2007 Hurricane Field Program Plan

Hurricane Research Division
National Oceanographic and Atmospheric Administration
Atlantic Oceanographic and Meteorological Laboratory
4301 Rickenbacker Causeway
Miami, FL 33149

Prepared by:

John Gamache, Jason Dunion, Joe Cione, Robert Rogers, Peter Dodge, John Kaplan, Sim Aberson, Shirley Murillo, Peter Black, James Carswell, and Neal Dorst

Frank D. Marks

30 June 2007

Frank D Marks, Jr
Director, Hurricane Research Division

Date

Distribution of the NOAA/HRD Hurricane Field Program Plan is restricted to personnel directly involved in the hurricane field program or to those persons who are on a need-to-know basis. This plan, in whole or in part, is not to be abstracted, cited or reproduced in the open literature.

Cover: To be changed

TABLE OF CONTENTS

INTRODUCTION

OPERATIONS

HRD RESEARCH EXPERIMENTS

SUPPLEMENTAL: OPERATIONAL MAPS

2007 HURRICANE FIELD PROGRAM PLAN

INTRODUCTION

National Oceanic and Atmospheric Administration
Atlantic Oceanographic and Meteorological Laboratory
Hurricane Research Division
Miami, Florida. USA

One of the key activities in NOAA's Strategic Plan Mission Goal 3 ("Reduce Society's Risks from Weather and Water Impacts") is to improve the understanding and prediction of tropical cyclones (TCs). The National Centers for Environmental Prediction (NCEP) National Hurricane Center (NHC) is responsible for forecasting tropical cyclones in the Atlantic and East Pacific basins, while the Environmental Modeling Center (EMC) provides NWP guidance for the forecasters. Together they have made great strides in improving forecasts of TC track. With support from the research community, forecast errors of TC track have decreased by about 50% over the past 30 years. However, there has been much less improvement in forecasts of TC intensity and rainfall. The lack of improvement in intensity and rainfall forecasting is largely the result of deficiencies in routinely collecting inner-core data and assimilating it into the modeling system, limitations in the numerical models themselves, and gaps in our understanding of the physics of TCs and their interaction with the environment. Accurate forecasts will rely heavily on the use of improved numerical modeling systems, which in turn will rely on accurate observational datasets for assimilation and validation.

The next-generation TC model, the Hurricane Weather Research and Forecasting model (HWRF), is currently under development at EMC and is anticipated to become operational in 2007. The HWRF will run at high resolution (≈10 km grid length initially), using improved data assimilation techniques and physical parameterizations. Such a configuration holds the hope of improving our understanding and forecasting of tropical cyclone track, intensity, structure, and rainfall. In order to realize such improvements, however, new data assimilation techniques must be developed and refined, physical parameterizations must be improved and adapted for TC environments, and the models must be reliably evaluated against detailed observations from a variety of TCs and their surrounding environments.

To conduct the research necessary to address the issues raised above, NOAA has proposed an experiment designed to improve operational forecasts of TC intensity, called the Intensity Forecasting EXperiment (IFEX). The goals of this experiment have been developed through a partnership involving NOAA's Hurricane Research Division (HRD), NHC, and EMC. The goals of IFEX are to improve operational forecasts of tropical cyclone intensity and rainfall by providing data to improve the operational numerical modeling system (i.e., HWRF) and by improving our understanding of the physics of intensity change and rainfall. These goals will be accomplished by satisfying a set of requirements and recommendations guiding the collection of the data:

- **Goal 1**: Collect observations that span the TC lifecycle in a variety of environments;
- **Goal 2**: Develop and refine measurement technologies that provide improved real-time monitoring of TC intensity, structure, and environment;
- **Goal 3**: Improve our understanding of the physical processes important in intensity change for a TC at all stages of its lifecycle;

A unique, and critical, aspect of IFEX is the focus on providing measurements of TCs at all stages of their life cycle, from pre-genesis to intensification and subsequent landfall, decay over water, or extratropical transition. The focus of hurricane research flights during the past 25 years has been on mature storms, leading to a dataset biased toward these types of systems. The strategy of observing the entire life cycle of a TC is new and unique, and it will provide invaluable information, particularly in sparsely observed environments. The ability to target multiple basins provides greater flexibility for observing TCs at different stages of their life cycle.

