9. Coupled Boundary Layer Air-Sea Transfer (CBLAST) Experiment

Program significance: Our primary goal is to improve our understanding of air-sea surface flux processes in high winds, specifically in the complex conditions of tropical cyclones where swell, sea spray and secondary boundary layer circulations play a significant role. In so doing, we plan to develop improved parameterizations for air-sea flux processes used in hurricane numerical models that will lead to improved forecasting of hurricane intensity change.

An ongoing collaborative effort, called Ocean Winds, will be conducted simultaneously by NESDIS to validate satellite scatterometer measurements in high-wind, hurricane environments. This effort uses and sponsors some of the same instrumentation systems used by CBLAST, especially the airborne scatterometer and radiometer systems.

The Hurricane Component of the Office of Naval Research (ONR) Coupled Boundary Layer Air-Sea Transfer (CBLAST) Departmental Research Initiative aims to measure, analyze, understand, and parameterize the air-sea fluxes in the tropical cyclone environment. Unlike mid-latitude cyclones where baroclinic processes are important, tropical cyclones draw their energy supply from the ocean. Fluxes of sensible heat and water vapor enrich the immediate atmospheric boundary layer (ABL). The momentum flux destroys the gradient balance and creates the cross-isobaric inflow transports the warm and moist air into the tropical cyclone inner region or rainbands to fuel the convective release of latent. Thus, the inward transport and air-sea fluxes ultimately determine the conversion of atmospheric available potential energy into kinetic energy of the storm. The significant air-sea flux exchanges greatly modify the near surface ocean temperature and current by mixing and three-dimensional transport. Under stationary or slow-moving hurricanes, the induced sea-surface temperature (SST) decrease can reach several degrees and the induced current can extend to great depths. The altered oceanic state can then feed back to modify the behavior of the overlaying tropical cyclone; they are indeed the most interesting and complex natural laboratory for air-sea interaction study.

The air-sea interfacial boundary under high wind is not well defined, and physical processes there are not properly quantified. The ocean surface waves and swell are characterized by limited fetch in the strongly forced regime. High winds and strong vertical wind shear mechanically form ocean spray, which is found to have significant effect on the thermal structure of ABL and may play an important role in hurricane thermodynamics, dynamics and intensity change. The ocean mixed layer is filled with air bubbles that can affect the air-sea exchange. This forms the basis for microwave and acoustic remote sensing of surface wind stress and allows inference of the surface wind. Standard boundary layer parameterizations, based on observations mostly taken at wind speeds below 20 m s^{-1} (39 kt), have not been validated for tropical cyclone conditions and highly disturbed sea states. Observation, understanding, and, eventually, the modeling of the structure and physical processes in the coupled hurricane-ocean boundary layer are the main objectives of the CBLAST Hurricane Component.

The research effort in the CBLAST Hurricane Component consists of re-examination of existing observations of hurricane-ocean boundary layer, wave conditions, and hurricane energetics. The effort also includes limited sensor development and calibration, and a refinement of observing strategies.

The objective of the work during the 2003 hurricane season is to conduct detailed measurements of the hurricane boundary layer, air-sea interface and ocean mixed layer using coincident airborne in-situ and remote sensing measurements, together with air-deployed drifting buoys and floats from AFRC WC-130J or other contract aircraft. The airborne turbulence measurements will be conducted with the two NOAA WP-3Ds, equipped with the Friehe radome-mounted gust probe. The lower WP-3D will also fly the NOAA/Field Research Division BAT (Best Atmomspheric Turbulence) probe mounted on the nose-boom for direct measurement methods of momentum, heat and moisture fluxes via eddy correlation. Complementary vapor flux measurements will be provided by the NOAA/OAR, University of

Miami/RSMAS Licor vapor flux package and the NOAA/AOC fast respnse hygrometer. Other instrumentation systems include the HRD and AOC Stepped Frequency Microwave Radiometers (SFMRs) for bulk surface wind and rain estimation, University of Massachusetts (UMASS) IWRAP system consisting of range-gated CSCAT/KSCAT scatterometers operating alternately in scatterometer and Doppler mode for simultaneous surface wind and boundary layer wind profile retrieval with a range resolution of 15-30 m. A new particle spectrometer will be used to measure spray droplet size distribution down to flight levels of 200 ft (60 m) in the rain-free, high-wind ABL. Spray flux measurements will be obtained from the University of Washington/ Applied Physics Lab Particle Density Analyzer (PDA).

The surface-wind measurements will be supplemented with GOES, QUIKSCAT, TRMM, RADARSAT, TOPEX, ERS2 satellite observations.

The GPS-sondes and AXBTs will be deployed to obtain vertical soundings of atmospheric and oceanic structure along the flight path. TOPEX/POSEIDON satellite altimetry will be utilized to analyze ocean heat content changes during hurricane passage. An additional set of GPS-sondes will be densely deployed in the inner high-wind core regions of developed hurricanes to infer surface fluxes and momentum and enthalpy based on the budget technique of Hawkins and Rubsam. The NASA airborne Scanning Radar Altimeter (SRA) will provide measurements of wave topography in all quadrants of hurricanes over open water. Directional wave and swell spectra will be deduced in real-time during the field experiment from SRA wave topography. A Scripps laser altimeter will be utilized to measure one-dimensional wave spectra between rainbands in order to estimate the high-frequency portion of the ocean wave field not resolved by the SRA. A Scripps MASS high speed visual and infrared wave-following camera system will be utilized to document wave breaking processes and generation of foam and spray.

In addition to AXBTs, neutrally buoyant, Lagrangian floats from the University of Washington/APL will be deployed by AFRC WC-130J aircraft to measure three-dimensional mean ocean currents and large eddy turbulence properties in the upper ocean. Wave spectra and momentum fluxes will be obtained from these Lagrangian floats as well as measurements of surface wind speed and rain rate by ambient noise. Modified ARGO/SOLO floats from Scripps, to also be deployed, will carry additional sensors to measure surface wave heights, breaking, voids, heat fluxes, rainfall, wind-speed, and thermal-salinity structure of the upper ocean. In addition an array of Scripps SVP and mini-met drifting buoys will be deployed ahead of the hurricane to obtain surface current and surface wind, air temperature and sea temperature observations. The detailed planning of logistics and coordination of aircraft operations necessary for the multi-sensor, simultaneous, hurricane-ocean measurement program to be successful, will be conducted at HRD/AOML. The CBLAST hurricane field measurements will be complemented in experimental design and cross validation with the modeling component of CBLAST.

The CBLAST hurricane field experiment will be coordinated with the USWRP Hurricane Landfall Program. The CBLAST field measurements are closely coordinated with complementary studies sponsored by other federal agencies. NESDIS is supporting an Ocean Winds project to validate satellite scatterometer algorithms at high wind speed that will make use of UMASS remote sensing equipment developed in part by CBLAST. NESDIS is also supporting the testing of new, high-speed aircraft-satellite communication links. NASA is supporting an investigation of the structure of secondary circulations in the hurricane atmospheric boundary layer that are revealed in SAR imagery from RADARSAT, ERS-2 and other satellites.

Long-Term Objective: Our ultimate goal and prime motivation for this work is to improve the accuracy of hurricane intensity and intensity change prediction.

Short-Term Objectives: This work intends to use airborne platforms to develop new surface wave-dependent flux parameterizations for the high wind hurricane ABL containing secondary (roll-vortex) circulations over fetch limited seas in the presence of sea spray, one or more swell components and ocean boundary layer secondary (Langmuir) circulations. We propose to test the following hypotheses:

1. that surface momentum exchange coefficients increase with wind speed for moderate winds (>30 m s^{-1} or 58 kt), are enhanced by fetch-limited waves or opposing swell, but level off or decrease above a high wind threshold (>45 m s^{-1} or 87 kt), especially in quadrants where swell has a significant downwind component,
2. that compensating mechanisms for enhanced surface air-sea enthalpy fluxes over and above current parameterizations must exist for storm maintenance and growth above some high-wind threshold wind speed, and
3. that candidate physical mechanisms are separable and can be estimated, such as (a) enhanced turbulent fluxes due to wave interactions, (b) spray evaporation and (c) secondary flow circulations (roll-vortex type) in the ABL.

NESDIS Ocean Winds and Rain Experiment: This experiment aims to improve understanding of microwave scatterometer retrievals of the ocean surface wind. The NOAA/ NESDIS/ Office of Research and Applications in conjunction with the University of Massachusetts' (UMASS) Microwave Remote Sensing Laboratory and the OMAO/Aircraft Operations Center have been conducting flights as part of the Ocean Winds and Rain Experiment for the past several years. The Ocean Winds and Rain experiment is part of an ongoing field program whose goal is to further our understanding of microwave scatterometer retrievals of the ocean surface wind vector in high wind speed conditions and in the presence of rain for all wind speeds. This knowledge will be used to help improve and interpret operational wind retrievals from current and future satellite-based scatterometers. The hurricane environment provides the adverse atmospheric and ocean surface conditions required. The Integrated Wind and Rain Airborne Profiler (IWRAP) and the Stepped Frequency Microwave Radiometer (SFMR), both designed and built by UMASS, are the critical sensors for these experiments. IWRAP consists of two scatterometers operating at Ku-band and C-band, which measure the reflectivity profile in precipitation in addition to the surface backscatter. The capabilities of IWRAP are essential in unraveling the effects of precipitation on scatterometer wind retrievals.

A secondary objective of the NESDIS experiments is to explore how much of this remotely-sensed data collected on the P-3 can be processed and sent off the plane in near real-time. Remotely-sensed surface data can be extremely useful to the hurricane analysts at the Tropical Prediction Center as has been demonstrated with the quasi-operational use of the SFMR on the NOAA P-3s over the past several years. For this experiment a near real-time processing system for IWRAP and SFMR is setup on N42 and integrated with a 9600 baud satellite phone.

Mission Description:

This experiment requires a minimal category 2 hurricane (winds>43 m s-1 or 84 kt) containing an identifiable eyewall structure. The primary measurement philosophy of this experiment is to treat the two WP-3D aircraft as a single “super” airborne platform. All phases of the initial CBLAST test flights will rely on the two WP-3D’s flying ‘in trail’, with one aircraft following the other at safe horizontal and vertical separation. Our approach is to conduct an initial survey pattern with high-density dropsonde sampling in the eyewall. This survey would be followed by several flight segments in at least two quadrants of a storm. These flight segments should cover as many as seven levels ranging from just above the top of the primary wind maximum, located just above the top of the ABL, to as close to the surface as is considered safe by the aircraft commander (in the range of 60-180 m or 200-500 ft).

