Appendix A

Tropical Cyclogenesis Module

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Program Significance: Tropical cyclogenesis can be viewed as a rapid increase of low-level cyclonic vorticity organized on the mesoscale within a region of enhanced convective activity. Numerous hypotheses have been advanced in the literature to explain how this vorticity develops and amplifies. In many of these genesis hypotheses an incipient midlevel (e.g., 850 – 500 mb) cyclonic vortex is required for development of the low-level cyclonic circulation. Where these hypotheses differ is in the role that the midlevel vortex plays in genesis. In one theory, downdrafts driven by evaporational cooling advect the vorticity of the midlevel vortex downward, enhancing convection and low-level vorticity production. Observations of multiple midlevel vortices prior to genesis have led some to view the genesis process as a stochastic one whereby chance merger and axisymmetrization of these midlevel vortices leads to growth of the circulation to the surface. Another hypothesis emphasizes the role of the midlevel vortex in axisymmetrizing nearby low-level convectively-generated cyclonic vorticity, leading to spin-up of the surface circulation. Yet another hypothesis emphasizes the role the midlevel vortex plays in providing a favorably-reduced local Rossby radius of deformation to retain the heating from convective bursts and spin up low-level vorticity through low-level stretching caused by the convective heating. The purpose of the proposed experiment is to identify what role, if any, midlevel vortices play in organizing and amplifying low-level cyclonic vorticity.

Since the onset of deep, moist convection is a crucial component in tropical cyclogenesis, the identification of large-scale environments favorable for such convective activity is an important step in identifying likely candidates for genesis. Environments favorable for genesis in the Atlantic Ocean have been revealed by composites of operational analyses and case studies of genesis and lysis events. Western and eastern Atlantic composites have shown the dynamical importance of ascent forced through cyclonic vorticity advection (CVA) in the incipient storm environment. Over the eastern Atlantic, this vorticity advection is generally found equatorward of a 200 mb zonally-oriented ridge axis in association with an upper-level easterly jet, while over the western Atlantic the CVA occurs downstream (upstream) of a 200 mb trough (ridge). In both composites the low-level disturbance is located beneath an area of CVA and near a minimum in vertical wind shear (200 mb-ATOLL level). Developing disturbances in both regions of the Atlantic are found downstream of a 700 mb southeasterly jet along the equatorward side of a ridge axis. The conditions important in the Atlantic basin are similar to those found to be important in other basins, where conditions of weak vertical shear, low-level positive vorticity, and the repeated development of convective bursts are all necessary conditions for tropical cyclogenesis.

Recent observations from airborne Doppler radar have identified important processes on the mesoscale that contribute to tropical cyclogenesis. For example, results obtained from a WP-3D aircraft investigation of Dolly (1996) indicate its genesis was strongly influenced by persistent, deep convection in the form of mesoscale convective systems (MCSs) that developed in association with an easterly wave over the Caribbean. Within this deep convection an eye-like feature formed, after which time the system was declared a depression. The initial development of the low-level circulation in both Dolly (1996) and Guillermo (1991) occurred in the presence of multiple midlevel vortices. The close proximity of the low- and mid-level vorticity maxima (often within 50-100 km horizontally) observed in these two genesis cases supports a further examination of the aforementioned vortex merger ideas. To adequately diagnose the role of the midlevel vortex, it is vital that it be sampled in its entirety (which will invariably depend on the distribution of precipitation scatterers) and with a temporal resolution that allows time continuity of the vortex to be established. For a complete picture detailed observations of the mid- and low-level thermal and moisture fields are also necessary.

Since both tropical cyclogenesis and tropical cyclone intensity change can be defined by changes in low- and mid-level vorticity, knowledge of the processes that play a significant role in genesis will also advance our understanding of intensity change. A better understanding of the processes that lead to an increase in low- and mid-level cyclonic vorticity will also allow NHC to better monitor and forecast tropical cyclogenesis and intensity change, improvements that would be especially valuable for those events that threaten coastal areas. Data obtained by aircraft investigating potential genesis events will positively impact operations and research in other ways as well. The ingestion of this data into the NCEP model analysis and initialization schemes will permit an improvement in NCEP model forecast performance based upon a better representation of the mesoscale and synoptic-scale structure in the vicinity of the incipient disturbance. In addition to improving the understanding and forecasting of tropical cyclogenesis and intensity change, the proposed experiment will yield useful insight into the structure, growth and ultimately the predictability of the systems responsible for almost all of the weather-related destruction in the tropical Atlantic. Investigation of systems that fail to complete the genesis process will also result in a better understanding and prediction of easterly disturbances in general so that distinction can be better made between developing and non-developing tropical disturbances.

Objectives: In keeping with the discussions above, the objectives of this experiment are as follows:

- Develop means for identifying likely candidates for tropical cyclogenesis and techniques for finding and tracking midlevel vortices within these candidates.
- Investigate role, if any, that midlevel vortex plays in organizing deep convection.
- Document the development of low-level vorticity in the presence of a midlevel vortex center.
- Study the interactions between low- and mid-level vortices in pre-genesis environments.

Mission Description: This experiment may be executed with aircraft from NOAA alone, or NOAA in cooperation with the USAF flying into pre-genesis and incipient tropical disturbances over the Atlantic Ocean, Caribbean Sea, Gulf of Mexico, and tropical eastern North Pacific Ocean. The primary mission will require two WP-3Ds flying back-to-back with the G-IV aircraft flying a coordinated pattern. The two WP-3Ds will fly mesoscale patterns in close proximity to any suspected mid-level vortices while the G-IV simultaneously flies at upper levels (200-300 mb) and collects observations to a distance of ~1500 km from the center of the disturbance. Crucial to a complete understanding of the genesis process is the collection of observations with high temporal and spatial resolution. Therefore, the staggered WP-3D missions are designed to commence on station at 3am local and again on station at 3 pm local. The G-IV mission would occur coincident with the afternoon flight and consistent with synoptic missions centered on the 00 GMT synoptic time. If available, the USAF WC-130 aircraft can be used to enhance flight-level observations.

The main aircraft for the mesoscale flights will be the two WP-3Ds. Doppler radar observations, GPS-sondes, and flight level observations obtained during these flights will help locate low- and mid-level vortices and help document their structures and life cycles. A primary aspect of this experiment will be to observe the complete life cycle and interaction of low- and mid-level vortices and understand how these vortices are influenced by the diurnal cycle of convection. The location of persistent areas of deep convection and candidate vortices will be determined using high-resolution visible and infrared GOES-winds produced at HRD and rapid-scan and super-rapid-scan visible satellite imagery provided by CIRA/Colorado State University. Additionally, favorable large-scale environments for deep convection and vortex development, such as those described in the Introduction, will be identified using water vapor loops, model analysis fields enhanced by satellite winds, and QuikScat imagery, all available at HRD.

Staggered missions with the two WP-3D aircraft will begin with the first aircraft flying one of the low-level patterns at 700-500 mb (10,000-18,000 ft) shown in Fig. 1. Leg lengths will be 325-430 nmi (600-800 km), and the pattern will be centered approximately on the vortex as identified from satellite analyses. The benefit of the diamond pattern shown in Fig. 1b is that it covers a relatively broad horizontal area, while the return flight allows for some temporal continuity (on the order of 3 hours) to the data. The primary purpose of these aircraft missions will be to collect F/AST Doppler radar and GPS-sonde data in the area of deep convection in order to map the evolution of the three-dimensional wind and thermodynamic structure of the deep convection and incipient vortex. Once a mid-level vortex is identified the aircraft will fly a pattern centered on the vortex (Fig. 2). Flight legs will be significantly reduced in length [100-135 nmi (180-250 km)] to allow for the collection of data with high temporal and spatial resolution in the vicinity of the vortex. The length of these flight legs is designed to completely include any low-level vortex within about 50-100 km of the midlevel vortex center. This will be important in documenting any interaction between the midlevel and low-level vortices.

If available, the G-IV will be most beneficial flying a synoptic-scale pattern. It will fly at maximum altitude observing the upper and lower troposphere with GPS-sondes in the pre-genesis and incipient tropical disturbance environment. A potential genesis event occurring in conjunction with primarily an upper tropospheric anticyclone will require a flight pattern similar to that given in Fig. 3a. The aircraft will dispense 20-25 GPS-sondes mostly on the poleward side of the incipient disturbance during the flight to help define wind, temperature and moisture patterns near the ridge axis. Should a potential genesis event occur in association with an upper-tropospheric trough-ridge couplet a flight pattern similar to that shown in Fig. 3b will be required. This flight pattern will collect observations in the vicinity of both the trough and ridge with upwards of 20-25 GPS-sondes. These flight patterns are designed to define those regions where large-scale forcing for ascent exists and persistent deep convection is favored.

An enhancement of the data collected during genesis by the three NOAA aircraft may be accomplished by adding observations from investigative USAF WC-130 aircraft. Should a USAF WC-130 aircraft be available it would be requested to fly at maximum altitude dispensing GPS-sondes in the southern and eastern quadrants of the incipient disturbance. This aircraft would be requested to fly a saw-tooth pattern centered on asymptotes of confluence, convective inflow bands, and/or thermal boundaries within ~300 nmi (500 km) of the incipient disturbance.

In addition to the satellite and airborne data described above, temperature soundings of the mid- and upper-level thermodynamic environment of the system will be obtained using the GOES satellite and the AMSU instrument aboard the polar-orbiting NOAA-15 satellite. These observations will yield important information about the response of the vortex's thermal structure to the convective bursts that will complement well the GPS sondes dropped from the aircraft. SSM/I imagery, available from the World Wide Web, will also be used to infer the intensity of incipient disturbances during times when the aircraft are not flying.

The possible availability of multiple aircraft during this experiment leads to several different scenarios. A summary of the potential combinations of aircraft during genesis experiments follows:

- Option 1 (lesser experiment):

The two core NOAA WP-3D aircraft alone will fly staggered figure-4 or grid patterns (Figs. 1-2) centered on the area of persistent deep convection and/or any low level vortex over a 2-4 day period.

- Option 2 (primary experiment):

Option 1 augmented with large-scale upper- and lower-tropospheric observations obtained by the G-IV aircraft flying patterns similar to those given in Fig. 3.

- Option 3 (optimal experiments):

A) Option 2 with USAF WC-130 flying a standard reconnaissance mission.

B) Option 2 with USAF WC-130 flying a targeted mission to sample asymptotes of confluence, convective inflow bands, and/or thermal boundaries within ~300 nmi (500 km) of the incipient disturbance.

C) Option 2 with the G-IV aircraft to collect quasi-continuous observations in the upper and lower troposphere within ~900 nmi (1500 km) of the disturbance.

D) Option 3B with the G-IV aircraft to collect quasi-continuous observations in the upper and lower troposphere within ~900 nmi (1500 km) of the disturbance.

TROPICAL CYCLOGENESIS EXPERIMENT

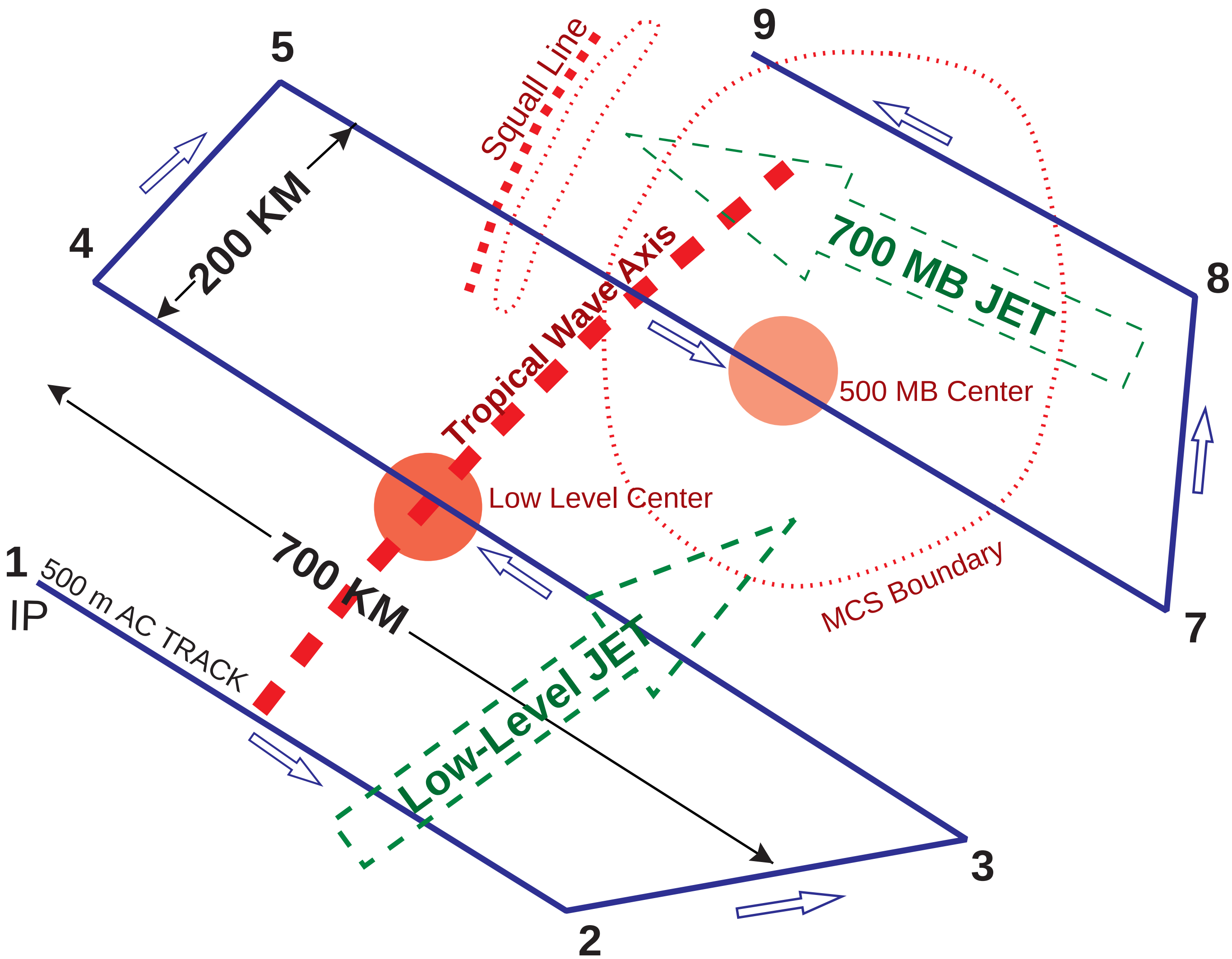

Fig. 1a. Low-level Grid Flight Track

• Note 1.	True airspeed calibration is required.
• Note 2.	The pattern is flown with respect to the wave axis, typically inclined at 30°–40° from N, or relative to circulation or vorticity centers.
• Note 3.	Fly **1—2—3—4—5—6—7—8—9** at 1,000 ft (300 m) or 10,000 ft (3.0 km) altitude, passing through the low–level jet, low–level circulation center (if it exists), MCS and associated mid–level center, or across mid–level jet.
• Note 4.	Set airborne Doppler radar to F/AST on all legs.

Tropical Cyclogenesis Experiment

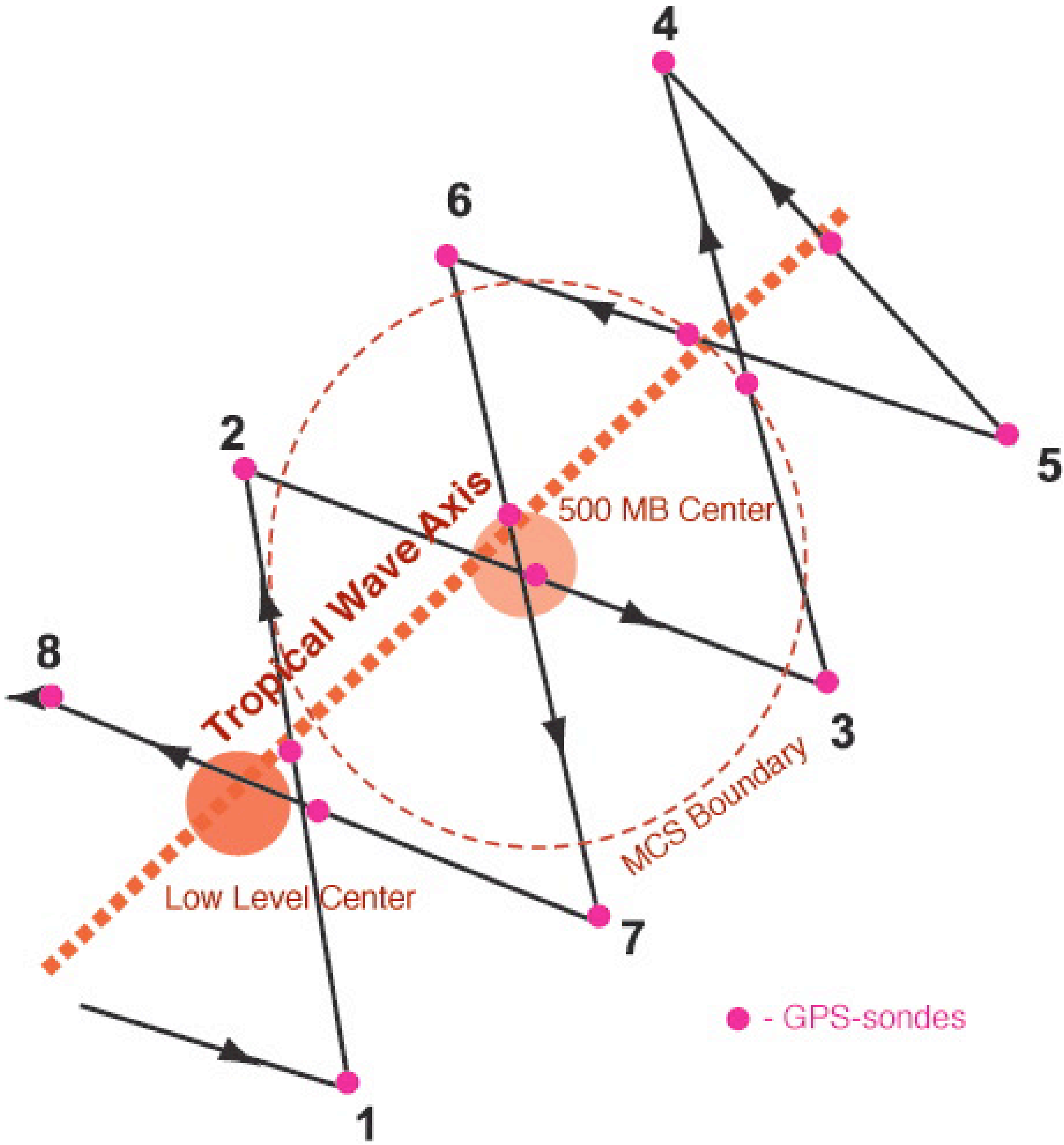

Figure 1b Alternate Grid Pattern

- Note 1: True airspeed calibration is required.
- Note 2. The pattern is flown with respect to the wave axis, typically inclined at 30-40° from N, or relative to circulation or vorticity centers.
- Note 3. Fly 1-2-3-4-5-6-7-8 at 1,000 ft (300 m) or 10,000 ft (3.o km) altitude, passing through the low-level jet, low-level circulation center, MCS and associated mid-level center, or across mid-level jet.
- Note 4. Set airboirne Doppler radar to scan F/AST on all legs.

