MATURE STAGE EXPERIMENT
Pattern and Module Descriptions

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Requirements: Categories 2–5

SCIENCE OBJECTIVE #1: *Collect observations targeted at better understanding internal processes contributing to mature hurricane structure and intensity change. These processes include mixing between the eye and eyewall, secondary eyewall formation, the TC diurnal cycle, and gravity waves that emanate from the TC inner core*
[Internal Processes]

TC DIURNAL CYCLE

P-3 Pattern #1: Internal Processes (TC Diurnal Cycle)

What to Target: Sample the inner core and near environments of the TC

When to Target: Any strength TC (though TC diurnal cycle signals tend to be stronger in Cat 2+ storms); no land restrictions. There are time restrictions for this experiment: in-storm sampling should occur in the time window from ~0200–1200 LST during the early stages of the TC diurnal cycle when the TC diurnal pulse is located at radius, R≤300 km (R≤160 n mi). Approximate radial locations of TC diurnal pulses relative to local time are shown by the TC diurnal clock (see Figure MA-1 in the Mature Stage Science Description). If possible, this P-3 pattern should be conducted in coordination with **G-IV Pattern #1: Internal Processes (TC Diurnal Cycle)**.

Pattern: Any standard P-3 pattern that provides symmetric coverage (e.g. Rotated Figure-4, Figure-4 Butterfly, etc.). Leg lengths should be adjusted as needed to ensure that the aircraft perpendicularly crosses TC diurnal pulses that are indicated by satellite imagery and/or the P-3 LF radar.

Flight altitude: 10–12 kft, or as high as possible to provide better vertical sampling by GPS dropsondes that are deployed.

Leg length or radii: Standard leg lengths (105 n mi), but legs should be extended as needed to ensure that the aircraft perpendicularly crosses TC diurnal pulses that are indicated by satellite imagery and/or the P-3 LF radar.

Estimated in-pattern flight duration: ~2.5–5.0 hr

Expendable distribution: Standard distribution of GPS dropsondes except increased density of ~15–20 n mi (30–35 km) spacing just ahead of, within, and behind the diurnal pulse convective features that will be identified in real-time using satellite imagery and/or the P-3 LF radar (10–25 GPS dropsondes total). AXBTs are not a mission requirement.

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

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G-IV Pattern #1: Internal Processes (TC Diurnal Cycle)

What to Target: Sample the inner core and near environments of the TC

When to Target: Any strength TC (though TC diurnal cycle signals tend to be stronger in Cat2+ storms); no land restrictions. There are time restrictions for this experiment: in-storm sampling should occur in the time window from approximately 0800–1500 LST during the middle to late stages of the TC diurnal cycle when the TC diurnal pulse is located between radius, R~200–400 km (~105–215 n mi). If possible, this G-IV pattern should be conducted in coordination with **P-3 Pattern #1: Internal Processes (TC Diurnal Cycle)**.

Pattern: Standard G-IV Star with Circumnavigation [*optimal*] or Star [*minimal*] pattern. Leg lengths should be adjusted as needed to ensure that the aircraft perpendicularly crosses TC diurnal pulses that are indicated by satellite imagery and/or the P-3 LF radar (if available).

Flight altitude: 41–45 kft, or as high as possible to provide better vertical sampling by GPS dropsondes that are deployed.

Leg length or radii: 190–215 n mi (350–400 km) for the outer points and ~60–90 n mi (110–165 km) for the inner points. If a circumnavigation is being performed, a constant radius [typically 60–90 n mi (110–165 km)] should be selected. Selection of the inner points and circumnavigation radii should be as close to the edge of the inner core convection as possible (this distance will be dictated by safety considerations) and will require coordination between the HRD LPS and the G-IV Flight Director.

Estimated in-pattern flight duration: ~4 hr without circumnavigation and ~5.25 hr with circumnavigation

Expendable distribution: Standard plus mid-points of star pattern (25–31 GPS dropsondes total) except increased density of ~15–20 n mi (30–35 km) spacing just ahead of, within, and behind the diurnal pulse convective features that will be identified in real-time using satellite imagery and/or the P-3 LF radar.

