NOAA “Hurricane Hunters” Flight Testing of Air-Launched UAS

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INTRODUCTION

The National Oceanic and Atmospheric Administration (NOAA) Aircraft Operations Center (AOC), in partnership with the Hurricane Research Division (HRD), has been tasked with testing and evaluating the ability to deploy air-launched Unmanned Aerial Systems (UAS) into tropical cyclones. NOAA AOC operates two "Hurricane Hunter" WP-3D aircraft to fly various weather reconnaissance missions. To meet this task, NOAA relied on industry for air-launched UAS vehicles that could collect data in conjunction with the WP-3D to gather the necessary meteorological data used to predict hurricane track and intensity forecasts. This allowed for the majority of testing to be focused on the mission, rather than the design of the nascent vehicle internally to the small test team. Employing UAS' in the tropical cyclone environment enables extended loiter time of critical data gathering instrumentation, as well as the ability to augment and support additional scientific tasking for the manned aircraft.

The NOAA AOC flight test section demonstrated the WP-3D's ability to safely launch and control small (<55lbs/25kg) deployable UAS' from the WP-3D. A variety of adapted flight test techniques and instrumentation were utilized to characterize each launch. AOC faces many constraints in flight test, namely: resource competition, aircraft availability, instrumentation, test article availability, and design boundaries. These constraints forced the team to develop the most agile test methods to accomplish the flights safely using a proven three-step process. Safe separation flight tests based on the WP-3D hurricane cruise flight condition were successfully accomplished on several different air-launched UAS vehicles. Upon completion of safe separation testing, a series of demonstration test events were conducted to validate and verify the meteorological and oceanographic (METOC) data gathered by the UAS. Operational Testing (OT) of multiple air-launched UAS' into the tropical cyclone flight environment will begin in 2023. A detailed focus of this paper will be demonstrating a safe and efficient methodology to flight test air-launched UAS' from piloted aircraft within common constraints by using an agile and adaptable framework.

1.0 CONSTRAINTS

1.1 Aircraft Availability

NOAA does not own test articles separate from operational aircraft and instrumentation. Unlike other DoD entities that may have a dedicated test squadron and aircraft, NOAA must conduct all flight testing on the operational aircraft. In this case, it represents executing flight test events on our two "Hurricane Hunter" aircraft (WP-3D), which are in very high demand due to the active 6-month long hurricane season in the United States. This challenge highlights one of the resource constraints facing the AOC Test Section throughout each stage of testing, when tasked with planning and executing test events. Planning these events around missions is challenged in that other AOC priorities such as: pilot training, science calibration, and aircraft maintenance are also competing for time on the aircraft. As we understand very keenly in the test world, time is a precious entity, and we experience that regularly at NOAA Test. This has forced our team into developing agile and efficient testing in every aspect of our planning and execution to accomplish our test objectives with the limited amount of time available for testing on these two aircraft. Furthermore, this aircraft availability constraint has presented an opportunity for us to evaluate our safe separation testing procedures with an exacting balance of safety and efficiency.

1.2 Instrumentation

Another constraint facing NOAA UAS testing is the prohibitive cost of telemetry for the UAS, since all mass models and UAS vehicles are considered expendable, resulting in each launch taking place without system recovery or ground-based data recording. Due to the lack of available telemetry, NOAA flight test has utilized other methods to monitor the safe separation of the UAS from the manned aircraft. These tools are discussed in the first step of our airworthiness certification process: safe separation testing.

1.3 Cost

As with every organization, NOAA is faced with budgetary resource constraints. In our case, this constraint is exacerbated by the nature of the UAS themselves- in that they are all nearly unrecoverable. One way to mitigate the costs of the UAS is by not contractually requiring the air vehicle to have the ability to land. Since we understand that all these weather reconnaissance UAS' are designed to be jettisoned in the ocean, we can save costs and engineering effort by eliminating a complex flight regime-landing. While this helps save money in the design and fabrication of the UAS, it obviously poses a separate challenge and extra budgetary constraints on the test team. Because we cannot land the UAS, each item ends up ditching in the ocean after each use. Losing every test article forces us to be efficient in our testing protocols to maximize every opportunity for gathering data. In rare instances that we have access to an over-land test range, we have had the ability to conduct some UAS testing utilizing a "ditch" mode to land the aircraft on the runway and refurbish the vehicle to re-use for operational missions. However, this only works with some UAS' that have enough command-and-control logic built into the flight guidance computer, limiting this option to very few of our UAS models.

