MATURE STAGE EXPERIMENT
Flight Pattern Descriptions

Experiment/Module: Research In Coordination with Operations Small Uncrewed Air Vehicle Experiment (RICO SUAVE)

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Requirements: Category 1-5

Mature Stage Science Objective(s) Addressed:

1) Test new (or improved) technologies with the potential to fill gaps, both spatially and temporally, in the existing suite of airborne measurements in mature hurricanes. These measurements include improved three-dimensional representation of the hurricane wind field, more spatially dense thermodynamic sampling of the boundary layer and more accurate measurements of ocean surface winds [APHEX Goal 2]

P-3 Pattern #1: *sUAS Eyewall Circumnavigation*

What to Target: Maximize azimuthal coverage of the *core region* of a mature TC

When to Target: After the hurricane eye is formed

Pattern: Any P-3 pattern that maximizes azimuthal eyewall coverage. Given that P-3 sUAS stringent range considerations should be a thing of the past, the P-3 will now be able to "go about its business" and not have to babysit the sUAS. That said, coincident P-3 flight level, TDR, dropsonde, AXBT, SFMR, and CDR observations for sUAS comparison and validation are highly desired. Given this, a P-3 pattern that maximizes eyewall sampling and penetration count would be preferred. Deconfliction between the P-3, sUAS, and other aircraft (e.g., AF C-130s) will be carried out according to inter-agency guidelines described in the *2021 Hurricane Season Small UAS Operating Rules and Deconfliction Procedures* document.

Flight altitude: 10 kft radar for sUAS deployment is requested. After deployment, any altitude that maintains safe sUAS-P3 separation is acceptable.

Leg length or radii: Standard recon leg lengths are possible [105 n mi (195 km)] but not required given that sUAS flight will remain within the core TC region. As such, shorter legs are acceptable and potentially desirable. So long as sUAS-P3 separation is kept to 125 n mi (230 km) or less, no complications should arise with respect to command and control between the sUAS and the P-3.

Estimated in-pattern flight duration: See the listing of standard pattern figures in the section entitled "Standard Patterns and Expendable Locations" section.

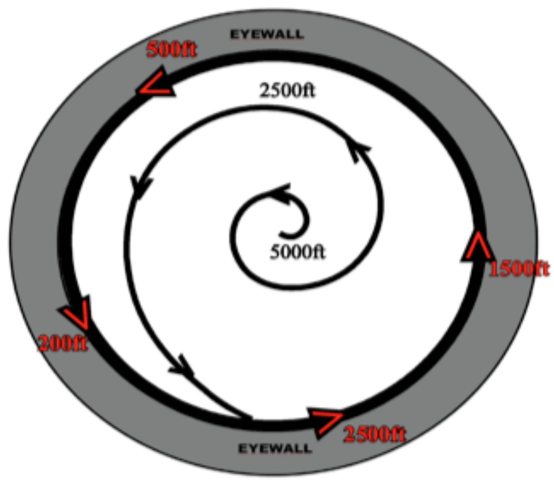
Expendable distribution: For all sUAS modules, establishing a pre-set number of expendables will not be possible. The exact number will depend on storm-specific conditions and the specific P-3 pattern that is ultimately flown. As for expendable types, it is requested that the remaining cache of

SST-capable dropsondes be used for all sUAS missions. In addition, ~10-15 AXBTs per sUAS flight are also desired. The sonde/AXBT deployment CONOP should maximize P-3 location with sUAS "under flight".

Instrumentation notes: Use TDR defaults. Use straight flight legs as safety permits.

sUAS flight details and notes specific to this module:

1. Eyewall/Radius of Maximum Winds Module



Primary Objective: Sample the highest winds of the TC at various altitudes within the eyewall.

Methodology/sUAS flight pattern: To conduct this module, the sUAS is deployed within the eye of a mature hurricane near the circulation center of the storm. A limitation on eye diameter should not exist since the deployment aircraft will not need to 'loiter' with the sUAS after it is released.

After separation from the P3, and stabilization of the sUAS occurs, the drone will descend in a counterclockwise spiral to an altitude of 5000 ft. Once at this altitude, the drone will continue its counterclockwise trajectory, increasing in radius until the sUAS merges and penetrates the eyewall. Once in the eyewall, the sUAS will continue its increasing radius flight plan, maintaining a close monitoring of the environmental wind speed. After the winds peak and begin decreasing, the sUAS slightly adjusts its heading radially inward until the radius of maximum winds are re-established.

