Skydweller Flight Demonstrations of Autonomous Aircraft for Development of an Unmanned Solar-Powered Aircraft

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ABSTRACT

Skydweller implemented a rapid development approach and process to quickly integrate and test the systems and functions required to evolve the piloted Solar Impulse 2 (SI2) design into the Skydweller autonomous perpetual flight vehicle performed through the progressive implementation of hardware, software, and control architectures within a combined safety approach and flight test method that quickly matured the system from fully piloted to a demonstrated capability of autonomous mode change and 3-D waypoint navigation in-flight.

This paper describes the flight demonstrations of Skydweller's critical hardware and software components and aircraft control during a series of flight tests. Highlighting test methodology used, safety case construction, airworthiness strategy to obtain the Permit to Fly(s) and flight-testing methods the aircraft. Emphasis is placed on flight test processes, including pilot training, testing, mission management and data analysis. These accomplishments verified the preliminary capabilities of Skydweller's systems technology and its advanced weather and climate data analysis over 10 flights performed from April to November of 2021. These tests culminated in three hours of uninterrupted, fully autonomous, 3D navigation flight, including a synthetic approach test of the autonomous landing logic.

Skydweller Aero Inc. is a U.S.-Spanish aerospace company, developing solar powered aircraft solutions for defense and commercial industries. Leonardo is a minority shareholder and technological investor. The combined initiative will result in the development and deployment of the Skydweller aircraft, the world's first solar-powered, unmanned aircraft capable of carrying large payloads with unlimited range and ultra-persistent endurance.

1.0 BACKGROUND AND APPROACH

In 2019 Skydweller acquired the technology and hardware used in the most pioneering and longest continuous solar powered flight program to date, Solar Impulse 2 (SI2). The aircraft is a different scale than any other existing solar aircraft, featuring a design weight of 2550 kg, a wingspan of 72m, the capability to close the 24-hour solar cycle and the operational robustness to circumnavigate the world.

The proven platform and Skydweller's capabilities enable development of a multi-month autonomous system. Solar Impulse had a mechanical control chain, but it also featured a minimal servo actuated autopilot to allow the pilot to rest. Skydweller leveraged this architecture to develop a Safety Piloted Vehicle (SPV).

The SPV program validated critical components of the autonomous technology and operations in a development environment where criticality is reduced. This included validation of future safety critical subsystems such as: INS, Air Data System, Altimeters, Weight on Wheels, GNSS; and the Flight Control algorithms: flying qualities augmentation, autopilot functions, and waypoint navigation. At the same time, development of tools and processes for meteorological forecasts to inform flight operation procedures and develop the skills necessary to operate the aircraft autonomously.

Typical unmanned aircraft development needs to show all flight safety critical functions to be correct in the initial flight. This has huge effects on the development cycle to validate and verify the development, leading to extensive modelling, analysis, and testing. Even so, some aspects can only be validated in flight, so the design is focused on being robust to uncertainties.

The SPV approach simplifies the approach by reducing the scope and design assurance of the functions to be executed by the autonomous system. The pilot can perform any missing functions at a given time. The objective of early prototypes and design approach is to learn and confirm the solution approach and algorithm thus saving modelling, analysis, and testing scope and increasing the pace of development. Functionality becomes flight proven as available and the amount of hidden technical risk is minimized.

2.0 FLIGHT TEST OVERVIEW

Skydweller’s SPV flight test campaigns consisted of 10 flights, totaling an approximate 25 hours of flight, and 2 taxi tests conducted between April 2021 and November 2021 in *Los Llanos* airbase (LEAB), Albacete, Spain. Flight time progressively increased from the completion of a single pattern around the airfield to almost 5 hours of flight. Automatic flight capabilities progressed from specific spot checks to over 3 hours of total time flying in closed loop during the final SPV test flight. Operations were primarily conducted around dawn and dusk to optimize weather conditions.