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

GRAVITY WAVE

P-3 Module #1: Internal Processes (Gravity Wave)

What to Target: Sample the inner core and near environments of the TC

When to Target: Any strength TC; no land restrictions. This module ideally should be conducted in quadrant with the least rainband activity, typically the upshear right or right-real quadrant. The best opportunity is at the end of a standard Figure-4 pattern, when the last leg terminates in a quadrant with less rainbands

Pattern: Any standard P-3 pattern that provides symmetric coverage (e.g. Rotated Figure-4, Figure-4 Butterfly, etc.). At the end of the last leg, continue outward to distance of 160 n mi from the center, or further if possible (see Fig. MA-1). Then turn the P-3 around and head directly back to the eye, retracing the previous leg in the opposite direction.

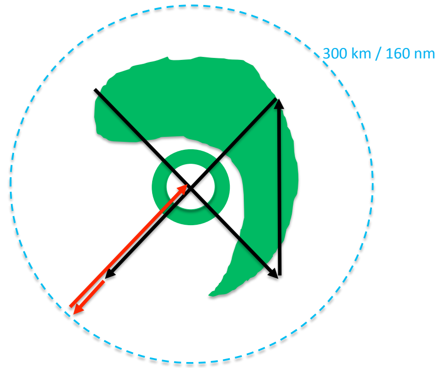

Figure MA-1. *Depiction of the Gravity Wave module in which the P-3 flies an extended leg (160 n mi) (red path) and reverses course along the same azimuth back to the eye*

Flight altitude: 10–12 kft or as high as possible

Leg length or radii: Leg lengths should extend to at least 160 n mi from the center, or further if time permits, including the turn leg back the center

Estimated in-pattern flight duration: ~40 min – 1 hr

Expendable distribution: Dropsonde and AXBTs are not a requirement

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

SECONDARY EYEWALL FORMATION (SEF)

P-3 Module #2: Internal Processes (Pre-SEF)

What to Target: Mature hurricane that has pronounced rainband activity, and possibly a secondary eyewall forming. We are targeting the inside edge of primary rainband and the overall primary rainband.

When to Target: Proposed flight pattern (Fig. MA-2) should take place when microwave satellite imagery indicates the presence of asymmetric rainbands occurring in the storm environment.

Pattern: Fly a combination of a Rotated Figure-4 and a rainband spiral along the inside edge of the rainband, within ~5–10 n mi of the inner edge of the rainband. Fly the spiral pattern straight and level as long as possible, i.e., keeping aircraft bank angle at a minimum, to minimize loss of radar data due to aircraft banking. Ferry time may preclude the second Figure-4.

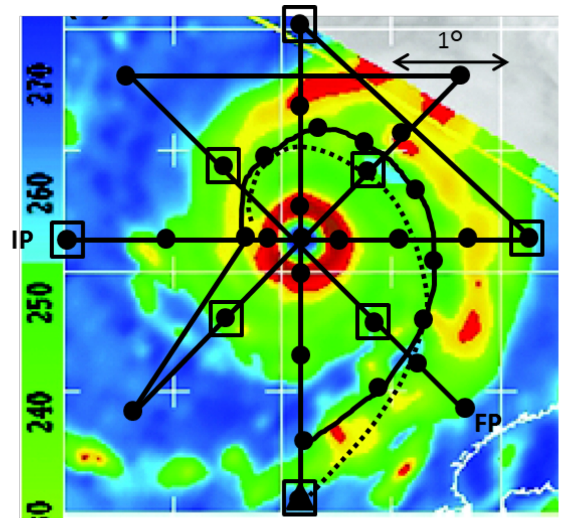

Figure MA-2. *Proposed flight pattern for pre-SEF with the P-3 that includes an initial Figure-4, and a track paralleling the primary rainband*

Flight Altitude: 10–12 kft preferable

Leg length or radii: The flight leg or radii depends on the primary rainband location. Ideally, the extension of the leg should be just outside of the primary rainband as indicated by Fig. MA-2.

Expendable distribution: For P-3, deploy dropsondes at all turn and mid-points in Figure-4, plus first center pass, at four locations in primary eyewall, and in the middle of rainband precipitation feature. Also release dropsonde at ~50 n mi spacing along rainband spiral. If Coyote is available, deploy it following the inflow path where it will collect observations that can be used to calculate boundary layer characteristics outside, within, and inside rainband.

Instrumentation Notes: N/A

P-3 Module #3: Internal Processes (Post-SEF)

What to Target: Mature hurricanes that are expected to have a secondary eyewall already formed or are undergoing an ERC. We are targeting the concentric rings and the moat region.

