RESULTS OF THE SCALED FLIGHT DEMONSTRATOR FLIGHT TESTS

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Abstract

Within the Large Passenger Aircraft Platform of the Clean Sky 2 Programme, a consortium led by ONERA including Airbus, CIRA and NLR completed a thorough validation of Scaled Flight Testing. This approach is complementary to conventional ground tests and numerical simulations to mature technologies or configurations affecting the aircraft dynamic behavior. After several years dedicated to theoretical studies related to scaling effects and the development of the Scaled Flight Demonstrator (SFD) - a dynamically scaled unmanned version of a known full-scale transport aircraft - the partners successfully carried out the Qualification Flight Tests in March-April 2022 in Deelen (NL) and Mission Flight Tests in October-November 2022 in Grottaglie (IT). This paper provides in a first part several details about this latter experimental campaign that required an important preparatory phase. The second part starts with a presentation of the parameter identification based on flight measurements that enabled a refinement of the demonstrator simulation tools. Subsequently, the section compares the SFD dynamic behavior against the one of the reference full-scale aircraft. With very little variations between the aircraft responses at both scales, the research activity concluded that the overall full scale aircraft behavior can be obtained accurately with a dynamically scaled model. This positive conclusion of the flight tests together with the various high-fidelity numerical simulations enabled Scaled Flight Testing to reach TRL 5 in January 2023.

Keywords: Scaled Flight Testing, Scaled Flight Demonstrator, SFD, Froude, Flight tests, Clean Sky 2

1. Introduction

In order to achieve carbon neutrality in the aviation sector by 2050, industry professionals, research centers, and universities are currently exploring various innovative and disruptive technologies. To mature these new solutions, design teams are relying on high-fidelity simulation codes and ground tests, such as in wind tunnels. However, for certain technologies such as distributed propulsion or disruptive configurations (flying wing) that have a significant impact on the dynamic behavior of the aircraft, the available tools are characterized by some limitations generating uncertainty in the design phase. One possible option to reduce the uncertainty and progress on the technology maturation is the use of scaled models. Largely used in the United States with well-known examples such as the X-48B [1], the approach has been recently detailed in [2] with a recall of past projects. To this review, one must add the important initiative carried out thanks to the European Clean Aviation program in the Large Passenger Aircraft platform between 2016 and 2022. With the objective of validating the Scaled Flight Testing approach, Airbus requested to assess the possibility of reproducing the dynamic behavior of a reference transport aircraft with a flying model respecting Froude similarity. In order to benefit from the NACRE project experience [3][4], a consortium of research centers and industry has been set up. It includes ONERA (coordinator and in charge of the transposition analysis), NLR (designer and operator of the SFD, qualification flight test lead), CIRA (advanced control system and mission flight test lead) and Airbus (providing requirements as customer of the new capability).

As detailed in [5], the activity is decomposed into a theoretical stream to understand the impact of scaling on the flight vehicle dynamic behavior and an experimental work with the design and flight test of the Scaled Flight Demonstrator (also called D03). The combination of the knowledge acquired through these 2 steps validates the Scaled Flight Testing approach. After several years of development, integration, and testing, the SFD, a 140 kg, 4-meter wingspan remotely piloted drone, completed 6 qualification flights in Deelen (NL) in March-April 2022. The results of this experimental campaign are detailed in [2]. This paper also describes the required activity on the control system to enable the subsequent mission flight tests. Indeed, for these flights dedicated to accurate data acquisition automated and repeatable maneuvers are mandatory. Such quality in the parameter identification process is needed to validate the Scaled Flight Testing approach. With the full system ready for Mission Flights, CIRA and NLR deployed the Scaled Flight Demonstrator and all associated subsystems in Grottaglie (IT). After an initial set-up phase, the experimental team completed 19 flights dedicated to data acquisition between the 17th and the 31st of October 2022. Through these flights, it has been possible to gather 8 hours of flight data and about 70 automated maneuvers have been executed. The objective of this paper is then to provide more details about these Mission Flight tests and to present the results of the experimental data analysis. Figure 1 illustrates the pilot view during one of the Mission Flight Test in Italy with the SFD.

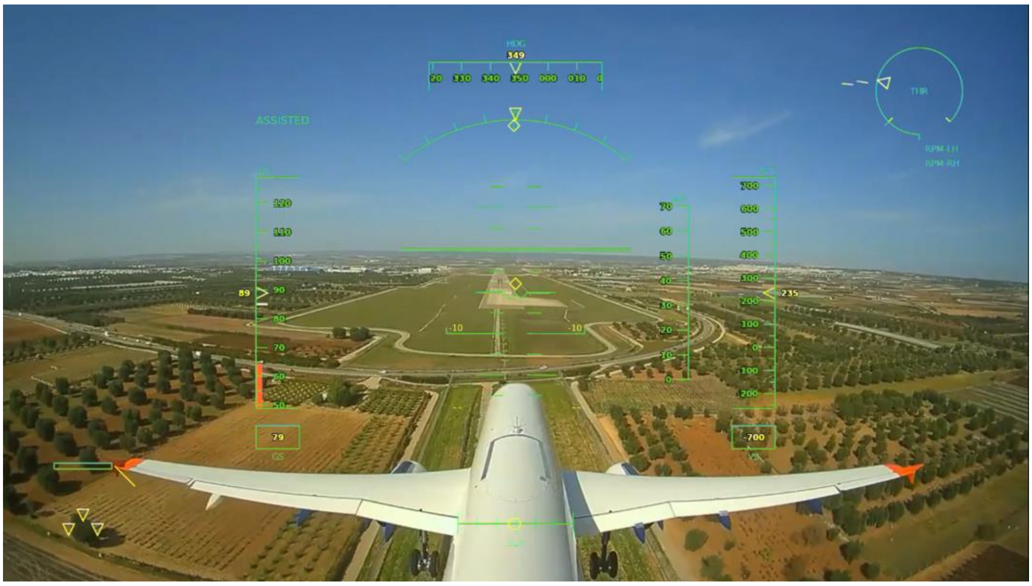

Figure 1 : Pilot view during the final approach at Grottaglie Airport

2. Mission Flight Tests at Grottaglie

2.1 Preparation

Prior to the flight tests, there were two main obligations to be fulfilled by the operational team: to obtain the flight authorization from ENAC (Ente Nazionale dell'Aviazione Civile), the Italian airworthiness authority and to organize operations of an unmanned flight vehicle on the civil airport of Grottaglie.

About flight operations, CIRA and NLR identified the process to follow during the preparatory phase: EASA regulation 2019/947. Then, because of its demonstrator status, one must take into account the fact that the SFD is classified as operating in the "Specific" category that features increased risk. Also, NLR cannot be registered in Italy to fly the SFD as it is already registered in the Netherlands as Unmanned Aerial System (UAS) Operator. Ensuing iterations between CIRA, NLR, ENAC and ILT (Civil Aviation Authority of the Netherlands), it is decided to apply Article 13 of the regulation entitled "Cross Borders Operations or operations outside the state of registration". One important element favoring this approach is that NLR already received the Operative Authorization (OA) granted by the Netherlands Civil Aviation Authority for the qualification flight test campaign. The next step consisted then in providing the required supporting documentation to enable flights in Italy: the Operational plan proving similar test activities and the same SAIL (Specific Assurance and Integrity Level) for the Mission Flight Test campaign and the report about system changes. Considering the information provided by Grottaglie Airport and the possible flight zone (R315 in Figure 2), the operational team decided initially to have the possibility to fly around the town of Monteiasi in case wind coming from from South to maximize the flight slots. However, ENAC issued concerns with flight path around Monteiasi town as the proposed flight operations were not consistent with the NLD-Operative Authorization safety levels. As shown in Figure 2, the route was indeed too close to the Monteiasi town with potential assemblies of people.