The experiment is viewed as a two-day mission. Day one would consist of a survey pattern plus ABL modules at two wind radii in a selected storm sector. Day two would consist of an abbreviated survey, most likely a single radial leg followed by ABL modules at two wind radii in two storm sectors.

These two missions will be conducted in coordination with deployment of drifting buoys and subsurface floats ahead of the storm by WC-130J aircraft operated by the Air force Reserve Command

(AFRC) 53rd Weather Reconnaissance Squadron. These systems will be deployed over a target area normal to the forecast hurricane track, roughly 24 h in advance of the storm. The first two legs of the initial survey pattern on day one would be oriented to overfly as many buoy and float positions as possible during the initial survey pattern. AXBTs would be deployed at buoy/float positions along the flight track in coordination with GPS-sonde deployments.

Pre-Storm Float and Buoy Deployment:

The float and drift buoy deployments are expected to be done as follows in 2003:

Three days, or 72 hr, prior to launch, an IP is identified that is projected to be 120 nm ahead of the NHC 72 hour forecast storm position (near the 96 hr forecast position) and 120 nm right or 60 nm left of track, depending on where the operating base is relative to the storm. Revise the IP the next day when any deployment would have to take place (T0-48 hr). On the third day, finalize the IP to be at or just beyond the gale force wind radius in the clear normal to the forecast 24 hour position, or the nominal 120 nm ahead of the storm.

Define a leg length of 180 nm normal to the storm track with 4 drop points outbound from the IP at 60 nm spacing and 4 points along the inbound leg displaced 30 nm further along the storm track and staggered to be in between the outbound drop points. There would be 8 drop points all together.

We want to carry 8 SVP/minimet boxes, 4 Lagrangian boxes and 4 Argo/Solo boxes, in one flight if this is logistically feasible. Otherwise a second flight would need to be scheduled immediately after the first with a second crew. Two options are envisioned. In the first option (Fig. 1a), we would drop one SVP box (2 buoys inside), one Lagrangian box and one Argo box at each outbound drop point (points 1-4). Then on the inbound leg, we would drop only the 4 remaining SVP boxes at points 5-8. The second option will be required if the C-130 is unable to deploy three boxes at one point. Two possible patterns are shown in Fig 1b and 1c . In the pattern shown in 1b we would drop one SVP box (2 buoys inside) and one Lagrangian box at each drop point on the outbound leg. (points 1-4) Then on the inbound leg, we would drop one SVP box and one ARGO box at each drop point 5-8. In the pattern shown in 1c we would drop one SVP box (2 buoys inside) and one Lagrangian box at each drop point on the outbound leg. (points 1-4) Then on the inbound leg, we would drop one SVP box and one ARGO box at each drop point 5-8. We *require* the deployment of the 2 or 3 buoy types at each drop point within 10 miles of each other.

CBLAST Day 1:

In route to the survey pattern Initial Point (IP), or alternatively, on return to base from the end of the flight pattern, a series of calibration maneuvers will be executed by the WP-3D aircraft (N43RF) that are designed to ensure proper post-flight calibration of aircraft turbulence sensors. These maneuvers are described in the turbulence calibration module. It is anticipated that these maneuvers may require about 30 min of flight time. If done in route to the start of the survey pattern, which would be the first choice, then N42RF would then delay takeoff by 30 min to rendezvous together at the IP.

For the initial survey pattern, nominal constant radar altitude (RA) for N43RF for the first penetration is 5,000 ft (1.5 km. Conditions permitting, N43RF would then descend to 2,500 ft (750m) for the remainder of the flight. N42RF would fly at 7,000 ft (2.1 km). For category 4 or 5 storms with intense turbulence, constant pressure altitudes would be flown with N43RF flying at 8,000 ft (2.4 km) and N42RF flying at 12,000 ft (3.6 km). AFRC WC-130H reconnaissance aircraft would most likely be flying at 10,000 ft (3 km). N43RF would lead N42RF to ensure a clear vertical path for dropsondes and AXBTs.

The nominal short survey pattern will be a figure-4 pattern that is designed to be flown on two successive days (Figs. 2 and 3). The pattern is designed to be flown in 2.5 h. Should the storm be close to a staging base, and more time is available for the survey, a three-legged long ‘butterfly’ pattern will be flown with maximum flight legs of 97 nm (180 km) for N43RF and 109 nm (200) km for N42RF, and requiring 4 h, as shown in Fig. 4.

The prime purpose of the survey pattern (Figs. 2 or 4) is to record data that will (1) allow the large scale structure of the storm to be analyzed, (2) allow bulk aerodynamic flux estimates to be computed using a variety of existing parameterizations and (3) to deploy sequences of GPS-sondes at short time intervals during eyewall penetration. Alignment of the pattern will depend on storm direction of motion, ABL shear orientation and distribution of pre-storm floats/buoys. We will use an 8-channel dropsonde receiving system on N42RF, where 8 GPS-sondes at 10-20 s intervals will be deployed following 4 GPS-sondes from N43RF to obtain a sequence of up to 12 GPS-sondes along four radial legs through the eyewall, as well as AXBT's and sonobuoys – the eyewall dropsonde module described below. Four additional sondes and AXBTs will be deployed from N42RF at 27 nm (50 km) intervals for the outer portion of each flight leg. The primary purpose of this measurement strategy is to diagnose the surface drag and enthalpy exchange coefficients at high winds using budget methods developed at the Massachusetts Institute of Technology (MIT).

Along the final leg of the survey pattern on day one, two relatively clear areas between rainbands will be determined in the right-rear quadrant of the storm relative to the storm motion vector. Three sectors representative of differing wave/swell conditions have been defined: (1) the rear quadrant representative of steep growing waves, (2) the right and right-front quadrants representative of mature swell moving approximately with the wind, and (3) the left-front and left quadrants where the swell that is moving at approximate right angles to the wind. The right-rear quadrant is also characterized by maximum ocean mixed layer currents, current shears at the base of the mixed layer and minima in SST, which are factors that may influence surface fluxes. The right quadrant typically contains the strongest inflow and active outer band convection. The downshear left quadrant typically contains the strongest eyewall convection.

Upon exiting from the initial survey pattern, the two aircraft will then proceed to the closest selected rain-free sector of interest at the 34-50 kt wind radius. First, a radial boundary layer flight leg normal to the wind will be flown, the boundary layer *crosswind* module (Fig. 5), prior to the *alongwind* module (Fig.6). Alternatively, the combined *crosswind and alongwind* module could be flown (Fig. 7). The purpose of these observations is to identify the structure of ABL secondary circulations.

Following the first completed ABL flight module at the 34-50 kt (17-26 m s^{-1}) wind radii, the two aircraft would proceed to the second rain-free sector at a hurricane force wind radius of 64-80 kt (33-41 m s^{-1}) in the same sector and repeat the sequence. Once the second ABL pattern is completed on day one, the aircraft would return to base with the N43RF executing the calibration maneuvers if they had not been done on the inbound flight.

CBLAST Day 2:

On day two, following the in-route calibration maneuvers an initial radial leg will be flown, which will simply be a single leg of the survey pattern at an RA of 5,000 ft (750 m). The aircraft would again select a region free of convection in the right-front quadrant and repeat the ABL pattern at the two wind radii. Following the initial pair of ABL patterns, the aircraft would proceed to a second sector in the left or left-rear quadrant which is identified as clear of strong convection. The ABL sequence should then be repeated for the two wind radii. The aircraft would then return to base.

Eyewall dropsonde sequence module:

The details of this pattern are shown in Figs 2b and 2c. **Inbound**, the aircraft fly coordinated legs, timed such that 43 will reach the eye at least 30 s before 42. 43's leg is displaced 3-6 nmi upwind of 42, so that 42 will overfly the splash points of 43's sondes. 43 begins with a combination GPS and AXBT drop and then drops 3 more GPS sondes at 2 nmi (30 s) intervals. 43 drops one more AXBT 30 s after its last GPS drop. When it comes in to the eye 43 turns upwind to orbit. 42 times its 8 drop sequence such that the first sonde drops at the same radius of 43's last sonde. The first 4 sondes from 42 are dropped at 2 nmi (30 s) intervals, but the last 4 are dropped at 1 nmi (15 s) intervals, as shown in Fig 2c , to better observe the highest windspeeds and their gradient. The final 2 sondes from 42 should be dropped inside the surface RMW, and the last drop is combined with a sonobuoy and AXBT drop. While the crew prepare sondes for the outbound leg, both aircraft should orbit in the eye in a polygonal patterns, because these segments of straight and level flight will produce better SFMR and IWRAP surface winds.

On the **outbound** legs, 43's leg is displaced 3-6 nmi upwind of 42, so that 42 will once again overfly the splash points of 43's sondes. To start the leg, 42 starts with a combination GPS and AXBT drop, inside the RMW as is the following drop, followed by 2 more drops spaced 1 nmi apart, and then 4 drops at 2 n mi seperation. 43 drops a BT at the same radius it did at the end of the inbound leg, and then times its sequence, with 2 n mi seperation in drops, such that its first GPS drop will occur at the same radial distance as the last drop of 42, and ends with a combination GPS and AXBT drop .

Boundary Layer multi-level modules:

The crosswind module, shown in Fig. 5, will consist of an out and back 5.5 min, 19 nm (35 km) leg (11 min, 38 nm (70 km) total) with N43RF flying 3500 ft (1.0 km) outbound and 2000 ft (600 m) inbound, while N42RF flies near the top of the ABL at 7,000 ft (2.1 km). N42RF will conduct a 5 sonde drop sequence on the outbound leg. AXBTs will be deployed from N42RF at the beginning, middle and end of the outbound radial flight leg, and 43 will deploy sonobuoys at the beginning and end of the first leg. 43 will then fly a stepped descent pattern, as shown in Fig.5, with cross-wind legs at 1,000 ft (300 m), 600 ft (180 m), 400 ft (120 m), and if possible at 200 ft (60 m). Each level will be limited to 7 min flight time, including the 180° turn and descent. Completion of the six levels will require 0.8 h flight time.

The alongwind module, shown in Fig. 6 , consists of roughly 27 nm (50 km) flight legs parallel to the wind, which will be about 6 min downwind and 9 min upwind in 34-50 kt (17-26 m s^{-1}) winds (5 min down wind, 11 min upwind in 64-80 kt (33-41 m s^{-1}) winds) at each level. N42RF will deploy 6 GPS sondes at 5.4 nm (10 km) intervals along the first flight leg from 7,000 ft (2.1 km). N43RF will commence its first leg at 3,500 ft (1 km). Flight legs will then be flown at 2,000 ft (600 m), 1,000 ft (300 m), 600 ft (180 m), 400 ft (120 m)and if possible at 200 ft (60 m). Each level will be limited to 5-11 min flight time, including the 180° turn and descent. Completion of the six levels will require 1.0 h flight time.