The field program aircraft missions presented in this document are separated into two distinct sections: 1) HRD Research Experiments; and 2) NHC and EMC Operational Missions. The flight patterns that comprise these various research experiments and operational missions address various aspects of the tropical cyclone lifecycle, and they all specifically address the main goals of IFEX. There is an experiment to investigate the impact of a phenomenon called the Saharan Air Layer on tropical cyclone intensity change, an experiment that will involve the use of the Aerosonde unmanned aircraft system (UAS) to sample the tropical cyclone environment, including the low-level regions of the tropical cyclone boundary layer, an experiment to study tropical cyclogenesis, an experiment to measure the structural and subsequent decay of tropical cyclones that make landfall, an experiment to sample mesovortices in the eye of intense hurricanes, an operational mission designed to improve model forecasts of tropical cyclone track by sampling the surrounding tropical cyclone environment, an operational mission to sample mature tropical cyclones to investigate tropical cyclone intensity/structure, provide data to initialize/validate operational forecast models, and improve/evaluate technologies for observing tropical cyclones, and a research experiment designed to improve understanding of microwave scatterometer retrievals of the ocean surface wind. These research experiments and operational missions will be conducted with the NOAA/Aircraft Operations Center (AOC) WP-3D N42RF and Gulfstream IV-SP aircraft. A summary of each experiment/operational mission, along with which IFEX goals each specifically addresses, is included below. A more detailed description of each experiment/operational mission follows, which includes a description of the scientific rationale for the experiment/operational mission and details of the associated flight patterns.

(1) Three-Dimensional Doppler Winds: This is a multi-option, single-aircraft operational mission designed to use the NOAA WP-3D to sample tropical cyclones ranging in intensity from tropical depression to a major hurricane. The definition is meant to separate this category from tropical waves and disturbances that have yet to develop a well-defined warm-core circulation. The main goals of these missions is: 1) to improve our understanding of the factors which modify the intensity and structure of tropical cyclones, 2) to provide a comprehensive data set for the initiation (including data assimilation) and validation of numerical hurricane simulations (in particular the Hurricane Weather and Research Forecasting model (HWRF), 3) to improve and evaluate technologies for observing tropical cyclones, and 4) to develop rapid "real-time" communication of these observations to the National Centers for Environmental Prediction (NCEP) of the National Weather Service (NWS). Two experiments comprise the overall Mature Storms Experiment: the Frequent-Monitoring Experiment, designed to obtain regular 12- or 24-h resolution airborne Doppler-radar observations of hurricanes, with optional GPS dropsondes and the NESDIS Ocean Winds and Rain Experiment, designed to improve our understanding of microwave surface scatterometery in high-wind conditions over the ocean by collecting surface scatterometery data and Doppler data in the boundary layer of hurricanes.

(2) Tropical Cyclone Landfall and Inland Decay Experiment: This experiment is a multi-option, single-aircraft experiment designed to study the changes in TC surface wind structure near and after landfall. The experiment has several modules that could also be incorporated into operational surveillance of reconnaissance missions. An accurate description of the TC surface wind field is important for warning, preparedness, and recovery efforts. This experiment addresses IFEX Goals 1, 2, and 3.

(3) Aerosonde Experiment: This is a multi-option, multi-aircraft experiment that uses the Aerosonde UAS and GPS dropwindsondes/aircraft expendable bathythermographs (AXBTs) launched from the NOAA WP-3D to fully demonstrate and utilize the unique capabilities of the Aerosonde platform to document areas of the tropical cyclone environment that would otherwise be either impossible or impractical to observe. It is planned that this effort will be based in Key West, FL. The immediate focus of this experiment is to document and significantly improve our understanding of the rarely-observed tropical cyclone boundary layer and undertake detailed comparisons between in-situ and remote-sensing observations obtained from manned aircraft (NOAA WP-3D and AFRES C-130) and satellite based platforms. In addition, a primary objective of this effort is to provide real-time, near-surface wind observations to the National Hurricane Center in direct support of NOAA operational requirements. These unique data will also be made available to EMC for both data initialization and forecast verification purposes. . This experiment addresses IFEX Goals 1, 2, and 3.