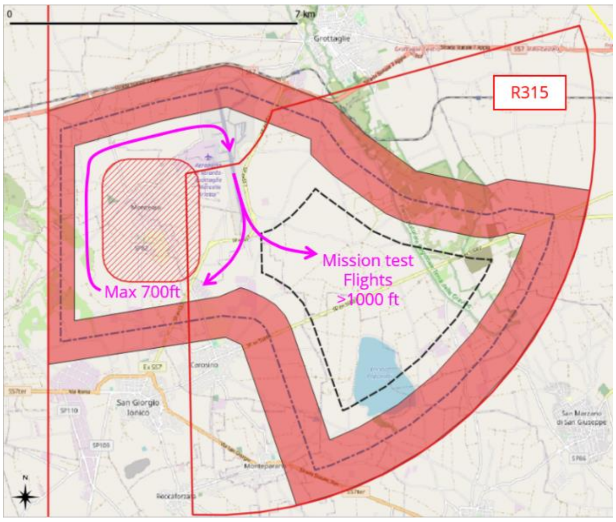

Figure 2: Possible flight path around Monteiasi in case of wind from South

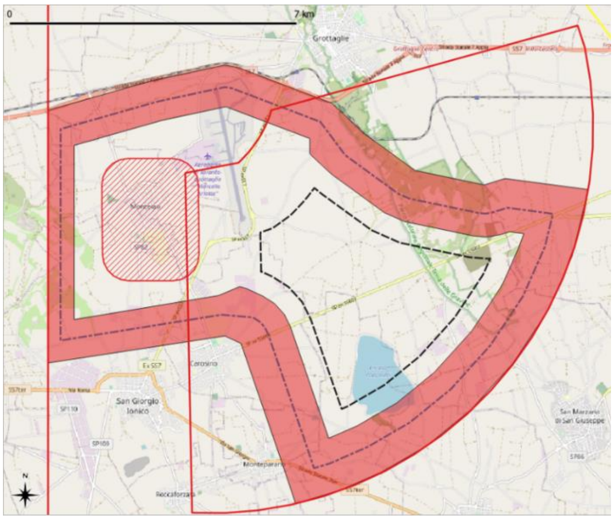

Figure 3: Regular flight path that remains within R315

Considering this input potentially blocking the Operational Authorization (OA) delivery and the additional request to be made to fly outside Area R315, the consortium decided to move away from the original plan and kept a single flight path validated by ENAC (Figure 3). With a clear impact on the overall experimental campaign efficiency, this choice has been made to reduce the project planning and uncertainties. With a consolidated application, the consortium made a formal request submitted to ENAC to get the confirmation that the OA obtained in the Netherlands is applicable to carry out the mission flight tests in Italy. On 23rd of September 2022, the consortium received the ENAC confirmation.

Concerning the organization of SFD flights in Grottaglie at Aeroporti di Puglia (AdP), several points had to be addressed. Indeed, the deployment of an unmanned flight vehicle and the associated operational team in a civil airport generates many constraints. First, all logistic and operational requirements had to be provided within a dedicated document (150 pages) subsequently added to the insurance contract. Then, dedicated contracts regarding any damages to the airport infrastructures caused by either people and/or the aircraft as well as specific contracts related to personnel injuries as prescribed by Public Safety Laws has to be agreed. Within the consortium, CIRA (as responsible for the Mission Flight Test campaign) managed these contractual aspects and acted as the interface between AdP and NLR, the SFD operator. In addition, as civil flights are taking place at AdP, the SFD operational team had to follow training courses about safety and security in order to get the mandatory airport passes to access the area. Specific driving licenses had to be also delivered so that personnel could rapidly move within the airport and the SFD could be moved to the Ground Control Station (GCS) location for pre-flight checks. Indeed, as it can be seen in Figure 4, the Hangar housing the operational team is located 1.4 km from the GCS location identified as “C”. This position is the result of many iterations between CIRA, NLR and AdP considering limitations associated to military operations, the possible blocking of the radio line-of-sight for all flight options and finally the flight restrictions associated to delivery of the OA.

With the conclusion of this lengthy preparatory phase, the consortium was ready to start the operations at Grottaglie Airport to be detailed in the next section.

Figure 4: Overview of Airport runway with an indication of the Hangar and the GCS location

2.2 Operations

The Qualification Flight Tests flown in Q2 2022 enabled the validation of the complete SFD system including the basic autopilot and the remote piloting from the GCS. In Grottaglie, the goal was to perform all flight maneuvers required to demonstrate the possibility to reproduce the dynamic behavior of the full scale reference aircraft with the scaled vehicle. To this end, one key change on the SFD between the Qualifications Flight Test and the Mission Flight Tests is the addition of the on-board Guidance, Navigation and Control (GNC) system developed by CIRA. Taking into account these elements, the Mission Flight Test campaign planned different sets of flights to achieve the acquisition of flight data to validate the Scaled Flight Testing approach:

1) Initial flight after reassembly and test of the complete system in Grottaglie

   The objective is to ensure that the complete system is functional and that the pilot feels comfortable in proceeding with the flights.

2) Area checkout

   These flights are necessary to build up confidence on the system within the AdP environment and the landing phase.

3) GNC tests

   During these flights, the GNC / pilot handover is tested and the first analyses of the SFD behavior are carried out.

4) Position Error Correction

   In order to make an accurate post flight analysis of the SFD behavior and comparison with the full scale aircraft, a flight is dedicated to the verification and improvement of the Air Data System calibration. Indeed, the static pressure measurement is very delicate and additional corrections are needed because the error depends on various parameters (Angle of Attack, Angle of Sideslip, Airspeed, …).

5) Autopilot tuning

   This series of flights is dedicated to the fine tuning of the GNC in order to enable automated and repeatable SFD maneuvers for an accurate parameter identification.

6) Automated maneuvers for parameter identification

   These flights are core of the Mission Flight Tests. Specific inputs are given to the Control Surfaces (C/S) of the SFD so that dynamic responses can be observed and measured. The subsequent analysis of the data allows a parameter identification and the comparison of the dynamic behavior for different scales. In Table 1, typical inputs commanded to the control surfaces are detailed (before flights, indications are given about the necessary deflections - excursion and duration - as well as the duration of the free response to be observed)

Table 1: Typical automated maneuvers

c/s	input	Comment
elevator	1-1	SPO difficult to monitor due to its large damping - watch n_z
elevator	*2-1-1*	*alternatively: larger response but also shifted pitch angle*
HTP	1-1	similar to previous, check HTP bandwidth
ailerons	3-2-1-1	Roll mode and aileron efficiency assessed during input
rudder	1-1	DR around level flight, but large side-slip excursions
rudder	2-1-1	lower side-slip excursion; final phi angle ~10° (spiral stability)

On the airport, the operational team operates in the 2 areas pointed out in Figure 4. First, there is the hangar where the SFD assembly and maintenance takes place (see the lower photo in Figure 5). Then, there is the GCS platform area where CIRA and NLR teams prepare each flight with a pilot briefing and pre-flight checks (see the upper photo in Figure 5). Naturally, the operational team has to interact regularly with the airport environment several times a day. During the experimental campaign, CIRA exchanges with AdP in order to activate the R315 segregated area, activate the NOTAM (Notice To Air Mission) and plan the timeslots for SFD flights considering military and civil traffic. In addition, the SFD activity has to be coordinated with Air Traffic Control personnel to ensure safest operations as possible.