The **combined alongwind and crosswind** module is shown in Fig. 7. In this case NOAA 43 will fly out-and-back alongwind and crosswind modules at 600 ft (180 m), 400 ft (120 m)and if possible at 200 ft (60 m). Each level would require 11 minutes crosswind, and 14 minutes up/ downwind, including turns, for a total of 1.2 h per module.

Ocean Winds module: This module (Fig. 8) consists of a series of pie-shaped wedges originating in the eye and extending outward to just beyond the eyewall and high wind inner core nominally 50 km (37 nm), and which rotate downwind with time. These pie slices will be concentrated in the high wind right and front quadrants of the storm and be flown with the two WP-3D aircraft flying 'in trail', maintaining sage lateral and vertical spacing.

Turbulence Calibration Module: For calibration of the BAT probe, this module should be executed on separate flights at the start and end of the CBLAST filed program.The following maneuvers are requested for turbulence sensor calibration:

- Pitch Up/Down maneuvers: One series, with pitch variations of ±8-10°, containing 10-20 complete sinusoids. Sinusoids in the series will have periods of roughly 5-6 s (the plane should actually react to this, i.e., change altitude).
- Dynamic sideslip: 1/2- to full-ball sideslips with 10-20 complete sinusoids. Series slow (5-6 s period).
- Steady-state Yaw: 1/2-ball, held for 10-15 s, full-ball held for 10-15 s, 1/2-ball, held for 10-15 seconds. Repeated on other side.

NOTE: above maneuvers should be done while trying to hold everything else constant (i.e. during side-slips and yaws, pilot should allow plane to lose altitude instead of increasing attack angle).

- Wind Circles: Two 360° standard rate turns: first clockwise, then counter-clockwise. We need 360° of data to be in a coordinated turn, so after the pilot enters the turn and it is coordinated, only then 'start the clock'.
- Acceleration/Deceleration runs (AC/DC): Start at slowest possible flight speed, accelerate to fast flight speed, decreasing attack angle. Then decelerate to slow flight speed. Two runs.
- Wind box: Straight and level box, 2 min on each side, standard rate 90° turn on the corners.

All of these maneuvers should be aligned with the wind. The boxes should have legs parallel and perpendicular to the wind. We should attempt to complete the calibrations at the mean radar altitude where we will be making the measurements, or roughly 1,000 ft (300 m). The maneuvers should be conducted in smooth air (as smooth as possible).

Hurricane Rainband Modules

These modules test proposed flight patterns and data analysis plans with a NOAA P3 to prepare fully for a rainband experiment proposed for 2004 when the ELDORA system is incorporated into the plans. Our emphasis is on rainbands outside the eyewall . The testing accomplished in the first year should allow us to go in the field in 2004 with lested flight patterns. The deployment of aircraft will be done according to a set of generic flight modules:

i. The concentric eyewall module will use 1-2 aircraft to investigate an existing double eyewall structure.
ii. The single-aircraft rainband module will be flown by 1 aircraft, to investigate the principal rainband or another major rainband that appears likely to be interacting with the eyewall region of the storm.
iii. The dual-aircraft rainband module will investigate the principal rainband or another major rainband that appears likely to be interacting with the eyewall region of the storm.

These modules are designed so that they can be applied to whatever eyewall and rainband pattern is present when the aircraft arrive in the vicinity of a hurricane. Since the development of a concentric eyewall is a rare but important event, the highest priority will be given to flying the concentric eyewall module. The second highest priority will be the 2-aircraft band module, which will probably be the most common flight situation. The hypothesis is that the Stationary Band Complex (SBC), and the principal band in particular, constitute a stationary heat source whose structure varies from convective on its downshear end farthest from the eyewall to stratiform on its upshear end nearest the eyewall. One of our primary goals is to map the convective-stratiform variability along the principal band and other features of the SBC. The third priority is the single-aircraft module, which is the optimal pattern to achieve our objectives when only one aircraft is available.

The three flight modules can be executed either singularly or in combination In a storm with a concentric eyewall, the concentric eyewall pattern can be flown in combination with one of the rainband modules. Flown simultaneously, these modules would give the best indication of interaction between the eyewall and rainband region. The modules are robust enough that they can be adapted to whatever combination of aircraft and storm structure occurs. Any module should provide some useful information on the mesoscale structures and interactions affecting storm intensity changes. When the aircraft are on station, the plan is to "mix and match" the three flight modules according to which aircraft are in the air as well as the actual eyewall/rainband pattern. The NOAA aircraft have lower fuselage radars and are better prepared to direct multi-aircraft missions in hurricanes. Accordingly, one NOAA aircraft will always be designated as the lead aircraft and the lead scientist on that crew will use the lower fuselage radar to direct all the aircraft in real time.

All the modules require GPS-sondes, and lower fuselage and Doppler radars. In this study, dual-aircraft options require ~40 tsondes (20 for each aircraft), single aircraft options require 20 sondes, and the rainband module requires 10-15 sondes. The next sections give detailed description of the modules.

Concentric eyewall module: This module will be flown only by the NOAA aircraft since it has the lower fuselage radar to guide the penetration of the eyewall To execute this module with the two NOAA aircraft, the planes will stagger their takeoffs. The first aircraft (AC1) will take off ~30-60 min before the second aircraft (AC2) and fly a figure-4 pattern at 3 km (10,000 ft) with 150 km (~80 nmi) legs to document the general reflectivity and wind structure of the storm (1-2-3-4 in Fig. 30). AC2 will fly 150 km (~180 nmi) legs at 4 km (~14,000 ft) and rendezvous near AC1 at point 4 (Fig. 30). GPS-sondes should be dropped inside and outside of the concentric rainband, and the tail Doppler radar should always scan in fore/aft scanning technique (F/AST). While it is preferred that both aircraft drop sondes and fly legs through the storm, it is essential that the two aircraft arrive at 4 at roughly the same time. To meet this requirement drops can be eliminated and legs can be shortened if necessary.

Single aircraft rainband module: For a single aircraft investigation of either the principal band or another outer rainband, a “figure-four” pattern with 150 km (~80 nmi) legs will be flown between 3 and 4 km (10,000-14,000 ft) to identify the overall structure of the storm and to choose a rainband for investigation. The Doppler radar should always scan in F/AST. Then a zigzag or sawtooth pattern (Fig. 9a) should be flown across the rainband of interest with GPS-sondes dropped on both sides of the band. At 9, the aircraft may fly downwind around the storm (flight option 1) or fly upwind to repeat the investigation of the rainband (flight option 2). In either case, GPS-sondes should be dropped along the flight track to gather information on the hurricane environment.

Dual-aircraft rainband module: This module uses two NOAA aircraft. AC1 will be at 3 km (10,000 ft) and begin its pattern inside the rainband (Fig. 9b). AC2 will continue to fly at 4 km (14,000 ft) and begin its segment of the pattern outside the rainband. At 5 the inside aircraft (AC1) will fly across the band to the outside, and AC2 will move to the inside. The aircraft will continue to switch from inside the band to outside the band while dropping sondes as seen in Fig. 9b until both aircraft have flown completely around the storm and arrive at 10. This pattern is designed to obtain kinematic and thermodynamic data inside and outside the band. Alternating which aircraft is inside the band assures that neither aircraft proceeds too far ahead of the other while traveling around the storm. It also allows flight level data to be gathered in the band itself. With careful coordination, insuring safety at all times, it may be possible to fly the band-crossing legs to create Doppler opportunities in several portions of the secondary eyewall.

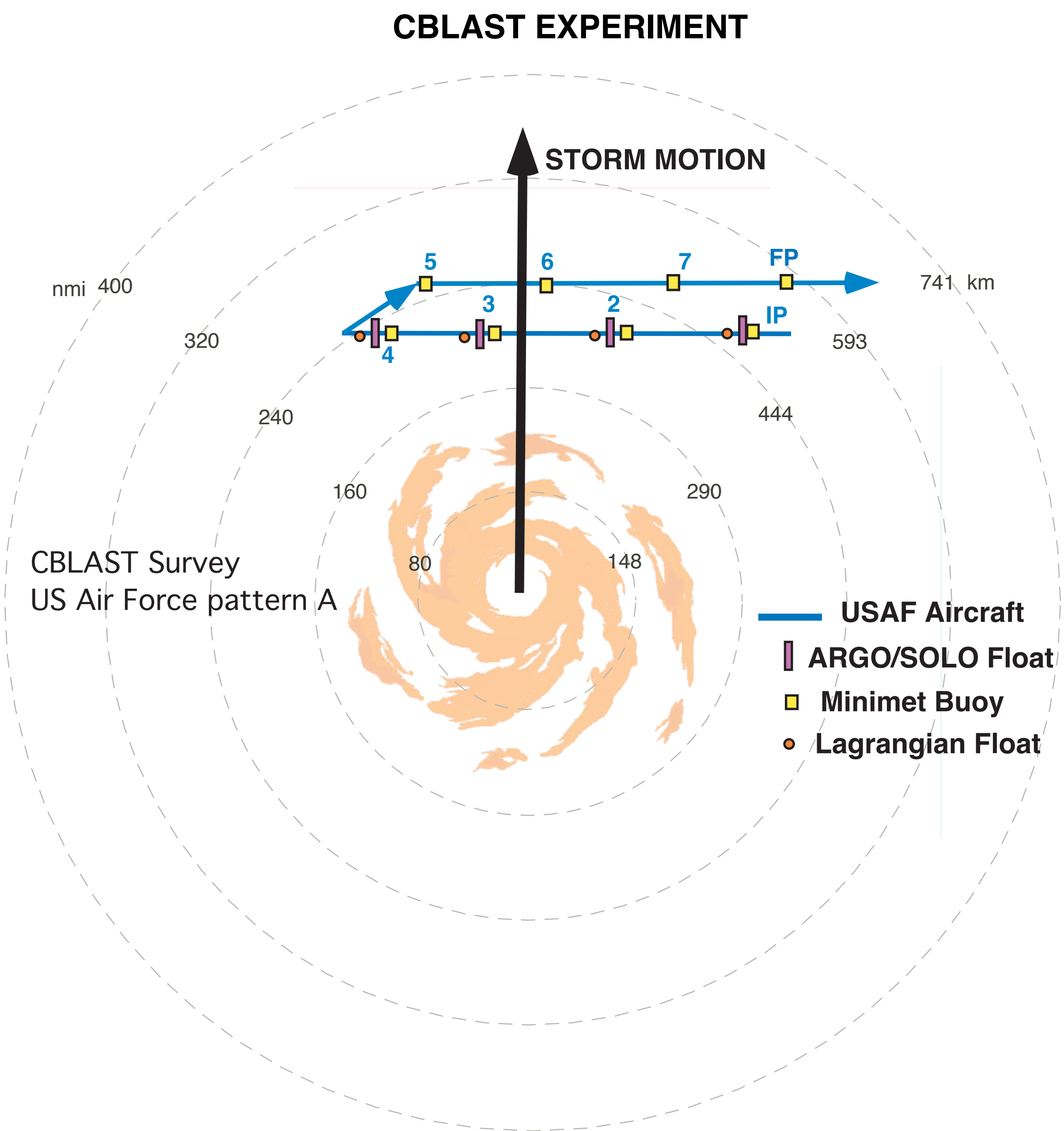

Figure 1a. Buoy drop pattern A, with triple package drops on outbound leg.