TROPICAL CYCLOGENESIS EXPERIMENT

Mesoscale Aircraft

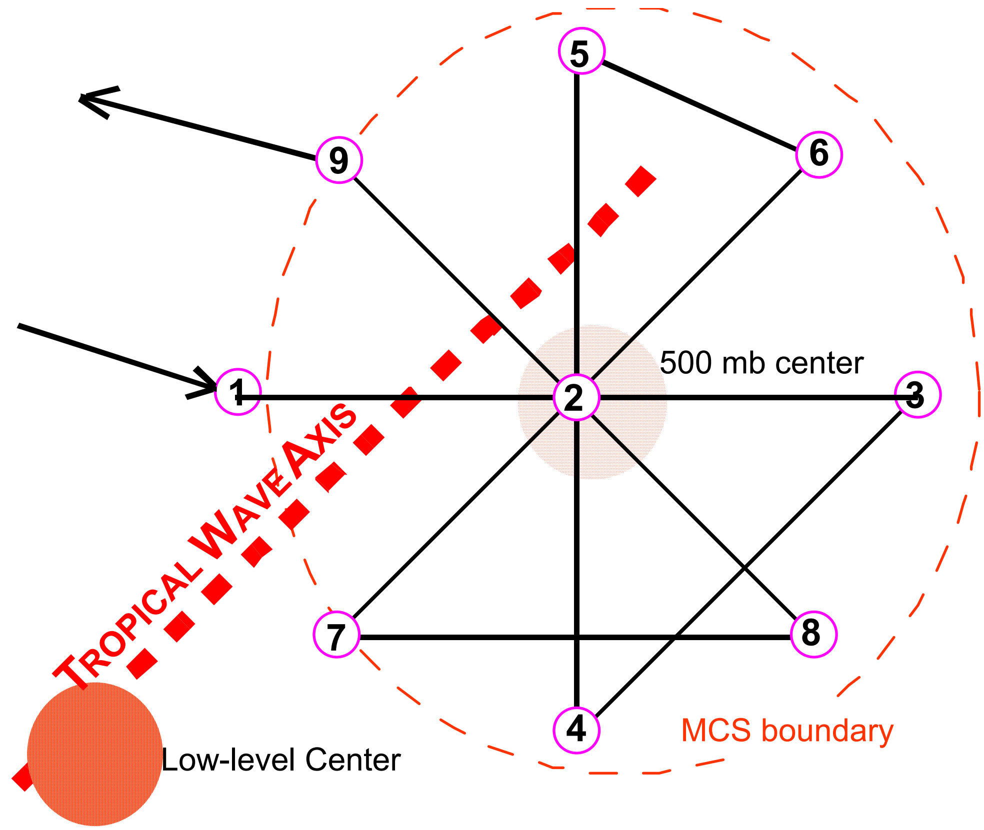

Fig. 2. Mesoscale Aircraft Flight Track

• Note 1.	True airspeed calibration is required.
• Note 2.	The pattern may be entered along any compass heading.
• Note 3.	Fly **1—2—3—4—2—5—6—2—7—8—2—9** at 600 or 700 mb (PA), 100–135 nmi (185-250 km) leg length.
• Note 4.	Point **2** is near the moving apex of the trough axis.
• Note 5.	Set airborne Doppler radar to continuously scan perpendicular to the track on radial penetrations, and F/AST on downwind legs.

TROPICAL CYCLOGENESIS EXPERIMENT

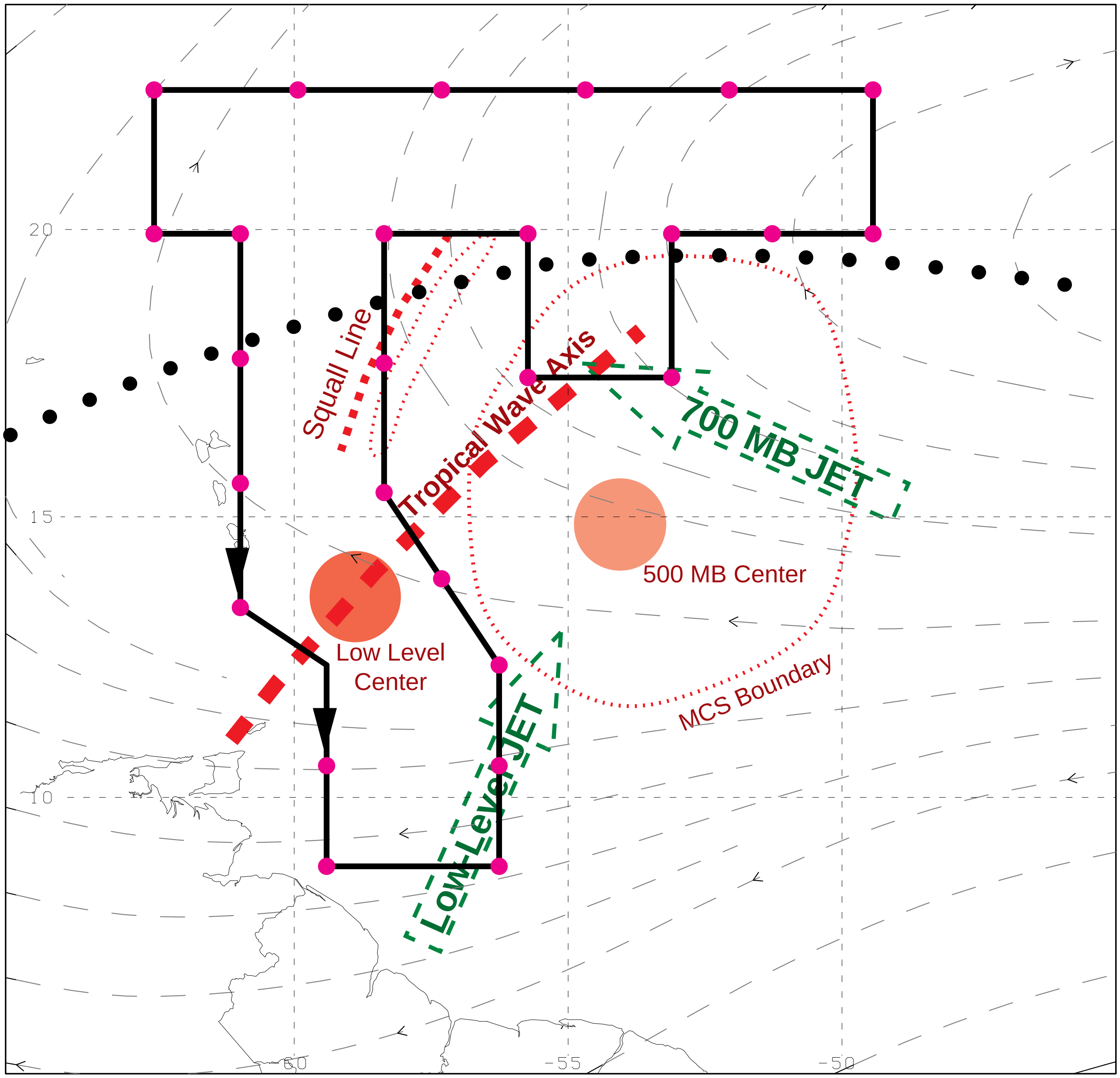

Fig. 3. (a) Cape Verde Region Sample G-IV Pattern

• Note 1.	During the ferry to the **IP**, The G-IV should climb to the 41,000 ft (200 mb) as soon as possible and climb as feasible to maintain the highest altitude for the duration of the pattern.

TROPICAL CYCLOGENESIS EXPERIMENT

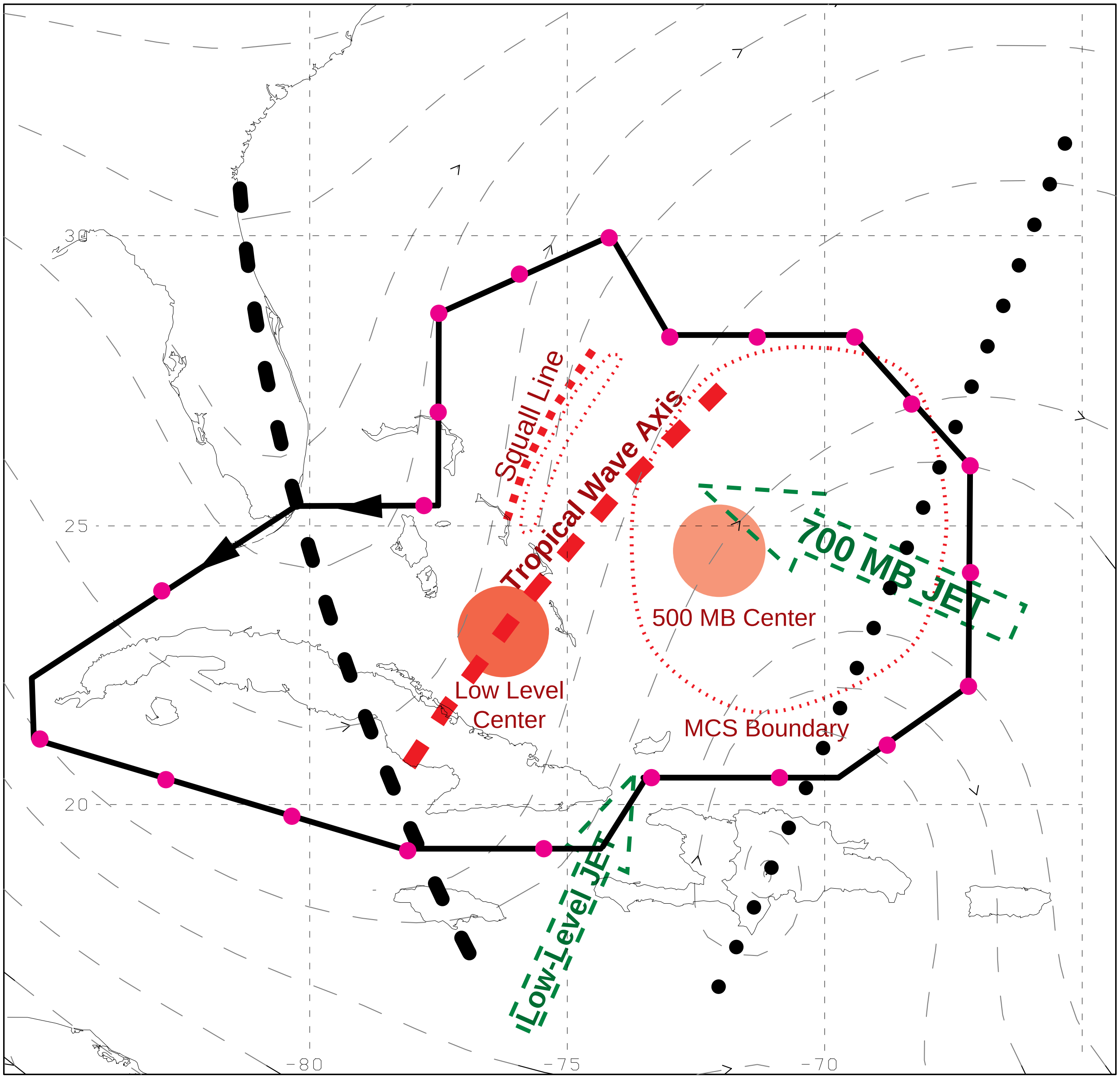

Fig. 3 (b) Bahamas Region Sample G-IV Pattern

• Note 1.	During the ferry to the **IP**, The G-IV should climb to the 41,000 ft (200 mb) as soon as possible and climb as feasible to maintain the highest altitude for the duration of the pattern.

Appendix B

Coordinated Observations of Vortex Evolution and Structure (COVES) Module

Principal Investigators: J. Gamache, S. Feuer, J. Cione, F. Marks, R. Black, M. Black, P. Black

Abstract

This experiment is designed to produce a “snapshot” of a mature hurricane from the top of the troposphere to 200 m deep in the ocean and from the center to a radius of 1000 km. It will also document the interaction of the hurricane with the ocean. This *multi-option, multi-aircraft* experiment will employ coordinated, simultaneous observations from the two NOAA WP-3D’s, and an AFRES WC-130J or the NASA ER-2 and DC-8. Included are measurements from several remote sensing instruments *(e.g.*, coordinated airborne Doppler observations) as well as many GPS-sondes dropped out to a radius of 400 km, and airborne expendable ocean probes. A pre-storm and two in-storm missions will be flown on successive days. Data beyond 400 km will be augmented by GPS-sondes launched from the G-IV.

1. Program Significance:

Research in the last two decades suggests that several environmental controls influence the change in TC intensity and structure, including wind shear, sea-surface temperature distribution, and upper-tropospheric interactions. Also important are the internal physics of the vortex, including dynamic, thermodynamic, and microphysical characteristics.

The COVES experiment is designed to collect data from a single TC using several different observing platforms and diagnose the qualities mentioned above. It also addresses a significant element of the USWRP HL initiative. This involves capturing complete snapshots of a TC's structure, horizontally within 540 nmi (1000 km) of the center and vertically from the top of the troposphere to at least 200 m below the ocean surface, for use in intensification studies. By combining NOAA's aircraft resources (two WP-3D and a supplemental G-IV) from the Hurricane Field Program with USAFRS WC-130J aircraft, COVES provides a unique opportunity to obtain a thorough depiction of the storm and its environment through a coordinated interagency effort that employs a greater variety of instruments than is usually available during the Hurricane Field Program.

One of the primary atmospheric instruments utilized is the GPS-sonde. In this experiment, GPS-sondes are capable of being deployed from all the COVES aircraft. They measure pressure, temperature, relative humidity, and winds every 0.5 s as they descend (~5 m vertical resolution near the surface). Since their introduction in 1996, reliability has proven to be outstanding and observational accuracy is quite high; the average error is less than 0.5° C for temperature, within 10% for humidity, and 1-2 m s^{-1} for winds. Most notably, the probes have helped to document extremely fine thermodynamic and kinematic variations in vertical structure, particularly in the boundary layer, and have permitted highly accurate point measurements near the surface in turbulent conditions.

The COVES experiment will add new contexts to the airborne Doppler observations often made in TCs. Recent studies using Doppler radar data collected by two WP-3D aircraft flying simultaneous orthogonal tracks have found that the wind structure in a TC can change drastically in as little as three hours. For example, in Hurricane Olivia (1994) increasing environmental shear eventually affected the eyewall circulation and caused as much as a 15-20 m s^{-1} decrease of the mean swirling wind in the mid-to-upper troposphere in less than 3 h. Unfortunately, since little was measured outside the 54 nmi (100 km) radius, it was difficult to gauge the strength of the environmental shear and how that shear was modified as it interacted with the vortex.

COVES combines many dropsonde observations in the TC inner core and rainband regions out to 216 nmi (400 km) from the center with Doppler radar observations within ~22 nmi (40 km). The drops will be particularly dense immediately outside the Doppler coverage area but will be spaced farther apart at larger radial distances. This data distribution will help us to verify our present theories concerning both the interaction of the vortex with environmental shear and the modification of the vortex by upper-tropospheric interactions. The data may also be supplemented with other environmental observations within 540 nmi (1000 km) of the center, including sondes dropped by the G-IV. It is hoped that data gathered at larger scales away from the center than those available when observing Hurricane Olivia will allow for accurate intercomparisons with nested models. The combination of *in situ* GPS-sonde and Doppler radar data will also permit small-scale dynamic features to be studied more extensively, such as vortex Rossby waves; results from Hurricane Olivia suggest that Rossby waves may be important features in the inner core circulation of developed TCs.

Modifications of the TC wind and pressure fields by oceanic thermodynamic influences are accomplished in two general fashions. First, pre-existing ocean temperature and circulation features modify the fluxes at the air-sea boundary as the storm passes over them. Such features include permanent currents, such as the Gulf Stream and Gulf Loop current; semi-permanent circulations, such as the Gulf of Mexico Warm Eddies; and transitory features, such as cold wakes from previous storms. Second, immediate modifications of SST and ocean mixed layer depth under the storm itself will affect the surface fluxes. Thus in this experiment we propose to use a mobile observing strategy that allows SSTs and mixed-layer depth structures to be mapped before, during, and after TC passage using Airborne Expendable Bathythermographs (AXBTs). Upper ocean current, temperature, and salinity during TC passage will also be mapped using Airborne Expendable Current Probes (AXCPs) and Airborne Expendable Conductivity, Temperature, and Depth (AXCTDs) probes. It is important to separate other environmental influences from those of the ocean. Surface and tropospheric wind field measurements from instruments including the GPS-sondes, Doppler radar, Ku/C-band Scatterometer (Ku/CSCAT), and Stepped Frequency Microwave Radiometer (SFMR) out to several hundred km from the center will help achieve this. Finally, surface-wave observations will be made by a Scanning Radar Altimeter (SRA).

Rainbands and outer eyewalls are internal components of the TC that modify the thermodynamic characteristics of the boundary layer air flowing into the storm. Their circulations tend to suppress convection and the secondary circulation in the inner eyewall. They may also protect the inner eyewall from the full effect of environmental wind shear. The large number of GPS-sondes dropped both in the inner core and rainband regions should help to monitor the effects of rainbands and the degree to which surface fluxes are able to restore the warm moist properties of the inflow air. Additionally, the near-surface inflow will be determined from SFMR and Ku/CSCAT data collected along the flight tracks.

Convection in the eyewall is usually quite asymmetric and tilted outward. Because there is a large shear of the swirling flow, convection should theoretically also be tilted azimuthally. This has been difficult to document from Doppler three-dimensional composites, since updrafts evolve quite rapidly and consequently undergo significant change during the time required to collect the data needed to create a composite wind field. One method to avoid problems resulting from evolution is to observe vertical incidence observations with two aircraft flying in the same direction, one somewhat downwind of the other. This type of pattern has been flown successfully in Hurricane Edouard (1996). COVES presents an opportunity to perform this between the USAFRS WC-130J aircraft and a NOAA WP-3D. The lower WP-3D may also fly an optional module, which will map the three-dimensional structure of eyewall convection.

Microphysical measurements contribute to a complete depiction of the TC. Cloud particle imagery and statistics permit more reliable estimates of the rainfall and rain content from land-based, airborne, and satellite-born radars, including TRMM. Ice imagery and measurements of cloud water, particle charge, and electric field help to document the roles of electric charge separation and ice multiplication. Accurate microphysics can improve dynamic models by permitting better estimates of the distribution and strength of precipitation drag and evaporation and the release or absorption of latent heats of condensation and fusion. Thus measurements of particle types and size distributions are essential for a full understanding of TCs. Furthermore, increased charge separation and resultant electrification and lightning imply the existence of cloud liquid water at temperatures well below freezing. In the naturally well-seeded TC environment, this suggests rapid vertical motion, which often accompanies intensification. Thus increases in lightning signal potential strengthening. Microphysical measurements at the -10°C level by the upper WP-3D may be possible in the latter part of the COVES flight pattern.

COVES will provide an opportunity to acquire the broadest set of observations ever collected in the TC eyewall and rainband regions. Hopefully, the myriad of mechanisms and factors mentioned here will be documented, leading to a better understanding of their relative roles in intensity and structural changes.

3. Objectives:

The primary goal of this experiment is to fully document the three-dimensional kinematic structure and temporal evolution of a mature TC and its environment from the top of the troposphere to 200 m into the ocean. This will be accomplished using a variety of airborne instruments, deployed expendable probes, remote sensing devices, and microphysics instruments. A TC undergoing a period of rapid intensification or weakening will be a prime candidate. Combined with GPS-sonde observations from a simultaneous G-IV synoptic surveillance mission, rawinsonde observations of opportunity, and supplementary satellite data, a comprehensive snapshot of convective, mesoscale, and synoptic features shall be obtained within ~540 nmi (1000 km) of the center.

Other scientific goals are:

- To examine the relationship of environmental wind shear with TC structure, evolution, intensity change, and rainfall distribution.
- To study the role that convective asymmetries play in TC evolution and motion.
- To validate and refine numerical models of TC eyewall vertical structure and evolution.
- To determine kinematic and thermodynamic attributes of rainbands and adjacent regions.
- To evaluate real-time empirical and satellite estimates of surface wind in TCs using *in situ* data.
- To compare airborne and satellite remote measurements with those from buoys and expendable probes.
- To study three-dimensional sensible and latent heat fluxes, energy and moisture fluxes in the atmospheric boundary layer.
- To measure changes in SST, mixed layer depth, currents, and waves caused by TCs.
- To study the role ocean processes play in modifying the TC boundary layer through air-sea interactions. and determine statistical relations.
- To improve estimates of upper ocean heat content before and during TC passage.
- To quantify the roles mixing and horizontal advection of SST and salinity gradients have on the ocean mixed layer and the effect TC precipitation has on mixed layer response.
- To improve TC forecast model initialization and parameterization of air-sea processes, upper oceanic features, and boundary layer conditions
- To study the distribution, structure, and temporal evolution of electrical charging mechanisms in TCs.
- To record the types and concentrations of all hydrometeors observed in TCs, particularly in electrically active areas.