Figure 5: Photos of the SFD ready for operations on the GCS platform area (top) and in the hangar for maintenance operations (bottom)

For each flight, in order to enhance efficiency and safety, members of the operational team have been assigned to specific roles and positions (inside or outside the GCS). Figure 6 shows the organization within the GCS during the Mission Flight Tests. Starting on the bottom left in the first picture, one can see the Navigation Supervisor, one experiment specialist dedicated to the Flight Test Instrumentation, one experiment specialist for the GCS and the flight test leader / pilot monitoring. Next to him, the pilot is seating on a tailored cockpit like environment with several screens enabling a quick overview of the SFD behavior (right picture in Figure 6). In addition to these persons, the flight safety officer, the flight test director and 2 experiment specialists are following the flight outside the GCS.

Figure 6 : View of the Ground Remote Pilot Station including the pilot cockpit (right) during operations

The SFD scaled is exactly 1/8.5 with respect to the reference aircraft. This difference in size (and flight domain) automatically brings the scientific question about the dynamic similarities between the two scales that this project aims at answering. However, from an operational point of view, the small scale generated an unforeseen issue that delayed the entire flight campaign. In fact, given the geometric scaling, the air inlet of the engine ended up being just a few centimeters above the runway pavement. This result in several Foreign Object Damages (FOD) on the turbomachines that needed to be send to the supplier for urgent repair. In Figure 7, the picture on the left shows how the dust that has been ingested during taxiing on the runway generated a friction between the blades and the internal surface of the engine inlet. This resulted in degraded performances on the propulsion system that at some point during the campaign forced the pilot to decide to abort the mission and to land as soon as possible. In the central picture of Figure 7, another damage can be seen: this time, an object located on the runway simply tore a blade causing one more time an important degradation of the aircraft performance.

Figure 7: FOD on the SFD engines (left and middle) and operational solution to mitigate the risk (right)

Without surprise, these issues caused a certain delay in the campaign as the engines needed to be changed, iterations between the engine manufacturer and the on-site engine specialist were necessary and ground tests of the updated SFD were mandatory. Besides, even if spare engines were available, the team ensured additional supplies to avoid discontinuity in the operations. In the end, after assessing the available information, the FOD risk has been associated to the SFD taxiing from the GCS position area to the takeoff starting position. Thus, to minimize this risk, the flight test team decided to replace these taxiing phases with a transportation of the SFD on a cart behind a car (right picture in Figure 7). This solution improved greatly the engine status and enabled an increase of the number of flights per day as there was more confidence in the propulsion system (as well as ramp up in the learning curve on operations with the SFD). At the end of the Mission Flight Tests, 3 flights per days were achieved showing a valuable level of data production for the Scaled Flight

Testing approach. Overall, the SFD operational team completed 19 flights for a total of 8 flight hours. The 6 last flights dedicated to data acquisition for validation purpose enabled to record a large set of dynamic responses based on about 70 automated maneuvers. Table 2 provides a complete list of the flights that took place in Grottaglie. In Appendix 1, this paper shows the SFD trajectory for the necessary initial flights. In Appendix 2, the trajectories of the Mission Flight Tests are presented.

Table 2: List of the Mission Flight Tests carried out at Grottaglie

Flight	Date	Purpose	Events	Time	GA	#Land	Wind		X-wnd
1	17-Oct	First flight	Darkness	0:22	2	1	030	6	4.2
2	18-Oct	Area checkout	Engine 1 problem	0:22	0	1	010	10	4.1
3	19-Oct	Area checkout	-	0:27	1	2	360	9	2.2
4	20-Oct	GNC checkout	Upset / flap problem	0:32	0	1	030	11	7.6
5	24-Oct	GNC checkout	-	0:27	0	1	200	4	2.2
6	24-Oct	PEC	-	0:24	0	1	220	4	3.2
7	25-Oct	1st buildup	Engine 2 problem	0:18	0	1	240	4	3.8
8	26-Oct	1st buildup	-	0:26	0	1	020	7	3.9
9	26-Oct	1st buildup	Link issues	0:25	0	1	350	9	0.6
10	28-Oct	3rd buildup	GNC maneuvers	0:27	0	1	350	9	0.6
11	28-Oct	3rd buildup	-	0:25	0	1	350	6	0.4
12	29-Oct	4th buildup	-	0:31	0	1	040	9	7.3
13	29-Oct	5th buildup	-	0:27	0	1	020	9	5.0
14	30-Oct	1st mission test	-	0:27	0	1	VAR	3	0.0
15	30-Oct	2nd mission test	-	0:27	0	1	340	7	0.7
16	30-Oct	3rd mission test	-	0:18	0	1	330	3	0.8
17	31-Oct	4th mission test	-	0:25	0	1	VAR	1	0.0
18	31-Oct	5th mission test	-	0:26	0	1	020	9	5.0
19	31-Oct	final mission test	-	0:27	0	1	340	4	0.4
				8:03		**20**			

3. Flight Tests Results

For the flight data analysis, it has been agreed during the project to have the recorded measurements packaged into Matlab files. Each measurement is fitted into a structure comprising the time basis, the corresponding data, plus relevant information such as names and units. The number of recorded variables is over 165 and the delivery for one single flight has a size of about 100 MB. After each flight, flight data has been transmitted by NLR to the partners for a preliminary assessment. For the final study of the SFD characteristics and the comparison of its dynamic behavior with respect to a reference aircraft the team decided to rely on a corrected database. Changes are associated to air data calibration, corrections to inertial data, slight rephasings for the various time bases and some data have been properly trimmed and re-interpolated with a common 100 Hz sampling base. In the next sections presenting the flight test results, only this corrected base has been used.

3.1 Parameter identification and simulation improvements

Specific identification tools have been developed for parameter identification. The classical identification methodologies include:

- Output error (minimizing the error between time evolutions of flight and simulated parameter);
- Equation error (minimizing the error between aerodynamic coefficients reconstructed from flight, and the corresponding outputs of the aerodynamic model calculated with the varying flight parameters);
- Filter error (minimizing the error between flight and a simulation kept close to the reference thanks to a Kalman filter).

As ONERA has a simulation model, the output error is the most direct method. However it requires the initial simulations not to be too far from the flight trajectories for the optimization algorithm to converge efficiently. On the other hand, equation error is quite efficient on non-linear aerodynamic models, thanks to its ability to discriminate very fine effects. However, it usually requires pre-processing the flight data, in order to get very good coherence (especially in time). Accurate models for MCI (Mass, Centering and Inertia) and thrust are also needed for inverting flight mechanics equations and get the time history of aerodynamic coefficients. Filter error methods strive to benefit from both previous methods with proper settings of the Kalman filter.