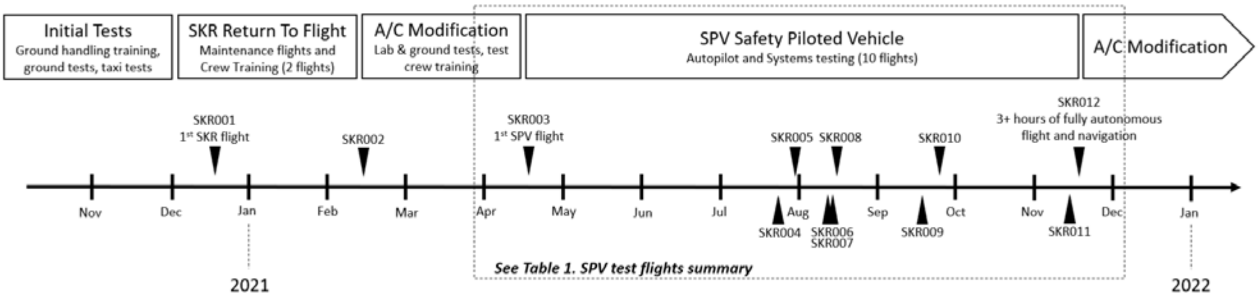

Figure 1. Flight test timeline.

Table 1. SPV test flights summary.

Flight	Description
SKR003	Successful autopilot engagement. Completed INS in-flight alignment.
SKR004	Pilot training. Timing issues found in the controller.
SKR005	Pilot training. Successful airspeed, vertical speed, roll, sideslip, and pitch control.
SKR006	Back-to-back flights. System identification maneuvers and disturbance rejection. Successful incorporation of new Air Data Boom into control laws.
SKR007	
SKR008	Autopilot envelope clearance to 26 kts. Initial track holding demonstration.
SKR009	Tested autopilot in different aircraft configurations. Began using autopilot for airspace management, increasing engagement time to 27 minutes.
SKR010	Waypoint navigation first prototype with accurate tracking. INS timing issues. Checked high wind protection logic. 113 minutes on closed loop.
SKR011	First flight with future onboard computer. Autopilot performance not satisfactory.
SKR012	Automatic flight down to minimum operational speed, maximum operational bank angle, with different airbrake and landing gear configurations. Successful waypoint navigation, synthetic approach, and take-off and landing logic shadowing. Over 3 hours of auto flight engagement, 80% Time on Condition

Flight test efficiency in time, effort and effectiveness were enhanced as the campaign progressed, owing to a set of essential factors:

Training and preparation philosophy to operate the system safely and effectively: This includes theoretical training on systems, table-top procedure review, on-aircraft systems familiarization, comprehensive simulator sessions, and low and high-speed taxi tests when required. The flight test and engineering team is closely integrated throughout development and testing to create a high level of aircraft and system proficiency early.

A safety approach to development: The pilot was given numerous ways for immediate autopilot disconnection or override, returning to the original, reversible mechanical control remaining within existing flight envelope.

The flight test and weather teams were coordinated: Accurate weather monitoring techniques and equipment allowed for improved airspace use and test card optimization before and during flight missions, as well as assured test crew rest times per requirements and operational availability at each weather opportunity.

Coordination and Monitoring from the Engineering Test Element: (ETE): containing the flight test team (Test Conductor, Test Director, Remote Command Operator) and Flight Test Support Engineers (FTSEs). Staffing and training allowed for FTSE redundancy. The ETE / aircraft infrastructure allows for comms and network engineers to gain additional access to increase the effectiveness of test flights through IP based debugging of systems and gathered information for further ETE improvement.

Autopilot testing was interleaved with manually piloted testing: This enabled envelope re-clearance post storage followed by (within minutes) autonomous flight control testing at each flight condition. Coordination of autopilot and manual testing maneuvers allowed for an efficient and adaptive flight test progression.

3.0 SAFETY CASE & AIRWORTHINESS

3.1 Safety Approach

The Skydweller safety strategy was identified prior to the start of the campaign and coordinated internally and externally. It defined three high level goals:

- Define impacted existing SI2 safety boundaries
- Identify potential safety risks of harm to people caused by implemented new functions and equipment.
- Demonstrate program safety risks achieve the safety criteria.

These objectives were used to identify acceptable failure condition probabilities, alert concepts, pilot training concepts and preflight testing required.

3.1.1 Flight Control & Engine Control Safety Schematics

Based on these objectives and the existing system design, safety boundaries were identified, and the updated systems architecture defined.