1.4 Flight Test Conditions

Unlike other test programs that may be able to conduct many test points across a wide range and variety of operational flight regimes, NOAA flight test does not have the time nor the requirement to create a fully expanded envelope. This task would also be difficult due to the fact that all of our air-launched UAS vehicles are designed to operate and perform in extremely harsh, dynamic, and austere weather conditions. Distinct from other challenging meteorological conditions such as extreme heat (desert operations) or cold (arctic operations), there is no way to simulate the environments of a tropical cyclone in a meaningful way that would be representative of the conditions encountered during hurricane flight operations. Even as the experts at collecting in-flight data in these environments, we could still not perform the hundreds of test points needed to characterize the performance and behavior of the UAS' in all the dynamic meteorological conditions it may encounter in a tropical cyclone. It would, again, be cost prohibitive because every UAS is also expendable (by design and necessity).

2.0 TEST TECHNIQUES

The NOAA test team has created a well-defined path for air-launched UAS testing that thoughtfully mitigates each constraint. It is a three step process that allows NOAA to execute the test points necessary to deliver the UAS to operational functionality.

2.1 Safe Separation

Preparation for safe separation begins with analysis and must mitigate the aforementioned constraints. The first of these challenges is the limited use of ground-based telemetry, due to cost and access. To mitigate the inability of the UAS to emit data on rotation and orientation during launch, we utilize the mass properties lab at Naval Air Station Patuxent River to "spin" the UAS and calculate the moments of inertia of each vehicle. This information helps us to predict the behavior of the UAS upon exit from the aircraft, thus providing another data point for the test and the ability to conduct an analysis by comparison of expected exit behavior. Additionally, prior to safe separation testing, we utilize "witness tape" (Figure 1) on areas of the aircraft in which we suspect the UAS could potentially impact the fuselage. By adhering this tape to the fuselage, it allows a thorough review and inspection of the areas before and after the flight to record if the UAS impacted these regions upon exit. Another method of gathering quantitative data is old fashioned distance markings. By utilizing high visibility tape to mark known distances on the fuselage and UAS (Figures 2 & 3), we can observe and record estimated fall rates, closest point of approach (CPA) of the UAS to the fuselage, estimated exit velocity, and other characteristics of the launch. In order to obtain this information, NOAA flight test has invested in high-speed cameras that can be placed external to the aircraft (Figure 4) to record (and replay in real time) the launch. These cameras can record up to 2,000 frames per second (fps) and provide detail that can be used for both qualitative and quantitative data gathering on the initial launch and separation of the UAS from the WP-3D. The cameras relieve AOC from providing a chase platform (a challenge with the aircraft availability scheduling constraint) for the safe separation testing, which was previously used during the first iterations of UAS safe separation testing at NOAA.

Figure 1-1: Witness Tape on WP-3D

Figure 1-2: Instrument Markings

Figure 1-3: External Distance Markings

Figure 1-4: High Speed Camera Look Angle from Wingtip

While the cameras and markings have addressed the instrumentation constraint, the team also developed the approach to verify the launch harmony between the manned and unmanned vehicles. This is the most critical and detailed step of the test process. Since NOAA does not own a CFD model of the WP-3D flow field (due to cost, technical expertise, and frequent outer mold-line changes), each safe separation test is a crucial data point to ensure the act of launching the UAS can be conducted safely with a full crew embarked. It is also very critical because it is the first opportunity to observe the expected and actual behavior of the vehicle as it exits the WP-3D. Since there is no fortified model by which to conduct a launch analysis or simulation, the "expected" behavior of the UAS during launch is derived from comparison to other known items ejected from the aircraft that have similar mass property characteristics. Defining the launch envelope for each UAS poses its own resource challenges. Like other safe separation (weapons, etc.) testing, we do employ the use of mass models during testing to reduce the cost and complexity of the test. However unlike other test programs, the resource constraint facing NOAA during safe-separation is not the item being ejected, but the platform from which the item is being launched. As previously detailed, NOAA flight test must compete with other interests that need the aircraft, resulting in a very limited amount of time (as measured in both calendar days and flight hours) to conduct the safe separation test flights. As such, NOAA cannot acquire a dedicated test aircraft for months to conduct dozens (if not hundreds) of test points to define the launch envelope. Instead, a very efficient and agile, yet thorough, method was created to collect enough of an envelope to meet the standards of the organization's airworthiness review board and the mission.

