4. Small Unmanned Aerial Vehicle Experiment (SUAVE)

Primary IFEX Goal: 2 - Develop and refine measurement technologies that provide improved real-time monitoring of TC intensity, structure, and environment

Link to the model evaluation activities: Conducting the UAS modules listed in this experiment (stand alone or as part of other HFP efforts) will enable enhanced high resolution comparisons between tropical cyclone boundary observations of temperature, moisture and wind with similar thermodynamic and kinematic output from NOAA's regional and global operational models.

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Coyote UAS

Coyote is an aircraft platform that is built by the Raytheon Company (formerly Sensintel Corporation and British Aerospace Engineering (BAE)) and is currently being used by the US NAVY. The intended deployment vehicle for the Coyote is the P-3 Orion. The Coyote is a small electric-powered unmanned aircraft with 1-3 hour endurance and is capable of carrying a 1-2lb payload. The Coyote can be launched from a P-3 sonobuoy tube in flight, and terrain-permitting, is capable of autonomous landing and recovery. The Coyote is supported by BAE's integrated control station, which is capable of supporting multiple aircraft operations via touch screens that simultaneously show real-time video. This control station can also be incorporated onto the deployment aircraft (i.e. P-3), allowing for in-air command and control after launch. The Coyote, when deployed from NOAA's P-3's within a hurricane environment, provide a unique observation platform from which the low level atmospheric boundary layer environment can be diagnosed in great detail. In many ways, this UAS platform be considered a 'smart GPS dropsonde system' since it is deployed in similar fashion and currently utilizes a comparable meteorological payload (i.e. lightweight sensors for P, T, RH, V) similar to systems currently used by NOAA on the GIV and P-3 dropsonde systems. Unlike the GPS dropsonde however, the Coyote UAS can be directed from the NOAA P-3 to specific areas within the storm circulation (both in the horizontal and in the vertical). Also unlike the GPS dropsonde, Coyote observations are continuous in nature and give scientists an extended look into important thermodynamic and kinematic physical processes that regularly occur within the near-surface boundary layer environment. Coyote UAS operations also represent a potentially significant upgrade relative to the more traditional "deploy, launch and recover" low altitude UAS hurricane mission plan used in the past (e.g. Aerosonde). By leveraging existing NOAA manned aircraft assets, Coyote operations significantly reduce the need for additional manpower. The Coyote concept of operations also reduces overall mission risk since there is no flight ingress/egress. This fact should also help simplify the airspace regulatory approval process. Specifications associated with the Coyote UAS are illustrated in Figure 4-1.

Coyote Specifications

Parameter	Value (U.S.)	Value (Metric)
Maximum Gross Takeoff Weight (MGTW)	14 lbs	6.4 kg
Nominal Mission Takeoff Weight (NMTW)	12 lbs	5.4 kg
Nominal Mission Endurance	1.5 Hours	
Motor	Brushless Electric Motor	
Airspeed (Cruise @ NMTW)	50 kts	93 kph
Airspeed (Dash - level flight @ NMTW)	75 kts	140kph
Airspeed (Max. Endurance @ NMTW)	45 kts	83kph
Airspeed (Stall @ NMTW)	38 kts	70kph
Airspeed (VNE @ NMTW)	100 kts	185kph
Navigation	GPS	
Service Ceiling	25,000 feet	7,610 meters
Payload (EO)	Sony FCB-IX10A EO Camera	
Payload (IR)	BAE SCC500, Uncooled IR	
Command and Control Radio (C2)	Up to 2 Watt, Discrete/Frequency Agile, Military Band / ISM Band Radio Modem (TX/RX)	
Command and Control Radio Range	20 nm, Line of Sight (LOS)	36 km, Line of Sight (LOS)
Video Transmitter	2 Watt (optional 5W), S-Band FM Video TX With Optional 19.2kbps Data Carrier	
Video Transmission Frequency Range	2.20-2.39 GHz	
Video System Range	20 nm, LOS	36 km, LOS
Payload Capacity	Up to 5 lbs	Up to 2.25 kg
Onboard Power	12V, 200Wh	
Propulsion	13x13 Foldable Propeller	

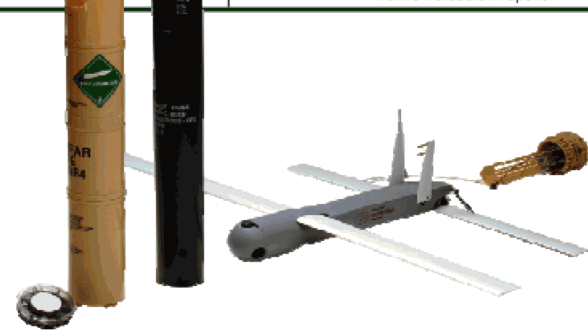

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Figure 4-1. Coyote Unmanned Aerial System Specifications (Courtesy: Raytheon)

