The antenna induced errors were derived based on the measurements of different antennas in anechoic chamber. Among the various antennas measured and analyzed within the project, it was chosen to derive the antenna models based on the antenna which had the largest group delay variation and closest to the limits specified in the DO0373 for both frequency bands.

Two different methodologies were considered to incorporate the antenna errrors, namely as a bias term and as a sigma term. While the first approach appeared more realistic, especially for en-routeflight, where the antenna contribution varies slowly with time (while it appears more fastly changing when the aircraft is banking), the second approach does not need any apriori assumption on the flight phase and can be more easily integrated in the current error budget terms, already considering multipath contribution as a sigma term. This last approach was considered more practical from the community. The initial methodology proposed within the project included an additional overbounding of the measurement data in order to account for the heavier tails of the distribution of the experimental data with respect to a normal distribution. However, this overbounding was considered to be too conservative by the community because with more data available the characteristic of the distribution might change.

The second objective of the project was to contribute to the standardization of the models. For achieving this objective continuous iteration and presentations at relevant working groups were made. This included mainly the EUROCA WG-62, RTCA SC-159 and preparation of the papers for the ICAO NSP Meetings. A summary of the standardization activities is given in Section 4.2.

In extension of the original scope of the study, analyses regarding the transient phase of the smoothing filter were added to the project to meet stakeholder needs for clarification. The transient phase denotes the initial phase of filtering, when a steady state has not been reached due to the insufficient amount of observations. Characterization of multipath errors during this phase is relevant to assess whether observations can be integrated into the position solution after a loss of lock before the filter has reached steady state. A conservative model based on time-invariant filtering and the worst-case bin was presented. Based on DUFMAN flight data, it was demonstrated that a parameterized transient phase filter coefficient model can be used to overbound the multipath error in non-steady state.During the NSP meeting in June 2020, the proposed model for the iono-free combination has been endorsed and it is considered as the baseline for DFMC SBAS SARPs for GPS or Galileo measurements augmented by SBAS.

2.2. Proposals for further studies

The DUFMAN project has strongly contributed to answering challenging questions regarding the multipath levels to be expected on board an aircraft when adopting the dual frequency dual constellation (DFDC) approach. It created insight into the physical mechanisms of multipath on the aircraft as well as on the different contributors that influence the amount of multipath (such as the antenna, the receiver parameters, the aircraft platform). The knowledge basis developed during the project lead to outstanding recognition from the community, as confirmed by the many publications, appreciation and endorsements, with ICAO endorsement for the DUFMAN model being the best example of it.

Moreover, the insight won with the DUFMAN analysis and the discussion with the community also brought the attention to further issues that need specific analysis and consideration in the upcoming years, due to their relevance in the scientific and standardization community as well as for their impact for the real use of DFDC systems in avionic applications. The most relevant points that, according to the DUFMAN team, should be addressed in further studies are listed in the following:

1. Extension of the multipath analysis for additional aeronautic platforms (such as helicopters, small business aircraft).

Rationale: in DUFMAN, the analysis was focused on commercial fixed wing aircraft, as required by avionic standards. However, as also discussed at RTCA and EUROCAE level (with the introduction of a disclaimer on the validity of the model and on the conditions/platforms under which it was validated), the same model is used also for other platforms, such as business aircraft and helicopters, but also UAVs. This is because there is no additional model available and might yield to potential safety risks due to its non-validity for such platforms. From a physical point of view and as demonstrated already preliminarily making use of the simulation environment developed in DUFMAN, the multipath conditions are very different on such platforms, due to the closer vicinity of the reflecting objects as well as the presence of obstacles above the antenna (e.g. in helicopters). It is therefore suggested to extend the analysis to further categories of avionic platforms.

2. Development of error models and hardware specifications for more advanced operation

Rationale: the overall current error budget for avionics, including the multipath model developed in DUFMAN, as much as the receiver and the antenna specifications in the standards are not thought yet to support advanced operations, like Cat III and ground operations (taxiing, rolling), for the sake of speeding the adoption of standards with basic functionalities (and not delaying them while trying to also include more advanced operations). In the midterm, however, more advanced operations, capable of providing improved guidance with better accuracy and integrity to the aircraft in all weather and all flight and ground phases, need to be pursued.

In order to achieve this goal, two key elements shall be addressed:

1. In order to guarantee higher performance, new error models shall be developed, enabling to reach more accurate positioning by refining the current models and addressing error budgets in a more accurate way (e.g. by proper distinction between bias-like and noise-like errors, by consideration of elevation-dependent errors from satellite group delays, by distinction of multipath error terms for ground operations and in general by inclusion of more specific error terms, capable of reducing the overall error budget through a better specification of each term)

2. Specifications for hardware with higher performance shall be developed starting as soon as possible. This includes for instance the specification of antenna with smaller group delay variations and better multipath suppression capability, as well as more sophisticated receiver hardware and software, making use for instance of improved cycle slip detectors, RFI mitigation techniques and so on. A quick start in developing such specifications would also have the benefit of giving a clear path to interested manufacturers, who could consider it for their future design such as to have market-ready products when hardware for advanced operation will be formally certifiable, hence not delaying the adoption and usability of the advanced operation concept.

It is therefore suggested to start the analysis on more stringent specifications for hardware (antenna, receiver) and to start the development of more accurate error models (further specifying each term and also including ground operations), capable to support advanced operation (e.g. Autoland or ground operations)

3. Project execution and steering

The DUFMAN project was executed according to the Project Management Plan [AD06][AD07][AD08] and its progress was continuously monitored through review meetings on different levels. The first version of the Project Management Plan (PMP) was reviewed and accepted at T0+2 and follows the SoW detailed in the tender specifications [AD01].

The project progress was continuously monitored and steered by means of

- Milestone review meetings with the project officer and project reviewers appointed by EC,
- Monthly web conference meetings with all project partners during the initial phase of the project,
- Weekly calls with the key partners during the implementation phase, to ensure close follow-up of time-critical activities related to flight testing and lab readiness. These meetings replaced monthly status meetings, and
- Daily meetings with the DLR project management team.

During the DUFMAN project, two major adjustments of the project[AD06] management plan were implemented. This section summarizes why the adjustments were made and how the adjustments effected achieving the project objective.