4. Mission Description:

In COVES, four to five aircraft provide simultaneous, coordinated observations of the TC. The aircraft involved are the two NOAA WP-3D as well as the USAFRS WC-130J. Missions should be planned to correspond with a NOAA G-IV synoptic surveillance flight, which will provide most of the observations between 270 and 540 nmi (500 and 1000 km) from the storm center. The experiment consists of the pre-storm ocean survey and coordinated in-storm modules. Other optional modules are also presented here.

These are the following requirements to commit:

- A hurricane or strong tropical storm within 540 nmi (1000 km) of land, which is a threat to the U.S. coast, but is not expected to make landfall for 48-72 h.

- Both WP-3D aircraft must have operational tail and lower-fuselage radars, and be fully equipped to launch and monitor GPS-sondes and AXBTs.
- Upper WP-3D must have working Ku/C-SCAT, SFMR, and microphysical instrumentation.
- Lower WP-3D (which will also be the pre-storm ocean survey aircraft) must have working SFMR, SRA, radome-mounted gust probe, and AXCP and AXCTD (if available) probes and receiver equipment.
- USAFRS WC-130J must have operational GPS-sonde equipment.
- If available, up to five subsurface floats should be deployed by USAFRS WC-130J aircraft prior to the pre-storm ocean survey.

Pre-Storm Survey Module: This module should be executed approximately 24-72 h prior to a forecasted landfall. The patterns shown in Fig. B-1a and B-1b correspond to full mission options designed to accurately measure the undisturbed structure of a (predetermined) asymmetric or a symmetric ocean feature, respectively, just prior to encountering the storm. A single WP-3D aircraft with AXBT/AXCP/AXCTD launching capability maps the ocean boundary and mixed layer structure of the ocean feature at least one day before TC/ocean feature interaction occurs. These patterns should be flown with the initial leg parallel to a TOPEX/POSEIDON satellite altimeter ground track (±32° inclination from true north) if possible. A constant altitude of 5,000 to 6,000 ft should be maintained throughout the mission. Doppler radar should be set to F/AST mode on all legs if there are any scatterers. Another single aircraft experiment, such as the XCDX, should ideally be conducted simultaneously or immediately following either of these options to measure internal storm structure prior to interaction. A third pattern shown in Fig. B-1c corresponds to an option that may be flown by either WP-3D aircraft following a primary storm survey module. During this pattern, the upper ocean mixed layer thermal structure is sampled directly ahead of the storm track. For all options of this module oceanic coverage should include an area over which the TC will potentially traverse for at least a 24-36 h period.

A) Asymmetric Ocean Feature Option: This is best suited for an elongated or irregularly-shaped ocean feature, such as the Gulf Stream in the Atlantic or the Loop Current in the Gulf of Mexico. The “lawn mower” pattern (Fig. B-1a) consists of flying four 135 nmi (250 km) transects, bisected by the feature’s major orientation axis and spaced apart by 54 nmi (100 km) intervals. These are followed by a return leg approximately 216 nmi (400 km) aligned with the feature’s major axis. 9 GPS-sondes, 18 AXBTs, 12 AXCTDs, and 17 AXCPs should be launched at regular intervals, as shown in Fig. C-1a. The AXCTDs in the spine of the feature should be deployed during the initial set of perpendicular legs. In the event the feature is the Gulf Loop Current, the positions of the other AXCTDs and the adjacent AXCPs on these legs should be reversed. The time on station needed to complete this option is about 5 h.

B) Symmetric Ocean Feature Option: If the ocean feature is circular in shape, such as a Gulf of Mexico Warm Eddy (GOMWE) ring, the pattern in Fig. B-1b should be executed. This pattern has six radial legs (three inbound and three outbound), and two downwind legs (**2-3** and **4-5** in Fig. B-1b); all have nominal length of 108 nmi (200 km) and are spaced 60° apart azimuthally. During each radial leg one or two probes will be launched at every 25 km interval beyond the feature center. A GPS-sonde and an AXBT will be dropped concurrently at 54 nmi (100 km) and 108 nmi (200 km) from the center. Another set of simultaneous GPS-sonde and AXBT probes will be launched at the midpoint of the two downwind legs. An additional solo AXBT will be launched at 13.5 nmi (25 km) from the center on each radial leg, and a GPS-sonde will be dropped in the center during the second pass. An AXCP will be deployed at 40.5 nmi (75 km), 67.5 nmi (125 km), and 94.5 nmi (175 km) from the center during each radial leg; and an AXCTD will be released at 27 nmi (50 km) and 81 nmi (150 km) from the center. The time on station needed to complete this option is about 4.5 h.

C) Ahead of Storm Track Option: Following the conclusion of a primary storm survey module, a 60° 90° wedge pattern is flown (Fig. B-1c). Two lines of AXBTs are deployed at positions roughly 12 h **(2-3)** and 24 h **(4-5)** ahead of and normal to the storm track. The actual pattern is highly dependent on the storm motion, as well as the time available. For example, if the storm is moving 10 kts, then the first line of AXBTs would be 120 nmi (222 km) ahead of the current storm position; and the second line would be 240 nmi (444 km) ahead. Whereas, if the motion is 8 kts, then the first line of AXBTs would be ~100 nmi (185 km) ahead of the storm; and the second line ~200 nmi (370 km) ahead. If the region 12 h ahead of the TC has already been well-sampled during the storm survey module, then only the second line of AXBTs needs to be dropped. For a slow moving storm (3-6 kts) it may be possible to drop AXBTs up to 36 h ahead of the storm, depending on time constraints and other factors. A maximum of 12 AXBTs will be launched during the pattern; the number may be decreased due to aircraft payload restrictions. The time on station needed to complete this option should be 2 h or less.

(**Note:** This option can be flown in conjunction with a single-aircraft XCDX mission.)

Primary Storm Survey Modules: One of the two primary storm modules should be executed on at least two successive days before the forecasted landfall. These are called the "Main" and "Coordinated-Leg" modules. The Main module is designed to maximize the radial coverage of the two NOAA WP-3D aircraft, permitting close coordination with the USAFRS aircraft only during the first center penetration. The Coordinated-Leg module shortens the WP-3D flight legs to permit coordination of all aircraft for all three center penetrations. A separate "Inner-Core" module may be substituted for the lower aircraft to fly in place of its standard pattern in the "Main" module. All other aircraft still fly the Main-module flight plans. Finally, a module called the "WP-3D-only" module is included in the event the USAFRS aircraft is unable to fly. For brevity, the flight plans for the upper WP-3D, the USAFRS WC-130J are all described according to reference points, which are numbered the same for all modules.

1) *USAFRS WC-130J Aircraft*. The USAFRS aircraft are not scheduled to fly in the WP-3D-only or inner core modules. The WC-130J will fly at a constant altitude throughout the pattern between 33,000 (FL310) and 37,000 (FL370) ft. The altitude selected should be at the level of the TC warm-core maximum, where the peak tangential wind decays most rapidly with height. The pattern has six radial legs (three inbound and three outbound), and two downwind legs (**B-C** and **D-E** in Figs. B-2a and B-3a); all have nominal length of 216 nm (400 km) except for the first leg in the Main module, which begins 324 nm (600 km) from the center (Fig. B-2a). Coordination will take place 108 nmi (200 km) from the center along the first inbound leg **(A-§** in Fig. B-2a) in the Main module, and at **A, C** and **E** on the three inbound legs in Fig. B-3a for the Coordinated-Leg module. The USAFRS WC-130J is scheduled to drop 18 GPS-sondes. The WC-130J will drop sondes on both inbound and outbound legs at radii of 81 nmi (150 km), 108 nmi (200 km), and 162 nmi (300 km) from storm center. The WC-130J may drop discretionary sondes in the inner core; however, to avoid hazards, coordination with the WP-3D's should be exercised before dropping extra sondes.

2) Upper WP-3D Aircraft. The upper WP-3D aircraft will fly initially at 18,000 ft (FL180) and climb to the maximum sustainable altitude by the end of the module. The altitudes should be chosen to avoid icing and electrical discharge. The pattern is essentially the same for all modules. In the Main and Coordinated-Leg modules, it will enter 90° to the left (upwind) of the WC-130J aircraft track. The pattern has six radial legs (three inbound and three outbound) that are orthogonal to those of the WC-130J and the lower WP-3D and two downwind legs. All radial legs extend to a radius of 189 nmi (350 km) in the Main and WP-3D-only modules and 135 nmi (250 km) in the Coordinated-Leg module. Coordination with the lower WP-3D along all inbound legs (**1-§, 3-§, and 5-§** in Figs. B-2a and B-3a) will take place 62 nmi (115 km) from the center; however the responsibility for altering track for coordination will lie with the lower WP-3D. The upper WP-3D will release a total of 9 GPS-sondes on each radial leg in the Main, Inner-Core or WP-3D-only modules or 8 sondes in the Coordinated-Leg module, for a total of 54 or 48 sondes, respectively. The inner most radii for GPS-sonde release in the Main, Coordinated-Leg, and Inner Core modules are 13.5 nmi (25 km), 27 nmi (50 km), 40.5 nmi (75 km), 54 nmi (100 km), 67.5 nmi (125 km), 81 nmi (150 km), and 108 nmi (200 km). Outer sondes will be dropped at 148 nmi (275 km) and 189 nmi (350 km) in the Main and Inner-Core modules, and 135 nmi (250 km) in the Coordinated-Leg module. The distances for the 9 sondes per leg in the WP-3D-only module are at 13.5 nmi (25 km), 27 nmi (50km), 40.5 nmi (75 km), 54 nmi (100 km), 81 nmi (150 km), 108 nmi (200 km), 135 nmi (250 km), 162 nmi (300 km), and 189 nmi (350 km). Twenty AXBTs should be launched concurrently with selected GPS-sondes as shown in Figs. B-2a for the Main and Inner-Core modules, eighteen AXBTs for the Coordinated-Leg module (Fig. B-3a). Fourteen AXBTs should be launched concurrently with the sondes in the WP-3D-only module as shown in Fig. B-4; in addition, two more AXBTs along downwind leg **2-3**. It may be desirable to launch additional GPS-sondes in the eye during the first and/or last penetration. The Main, Inner-Core, and WP-3D-only modules will last approximately 6 h, while the Coordinated-leg module will last 4 h.

3) Lower WP-3D Aircraft (Main, Coordinated-Leg and WP-3D-only modules). In all modules, the lower WP 3D has the responsibility for coordinating with the upper WP-3D and with NASA, and it will alter its track as necessary to remain coordinated with the other aircraft. The lower WP-3D should fly between 5,000 and 12,000 ft in the Main and Coordinated-Leg modules, depending upon the storm intensity, and observational focus. The altitude in the WP-3D-only module should be 2,000-4,000 ft below the upper WP-3D, to increase the depth of the soundings. All three modules have six radial legs (three inbound and three outbound) that are orthogonal and downwind of the corresponding upper WP-3D legs. The nominal leg lengths of the Main, Coordinated-Leg and WP-3D-only modules are 162 nmi (300 km), 108 nmi (200 km), and 176 nmi (325 km), respectively. Coordination with the upper WP-3D and NASA aircraft along all inbound legs **(1-§, 3-§, 5-§** in Figs. B-2b, B-3b, and B-4) will occur at 54 nm (100 km) from the center in the Main and WP-3D-only modules (Figs. B-2b and B-4), and at points ***1***, ***3***, and ***5*** in the Coordinated Leg module (Fig. B-3b). The Main and WP-3D-only modules will last approximately 6 h, while the Coordinated-leg module will last about 4 h.

In the Main and Coordinated-Leg modules an AXCTD will be deployed at a radius of 27 nmi (50 km) along each inbound and outbound radial leg for a total of 6. AXCPs will be deployed along each radial leg in the eyewall and at radii of 40.5 (75 km), 67.5 (125 km) and 94.5 nmi (175 km), for a total of 24.

AXBTs and GPS-sondes will be dropped differently in each module to coordinate with the upper WP-3D drops. In the Main module (Fig. B-2b) AXBTs and GPS-sondes will be dropped concurrently at inbound and outbound radii of the eyewall, 54 nmi (100 km) and 108 nmi (200 km) along ***1-2*** and ***3-4***, and at inbound and outbound radii of the eyewall and 54 nmi (100 km) along ***5-6***. Four more AXBTs and GPS-sondes will be dropped together at ***2, 3***, and at two equally spaced points between ***2*** and ***3***. Other GPS-sondes may be dropped in the eyewall at the discretion of the lead scientist

In the Coordinated-Leg module (Fig. B-3b), AXBTs and GPS-sondes will be dropped concurrently at the eyewall and at radii of 54 nmi (100 km) and 108 nmi (200 km) along all inbound and outbound radial legs. Two others will be dropped at equally spaced intervals between ***2*** and ***3***. Additional GPS-sondes may be dropped in the eyewall at the discretion of the lead scientist.

In the WP-3D-only module (Fig. B-4) the lower plane releases 54 GPS-sondes. There will be 9 sondes per radial leg dropped at radii 13.5 nmi (25 km), 27 nmi (50 km), 40.5 nmi (75 km), 54 nmi (100 km), 67.5 nmi (125 km), 94.5 nmi (175 km), 121.5 nmi (225 km), 148.5 nmi (275 km), and 175.5 nmi (325 km). Concurrent AXBTs will be dropped at radii of 27 nmi (50 km), 94.5 nmi (175 km), and 148.5 nmi (275 km) along ***1*-§** and ***3*-§**; at radii of 27 nmi (50 km) and 94.5 nmi (175 km) along **§-*2*, §-*4*, and *5*-§**; and at radii of 27 nmi (50 km), 54 nmi (100 km), 94.5 nmi (175 km), and 148.5 nmi (275 km) along **§-*6***. No AXCPs or AXCTDs are launched in this module.

4) Lower WP-3D Aircraft (Inner-Core module). This is the only module where the tail radar will be operated in continuous mode. F/AST should be used on downwind legs, while continuous mode normal to the aircraft track should be used on all radial legs. The lower WP-3D will fly a wedge pattern between 5,000 to 12,000, depending on the storm intensity and the altitude of the AFRS WC-130J. This pattern includes 7 inbound and 7 outbound radial legs that are 54 nmi (100 km) long (Fig. B-2c). The legs from **2,13-§** and **§-12,16** will be flown twice. There are just two coordination points with the upper WP-3D at **2** and **15.** AXBTs and GPS-sondes will be dropped concurrently at **10-15**. On the radial legs from **4-§, §-5, 6-§, §-7, 8-§**, and **§-9** an AXBT will be dropped in the eyewall with a GPS-sonde. Other GPS-sondes will be dropped at the discretion of the lead scientist along each radial leg with the goal of obtaining a representative distribution of eyewall soundings. No AXCPs or AXCTDs are launched in this module. Optionally, the lower WP-3D may begin the module at **2** one half hour after the upper WP-3D reaches its IP and/or end the module at **16** one half hour after the upper WP-3D reaches its FP. The module should take 5-6 h to complete.

Auxiliary Storm Survey Modules: These are stand-alone "plug-in" modules that are two hours or less in duration and can be executed after the selected primary storm module. Execution is dependent on storm attributes, storm track, aircraft instrumentation, aircraft fuel and weight restrictions, and proximity to operations base.

(1) Electrification of TC Convection Module: This module, described in the Tropical Cyclone Landfall Experiment, documents the microphysical characteristics of electrically active convection using a single WP-3D aircraft. The PMS 2-D grayscale probes, the new PMS FSSP-100, five DRI field mills, the tail Doppler radar, the NASA HVPS, and the Johnson-Williams cloud liquid water probe are essential. It is desirable to have 4-6 GPS-sondes deployed to obtain soundings outside the convection in the inflow near the areas of interest.

(2) C-BLAST Module: This module is designed to test the logistics of flying a stair-step pattern and the feasibility of estimating the momentum and sensible heat flux near the top and bottom of the well-mixed layer. A single WP-3D flies a series of stair-step descents from 5,000 ft to the lowest altitude deemed 'safe.' This pattern is executed in crosswind and upwind/downwind directions within both a rain-free, gale-force wind region and a storm-force to hurricane-force wind region. Typically, the former will be located radially outward from the outer principle rainband, while the latter will be located between the eyewall and an outer convective rainband. Fig. B-5 shows a typical upwind/downwind flight pattern. The legs are approximately parallel to the low-level inflow. Companion legs normal to the flow are also desired to resolve secondary circulation features in the well-mixed layer. The capability of measuring latent heat flux will be added as instrumentation becomes available.

The stair-step descent (SSD) consists of a series of 37-50 nmi (60-80 km) long legs, each lasting 1-2 minutes and executed at a successively lower altitude than the previous leg. Typical altitudes will be 5,000, 3,000, 2,000, 1,500, 1,000, 500, and 300 ft; these levels may be adjusted depending on the altitude of the top of the well-mixed layer. It is desirable to have two legs positioned above the well-mixed layer. The lower levels are flown only if the turbulence and visibility are assessed as safe. At no time does the aircraft need to fly into rainbands, the eyewall, or any strong cells in between these two features. The aircraft should launch three GPS-sondes, one at the beginning, midpoint, and end of the pattern, to assess changes in the bulk mixed-layer and surface layer thermodynamic and kinematic structure along the flight path. Concurrent AXBTs should be deployed with the two GPS-sondes at the beginning and end of the pattern. Also, 2-3 other AXBTs should be deployed at 20-km intervals along the flight path. The total time for this module is about 2 h.

(3) Rainband Thermodynamic Structure Module: This module is described in the TC Landfall Experiment (and shown in Fig. B-6).

5. Instrumentation

To conduct these experiments, both aircraft should have working lower fuselage and tail Doppler radars. The airborne Doppler radars should be set in F/AST mode except during penetrations into the eye. The SFMR and C-SCAT should be on one WP-3D. The standard flight-level data instrumentation, the GPS AVAPS dropwindsonde system, and AXBT instrumentation should be operational. Sufficient GPS-sondes and AXBTs must be carried to perform the drops noted in each option. Nose, vertical and side-looking video cameras are required. This capability is made possible by the availability of an airborne Doppler radar on both NOAA aircraft and the addition of the SFMR and the airborne C-SCAT for high-resolution measurements of surface wind speed and rain rate. The GPS-sondes, AXBTs, and the radome and nose boom-mounted gust probes (with Lyman-a and Rosemount temperature sensors) insure that valuable supporting data on air-sea stability and turbulent fluxes are obtained. If it is available we would also like to have the NASA wave imaging system to provide estimates of foaminess on the surface and breaking wave characteristics.

The following instrumentation and expendables are required on two flight days: pre-storm and storm flights:

Special Instrumentation: WP-3D high (N42RF)- high:
- UMASS CSCAT/KSCAT with dual polarization and Doppler modules
- UMASS SFMR
- Radome-mounted gust probe
- GPS-sonde system
- AOC AXBT receiver system

Special Instrumentation: WP-3D (N43RF)- low:
- Radome-mounted and BAT nose boom-mounted gust probe
- Fast response humidity (Lyman alpha or equivalent)
- HRD SFMR-horn antenna
- AOC pod-mounted SFMR
- NASA/Wallops SCR
- UM/HRD AXCP/AXCTD receivers
- AOC AXBT receivers
- GPS-sonde system
- Scripps laser wave height altimeter
- downward-looking Scripps high-speed, low-light wave imaging video system
- wing pilon-mounted Model CIP airborne cloud/precipitation droplet probe (CPDP) from Droplet Measurement Technologies (DMT)
- window-mounted U. Washington phase-Doppler anemometer (PDA)

Expendables: WP-3D (42RF)- high:
35 GPS-sondes
35 AXBTs
3 DAT radar/Doppler tapes
2 DAT cloud physics tapes

Expendables: WP-3D (43RF)- Low:
35 GPS-sondes
25 AXCTDs
35 AXCPs
20 AXBTs
3 DAT radar/Doppler tapes
2 DAT cloud physics tapes

6. Data Management

Data management will be under the control of HRD.

7. Funding

The AXBTs and GPS-sondes would be provided by HRD. Flight hours will be from AOC base-funded hours. AXCP's would be provided by NSF. Funds for AXBT/AXCP receiver upgrade would be provided by NSF and UM/RSMAS. The SRA would be provided by NOAA/ETL and NASA Wallops. The support for SFMR and Ku/C-SCAT maintenance will be provided by UMASS. Support for HRD SFMR SFMR will be provided by Pro-Sensing, Inc. AOC pod-mounted SFMR will be provided for by the Office of the Federal Coordinator for Meteorology and Supporting Research. Support for radome gust probe operations would be provided by NASA, ONR/CBLAST and UM/RSMAS. The nose-boom gust probe, NASA SRA, Scripps laser altimeter and Scripps video system would be supported under the ONR C-BLAST program. Funds to reduce and analyze the data for NOAA PI's will be from HRD base funds, and research grants from NSF and ONR for non-NOAA principal investigators.