<u>Relevance to NOAA</u>

In recent years, an increasing number of hurricanes have impacted the United States with devastating results, and many experts expect this trend to continue in the years ahead. In the wake of Hurricane Sandy (2012), NOAA is being looked at to provide improved and highly accurate hurricane-related forecasts over a longer time window prior to landfall. NOAA is therefore challenged to develop a program that will require applying the best science and technology available to improve hurricane prediction without placing NOAA personnel at increased risk. UAS are an emerging technology in the civil and research arena capable of responding to this need.

In late February 2006, a meeting was held between NOAA, NASA and DOE partners (including NOAA NCEP and NHC representatives) to discuss the potential for using UAS in hurricanes to take measurements designed to improve intensity forecasts. The group came to a consensus around the need for a UAS demonstration project focused on observing low-level (<200 meters) hurricane winds for the following reasons:

- Hurricane intensity and track forecasts are critical at sea level (where coastal residents live)

- The hurricane's strongest winds are observed within the lowest levels of the atmosphere

- The air-sea interface is where the ocean's energy is directly transferred to the atmosphere

- Low-level observations will help improve operational model initialization and verification (especially boundary layer observations of temperature and moisture which are especially sparse)

- The low-level hurricane environment is too dangerous for manned aircraft

The potential importance of low-level UAS missions in hurricanes is further emphasized by the findings of the Hurricane Intensity Research Working Group established by the NOAA Science Advisory Board. Their recommendation is that:

"Low and Slow" Unmanned Aircraft Systems (UAS) have demonstrated a capacity to operate in hurricane conditions in 2005 and in 2007. Continued resources for low altitude UAS should be allocated in order to assess their ability to provide in situ observations in a critical region where manned aircraft satellite observations are lacking.

This effort is in direct support of NOAA's operational requirements and research needs. Such a project will directly assist NOAA's National Hurricane and Environmental Modeling Centers better meet several of their operational requirements by helping to assess:

The strength and location of the storm's strongest winds

The radius of maximum winds

The storm's minimum sea level pressure *(potentially give forecasters advanced warning as it relates to dangerous episodes of tropical cyclone rapid intensification)*

Thermodynamic conditions (particularly low level moisture) within the lower troposphere

In addition to these NOAA operational requirements, developing the capability to regularly fly low altitude UAS into tropical cyclones will also help advance NOAA research by allowing scientists to sample and analyze a region of the storm that would otherwise be impossible to observe in great detail (due to the severe safety risks associated with manned reconnaissance). It is believed that such improvements in basic understanding are likely to improve future numerical forecasts of tropical cyclone intensity change. Reducing the uncertainty associated with tropical cyclone intensity forecasts remains a top priority of the National Hurricane Center. Over time, projects such as this, which explore the utilization of unconventional and innovative technologies in order to more effectively sample critical regions of the storm environment should help reduce this inherent uncertainty.

This HRD field program module is designed to build on the successes from earlier NOAA UAS missions conducted in 2005 (Ophelia) and 2007 (Noel) while also fulfilling objectives from the recently funded Sandy Supplemental project entitled: *The Impact of Emerging Observing Technologies on Future Predictions of Hurricane Structure and Intensity Change.* As part of this NOAA supported effort, all UAS data collected will be made available to NOAA's National Hurricane and Environmental Modeling Centers.

General Coyote UAS Mission Description:

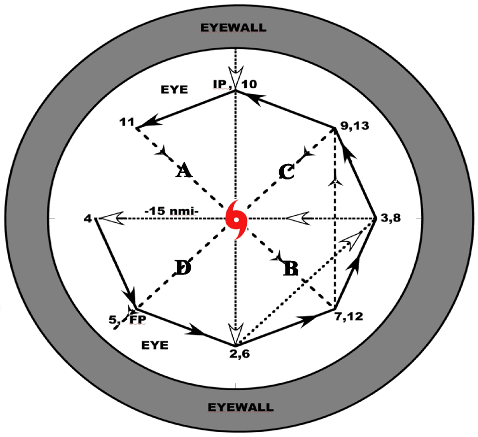
The primary objective of this experiment is further demonstrate and utilize the unique capabilities of a low altitude UAS platform in order to better document areas of the tropical cyclone environment that would otherwise be either impossible or impractical to observe. For this purpose, NOAA is proposing to use the Coyote UAS. Since the Coyote will be deployed from the manned P-3 aircraft, no UAS-specific forward deployment teams will be required. Furthermore, since the Coyote is launched using existing AXBT launch infrastructure, no special equipment is required beyond a 'ground' control station that Coyote operators will have onboard the P-3.