3.1. Extension of the project schedule – PMP v2.0 [AD07]

The target schedule for the project was originally set at T0+20 for completion of the project scope. At the time of reaching the PM5 milestone, it had become apparent that the project was failing to provide sufficient amounts of raw data in order to complete the generation of the DFMC model. The reasons for this delay were as follows:

- A late project start caused the project team to miss a large flight opportunity in 2018 that was originally planned as one of the major contributors to the flight data recording activity.
- The certification of experimentation equipment on different aircraft took longer than planned, in particular qualification of a suitable antenna (no commercial DFMC antenna was available that already fulfilled the requirements for flight), and an additional temperature dependent malfunction discovered at one of the first antenna units. The latter issue further delayed qualification for A320 of the antenna as clarification required the antenna sent as RMA back to the manufacturer. Installation of the equipment could take place in January 2019 and the first flight was recorded on Feb 15, 2019.
- Technical issues with the logging facility used onboard A350 resulted in data corruption affecting some of the early flights on this aircraft. After the problem became apparent immediate action was taken to effect an architecture change into the backup architecture, reverting to the RF recorder scenario. This incident caused loss of the corresponding datasets for further processing.

- A thermal problem occurred with the RF recording device used as a replacement for the MMR based recording architecture, causing the unit to go into overheating mode. The failed unit was immediately sent for repair and the installation architecture was changed to mitigate the risk of thermal issues. With the RF recording option already being a contingency option, this event caused loss of several hours of flight data from multiple flights on A350 before the problem could be fixed.

As a result from these issues, the project schedule was extended by 6 months to a total duration of 26 months, effective with PMP 2.0 [AD07]. The relevant work packages were extended to cover the additional time frame, including processing and analysing the raw data expected during this period, and standardization activities.

The relaxation of the project timeframe was furthermore useful to increase engagement with key stakeholders in the standardization community and on scientific level. In particular, the DFMC Airborne Errors session held at ITM 2020 brought additional momentum to finalize the results and seek broad acceptance in the community.

3.2. Extension of the project schedule and scope change – PMP v3.0 [AD08]

Early 2020 introduced a world-wide pandemic crisis affecting the DUFMAN project at multiple levels. All activities at the subcontractor Airbus SAS stopped from March 2020 before first flights planned in 2020 could be started. This constituted a case of Force Majeure preventing the subcontractor to deliver the agreed results.

In preparation of the final review scheduled in July 2020, the project management team therefore discussed possible options with EC and with the project partners. Because of the high dependency of physical presence for activities both related to laboratory work and to flight experimentation, the subcontractor ASAS was unable to continue work on DUFMAN project activities for an extended timeframe. Restrictions and limitations to access laboratories have persisted since then, and a consolidated plan regarding flights in 2021 could not be presented at the time of discussion.

As a consequence to the situation, it was agreed that a second extension of the project with the goal of securing more flight hours was not an option. Instead, the focus of the project was re-adjusted to ensure maximum impact of the results that could be made available from existing flight data. As the partners' contributions were completed according to the plan by then, the work packages and subcontracts related with partner contributions were consequently not extended beyond T0+26, with the exception of additional efforts at ASAS side to recover the corrupted dataset from an early A350 flight. DLR's activity was extended to incorporate more scientific groundwork on specific questions relevant for stakeholder acceptance of the model, in particular related to group delay variation bounding and its dependencies with multipath models.

The PMP v3.0 [AD08] extended the project duration by another 6 months to a total duration of 32 months. WP2.4 was added to the scope to incorporate the aforementioned scientific work.

3.3. Management report on the last project period, PM7 until FR

The final version of the high-level project schedule is presented in Figure 1. It shows the schedule extended to T0+32 as defined in [AD08]. With this last version of the PMP, the project was extended to add additional scientific scope related to the DFMM modeling process and its adoption in the standardization community. This activity was assigned a new work package WP2.4, and sustained contribution to the standardization community (in particular, preparation of additional material for ICAO NSP) was carried out under an extended WP 4.2.

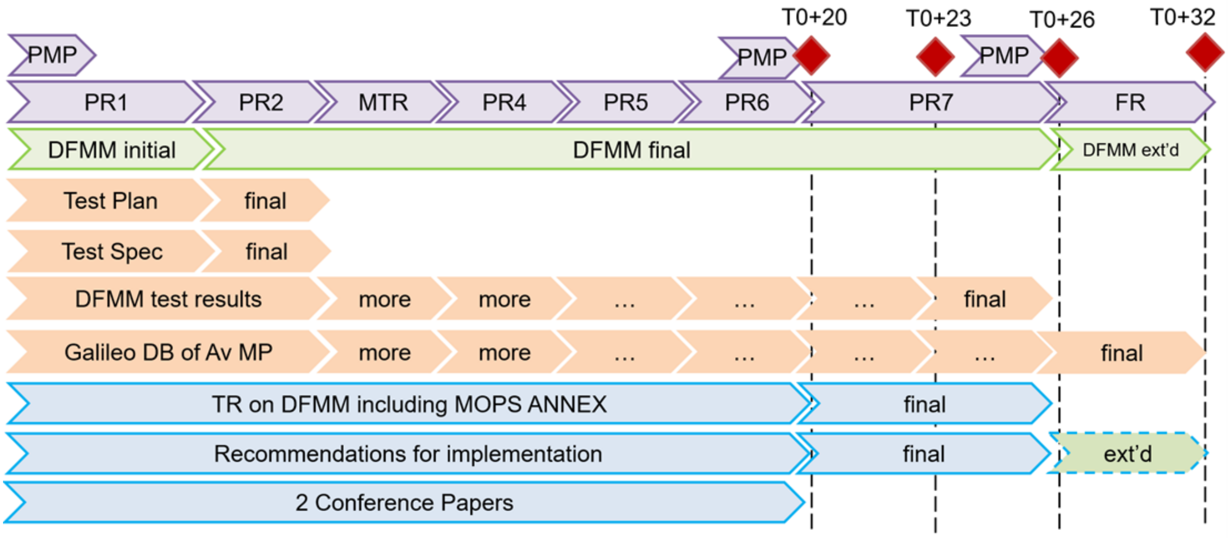

Figure 1: Project Schedule

At ASAS, a renewed attempt was made to process the data from the missing A350 flight dataset once lab was again possible under limited circumstances. To support this activity, DLR sent back some hard drives containing the flight dataset to ASAS where it was again replayed in their Syntony replay device. The extended debugging session took place in September 2020 on two days. The result of this replay test was a final confirmation that the datasets do not contain any signal. According to ASAS, possible reasons for this non-recoverable fault could be an unobserved fault in the recording setup (wiring) or a failure in one of the devices in the processing chain: ECHO-R, amplifier, wire, splitter or antenna.

