MATURE STAGE EXPERIMENT
Flight Pattern Description

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

Investigator(s): Joseph Cione, Jun Zhang, Josh Wadler (ERAU), George Bryan (NCAR), Ron Dobosy (NOAA/ARL-ret), Xiaomin Chen (UAH), Altug Aksoy, Sim Aberson, Frank Marks, Kelly Ryan, Brittany Dahl, Johna Rudzin-Schwing (MS State), Josh Alland (NCAR), Rosimar Rios-Berrios (NCAR), Don Lenschow (NCAR), Chris Rozoff (NCAR), Eric Hendricks (NCAR), Falko Judt (NCAR), Jonathan Vigh (NCAR)

Requirements: Categories 2–5

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 wind velocity [*APHEX Goal 2*].
2) Collect observations targeted at better understanding internal processes contributing to mature hurricane structure and intensity change [*APHEX Goals, 1 3*].

P-3 Pattern #1 ***<u>sUAS Eyewall Circumnavigation</u>***

What to Target: Maximize azimuthal coverage of the *core region* of a mature tropical cyclone (TC)

When to Target: After the hurricane eye has formed

Pattern: Any P-3 penetration of the eyewall of a mature hurricane. 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, Tail Doppler Radar (TDR), dropwindsonde, 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) is an issue that has been worked out and will be adopted in the 2023 version of the National Hurricane Operations Plan (NHOP).

Flight altitude: 10 kft radar for sUAS deployment is requested. After deployment, any altitude that maintains safe sUAS-P-3 separation is acceptable.

Leg length or radii: Standard leg lengths are possible [105 n mi (195 km)] but not required given that the sUAS flight will remain within the core region. As such, shorter legs are acceptable and potentially desirable. So long as sUAS-P-3 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.

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Expendable distribution: For all sUAS modules, establishing a pre-set number of expendables will not be possible. The exact number will depend on mission-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. After releasing in the eye, the P-3 may perform circles until communication is established with the sUAS. After communication is established, use straight flight legs as safety permits.

sUAS flight details and notes specific to this module:

1. **Eyewall/RMW Module**

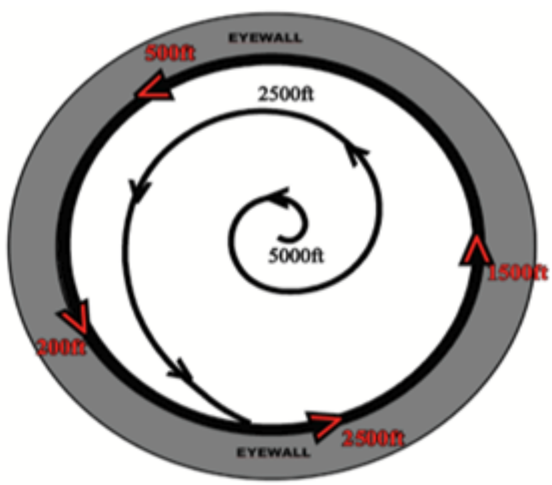

Figure 1: A schematic view of the sUAS eyewall/RMW module

Primary Objective: Sample the maximum wind speed of the hurricane 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. 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 P-3, and stabilization of the sUAS occurs, the sUAS 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 penetrates the eyewall. Once in the eyewall, the sUAS will continue its increasing-radius flight plan, closely monitoring the wind speed. After the wind speed measurements peak and begin decreasing, the sUAS slightly adjusts its heading radially inward until the RMW is re-established.

Once at the radius of maximum wind speed (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 found, the aircraft heading should continually adjust, with the goal of maintaining the local wind direction at its tail.

Note 2: 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 to have a launch location of the sUAS in the downshear-left quadrant. Since a goal of the inflow module would be to sample the region of downdraft cooled air (left image in picture below), the P-3 would fly an inflow pattern in the rain-free region between rainband regions (red arrow in right image below). The P-3 would release up to 10 equally spaced dropsondes along the inflow trajectory. Upon reaching the upshear direction, or reaching precipitation, the P-3 turns towards the eye and begins a standard figure-4 or rotated figure-4 pattern depending on time left in mission. As with all sUAS TC missions, coincident P-3 flight level, TDR, dropsonde, Steamsonde, Airborne eXpendable BathioThermograph (AXBT), Stepped Frequency Microwave Radiometer (SFMR) for sUAS comparison and validation are highly desired. With a figure-4 flight pattern, the coincident observations can happen after the second leg. 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 *2023 NHOP.*