(4) Tropical Cyclogenesis Experiment*:* This multi-option, multi-aircraft experiment is designed to study how a tropical disturbance becomes a tropical depression with a closed surface circulation. This experiment seeks to answer the question through multilevel aircraft penetrations using dropsondes, flight-level data, and radar observations on the synoptic, mesoscale, and convective spatial scales. It will focus particularly on dynamic and thermodynamic transformations in the low- and mid-troposphere and lateral interactions between the disturbance and its synoptic-scale environment. This experiment addresses IFEX Goals 1 and 3.

(5) Tropical Cyclone Eye Mixing Module: This is a multi-option, single aircraft experiment designed to use the NOAA WP-3D to collect observations within the eye below the inversion to investigate the dynamic and thermodynamic structures of eyewall mesovortices and improve our knowledge of small-scale features and intensity changes in very strong TCs. This experiment addresses IFEX Goal 3.

(6) Eyewall Sampling and Intensity Change Experiment: This is a multi-option, single-aircraft module designed to provide high resolution thermodynamic and wind data in the eyewall to help understand hurricane intensity change better. With a symmetric distribution of dropsondes dropped in a circumnavigation of the eye, computations of budgets and fluxes could be determined.

(7) Canted SFMR Module: This is a single-aircraft module designed to obtain measurements off nadir of the sea surface to help develop retrieval models for the Hirad, and new canted stepped frequency microwave radiometer.

(8) SFMR-Bathymetry Flight Module: This is a single- or multi-aircraft module designed to measure surface winds from SFMR and dropsondes to determine the effect shallow bathymetry has on the SFMR estimates of surface wind speed.

(9) Saharan Air Layer Experiment: This is a multi-option, multi-aircraft experiment which uses GPS dropwindsondes launched from the NOAA G-IV and NOAA WP-3D to examine the thermodynamic and kinematic structure of the Saharan Air Layer (SAL) and its potential impact on tropical cyclone (TC) genesis and intensity change. The GPS dropwindsonde drop points will be selected using real-time GOES SAL tracking imagery from UW-CIMSS and mosaics of SSM/I total precipitable water from the Naval Research Laboratory. Specific effort will be made to gather atmospheric information within the Saharan Air Layer as well as regions of high moisture gradients across its boundaries and the region of its embedded mid-level easterly jet. The goals of this experiment are to better understand and predict how the SAL's dry air, mid-level easterly jet, and suspended mineral dust affect Atlantic TC intensity change and to assess how well these components of the SAL are being represented in forecast models. This experiment addresses IFEX Goals 1 and 3.

(10) Hurricane Synoptic-Flow Experiment: This is a multi-option, single or multi-aircraft operational mission that uses GPS dropwindsondes launched from the NOAA G-IV, the NOAA WP-3D, or the Air Force Reserve C-130 to improve landfall predictions of TCs by releasing GPS dropwindsondes in the environment of the TC center. These data will be used by TPC/NHC and NCEP to prepare objective analyses and official forecasts through their assimilation into operational numerical prediction models. Because the atmosphere is known to be chaotic, very small perturbations to initial conditions in some locations can amplify with time. However, in other locations, perturbations may result in only small differences in subsequent forecasts.

Therefore, targeting locations in which the initial conditions have errors that grow most rapidly may lead to the largest possible forecast improvements. Locating these regions that impact the particular forecast is necessary. When such regions are sampled at regularly-spaced intervals the impact is most positive. The optimal targeting and sampling strategies is an ongoing area of research. This experiment addresses IFEX Goal 1.