Module/Option 1a: UAS Eye/Eyewall with P-3 loiter-

For this module the target candidate storm is a mature hurricane (likely strong category 2 or more) with a well-defined eye. Furthermore, since the P-3 will have to operate within the eye, daylight missions will be required so as to maintain P-3 visual contact with the eyewall at all times. In addition, other less restrictive Coyote-P3 modules are being developed and considered (see Module 1b). A 350-MHz communication stream between the UAS and the P-3 will be used to control the UAS flight characteristics and to receive data back from the Coyote. This capability will have the dual positive effect of minimizing risk to both science and safety, since the 350-MHz stream will permit communication over a range of at least 50 km. The immediate focus of this experimental module will be to test the operational capabilities of the Coyote UAS within a hurricane environment. Besides maintaining continuous command and control links with the P-3, these flights will test the accuracy of the new ITRI METOC payload by comparing UAS measurements with coincident observations taken from dropsondes released from the P-3. The UAS will be tested to see if it can maintain altitudes according to command. In addition, the Coyote UAS will attempt to fly at extreme altitudes (as low as 200 ft) in low (eye) and high (eyewall) wind conditions within the hurricane environment. The longer term goal for this UAS platform is to assist scientists so they can better document and ultimately improve their understanding of the rarely-observed tropical cyclone boundary layer. To help accomplish this, the UAS will make detailed observations of pressure, temperature, humidity, wind speed and wind direction (PTHU) at low altitudes within the hurricane eye and eyewall that will then be compared with multiple in-situ and remote-sensing observations obtained from manned aircraft (NOAA P-3 and as opportunities arise AFRES C-130, Global Hawk UAS) as well as select satellite-based remote sensor platforms. In addition, a primary objective (but not an immediate requirement) for this effort will be to provide real-time, near-surface wind observations to the National Hurricane and Environmental Modeling Centers in direct support of NOAA operational requirements. These unique data will also be used in a 'post storm' analysis framework in order to potentially assist in the numerical and NHC verification process.

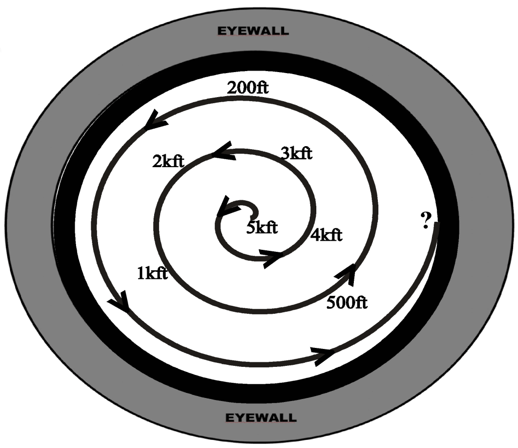
For this experiment, the NOAA P-3 will descend to just above the top of the cloud layer in the eye (Fig. 4-2), and return to the previous altitude when the module is concluded. Assuming multiple UAS are available, both (~1.5h duration) modules could be conducted on the same mission. The eye-only module would be conducted first, followed by the eye-eyewall UAS module. The P-3 flight pattern is identical for both eye and eye-eyewall UAS modules. GPS dropsonde and AXBT drop locations are also identical for each UAS module. AXBT and GPS drop locations are explicitly illustrated in the flight plan below. UAS deployment on leg 3-4 is also identical for both modules. UAS operational altitude will be entirely below 5000ft. UAS motor will not be activated until an altitude of 5000ft is met. The UAS will be conducting a controlled, spiral glide (un-powered) descent from 10000ft to 5000ft.