The contributions from the partners ADS, Collins Aerospace and THAV have ended with closure of PM7.

To wrap up the project, the last phase of the project was used to organize and cross-check the final version of the Galileo Database of Aviation Multipath (D3400) which will be delivered with this report.

4. Dissemination

This section summarizes the dissemination activities in the DUFMAN project.

The key objective of the project was to establish the basis for a new multipath model standard for airborne GNSS users of Galileo and GPS. Consequently, dissemination of the project activity and results had high priority during the entire duration of the project. Dissemination activities included

- Initiating discussions and soliciting feedback on the modeling methodology
- Discussion of the results derived from flight measurements
- Contribution to the standardization process

Dissemination activities were directed both towards the scientific community and to standardization bodies and working groups such as ICAO NSP, EUROCAE WG-62 and RTCA WC 159.

On the scientific side, methodology and results were continuously presented and published at various conferences and in peer reviewed publications. In the last phase of the project, the project team succeeded in organizing a dedicated session on DFMC airborne error models [Figure 2], [RD46]. Co-chaired by the DUFMAN project officer, Matteo Sgammini, and the project manager Markus Rippl, this session included four paper presentations resulting from DUFMAN project activity. Together with additional papers from authors outside of the DUFMAN project, this scientific session fostered many useful discussions around DFMC multipath error standardization that helped reaching the DUFMAN objective and securing consensus on the results.

The following paragraphs list all publications resulting from DUFMAN project activities. The list of publications is also appended as a separate document to this report [RD33].

TECHNICAL SESSIONS

Session A1: DFMC Airborne Error Models
Room: Bayview Ballroom 1
1:45 p.m. – 5:30 p.m.

Matteo Sgammini
European Commission, Italy

Markus Rippl
German Aerospace Center (DLR), Germany

1:50 Standardization of New Airborne Multipath Models: Michael Felux, Mihaela-Simona Circiu, Stefano Caizzone, Markus Rippl, German Aerospace Center (DLR), Germany; Pierre Durel, GSA; Matteo Sgammini, EC, Italy

2:12 Multipath Suppression Capability and Indicators for Airborne Dual Frequency GNSS Antennas: S. Caizzone, M.-S. Circiu, W. Elmarissi, C. Enneking, A. Winterstein, German Aerospace Center (DLR), Germany

2:35 Airborne Multipath Models for Dual-constellation Dual-frequency Aviation Applications: Mihaela-Simona Circiu, Michael Felux, Stefano Caizzone, Christoph Enneking, Friederike Fohlmeister, Markus Rippl, German Aerospace Center (DLR), Germany; Ioana Gulie, David Rüegg, Airbus Defence and Space GmbH, Germany; Joseph Griggs, Collins Aerospace; Rémy Lazzerini, Florent Hagemann, Francois Tranchet, Airbus Operation SAS; Pierre Bouniol, Thales Avionics; Matteo Sgammini, Joint Research Centre, Italy

2:58 Effects of Preliminary DFMC Multipath Models on ARAIM Performance: Joseph Griggs, Collins Aerospace; Markus Rippl, Mihaela-Simona Circiu, Stefano Caizzone, German Aerospace Centre (DLR), Germany

3:25 - 3:55, Break. Refreshments in Exhibit Hall

4:00 GMP-Overbound Parameter Determination for Measurement Error Time Correlation Modeling: Sandeep Jada and Mathieu Joerger, Virginia Tech

4:23 Impact of DME/TACAN on GNSS L5/E5a Receiver: Axel Javier Garcia Pena, Christophe Macabiau, ENAC, France; Mikael Mabilleau, Pierre Durel, GSA, France

4:46 Impact of Satellite Biases on the Position in Differential MFMC Applications: Steffen Thoelert, Mihaela-Simona Circiu, Michael Meurer, German Aerospace Center (DLR) and RWTH Aachen University, Germany

Figure 2: Session schedule at ITM 2021, Session A1: DFMC Airborne Error Models

4.1. Summary of scientific dissemination activities

ION GNSS 2018

1. Caizzone, S., Circiu, M.-S., Elmarissi, W., Enneking, C., Felux, M., Yinusa, K., "Multipath Rejection Capability Analysis of GNSS Antennas," *Proceedings of the 31st International Technical Meeting of the Satellite Division of The Institute of Navigation (ION GNSS+ 2018)*, Miami, Florida, September 2018, pp. 3478-3489. https://doi.org/10.33012/2018.16109
[RD34]

2. Circiu, Mihaela-Simona, Caizzone, Stefano, Felux, Michael, Enneking, Christoph, Meurer, Michael, "Improved Airborne Multipath Modelling," *Proceedings of the 31st International Technical Meeting of the Satellite Division of The Institute of Navigation (ION GNSS+ 2018)*, Miami, Florida, September 2018, pp. 2195-2209. https://doi.org/10.33012/2018.15855
[RD35]

ION ITM 2019

3. Felux, Michael, Circiu, Mihaela-Simona, Caizzone, Stefano, Enneking, Christoph, Fohlmeister, Friederike, Rippl, Markus, "Towards Airborne Multipath Models for Dual Constellation and Dual-frequency GNSS," *Proceedings of the 2019 International Technical Meeting of The Institute of Navigation*, Reston, Virginia, January 2019, pp. 62-68.
https://doi.org/10.33012/2019.16683
[RD36]

ION GNSS 2019

4. Caizzone, Stefano, Circiu, Mihaela-Simona, Elmarissi, Wahid, Enneking, Christoph, Winterstein, Andreas, "Airborne Antenna and Multipath Error Characterization for DFMC Error Standardization," *Proceedings of the 32nd International Technical Meeting of the Satellite Division of The Institute of Navigation (ION GNSS+ 2019)*, Miami, Florida, September 2019, pp. 1453-1463.
https://doi.org/10.33012/2019.16908
[RD37]

5. Circiu, Mihaela-Simona, Felux, Michael, Caizzone, Stefano, Enneking, Christoph, Fohlmeister, Friederike, Rippl, Markus, Gulie, Ioana, Rueegg, David, Griggs, Joseph, Lazzerini, Rémy, Hagemann, Florent, Tranchet, Francois, Bouniol, Pierre, Sgammini, Matteo, "Initial Results for Dual Constellation Dual-frequency Multipath Models," *Proceedings of the 32nd International Technical Meeting of the Satellite Division of The Institute of Navigation (ION GNSS+ 2019)*, Miami,