When to Target: These concentric rings can be easily detected based on radar or microwave satellite imagery. For storms that are already undergoing these ERCs and repeated ERCs are forecast, sampling patterns as indicated in Fig. MA-3 are proposed.

Pattern: Fly a combination of a Rotated Figure-4 and a circumnavigation in the moat region, within ~5–10 n mi of the inner edge of the outer eyewall (see Fig. MA-3). Fly the circumnavigation straight and level as long as possible, i.e., keeping aircraft bank angle at a minimum, to minimize loss of radar data due to aircraft banking. Ferry time may preclude the second Figure-4.

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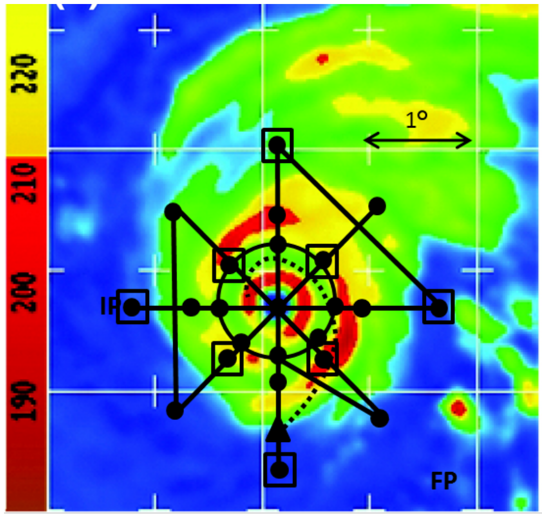

Figure MA-3. *Proposed flight pattern for post-SEF with the P-3 that includes an initial Rotated Figure-4 and a follow-on circumnavigation of the moat region*

Flight Altitude: 10–12 kft preferable

Leg length or radii: The flight leg or radii depends on the primary rainband location. Ideally, the extension of the leg should be just outside of the primary rainband as indicated by Fig. MA-3 and the circumnavigation is inside the moat region.

Expendable distribution: Deploy dropsondes at all turn and mid-points in Rotated Figure-4 survey pattern, plus first center pass, at four locations in primary eyewall. Also release dropsonde at ~50 n mi spacing along circumnavigation in moat region. If Coyote is available, deploy it following the inflow path where it will collect observations that can be used to calculate boundary layer characteristics outside, within, and inside outer eyewall.

Instrumentation Notes: Preferably fly DWL for the circumnavigation, maintaining straight legs as best as possible while executing circumnavigation

G-IV Module #1: Internal Processes (SEF)

What to target: Sample the environment of a TC right outside of the primary rainband

When to target: Proposed flight pattern should take place when microwave satellite imagery indicates the presence of asymmetric rainbands occurring in the storm environment when there is a high chance the storm may undergo SEF. In the case that the ERC is already occurring, these concentric rings can be easily detected based on radar or microwave satellite imagery. Fly the circumnavigation patterns outside of the outer rainband.

Pattern: G-IV Circumnavigation; fly pattern such that the innermost circumnavigation (octagon or hexagon) is as close to outer edge of rainband as is safely allowed. Standard circumnavigation (octagon or hexagon) would work as long as the inner radius is close to outer edge of the rainband.

Flight altitude: 41–45 kft preferable

Leg length or radii: The flight leg or radii depends on the primary rainband location. The innermost radius should be as close to the outer edge of the rainband as is safely allowed.

Expendable distribution: Deploy dropsondes at all turn points. The octagons are all turn points could also be staggered rather than aligned to achieve better azimuthal sonde coverage.

Instrumentation Notes: N/A

EYE-EYEWALL MIXING

P-3 Module #4: Internal Processes (Eye-Eyewall Mixing)

What to Target: This module requires a TC with a clearly defined, visible eye, eyewall, and inversion and an eye diameter of at least 25 n mi.

When to Target: The module should only be attempted during daytime missions. It can be included within any missions during aircraft passage through the eye.

Pattern: This is a break-away pattern that is compatible with any standard pattern with an eye passage (all P-3 patterns except the Square spiral or Lawnmower). The P-3 will penetrate the eyewall at the standard-pattern altitude. Once inside the eye, the P-3 will descend to a safe altitude below the inversion while performing a Figure-4 pattern (Fig. MA-4). The leg lengths will be determined by the eye diameter, with the ends of the legs at least 2 n mi from the edge of the eyewall. Upon completion of the descent, the P-3 will circumnavigate the eye about 2 n mi from the edge of the eyewall in the shape of a pentagon or hexagon (Fig. MA-4). Time permitting; another Figure-4 will be performed during ascent to the original flight level. Depending upon the size of the eye, this pattern should take between 0.5 and 1 h.