Once at the RMW, the sUAS flight heading should continually adjust with the goal of maintaining the local wind direction at its tail.

After a set amount of time, descent to a lower altitude will commence.

Assuming the 1st 20-30 minutes of duration are used to launch, stabilize, transit to the eyewall, and locate the RMW, ~210-220 minutes of flight time should remain. The concept of operation will be for the sUAS to maintain the following 7 flight altitudes (in ft.) for 30 minutes. The "excess" 10-20 minutes are to be consumed during the periods of descent.

5000 3000 1000 500 250 150 100 (in ft.)

Note 1: After each descent is completed, the sUAS should perform a gradual S-pattern to "find" the RMW at the new altitude. Once the RMW is attained, and as noted previously, the aircraft heading should continually adjust, with the goal of maintaining the local wind direction at its tail.

Note2: If additional time remains after the 100 ft. flight leg is complete, the sUAS will attempt to head directly into the wind and continue at this altitude until power is fully exhausted.

P-3 Pattern #2: *sUAS Inflow*

What to Target: Fully document the thermodynamic and kinematic structure of the TC inflow layer

When to Target: After the hurricane eye is formed

Pattern: Preferred flight path would be a standard lawnmower pattern whereby the P-3 flies orthogonal to the sUAS inflow trajectory. As with all sUAS TC missions, coincident P3 flight level, TDR, dropsonde, AXBT, SFMR, and CRL observations for sUAS comparison and validation are highly desired. Deconfliction between the P-3, sUAS, and other aircraft (e.g., AF C-130s) will be carried out according to inter-agency guidelines described in the *2021 Hurricane Season Small UAS Operating Rules and Deconfliction Procedures* document.

Flight altitude: 10k radar for sUAS deployment is requested. After deployment, any altitude that maintains safe sUAS-P3 separation is acceptable.

Leg length or radii: Standard recon leg lengths should be possible [105 n mi (195 km]). So long as sUAS-P3 separation is kept to 125 n mi (230 km) or less, no complications should arise with respect to command and control between the sUAS and the P-3.

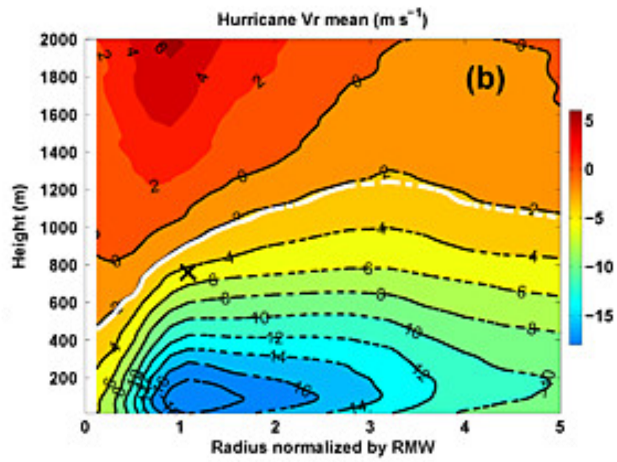
Estimated in-pattern flight duration: See the listing of standard pattern figures in the section entitled "Standard Patterns and Expendable Locations" section.

Expendable distribution: For all sUAS modules, establishing a pre-set number of expendables will not be possible. As for expendable types, it is requested that the remaining cache of SST-capable dropsondes be used for all sUAS missions. In addition, ~10-15 AXBTs per sUAS flight would are also desired. The sonde/AXBT deployment CONOP should maximize P-3 location with sUAS "under flight".

Instrumentation notes: Use TDR defaults. Use straight flight legs as safety permits.

sUAS flight details and notes specific to this module:

2A. Inflow Module A



Hurricane Vr normalized by peak inflow

Primary Objective: Sample the thermodynamic and kinematic structure of the Hurricane inflow/outflow boundary layer.

Methodology/sUAS flight pattern: To conduct this module, the sUAS is deployed at 10 kft in a mature hurricane at the end of a P3 105 n mi (195 km) radial leg (not in the eye).