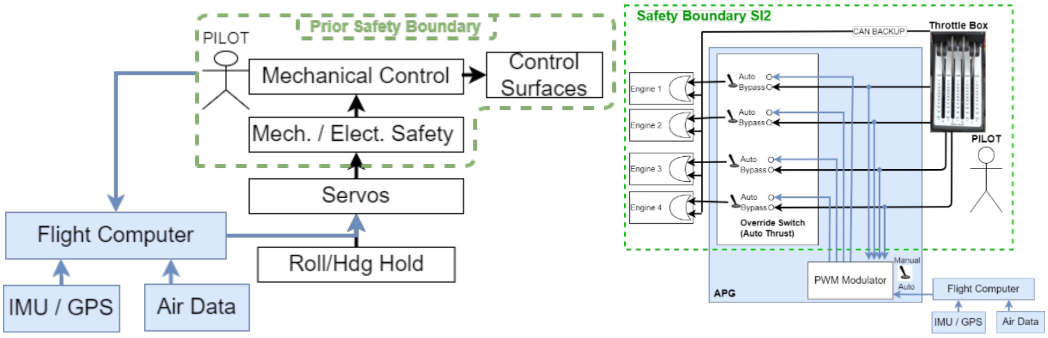

Figure 2 – Flight Control and Throttle Safety Boundaries

The Flight control boundaries were maintained, and the existing actuator command replaced with the flight computer output. The failure modes were similar to, and bounded by, existing failure analysis. The pilot had multiple independent methods for autopilot disconnection or mechanical override.

To control the throttle, an Auto-throttle Pulse Generator (APG) was custom created as a "man-in-the-middle" system. To mitigate possible failure modes, four independent bypass switches were used, and sense lines protected with dual redundant isolation resistors. Additionally, the existing CAN bus backup was not modified. This highly redundant configuration met the required failure condition safety objectives.

Based on the analysis above and below, all flight control software and other hardware was determined to be DAL-E. Skydweller applied higher internal development methods and processes to assure configuration and performance.

3.1.2 Pilot Response Requirement Analysis

Since full deflections of the surfaces may result in departure from controlled flight, the monitoring pilot response must be within reasonable human detection and reaction times. Assumed response time expected of a line pilot for autopilot failures, hardovers are elaborated from as high as 3s in cruise to “instantaneous” below 25m[1]. Skydweller pilots are highly trained/experienced and in a flight test environment; A minimum criteria of 1.5s was accepted within the safety case.

Dynamic simulations were performed to identify required detection + reaction time requirements to avoid unsafe attitudes or airspeeds. This analysis showed low sensitivity to actuator rate and easily accepted pilot reaction times of >6s in yaw and roll. The very low excess kinetic energy of the airframe in cruise flight results in lower required response times before aircraft stall (or overspeed) as shown in Figure 3 and assuming no actuator torque limits; all meet the criteria. The actuator torque limits resulted in deflection limitations between 4-6 degrees from trim providing additional reaction time.

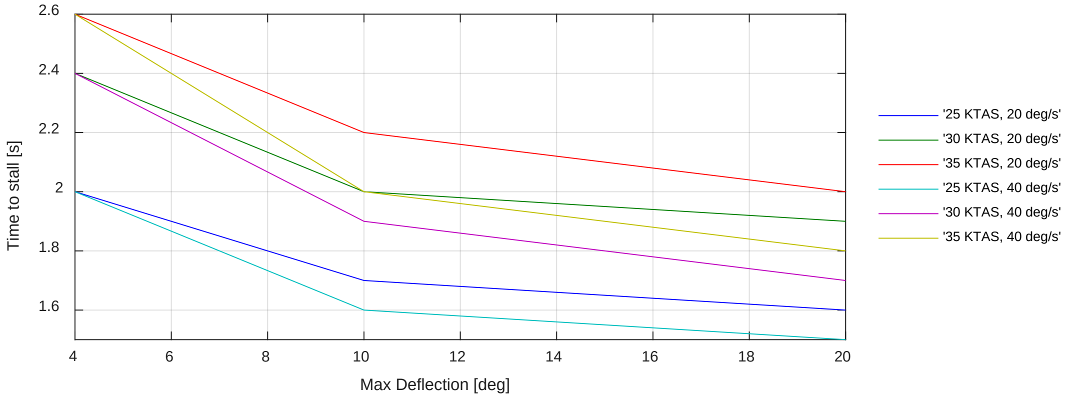

Figure 3 – Minimum Time to Stall at Sea-Level

3.2 Airworthiness Substantiation

Collaboration between Skydweller Airworthiness teams and the airworthiness authority agreed to system design philosophies, hardware features, safety criteria, test environment and test methods.