Florida, September 2019, pp. 1401-1417; https://doi.org/10.33012/2019.16906
[RD38]

ION ITM 2020

6. Felux, Michael, Circiu, Mihaela-Simona, Caizzone, Stefano, Rippl, Markus, Sgammini, Matteo, Durel, Pierre, "Standardization of New Airborne Multipath Models," *Proceedings of the 2020 International Technical Meeting of The Institute of Navigation*, San Diego, California, January 2020, pp. 146-153. https://doi.org/10.33012/2020.17133
[RD39]
7. Caizzone, S., Circiu, M.-S., Elmarissi, W., Enneking, C., Winterstein, A., "Multipath Suppression Capability and Indicators for Airborne Dual Frequency GNSS Antennas," *Proceedings of the 2020 International Technical Meeting of The Institute of Navigation*, San Diego, California, January 2020, pp. 154-161. https://doi.org/10.33012/2020.17134
[RD40]
8. Circiu, Mihaela-Simona, Felux, Michael, Caizzone, Stefano, Enneking, Christoph, Fohlmeister, Friederike, Rippl, Markus, Gulie, Ioana, Rüegg, David, Griggs, Joseph, Lazzerini, Rémy, Hagemann, Florent, Tranchet, Francois, Bouniol, Pierre, Sgammini, Matteo, "Airborne Multipath Models for Dual-constellation Dual-Frequency Aviation Applications," *Proceedings of the 2020 International Technical Meeting of The Institute of Navigation*, San Diego, California, January 2020, pp. 162-173. https://doi.org/10.33012/2020.17135
[RD41]
9. Griggs, Joseph, Rippl, Markus, Caizzone, Stefano, Circiu, Mihaela-Simona, "Effects of Preliminary DFMC Multipath Models on ARAIM Performance," *Proceedings of the 2020 International Technical Meeting of The Institute of Navigation*, San Diego, California, January 2020, pp. 174-188. https://doi.org/10.33012/2020.17136
[RD42]

ION ITM 2021

10. Bang Eugene, Circiu Mihaela-Simona, Caizzone Stefano and Rippl Markus "Antenna Group Delay Variation Bias Effect on Advanced RAIM", ION ITM 2021
[RD43]
11. Circiu, Mihaela-Simona, Felux, Michael, Caizzone, Stefano, Enneking, Christoph, Fohlmeister, Friederike, Rippl, Markus, Gulie, Ioana, Rüegg, David, Griggs, Joseph,

Lazzerini, Rémy, Hagemann, Florent, Tranchet, Francois, Bouniol, Pierre, Sgammini, Matteo, "Final Results on Airborne Multipath Models for Dual-constellation Dual-frequency Aviation Applications," ITM 2021, San Diego, California, Jan 2021.
[RD44]

Journal paper

12. Circiu, M-S, Caizzone, S, Felux, M, Enneking, C, Rippl, M, Meurer, M. Development of the dual-frequency dual-constellation airborne multipath models. *NAVIGATION*. 2020; 67: 61– 81. https://doi.org/10.1002/navi.344
[RD45]

4.2. Summary of working group dissemination activities

The following dissemination activities were executed during the project duration (scientific, stakeholder related or standardization targeted activities):

Table 4: Dissemination actions during reporting period

Activity	Date	Type	Presenter	Focus	Result
IGWG (Krakow)	18.5.2018	Working Group	DLR (Felux)	Project Introduction	Questions by FAA, follow-on with Boeing (no particular result here). Good reception
SESAR 14.03.01	14.06.2018	Project Networking	DLR (Felux)	Project Introduction	well received, waiting for project results
IWG	Sept 2018	Working Group	DLR (Circiu)	General presentation on CNMP research @DLR, including DUFMAN references	
WG-C	Nov. 2018	Working Group	DLR (Rippl)	DFMM results & Methodology	Presentation was well received and returned request for clarification on technical level regarding the different performance levels on Galileo L1 vs. GPS L1. Interaction with an FAA project on aviation multipath was initiated.

Activity	Date	Type	Presenter	Focus	Result
WG-62	Dec 2018	Standardization	DLR (Circiu)	DFMM results & Methodology	The presentation was well received. Action: The results from DUFMAN should be integrated in the next version DFMC SBAS MOPS
LATO Meeting	Feb 2019	Working Group	DLR (Felux)	Methodology and initial results	Work appreciated, further updates requested as they become available
RTCA SC-159	Mar 2019	Standardization	DLR (Caizzone, Felux)	Methodology, antenna results, performance prediction by simulation	
ICAO NSP	Apr 2019	Standardization	EC (Chatre), DLR via telco (Caizzone)	antenna results, performance prediction by simulation	Work appreciated, further results requested for future meetings.
Eurocae WG62	13.-17. May 2019	Standardization	DLR (Felux)	Initial flight test results	
Discussion with FAA Multipath Project	May 14 2019	Coordination with project	DLR (Rippl/Circiu)	Focus, methodology comparison, technical exchange	Initiated during WG-C Chicago meeting. First step is a telco
WG-C	20.-23. May 2019	Working Group	DLR (Caizzone, Felux)	Initial flight test results, error bounding concepts w.r.t. antenna	
IGWG	17.-20. June 2019	Working Group	DLR (Felux)	Flight test results, project status	
Eurocae WG-62	9.-13. September 2019	Standardization	DLR (Circiu)	Update on flight campaign A330, impact of receiver chip spacing	

Activity	Date	Type	Presenter	Focus	Result
RTCA SC-159	30. Sep.-4.Oct. 2019	Standardization	DLR (Caizzone).	Update on the antenna investigations	
WG-C	7.-10. October 2019	Working Group	DLR (Felux)	Initial models based on A321 and A330 data, antenna impact	
ICAO NSP	14.-25. October 2019	Standardization	t.b.d.	Initial Model Suggestion	
WG-62/RTCA WG-4/WG-7	March 2020	Standardization	DLR	Preliminary model proposal, "Position paper", Suggestion to separate AGDV/Multipath	Mixed comments requiring consolidation of the discussion with reviewers
ICAO NSP	June 2020	Standardization	Prepared: DLR Presented by Eric Chatre (EC)	WP21: DUFMAN Multipath Model Proposal	DFMC SBAS multipath model proposed for iono-free combination on the basis of the H2020 DUFMAN project was endorsed.
WG-62	July 2020	Standardization	DLR (Circiu/Caizzone)	Final models for multipath and antenna	Comments were raised related to the validity of the approach
RTCA SC 159/WG-62	10/2020	Standardization	EC (Sgammini)	Final models and safety analysis of the proposed models	

5. List of deliverables

This section details the deliverables submitted from kick-off until the end of the project.