In addition to the experiments presented above that comprise IFEX, there are several experiments that are also occurring simultaneously and will be partnering with HRD’s IFEX:

1. NOAA/NESDIS will be conducting the Ocean Winds Experiment, using N42RF for part of the season. The goal of this experiment is to further our understanding of the ocean surface wind vector retrievals in high wind speed conditions and in the presence of rain for all wind speeds from microwave remote-sensing measurements.
2. NOAA/NWS/NCEP/EMC will be running HWRF in operational mode for the first time in 2007. In addition a “parallel” run of HWRF will be run that assimilates the airborne Doppler observations. These will not be run simultaneously with the operational run but will be run soon thereafter to do an early evaluation of the assimilation of airborne Doppler observations.

OPERATIONS

1. Locations

Starting on 05 July, the NOAA WP-3D (N42RF) and Gulfstream IV-SP aircraft will be available for possible HRD research missions. Operations for both aircraft will primarily base out of Tampa, Florida, with provision for deployments to Barbados, St. Croix, and Bermuda for storms in the Atlantic basin (including the Atlantic Ocean and the Caribbean Sea) and deployments to U.S. coastal locations in the western Gulf of Mexico for suitable Gulf storms. Occasionally, post mission recovery may be accomplished elsewhere.

2. Field Program Duration

The HRD hurricane field research program will be conducted from 05 July through 30 September 2006.

3. Research Mission Operations

The decision and notification process for hurricane research missions is shown, in flow chart form, in Appendix A of the HFP (Figs. A-1, A-2, and A-3). The names of those who are to receive primary notification at each decision/notification point shown in Figs. A-1, A-2, and A-3 are also listed in Appendix A of the HFP. Contacts are also maintained each weekday among the directors of HRD/AOML, TPC/NHC, NCEP/EMC, and AOC to discuss the "storm outlook."

Research operations must consider that the research aircraft are required to be placed in the National Hurricane Operations "Plan of the Day" (POD) 24 h before a mission. If operational "fix" requirements are accepted, the research aircraft must follow the operational constraints described in Section 7.

4. Task Force Configuration

The NOAA WP-3D aircraft (N42RF), equipped as shown in Appendix G of the HFP, will be available for research operations on a non-interference basis with operational “tasked” missions from 05 July to 30 September 2006. Also, the G-IV aircraft should be available, on a non-interference basis with operational “tasked” missions from 05 July to 30 September 2006.

5. Field Operations

5.1 Scientific Leadership Responsibilities

The implementation of the HRD 2006 Hurricane Field Program Plan is the responsibility of the field program director, who in turn, reports directly to the HRD director. The field program director will be assisted by the field program ground team manager. In the event of deployment, the field program ground team manager shall be prepared to assume overall responsibility for essential ground support logistics, site communications, and HRD site personnel who are not actively engaged in flight. Designated lead project scientists are responsible to the field program director or designated assistants. While in flight, lead project scientists are in charge of the scientific aspects of the mission.

5.2 Aircraft Scientific Crews

Tables B-2.1 through B-2.4 (Appendix B of the HFP) list the NOAA scientific crewmembers needed to conduct the 2006 hurricane field experiments. Actual named assignments may be adjusted on a case-by-case basis. Operations in 2006 will include completion of detailed records by each scientific member while on the aircraft. General checklists of NOAA science-related functions are included in Appendix E of the HFP.

5.3 Principal Duties of the Scientific Personnel

A list of primary duties for each NOAA scientific personnel position is given in Appendix D of the HFP.

5.4 HRD Communications

The HRD/Miami Ground Operations Center (MGOC) will operate from offices at AOML on Virginia Key (4301 Rickenbacker Causeway, Miami, Florida) or from TPC/NHC (11691 S.W. 17th Street, Miami, Florida).

During actual operations, the senior team leader of the MGOC, or his/her designee, can be reached by commercial telephone at (305) 221-4381 (HRD/TPC/NHC) or at (305) 361-4400 (HRD/AOML). At other times, an updated, automated telephone answering machine [(305) 221-3679] will be available at the MGOC. In addition, MGOC team leaders and the field program director can be contacted by calling their cell phones or pager (phone numbers available at a later date).