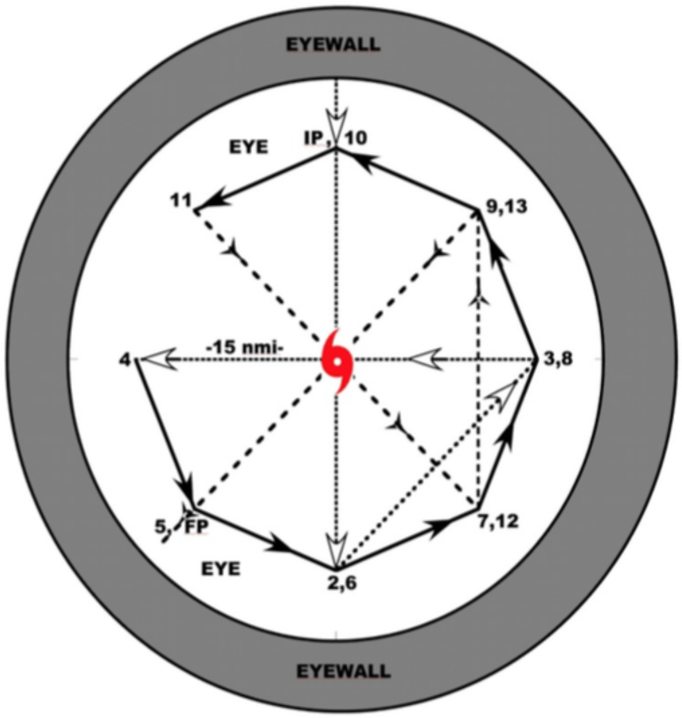

Figure MA-4. *Depiction of the eye-eyewall mixing module*

Flight altitude: The flight altitude will vary from just below the inversion inside the eye to the standard-pattern altitude.

Leg length or radii: The leg lengths will be determined by the eye diameter, with the ends of the legs at least 2 n mi from the edge of the eyewall. Upon completion of the descent, the P-3 will circumnavigate the eye about 2 n mi from the edge of the eyewall in the shape of a pentagon or hexagon.

Estimated in-pattern flight duration Depending upon the size of the eye, this pattern should take between 0.5 and 1 h.

Expendable distribution: No expendables required

Instrumentation Notes: No special instructions for operation. If DWL is available, it should scan downward, though not exclusively, during the pattern. Each leg of the pattern should be straight within safety constraints.

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SCIENCE OBJECTIVE #2: *Collect observations targeted at better understanding the response of mature hurricanes to their changing environment, including changes in vertical wind shear and underlying oceanic conditions* [Environment Interaction]

TC IN SHEAR

P-3 Pattern #1: Environment Interaction (TC in Shear)

What to Target: Sample the *core region* of a TC for which the distance of the center from significant land mass and significant SST gradients exceeds ~ 3x the radius of maximum wind.

When to Target: Sample before a significant increase in environmental vertical wind shear. The P-3 should be coordinated with **G-IV Pattern #1: Environment Interaction (TC in Shear)**.

Pattern: Rotated Figure-4. Alternate patterns: Butterfly; Fig-4; Alpha

Flight altitude: 12 kft preferable for best dropsonde coverage

Leg length or radii: 105 n mi

Estimated in-pattern flight duration: ~ 5 h

Expendable distribution: Modify standard by including an RMW dropsonde, moving the mid-point dropsonde to half the radius of innermost G-IV circumnavigation (or 30 n mi) and removing turn-point dropsondes. Modification ensures eyewall thermodynamic coverage and 30 n mi radial sampling of thermodynamic fields immediately outside the eyewall. Modification also leverages availability of G-IV dropsondes (20 dropsondes total).

Instrumentation Notes: Use TDR defaults. Use straight flight legs as safety permits. Inbound-outbound passes should be uninterrupted.

P-3 Pattern #2: Environment Interaction (TC in Shear)

What to Target: Sample the *core region* of a TC for which the distance of the center from significant land mass and significant SST gradients exceeds ~ 3x the radius of maximum wind.