Some deliverables were prepared in an iterative cycle and updated one or multiple times at subsequent milestones after their respective initial version. These documents are represented with multiple entries in the table below. For each scheduled delivery of the respective report, the final version number is indicated.

Table 5: List of completed deliverables

ID	Version	Title	Ref	Comment	Scheduled	Delivered	Status		Distribution[2]	WP
D1100	1.0 17.08.2018	Project Management Plan (PMP)	[AD06]		T0+1	T0+2	Completed		CO	1
D1100	2.0 13.12.2019	Project Management Plan (PMP)	[AD07]		-	T0+18	Completed		CO	1
D1100	3.0 21.07.2020	Project Management Plan (PMP)	[AD08]		-	T0+26	Completed		CO	1
D1201	1.01 20.11.2018	Progress Report 1 (PR1)	[RD01]		T0+5	T0+5	Completed		CO	1
D1202	1.03 19.02.2019	Progress Report 2 (PR2)	[RD02]		T0+8 Version 2	T0+8	Completed		CO	1
D1203	1.01 14.05.2019	Progress Report 3 (PR3)	[RD03]		T0+11 Version 3	T0+11	Completed		CO	1
D1204	1.02 27.08.2019	Progress Report 4 (PR4)	[RD04]		T0+14 Version 4	T0+14	Completed		CO	1
D1205	1.00 18.10.2019	Progress Report 5 (PR5)	[RD05]		T0+17 Version 5	T0+17	Completed		CO	1

[2]PU = Public, open for public dissemination (public deliverables shall be of a professional standard in a form suitable for print or electronic publication);

CO = Confidential, restricted under conditions to be set out in the Contract. Irrespective of the status, all reports and deliverables must be made accessible to the other project participants, and to the contracting authority.

D1206		*Progress Report 6 (PR6)*	*n/a*	*Introduced in [AD07]*	*T0+20 Version 6*	*-*	*Not delivered*		*CO*	*1*
D1207	1.00 28.07.2020	Progress Report 7 (PR7)	[RD06]	Introduced in [AD08]	T0+26 Version 7	T0+26	Completed		CO	1
D1300	1.00 21.01.2021	Final Report (FR)	*This report*		T0+32		*This report*		PU	1
D2100	1.01	Dual Frequency Multipath Model	[RD07]		T0+5 Version 1	T0+5	Completed		PU	2.1 2.3
D2100	2.01	Dual Frequency Multipath Model	[RD08]	Rescheduled in [AD07]	T0+26 (version for PM7, „final" model for ICAO)	In submission	Completed		PU	2.3
D2100	3.00	Dual Frequency Multipath Model	[RD09]		T0+32 Final Version extended	T0+32	*Delivered with this report*		PU	
D3100	1.01	DFMM Test Plan	[RD10]		T0+5 Version 1	T0+5	Completed		PU	3.1
D3100	2.00	DFMM Test Plan	[RD11]		T0+8 Version 2	T0+8	Completed		PU	3.1
D3100	2.10	DFMM Test Plan	[RD12]	Irregular update: Flight Plans	T0+11 Version 2.10	T0+11	Completed		PU	3.1
D3100	2.20	DFMM Test Plan	[RD13]	Irregular update: Flight Plans	T0+14 Version 2.20	T0+14	Completed		PU	3.1
D3200	1.00	DFMM Test Specifications	[RD14]		T0+5 Version 1	T0+5	Completed		PU	3.1
D3200	2.02	DFMM Test Specifications	[RD15]		T0+8 Version 2	T0+8	Completed		PU	3.1
D3200	2.11	DFMM Test Specifications	[RD16]	Irregular update: MMR specs	T0+11 Version 2.10	T0+11	Completed		PU	3.1
D3200	2.20	DFMM Test Specifications	[RD17]	Irregular update: MMR specs	T0+14 Version 2.20	T0+14	Completed		PU	3.1

D3300	1.02	DFMM Test Results	[RD18]		T0+8 Version 1	T0+8	Completed		PU	3.5
D3300	2.01	DFMM Test Results	[RD19]		T0+11 Version 2	T0+11	Completed		PU	3.5
D3300	3.00	DFMM Test Results	[RD20]		T0+14 Version 3	T0+14	Completed		PU	3.5
D3300	4.00	DFMM Test Results	[RD21]		T0+17 Version 4	T0+17	Completed		PU	3.5
D3300	5.01	DFMM Test Results	[RD22]	Introduced in [AD07]	T0+26 Final Version	T0+26	Completed		PU	3.5
D3400	1.0	Galileo Database of Aviation Multipath	[RD23]		T0+8 Version 1	T0+8	Completed		PU	3.4
D3400		*Galileo Database of Aviation Multipath*	*n/a*		*T0+11* *Version 2*	-	*Not delivered*		*PU*	*3.4*
D3400		*Galileo Database of Aviation Multipath*	*n/a*		*T0+14* *Version 3*	-	*Not delivered*		*PU*	*3.4*
D3400		*Galileo Database of Aviation Multipath*	*n/a*		*T0+17* *Version 4*	-	*Not delivered*		*PU*	*3.4*
D3400	5.0	Galileo Database of Aviation Multipath	[RD24]		T0+26 Version 5	T0+26	Completed		PU	3.4
D3400	6.0	Galileo Database of Aviation Multipath	[RD25]		T0+32 Final Version	T0+32	*Delivered with this report*		PU	3.4

D4100		Technical Report on DFMM for Aviation	[RD26], [RD27], [RD28],	NSP information and working papers	T0+20 Version 1	T0+23	Completed		PU	4.1
D4100		Technical Report on DFMM for Aviation	[RD32], [RD29]	Position paper iterated with EC and GSA; NSP working paper submitted to ICAO and presented at EUROCAE and RTCA	T0+26 Final Version	T0+26	Completed		PU	4.1
D4200		Recommendations for implementation of DFMM for Aviation	[RD31]	Technical Note Model Development	T0+20 Version 1	T0+21	Completed		PU	4.1
D4200		Recommendations for implementation of DFMM for Aviation	[RD31]	Technical Note Model Development	T0+26 Final Version	T0+21	Completed		PU	4.1
D4200		Recommendations for implementation of DFMM for Aviation	[RD30]	NSP working paper	T0+32: *Additional material on extended model if requested*				PU	4.1
D4310 D4320		Conference Papers #1 Conference Paper #2	See [RD33]	Multiple papers at ITM 2020, see Section 4.1	Before T0+20 (acceptance of paper)	Presented: T0+20 (ITM 2020)	Completed		PU	4.2
D4320			See [RD33]	Multiple papers at ITM 2020, see Section 4.1	Before T0+20 (acceptance of paper)	Presented: T0+20 (ITM 2020)	Completed		PU	4.2

5.1. RIDs

As part of the milestone review meetings, all deliverables have gone through formal acceptance by EC. The Review Item Discrepancies (RIDs) identified in this process were managed in a common table across all deliverables which was appended with the new review items at each milestone. The final version of this table shall reflect complete closure of all open items and thus full and complete acceptance of the project deliverables.