Based on analysis of the changes, safety case and architecture, and the relevant regulation criteria, the test flights were performed under three Permission to Fly approvals by AESA (Agencia Española de Seguridad Aérea, the Spanish Civil Certification Authority).

- PtF 1: Flight Sensors INS, GPS, ADS, Data Acquisition, Data Recorder, LOS Radio, Network, Altimeter, DC/DC, temporary QNX computer
- PtF 2: Comms upgrade, camera
- PtF 3: Port of SW to future flight computer, satcom upgrade

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[1] CFR 25, “CFR 25.1329 § 100.b.3.b & § 100.b.4 (3 seconds in cruise down to “instantaneous” detection below 25m), critical engine failures Appendix 1 to CRD 18/2006 § 14.2.1.3 (3s), and time delay to critical engine failures CS23 §23.147.(b) (2s)”.

Each PtF contained basis and artifacts from:

- Evaluation of severity of change and AW Authority
- Criteria where applicable taken from CS-23, and FAA AC 25.1239,
- Structural assessment based on inspections, wing limit load tests, Taxi-Vibration test
- Strength analysis justification and functional tests of mountings and wiring
- Environmental Assessment, Stress report, Safety Assessment against safety boundary
- APG Compliance criteria
- Functional Test Reports, EMI/EMC, configuration audits, maintenance record reviews

Test results and safety evidence were reviewed, and some tests witnessed. This coordination enabled an understanding and mitigation of risks before and during the test campaign.

4.0 WEATHER

Skydweller had a 12-hour "Deploy to Test Site" posture supporting deployment of all critical persons in a rested condition. Flight test opportunities were presented to the program using a probability matrix showing the window's viability evolution over time. This allowed effective management of resources and opportunities. For these 12 flights, the team deployed only 16 times: a clear demonstration of tool and process effectiveness at this early stage.

The weather team pursued multiple avenues to provide the best possible predictions and assessments of key weather challenges at the test site. The meteorology team leveraged an in-house risk indexing methodology and ensemble forecasting methods to understand certainty and better derive a chance of success.

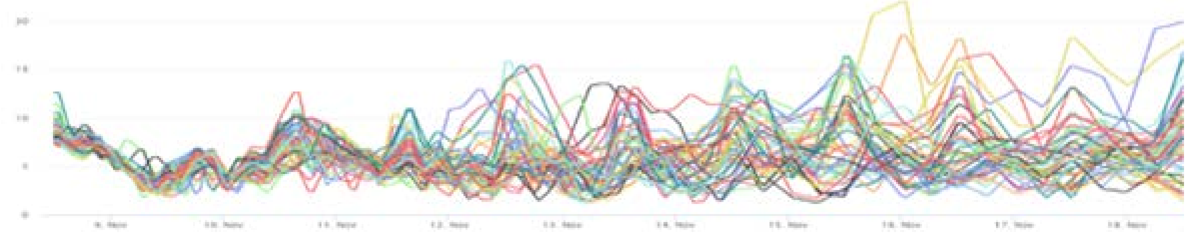


Figure 4 - Ensemble Wind Speed Gusts

Albacete comes under the influence of regional upper-level jets which impacted our flight test profiles. To view this feature over time and find potential windows which we could operate the following weather product was used to understand it's entry and exit from the region.

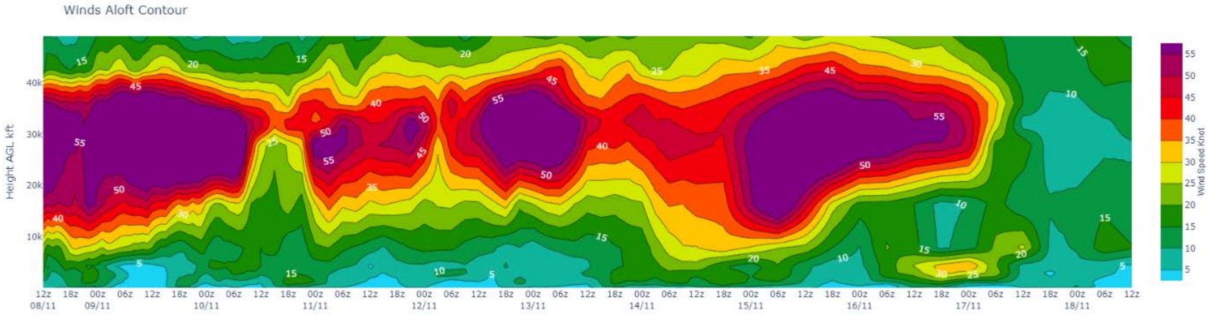


Figure 5 - Upper-Level Winds Contour Plot

The Albacete region is weather-data sparse and does not have a large initialization contribution to global models for surface data. To mitigate this, Skydweller provisioned a mesoscale model to resolve fine scale physics such as thermal cut in times and surface gusts. A radiosonde system was used to improve understanding of the levels above and model correlation.