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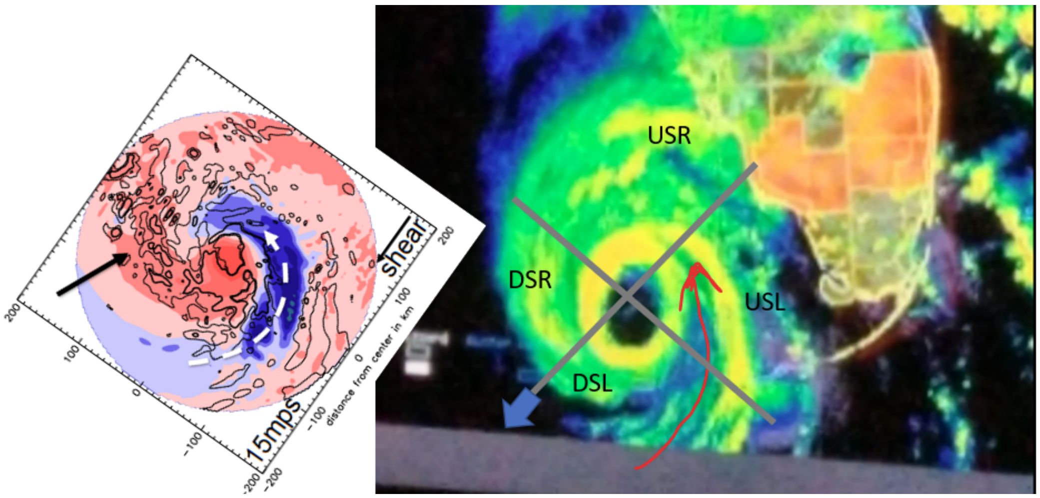

Figure 2: The left panel in the figure is boundary layer entropy in an idealized numerical simulation in Riemer et al. (2010). The white arrow indicates an inflow trajectory which should be on the inner-edge of the principal rainband. That pattern is outlined in the right panel, which is a radar image taken of Hurricane Ian (2022). The shear-relative quadrants: DSR (downshear-right), downshear-left (DSL), upshear-right (USR), and upshear-left (USL) are outlined. The proposed inflow flight pattern for the P-3 is in red.

Flight altitude: 10 kft radar for sUAS deployment is requested. After deployment, any altitude that maintains safe sUAS-P-3 separation is acceptable.

Leg length or radii: After the inflow module, standard leg lengths should be possible [105 n mi (195 km]). So long as sUAS-P-3 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 are also desired. The sonde/AXBT deployment concept of operations (CONOP) should maximize P-3 location with sUAS "under flight".

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

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

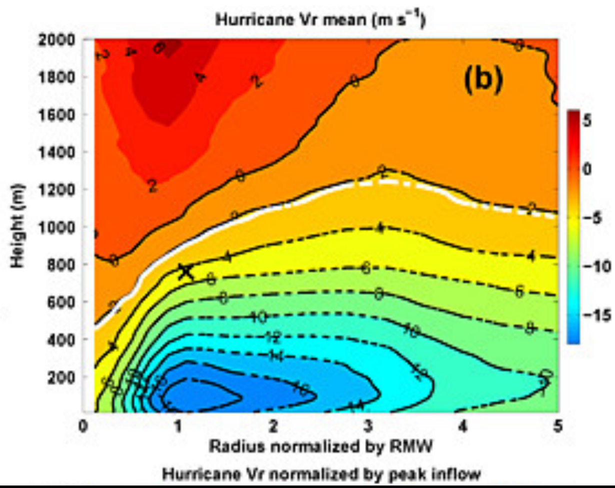

Figure 3: A view of the azimuthally averaged inflow layer

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 P-3 105 n mi (195 km) radial leg (not in the eye; actual distance is dependent on mission logistics but is ideally around 1.5 times the RMW). Ideally, the first radial leg from the P-3 will be from the downshear-right to the upshear-left quadrant, so that the sUAS is released in the upshear-left quadrant. The sUAS will fly near the top of the inflow layer. The inflow layer depth can be determined from the real-time TDR radar analysis in the downshear-right quadrant from the P-3's first pass, but is typically between 1000 m to 1500 m.