When to Target: Sample as the large-scale, deep-layer shear increases and downshear convective asymmetry is evident; when the TC core exhibits large vertical tilt (an intensifying TC may have reduced its rate of intensification or begun to weaken); and when the TC core has realigned (a weakening or steady state TC may have begun to intensify).

Pattern: Figure-4, fly 45 deg downwind, then uninterrupted small-scale Rotated Figure-4. Orient initial pass along shear vector if possible. Purpose of small-scale Rotated Figure-4 is high-temporal-resolution sampling of eyewall and near-eyewall thermodynamic structure. Alternate (small-scale) patterns: Butterfly for coarser azimuthal sampling; P-3 Circumnavigation

Flight altitude: 12 kft preferable for best dropsonde coverage

Leg length or radii: 105 n mi (initial Figure-4); small-scale Rotated Figure-4 should extend just beyond the primary region of organized convection outside the eyewall (~15–30 n mi beyond *mean* radius of maximum wind).

Estimated in-pattern flight duration: ~ 4 h 45 min for Figure-4 + Rotated Figure-4 (45 n mi legs)

Expendable distribution: For initial Figure-4, modify standard by removing mid-point dropsondes (if G-IV present, remove IP and turn-point dropsondes). For small-scale Rotated Figure-4, modify standard by launching 4 equally-spaced dropsondes from the *mean* radius of maximum wind to the turn point of each leg (42 dropsondes total, 38 if G-IV present). Given limited resources, may target only quadrant *downwind* of organized convection (22 dropsondes total, 18 if G-IV present).

Instrumentation Notes: Use TDR defaults. Use straight flight legs as safety permits. Inbound-outbound passes should be uninterrupted.

G-IV Pattern #1: Environment Interaction (TC in Shear)

What to Target: Sample the *environment* of a TC for which the distance of the center from significant land mass and significant SST gradients exceeds ~ 3x the radius of maximum wind.

When to Target: Sample before a significant increase in environmental vertical wind shear; during the period of maximum vortex tilt. Coordinate G-IV takeoff with the corresponding P-3 mission such that the innermost G-IV circumnavigation coincides with the P-3 sampling.

Pattern: G-IV Circumnavigation (Hexagon). Should be storm centered. Alternate patterns: G-IV Circumnavigation (Octagon) for more sondes; G-IV Star if TDR coverage is not crucial

Flight altitude: 41–45 kft

Leg length or radii: 150 n mi, 90 n mi, and 60 n mi

Estimated in-pattern flight duration: ~ 4 h 25 min

Expendable distribution: Standard (18 dropsondes total).

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

<u>ARC CLOUD</u>

P-3 Module #1: Environment Interaction (Arc Cloud)

What to Target: Large arc cloud features (100’s of km in length) emanating from the periphery of TCs

When to Target: There are optimal times of day when large arc clouds occur and therefore preferred times of day for conducting this module. Arc clouds are linked to the position of radially propagating TC diurnal pulses that pass through areas of dry mid-level air (≤45 mm Total Precipitable Water

[TPW]) and therefore will tend to occur from ~0400–1200 LST in the approximate radial operating area of the P-3.

Pattern: Transect orthogonal to the radially propagating arc cloud

Flight altitude: 10–12 kft, or as high as possible to provide better vertical sampling of arc clouds by GPS dropsondes that are deployed

Leg length or radii: Variable depending on the location of the arc cloud, but a transect through the arc cloud should be made that spans from the convective area where the arc cloud originated to at least 20 km beyond the leading edge of the arc cloud.

Estimated in-pattern flight duration: ~30–60 min added to the mission

Expendable distribution: GPS dropsonde spacing should be ~10 n mi (20 km) [reduced to ~5 n mi (~10 km) spacing closer (10 n mi [20 km]) to the arc cloud] and the transect can be made inbound (sampling in front of, across, and behind the arc cloud) or outbound (sampling behind, across, and then ahead of the arc cloud) relative to the convective core region of the AEW/TC.

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

G-IV Module #1: Environment Interaction (Arc Cloud)

What to Target: Large arc cloud features (100's of km in length) emanating from the periphery of TCs.

When to Target: There are optimal times of day when large arc clouds occur and therefore preferred times of day for conducting this module. Arc clouds are linked to the position of radially propagating TC diurnal pulses that pass through areas of dry mid-level air (≤45 mm TPW) and therefore will tend to occur from ~0400–1500 LST in the approximate radial operating area of the G-IV.