• Note 1. The US Air Force aircraft will also deploy GPS dropsondes at each buoy drop point along the track.

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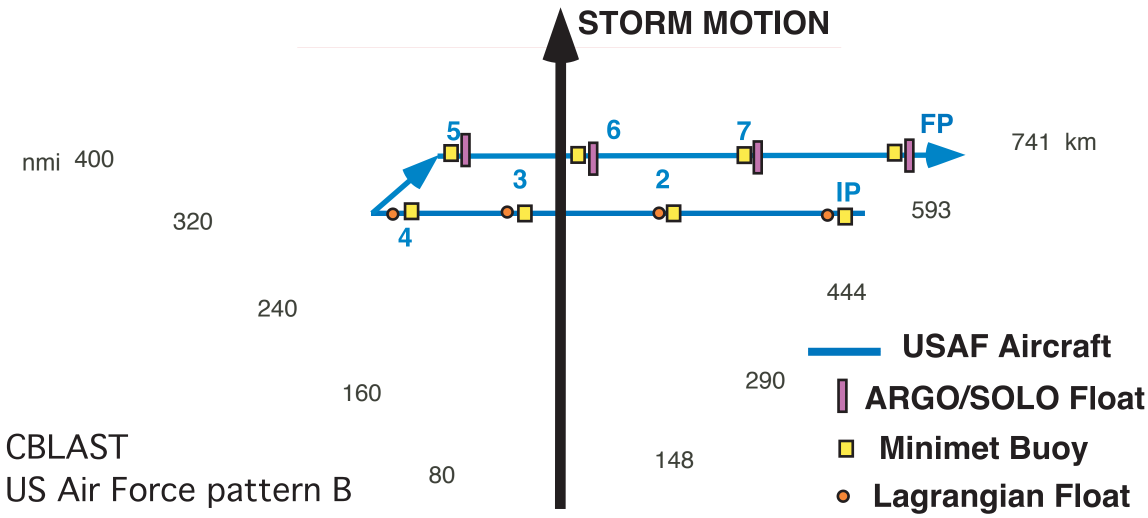

Figure 1b. Buoy drop pettern B, with double package drops on both legs.

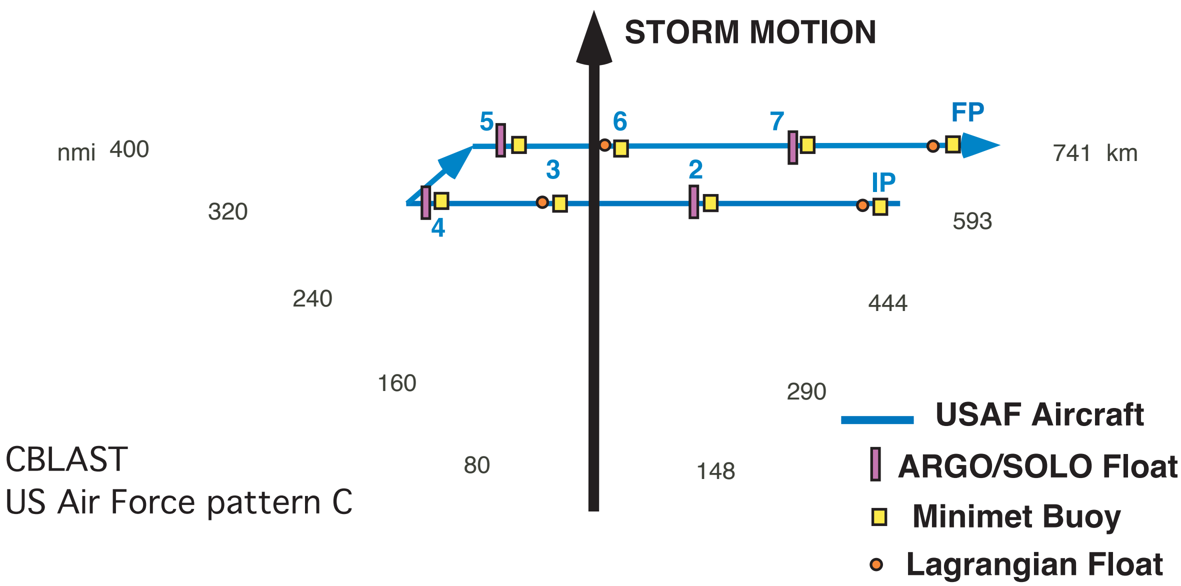

Figure 1c. Buoy flight pattern C, alternative double package drop on both legs.

• Note 1. The US Air Force aircraft will also deploy GPS dropsondes at each buoy drop point along the track.

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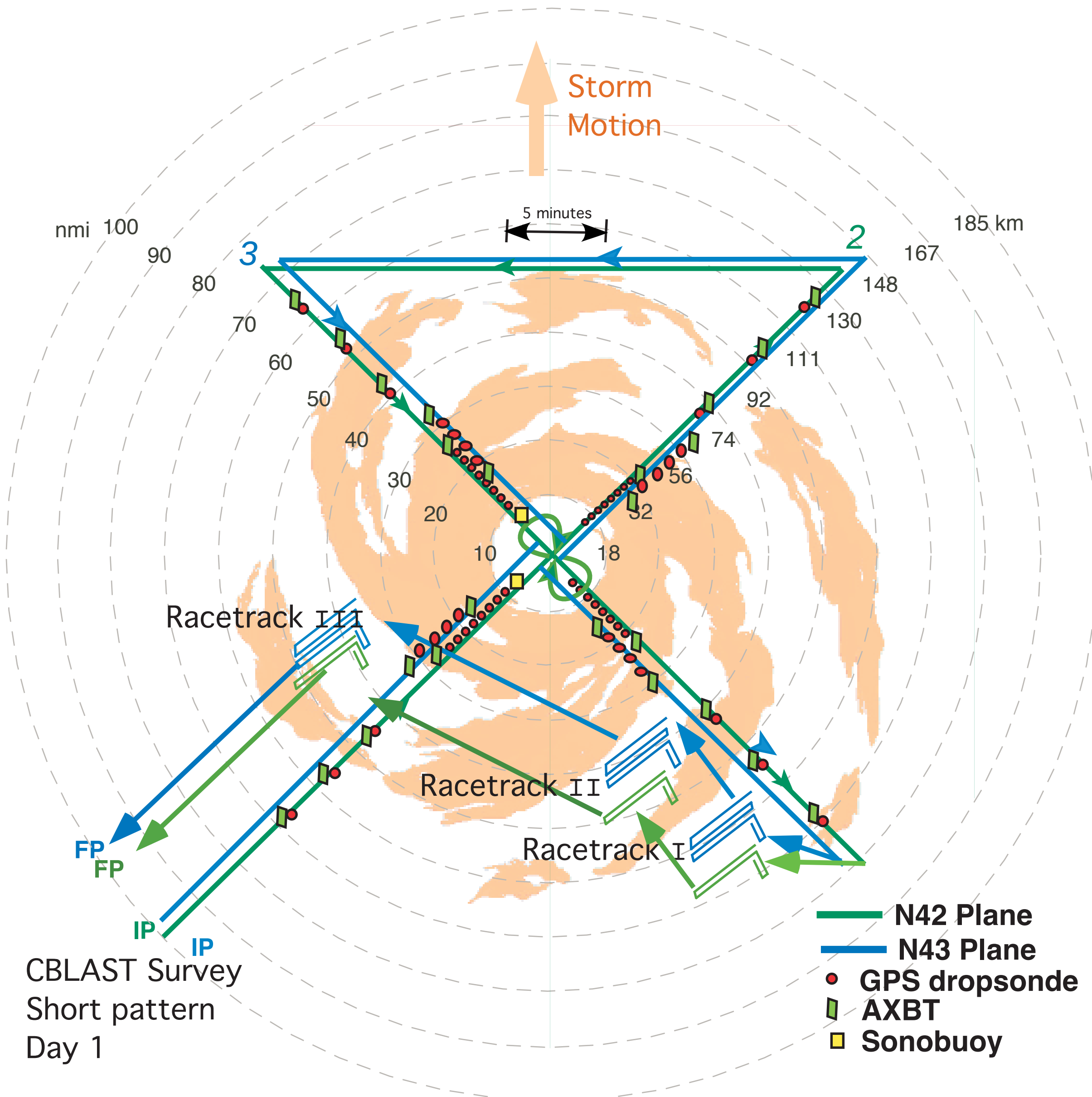

Fig. 2. CBLAST short pattern, Day 1.

- Note 1. The pattern should be aligned 45° from storm heading. Preferred **IP** is in left-rear quadrant, but can be in any quadrant.
- Note 2. The two WP-3Ds fly 'in trail' with high plane at 7,000 ft RA (12,000 ft in CAT 4 or 5) and low plane at 5,000 ft RA from **IP** to **2**, 2,500 ft RA thereafter, conditions permitting (8,000 ft for CAT 4 or 5). The lower WP-3D will lead the upper WP-3D.
- Note 3. Aircraft should reach their respective **IP's** as simultaneously as possible, with the **IP** for upper WP-3D at a radius of 120 nm, and the **IP** for the lower WP-3D at a radius of 108 nm.
- Note 4. Operate NOAA 43 Tail Doppler in continuous mode on all coordinated legs.