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COVES EXPERIMENT

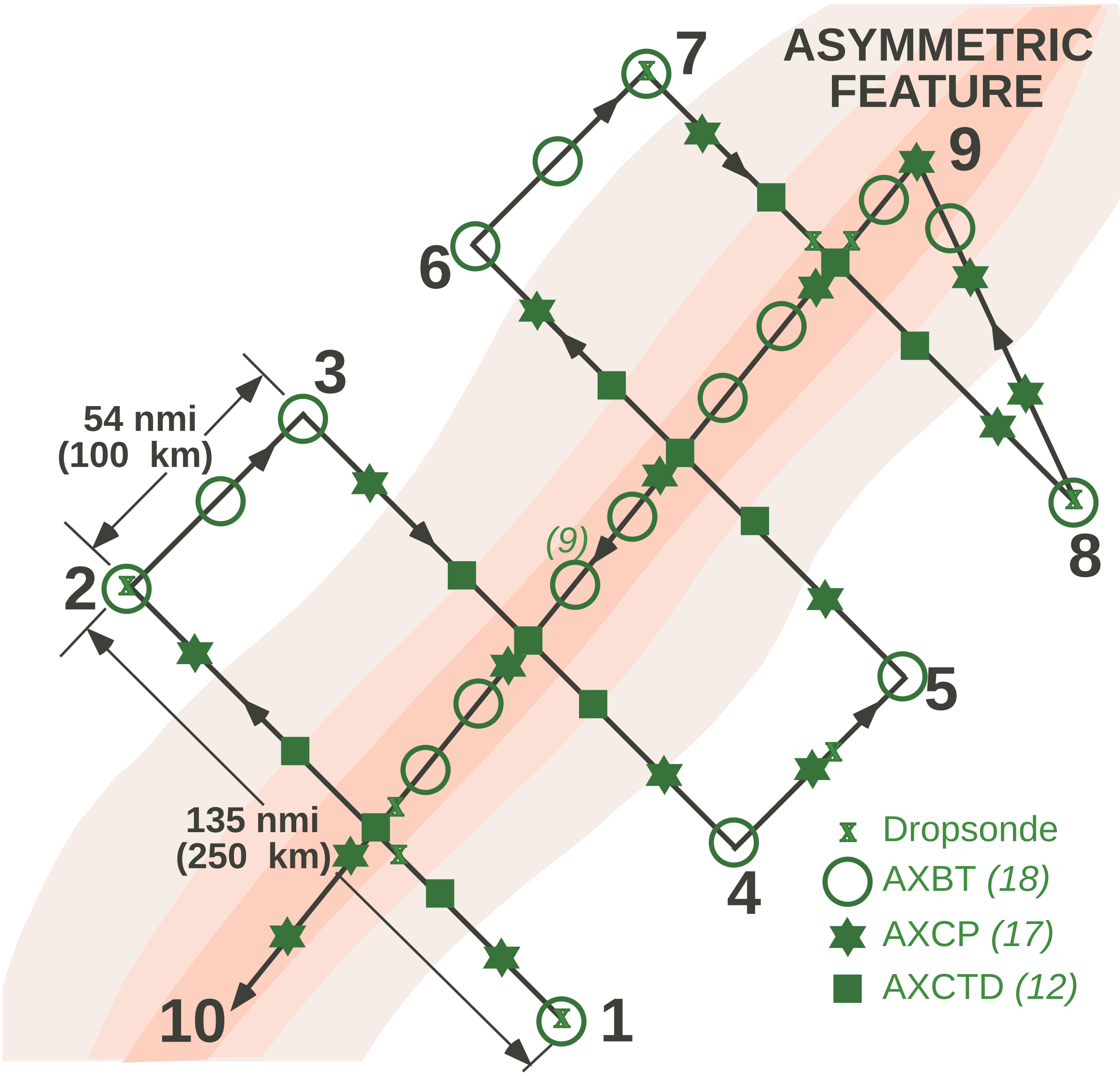

Fig. B-1. (a) Pre-storm Ocean Survey Pattern

• Note 1.	Flight altitude should be 5,000 ft RA
• Note 2.	IAS should be decreased to 190 kt when launching AXCPs

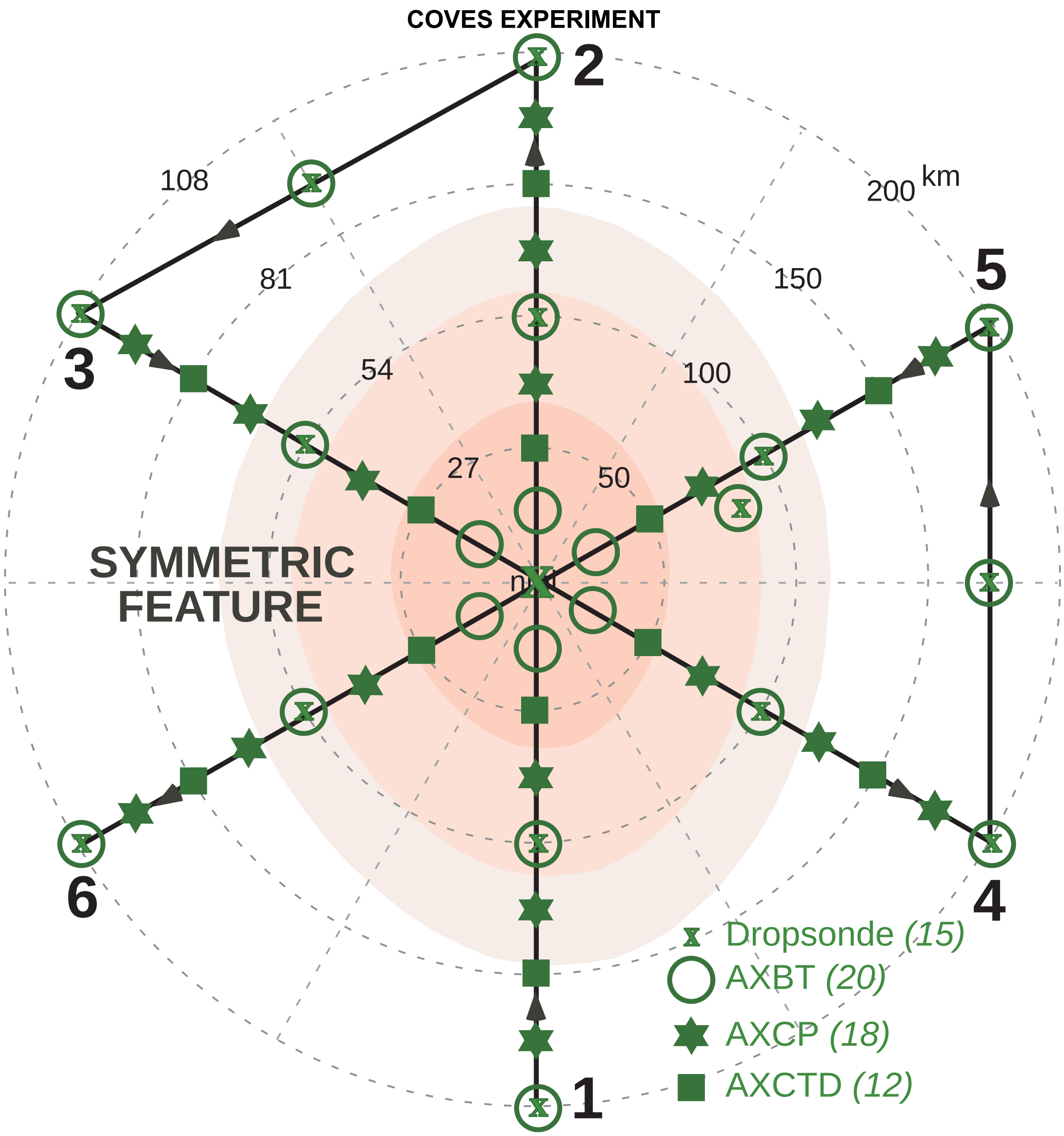

Fig. B-1. (b) Pre-storm Ocean Survey Pattern

• Note 1.	Flight altitude should be 5,000 ft RA
• Note 2.	IAS should be decreased to 190 kt when launching AXCPs

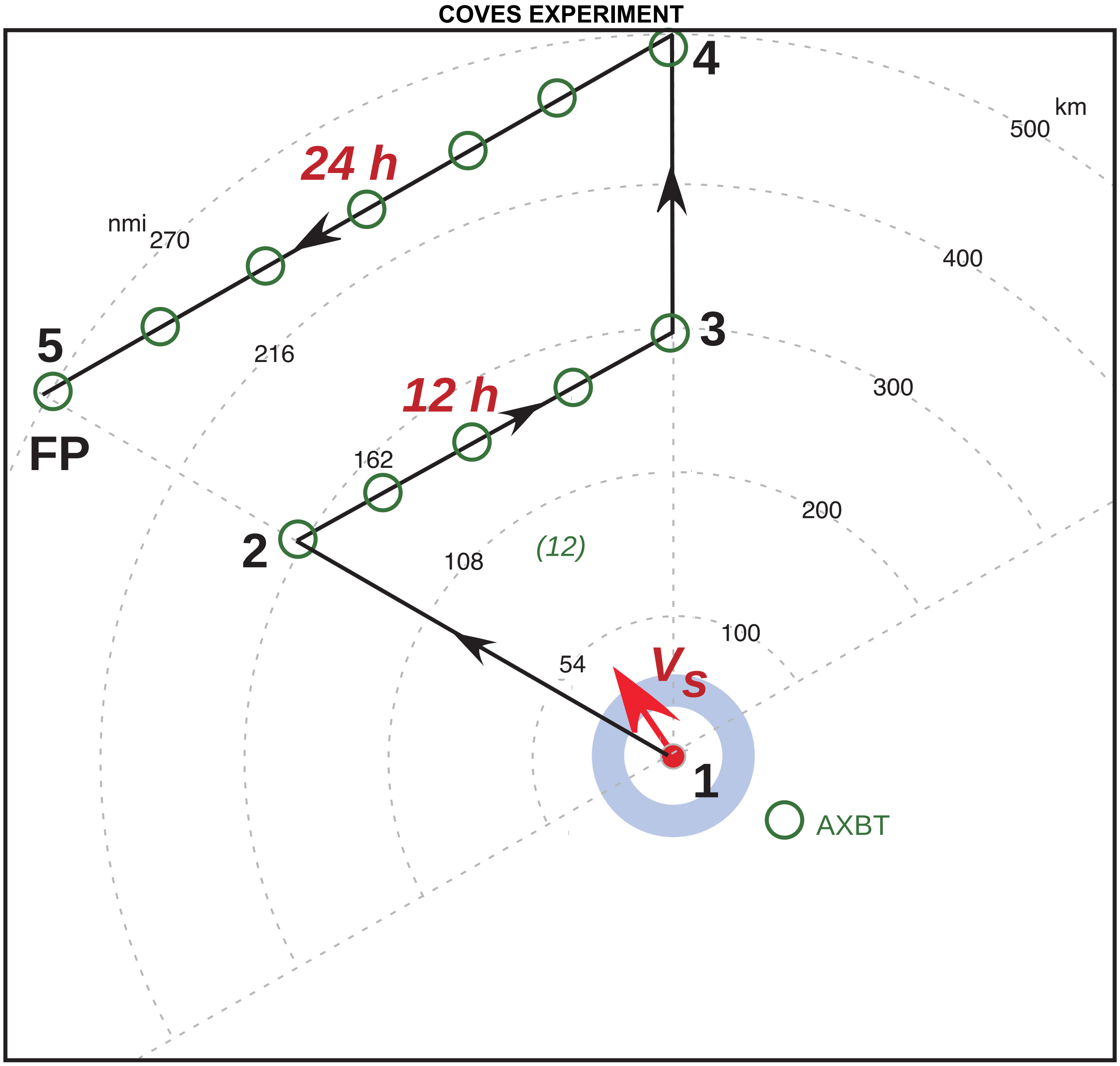

Fig. B-1. **(c) Pre-storm Ocean Survey Module**

• Note 1.	Aircraft should begin pattern at the end of the COVES mission if there is enough time to complete it during the ferry home.
• Note 2.	The pattern may be entered at any compass heading, and entry azimuth should be at least 30° downwind of the current storm motion (V_s) with cross track legs at estimated 12-h and 24-h storm displacements based on current storm track.
• Note 3.	The first cross-track leg (**2-3**) may be omitted if this portion of the storm was already well-sampled during the primary mission.
• Note 4.	If there are any scatterers the airborne Doppler radar should be operated in F/AST mode, with a single PRF of 2400 or greater, and a tilt of 20°.

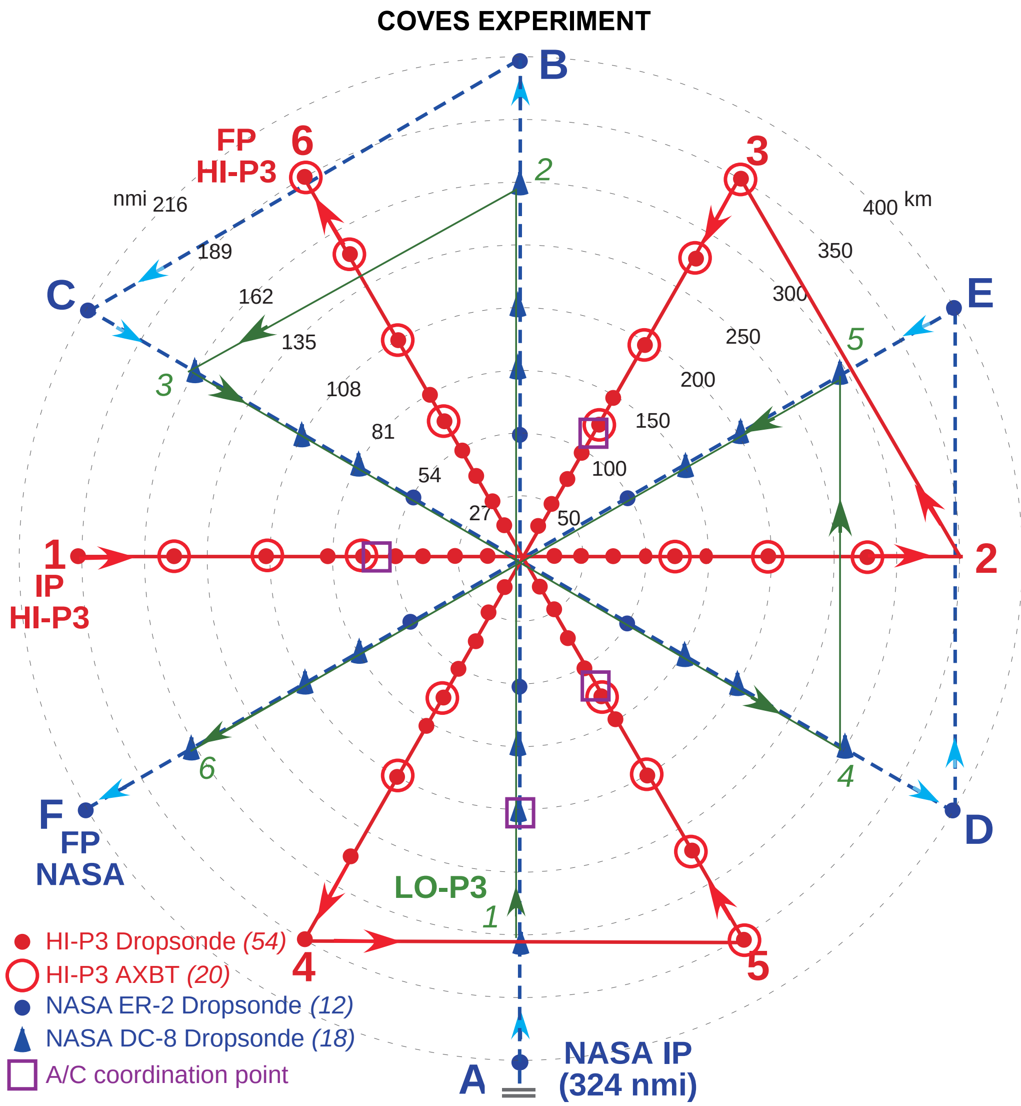

Fig. B-2. Coordinated Pattern: (a) Upper WP-3D and WC-130J (formerly DC-8)

• Note 1.	All aircraft should reach their respective IP's as simultaneously as possible, and the upper WP-3D is responsible to ensure that all aircraft depart the coordination points together.
• Note 2.	Aircraft should not deviate from pattern to find the center in the eye.
• Note 3.	The pattern may be entered at any compass heading and the WC-130J entry should be along the same heading as the lower WP-3D, 90° downwind from the upper WP-3D.
Note 4.	The WC-130J should attain the 300-hPa level (about 35,000 ft or FL350) as early in the mission as possible and then maintain this altitude for the duration of the pattern. Upper WP-3D should begin pattern at 18,000 ft, then climb to maintain maximum safe altitude.
• Note 5.	WP-3D Doppler radar should be operated in F/AST mode at a single PRF ≥2400 and 20° tilt.
• Note 6.	GPS-sondes and the downward-pointing laser on the WC-130J aircraft may pose a hazard to the WP-3D. Communication with these aircraft is the responsibility of the WC-130J aircraft and must be obtained before sondes are released.

COVES EXPERIMENT

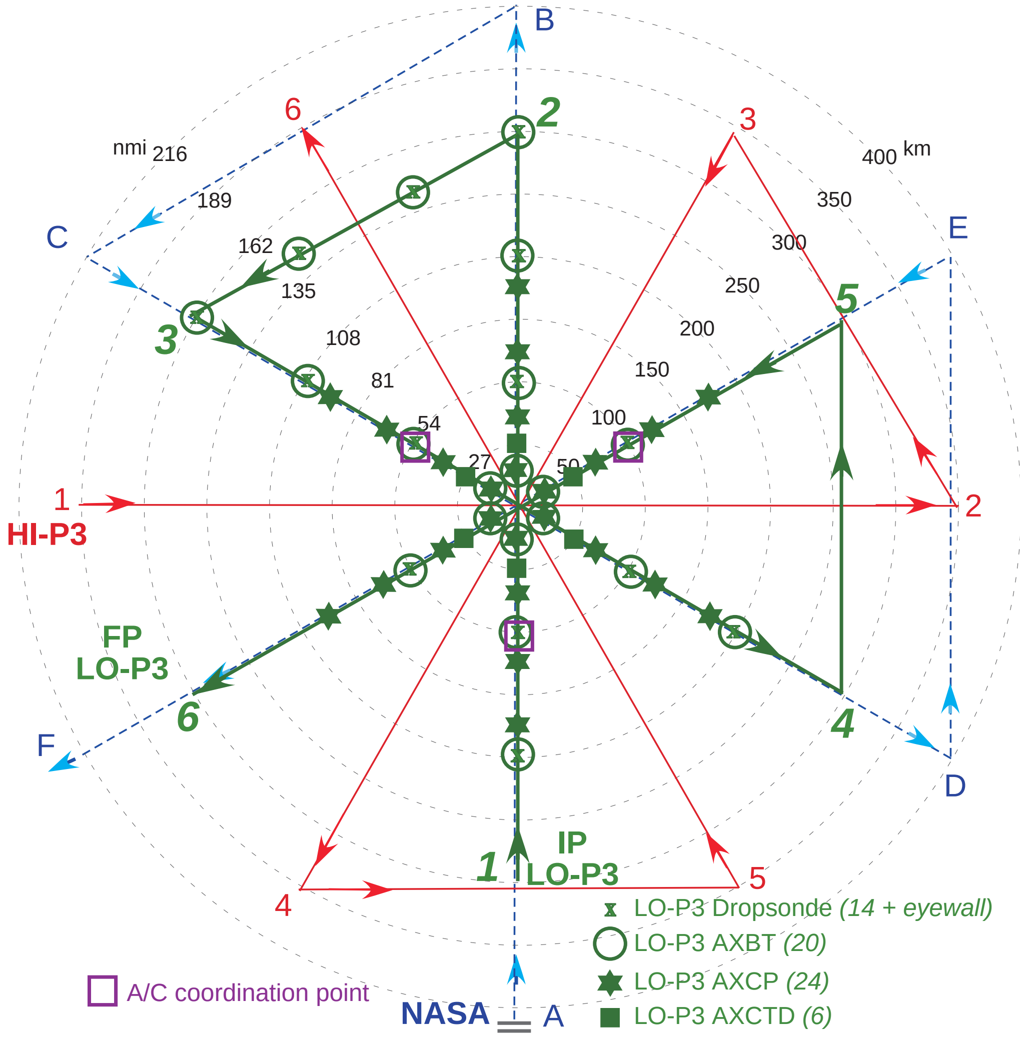

Fig. B-2. Coordinated Pattern: (b) Lower WP-3D

• Note 1.	All aircraft should reach their respective IP's as simultaneously as possible.
• Note 2.	Aircraft should not deviate from pattern to find the center in the eye.
• Note 3.	The pattern may be entered at any compass heading and the WC-130J entry should be along the same heading as the lower WP-3D.
• Note 4.	The lower WP-3D aircraft should fly at 5,000-12,000 ft.
• Note 5.	WP-3D Doppler radar should be operated in F/AST mode at a single PRF ≥2400 and 20° tilt.
• Note 6.	Lower WP-3D sondes and AXBTs within the eyewall are launched at the discretion of the lead scientist.