Coyote UAS - P3 Mature Hurricane Eye/Eyewall Module



P-3 FLIGHT PATTERN

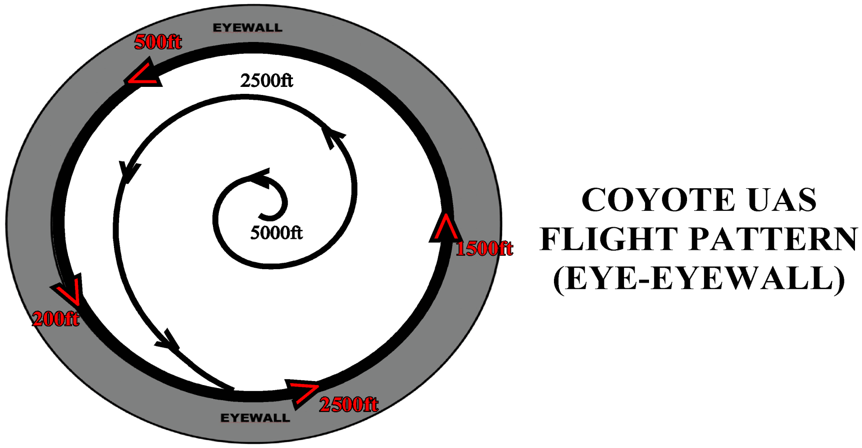
The P-3 approaches from the north at an altitude of 10,000ft, penetrates the eyewall into the eye, and performs a figure-4 (dotted line) in the eye. **Midway during leg 3-4 the Coyote UAS is released.** The P-3, remaining at 10,000ft, circumnavigates the eye in an octagon pattern and conducts another figure-4 rotated 45 degrees from the original (dashed line). Flight duration for this module should be close to 1 hour. An add-on ~45 minute duration module may also be conducted. This optional module would initiate where the preceding module ended (point 'FP'). The P-3 would proceed counterclockwise, repeating points 6-13 and completing the pattern once again at point 'FP'. **14 Dropsonde releases** should be conducted during the primary 1h module at the following locations: IP;2-5;7;9;11;A-D and midway during legs IP-2 and 13-FP. In addition, **9 AXBT launches** should be conducted at points 4 through 11 and midway during leg 11-12. (Note: except for AXBT drop at point 4, it is acceptable to launch all remaining 8 AXBT probes during the optional 45 minute second module.)



COYOTE UAS FLIGHT PATTERN (EYE ONLY)

Midway during P-3 leg 3-4, the Coyote UAS is released at 10,000ft altitude. The Coyote UAS proceeds to glide (unpowered) in a downward counterclockwise spiral to an altitude of 5,000ft. **At 5000ft, the UAS motor is started and the Coyote continues its counterclockwise descent in 1000ft increments.** At each interval (4kft,3kft,2kft,1kft), the UAS maintains altitude for 3 minutes prior continuing its counterclockwise, radially expanding with decreasing altitude, spiral descent. After 3 minutes at 1000ft, the Coyote descends to 500ft and remains at this altitude for 3 minutes. **The UAS continues to descend in 100ft increments down to 200ft, maintaining altitude for 3 minutes at each level.** The remainder of the flight is conducted at 200ft until battery power is fully expended and the UAS reaches the ocean surface. (Note: If full descent to 200ft is achieved and the UAS has sufficient battery power to continue, **an optional 'eyewall penetration' module may be considered** if conditions present themselves. Prior to any attempted UAS eye-eyewall penetration, the Coyote should ascend from 200ft to a (minimum) altitude of 500ft.)

Coyote UAS - P3 Mature Hurricane Eye/Eyewall Module



Midway during P-3 leg 3-4, the Coyote UAS is released at 10,000ft altitude. The Coyote UAS proceeds to glide (unpowered) in a downward counterclockwise spiral to an altitude of 5,000ft. At 5000ft, the UAS motor is started and the Coyote continues its counterclockwise descent to 2500ft**. The UAS maintains 2500 ft altitude and continues its outward counterclockwise spiral until it reaches the hurricane eyewall.** Once the Coyote penetrates and stabilizes **within the hurricane eyewall, the UAS begins a step-decent pattern from 2500ft down to 500ft** (while maintaining altitude for 3 minutes at each level). After reaching and maintaining 500ft for 5 minutes begin a steady decent down to 200ft within the eyewall. **Maintain 200ft altitude within the hurricane eyewall until battery power is fully expended and the UAS reaches the ocean surface.**

Figures 4-2a-c. *(P-3 eye, UAS eye, UAS eyewall)*

<u>Module/Option 1b: UAS Eye/Eyewall *without* P-3 loiter-</u>

This module is identical to Module 1a with the notable exception that the P-3 does not loiter in the eye. For this module, the target storm can be weaker than in Module 1a (e.g. Category 1) since the P-3 will not loiter in the eye after releasing the UAS at altitude near the TC center of circulation. This module can be conducted in the day time or at night. The UAS patterns identified in Module 1a remain the same for Module 1b. However, the P-3 pattern for Module 1b would include repeated eyewall penetrations using a rotating figure 4 pattern (see Figure 4-3 below). So as to maximize the ability to compare P-3 based observations with UAS observations (primarily PTHU from GPS dropsondes and winds from Doppler radar) the radial legs for the P-3 aircraft should be kept to a minimum in order to maximize the number of eye/eyewall penetrations. For this reason legs ≤ 40nm (measured from the IP to TC center) are preferred. Default P-3 penetration altitude is set to 10,000ft but can be adjusted as mission or storm specific conditions dictate.