After separation from the P3, and stabilization of the sUAS occurs, the drone will descend to 3500ft. Once at this altitude, the drone will adjust its heading towards the TC center and orient the local winds at its tail.

Assuming the first 15 min of duration are used to launch, stabilize, and reach the initial 3500 initial inflow altitude, ~105 min of flight time should remain. Note, the assumption here is for a 2 h duration mission since multiple ascents are called for and would result in significant endurance reduction (relative to a nominal 4 h mission typically expected for the long duration sUAS).

For the initial descent, the sUAS will maintain the following 4 flight altitudes for 4 min.

3500 2500 1500 500 (in ft.)

After the 500 ft flight leg is completed, the sUAS will still be over 60 n mi (110 km) from the high wind eyewall when it begins its initial ascent. Each altitude below would be maintained for 5 min.

1000 2000 3000 (in ft.)

Once the 3000 ft altitude is reached, the eyewall is penetrated.
Once in the eyewall, the sUAS will ascend and remain at the noted flight levels below for 5 min:

5000 6500 (in ft.)

After the 6500 ft leg is complete, the sUAS will begin a trajectory that takes it radially outward from the RMW and TC center. The angle of the outward radial spiral will be somewhat aggressive (~30-45) degrees. This outward trajectory will continue for 15 min.

After the outward spiral pattern is complete, the sUAS will re-orient such that the direction of the winds matches the sUAS heading. The sUAS will descend from 6500 ft to the altitudes noted below while maintaining constant altitude for 4 min.

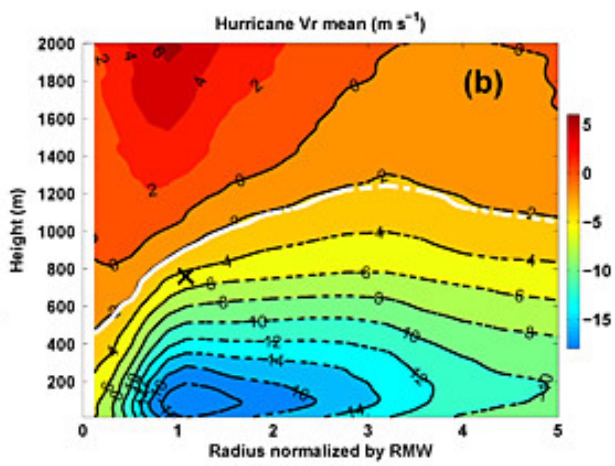
4500 2500 500 250 (in ft.)

After the 250 ft leg is complete, the sUAS merges/penetrates the eyewall and gradually continues radially inward until the sUAS enters the much lower wind speed eye.

Note 1: The assumption of a 120 min mission includes ~30 min of vertical adjustment between the levels mentioned above. Still, there is a fair degree of uncertainty regarding the real world actual duration for this mission given the multiple altitude changes (including upward).

Note 2: If sufficient battery power remains after the drone gets into the eye, the sUAS has the option of attempting to conduct a TC center fix.

2B. Inflow Module B



Hurricane Vr normalized by peak inflow

Primary Objective: Sample the thermodynamic/kinematic structure and turbulence information of the Hurricane inflow/outflow boundary layer. The goal is to retrieve the vertical eddy diffusivity of momentum (Km) in the inflow boundary layer at different wind ranges.

Methodology/sUAS flight pattern: To conduct this module, the sUAS is deployed at 10 kft in a mature hurricane. We launch the sUAS during the P-3 radial leg when surface winds are within 18-30 m s^{-1} and above the hurricane intensity (e.g., 35-55 m s^{-1}). One sUAS is released for each wind range. The retrieved