CBLAST EXPERIMENT

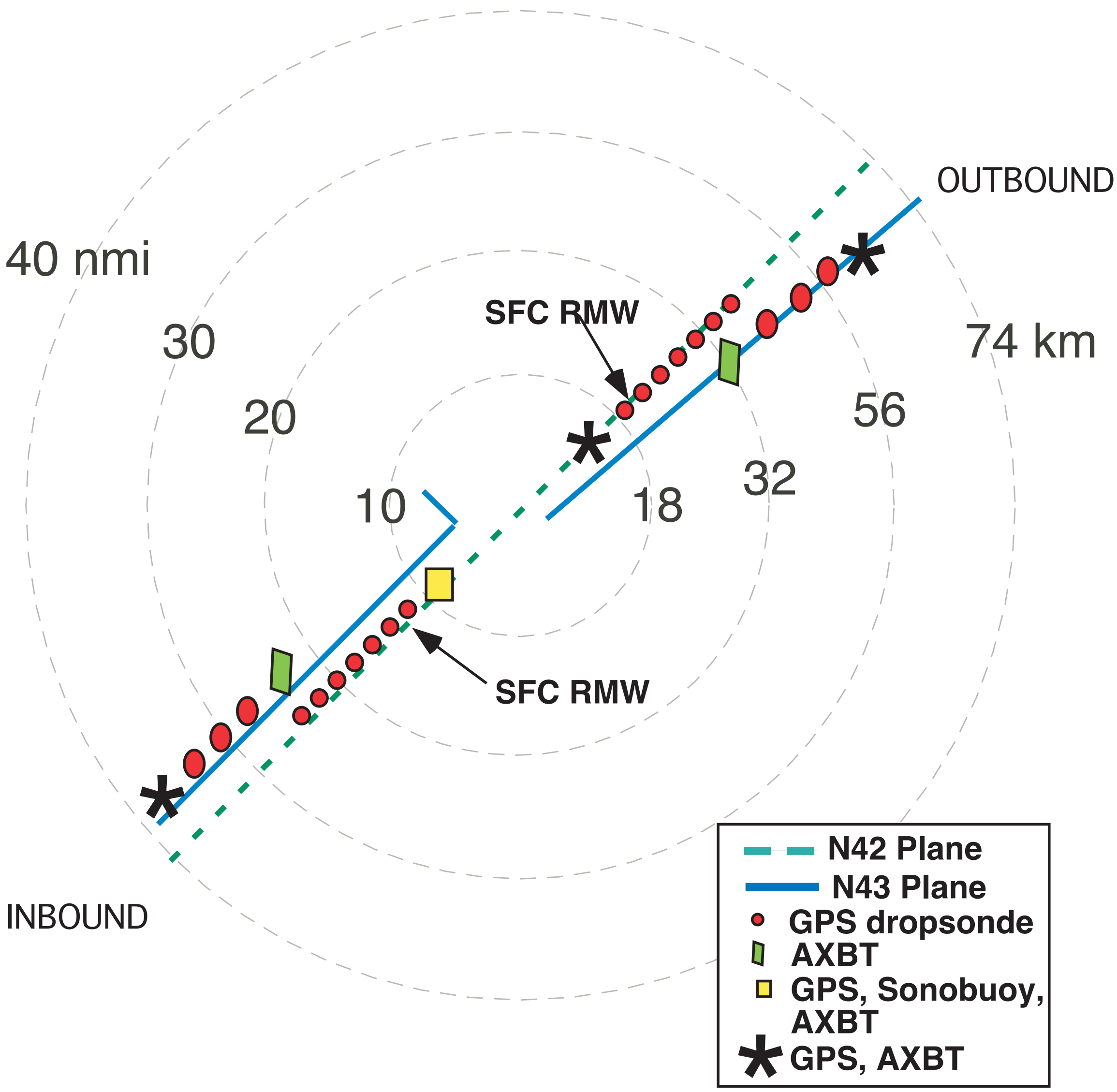

Figure 2b. Eyewall Dropsonde Module: Horizontal View

Note 1.	NOAA 43 (lower aircraft) starts a sequence of four near-eyewall drops on inbound legs at ~2RMAX . NOAA 42 should start 8 eyewall drops 30 s after end of 43's drops, ending at inner edge of eyewall. Orbit in the center until all drops have cleared. Reverse the sequence on the outbound legs.
Note 2	NOAA 43 legs are 3-6 nmi upwind of 42 leg, to ensure 42 overflies 43 drop splash points for IWRAP verification.
Note 3.	Last 2 sondes on inbound leg and first 2 sondes on outbound leg of 42 should be inside the surface RMW.
Note 4.	42 does triple drop (GPS, Sonobuoy and AXBT) after 43 has made upwind turn in eye.
Note 5.	42 and 43 fly polygonal patterns in eye (not circles) while crew prepares sondes for outbound leg.
Note 6	43 drops BT 30s after dropping last sonde inbound, and 30 s before first sonde on outbound leg.
Note 7	Innermost 4 sondes from 42 are dropped at 1 nmi) (15 s) intervals. 42 outermost 4 and 43 sondes are dropped at 2 nmi (30 s) intervals.

CBLAST EXPERIMENT

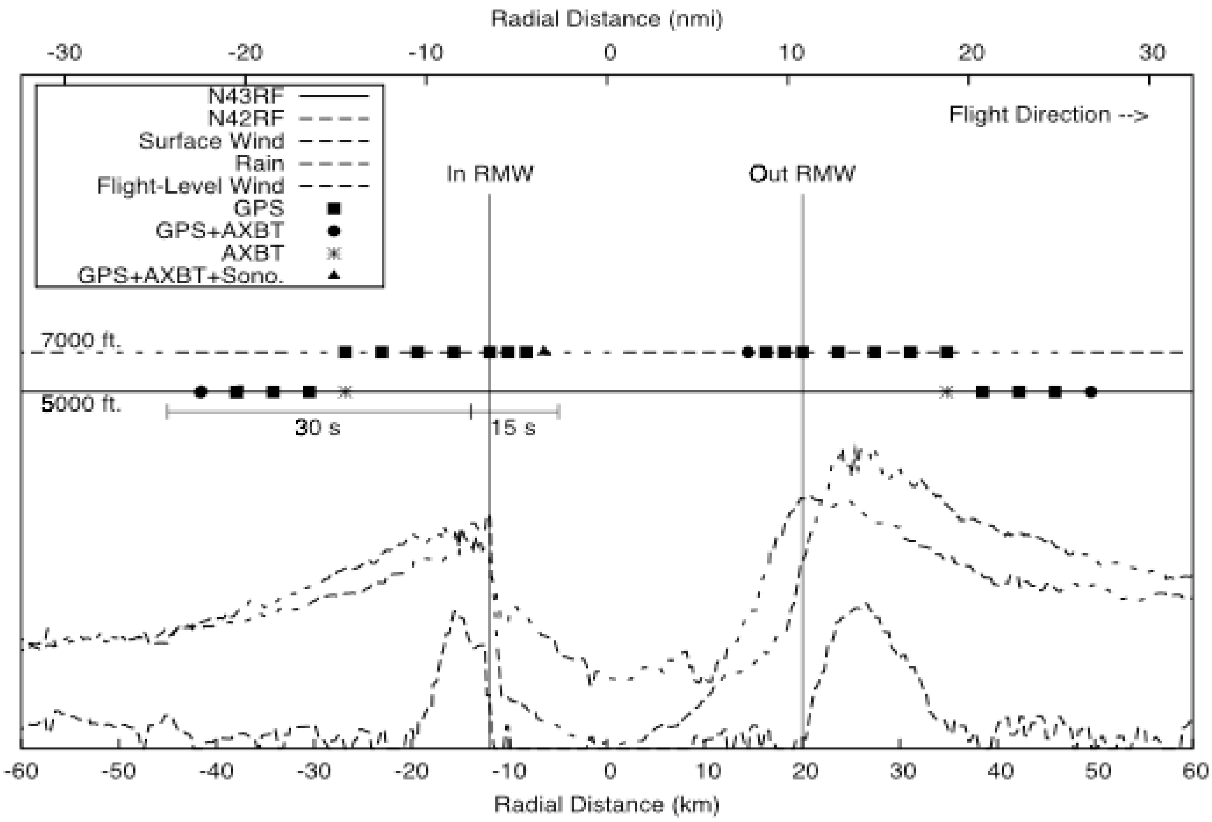

Figure 2c: Eyewall Dropsonde Module: Vertical Cross Section.

Note 1.	NOAA 43 (lower plane) starts a sequence of four near-eyewall drops on inbound legs at ~ 2RMAX . NOAA 42 should start 8 eyewall drops 30 s after end of low plane drops, ending at inner edge of eyewall. Orbit in the center until all drops have cleared. Reverse the sequence on the outbound legs.
Note 2	NOAA 43 legs are 3-6 nmi upwind of 42 leg, to ensure 42 overflies 43 drop splash points for IWRAP verification.
Note 3.	Last 2 sondes on inbound leg and first 2 sondes on outbound leg of 42 should be inside the surface RMW.
Note 4.	42 does triple drop (GPS, Sonobuoy and AXBT) after 43 has made upwind turn in eye.
Note 5.	42 and 43 fly polygonal patterns in eye (not circles) while crew prepares sondes for outbound leg.
Note 6	43 drops BT 30s after dropping last sonde inbound, and 30 s before first sonde on outbound leg.
Note 7	Innermost 4 sondes from 42 are dropped at 1 n mi (15 s) intervals. 42 outermost 4 and 43 sondes are dropped at 2 n mi (30 s) intervals.