With preliminary comparisons showing that the simulated trajectories did not depart too much from flight data (after setting proper offsets), the output error method was judged as the most suitable to be implemented. Another argument is the requirement to get the right dynamic behavior from the identified model, which is precisely what output error is good at. Relying on the non-linear aerodynamic model proposed by NLR after the wind tunnel tests, additive linear aerodynamic coefficients are superimposed. It means that the identification process tries to correct linearly the non-linear model around the flight condition selected for the test campaign. All the classical linear aerodynamic coefficients can be selected for identification. The principal coefficients are the angular rate effects, the Control Surface deflection effects and the main angles of attack and sideslip effects. The effects on moments are of prime importance for the dynamic behaviour while effects on forces are both less important, and better modeled after the Wind Tunnel Tests.

The algorithm implemented is similar to what ONERA has been using for years, and transferred to Airbus in various identification tools. It relies on a Gauss-Newton optimization algorithm, with possible regularization (Levenberg-Marquardt). The criterion is quadratic, based on the differences between simulation and flight for selected variables (with user-defined ponderations). The process performs finite differences on the identified variables, so as to calculate the criterion gradient and the approximate Hessian. The identification process assembles several maneuvers in the same run. Simulations are usually done with restricted degrees of freedom: typically, only the lateral or the longitudinal dynamics are free, depending on the variables to identify.

<u>Lateral maneuvers</u>

The most noticeable discrepancy between flight tests and simulation appears in the free response following rudder inputs: the Dutch roll mode (see Figure 8). This mode is more dampened in simulations, which may be attributed mostly to ill-fitted angular effects (knowing that those effects were only modeled through Computational Fluid Dynamics simulations, not Wind Tunnel Tests).

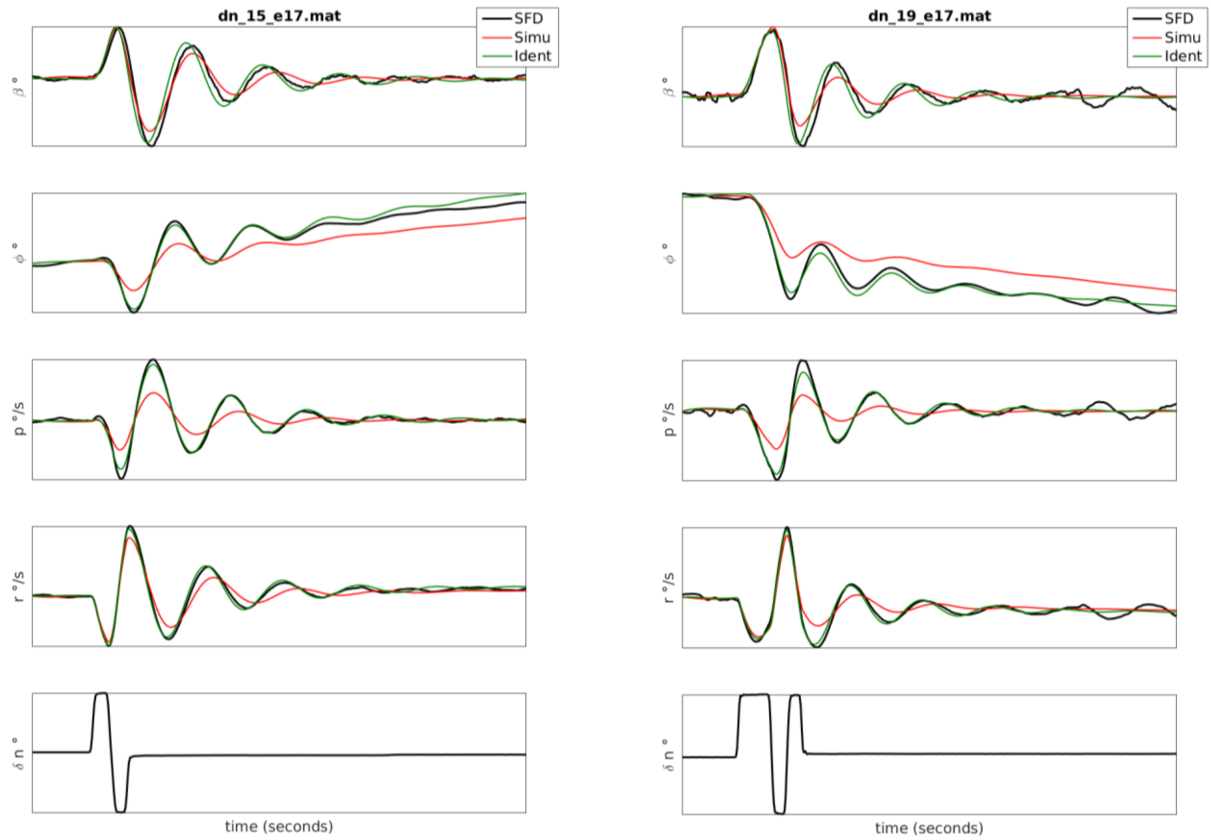

Figure 8: SFD responses to rudder inputs (Simulation, Flight Tests, Corrected simulations after parameter identification)

Another difference appears in aileron efficiencies, as visible in aileron input maneuvers illustrated in Figure 9.

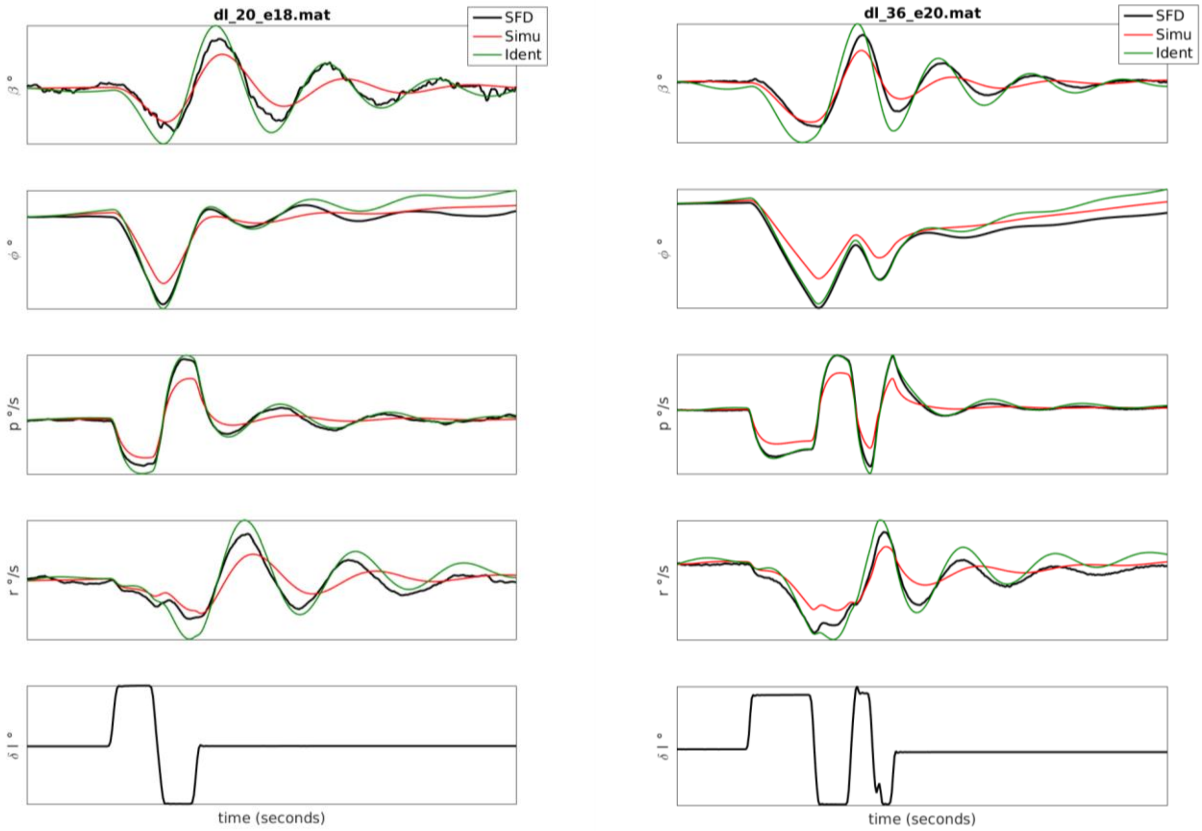

Figure 9: SFD responses to aileron inputs (Simulation, Flight Tests, Corrected simulations after parameter identification