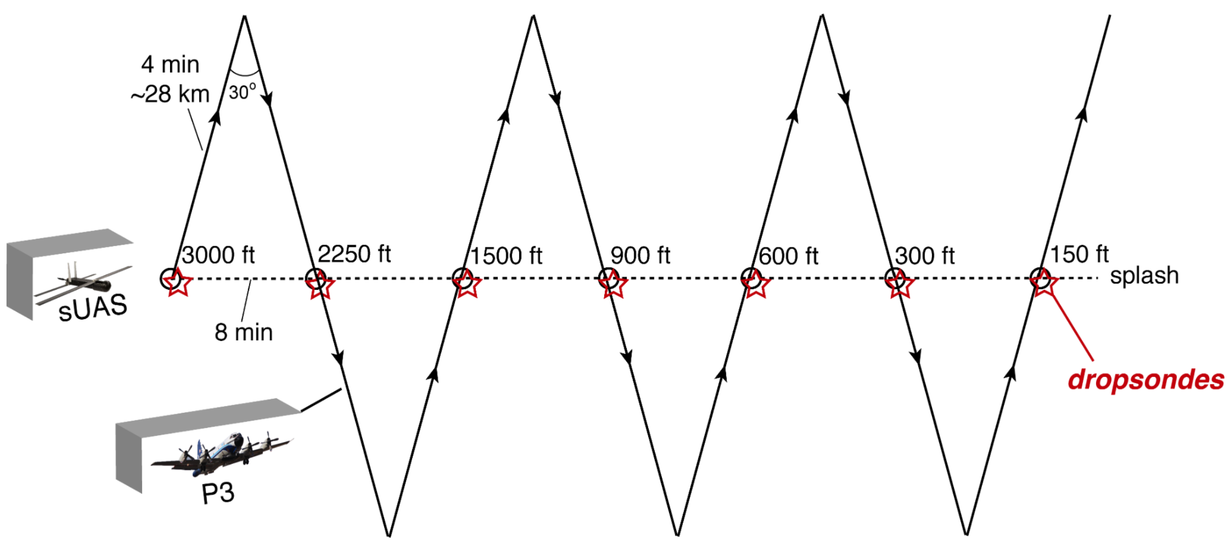
Km under 18-30 m s^{-1} can be directly compared to the results of Zhang and Drennan (2012). In the 35-55 m range, the retrieved Km can be used to evaluate the LES simulations and different PBL schemes.

After separation from the P3, and stabilization of the sUAS occurs, the drone will descend to 3500 ft. Once at this altitude, the drone will adjust its heading towards the TC center and orient the local winds at its tail. Short-duration sUASs (1-1.5h) are preferred. Assuming the first 15 minutes of duration are used to launch, stabilize, and reach the initial 3500 initial inflow altitude, ~45-55 minutes of flight time should remain.

For the initial descent, the sUAS will maintain the following 5 flight altitudes for 7 minutes, which will allow a long enough leg for the turbulence calculation. The 5 altitudes are selected due to the fine vertical structure of Km in the lower boundary layer (see Zhang and Drennan 2012).

2250 1500 900 500 200 (in ft)

The flight patterns for P3 and sUAS are shown below.



***Stepped descend module of sUAS**

At the beginning of each leg of sUAS, a dropsonde is released to get the mean wind information of the environment. Considering the 2-3 min descending between each leg of Coyote, the whole module takes ~1-1.25h.

P-3 Pattern #3: ***sUAS center fix/eye loiter/eye-eyewall sampling module***

What to Target: Hurricane boundary layer eye and eye-eyewall interface

When to Target: After the hurricane eye is formed

Pattern: Any P-3 pattern that maximizes inner core coverage. As with previous modules coincident P3 flight level, TDR, dropsonde, AXBT, CRL, and SFMR observations for sUAS comparison and validation are highly desired. Given this, a P3 pattern that maximizes inner core sampling would be preferred. Deconfliction between the P-3, sUAS, and other aircraft (e.g., AF C-130s) will be carried out according to inter-agency guidelines described in the *2021 Hurricane Season Small UAS Operating Rules and Deconfliction Procedures* document.

Flight altitude: 10 kft radar for sUAS deployment is requested. After deployment, any altitude that maintains safe sUAS-P3 separation is acceptable.

Leg length or radii: Standard recon leg lengths are possible [105 n mi (195 km)] but not required given that sUAS flight will remain within the core TC region. As such, shorter legs are acceptable and potentially desirable. So long as sUAS-P3 separation is kept to 125 n mi (230 km) or less, no complications should arise with respect to command and control between the sUAS and the P-3.