After separation from the P-3, and stabilization of the sUAS occurs, the drone will descend to just below the height of the inflow layer. The sUAS should fly the same pattern as the P-3 in the right panel of Figure 2. The ideal radius for the sUAS to start the module is 1.5 times the RMW, which can also be determined from the real-time TDR analysis from the first pass. Once at this radius and altitude, the drone will adjust its heading towards the rain free region between the rainbands.

The first option is for the sUAS to follow the local winds at the same altitude throughout the inflow trajectory. This option is to target air from downdrafts and to estimate parcel trajectories as air flows towards the hurricane eyewall. Ideally, as shown in Figure 2, the P-3 flies the same flight path as the sUAS (at a higher altitude), releasing sonde/AXBT combos, every 30 degrees azimuth. This can be completed in between radial passes of standard flight patterns or right after the launch of the sUAS (preferred). If time remains once the sUAS reaches the eyewall, the mission can be converted to an eyewall module and/or sampling a mesovortex in the eye for a determination of eye-eyewall mixing.

The second option is to have a stepped descent in the inflow layer. This option is to maximize sampling of the boundary layer for model evaluation and comparison. For the initial descent, the sUAS will maintain the following 4 flight altitudes for 4 min each.

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 hurricane 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 track. 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 250ft 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 of the sUAS 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 center fix.

P-3 Pattern #3: ***<u>sUAS inflow-layer turbulence module</u>***

What to Target: Turbulence information at hurricane-force wind speeds in the inflow boundary layer

When to Target: After the hurricane eye is formed, preferred for the mature stage.

Pattern: Any P-3 inbound flight leg, with one sUAS released in the conditions of hurricane-force wind speeds (V_{10} > 65 kt). sUAS will start a stepped-descent mode consisting of 7 flight levels after stabilizing and descending to 3kft height. Prior to the sUAS stepped-descent mode, the P-3 will conduct a "zig-zag" flight pattern (see Fig. 4) such that it can slow down its radial penetration and keep up with the pace of sUAS. P3 will release a dropsonde at the beginning of each sUAS flight leg, up to 7 dropsondes in total.

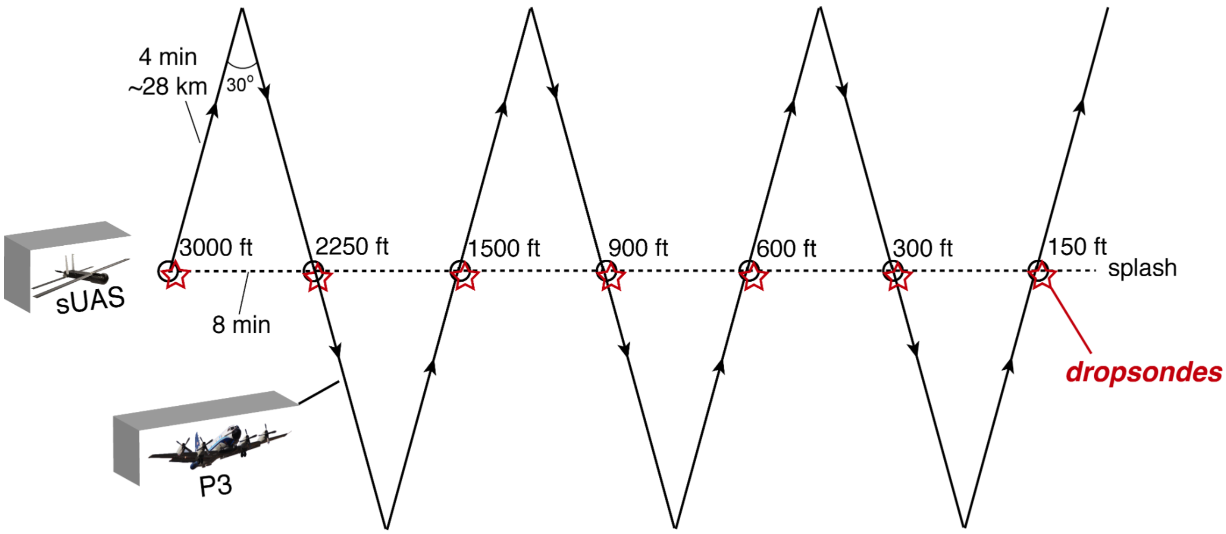

Fig. 4: P-3 and sUAS flight patterns for the inflow-layer turbulence module. sUAS conducts a stepped-descent mode from 3kft (dashed lines), consisting of 7 flight legs at 3000, 2250, 1500, 900, 600, 300, 150 (in ft). P3 flies a "zig-zag" pattern (solid black lines with arrows) to keep up with the speed of sUAS, with a dropsonde (red star) released at the beginning of each sUAS flight leg.