The capability to predict and monitor planetary boundary layer height using the LiDAR system were critical to successful test flights minimizing our exposure and allowing flights to extend later into the mornings where models predictions were poor.

Lidar systems can be used to monitor boundary layer physics and scan for thermal strengths and frequency which is specific risk for the Skydweller platform. Skydweller received a Halo Photonics Streamline LiDAR system in March 2021 which was brought into service collaborating with the University of Granada [Instituto de Investigación del Sistema Tierra en Andalucía] as a research partner as part of the flight forecasting system for use in the flight test campaigns. Volumetric scanning and point based vertical motion scanning are used to good effect in the flight test environment. Strong thermic activity was avoided through forecasting and avoidance of areas/times identified as using a custom vertical stability algorithm.

The region was challenging to forecast for with many models failing to resolve nocturnal low-level jets while also having strong thermic activity which we sought to avoid during testing both through forecasting and active avoidance of levels identified by LiDAR.

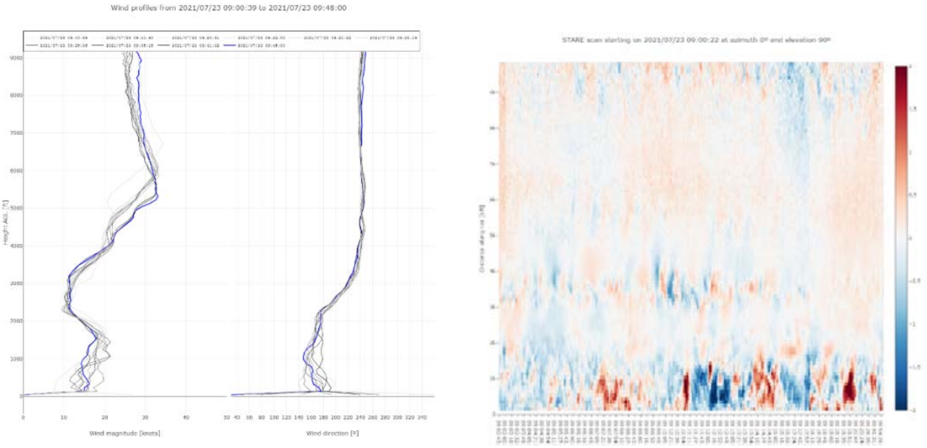


Figure 6 - Winds Vertical Profile from LiDAR (Left) // Post Processed Vertical Velocity Stability from LiDAR (Right)

The structure of the flight test activity with weather monitoring as an integral part of the engineering test team allowed constant communication of risk evolution and management of test points at optimal altitudes and positions.

5.0 AUTONOMOUS SYSTEM

5.1 Navigation System

To support the Skydweller mission, a new navigation system has been integrated in the aircraft to provide navigation state and flight dynamics information. The selected system uses an Inertial Navigation System (INS) integrated with a GNSS receiver through a tightly coupled Kalman Filter. The SPV Navigation System is managed by the onboard Skydweller Vehicle Management Computer (VMC).

Once alignment is completed, the INS provides free-inertial navigational data and, when GNSS augmentation is provided, hybrid navigational data to the autonomous systems. The INS also exploits pressure altitude provided by the air data system to compute the inertial altitude and vertical speed.

The main flight test objectives are to:

1. Verify that navigation system as-installed accuracy meets SPV control law requirements.
2. Prove the GNSS capability to track satellites and remain in Navigation/SBAS Navigation mode.
3. Validate the execution of INS on-ground and in-flight alignment.