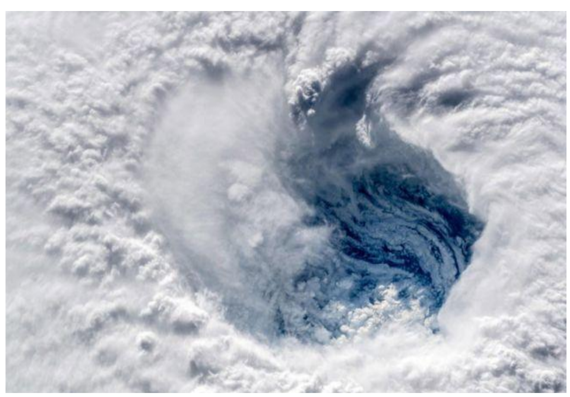
Estimated in-pattern flight duration: See the listing of standard pattern figures in the section entitled "Standard Patterns and Expendable Locations" section.

Expendable distribution: For all sUAS modules, establishing a pre-set number of expendables will not be possible. The exact number will depend on storm-specific conditions and the specific P-3 pattern that is ultimately flown. As for expendable types, it is requested that the remaining cache of SST-capable dropsondes be used for all sUAS missions. In addition, ~10-15 AXBTs per sUAS flight would are also desired. The sonde/AXBT deployment CONOP should maximize P-3 location with sUAS "under flight".

Instrumentation notes: Use TDR defaults. Use straight flight legs as safety permits.

<u>sUAS flight details</u> and notes specific to <u>this</u> module:

3. <u>Center Fix/Eye Loiter/Eye-Eyewall Sampling Module</u>



Primary Objective(s): Conduct one or more TC center fixes; conduct thermodynamic and kinematic eye profiles; loiter in the eye at low altitude.

Methodology/sUAS flight pattern: Prior to deploying the sUAS, the P3 will perform a TC center fix from 10 kft.

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For this module, the sUAS is deployed in the eye of a mature hurricane at 10K feet near the circulation center of the storm. A limitation on eye diameter should not be a factor since the deployment aircraft will not need to 'loiter' with the sUAS after it is released.

After separation from the P3, and stabilization of the sUAS occurs, the drone will descend in a "tight" counterclockwise spiral to an altitude of 1000ft. Once at this altitude, the drone will proceed to the lat/lon pair identified by the most recent NOAA TC estimated center location. At this fine scale, the sUAS will continually adjust its heading to find the lowest pressure as well as minimum wind speed (which, by definition, represents the exact location of the storm's center of circulation).

Once the surface center estimate has been established, the sUAS will conduct a spiral ascent centered around the sUAS center estimate with intermittent "level flight" occurring every 3000 ft. up to 15000ft (*if acceptable after AOC ORM*). Each level flight radius will continue for 2 orbits before resuming the spiral ascent. This process is then to be reversed, with the first level at 12000 and descending in 3000 ft. increments thereafter down to a final altitude of 1000 ft.

After the final sUAS 1000 ft orbit is complete, a second center fix will be attempted and the sUAS will establish a tight orbit around this new center point at 1000ft.

The sUAS will continue to loiter/orbit while attempting to match the estimated heading and forward speed of the TC during this period. This loiter/tracking pattern will continue until 30 minutes of battery time remains.

Finally, in order to provide information on near-surface pressure (and SST) variability within the eye, the sUAS will travel radially outward at 1000 ft to the eyewall edge (where eye diameter will be known). Once at/near the eyewall edge, the sUAS will briefly penetrate the eyewall and remain within the eyewall for 2 minutes before returning to the eye and spiraling back towards the center of the storm and (if time permits) establish a 3rd TC center fix.

Note 1: Careful coordination (assuming ORM approval has been granted) will have to occur during the 15,000 ft. eye profile to make sure the P-3 is not in the eye during the time of sUAS ascent or descent

Note 2: After discussions with NOAA/AOC flight Director Rich Henning about the most efficient way to conduct a center fix with an aircraft capable of measuring winds, he added this. Please consider his comments and expertise when coding up how to autonomously conduct a TC center fix with a small drone.

"For hunting the center, employing the old FD/ARWO methodology of keeping the winds 90 degrees off the track of the UAS is likely to be more efficient. My thought is that by "sniffing" via trial and error for lower pressure and lighter winds that it would take longer to achieve the first and subsequent fixes. You can program in a "desired track parameter" that is 90 degrees off the wind. There is also the corollary method of trying to match ground speed with true airspeed (if GS higher than TAS then turn left or ground speed low turn right (GSHTL) as I learned many years ago) you can program in the 90-degree difference between wind and track along with GSHTL and GSLTR (groundspeed low turn right)."