For this module, GPS sondes will be released at all leg endpoints, directly in the eyewall and within the eye. This translates to 5 GPS when measured from leg end point to leg end point. In addition, AXBTs will be launched at all end points and for each eyewall penetration, which equates to 4 AXBTs per ‘end point to end point' leg flown. The total number of GPS and AXBT deployed will depend upon how many penetrating legs are conducted. Based on the P-3 leg configuration described above, and assuming a 1hr UAS flight duration, 3 full penetrations should be possible.

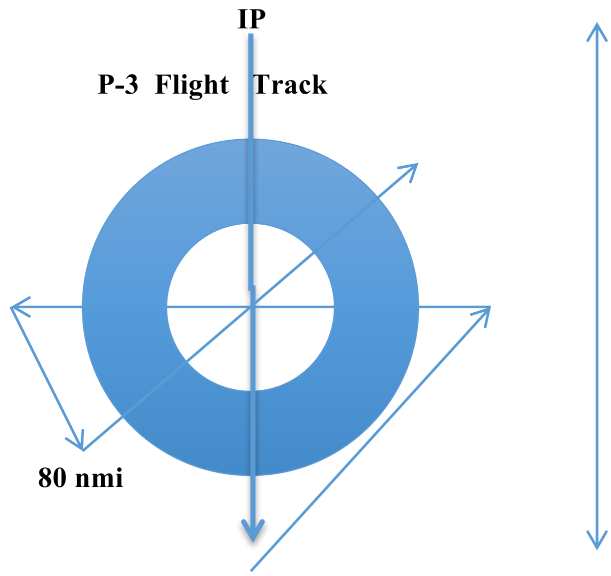


Figure 4-3. *(P-3 'short leg' figure 4 pattern)*

Module/Option 2: Boundary Layer Entrainment/Convective Downdraft module-

This module builds upon and complements the existing 'Boundary Layer Entrainment' (see HFP 2013, experiment 14 for additional details). No modifications to the existing P-3 patterns are required for this module. Instead, the low flying Coyote UAS will conduct very low (down to 100m) stepped descents in addition to patterns flown by the P-3 manned aircraft (see Figure 4-4). These very low altitude UAS patterns should allow for (a more direct) estimation of surface fluxes. In turn, the UAS-derived estimates can then be compared with surface fluxes computed by sampling the top of the boundary layer (residual method). In addition, it is also possible to conduct a UAS box pattern at 100-120m to complement the P-3 1-2km box pattern (not shown) that was designed to estimate divergence in precipitation-free areas.

It should also be noted that an additional goal of this module is to see how vertical mixing occurs above and within the boundary/surface layer just outside areas of active convection (e.g. near rainbands and radially outward of the TC's primary convective envelop). A goal of this module is to compare observational details from these convectively driven processes with comparable output from high-resolution operational regional and global model simulations.

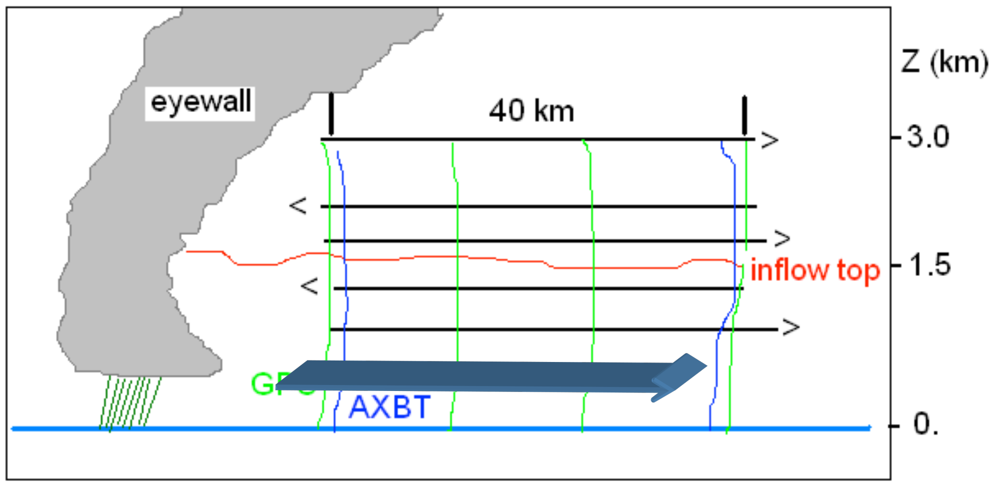


Figure 4-4. *(From HFP Boundary Layer Entrainment Module) Vertical cross-section of the stepped-descent module. P3 pattern is in black, low altitude Coyote UAS in heavy blue.*