CBLAST EXPERIMENT

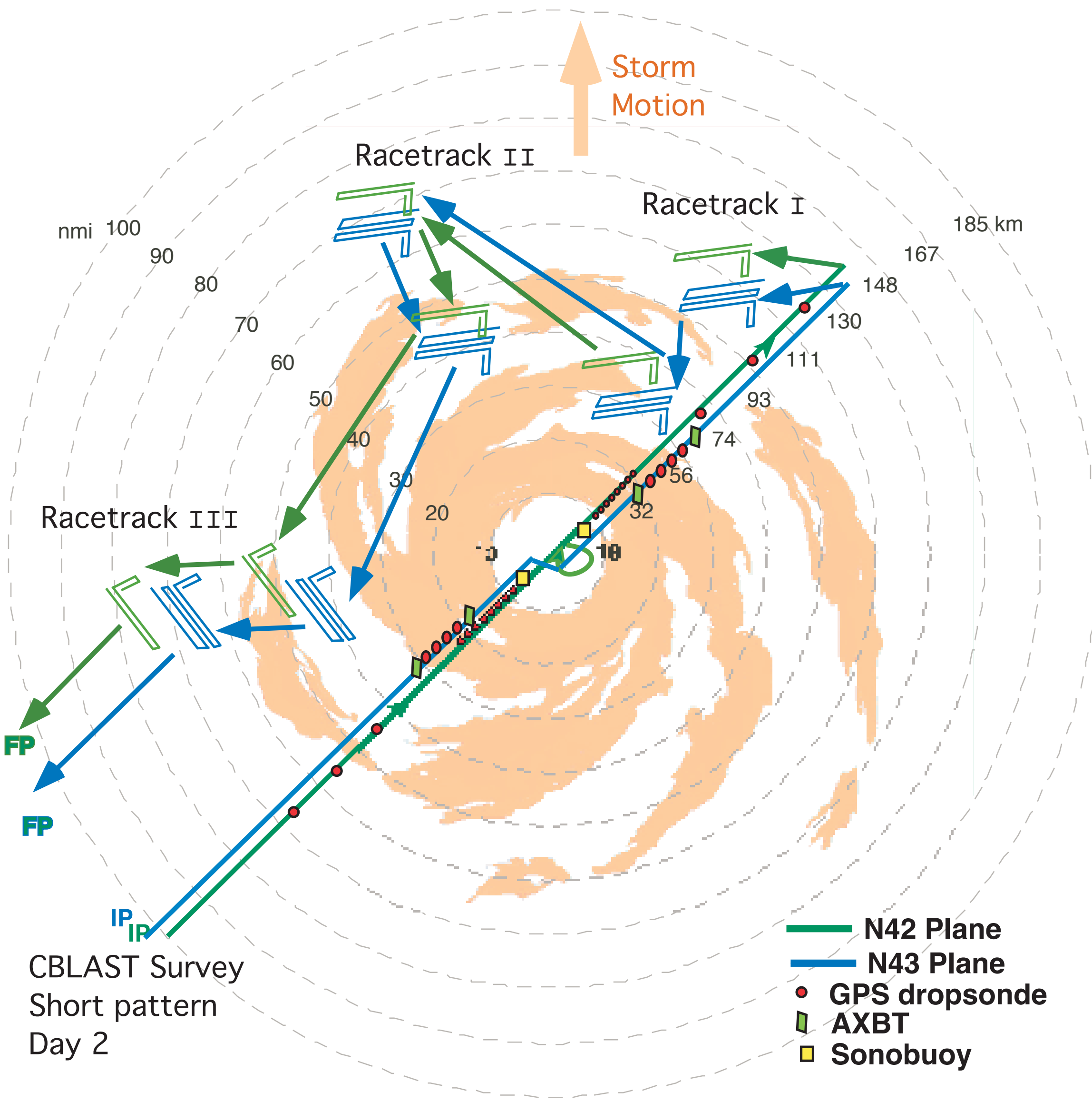

Fig. 3. CBLAST short pattern, Day 2.

• Note 1.	The pattern should be aligned 45° from storm heading. Preferred **IP** is in left-rear quadrant.
• Note 2.	The two WP-3Ds fly 'in trail' with high plane at 7,000 ft RA (12,000 ft in CAT 4 or 5) and low plane at 5,000 ft RA from **IP** to **2**, 2,500 ft RA thereafter, conditions permitting (8,000 ft for CAT 4 or 5). The lower WP-3D will lead the upper WP-3D.
• Note 3.	Aircraft should reach their respective **IP's** as simultaneously as possible, with the **IP** for upper WP-3D at a radius of 120 nm, and the **IP** for the lower WP-3D at a radius of 108 nm.
• Note 4.	The lower WP-3D will start a sequence of four near-eyewall drops on inbound legs at approximately $2R_{MAX}$. High-level aircraft should start series of 8 eyewall drops 30 s after end of low plane drops, ending at inner edge of eyewall. Orbit in the center till all drops have cleared. Reverse the sequence on the outbound leg.

CBLAST EXPERIMENT

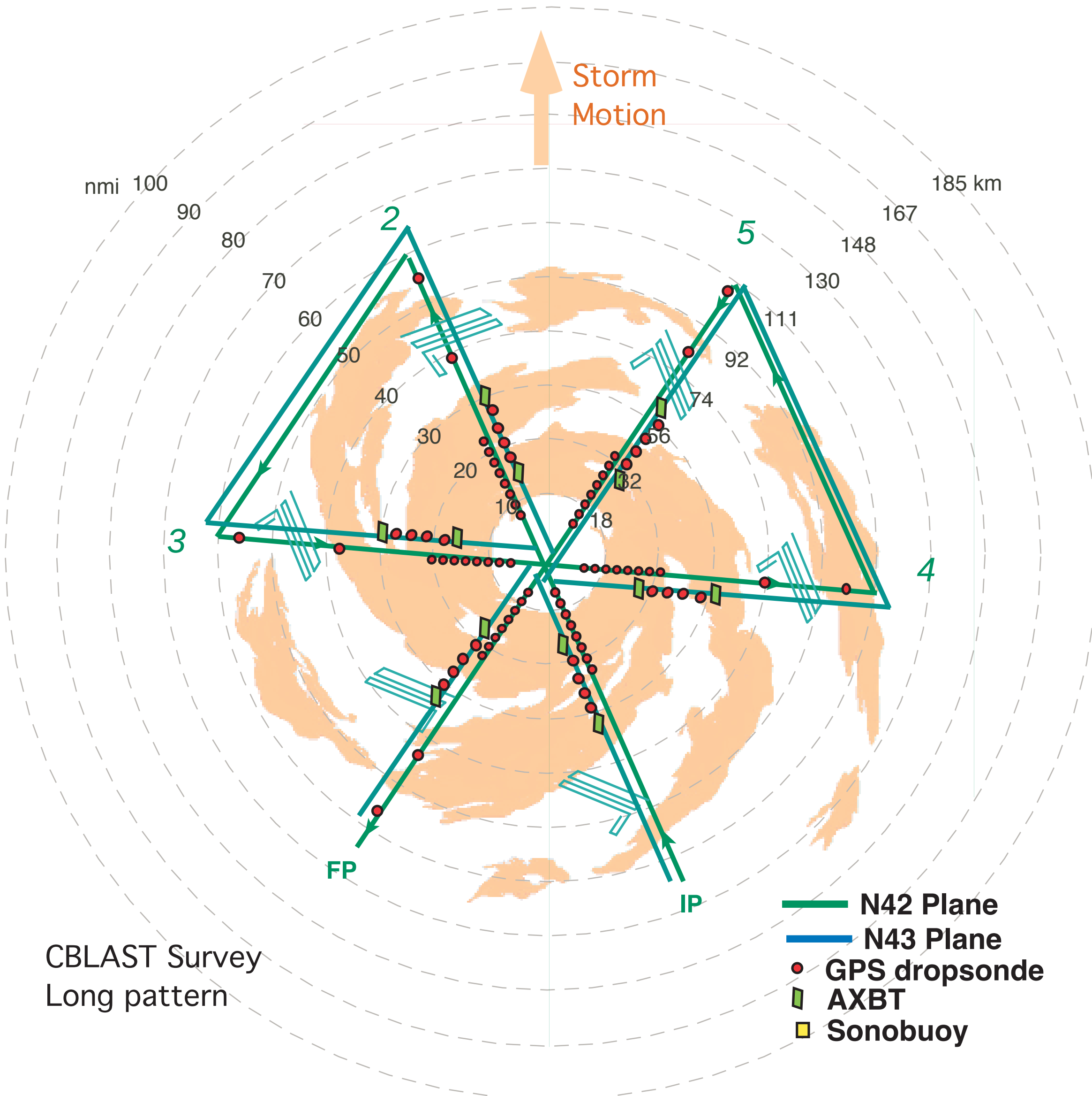

Figure 4. CBLAST long pattern.

• Note 1.	The pattern should be aligned 30° from storm heading. Preferred **IP** is in left-rear quadrant, but can be in any quadrant.
• Note 2.	The two WP-3Ds fly 'in trail' with high plane at 7,000 ft RA (12,000 ft in CAT 4 or 5) and low plane at 5,000 ft RA from **IP** to **2**, 2,500 ft RA thereafter, conditions permitting (8,000 ft for CAT 4 or 5). The lower WP-3D will lead the upper WP-3D.
• Note 3.	Aircraft should reach their respective **IP's** as simultaneously as possible, with the **IP** for upper WP-3D at a radius of 108 nm, and the **IP** for the lower WP-3D at a radius of 97 nm.
• Note 4.	The high WP-3D will commence a sequence of six eyewall drops on inbound legs at approximately 1.5RMAX or near the outer edge of the eyewall, ending at inner edge of eyewall. Reverse the sequence on the outbound legs.

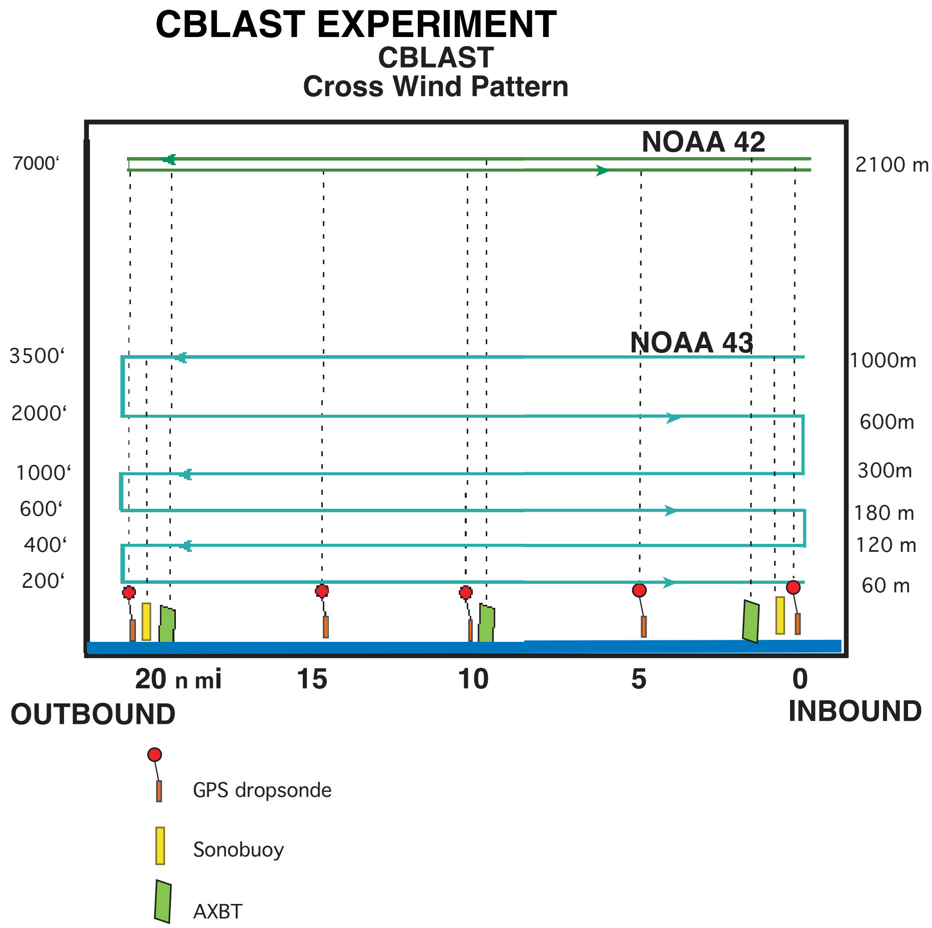

Figure 5 CBLAST stepped descent pattern (racetracks) in cross wind direction.