A consolidated RID table including RID entries from all progress meetings is appended to this report [RD49]. During the acceptance process of this report and the accompanying deliverable documents, it is expected that this RID document will be further iterated until all entries can be closed.

5.2. Review Meetings and Minutes of Meeting

The review meetings are summarized in Table 6 below:

Table 6: Review Meetings

Meeting Name	Location	Date	Participants	Minutes
KOM	Online	03.05.2018	DLR, ASAS, ADS, RC	[RD50]
TKOM	JRC, Ispra, IT	15.6.2018	DLR (3), ASAS, ADS, RC	[RD51]
PM1	ASAS, Toulouse, FR	18.10.2018	DLR (3), ASAS (2), ADS, RC	[RD53]
PM2	DLR, Oberpfaffenhofen, DE	5.2.2019	ADS, ASAS, DLR, RC	[RD54]
PM3	DLR, Oberpfaffenhofen, DE	23.5.2019	ADS, DLR, Collins	[RD55]
PM4	ADS, Ottobrunn, DE	6.8.2019	ASAS, Collins, DLR, ADS	[RD56]
PM5	DLR, Oberpfaffenhofen, Germany	15.11.2019	ADS, ASAS, Collins, THAV	[RD57]
PM6	*n/a*	*n/a*[3]		-/-

[3] Caused by significant delays in the project, PM6 was postponed until CP2. PR7 covers the reporting period from PM5 (T0+17) until PM7 (T0+26)

CP2	Online	13.02.2020	ASAS, DLR	[RD58]
PM7[4]	Online	29.07.2020	DLR, ADS, ASAS, Collins Aerospace	[RD59]
CP3	Online	07.12.2020	DLR, ASAS	[RD60]

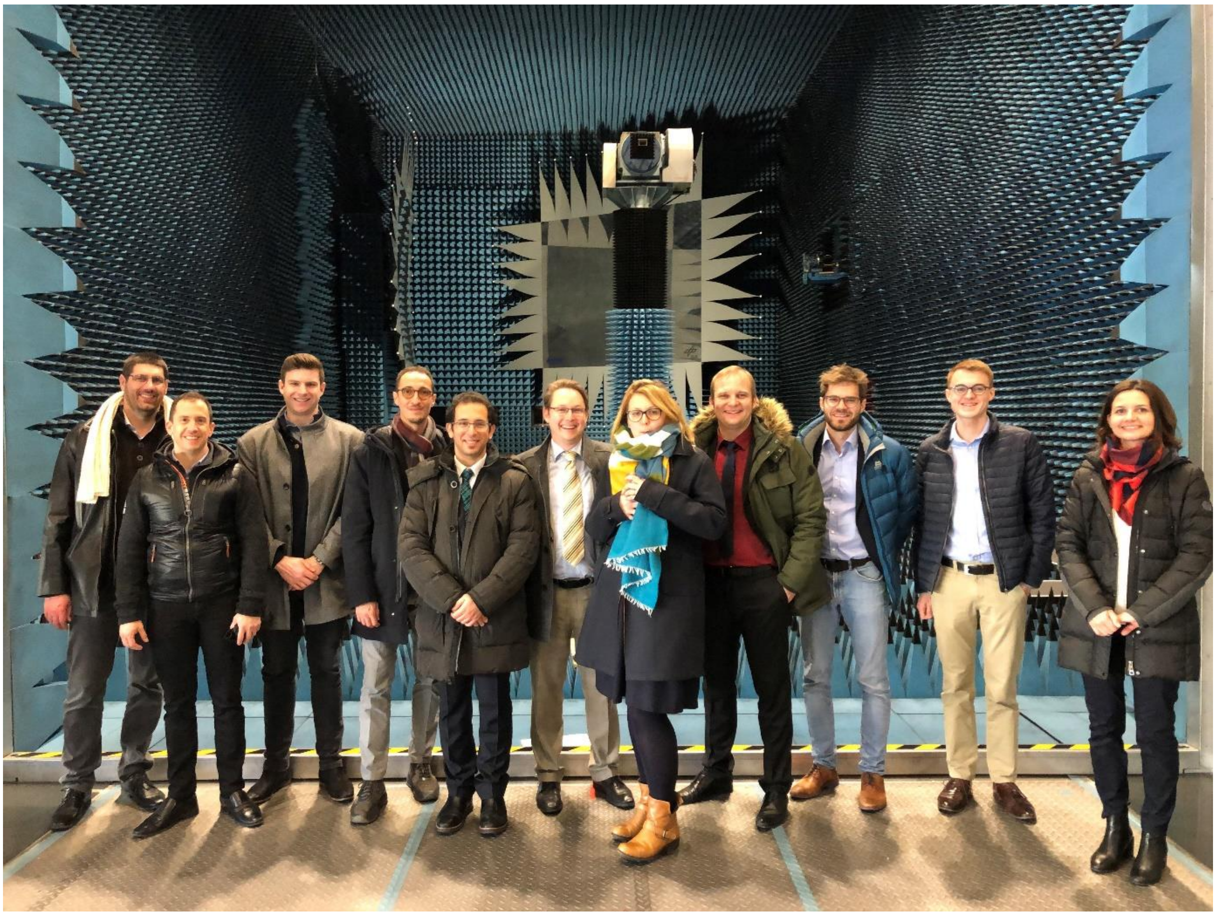

Figure 3: Group picture of DUFMAN team visiting the Compact Range Antenna Measurement site at DLR Oberpfaffenhofen. Progress Meeting 2, Feb. 2019

[4] The meeting concluded activities from the partners ADS, Collins Aerospace, and THAV; it doubled as FR meeting for these partners as originally planned until PMP 2.0 [AD07].