Module/Option 3: Enhanced Boundary Layer Inflow Sampling-

This module builds upon the existing 'Boundary Layer Inflow experiment (see HFP 2012, experiment 16 for additional details). As in Modules 1-2, the P-3 pattern remains unchanged. At the IP the Coyote is released and slowly step descends down to 100m as it spirals inward (See Figure 4-5 below). Once at 100m the UAS step ascends up to an altitude just above the inflow layer (~1.5km). Then again descends to 100m. This process continues until eyewall penetration occurs at 500m. Once in the eyewall the UAS step descends in 50m increments every 5 minutes until it reaches 50m and maintains altitude until battery failure.

This module extends work originally conducted by Cione et al. in 2000. It also expands the capabilities associated with the original BLI experiment by providing continuous (vs. instantaneous) data at altitudes, radii and azimuths not previously sampled by GPS sonde deployments. In addition, these UAS data will help capture additional vertical variability associated with the inflow layer as a function of radius from the storm center. Once in the eyewall, UAS observations will provide wind and thermodynamic data utilizing a highly unique step descent eyewall orbiting sampling strategy. Depending on storm conditions and other factors, it may be possible to combine portions of UAS Modules 2 and 3 into one UAS mission.

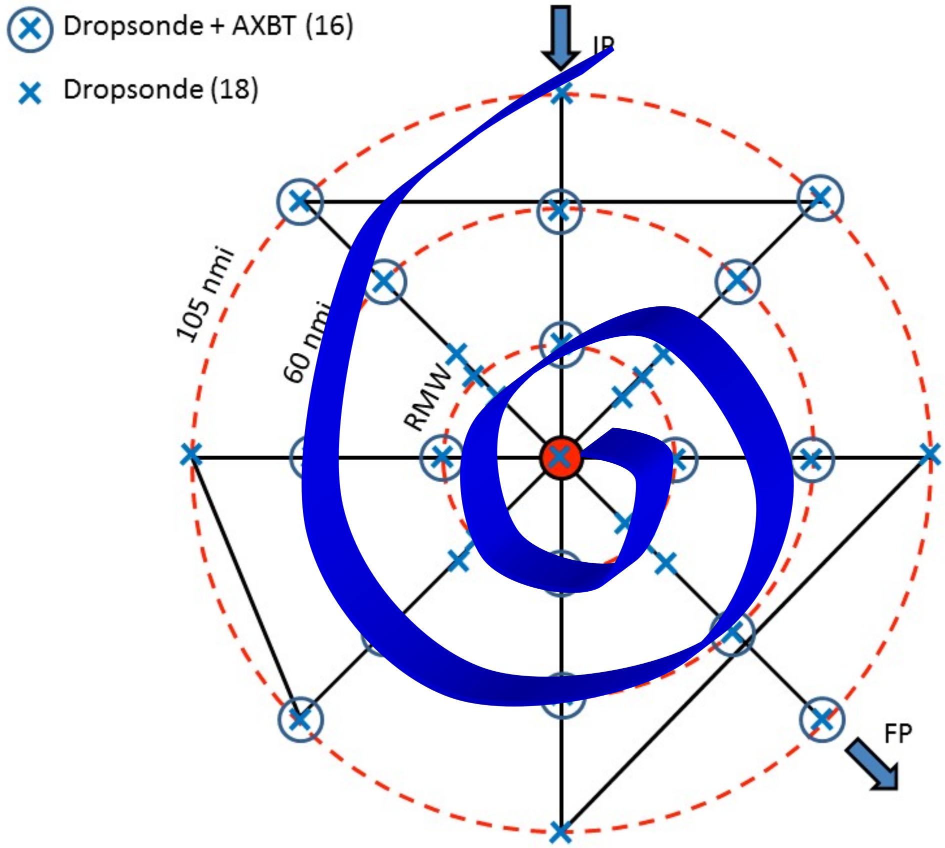


Figure 4-5 *(from the HFP Boundary Layer Inflow Experiment): Boundary Layer Inflow Module. GPS dropwindsondes (34 total) are deployed at 105 nmi and 60 nmi radii and at the radius of maximum wind along each of 8 radial legs (rotated alpha/Figure-4 pattern). On 4 of the 8 passes across the RMW, rapid deployment (~1 min spacing) of 3 sondes is requested. Center drops are requested on the initial and final pass through the eye. AXBT (16 total) deployments are paired with dropsondes at the indicated locations. Flight altitude is as required for the parent TDR mission, and initial and final points of the pattern are dictated by these same TDR mission requirements. Projected Coyote UAS spiral inflow pattern (in heavy blue) is overlayed.*