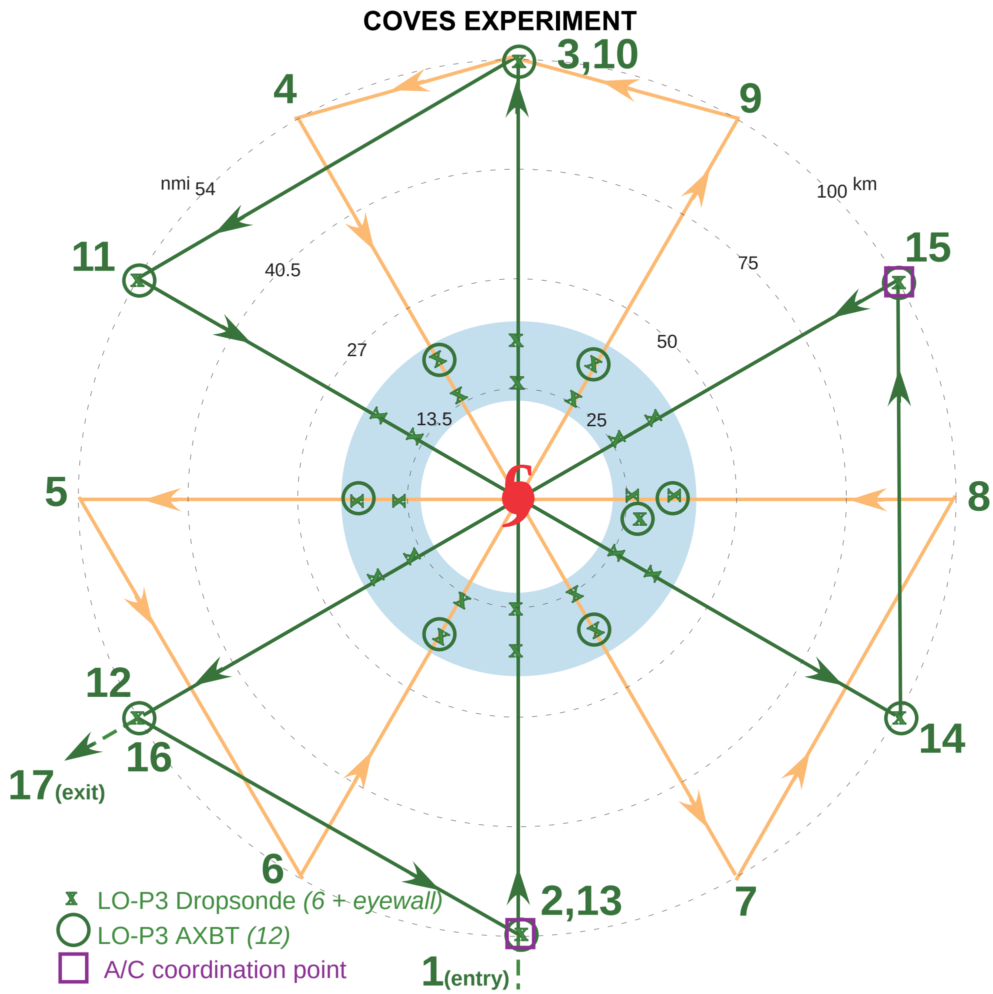

Fig. B-2. **Inner Core Pattern: (c) Lower WP-3D only**

• Note 1.	All aircraft should reach their respective IP's as simultaneously as possible.
• Note 2.	No AXCPs or AXCTDs are launched during this module.
• Note 3.	Lower WP-3D aircraft should fly at 5,000-12,000 ft (1,500-3,500 m).
• Note 4.	Lower WP-3D aircraft will modify pattern to coordinate with upper WP-3D at **2** and **15**.
• Note 5.	Lower WP-3D sondes and AXBTs dropped in the eyewall are launched at the discretion of the lead scientist.
• Note 6.	WP-3D Doppler radar should be operated in continuous modes on all radial penetrations and F/AST mode on all downwind legs.

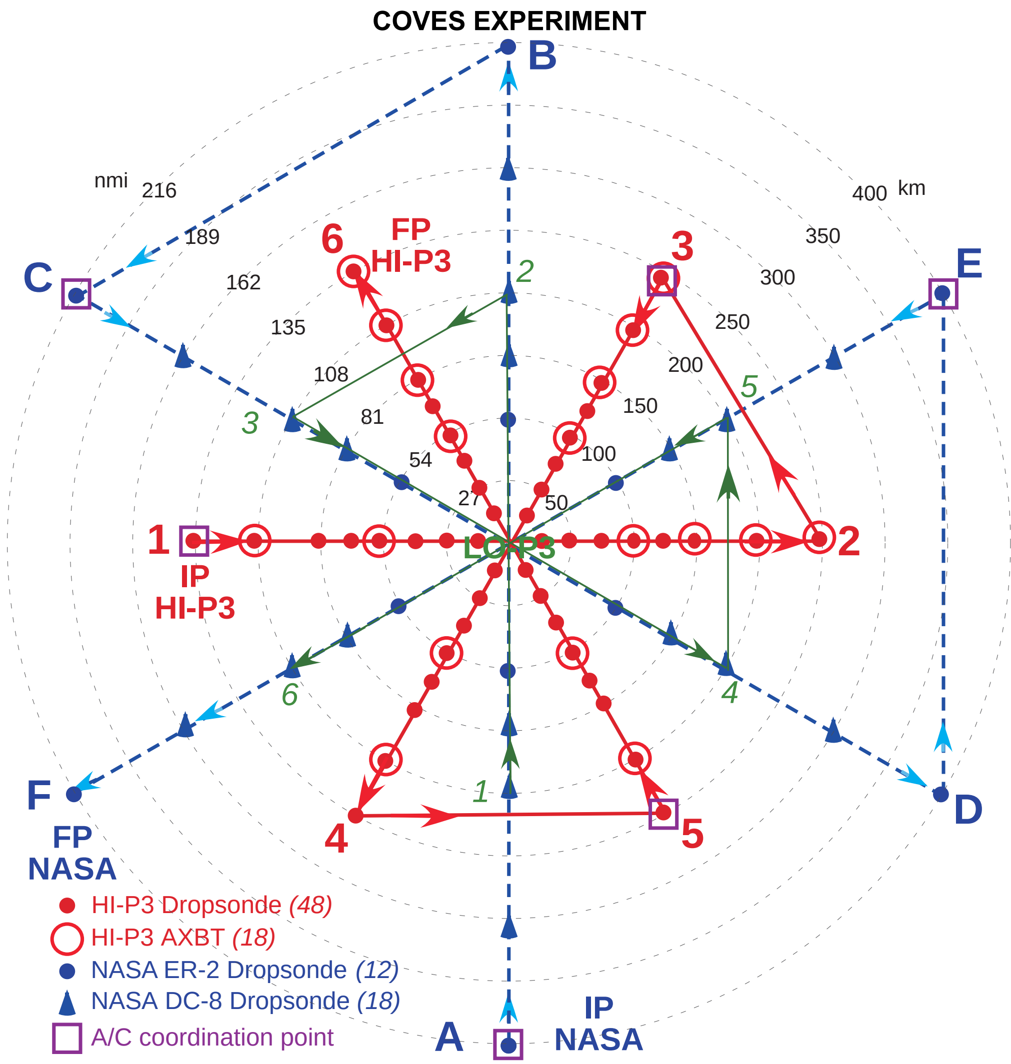

Fig. B-3. Coordinated Short Pattern: (a) Upper WP-3D and WC-130J (formerly DC-8)

• Note 1.	All aircraft should reach their respective IP's as simultaneously as possible, and the upper WP-3D is responsible to ensure that all aircraft depart the coordination points together.
• Note 2.	Aircraft should not deviate from pattern to find the center in the eye.
• Note 3.	The pattern may be entered at any compass heading and the WC-130J entry should be along the same heading as the lower WP-3D, 90° downwind from the upper WP-3D.
Note 4.	The WC-130J should attain the 300-hPa level (about 35,000 ft or FL350) as early in the mission as possible and then maintain this altitude for the duration of the pattern. Upper WP-3D should begin the pattern at 18,000 ft, then climb to maintain maximum safe altitude.
• Note 5.	WP-3D Doppler radar should be operated in F/AST mode at a single PRF ≥2400 and 20° tilt.
• Note 6.	GPS-sondes from the WC-130J aircraft may pose a hazard to the WP-3D. Communication with these aircraft is the responsibility of the WC-130J aircraft and must be obtained before sondes are released.

COVES EXPERIMENT

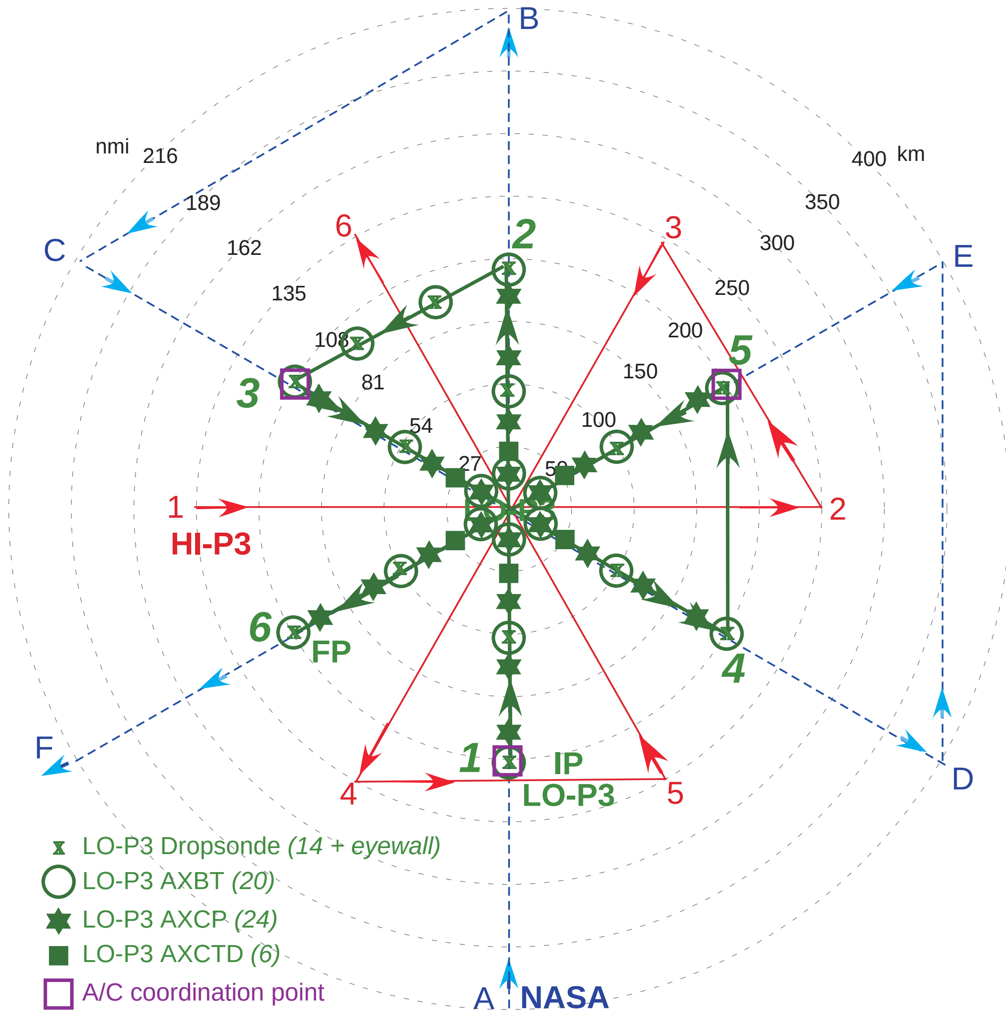

Fig. B-3. Coordinated Short Pattern: (b) Lower WP-3D

- Note 1. All aircraft should reach their respective IP's as simultaneously as possible.
- Note 2. Aircraft should not deviate from pattern to find the center in the eye.
- Note 3. The pattern may be entered at any compass heading and the WC-130J entry should be along the same heading as the lower WP-3D.
- Note 4. The lower WP-3D aircraft should fly at 5,000-12,000 ft.
- Note 5. WP-3D Doppler radar should be operated in F/AST mode at a single PRF ≥2400 and 20° tilt.
- Note 6. Lower WP-3D sondes and AXBTs within the eyewall are launched at the discretion of the lead scientist.
- Note 7. Lower WP-3D is responsible for remaining coordinated with WC-130J during legs 2-3.

COVES EXPERIMENT

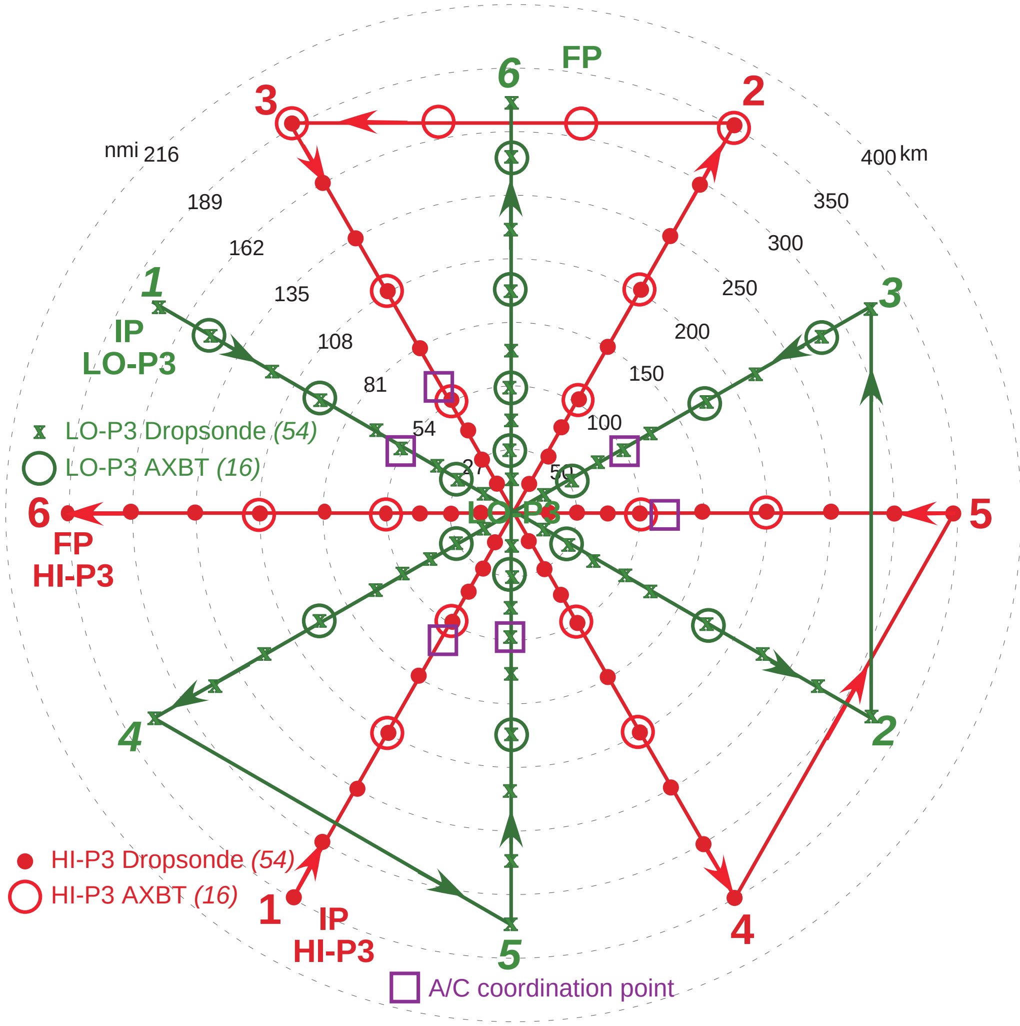

Fig. B-4. Coordinated WP-3D Only Pattern

• Note 1.	Aircraft should not deviate from pattern to find the center in the eye.
• Note 2.	The pattern may be entered at any compass heading, with higher WP-3D entering 90° downwind of lower WP-3D.
• Note 3.	Aircraft should reach their respective IP's as simultaneously as possible, and the upper WP-3D is responsible to ensure that all aircraft depart the coordination points together.
• Note 4.	Upper WP-3D should begin the pattern at 18,000 ft, then climb to maintain maximum safe altitude. Lower WP-3D aircraft should fly ≥2,000 ft below the upper WP-3D.
• Note 5.	WP-3D Doppler radar should be operated in F/AST mode at a single PRF ≥2400 and 20° tilt.
• Note 6.	Lower WP-3D sondes and AXBTs within the eyewall are launched at the discretion of the lead scientist.