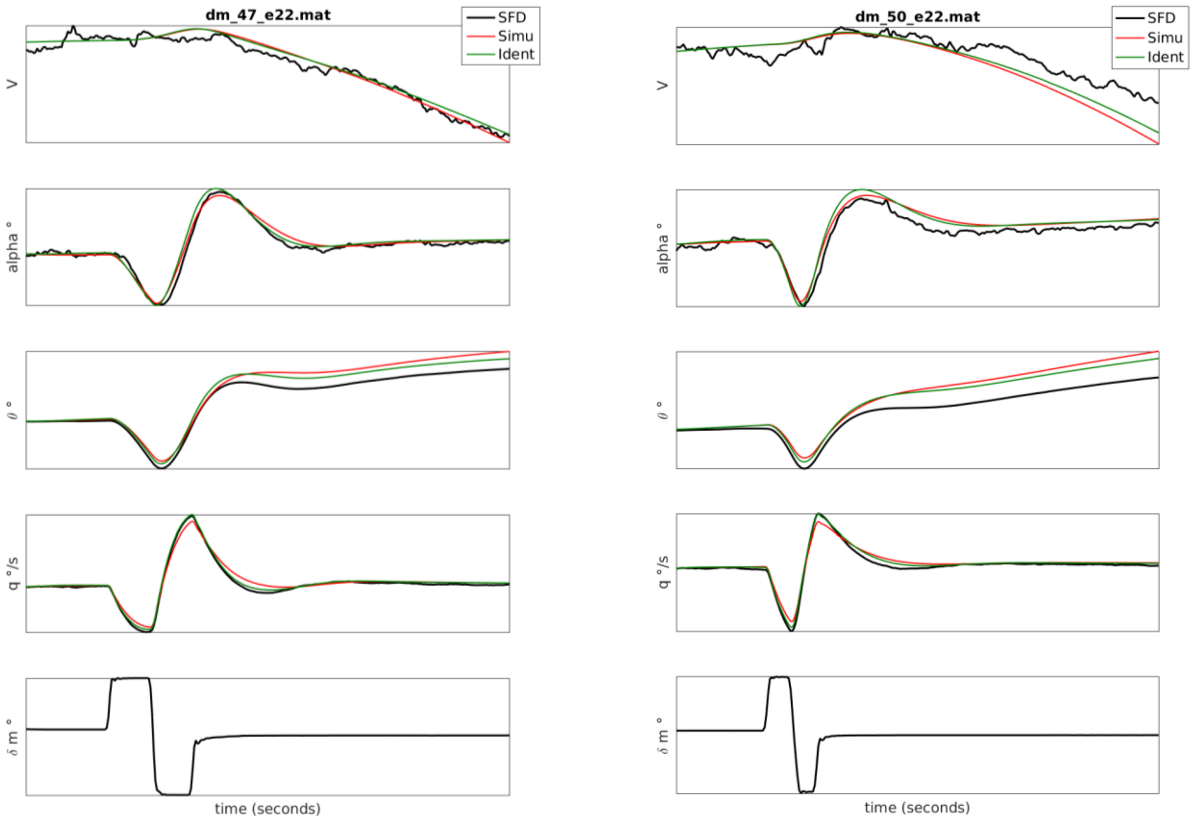

Figure 10: SFD responses to elevator inputs (Simulation, Flight Tests, Corrected simulations after parameter identification

Finally, lateral coefficient and rudder effect identification was conducted using all rudder maneuvers in a single process. To ease the optimization, two biases per maneuver were added, acting on roll and yaw coefficients. The longitudinal motion is kept on the flight parameter: only the lateral equations are integrated during the simulation (4 DOFs). In a second step, aileron efficiencies have been tuned on the corresponding maneuvers. At the end, the angular rate effects have been reduced, while aileron and efficiencies have been increades. The resulting corrections have been implemented in the simulator.

Longitudinal maneuvers

The longitudinal maneuvers are well restituted without tuning as shown in Figure 10. The identification has been performed following the approach in order to enhance the fitting to flight data. The identification has been restricted to the pitching moment equation, focusing on the Short Period Oscillation and elevator inputs. Biases per maneuvers have also been introduced. Classically also, the simulation was limited to longitudinal dynamics considering pitch rate, pitch angle and angle of attack (3 DOFs) excluding velocity. Holding velocity and altitude allows to address specifically what comes from the longitudinal aerodynamic model, without side effects from possibly inaccurate propulsion equation. The selected maneuvers to be taken into account are all associated to elevator inputs. In this case, control efficiency and pitch damping coefficient have been increased.The additive corrections on the identified longitudinal coefficients are subsequently integrated in the SFD simulation code.

3.2 Comparison between the SFD and the reference full-scale aircraft dynamic behavior

As stated in the initial paragraph, the goal of the Clean Sky 2 activity is to validate the Scaled Flight Testing approach. The key step towards this objective is the comparison of the time evolutions of D03 with the ones of the reference full-scale aircraft. Regarding this vehicle, the data to be used as reference are generated by OSMA, the Airbus' simulation tool (6 Degrees of Freedom) that has been fine tuned based on flight data. For an evaluation against the SFD dynamic responses, the OSMA outputs have been scaled down according to Froude. The systematic comparison was performed, taking into account every elevator, rudder and aileron maneuvers carried out during the Mission Flight Tests. It must be noted that this direct comparison of the dynamic responses for both the SFD and the reference aircraft was possible only since: maneuvers are not too long, the aircraft has sufficient stability, initial trim is good and the simulation model is close to actual aircraft.

Elevator inputs

The elevator inputs are meant to characterize longitudinal stability and elevator efficiency. Longitudinal stability is directly related to the frequency and damping of the SPO mode. As determined within the project, the database comprises 21 elevator inputs: doublets of various amplitudes and durations, plus repetitions. The doublets were performed nose-down first in order to keep a comfortable margin from stall. In the left plot of Figure 20, it is possible to observe the small difference between the SFD behavior in flight (black curve) and the corresponding simulation for the reference aircraft (blue curve) given the same input sequence on the elevator.