Module/Option 4: Radius of Maximum Wind (RMW) Mapping-

As in Modules 1-3, the P-3 pattern remains unchanged. After Coyote launch in the eye, the UAS would descend to as low a level as feasible (300 m would be ideal, but 500 to 1000 m would still be of interest) and head outward toward the eyewall and radius of maximum wind (Fig. 4-6). After reaching the RMW, the Coyote would continue outbound and downwind until the winds drop off by 10-20%, perhaps 20-40 nm outside the RMW. Then the UAS would turn inbound and downwind crossing the RMW and reaching the eye. This sequence would continue for the duration of the mission.

One difficulty with this plan may be in fighting the strong boundary layer inflow while trying to fly outbound across the eyewall/RMW. Flying the mission higher (closer to 1000 m vs 30 m) may be required. Mapping out the low-level RMW all the way around a hurricane would be a unique capability, which would be of considerable use in operations.

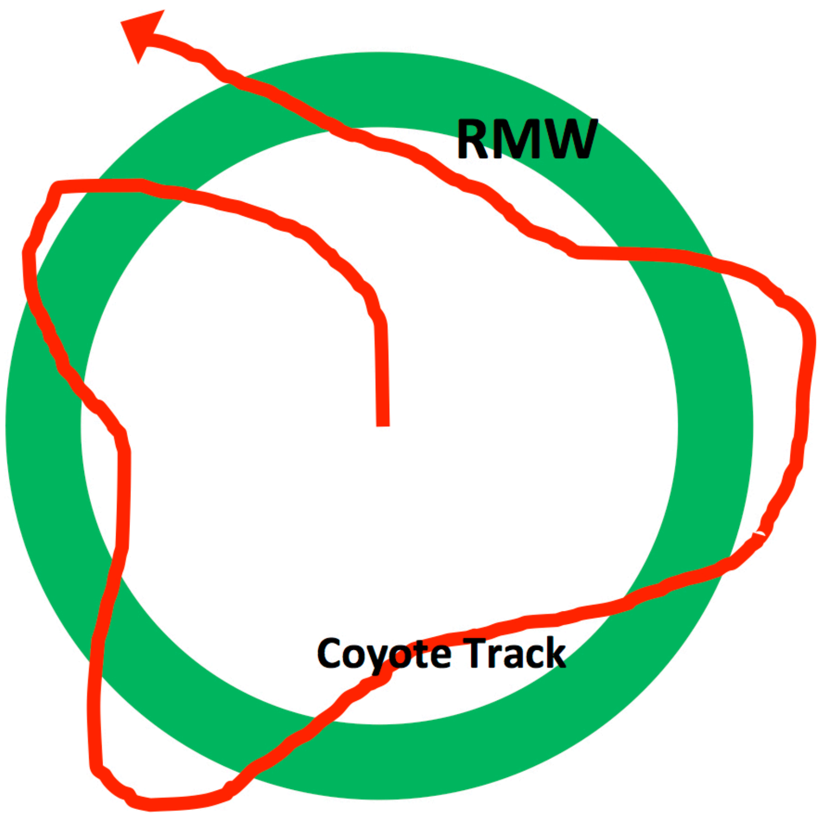


Figure 4-6: *Radius of Maximum Wind (RMW) Mapping. For this module the NOAA P3 pattern is shown in Figure 4-2a. P3 would not be required to continuously loiter. However, P3-UAS range considerations would need to be taken into consideration. Optimally up to 10 GPS/IR sondes would be deployed along with 5 AXBTs. These data would be used to compare with similar ocean/atmospheric data collected by the Coyote UAS. Coyote UAS track is shown in red while the hurricane RMW is denoted by a green ring. Once the UAS is deployed from the P3 within the eye, the Coyote descends to the desired altitude of 300m. Once at this level, the UAS proceeds to the eyewall and begins a counter clockwise flight path. Once the RMW is reached, the UAS continues radially outward and downwind until the maximum wind attained by the platform decreases by ~10-20%. Once this is level is achieved, the Coyote heads inbound and downwind until it enters the storm eye. This sequence would continue for the duration of the mission.*

<u>Module/Option 5: Eddy Dissipation Rate Measurements</u>

For this module, the target storm is a hurricane of any intensity, since low-altitude measurements of eddy dissipation rate and other turbulent quantities are rare in winds of 35 m s^{-1} and greater. To complete this module, approximately 30 minutes of battery life are required. Therefore, this experiment does not need to be the sole focus of a particular Coyote flight. Instead, the eddy dissipation rate measurements can be made following a Coyote eyewall penetration (Module 1) or at the conclusion of the Boundary Layer Inflow experiment (Module 3) or the Radius of Maximum Wind Mapping experiment (Module 4), both of which terminate with the Coyote near or in the eyewall.