5.1.1 Verify INS Hybrid Data Accuracy & Integrity

The navigation system provides information on figure of merits and integrity levels to the VMC to allow monitoring of the navigation data exploited by the SPV autopilot. The figure of merits and integrity levels were continuously monitored in the ground control station during all the flights of the test campaign; post-flight data was exploited to analyze the time histories. As shown in the next figures, the figure of merits behaved properly post boot, decreasing to the required performance.

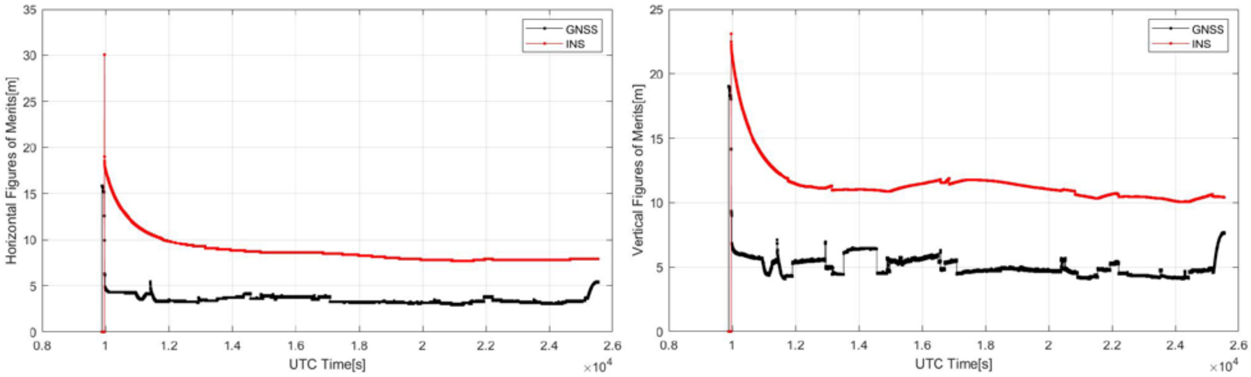


Figure 7: Navigation system as-installed figures of merits.

5.1.2 Validation of INS Alignment

Correct execution of the INS alignment has been verified by telemetry. The validation of the INS in-air alignment is an important result that allows to perform future in-air resync – which will be a useful capability for future long endurance flights. On-ground alignment has been verified by analyzing data during all the flights of the test campaign, whereas the in-flight alignment was performed once. The INS modes transition was as expected and there was no degradation of the INS performance after alignment. The on-ground alignment took less than 3 minutes, within the specification at Albacete's latitude.

5.1.3 Validation of GNSS Satellites Tracking Capability

The GNSS satellites tracking capability has been successfully validated in flight. This verified that aircraft structure's shadowing effect is minimized. The GNSS operated in SBAS Navigation Mode during all the flights, and the number of tracked satellites was always between 7 and 12, always greater than the minimum of 4 needed to compute a navigation solution. This enabled GNSS integrity functions including RAIM to be continuously active. The next table summarizes the minimum and maximum number of tracked satellites from SKR005, which was the first flight with the GNSS installed.

Table 2. Summary of number of tracked satellites.

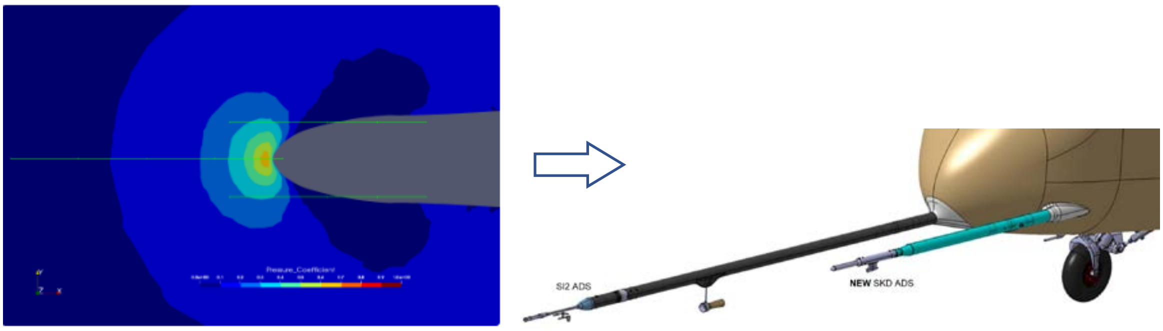
Number of tracked satellites	**SKR005**	**SKR006**	**SKR007**	**SKR008**	**SKR009**	**SKR010**	**SKR011**	**SKR012**
Minimum	8	7	7	7	7	7	7	8
Maximum	12	11	11	11	10	12	12	12