6. Travel activities

The following travel activities in the frame of DUFMAN took place during the duration of the project:

Table 7: Travel activities during reporting period

Meeting Name	Location	Date	Participants
TKOM	Ispra	15.6.2018	DLR (3), ASAS, ADS, RC
PM1 Progress Meeting	Toulouse, France	18.10.2018	DLR (3), ASAS (2), ADS, RC
PM2 Progress Meeting	DLR Oberpfaffenhofen, Germany	5.2.2019	ADS, ASAS, DLR, RC
PM3 Progress Meeting	DLR Oberpfaffenhofen, Germany	23.5.2019	ADS, DLR, Collins
PM4 Progress Meeting	ADS Ottobrunn, Germany	6.8.2019	ASAS, Collins, DLR, ADS
PM5 Progress Meeting	DLR Oberpfaffenhofen, Germany	15.11.2019	DLR, EC
ION GNSS+ & IWG	U.S.	Sept 2018	DLR (1)
WG-C	Chicago US	27./28.11.2018	DLR (1)
WG-62	Toulouse	13.12.2018	DLR (1)
ION ITM 2019	Reston VA, U.S.	Jan 2019	DLR (1)
RTCA SC-159	U.S.	March 2019	DLR (2)
Flight test readiness meeting	ASAS TLS	18.01.2019	ADS (1), DLR (2)
WG-62 meeting	Toulouse	11.-13.09.2019	DLR (1)
ION GNSS+ 2019	Miami, USA	17.-19.9.2019	DLR (2)
ION ITM 2020	San Diego USA	Jan 2020	DLR (4), Collins (1)

As a result of the Covid-19 travel restrictions, no travel activities were possible after March 2020. Consequently, all remaining milestone reviews and checkpoints were held virtually.

7. Inventory List

The DUFMAN inventory list constitutes the inventory of items procured through funding of the DUFMAN project and their current location. During project execution, it was maintained in the internal section of the project teamsite. The final inventory list is represented at high level in Table 8. The complete list is also provided as a separate file with this report [RD48].

Table 8: Project Inventory

ID	Owner	Description	Remark
DI001	DLR	GNSS Antenna L1/L5	ASAS flight test team A320
DI002	DLR	GNSS Antenna L1/L5	ASAS lab team
DI003	DLR	GNSS Antenna L1/L5	ex lab antenna
DI004	DLR	GNSS Antenna L1/L5	ASAS flight test team A350
DI005	DLR	GNSS Antenna L1/L5	
DI006	DLR	Hard Drive 8TB	First disk for THAV replay tests
DI007	DLR	Hard Drive 8TB	
DI008	DLR	Hard Drive 8TB	Returned to ASAS (Recovery lab run)
DI009	DLR	Hard Drive 8TB	
DI010	DLR	Hard Drive 8TB	Returned to ASAS (Recovery lab run)
DI011	DLR	Hard Drive 8TB	Returned to ASAS (Recovery lab run)
DI012	DLR	Hard Drive 8TB	Received from Collins US
DI013	DLR	Hard Drive 8TB	received at THAV
DI014	ADS	NAS Server	NAS was transferred to DLR for final check
DI015	ADS	HDD 8TB	NAS was transferred to DLR for final check
DI016	ADS	HDD 8TB	NAS was transferred to DLR for final check
DI017	ADS	HDD 8TB	NAS was transferred to DLR for final check
DI018	ADS	HDD 8TB	NAS was transferred to DLR for final check
DI019	ADS	HDD 8TB	NAS was transferred to DLR for final check

DI020	ADS	HDD 8TB	NAS was transferred to DLR for final check
DI021	ADS	HDD 8TB	NAS was transferred to DLR for final check
DI022	ADS	HDD 8TB	NAS was transferred to DLR for final check
DI023	ADS	HDD 8TB	NAS was transferred to DLR for final check
DI024	ADS	HDD 8TB	NAS was transferred to DLR for final check
DI025	ADS	HDD 8TB	NAS was transferred to DLR for final check
DI026	ADS	HDD 8TB	NAS was transferred to DLR for final check
DI027	ADS	HDD 8TB	NAS was transferred to DLR for final check
DI028	ADS	HDD 8TB	NAS was transferred to DLR for final check
DI029	ADS	HDD 8TB	NAS was transferred to DLR for final check
DI030	ADS	HDD 8TB	NAS was transferred to DLR for final check
DI031	ADS	HDD 8TB	NAS was transferred to DLR for final check
DI032	ADS	HDD 8TB	NAS was transferred to DLR for final check
DI034	ADS	HDD 8TB	NAS was transferred to DLR for final check
DI035	ADS	HDD 8TB	NAS was transferred to DLR for final check
DI036	ADS	HDD 8TB	NAS was transferred to DLR for final check
DI037	ADS	HDD 8TB	NAS was transferred to DLR for final check
DI038	ADS	HDD 8TB	NAS was transferred to DLR for final check
DI039	ADS	HDD 8TB	NAS was transferred to DLR for final check
DI040	ADS	HDD 8TB	NAS was transferred to DLR for final check
DI041	ADS	HDD 8TB	NAS was transferred to DLR for final check
DI042	ADS	HDD 8TB	NAS was transferred to DLR for final check
DI043	ADS	HDD 8TB	Cleanup before shipping

DI044	Collins	MMR	ASAS DO team
DI045	Collins	MMR	ASAS flight test team A350
DI046	Collins	MMR	ASAS DO team
DI047	Collins	MMR	Sent to ASAS for return to Collins FR
DI048	DLR	Hard Drive 8TB	received at THAV
DI049	DLR	Hard Drive 8TB	Returned to DLR (delivery problem)
DI050	DLR	Hard Drive 8TB	Returned to DLR (delivery problem)
DI051	DLR	Hard Drive 8TB	Returned to DLR (delivery problem)

8. IPR List

Table 9: Intellectual Property Rights (IPR)