• Note 1.	The high WP-3D flies at 7,000 ft deploying five sondes along the track of the low WP-3D for the first leg. The low WP-3D leads and orbits past the endpoint until the last sonde has splashed.
• Note 2.	A spiral descent is executed at the end of each leg.
• Note 3.	Each level will be limited to 7 min flight time, including the 180° turn and descent.

CBLAST EXPERIMENT

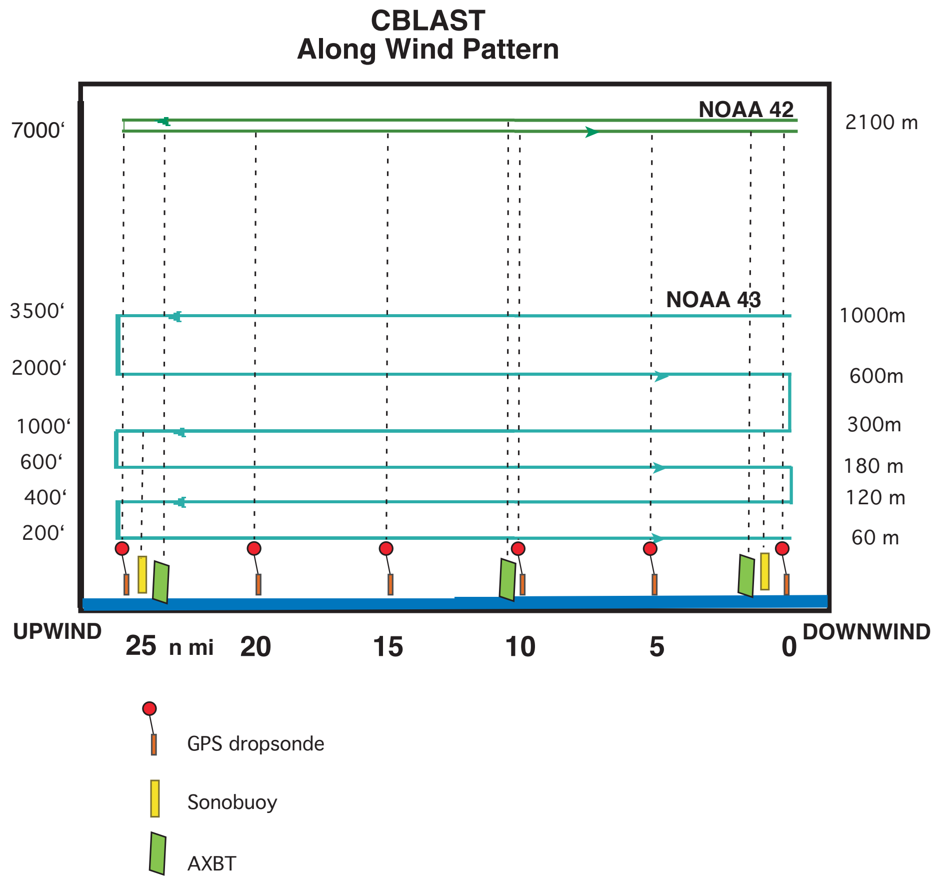

Figure 6. CBLAST stepped descent pattern (racetracks) in upwind / downwind direction.

• Note 1.	The high WP-3D flies at 7,000 ft deploying six sondes along the track of the low WP-3D for the first leg. The low WP-3D leads and orbits past the endpoint until the last sonde has splashed.
• Note 2.	A spiral descent is executed at the end of each leg.
• Note 3.	27 n mi legs will require 6 min downwind and 9 min upwind in 34-50 kt (17-26 m s^{-1}) winds (5 min down wind, 11 min upwind in 64-80 kt (33-41 m s^{-1}) winds).

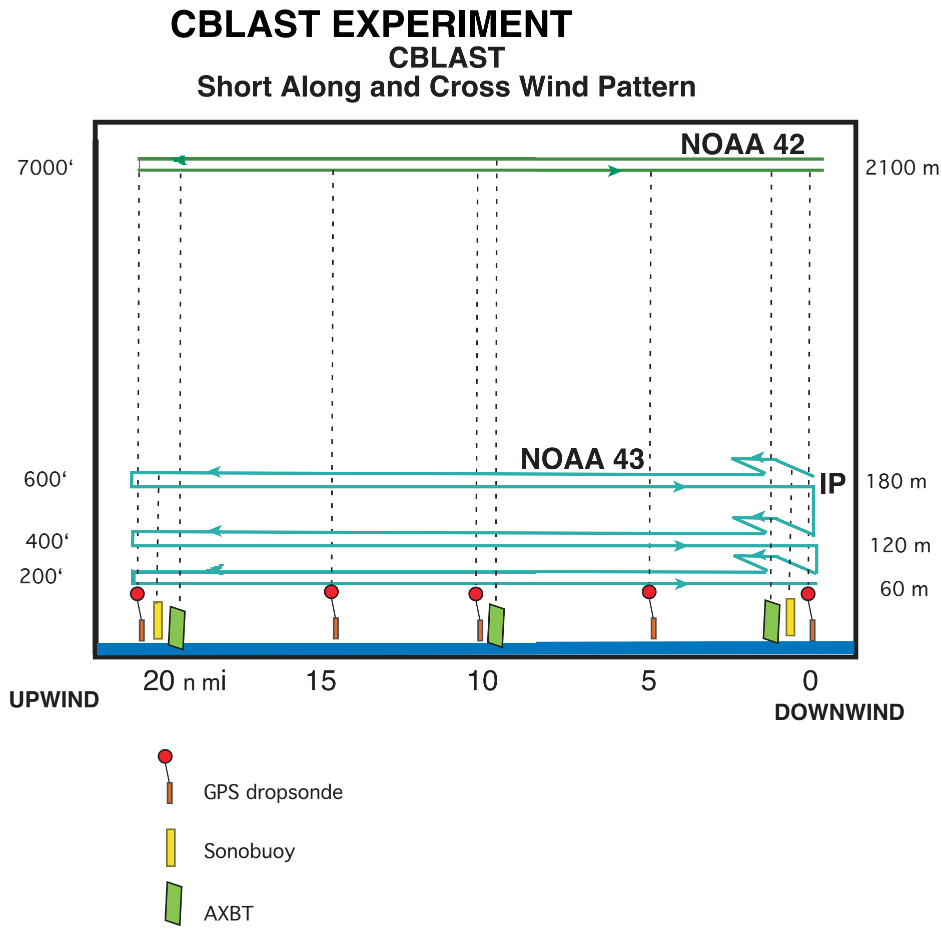

Figure 7. CBLAST short stepped descent pattern (racetracks) in upwind / downwind and cross wind directions.

- Note 1. The high WP-3D flies at 7,000 ft deploying five sondes along the track of the low WP-3D for the first leg. The low WP-3D leads and orbits past the endpoint until the last sonde has splashed.
- Note 2. Legs are flown outbound, then outside turn and crosswind at the same altitude. A spiral descent to the next level is executed at the end of each along and cross wind leg leg.
- Note 3. Each level requires 11 minutes crosswind, and 14 minutes up/ downwind,