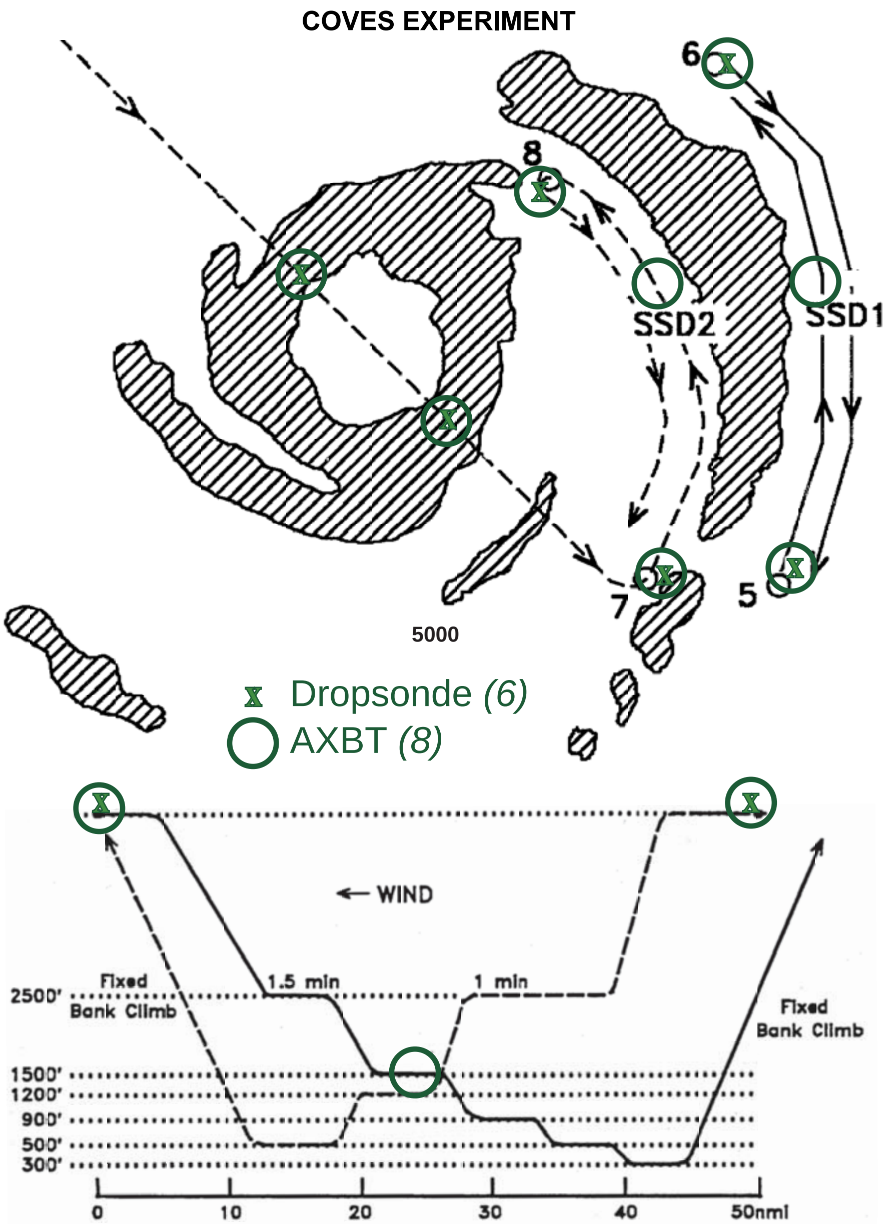

Fig. B-5. CBLAST Option Pattern

• Note 1.	Aircraft commences stair-step descent (SSD) patterns in clear between **5–6**, **7–8**, maintaining ~5 nmi (10 km) separation from edge of band.
• Note 2.	Descent/ascent rate of 1,000 ft min^{-1}.
• Note 3.	WP-3D Doppler radar should be operated in F/AST mode at a single PRF ≥2400 and 20° tilt

Appendix C

Tropical Cyclone Wind Fields Near Landfall

(Principal Investigators: Peter Dodge, John Kaplan, Mike Black, and Mark Powell)

1. Abstract

An accurate description of the tropical cyclone surface windfield near and after landfall in real-time is important for warning, preparedness, and recovery efforts. HRD is developing a real-time surface wind analysis system to aid the National Hurricane Center(NHC) in the preparation of warnings and advisories in tropical cyclones. The analyses could reduce uncertainties in the size of hurricane warning areas. Flight-level and Doppler wind data collected by a NOAA WP-3D will be transmitted to NHC where they could result in improved real-time and post-storm analyses. Doppler data collected near a WSR-88D would yield a time series of three-dimensional wind analyses showing the evolution of the inner core of tropical cyclones near and after landfall.

2. Program Significance:

An accurate real-time description of the tropical cyclone surface wind field near and after landfall is important for warning, preparedness, and recovery efforts. During a hurricane threat, an average of 550 km of coastline is placed under a hurricane warning, which costs about $50 million in preparation per event (Sheets 1990). The size of the warned area depends on the extent of hurricane and tropical storm force winds at the surface, evacuation lead-times, and the forecast of the storm's track. Research has helped reduce uncertainties in the track and landfall forecasts, but now there is an opportunity to improve the accuracy of the surface wind fields in tropical cyclones, especially near landfall.

HRD is developing a real-time surface wind analysis system to aid the National Hurricane Center (NHC) in the preparation of warnings and advisories in tropical cyclones. The real-time system was first tested in Hurricane Emily of 1993 (Burpee et al 1994) and has also been used in tropical cyclones in 1994-1996, but the system needs further testing before use in operational forecasts and warnings. The surface wind analyses could reduce uncertainties in the size of hurricane warning areas and could be used for post-storm damage assessment by emergency management officials. The surface wind analyses will also be useful for validation and calibration of an operational inland wind forecast model that HRD is developing under Federal Emergency Management Agency (FEMA) sponsorship. The operational storm surge model (SLOSH) could be run in real-time with initial data from the surface wind analysis (Houston and Powell 1994).

As a tropical cyclone approaches the coast, surface marine wind observations are normally only available in real-time from National Data Buoy Center (NDBC) buoys, C-MAN platforms, and a few ships. Surface wind estimates must therefore be based primarily on aircraft measurements. Low-level (<1500 m) NOAA and Air Force Reserve aircraft flight-level winds are adjusted to estimate surface winds. These adjusted winds, along with C-Band Scatterometer (C-SCAT) and Stepped Frequency Microwave Radiometer (SFMR) wind estimates, are combined with actual surface observations to produce surface wind analyses. Such analyses were done after Hurricane Andrew's landfall in South Florida (Powell and Houston 1996a), for the landfalls of Hurricanes Erin and Opal in 1995 (Powell and Houston, 1996b), and Fran in 1996.

The surface wind analyses may be improved by incorporating airborne Doppler radar-derived winds for the lowest level available(~1.0 km). To analyze the Doppler data in real-time, it is necessary to use a Fourier estimation technique. Carbone and Marks (1989) developed the Velocity-Track Display (VTD) to estimate the mean tangential and radial circulation in a vortex from a single pass through the eye. Lee et al (1994) applied the technique to Doppler data collected in Hurricane Gloria (1985) and found that the mean winds corresponded well with winds derived by pseudo-dual Doppler (PDD) analysis. Roux and Marks (1991) extended VTD (EVTD) to combine data from several passes through the storm, resolving the vortex circulation up through the wave #1 component. They used EVTD on data collected during six passes into Hurricane Hugo (1989) to show the development of mean tangential winds >50 m s^{-1} over 7 h. EVTD analyses are computed quickly on the airborne HRD workstation and could be sent to NHC shortly after their computation. The wind estimates could then be incorporated into the real-time surface wind analyses.

Dual-Doppler analysis provides a more complete description of the wind field in the inner core. While these techniques are still too computationally intensive for real-time wind analysis, the data are quite useful for post-storm analysis. Marks et al (1992) estimated the kinematic wind field in Hurricane Norbert (1984) by PDD analysis of airborne radar data. They found radial inflow at the front of the storm at low levels that switched to outflow at higher levels, indicative of the strong shear in the storm's environment. Powell et al (1991) used PDD data collected in Hurricane Hugo near landfall to compare the vertical variation of winds over water and land. The profiles showed that the strongest winds are often not measured directly by reconnaissance aircraft.

By 1989 both WP-3D aircraft were equipped with Doppler radars. Gamache (1993) computed several three-dimensional wind fields from true dual-Doppler data collected by two WP-3D's in Eastern Pacific Hurricane Jimena (1991) and showed that a pulse of radial wind developed in the eyewall with a corresponding decrease in the tangential winds. By the fourth pass, however, the radial pulse was gone and the tangential winds had returned to their previous value. Gamache suggested that the maintenance of a mature storm may not be a steady-state process. Further study is necessary to understand the role of such oscillations in eyewall maintenance and evolution.

While collection of dual-Doppler radar data by aircraft alone requires two WP-3D aircraft flying in well-coordinated patterns, a time series of dual-Doppler data sets could be collected by flying a single WP-3D toward or away from a ground-based Doppler radar. In that pattern, the aircraft Doppler radar rays are approximately orthogonal to the ground-based Doppler radar rays (Fig. C-1), yielding true Dual-Doppler coverage. The Atlantic and Gulf coasts are covered by a network of Doppler radars (WSR-88D) deployed by the National Weather Service (NWS), Department of Defense, and Federal Aviation Administration (Fig. C-2). The NWS has equipped each radar with a digital recorder (Crum and Alberty 1993) to store the base data (Archive Level II). In precipitation or severe weather mode the radars collect volume scans every 5-6 min. The University of Oklahoma has portable 9.5 GHz Doppler radars on trucks (Wurman et al 1995) to observe intense convective-scale and mesoscale phenomena such as tornadoes and hurricanes. In 1996 the Doppler on Wheels (DOW) group deployed a portable radar (DOW1) to the North Carolina coast and recorded high resolution Doppler data in the boundary layer of the eyewall of Hurricane Fran at landfall. The DOW group plans to continue deployments in hurricanes, in cooperation of HRD field experiments.

If a hurricane with sufficient radar scatterers to define the vortex moves within 230 km (Doppler range) of a coastal WSR-88D Doppler radar, a WP-3D will obtain Doppler radar data to be combined with data from the WSR-88D radar in dual-Doppler analyses. These analyses could resolve phenomena with time scales <10 min, the time spanned by two WSR-88D volume scans. This time series of dual-Doppler analyses will be used to describe the storm's inner core wind field and its evolution. The flight pattern for this experiments designed to obtain dual-Doppler analyses at intervals of 10-20 min the inner core. Unfortunately, these WSR-88D/aircraft dual-Doppler analyses will not be available in real-time, but the Doppler wind fields could be incorporated into post-storm surface wind analyses. The data set will also be useful for development and testing of tropical cyclone algorithms for the WSR-88D. The Doppler data will be augmented by dropping new GPS sondes near the coast, where knowledge of the boundary-layer structure is crucial for determining what happens to the windfield as a strong storm moves inland. If the DOW radars have been deployed on the coast, then the flight tracks will be modified to include their locations.

To augment the inner core analyses, dual-Doppler data can be collected in the outer portions of the storm (where the aircraft's drift angle is small) from a single aircraft using the Fore/Aft Scanning Technique (F/AST) (Jorgensen and DuGranrut 1991). The tail radar is tilted to point 20° forward and aft from the track during successive sweeps. The alternating forward and aft scans intersect at 40°, sufficient for dual-Doppler synthesis of winds.

Several studies (Bergeron 1954, Miller 1964) indicate that loss of the oceanic moisture source is responsible for the decay of landfalling tropical cyclones. These studies relied on surface observations that are usually sparse at landfall and require time-to-space compositing techniques that assume stationarity over relatively long time periods. More complete observations could help improve our knowledge of intensity change during and after landfall. The U.S. Air Force monitored Hurricane Andrew's landfall in southeast Florida for two passes after landfall, and NOAA flew in Hurricanes Opal (1995) and Fran (1996) after they moved inland, but the decay of a tropical cyclone over land has not been well documented by aircraft observations. If the safety requirements can be met, the combination of WSR 88D observations with NOAA airborne Doppler radar and flight level measurements would allow detailed documentation of the thermodynamic and kinematic structural changes during landfall.

3. Objectives:

- Collect flight-level wind data and make surface-wind estimates to improve real-time and post-storm surface wind analyses in hurricanes.

- Collect single airborne Doppler radar data, analyze with EVTD, and send wind analyses in near real-time to NHC.

- Collect airborne Doppler radar to combine with WSR-88D radar data in post-storm three-dimensional wind analyses.

- Investigate the incorporation of EVTD wind fields into real-time surface wind analyses.

- Document thermodynamic and kinematic changes in the storm during and after landfall.

4. Mission Description:

This experiment will be flown with a single aircraft if a hurricane moves within 215 nmi (400 km) of the coast of the United States. If the storm moves slowly parallel to the coastline and resources permit, the experiment may be repeated with a second flight. The aircraft must have working lower fuselage and tail radars. The HRD workstation should be on board, so we can transmit radar images and an EVTD analysis back to NHC. Microphysical data should be collected, to compare rainfall rates with those used in the WSR-88D precipitation products. The SFMR should be operated, to provide estimates of wind speed at the surface. If the C-SCAT is on the aircraft then it should also be operated to provide another estimate of the surface winds. If the storm will be within 125 nmi (230 km) of a WSR-88D, arrangements must be made to ensure that Level II data are recorded. If NDBC resources permit, drifting buoys could be deployed ahead of the storm to improve the off-shore wind description.

The primary module of the experiment, the "real-time module", will support real-time and post-storm surface wind analyses. Two dual-Doppler options can be flown if the storm is near a WSR-88D radar. A coastal-survey option can be flown when the storm is too close to the coast to permit radial penetrations. The flight patterns will depend on the location of the storm relative to surface observing platforms and coastal radars. Experience in recent tropical cyclone landfall experiments has shown that considerable flexibility is needed to design and execute a flight pattern for a particular storm. The following modules are described for a storm making landfall on the south Florida coast. These modules were adapted and used in flights in Hurricane Erin (1995), Fran (1996) and Tropical Storm Josephine (1996).

Real-time module:

The real-time module combines passes over marine surface platforms with one or more figure-4 patterns in the core of the hurricane. The aircraft flies at or below 5,000 ft (1.5 km) (ideally at 2,500 ft [750 m]), so that flight level winds can be adjusted to 30 ft (10 m) to combine with measurements from marine surface platforms. Flight-level data and GPS sondes dropped near the platforms will be used to validate the adjustment method. Doppler data collected in the figure-4 will be analyzed with EVTD in real-time on the HRD workstation. The lowest level of the EVTD analysis may be sent to NHC where the Doppler winds can also be adjusted to the surface and made available to HRD's real-time surface wind analysis system. Note that if the storm is outside of WSR-88D Doppler range then the figure-4 pattern could be repeated before returning home.

For example, if a hurricane moves within range of Melbourne, Florida, then the flight pattern should take advantage of buoys 41009 and 41010. The aircraft descends at the initial point and begins a low-level figure-4 pattern, modifying the legs to fly over the buoys (Fig. C-3). Whenever the drift angle permits the radar will be in F/AST mode, except in the eye penetrations. If time permits the aircraft would make one more pass through the eye and then fly the dual-Doppler module. In this example the pattern would be completed in about 2.5 h. GPS sondes would be dropped near the buoys.

Dual-Doppler Option 1:

If the tropical cyclone moves within Doppler range of a coastal WSR-88D 125 nmi (230 km), then we will fly a second module, to collect a time-series of dual-Doppler data from the storm's inner core. Note that the optimal volume scans for this pattern will be obtained when the storm is 32-80 nmi (60-150 km) from the radar, because beyond 80 nmi (150 km) the lowest WSR-88D scan will be above 5,000 ft (1.5 km) which is too high to resolve the low-level wind field. Within 32 nmi (60 km) the volume scan will be incomplete, because the WSR-88D does not scan above 19.5°.

The pattern will depend on the location of the storm relative to the coastal radar. Depending on safety and operational considerations, the aircraft could fly this portion of the experiment at a higher altitude, although 5,000 ft (1.5 km) would still be preferred. Continuing our example for the Melbourne WSR-88D, after completing the real-time module the aircraft flies to an initial point on the track intersecting the storm center and the coastal radar (Fig. C-3). The aircraft then makes several passes through the eyewall (A-B in Fig. D-3), with the tail radar scanning perpendicularly to the track. Depending on the size of the eyewall each pass should last 10-20 min. It is essential that these passes be flown as straight as possible, because turns to fix the eye will degrade the Doppler radar coverage. After each pass the aircraft turns quickly and heads back along the same track, adjusted to keep the storm center and the coastal radar on the same line. In 2 h, 6-12 volume scans will be collected. The last pass should be followed by a pass through the eye perpendicular to the other legs, to provide data for EVTD and PDD analyses. If time permits, the real-time module could be repeated before returning home, or the coastal-survey module could be flown.

Dual-Doppler Option 2:

If dual-Doppler data are desired over a larger area, then another module will be flown where the aircraft flies along three WSR-88D radials to survey both the inner core and surrounding rainbands (Fig. D-4). In the example shown, this pattern could be flown in about 2 h. Note that the legs outside the inner core should be flown with the tail radar in F/AST mode because the drift angle would be smaller. In the example the module concludes with a coastal-survey pass south along the coast.

Coastal Survey option:

When the hurricane is making landfall, this module will provide information about the boundary layer in the onshore and offshore flow regimes. The WP-3D would fly a coastal survey pattern parallel to the coast, as close as safety permits, at 5000' (1.5 km) or less, and drop GPS sondes on either side of the storm track, to sample both onshore and offshore flow regimes (Fig. C-5). The Doppler radar would be in F/AST mode, to provide wind estimates on either side of the aircraft track. This module could be flown when the hurricane is making landfall or after the storm moves inland. The pattern could be flown in ~1 h. GPS sonde drop sites could be adjusted to be near surface platforms.

Post-landfall option:

If the structure of the storm is such that flight patterns at 10,000' (3.5 km) or 15,000' (5 km) are feasible over land, then the storm would be followed inland as long as time and safety considerations permits, perhaps including a second flight. Fig. D-5 also shows an example from Hurricane Fran (1996). The pattern would be flown around the core with the radar in F/AST scanning mode. Note that overland penetration of the eyewall is not essential. However, the flight tracks should be designed to take advantage of WSR-88D radials if possible. The aircraft would avoid penetrating intense reflectivity features and areas where of sharp reflectivity gradients.

Other options: Timing is crucial for this experiment. If we are too early or too late, we could fly modules from other experiments until our modules are viable. For example, if the storm is too far offshore during the initial part of the flight, or if it is unsafe to fly the post-landfall option, we could also fly the rainband module (Fig. C-6), to gather Doppler and thermodynamic information.

5. Special instrumentation:

The aircraft should have an HRD workstation, the C-Band Scatterometer, and the Stepped Frequency Microwave Radiometer.

6. Data Management:

HRD will manage the data collected by AOC. The National Climatic Data Center will archive the WSR-88D Level II data.

Expendable supplies:

- 4-6 DAT radar tapes
- 10 DAT cloud physics tapes
- 5 DAT workstation archive tapes
- 10 GPS sondes

7. Funding:

HRD will provide expendable supplies and funds to reduce and analyze the data. Flight hours will be from HRD base funds.

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TROPICAL CYCLONE WINDFIELDS NEAR LANDFALL EXPERIMENT

Ground-based/Airborne Doppler Scanning Strategy

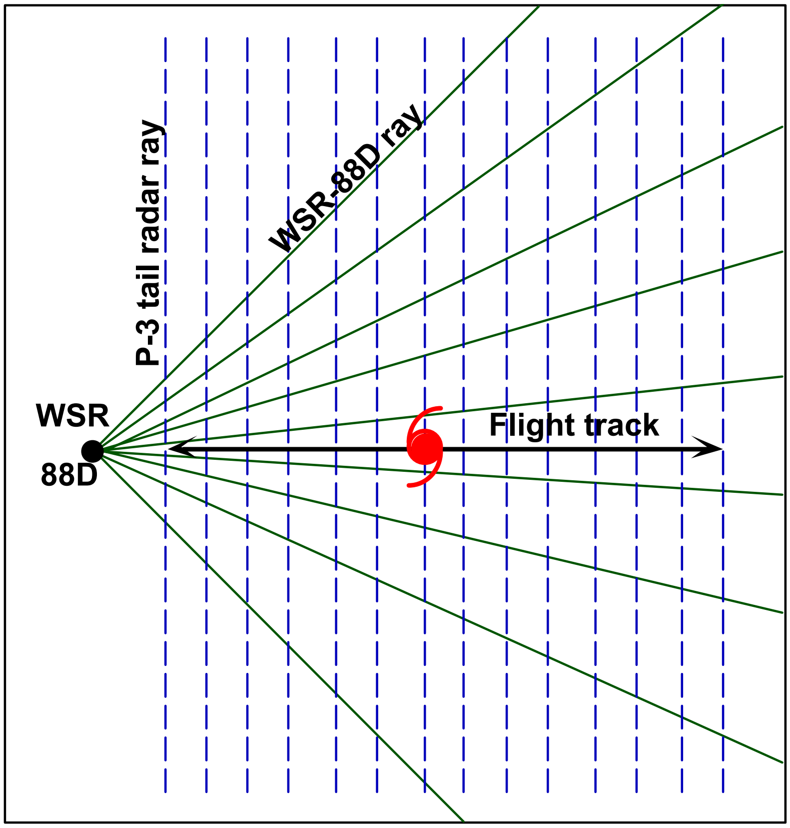

Fig. C-1. Airborne Doppler Radar Flight Track

• Note 1.	The legs through the eye may be flown along any compass heading along a radial from the ground-based radar.
• Note 2.	Set airborne Doppler radar to scan continuously perpendicular to the track on all legs.