Flight altitude: 10 kft radar for sUAS deployment is requested. After deployment, any altitude that maintains safe sUAS-P-3 separation is acceptable.

Leg length or radii: During the P-3 zig-zag flight pattern, the leg length is ~15 n mi (28 km) for either deviating or approaching the direction of the original flight track. The short separation distance between sUAS and P-3 will involve no complications with respect to command and control between the sUAS and the P-3.

Estimated in-pattern flight duration: 1-1.5 h (see details in the sUAS flight details below).

Expendable distribution: 7 dropsondes per sUAS mission.

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:

Primary Objective: Sample the thermodynamic/kinematic structure and momentum stress in the inflow boundary layer. The goal is to retrieve the vertical profile of eddy viscosity (K_m) at hurricane-force wind speeds.

sUAS flight pattern: To conduct this module, sUAS is expected to be released during the P-3 radial leg at hurricane-force wind speeds (e.g., $V_{10} \approx 35-55$ m s^{-1}). Short-duration sUASs (1-1.5h) are preferred. Assuming the first 15 minutes of duration are used to launch, stabilize, and descend to 3500 ft. Once at this altitude, the sUAS will adjust its heading towards the center and orient the local winds at its tail, with ~45-75 minutes of flight time remaining for the stepped descent. The stepped descent mode of sUAS includes 7 flight legs at different heights (shown below, also see Fig. 4).

3000 2250 1500 900 600 300 150 (in ft)

Each flight leg's duration is ~8 min (can be adjusted to 6 min if necessary). Considering the 2-3 min descending between each leg of the sUAS, the whole module takes ~1-1.5h.

P-3 Pattern #4: ***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. Coincident P-3 flight level, TDR, dropsonde, AXBT, CRL, and SFMR observations for sUAS comparison and validation are highly desired. Given this, a P-3 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 *2023 NHOP.*

Flight altitude: 10 kft radar for sUAS deployment is requested. After deployment, any altitude that maintains safe sUAS-P-3 separation is acceptable.

Leg length or radii: Standard leg lengths are possible [105 n mi (195 km)] but not required given that sUAS flight will remain within the core region. As such, shorter legs are acceptable and potentially desirable. So long as sUAS-P-3 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 mission-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.

sUAS flight details and notes specific to this module:

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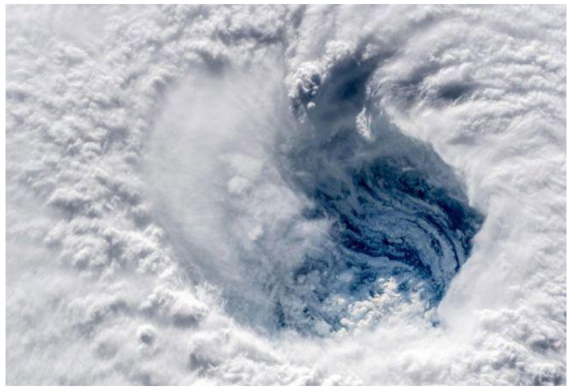

Primary Objective(s): Conduct one or more center fixes; conduct thermodynamic and kinematic eye profiles; loiter in the eye at low altitude.

Methodology/sUAS flight pattern: Prior to deploying the sUAS, the P-3 will perform a center fix from 10 kft.

For this module, the sUAS is deployed in the eye of a mature hurricane at 10K feet near the circulation center. 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 P-3, and stabilization of the sUAS occurs, the drone will descend in a "tight" (i.e., high bank angle) 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 minimum wind speed (which, by definition, represents the exact location of the center of circulation)as well as the lowest pressure as well as .

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

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

The sUAS will continue to loiter/orbit while attempting to match the estimated heading and forward speed of the hurricane 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 hurricane and (if time permits) perform a 3rd 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 aircraft are 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 wind velocity, he added this. Please consider his comments and expertise when coding up how to autonomously conduct a 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)."