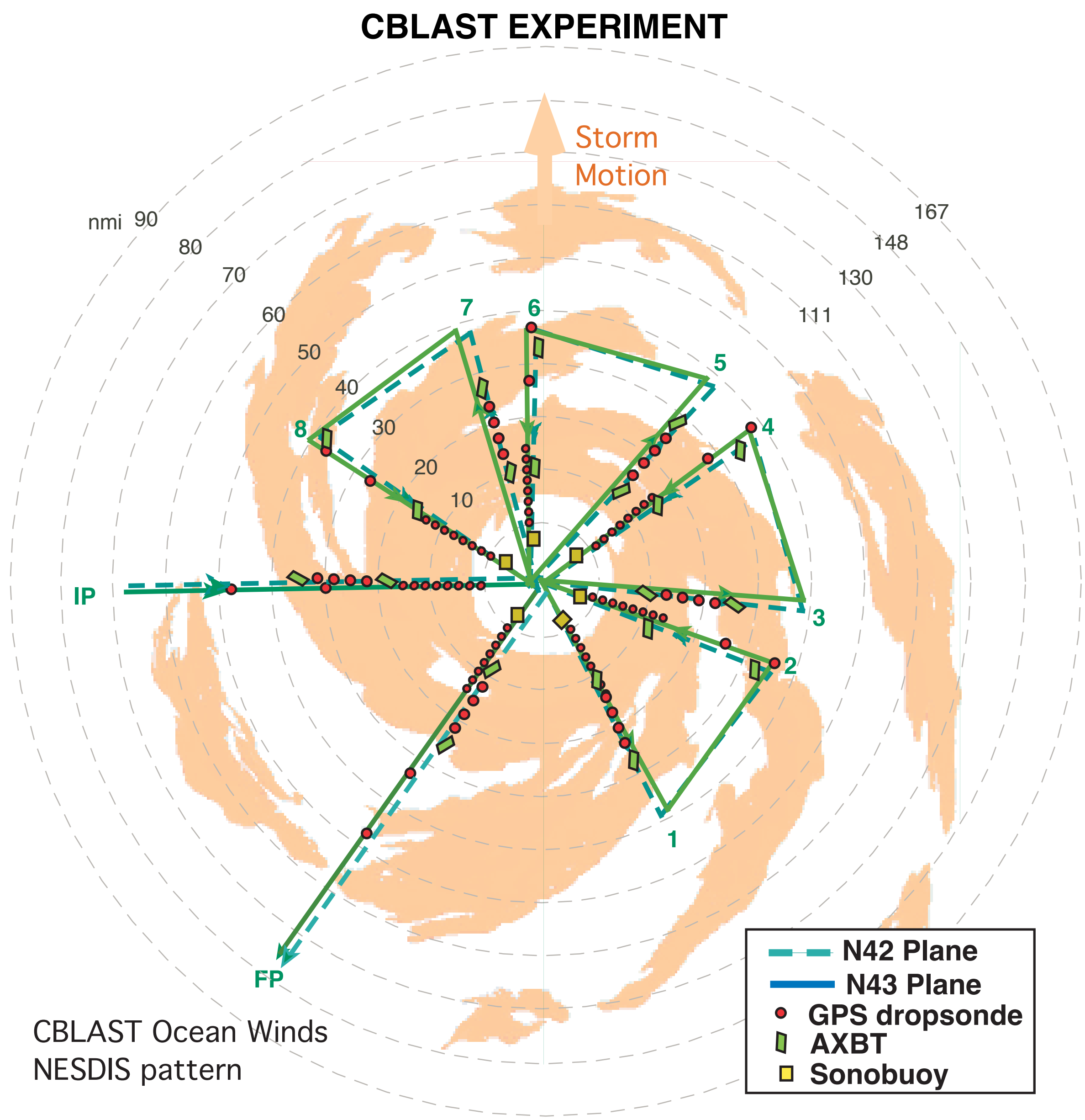

Figure 8. Ocean Winds Pattern

- Note 1. Preferred **IP** is in west quadrant, but can be in any quadrant.
- Note 2. The two WP-3Ds fly 'in trail' with high plane at 7,000 ft RA (12,000 ft in CAT 4 or 5) and low plane at 5,000 ft RA from **IP** to **2**, 2,500 ft RA thereafter, conditions permitting (8,000 ft for CAT 4 or 5). The lower WP-3D will lead the upper WP-3D.
- Note 3. Aircraft should reach their respective **IP's** as simultaneously as possible, with the **IP** for upper WP-3D at a radius of 108 nm, and the **IP** for the lower WP-3D at a radius of 97 nm.
- Note 4. The high WP-3D will commence a sequence of six eyewall drops on inbound legs at approximately 1.5RMAX or near the outer edge of the eyewall, ending at inner edge of eyewall. Reverse the sequence on the outbound legs.
- Note 5. NOAA 43 TA radar should be operated in continuous mode (**not** F/AST) while flying coordinated legs with NOAA 42.

CBLAST EXPERIMENT

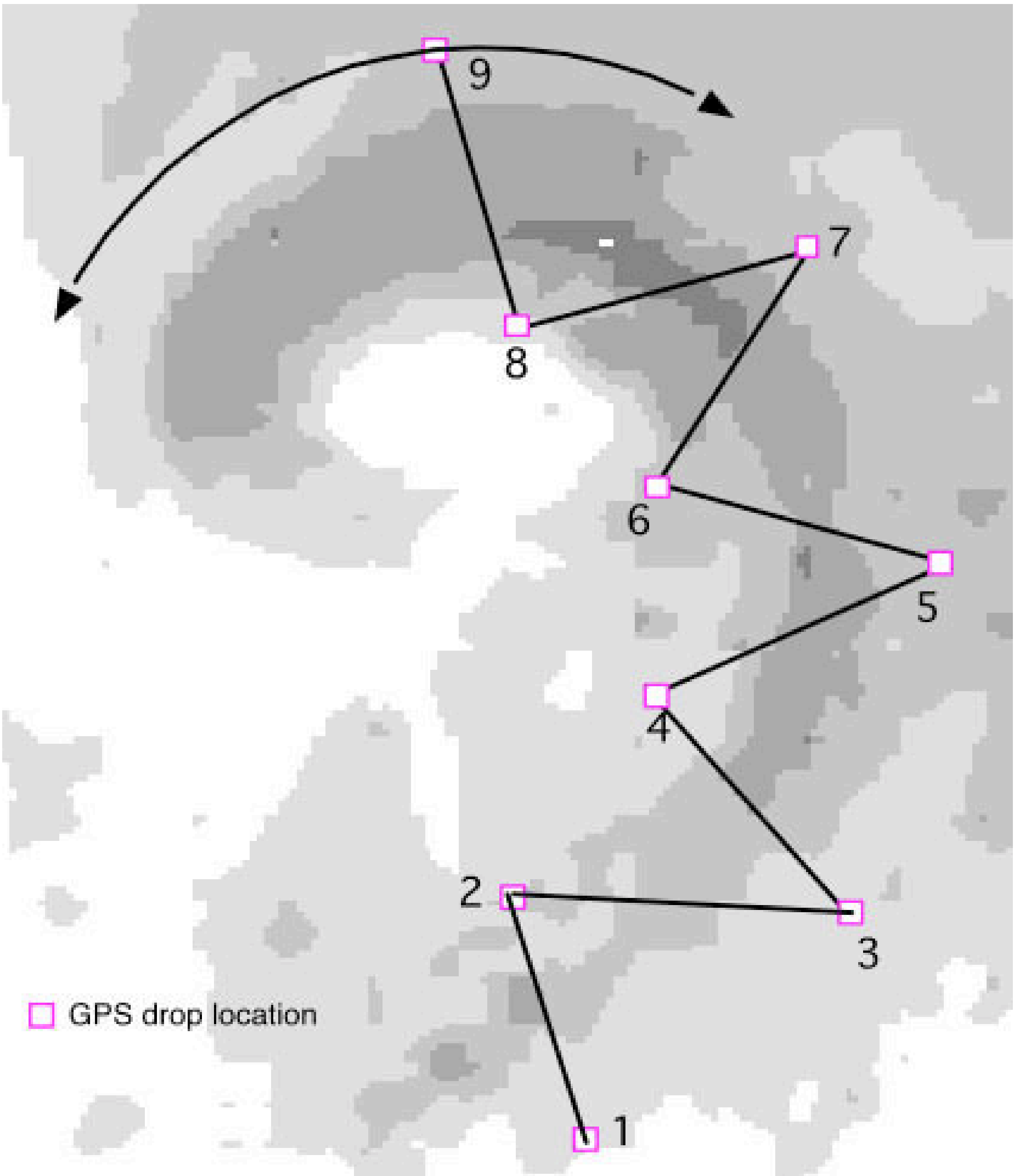

Figure 9a Rainband test pattern: Single Aircraft Option

- Note 1. True airspeed calibration required.
- Note 2. WP-3D Tail Doppler radar should be operated in F/AST mode at a single PRF ≥2400 and 20° tilt

CBLAST EXPERIMENT

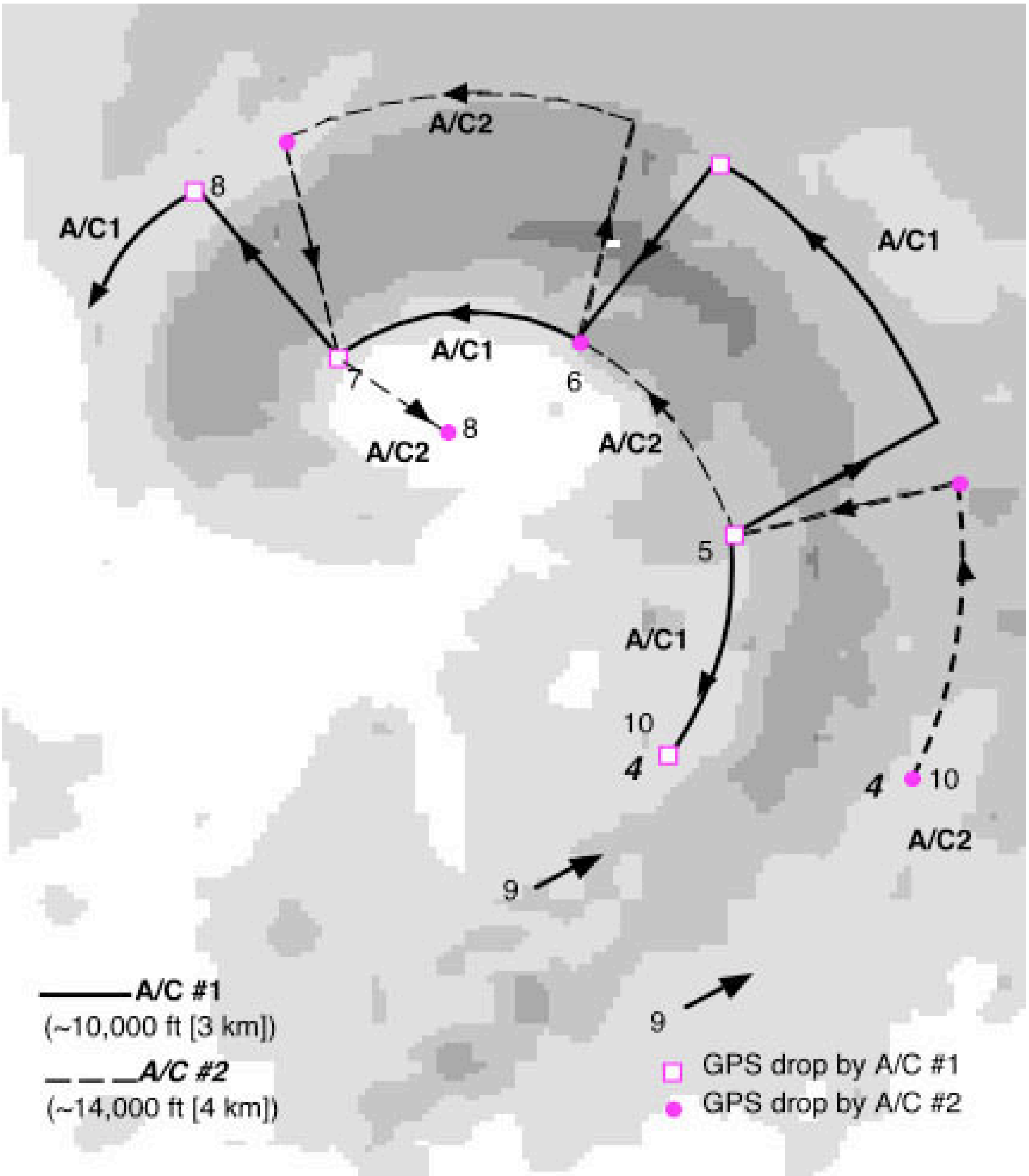

Figure 9b Rainband test pattern: Dual Aircraft Option

• Note 1.	True airspeed calibration required.
• Note 2.	Both aircraft should operate their Tail Doppler radars in F/AST mode at a single PRF ≥2400 and 20° tilt