To accomplish this, the test section identified the most common expected launch regimes for the unmanned systems. Since all the UAS' thus far have gone through acquisition with the goal of gathering meteorological data in the storm environment, a generalized set of launch conditions could be used for each UAS. But how could we ensure that we properly covered all possible launch altitude, airspeed and load factor regimes for the launch envelope given the resource constraints identified? First, we had to make several assumptions: all launches would be conducted in wings level flight at 1g (thus eliminating the load factor consideration), and the behavior of the vehicle during launch in clear air was similar enough to the behavior of launch in a tropical cyclone. While the assumptions were large, we did not assume the behavior of the *vehicle* was the same in both conditions, rather the behavior of the vehicle *during launch* was the same. Fundamentally, we are assuming that the 1 second it takes to safely clear the aircraft is small enough to not cause any appreciable changes in exit behavior (even in the dynamic conditions of a tropical cyclone). Once those assumptions were accepted, we still had to tackle the problem of defining a launch envelope within the constraints of 2 flight test events and a total of 4-6 flight hours of testing for all of the safe separation flights. A further constraint, as previously outlined, is the cost associated with instrumenting the mass model with telemetry to observe and record quantitative data associated with the launch. Given these two constraints, it was evident we could not launch multiple mass models per flight (each at different test points) because we could not verify safe separation between each successive launch. This would violate one of the foundational tenets of flight test: build up.

With the understanding that we had 2 flights, no instrumentation, and were required to define the launch envelope, we decided the best method to conduct the testing, and thus define the envelope, would be to utilize dynamic pressure (q) and angle of attack (α) at each edge of the possible launch conditions. We used predicted q and α values to determine two launch points that would govern a "high q" and "low q" limit. By calculating various altitudes and airspeeds within the normal WP-3D hurricane operational envelope (altitude: 1,000-20,000 ft MSL, airspeed: 168KIAS-259KIAS) we defined precise test points that would encompass each of the q values at standard day. Once each of the end test points were determined (example: 180 KIAS at 4,500ft. MSL and 225 KIAS at 15,000ft MSL), these became the two target launch conditions at which the test pilot would execute the safe separation launch. Naturally, our tests would not occur at standard day conditions, so after the test we would correct the data to account for actual launch conditions from the observed atmospheric state variables present during the test event. This would give us our *actual* low and high q values, which we used to create the launch envelope (Table 1 and Figure 5). Once we had the high and low q points, we could then create an entire launch envelope with infinite altitudes and airspeeds by holding one constant while varying the other (since we knew the tested dynamic pressure limit). This was a very elegant solution to creating an entire envelope by only conducting two safe separation drops (one at high q and one at low q).

Table 2-1: Example Dynamic Pressure Test Table

		Low Point	High Point
Enter Here		92.43	121.41
Density	Altitude	Airspeed	Airspeed_H
0.0023082076	1000	168	192
0.0022745538	1500	169	194
0.0022409000	2000	170	195
0.0022080006	2500	171	196
0.0021751012	3000	173	198
0.0021430006	3500	174	199
0.0021109000	4000	175	201
0.0020795374	4500	177	202
0.0020481747	5000	178	204
0.0020175374	5500	179	206
0.0019869000	6000	181	207