5.2 Air Data System

A new Air Data System (ADS) accurate at very low airspeed, has been integrated in the aircraft to support autonomous flight and redundancy requirements. The highly integrated smart air data system has an Air Data Computer (ADC) and a self-contained multi-hole Air Data Probe (ADP) with an embedded regulated heating and drainage. The system provides static and impact pressures, angles of attack and sideslip, and outside air temperature, which are corrected for installation errors in the VMC, and then used to compute airspeeds, baro altitude and any necessary derived air data parameters. The ADS provides continuous health status, adding value for fault detection and reconfiguration.

The main flight test objectives for the ADS are:

- Validate the selected location of the Air Data Probe following a thorough aerodynamic study (CFD) and a tradeoff among mechanical, performance, and safety requirements
- Prove that the ADS meets required desired measurement accuracy at the low airspeeds characteristic of the Skydweller aircraft
- Validate and verify the installation error compensation algorithms embedded in the VMC SW.
- Prove the ADS system and installation is a robust solution for future Skydweller projects



- **Figure 8: CFD location study and Location of the new ADS on aircraft**

Corrections based on CFD was used to correct air data measurements from installation error sources. The SW employs Look-Up tables (LUTs) to correct raw data coming from the new ADS equipment to corrected air data used by the flight control functions. The LUTs are the precalculated via CFD. The LUTs were expanded and optimized to improve performance quickly between flights since they are outside the safety boundary. The SPV approach allowed rapid and robust ADS development and flight validation. No further changes of the ADS installation or algorithms have been identified prior to future unmanned flights.

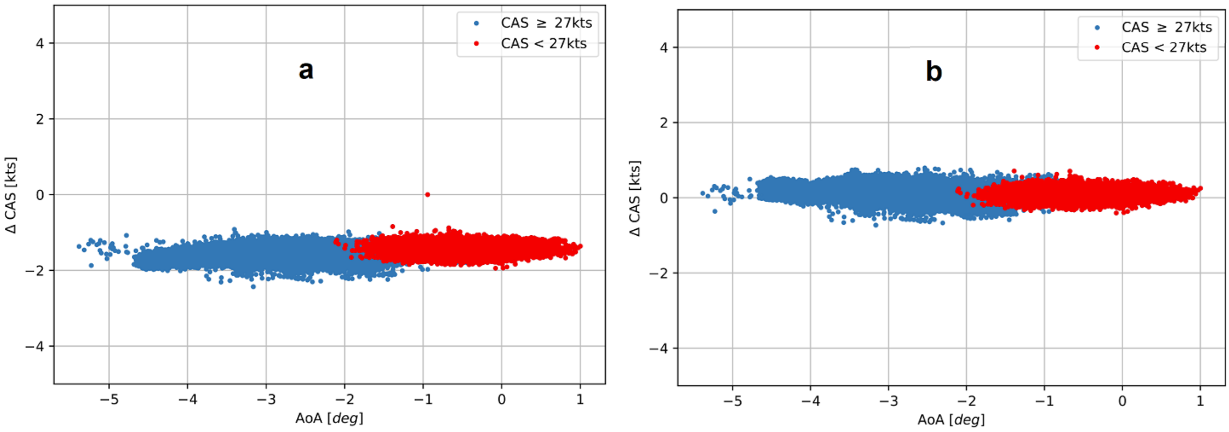


Figure 9: Uncorrected New ADS data vs. SI2 ADS data (b) and Corrected New ADS data vs. SI2 ADS data (b) – SKR008

5.3 Flight Control System

While the aircraft configuration is not unconventional, its flying qualities are unique in the size to airspeed ratio. Sensor relative location, and wing tip dynamic pressure due to local velocity induced by rotations is significant with respect to the free stream. The low wing loading of the airplane leads to a fast control in the longitudinal axis and a fast roll subsidence, however flying at low speeds the lateral directional modes and control get coupled, due to high adverse yaw and the difference of lift between the inner and outer wings in a turn.

The SPV configuration reduced the analysis necessary to test fly a controller. Controller prototypes were developed against models. In flight loop shape tuning and verification was performed sequentially, confirming results from preliminary models, and validated model updates.