MGOC, operating from AOML or TPC/NHC, will serve as "communications central" for information and will provide interface with AOC, TPC/NHC, and CARCAH (Chief, Aerial Reconnaissance Coordinator, All Hurricanes). In the event of a deployment of aircraft and personnel for operations outside Miami, HRD's field program ground team manager will provide up-to-date crew and storm status and schedules through the field program director or the named experiment lead project scientist. HRD personnel who have completed a flight will provide information to MGOC, as required.

6. Data Management

Data management and dissemination will be according to the HRD data policy that can be viewed at:
http://www.aoml.noaa.gov/hrd/data2.html

A brief description of the primary data types and HRD personnel contact information may be found at:
http://www.aoml.noaa.gov/hrd/data/products.html

Raw data are typically available to all of NOAA-sponsored personnel and co-investigators immediately after a flight, subject to technical and quality assurance limitations. Processed data or other data that has undergone further quality control or analyses are normally available to the principle and co-investigators within a period of several months after the end of the Hurricane Field Program. Examples of co-investigators are NASA-sponsored NAMMA investigators and associated university or other Governmental partners.

All requests for NOAA data gathered during the 2006 Hurricane Field Program should be forwarded by email to the associated contact person in the HRD data products description (link above) or in writing to: Director, Hurricane Research Division/AOML, 4301 Rickenbacker Causeway, Miami, Florida 33149.

7. Operational Constraints

NOAA WP-3D aircraft are routinely “tasked” by NHC through CARCAH to perform operational missions that always take precedence over research missions. Research objectives can frequently be met, however, on these operational missions. Occasionally, HRD may request, through NHC and CARCAH, slight modifications to the flight plan on operational missions. These requests must not deter from the basic requirements of the operational flight as determined by NHC and coordinated through CARCAH.

Hurricane research missions are routinely coordinated with hurricane reconnaissance operations. As each research mission is entered into the planned operation, a block of time is reserved for that mission and operational reconnaissance requirements are assigned. A mission, once assigned, *must be flown in the time period allotted and the tasked operational fixes met.* Flight departure times are critical. Scientific equipment or personnel not properly prepared for the flight at the designated pre-take-off time will remain inoperative or be left behind to insure meeting scheduled operational fix requirements. Information on delays to or cancellations of research flights must be relayed to CARCAH.

8. Calibration of Aircraft Systems

Calibration of aircraft systems is described in Appendix B of the HFP (B.1 en-route calibration of aircraft systems). True airspeed (TAS) calibrations are required for each NOAA flight, both to and from station and should be performed as early and as late into each flight as possible (Fig. B-1).

IFEX Missions

1. Three-Dimensional Doppler Winds

Program significance: This experiment, a derivative of previous “Mature Storms” experiments, has been renamed to remove confusion about the sort of tropical systems that will be investigated, and to emphasize the reason for the experiment and the flight profiles chosen. The experiment is a response to the requirement listed as “Core Doppler Radar” in section 5.4.2.9 of the National Hurricane Operations Plan. The goal of that particular mission is to gather airborne-Doppler wind measurements that permit a more accurate initialization of the Hurricane Weather Research and Forecasting (HWRF) model, and also provide three-dimensional wind analyses for forecasters.

There are four main goals of this experiment: 1) to improve our understanding of the factors which modify the intensity and structure of tropical cyclones, 2) to provide a comprehensive data set for the initiation (including data assimilation) and validation of numerical hurricane simulations (in particular the Hurricane Weather and Research Forecasting model (HWRF), 3) to improve and evaluate technologies for observing tropical cyclones, and 4) to develop rapid “real-time” communication of these observations to the National Centers for Environmental Prediction (NCEP) of the National Weather Service (NWS).