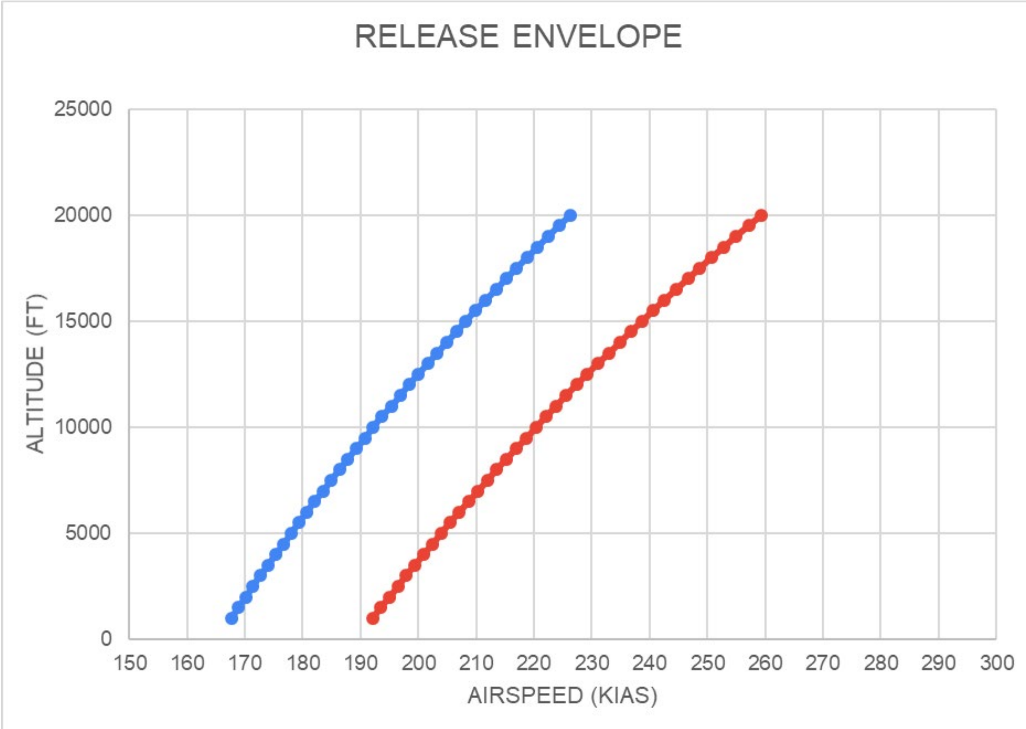

Figure 2-1: Derived Launch Envelope from Dynamic Pressure Test Points

Additionally, due to the large spread in airspeeds used during the two test launches, we have a natural variation in angle of attack (α), which is important for our safe separation testing, as changes in α also create changes in fuselage geometry relative to the launch position of the UAS (assuming constant altitude). Therefore, by varying α, we are also effectively changing the attitude of the plane and thus ensuring that the higher pitch attitude that would generally accompany low q test points does not interfere with the safe separation of the UAS during launch. Through our UAS safe separation tests, we have generally encountered a mission representative α spread, which equates to about 5° of pitch change, and encompasses the entire operational flight regime during a typical hurricane mission.

2.2 Developmental Test

NOAA classifies developmental test (DT) as our first opportunity to observe the performance of the vehicle against the requirements listed in the contract. While this DT follows many classical models of conducting test, the main distinction that separates DT from OT at NOAA is the environmental conditions. In order to continue a build-up approach to testing, we progress from safe-separation into DT, to make an initial evaluation of the performance of the UAS. We conduct DT understanding that results may be dramatically different in the hurricane environment, as we conduct all DT in a clear-air, visual meteorological conditions (VMC) environment. The clear-air tests allow for the first look at the integrity of the system as a whole. Principal to our ability to utilize the UAS effectively is the capability to transmit and receive data between the UAS and the manned aircraft. Since the CONOPS for all of the air-launched UAS’ involve co-existing spatially and temporally with the manned aircraft (WP-3D), the ability to communicate between both platforms is vital to the success of the mission. In the current tested designs, all the UAS METOC data has to be transmitted back to the WP-3D prior to dissemination to the National Hurricane Center (NHC) and ingestion into the track and intensity forecast models. Therefore, a suitable data transmission distance and transfer speed are paramount to ensuring the UAS can complete the mission. Even in nominal conditions, mission representative behavior can be characterized. For example, because hurricanes produce a lot of water, we can calculate estimated transmission attenuation caused by dense precipitation within the storm. We then assume that the calculated attenuation rate is very close to actual attenuation rate experienced during the storm, enabling us to conduct clear-air transmission testing that serves as a reliable expected baseline for UAS performance in the hurricane environment, and adding a correction factor to compare to OT results. Another example of DT efficiency is operating the UAS using the maximum propulsion available, as this can best approximate the necessary flight regimes the UAS will need in the tropical cyclone environment. By operating the UAS at maximum throttle, we can then identify minimum endurance time and maximum vehicle performance ("dash" speed, climb, and descent rates, etc); two critical elements used to establish TTP's for the employment of the UAS. Finally, we use DT to gather all the requisite data needed to verify the UAS will meet the needs of the mission. Outside of very few performance parameters, we do not use many classical flight test techniques, as we are more interested in the ability of the UAS to accurately employ the sensor package and transmit that data back to the WP-3D. Some other testing efficiencies we use to do this include the contractor performing wind tunnel testing and captive carry tests early in the DT process just to identify any large-scale errors in the METOC sensors.