TROPICAL CYCLONE WINDFIELDS NEAR LANDFALL EXPERIMENT

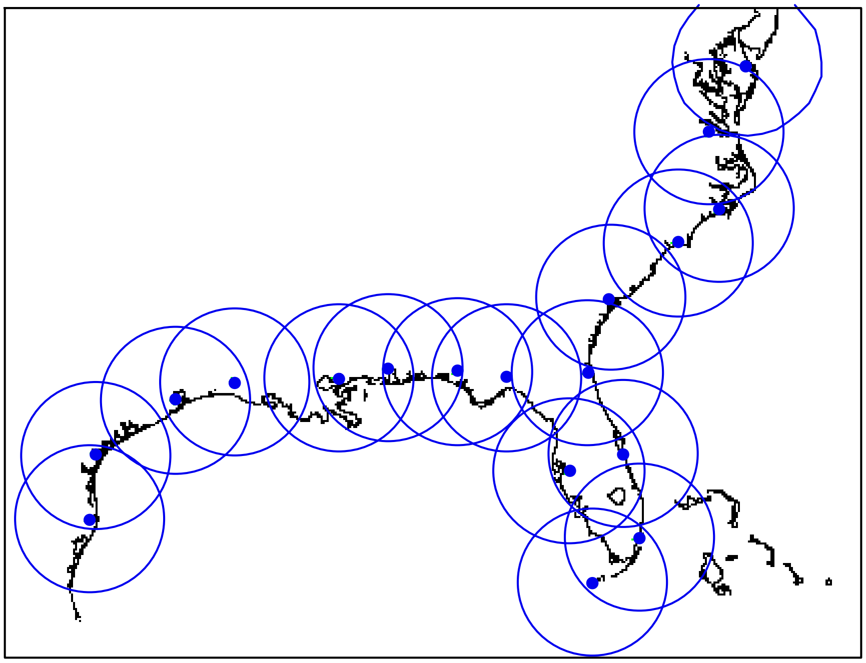

Fig. C-2. The locations of the WSR–88D coastal radar sites. Range rings are at 125 nmi (230 km) radius.

TROPICAL CYCLONE WINDFIELDS NEAR LANDFALL EXPERIMENT

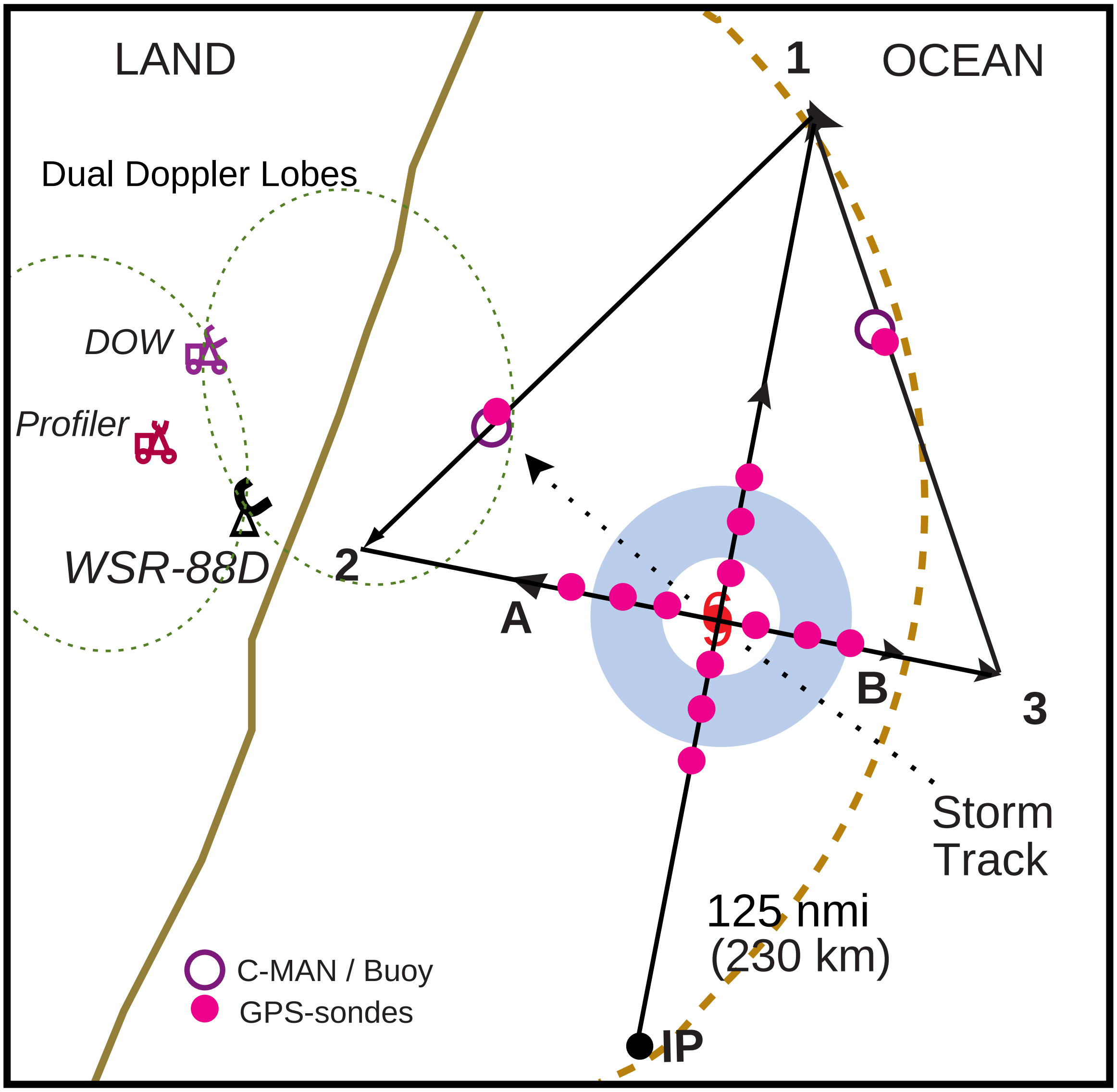

Fig. C-3. Flight track for the real-time module with over flights of moored buoys for a storm passing within range of a coastal WSR-88D.

• Note 1.	True airspeed calibration required.
• Note 2.	The legs through the eye may be flown along any compass heading along a radial from the ground-based radar. The **IP** is approximately 100 nmi (185 km) from the storm center. Downwind legs may be adjusted to pass over buoys.
• Note 3.	Dual-Doppler sampling is along a radial from the WSR-88D radar (**A-B**) and may be repeated a number of times.
• Note 4.	Set airborne Doppler radar to scan continuously perpendicular to the track on radial penetrations, and to F/AST on all downwind legs.

TROPICAL CYCLONE WINDFIELDS NEAR LANDFALL EXPERIMENT

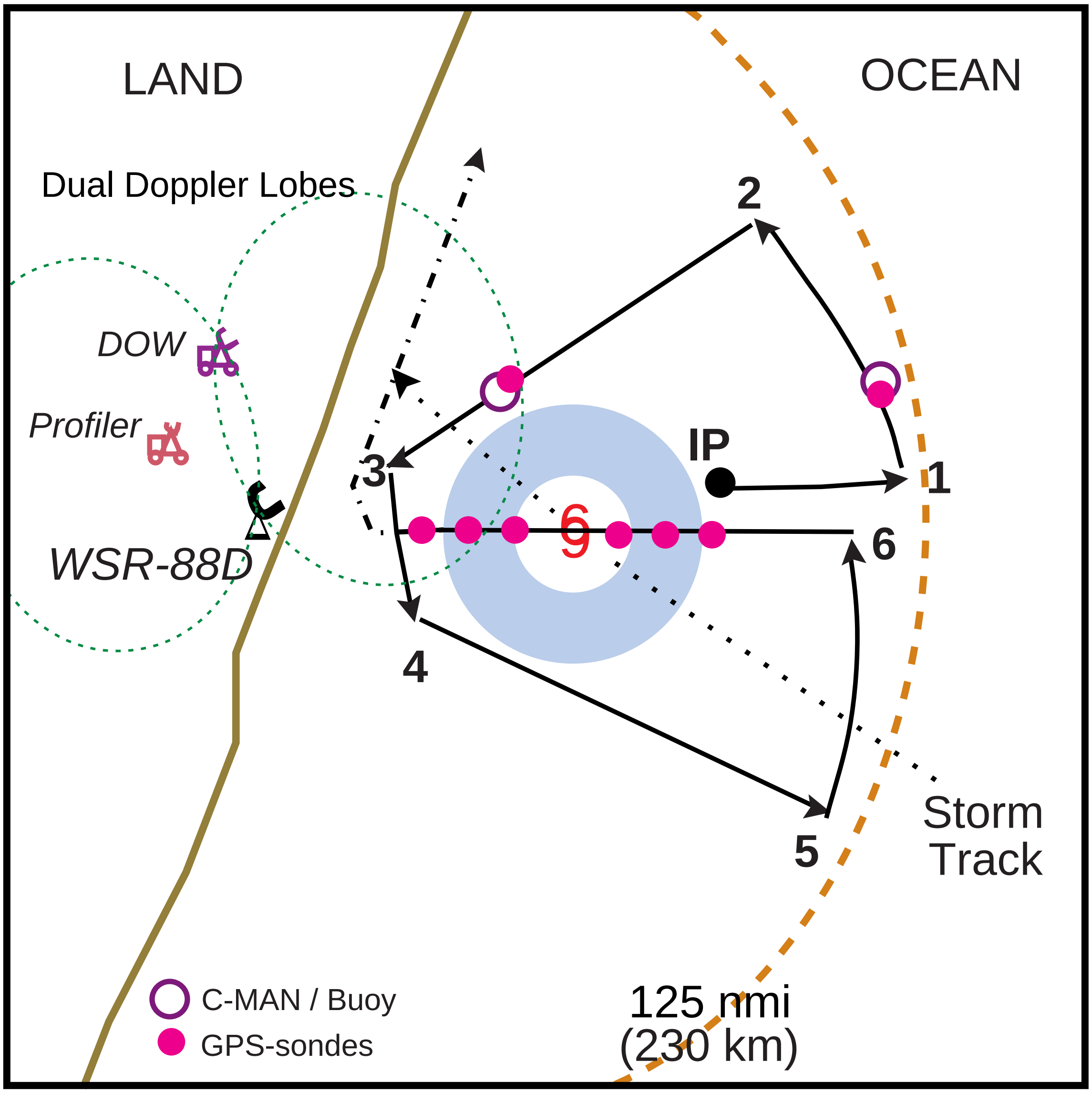

Fig. C-4. **Flight track for the dual-Doppler option that covers the inner core and surrounding rainbands.**

• Note 1.	True airspeed calibration required.
• Note 2.	The legs through the eye may be flown along any compass heading along a radial from the ground-based radar. The **IP** is at the end of the last leg in the real-time module. Downwind legs may be adjusted to pass over buoys.
• Note 3.	Dual-Doppler sampling is along a radial from the WSR-88D radar (**A-B**) and may be repeated a number of times.
• Note 4.	Set airborne Doppler radar to scan F/AST on all legs except from **IP-1**.

TROPICAL CYCLONE WINDFIELDS NEAR LANDFALL EXPERIMENT

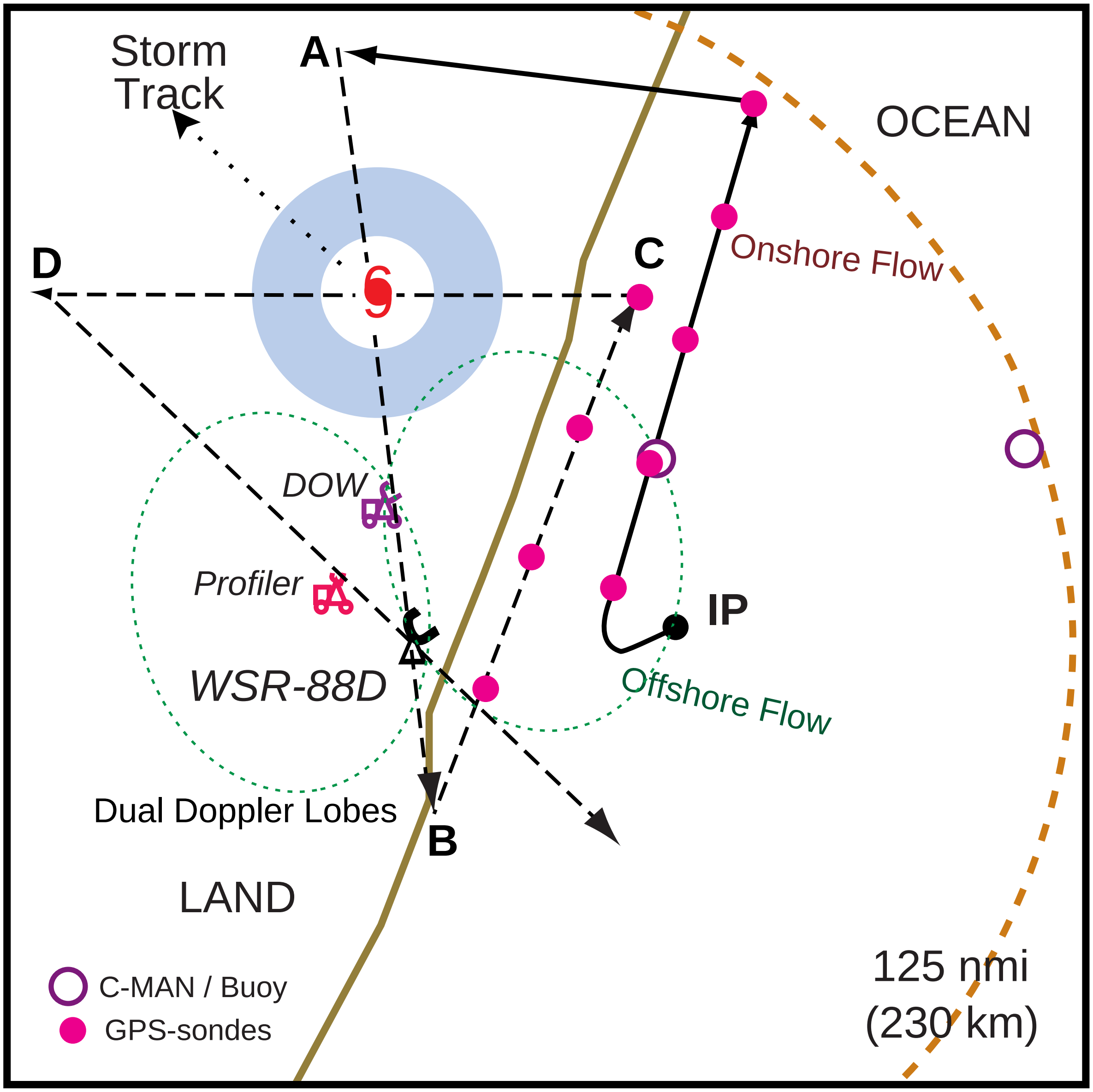

Fig. C-5. Flight track for the real-time module with over flights of moored buoys and GPS-sonde drops for a storm after landfall.

• Note 1.	Begin pattern after execution of the coastal survey option. Execute figure-4 or triangle pattern on circulation center with ~60 nmi (110 km) legs at 14,000 ft (4 km) altitude (dashed line).
• Note 2.	GPS-sondes should be dropped at least 10 nmi (18 km) offshore in the onshore flow regime, and as close as possible to the coast in the offshore flow regime.
• Note 3.	Avoid penetration of intense reflectivity or reflectivity gradient areas. Wind center penetrations are optional.
• Note 4.	If possible the legs of the pattern should be lined up on WSR-88D radials. Set airborne Doppler radar to F/AST scanning on all legs.

TROPICAL CYCLONE WINDFIELDS NEAR LANDFALL EXPERIMENT

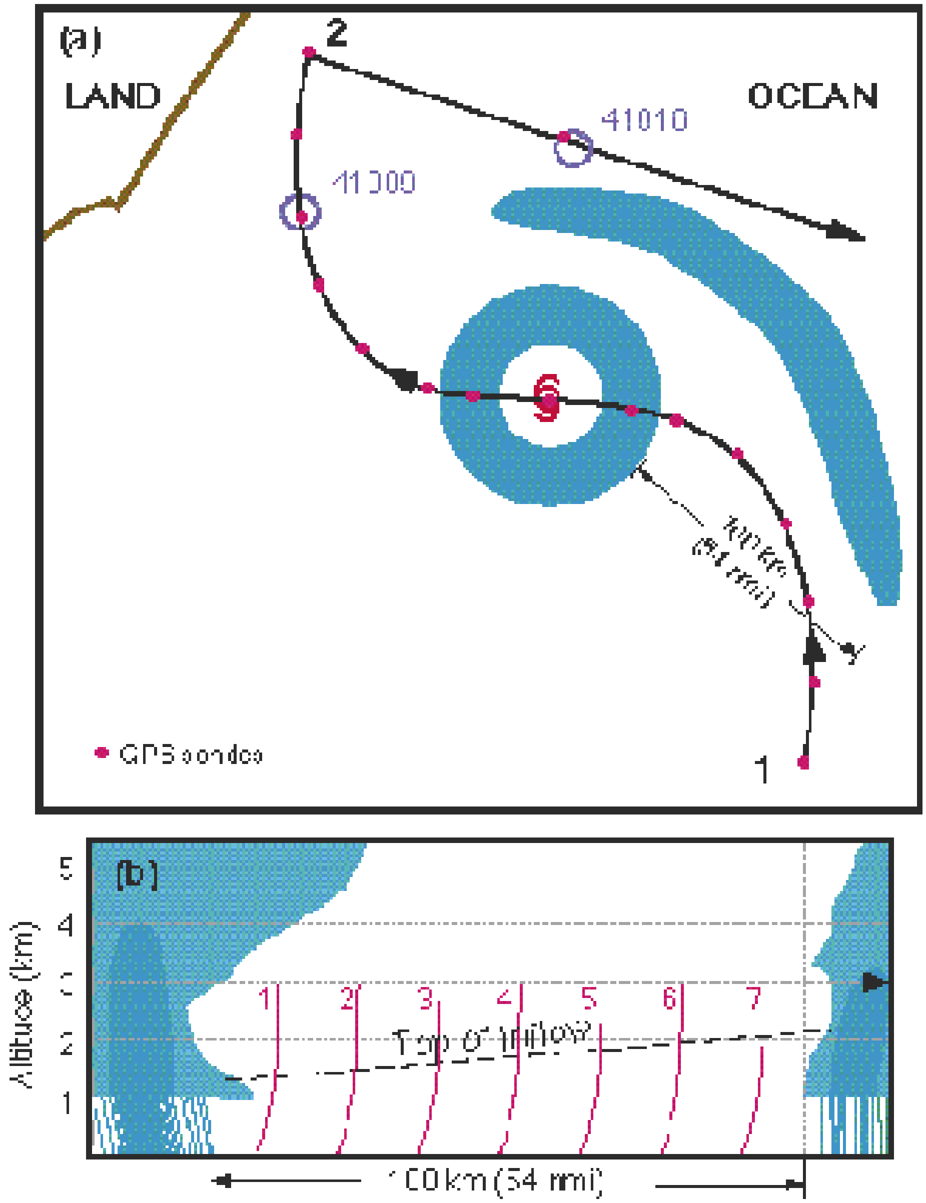

Fig. C-6. **Rainband Thermodynamic Structure Module (a) Plan view; and Aircraft track-height depiction of (b) the GPS deployment experiment.**

Appendix D

Hurricane Synoptic Surveillance

(Principal Investigator: Sim Aberson)

1. Abstract

With the arrival of the NOAA Gulfstream IV-SP high-altitude jet (G-IV), the Hurricane Synoptic Flow Experiment made the transition from a research program to operations. Beginning in 1997, the G-IV conducted routine "hurricane surveillance" missions that are essentially HRD Synoptic Flow experiments. When coordinated with these operational G-IV flights, the HRD Synoptic Flow experiment now becomes a *single-option, triple aircraft* experiment. As in previous years, the experiment seeks to obtain accurate, high-density wind and thermodynamic data sets from the environment and vortex regions of hurricanes that are within 72 h of potential landfall. The availability of the G-IV, however, greatly increases the amount of environment that can be sampled. GPS-based dropwindsondes will be released from the G-IV and the two NOAA/AOC WP-3D aircraft to obtain data over the normally data-void oceanic regions at distances up to 810 nmi (1500 km) from the hurricane center. Mandatory and significant level dropwindsonde data will be transmitted in real time for use in the objective statistical and dynamical hurricane prediction models at the National Hurricane Center (NHC) and the National Centers for Environmental Prediction (NCEP). In a research mode, these data will be used to help improve short and medium term (24-72 h) hurricane track prediction through diagnostic studies of the influence of synoptic-scale fields on vortex track and intensity, and in investigations of optimal deployment strategies using ensemble forecasts. In addition, the data will be used to assess methods for obtaining satellite soundings.