Rudder inputs

Rudder inputs are meant to characterize lateral stability and rudder efficiency. Lateral stability is directly related to the frequency and damping of the Dutch roll mode. The database holds 16 rudder inputs: doublets and 2-1-1 inputs of various amplitudes and durations plus repetitions. In the central plot of Figure 20, the reference aircraft response as well as the SFD flight behavior associated to a rudder doublet is shown. The time responses are analyzed via yaw-rate (the axis on which rudder acts directly), sideslip angle and roll-rate in order to visualize the classical Dutch roll dynamics. There again, the comparison between SFD and OSMA is quite good: the dampings are very similar even though the periods are slightly shorter in flight data (the camera on the tail might possibly account for a little more lateral stability). Also, the amplitudes calculated by OSMA are slightly larger: this could be explained by more rudder efficiency, and possibly a larger coupling by dihedral effect.

Aileron inputs

In aileron input maneuvers, free responses are not the principal interest, contrary to rudder inputs. For this reason, they were set shorter. The main point of these maneuvers is to characterize roll dynamics and aileron efficiency, while getting extra data on the yaw / roll coupling. The database comprises 16 aileron inputs: doublets, 2-1-1 and 3-2-1-1 inputs of various amplitudes and durations, plus repetitions. The right plot of Figure 11 details both SFD and reference aircraft responses given a 3-2-1-1 input command. In this case, aileron efficiency is to be sought primarily on roll-rate time response (p) and consequently on the roll angle (Φ). From the plot, it appears that roll efficiency is higher on SFD than what is predicted by OSMA but the overall response is well reproduced.

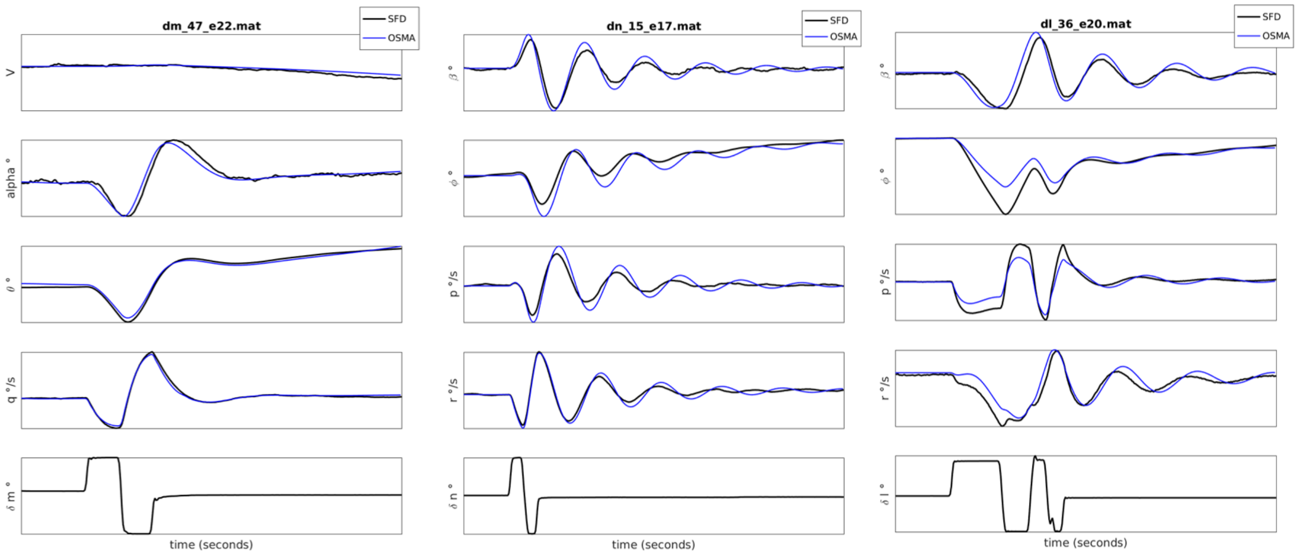

Figure 11 : Comparison between the SFD and reference aircraft responses (left: elevator inputs – center: rudder inputs – right: aileron inputs)

Overall, the comparison between SFD flight measurement and properly scaled OSMA simulations shows that their dynamic behaviors are quite close, both as regards longitudinal and lateral modal characteristics, and control efficiencies. The most significant differences are found in aileron input maneuvers, the SFD demonstrating higher-than-expected control efficiency. Interestingly, the similarity between scaled demonstrator and reference aircraft was found even better that what was anticipated based on the simulation model. This very good agreement is a strong argument in favor of the representativity of scaled demonstrators, at least in the conditions that has been verified in the project, i.e. within same parts of the flight domain.

4. Conclusion and next steps

In order to reach the stringent objectives towards a decarbonized civil aviation, industry is exploring new technologies and new configurations. For promising solutions that affect the dynamic behavior of the airplane, Scaled Flight Testing is considered a new capability complementary to ground testing and simulations. Through a complete demonstration including flight tests with the Scaled Flight Demonstrator that is representative of an existing reference aircraft, Airbus, CIRA, NLR and ONERA demonstrated that the overall full scale aircraft behavior can be obtained with a dynamically scaled model. During the project, Research Centers took into account industry requirements as early as possible so that the technical need would be matched. Besides, a theoretical analysis stream enabling the identification of the scaling effects has been carried out in parallel to the experimental phase for a thorough validation. Last, a stringent Verification and Validation process has been followed by the various entities with many reviews to minimize risk and maximize safety. Given the overall activity and results, Scaled Flight Testing successfully passed TRL 5 (Technology Readiness Level) in Q1 2023, as the approach proposed a high level of integration in relevant environment with a confirmation of the benefits. The quality of the work has been also emphasized by the EREA Best Paper Awards in 2023 [7].

A first example of a Scaled Flight Testing application already took place in Clean Sky 2 for the maturation of distributed electric propulsion. Identified by Airbus as a possible solution with benefits in terms of propulsive efficiency, induced drag reduction, and wing blowing, this architecture allows the distribution of sources in the case of using new onboard energies such as hydrogen (podded-configuration). Thus, to derisk this technology which has a strong impact on the aircraft's dynamics (differential propulsion, blowing effects), a modified version of the SFD has been developed to test the aircraft's responses to different combinations of solicitations has been developed. This new version called D08 should be considered as a flying demonstrator dedicated to the "Distributed Electric Propulsion" technology, while the SFD in its original version is a flying model based on Froude similarity. In Q2-Q3 2024, the demonstrator D08 successfully completed 27 flights generating thus and important dataset for technology maturation. Details of the specific technical activities are presented in [8] and [9].

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7. Copyright Statement

References

[1] J. R. Chambers, “Modeling Flight, The Role of Dynamically Scaled Free-Flight Models in Support of NASA’s Aerospace Programs”, NASA SP 2009-575, 2009

[2] A. Raju Kulkarni, G. La Rocca, L.L.M. Veldhuis, G. Eitelberg, “Sub-scale flight test model design: Developments, challenges and opportunities”, Progress in Aerospace Sciences, Volume 130, 2022,

[3] P. Schmollgruber, H. Jentink, M. Tuinstra, „IEP: A Mulidisciplinary Flying Testbed for New Aircraft Concepts”, 27th Congress of the International Council of the Aeronautical Sciences, Nice, France, 2010

[4] P. Schmollgruber *et al*., “An innovative evaluation platform for new aircraft concepts”, The Aeronautical Journal, 114(1157):451-456, 2010

[5] P.Schmollgruber, A. Lepage, F. Bremmers, H. Jentink, N. Genito, A. Rispoli, M. Huhnd, D. Meissner, “Towards validation of Scaled Flight Testing”, Aerospace Europe Conference 2020, Bordeaux, France, 2020

[6] P. Schmollgruber, C. Toussaint, A. Lepage, F. Bremmers, H. Jentink, L. Timmermans, N. Genito, A. Rispoli, D. Meissner, D. Kierbel, “Validation of Scaled Flight Testing”, 33rd Congress of the International Council of the Aeronautical Sciences, Stockholm, Sweden, 2022

[7] Website: https://erea.org/events/erea-annual-event-2023/

[8] H. Jentink, C. Döll, P. Iannelli, M. Hoogreef, D. Kierbel, “Scaled Flight Testing for evaluating distributed electric propulsion”, 34th Congress of the International Council of the Aeronautical Sciences, Florence, Italy, 2024.