The objective is to collect measurements of eddy dissipation rate in strong wind conditions (35 m s^{-1} or greater), with a focus on how the dissipation rate changes with altitude in the lower portion of the tropical cyclone boundary layer and in the surface layer. It is therefore preferable for the Coyote to remain at a constant radius from the tropical cyclone center (ideally at the radius of maximum wind) throughout the experiment. This will prevent the height-dependence of eddy dissipation from being confused with any dependence on distance from the tropical cyclone center.

Figure 4-7 is a schematic of the experimental design. The experiment will begin with the Coyote at a height of 350 m, in the eyewall and/or at the radius of maximum wind. The Coyote then will initiate and maintain a constant descent rate of 1/6 = 0.167 m s^{-1}. This descent rate was chosen because it will allow the Coyote to descend to a height of 50 m at the end of the 30-minute period. At this point, the Coyote may continue to descend at the constant rate, but errors in the GPS vertical position of up to 30 m and waves up to 20 m tall could end the Coyote flight shortly thereafter.

The only requirement of the P-3 flight pattern for this module is that the P-3 remains within 50 km of the Coyote position during the experiment (to prevent loss of communication between the two platforms). This proximity requirement can be satisfied either by the P-3 loitering within the eye (see Module 1a; Fig. 2a) or by the P-3 completing multiple passes through the eye and eyewall using a rotated figure-four pattern with shortened legs (see Module 1b; Fig. 3). The second option may only be feasible in storms with a small radius of maximum wind (15 km or less), since the distance between the P-3 and the Coyote will at times exceed twice the radius of maximum wind when the P-3 samples the opposite side of the storm.

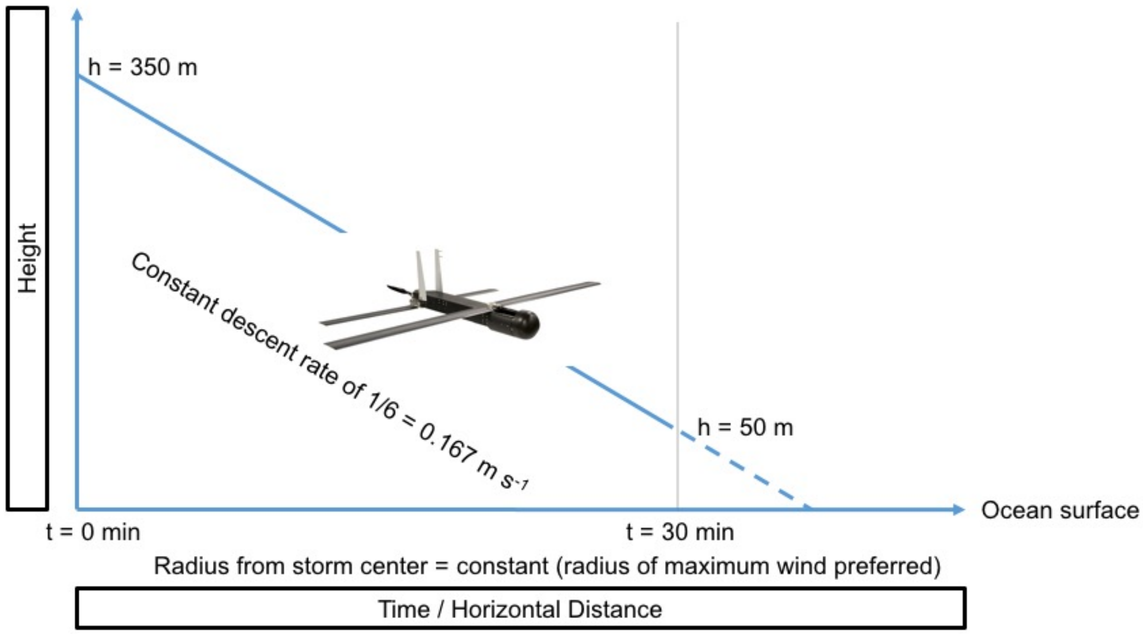


Figure 4-7*: Eddy dissipation measurements. The Coyote begins the experiment at a height of 350 m, descends at a constant rate of 1/6 = 0.167 m* s^{-1}*, and reaches a height of 50 m after 30 minutes. The entire descent is conducted at a constant radius from the storm center (preferably at the radius of maximum wind).*