The main flight test objectives are to:
1. Validate in flight the controllers with a reduced development timeline and validation efforts
2. Allow early identification of control performance to minimize controller rework
3. Verify the logic and operational sequences used for takeoff and landing
4. Identify uncertainties in aircraft modelling for later system identification efforts

The first SPV flight featured simple functionality, allowing surface hold to confirm positive surface command and the servo loop closure. A non-negligible Limit Cycle Oscillation (LCO) on the elevator was experienced. This was quickly solved for the series of flights by combining servo and surface position feedback with a complimentary filter and demonstrated without detailed modelling. Later investigation verified stiction in the chain.

The second flight test period focused on the inner loop and consisted of five flights over a month. The first of these flights on July 25th identified timing issues on the stand-in flight computer affecting controller performance. Since the software was not safety critical, the team identified, proposed, and flew the solution in days, leading to a successful flight on July 30th. This demonstrated, inner-loop and outer loop performance in horizontal and vertical axes. Later flights expanded the controller's capability across most of the aircraft's low altitude envelope and assessed disturbance rejection capability.

The development periods introduced higher level guidance logic, waypoint navigation, and mission plan execution capabilities including some platform specific functions. I.e., path controllers which behave predictably in winds similar to or greater than aircraft true airspeed. Flight SKR012 focused on testing takeoff and landing logic. This consisted of an automatic elevated approach and testing of the logic performed by running flight control in the background while the pilot performed takeoff and landing by verifying the system detects all the transitions correctly in a real-world environment.

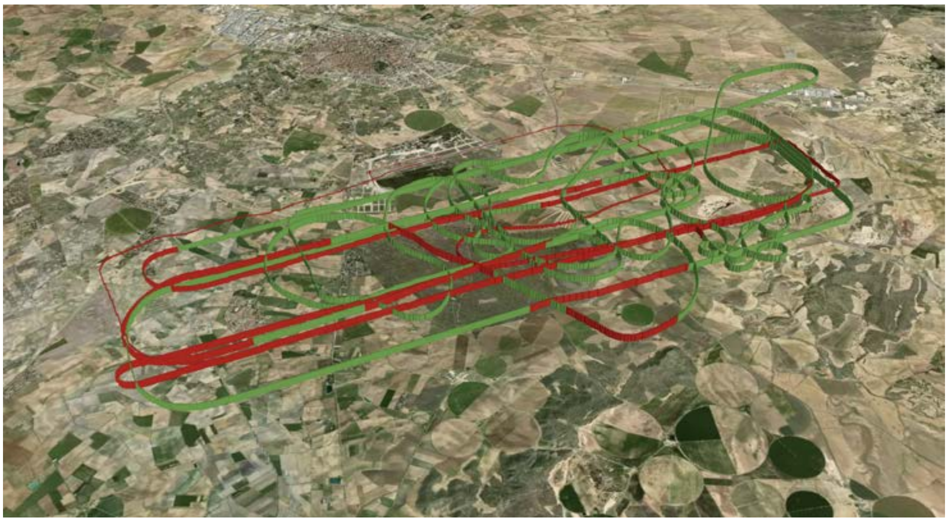


Figure 10: (SKR012) - Flight Trajectory: red represents pilot in control, green closed loop flight

6.0 CONCLUSION

The company has achieved the capability to operate the aircraft from a crew and decision-making perspective and has developed the infrastructure and processes to support the development, integrating the flight test team and the engineering team. The weather modelling approach has been confirmed, both for flight window prediction and for real time data incorporation into the decision-making process.

Risks on autonomous system development have been eliminated by flight testing of incremental capabilities. The INS and GNSS integration has succeeded at meeting required navigation performance, validating the suitability of their installation from a flight control and aeroelasticity point of view, and in-air realignment and initialization have been satisfactorily shown. The air data system has been validated at low speeds, including takeoff and landing, providing precise angular measurements and correct estimation of installation errors. Flight control has shown positive aircraft control and verifying the logic for takeoff and landing maneuvers.

The SPV approach was successful at integrating the system development, flight testing and weather activities in an efficient manner thanks to the system architecture and the safety approach. The company went from returning the SI2 aircraft to flight to demonstrating closed loop control in flight in less than a year. Proposing a safety piloted approach where autonomous functions could be isolated from the pilot and therefore be tested as non-safety critical has provided an environment that enabled a rapid progression in the operational capabilities and autonomous system design.