[9] C. Döll, S. Waitman, “Control Allocation for a Distributed Electric Propulsion Aircraft using differential thrust”, 34th Congress of the International Council of the Aeronautical Sciences, Florence, Italy, 2024.

Appendix 1 – Overview of Mission Flight Tests (Initial Flights)

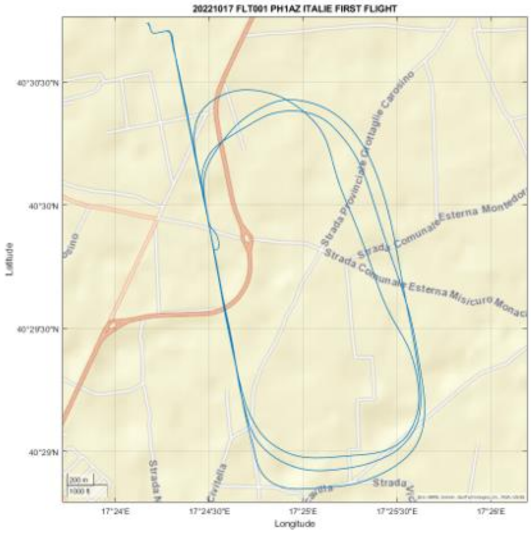

Figure 12: First flight in Grottaglie

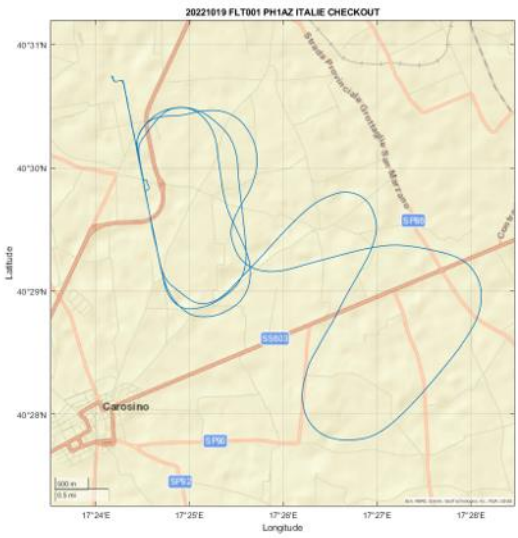

Figure 13: Area checkout

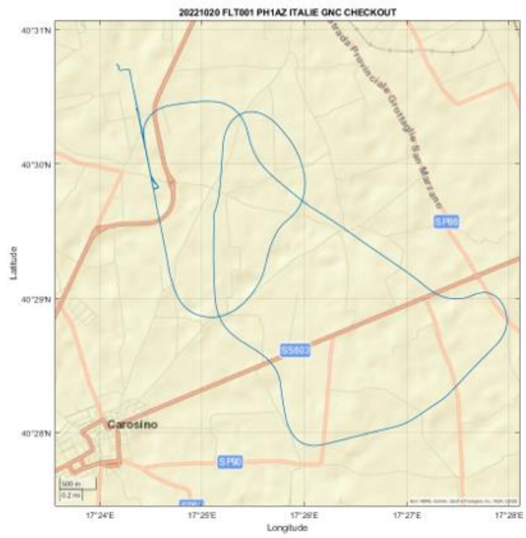

Figure 14: GNC check with upset

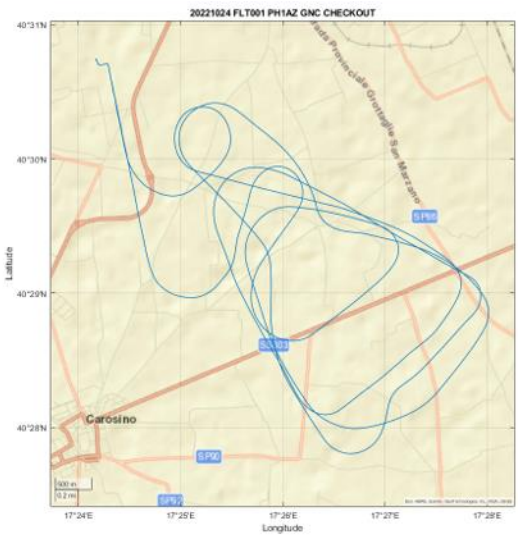

Figure 15: GNC Test 1

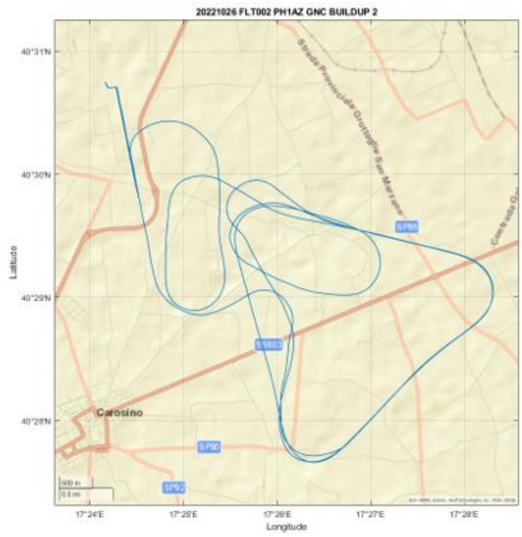

Figure 16: GNC Test 2

Appendix 2 – Overview of Mission Flight Tests (Mission Flights)