The ultimate requirement for the NCEP’s Environmental Modeling Center (EMC) is to obtain the three-dimensional wind field of Atlantic tropical cyclones from airborne Doppler data every 6 hours to provide an initialization of HWRF through assimilation every 6 h. In 2007, the maximum possible rotation of missions is two per day or every 12 h. In hurricanes, coordination will be required between HRD, NCEP, and NESDIS, to effectively collect observations for both the Three-Dimensional Doppler Winds Experiment and the Ocean Winds and Rain Experiment, a NESDIS experiment designed to improve our understanding of microwave surface scatterometery in high-wind conditions over the ocean by collecting surface scatterometery data and Doppler data in the boundary layer of hurricanes.

Rationale: This experiment is designed specifically to address the IFEX goal of obtaining hurricane data sets that can address both the assimilation and validation needs of hurricane modelers, and in particular, the needs of those at NCEP/EMC (National Centers for Environmental Prediction/Environmental Modeling Center) developing modeling and assimilation techniques to work with the Hurricane Weather and Research Forecasting model (HWRF). EMC experience with assimilation and initialization have led to the following conclusions about data requirements: 1) When possible, data in mature storms should be collected to the outermost closed isobar, 2) wavenumbers 0 and 1 should be sufficient to obtain a good initialization of strong hurricanes, 3) azimuthal resolution needs increase for weaker storms which are less-completely organized. Resolutions finer than wavenumber 2 may be impractical from flight-level *in situ* data, but might be possible from airborne Doppler observations if azimuthal Doppler coverage within the radius of the outermost isobar is nearly complete. Fortunately, the radius of the outermost closed isobar tends to decrease with decreased age or intensity of the tropical cyclone.

There is a goal within IFEX to better define the structure and evolution of a tropical cyclone throughout its lifetime. Also, to verify hurricane simulations, measurements collected over several observation cycles are needed to better assess the models. The Three-Dimensional Doppler Winds experiment will obtain observations every 12-24 h. This schedule will allow the results of several model initializations to be compared with actual observations of the same system.

It appears from running of operational models that the most vertical resolution is needed in the boundary and outflow layers to assimilate numerical simulations. One might also assume that this is where the most vertical resolution is needed in observations to verify the initialization and forecasts of the model. For this reason it is desirable that if sufficient dropsondes are available, they should be dropped in the radial penetrations in the Three-Dimensional Doppler Winds experiment to verify that the boundary-layer and surface winds produced in HWRF resemble those in observations. If sufficient dropsondes are not available, a combination of SFMR, IWRAP, and airborne Doppler data will be used for verification.

NESDIS Ocean Winds and Rain Experiment: This experiment will be executed by NOAA/NESDIS and 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 and radiometer 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 (USFMR), 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 raw data mode acquisition system was tested for IWRAP during the Winter Storms Experiment this year, and it will be fully implemented during this hurricane season. Collecting the raw data allows spectral processing to be done which will allow the rain and surface contributions in the IWRAP data to be decoupled. This is critical in understanding the impacts of rain on the measurements, and thus, the ocean surface wind vector retrievals.

A secondary objective of the NESDIS experiments is to explore how much of this remotely-sensed data collected on the WP-3D can be processed and sent off the plane in near real-time. NESDIS has been working with Remote Sensing Solutions, Inc. in developing an effective data processing, distribution and display system to accomplish this within the constraints of a satellite phone data connection. The NOAA Aircraft Operations Center and Hurricane Research Division have been integral partners in accomplishing this task. Remotely-sensed surface data is not only extremely useful for experiment flight planning but also to the hurricane analysts at the Tropical Prediction Center as has been demonstrated with the experimental use of the SFMR on the NOAA P-3s over the past several years, which became fully operational last year. For this season N42RF will be equipped with a dedicated Globalstar satellite phone and a computer system to process and distribute to the ground the flight level serial data stream and the lower fuselage radar data in near real-time. Additionally on N42, a second Globalstar satellite data connection will be used to test dissemination of products derived from the X-band tail radar, a near real-time processing system for IWRAP and USFMR, and the serial data stream from the AVAPS station. The transmission of full resolution tail radar data packets may also be tested if a higher bandwidth satellite phone system becomes available on N42.