Pattern: Arc cloud transect

Flight altitude: 41–45 kft, or as high as possible to provide better vertical sampling of arc clouds by GPS dropsondes that are deployed

Leg length or radii: Variable depending on the location of the arc cloud, but a transect through the arc cloud should be made that spans from the convective area where the arc cloud originated to at least 30 n mi (50 km) beyond the leading edge of the arc cloud.

Estimated in-pattern flight duration: ~30 min added to the mission

Expendable distribution: GPS dropsonde spacing should be ~20 n mi (~35 km) and the transect can be made inbound (sampling in front of, across, and behind the arc cloud) or outbound (sampling behind, across, and then ahead of the arc cloud) relative to the convective core region of the AEW/TC.

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

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SCIENCE OBJECTIVE #3: *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*
[New Observing Systems (NOS)]

COYOTE

P-3 Module #1: NOS (Coyote, Eyewall A)

What to Target: Sample the *core region* of a mature TC

When to Target: After the hurricane eye is formed

Pattern: "Sun Pattern" with varying orientation and number of "rays" (Fig. MA-5) or "Pizza Slice" pattern with varying orientation and number of "slices" (see Fig. MA-6). Orientation will be determined by characteristics of the hurricane.

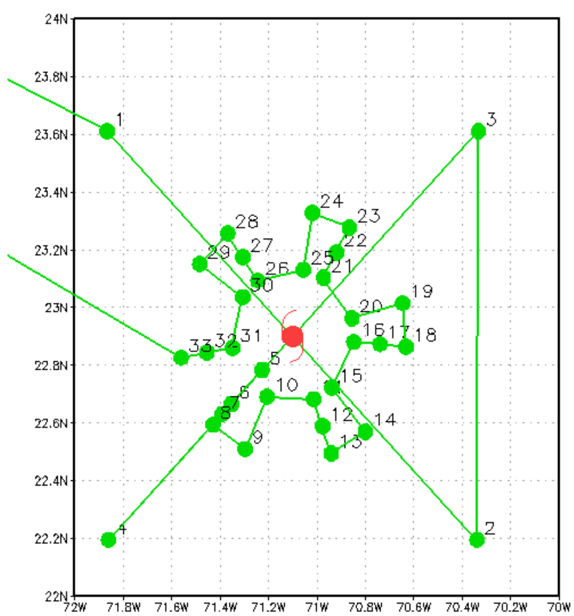

Figure MA-5. *Example "sun pattern"*

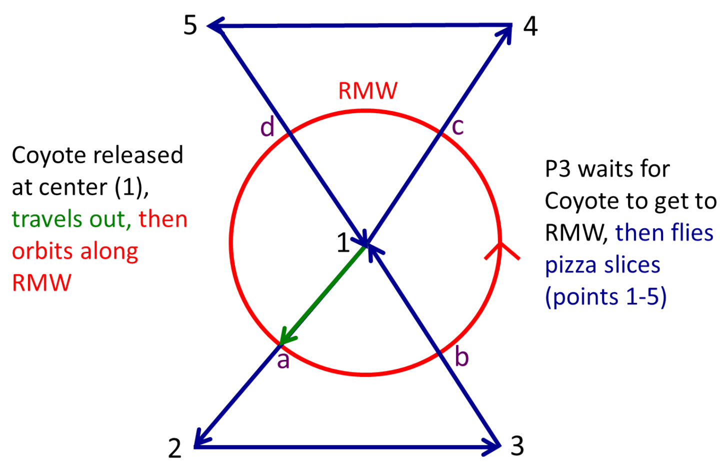

Figure MA-6. *Example "pizza slice" pattern*

Flight altitude: 10–12 kft

Leg length or radii: Will depend on radius of maximum wind (RMW) and estimated wind-speed intensity (longest legs such that Coyote-P-3 communication is maintained)

Estimated in-pattern flight duration: ~ 1 h

Expendable distribution: The Coyote UAS will be dropped in the eye and directed at an orientation determined by the characteristics of the hurricane. 1 center sonde and 2 sondes per ray/slice are required for this module (i.e. a total of 13 sondes for a 3 ray/slice pattern). Dropsondes will be deployed along the RMW such that they fall within 10 km of the Coyote at the given time (but no closer than 5 km). For this module, IR sondes are used at outer and inner portions of each ray/slice and for the center drop. If available, AXBTs will accompany outer IR sondes.

Instrumentation Notes: Use straight flight legs as safety permits.