2.3 Operational Test

NOAA treats operational testing (defined as UAS vehicle performance in the tropical cyclone) as "living test campaigns." Like "living documents" and other related vernacular that is continually updated and revised as new information becomes available, the "living test campaign" takes an iterative approach to testing. Due to the nature of the need to expend the instruments (UAS) in the operational environment, combined with the cost associated with losing every vehicle, each release of a UAS in the operational environment provides a data point from which to determine how to either: modify the UAS or modify the tactics, techniques, and procedures (TTP's) used for employment of the vehicle. Therefore, the NOAA testing protocol for OT is a blended solution of actual operational data collection (to the extent the instrument can perform the demands placed upon it) with test points commensurate the unique atmospheric state variables present during that specific launch. Utilizing this approach accomplishes several objectives: it gets the UAS to operations faster, it maximizes the test opportunities while balancing the unique nature of losing every test article and provides the ability to create a catalog of test points for each UAS as they are dropped and employed in the operational environment.

Operational test is our first chance to evaluate the UAS in the tropical cyclone environment and we accomplish this with a full mission crew working in the real-life challenges of severe weather operations. As previously stated, OT is a blend of actual tasked missions for the UAS, and continued test data points. During tasking, NOAA meteorologists and research scientists are collecting data from on-board sensors and reviewing the data received from the UAS. Because the UAS meteorological data has not completed full verification, we mitigate the operational tasking impacts by either labeling the UAS data as "experimental" or not using the data in the official forecast models. The nature of the data collection is very sensitive, and therefore requires a high degree of confidence as to the accuracy of the data. Until several vehicles of the same model UAS have flown in a hurricane, and we can compare it to a truth source (other calibrated instruments deployed from/aboard the WP-3D), it is very hard to extrapolate the accuracy of the METOC data from DT (clear air) to OT (hurricane). As OT is the final step of testing, it is this last part of data verification that is most important to classifying the UAS as "operational."

The other information gleaned from OT is the performance of the UAS vehicle in the storm environment. Because we have an established datalink with the UAS during OT, we can monitor and evaluate UAS classical aircraft performance characteristics such as maximum forward airspeed, climb and descent rates, and turn radius and rate. Additionally, the storm environment gives us the first chance to compare the actual behavior of the vehicle to that which was commanded from the operator station in the WP-3D. These vital data points are important markers for determining atmospheric limits that the vehicle can operate in, thus enabling NOAA to adjust the TTP's for the UAS to maximize vehicle use in known tropical cyclone conditions.

The dynamic of a full crew and changes to tasking provide the flight test conditions that can't be simulated in DT, which allows the TTP's to be refined and all stakeholders to solicit input changes. But the novelty of testing an air-launched UAS and controlling it in the storm from another science aircraft, proves even larger concepts for the mission. The storm environment currently only allows a maximum of two manned aircraft collecting data, usually within a 4,000 ft. altitude band. These aircraft have no common data link other than passing information about the storm's movement and position. Each OT flight with the air-launched UAS allows the manned aircraft to collect more data concurrently, with the UAS operating at altitudes well below the manned aircraft, allowing for multiple simultaneous perspectives within the storm. It also establishes common data links within the storm environment that has the potential to be used as nodes in future iterations of the hurricane CONOPS.

Utilizing OT as a model for testing new sensors in the storm environment, NOAA flight test envisions the evolution of these air-launched UAS' to one day provide real time truth source data (once the system can be trusted) for verification of new science instruments on-board the *manned* aircraft. While OT is currently limited to verifying the UAS data and performance, once this system is proven, it will allow us to leverage its mobility, cost, and endurance to use it as a truth source for new science equipment, allowing us to certify new sensors even faster.

3.0 CONCLUSION

The constraints and test methods detailed above have highlighted our current ability to work through some of the obstacles that would normally create a long, costly, and intensive test campaign for certification of each air-launched UAS. When faced with creating test events that would be accepted through the NOAA airworthiness certification process, the test section ensured that each UAS test event was thorough enough to meet the standards of the airworthiness review board, as well as agile enough to be completed within the documented resource constraints. By employing creative test techniques and maximizing the efficiency of testing and gathering data points, NOAA Flight Test is perhaps pioneering methods in the testing of air-launched unmanned aerial systems.

The majority of our UAS testing to date has been conducted on experimental air-launched UAS' from a manned aircraft. While we have had a modicum of success in the operational viability of the air-launched UAS', we have developed the ability to successfully test this new technology through lean methods crafted over the past several years. As we move forward, our three step process will most likely evolve, but never at the risk of adding excessive processes. Our test team is always open to collaboration and publishes this summary of our methods and experiences with the hope to inspire the same level of creative problem solving in other equally constrained organizations that are pushing the envelope of technology and science, safely.