Links to IFEX: The Three-Dimensional Doppler Winds experiment supports the following NOAA IFEX goals:

- **Goal 1:** Collect observations that span the TC lifecycle in a variety of environments;
- **Goal 2:** Develop and refine measurement technologies that provide improved real-time monitoring of TC intensity, structure, and environment

Mission Descriptions:

The NESDIS Ocean Winds and Rain Experiment will be executed by NOAA/NESDIS. Specific details regarding these NESDIS missions are not included here.

Three-Dimensional Doppler Winds: Several different options are possible with this experiment. These are 1) the "lawn mower" pattern, 2) the box spiral pattern, 3) the rotating figure 4 pattern, 4) the "butterfly" pattern that consists of 3 penetrations across the storm center at 60-degree angles with respect to each other, and 5) the single figure 4. These patterns provide the maximum flexibility in planning, in which the need for dense date coverage must be balanced against the need to sample the entire vortex.

Single-aircraft option: Temporal resolution (here defined as data collected as close as possible to a 6-hourly interval as possible) is important, for both initialization and verification of HWRF. This has been verified in communication with EMC. In 2007, to obtain the maximum temporal resolution feasible, this mission is expected to be a single-P3 mission, to allow another crew to operate 12 h later, and to continue in a 12-h cycle of sorties. The type of flight pattern will be determined from the organization, strength and radial extent of the circulation.

"Lawn Mower" pattern: This pattern will be chosen for systems with small, weak, newly developed circulations, namely tropical depressions and weak tropical storms. If the system is small enough, Lawn Mower pattern A (Fig. TDDW-1) will be chosen, to permit complete coverage of all reflectors within the developing circulation. Otherwise pattern B will be flown. Pattern B permits a larger area to be sampled, at the expense of some gaps in the Doppler coverage. A specific flight level is not required for this mission. It is likely that the Air Force will be flying at an investigation level at this time, and the Three-Dimensional Doppler Winds Experiment can be flown anywhere from 5,000 ft to 14,000 ft. If detailed thermodynamic data from dropsondes is desirable, then the preferred level would be 14,000 ft to allow the deepest observation of the thermodynamic structure from the dropsondes, while reducing the likelihood of lightning strikes by staying below the melting level. Any orientation of the long and short flight legs may be flown, to permit the location of the initial and final points to be closest to the base of operations.

"Box Spiral" pattern: As the weak, developing, poorly-organized circulations become larger, it will be necessary to spread out the pattern to cover a larger area at the expense of complete Doppler coverage. Pattern A, as shown n Fig. TDDW-4, is designed to cover a box 280 nm x 280 nm with radial gaps in the coverage. As long as the circulation is still weak, but covers a larger area, this pattern will be considered; however, lack of symmetric coverage at all radii render this a less viable option as the system becomes more organized. Pattern B has denser coverage within the outside box, and it will be considered in smaller systems. A specific flight level is not required for this mission. It is likely that the Air Force will be flying at an investigation level at this time, and the Three-Dimensional Doppler Winds Experiment can be flown anywhere from 5,000 ft to 14,000 ft. If detailed thermodynamic data from dropsondes is desirable, then the preferred level would be 14,000 ft to allow the deepest observation of the thermodynamic structure from the dropsondes, while reducing the likelihood of lightning strikes by staying below the melting level. Any orientation of the box may be flown, to permit the location of the initial and final points to be closest to the base of operations.

"Rotating Figure 4" pattern: As the system intensity and/or organization increases, and a circulation center becomes more clearly defined, a rotating figure 4 pattern may be preferred. The advantage of this pattern over the larger versions of the "lawn mower" pattern is more symmetric wind coverage, and the advantage over the box spiral pattern is good definition of the wind field at all radii within the pattern. This pattern is obviously preferable to the lawn mower pattern in the event there is any operational fix responsibility for the aircraft. A specific flight level is not required for this mission. It is likely that the Air Force will be flying at 5,000 or 10,000 ft at this time, and the Three-Dimensional Doppler Winds Experiment can be flown anywhere from 5,000 ft to 14,000 ft. If detailed thermodynamic data from dropsondes is desirable, then the preferred level would be 14,000 ft to allow the deepest observation of the thermodynamic structure from the dropsondes, while reducing the likelihood of lightning strikes by staying below the melting level. Any orientation of the flight legs may be flown, to permit the location of the initial and final points to be closest to the base of operations.