P-3 Module #2: NOS (Coyote, Eyewall B)

What to Target: Sample the azimuthal location of the maximum wind (Vmax) of a mature TC *after* a P-3 Figure-4 is complete and provides sufficient TDR coverage of the RMW

When to Target: After the hurricane eye is formed and after Vmax azimuth is identified

Pattern: "Sun Pattern" with 2nd or 3rd leg oriented along the same azimuth as Vmax and a varying number of "rays" (Fig. MA-5) or "Pizza Slice" pattern with 1st or 2nd leg oriented along the same azimuth as Vmax and a varying number of "slices" (see Fig. MA-6). Variation of P-3 Pattern 1; see **Figure 3** for additional sondes. Orientation will be determined by characteristics of the hurricane.

Flight altitude: 10–12 kft

Leg length or radii: Will depend on radius of maximum wind (RMW) and estimated RMW wind-speed (longest legs such that Coyote-P-3 communication is maintained)

Estimated in-pattern flight duration: ~ 1 h

Expendable distribution: The Coyote UAS will be dropped in the eye and will be directed at an azimuth larger than that of Vmax. This first azimuth will be determined by the estimated hurricane wind speed and will allow the Coyote to reach the azimuth of Vmax at ~20 minutes into the module. 1 center sonde and 2 sondes per ray/slice are required for this module (i.e. a total of 13 sondes for a 3 ray/slice pattern) in addition to 6 sondes deployed on either side of the RMW during inbound/outbound legs along the Vmax azimuth. RMW sondes will be deployed along the RMW such that they fall within 10 km of the Coyote at the given time (but no closer than 5 km). For this module, IR sondes are used at outer and inner portions of each ray/slice and for the center drop. If available, AXBTs will accompany outer IR sondes.

Instrumentation Notes: Use straight flight legs as safety permits

P-3 Module #3: NOS (Coyote, Inflow)

What to Target: Sample the *inflow layer* of a TC

When to Target: No constraint

Pattern: Lawnmower pattern; number of legs determined by estimated hurricane RMW and wind speed

Flight altitude: 10–12 kft

Leg length or radii: Determined by estimated speed of inflow (longest legs such that Coyote-P-3 communication is maintained)

Estimated in-pattern flight duration: ~ 1 h

Expendable distribution: 1 sonde during each P-3-Coyote path intersect such that they fall within 10 km of the Coyote at the given time (but no closer than 5 km) and at select turn points. A total of 8 drops are estimated, and IRsondes are preferred. Up to 3 AXBTs may be deployed as well (LPS discretion).

Instrumentation Notes: Use straight flight legs as safety permits

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NESDIS OCEAN WINDS

P-3 Pattern #1: NOS (Ocean Winds)

What to Target: The highest-wind region of a TC

When to Target: The ideal ocean winds storm would typically be a developed hurricane (category 1 and above) where a large range of wind speeds and rain rates would be found. However, data collected within tropical depressions and tropical storms would still provide very useful observations of rain impacts.

Pattern: Start with a survey pattern (Figure-4 or Butterfly). Then execute a racetrack or Lawnmower pattern over a feature of interest such as a rain band or wind band. Constant bank circles of 10–30 degrees: inserted along flight legs where the desired environmental conditions were present (region of no rain and where we might expect the winds to be consistent over a range of about 6–10 miles, about the diameter of a circle). This would not be something we would want to do in a high gradient region where the conditions would change significantly while we did the circle.

Flight altitude: The sensitivity of the IWRAP system defines the preferred flight altitude to be below 10 kft to enable the system to still measure the ocean surface in the presence of rain conditions typical of tropical systems. With the Air Force typically flying at 10-kft pressure, we have typically ended up with an operating altitude of 7-kft radar.

Leg length or radii: Initial survey extends 20–50 n mi from the storm center. The actual distance would be dictated by the storm size and safety of flight considerations. The racetrack/Lawnmower legs are just long enough to cover the feature of interest.

Estimated in-pattern flight duration Typically 8–9 h for full-duration mission

Expendable distribution: Sondes dropped in high-wind regions

Instrumentation Notes: Operating at a constant radar altitude is desired to minimize changes in range and thus measurement footprint on the ground. Higher altitudes would limit the ability of IWRAP consistently see the surface during precipitation, but these altitudes would provide useful data, such as measurements through the melting layer, to study some of the broader scientific questions. Straight and level flight with a nominal pitch offset unique to each P-3 is desired during most flight legs.