2. Program Significance and Scientific Justification

Hurricane Synoptic Flow experiments conducted prior to 1997 used the WP-3Ds and the previous Omega-based generation of dropwindsondes (ODWs) to gather vertical profiles of wind, temperature, and humidity within 540 nmi (1,000 km) of hurricanes. The experiment was typically conducted over the data-sparse oceanic regions of the western Atlantic or Gulf of Mexico roughly 48-72 hours before the projected landfall of a mature hurricane on the coast of the United States. While satellites typically provide wind data in the upper and lower troposphere (near 200 and 850 mb, respectively), the middle levels the levels most directly related to tropical cyclone motion are frequently almost void of observations. As a result, operational models often fail to predict important changes of storm speed or direction due to inadequate initial data, rather than inadequate physics of the prediction models. During the Synoptic Flow experiments, ODWs released from the WP-3Ds defined the hurricane's surrounding large-scale flow, particularly in the critical 400-700 mb middle tropospheric layer.

Synoptic Flow experiments were conducted on 18 occasions from 1982-93. Recent research at HRD, NCEP, and GFDL with this sample of cases demonstrates conclusively that the ODW data produce significant improvements in the operational models that are the primary guidance for NHC's official track forecasts. For consensus (averaged) forecasts from the three primary operational dynamical models (HRD's barotropic VICBAR model, GFDL's nested grid model, and NCEP's global spectral model), the ODWs were responsible for statistically significant 12-60 hour track forecast improvements of 16%-30%. These improvements are at least as large as the accumulated improvement in operational forecasts achieved over the last 20-25 years.

The size of these improvements suggests that operational dropwindsonde missions will be a highly effective way to reduce the costs associated with overwarning. Hurricane warnings are usually issued 18-24 hours before landfall for a length of coastline averaging 300 nmi (555 km). The swath of damaging winds and tides caused by hurricanes that strike land, however, is generally <100 nmi (185 km). Thus, current forecasting skill results in an overwarning zone of ~200 nmi (370 km) that is a trade-off between maximizing warning lead time and keeping the warning area as small as possible. In 1995, NHC estimated that the preparation costs alone incurred by the public placed under a hurricane warning were nearly $190,000 per nmi ($350,000 per km) of coastline. By comparison, the cost of a three-aircraft dropwindsonde mission using 70 GPS sondes (at $500 apiece) and 27 hours of flight time (at $2,800 per hour) is about $111,000. If forecasters are able to reduce the over-warning area by only 5% (11 nmi [20 km]) by taking advantage of dropwindsonde-improved numerical guidance, the savings in warning response costs would greatly exceed (by a factor of 60) the cost of obtaining the additional observations.

In addition to direct operational benefits of the Synoptic Flow experiments, diagnostic case studies of the ODW observations have led to improvements in our basic understanding of hurricane motion. Analyses of the existing data sets have helped to document the relationship between vortex motion and the environmental flow and have provided the first observational evidence of the beta-gyres commonly found in barotropic models. A multi-scale, nested analysis of the Gloria data set has also been completed. This analysis identified a "steering envelope" in the deep-layer-mean flow just outside Gloria's eyewall.

The Gloria analyses have also been used to document, for the first time, the potential vorticity (PV) distribution in a hurricane's core and environment. Recently-published work involving the inversion of Gloria's PV distribution is providing a powerful new tool for diagnosis of the synoptic features responsible for a given hurricane's steering flow. Preliminary results indicate that upper level PV features dominate, and can act from large distances from the hurricane's center. Synoptic Flow experiments using the G-IV and WP-3Ds simultaneously will offer an unprecedented opportunity to document these features. In a related study, data from recent Synoptic Flow experiments are being examined to assess the ability of growing modes and/or singular vectors to define regions of large error growth in ensemble forecasts. This work has the potential to define an adaptive observing strategy to maximize the impact of the dropwindsonde data on operational hurricane forecasts.

3. Objectives

The ultimate objective of these experiments is the improvement of short- and medium-range (24-72 h) hurricane track prediction. The immediate requirement is the collection of one or two comprehensive data sets of GPS-dropwindsonde soundings within 1500 km of hurricanes that are threatening the United States. These data will be used by NHC and NCEP to prepare *real-time* analyses and official forecasts and will be incorporated in the objective statistical and dynamical hurricane prediction models.

The ODW's have been shown to be capable of improving hurricane track forecasts; however, the optimal deployment strategy is unknown. The increased range and altitude capability of a three-aircraft coordinated pattern, coupled with the PV inversion tools presently developed, and the use of growing modes and/or singular vectors in ensemble forecasts, will allow the determination of optimal adaptive deployment strategies. These data sets will also be used to study the influence of synoptic-scale fields on changes in vortex intensity and track and to assess satellite-derived products.

4. Mission Description

To collect a relatively uniform distribution of dropwindsonde soundings within ~1500 km of hurricanes over a minimum period of time, both NOAA/AOC WP-3D aircraft will operate simultaneously in regions within and surrounding the hurricane. *The WP-3Ds will operate simultaneously and in coordination with operational surveillance missions of the G-IV high altitude jet.* Specific flight tracks will vary depending on such factors as the location of the storm, relative both to potential bases of operation and to particular environmental meteorological features of interest, and the operational pattern being flown by the G-IV.

A sample mission is shown in Fig. D-1. The two WP-3D aircraft and the G-IV will begin their missions at the same time. Subject to safety and operational constraints, each WP-3D will climb to the 500-mb level (about 18,000 ft [FL 180]) or above, then proceed, step-climbing, along the routes assigned during preflight. *It is particularly important that both aircraft climb to and maintain the highest possible altitude as early into the mission as aircraft performance and circumstances allow, and attain additional altitude whenever possible during the mission.*

Dropwindsondes are released in one of two modes. Beyond 40 nmi (75 km) from the storm center, drops are made at pre-assigned locations, generally every 25 min or 120 nmi (222 km). These drop locations are provided with the particular mission flight tracks 2 h before blockout. Within 40 nmi (75 km) of the hurricane's center, drop locations are specified relative to the center's position (e.g., 40 nmi [75 km] north of the eye). During in-storm portions of the mission, drops will be made with possible spacing < 8 min or 40 nmi (75 km). Efforts should be made to avoid making drops in heavy precipitation, unless necessary. Aircraft turns are not expected to affect the dropwindsonde wind accuracy, but we expect to continue the practice of making drops AFTER THE TURN IS COMPLETE.

Usually, one aircraft will fly through the hurricane center and execute a Doppler figure-4 pattern. This aircraft's Doppler radar should be set to scan perpendicular to the aircraft track. *"Hard" center fixes are not desirable*. On the downwind leg of the figure-4, the Doppler should be set to record forward and aft (F/AST) continuously. If both aircraft penetrate the storm, the figure-4 pattern will generally be executed by the *second* aircraft through the storm, and the first aircraft through will collect vertical incidence Doppler data. Coordination with potential USAF reconnaissance is necessary to ensure adequate aircraft separation. The in-storm portion of the missions is shown schematically in Fig. D-2, although the actual orientation of these tracks may be rotated.

Of paramount importance is the transmission of the dropwindsonde data to NCEP and NHC for timely incorporation into operational analyses, models, forecasts, and warnings. Operational constraints dictate an 0600 or 1800 UTC blockout time, so that the dropwindsonde data will be included in the 1200 or 0000 UTC analysis cycle. Further, limiting the total block time to 9 h allows adequate preparation time for aircraft and crews to repeat the mission at 24-h intervals. These considerations will ensure a fixed, daily real-time data collection sequence that is synchronized with NCEP and NHC's analysis and forecasting schedules. If the missions are not to be repeated, then requested block times may exceed 9 h. In addition to the dropwindsonde data, *three to four RECCO's per hour should be taken and transmitted during each mission.*

Special Notes:

Missions very similar to the Synoptic Flow missions may be flown in clear-air (non-hurricane) conditions to collect dropwindsonde data sets for satellite sounding evaluations and adaptive observing system studies. These clear-air missions differ from the normal experiment as follows:

a) Block times are 10 h, and the experiment is not repeated on the following day.
b) In-storm portion of the pattern (Fig. E-2) is omitted and no Doppler data are collected.
c) The G-IV does not participate in the mission.

5. Instrumentation and Expendables:

The Synoptic Flow Experiment requires the standard suite of flight-level sensors and the AVAPS dropwindsonde system. There are no requirements for special instrumentation. Forty dropwindsondes are required per experimental day. The estimated tape requirement for the radar data systems is about 2 DATs per experimental day. Expendables for the operational G-IV portion of the mission (about 30 dropwindsondes) will be provided by the National Weather Service.

6. Data Management

The operational dropwindsonde data are archived at NCEP. Researchers at NCEP use the archived data sets to evaluate the impact of the dropwindsondes in hurricane track forecasts made by the operational NCEP models. The dropwindsonde data recorded on the aircraft are post-processed at HRD and made available to all interested users. A multi-level objective analysis algorithm has been developed at HRD. The analysis software is capable of incorporating winds, temperature, and relative humidity from the dropwindsondes and other available data sources, including Doppler radar, rawinsondes, satellite products, and commercial aircraft. The analysis uses a nested-mesh technique to increase resolution of smaller scale features near the storm center. The package has been used to analyze core and environmental wind data from Hurricane Gloria (1985). These multi-scale analyses are being made available to interested researchers. Synoptic-scale analyses of the entire sample of cases have recently been completed, for use in diagnostic and prognostic studies of hurricane motion and intensification. These analyses could also be provided to researchers at universities and other laboratories.

7. Funding

Flight hours are obtained from AOC base funds. Expendables (for the P-3s) are funded from HRD base funds.

Publications

The following publications have resulted from previous Synoptic Flow Experiments:

Burpee, R. W., D. G. Marks and R. T. Merrill, 1984: An assessment of dropwindsonde data in track forecasts of Hurricane Debby (1982). *Bull. Amer. Meteor. Soc.*, **65**, 1050-1058.

Burpee, R. W., J. L. Franklin, S. J. Lord, R. E. Tuleya, and S. D. Aberson, 1996: The impact of Omega dropwindsondes on operational hurricane track forecast models. *Bull. Amer. Meteor. Soc.*, **77**, 925-933.

Franklin, J. L. and S. Lord, 1988: Comparisons of VAS and Omega dropwindsonde thermodynamic data in the environment of Hurricane Debby (1982). *Mon. Wea. Rev.*, **116**, 1690-1701.

Franklin, J. L., S. Lord and F. D. Marks, Jr., 1988: Dropwindsonde and radar observations of the eye of Hurricane Gloria (1985). *Mon. Wea. Rev.*, **116**, 1237-1244.

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Franklin, J. L., S. J. Lord, S. E. Feuer and F. D. Marks, Jr., 1993: The kinematic structure of Hurricane Gloria (1985) determined from nested analyses of dropwindsonde and Doppler radar data. *Mon. Wea. Rev.*, **121**, 2433-2451.

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Lord, S. J. and J. Franklin, 1987: The environment of Hurricane Debby (1982). Part I: Winds. *Mon. Wea. Rev.*, **115**, 2760-2780.

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Shapiro, L. J., 1996: The motion of Hurricane Gloria: a potential vorticity diagnosis. *Mon. Wea. Rev.*, **124**, 2497-2508.

HURRICANE SYNOPTIC FLOW EXPERIMENT

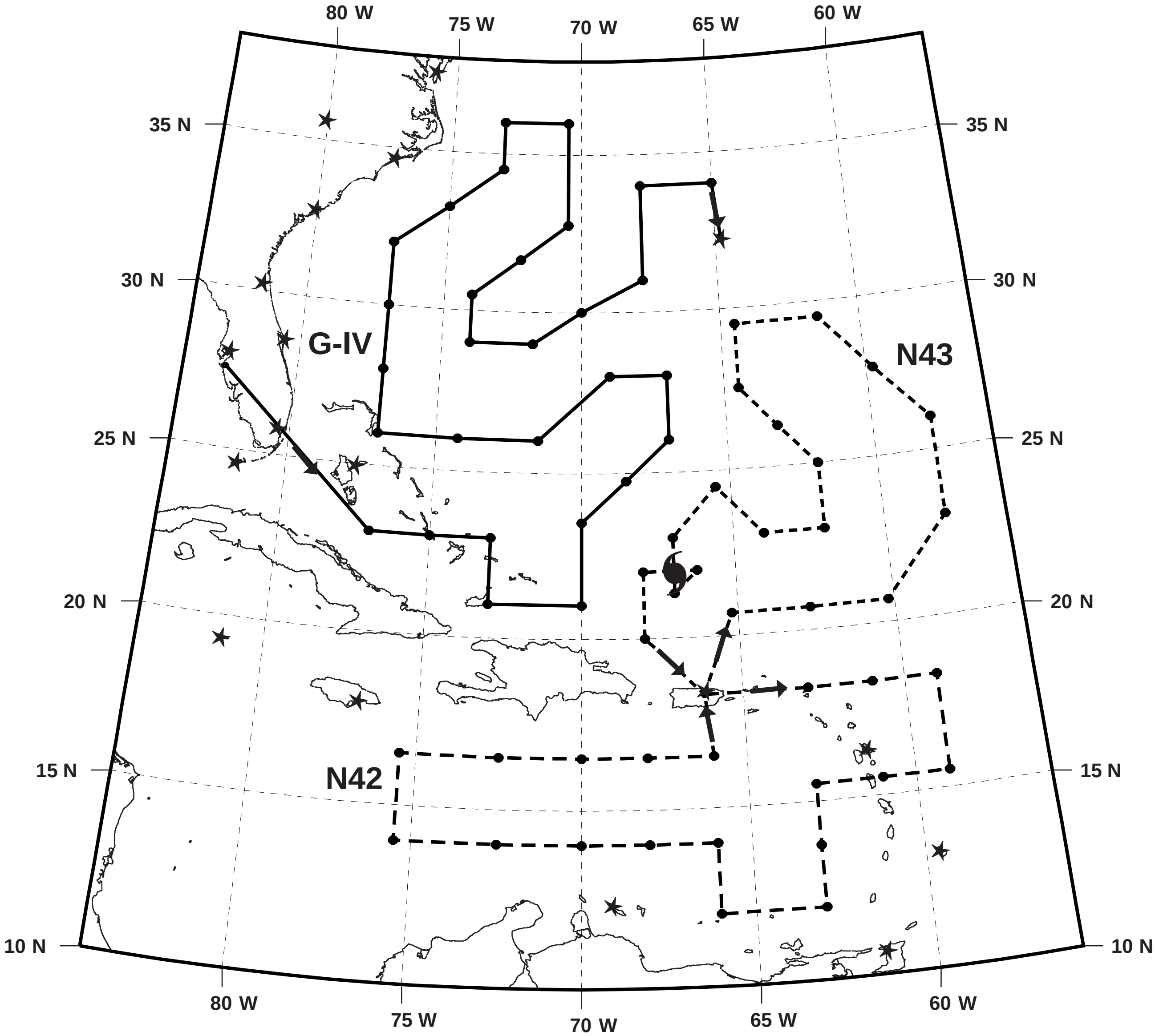

Figure D-1. Sample flight pattern

• Note 1.	During the ferry to the **IP**, the WP-3D aircraft will climb to the 500 mb level (about FL 180). The 400 mb level (about FL 250) should be reached as soon as possible and maintained throughout the remainder of the pattern, unless icing or electrical conditions require a lower altitude.
• Note 2.	During the ferry to the **IP**, The G-IV should climb to the 41,000 ft (200 mb) as soon as possible and climb as feasible to maintain the highest altitude for the duration of the pattern.

HURRICANE SYNOPTIC FLOW EXPERIMENT

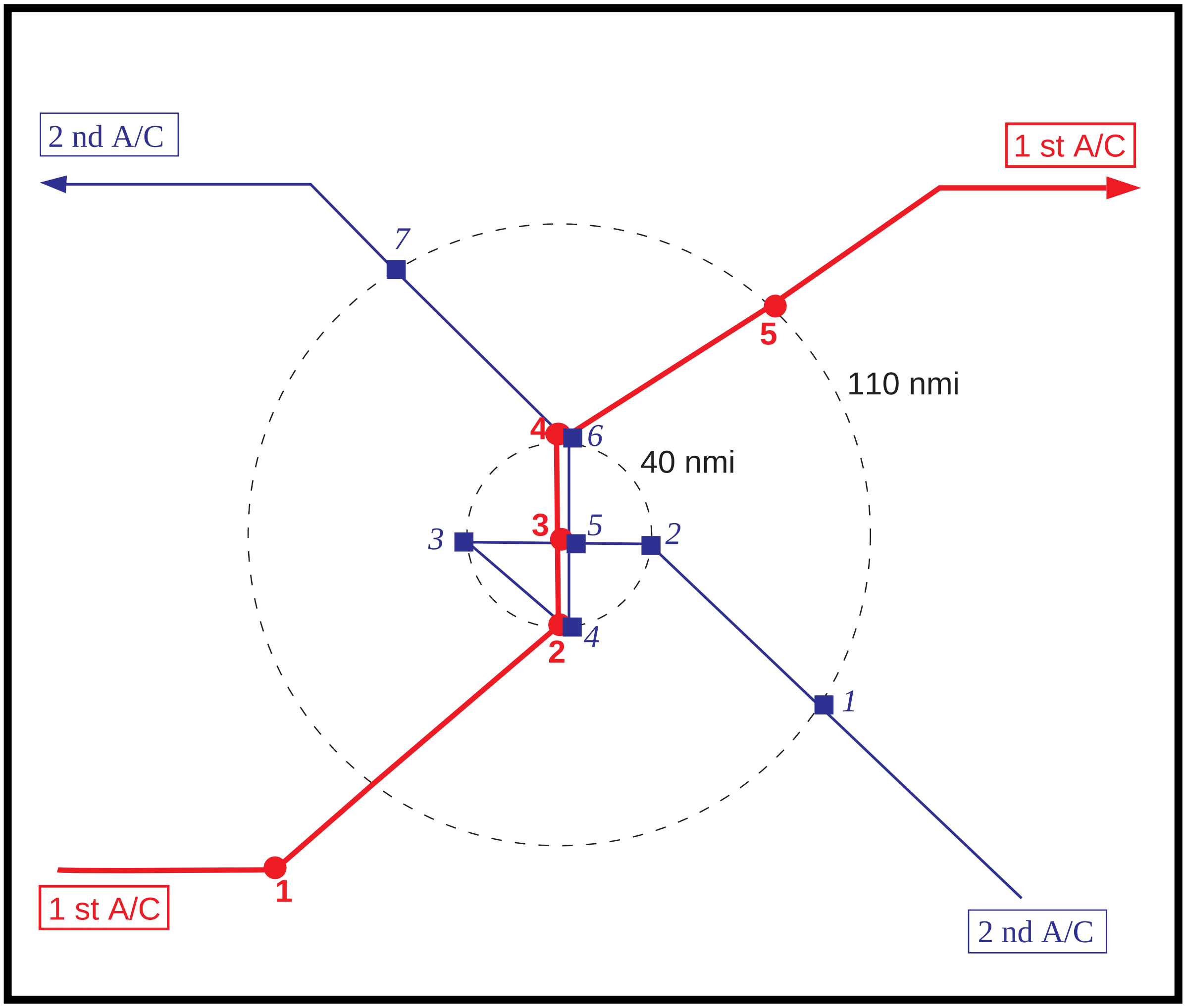

Fig. D-2 In-Storm Patterns

• Note 1.	Within the 40 nmi (75 km) range ring, all legs are on cardinal tracks.
• Note 2.	The second aircraft through the storm will execute the Doppler "figure-4" pattern. The Doppler radar should be set to continuously scan perpendicular to the track during radial penetrations and to F/AST on the downwind leg.
• Note 3.	Numbered symbols (u, n) reflect scheduled drops for each aircraft.
• Note 4.	Drop #5 in the "figure-4" pattern occurs on the second pass through the eye.
• Note 5.	A/C 1 should collect vertical incidence Doppler data during storm penetration.
• Note 6.	If missions are not repeated, then block times may exceed 9 h. In addition to the GPS-sonde data, *3-4 RECCO's h^{-1} should be transmitted during each mission.*