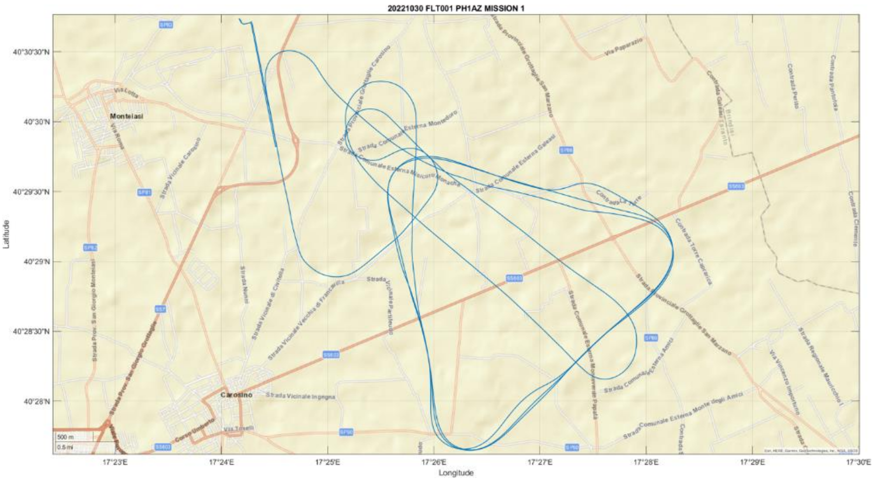

Figure 17: Flight path of Mission Flight n°1

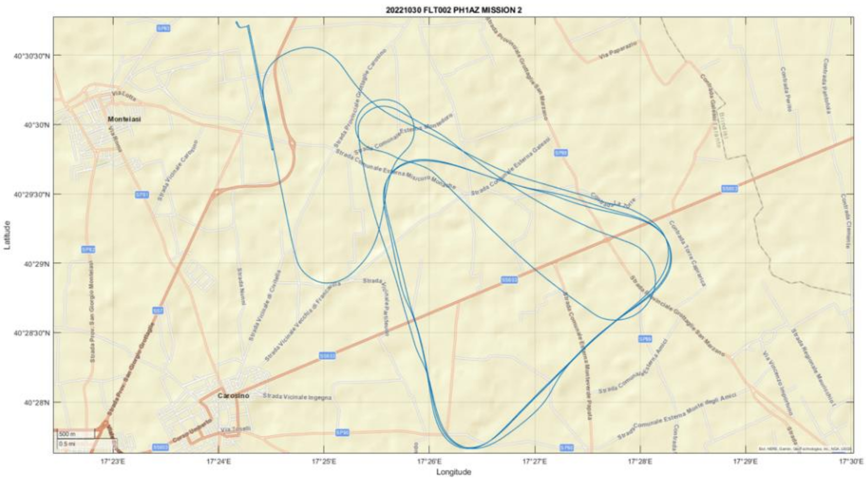

Figure 18: Flight path of Mission Flight n°2

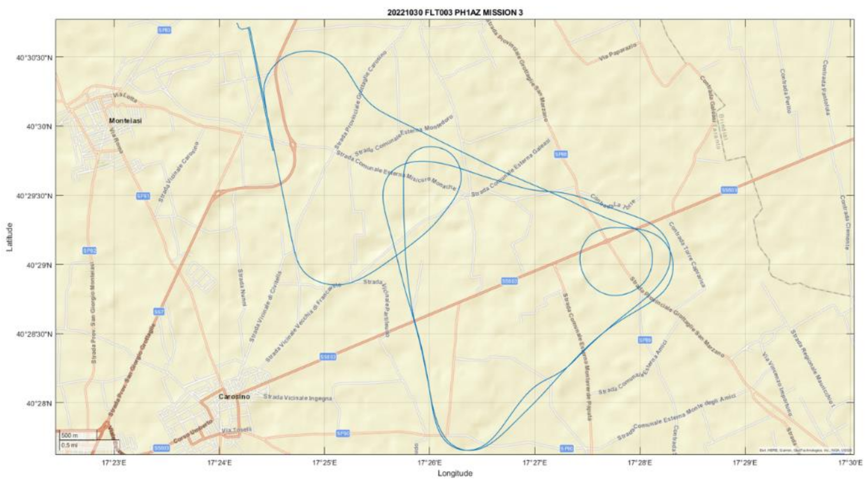

Figure 19: Flight path of Mission Flight n°2

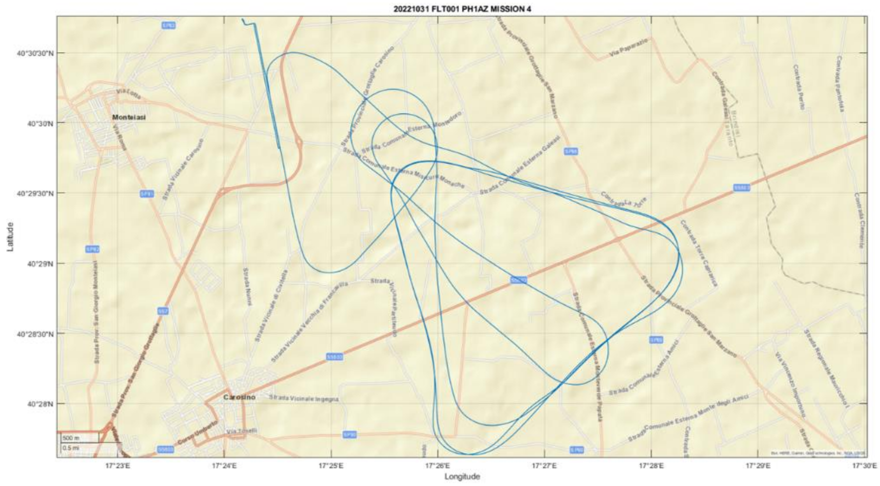

Figure 20: Flight path of Mission Flight n°4

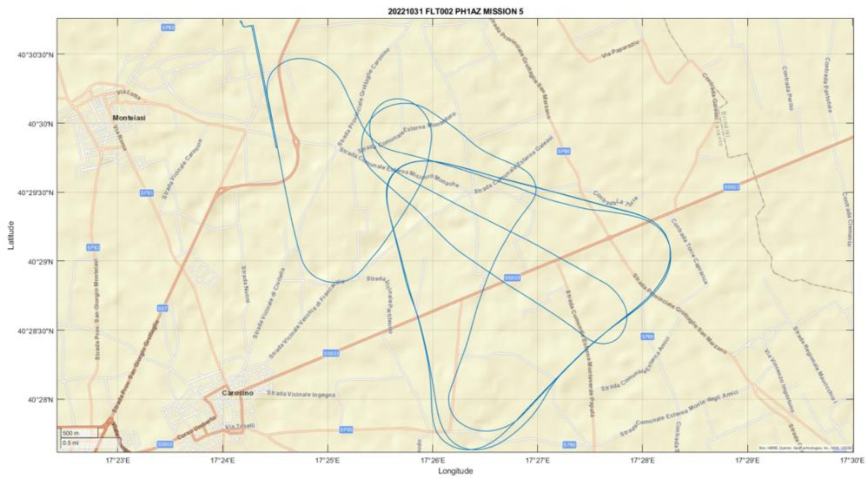

Figure 21: Flight path of Mission Flight n°5

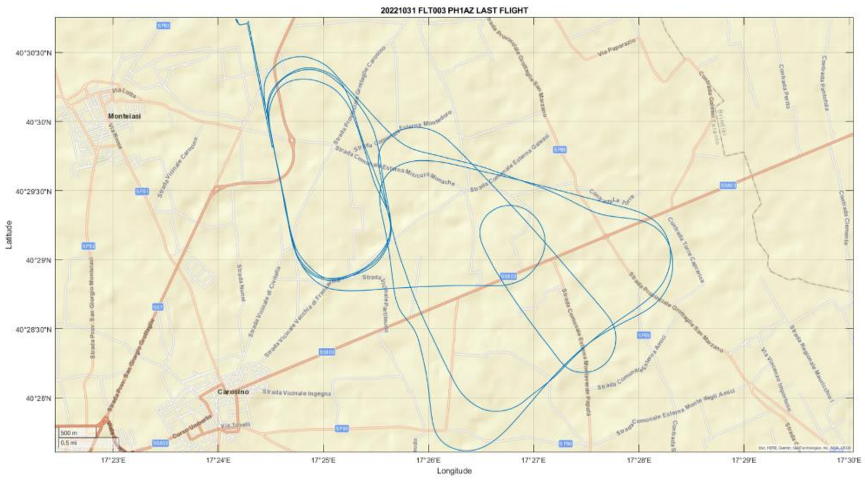

Figure 22: Flight path of Mission Flight n°6