IPR ID	Owner	Description	Remark
1	DLR	Software Source Code to calculate, plot and convert antenna parameters (group delay, gain and phase pattern, multipath suppression capability,…) from measurements/simulations Results concerned: Estimation and display of antenna characteristics	Source code will be made available to EC on basis of a non-exclusive, non-transferable license to enable exploitation of DUFMAN results.
2	DLR	Software Source Code for multipath estimation including all the processing steps and a GUI for visualization of different parameters and results. The version used to generate the initial version is under: https://kngitlab.kn.op.dlr.de/AirborneMultipath/ACM Results concerned: Estimation and display of multipath error distribution from observation data	Source code will be made available to EC on basis of a non-exclusive, non-transferable license to enable exploitation of DUFMAN results.
3	DLR	ARINC Interface to the MMR that was procured by DLR from Collins Aerospace from internal funding	The connector is being used within the DUFMAN project in the ADS laboratory
4	Airbus Defence and Space GmbH	Patent No. EP2796896 A1: Method for tracking signals comprising at least one subcarrier. Method for tracking BOC, BOCc, and CBOC signals, which exploits the subcarrier accuracy to the full und solves the subcarrier ambiguity based on the correlation envelope of the code. Results concerned: Tracking results of GNSS end-to-end simulator	• Patent, Ownership of Airbus Defence and Space GmbH (formerly known as Astrium GmbH) • Used for the development only Since neither the pre-existing rights are incorporated in the results nor the results incorporate any know-how, there is no need to licence this pre-existing rights for any use that the contracting authority may envisage

5	Airbus Defence and Space GmbH Ownership Internal R&D	Positioning and Integrity Performance Evaluator (PIPE) : PIPE is a simulation toolset written in C++, and runs on normal linux machines. It contains means for generating realistic scenarios (trajectory, multipath, interference), allows to generate corresponding GNSS baseband samples of BOC and BPSK signals as well as additional sensor data (IMU, baro, odometer, magnetometer), and contains acquisition and tracking algorithms, as well as modules for PVT calculation, including loose, tight and ultra-tight integration with INS. Additionally, RAIM and other integrity algorithms are available as well. Results concerned: GNSS end-to-end simulator results.	• Used for the development only 1) Since neither the pre-existing rights are incorporated in the results nor the results incorporate any know-how, there is no need to licence this pre-existing rights for any use that the contracting authority may envisage
6	DLR	Recorded GNSS observation data and Flight Test metadata from DLR internal projects used in DFMM v1 and made available to the Galileo Database of Aviation Multipath (D3400): • RINEX observations and/or equivalent binary data from GNSS receiver • FTI data specifying position, altitude, attitude and other state data of the aircraft	• Flight test results originating outside DUFMAN have been used to process the initial DFMM. Subsets of these results/measurements are made available through the Galileo Database of Aviation Multipath (D3400) and are licensed to EC on a non-exclusive and non-transferable basis. Dissemination of these data outside EC/JRC requires express written consent by DLR.
7	Collins Aerospace	GLU-2100 prototype: prototype used for the project which is based on the GLU-2100 product line, including hardware, software and all the associated documentation.	
8	Collins Aerospace	GNSS Vision: Tool used to process the data provided by the GLU-2100 DUFMAN prototype.	

9. Lessons learned

The following major points have been identified as candidates for improvement, or as best practices for future similar projects or activities:

9.1. Dependency on experimentation data and best effort funding of flight campaign

The DUFMAN Project had very ambitious requirements on experimentation: The use of large commercial aircraft was crucial for the collection of relevant data to be analyzed. Experimentation integration was challenging because the design required changes to antenna and avionics architecture on a commercial aircraft.

Planning of joint flight tests with other experimentation was sometimes inhibited due to competing experimentation objectives, e.g. qualification of avionics components while allowing changes to relevant parts of the avionics architecture by the DUFMAN experiment. Exclusive access to test aircraft was out of reach under the given funding.

In this situation, any experimentation planning was necessarily subject to a high amount of external constraints and factors changing rapidly during the course of the project. It soon became evident that no useful predictions on flight schedule and experimentation activity could be delivered. The project team had to mitigate the lack of planning reliability by employing as much redundancy on the experimentation activities as was feasible. Still, the amount of successful experimentation fell back significantly behind expectation.

9.2. Preparation of flight experimentation

Flight testing was prepared by DUFMAN project team at ASAS, but flight test execution was not directly under control of the project team. The design of the experimentation setup was restricted by domain specific constraints such as flight safety rules and policies.

9.3. Quality assurance of flight experiments

Planning quality assurance aspects into flight experimentation was inhibited by the structure of the experimentation process in the subcontractor's company. Even though it was understood and accepted on the technical side of all project staff members, it was not possible to set up integration and testing of the relevant components such that it could have been verified before actual flight that the components are fully functional. This restriction led to actual problems in some of the flights where a previous test would potentially have discovered technical issues before the flight slot.

However, all aspects where integration testing was feasible have been tested prior to installation, e.g. combination of antenna and recording device for RF data recording, and the posterior replay and processing of the recorded data.

9.4. Stakeholder management

External Stakeholders the project team engaged with were relevant standardization groups and expert groups relevant for the development of GNSS navigation for aviation. The individuals forming these groups have different backgrounds: Scientific experts in academia, engineering experts affiliated with manufacturers or other economic actors in the field, and policy managers affiliated with different authorities in Europe and the U.S. .

- Dissemination of the results was well prepared and endorsed by the key EU stakeholders relevant to the respective groups, e.g. the chairpersons of the working groups.
- Timing of the DUFMAN inputs to the respective groups was continuously monitored and adjusted to meet the needs of the on-going standardization discussion
- Scope of the study was iteratively changed and extended based on feedback from the stakeholder groups, e.g. more detailed studies on different smoothing times, impact of different bounding models.
- Some discussions on the foundation of the model brought up by actors in the stakeholder groups were difficult to manage. Break-out discussions between these stakeholders, the DUFMAN engineers and the policy stakeholders were finally sufficient to achieve acceptance of the results and way forward for the study outcomes.

9.5. Planning and steering approach in project management

The following outcomes refer to the lessons learned from management activities in the DUFMAN project.

- Waterfall planning worked inefficiently for this type of activity, because many key aspects of the project could not be known in the early stage. The timeline for collection and analysis of study data, and dissemination of results, was planned in an iterative manner leaving sufficient degrees of freedom to meet high-level schedule.
- Iterative and rapid management allowed for small but continuous steps developing experimentation design and study design, but required high amount of management effort.
- Executing project as "one team" vs subcontracting was necessary from technical perspective, and was mostly implemented and accepted by all subcontractor resources.
- Many internal stakeholders across the different partners required significantly more communication efforts than planned for in order to efficiently manage the project outcomes and schedule.
- The overall resources planned for management effort were greatly underestimated.

10. Issue log

Project issues were discussed and documented in an issue log during the project, facilitating the resolution of such issues by managing the corresponding action items.

The action items were continuously managed and monitored in the DUFMAN team site at https://teamsites-extranet.dlr.de/kn/DUFMAN/Lists/Tasks. A copy of the complete action list is provided with this report [RD47].

All actions have been closed.