“Butterfly” pattern: This pattern should be flown in larger, more organized tropical cyclones, generally in hurricanes. As the hurricane circulation becomes larger, it will be necessary to get the full radial coverage at the expense of full Doppler coverage. As an example, a butterfly pattern out to 100 nm could be flown in 3.3 h, compared to a similar “lawn mower” coverage that would take 4.8 h. This pattern is obviously preferable to the lawn mower pattern in the event there is any operational fix responsibility for the aircraft. A specific flight level is not required for this mission. It is likely that the Air Force will be flying at 5,000 or 10,000 ft at this time, and the Three-Dimensional Doppler Winds Experiment can be flown anywhere from 5,000 ft to 14,000 ft. If detailed thermodynamic data from dropsondes is desirable, then the preferred level would be 14,000 ft to allow the deepest observation of the thermodynamic structure from the dropsondes, while reducing the likelihood of lightning strikes by staying below the melting level. Any orientation of the flight legs may be flown, to permit the location of the initial and final points to be closest to the base of operations.

Single “Figure 4” pattern: This pattern will be flown in very large circulations. It still provides wavenumber 0 and 1 coverage with airborne Doppler data, which should be sufficient in strong, organized systems. Radial coverage out to 240 and 300 nm (4 and 5 degrees) is possible in 5.4 and 6.8 h in pattern. A specific flight level is not required for this mission. It is likely that the Air Force will be flying at 5,000 or 10,000 ft at this time, and the Three-Dimensional Doppler Winds Experiment can be flown anywhere from 5,000 ft to 14,000 ft. If detailed thermodynamic data from dropsondes is desirable, then the preferred level would be 14,000 ft to allow the deepest observation of the thermodynamic structure from the dropsondes, while reducing the likelihood of lightning strikes by staying below the melting level. Any orientation of the flight legs may be flown, to permit the location of the initial and final points to be closest to the base of operations.

Three-Dimensional Doppler Winds Experiment Flight Planning Approach:

During the 2007 Hurricane Field Program (01 June to 30 November), the primary objective will be to meet IFEX goals 1 through 3, which involve collecting airborne Doppler radar and flight-level data over a period of several days in storms of varying intensity and structural type, but with emphasis during this period on intensity changes throughout the tropical-cyclone lifecycle. Priorities and constraints on resources may reduce the amount of effort devoted in 2007 to IFEX goal 3 (physical process), but there will be opportunities for physical-process research to “piggy back” on the Three-Dimensional Doppler Winds flights. A subset of the IFEX goals will be accomplished in the context of the Three-Dimensional Doppler Winds Experiment, with flight patterns that generally involve using one NOAA WP-3D aircraft at a time (N42RF).

NOAA will conduct a set of three-dimensional Doppler-wind experiments over several days, encompassing as much of a particular storm’s life cycle as possible. This would entail using the two available NOAA WP-3D on back-to-back flights on a 12-hour schedule when the system is at depression, tropical storm, or hurricane strength.

At times when more than one system could be flown, one may take precedence over others depending on factors such as storm strength and location, operational tasking, and aircraft availability. All other things being equal, the target will be an organizing tropical depression or weak tropical storm, to increase the observations available in these systems. One scenario could likely occur that illustrate how the mission planning is determined:

An incipient TC, at depression or weak tropical storm stage is within range of an operational base and is expected to develop and remain within range of operational bases for a period of several days. Here, the highest priority would be to start the set of Three Dimensional Doppler Winds flights, with single NOAA WP-3D missions, while the TC is below hurricane strength (preferably starting at depression stage), with continued single NOAA WP-3D missions at 12-hour intervals until the system is out of range or makes landfall. During the tropical depression or tropical-storm portion of the vortex lifetime, higher azimuthal resolution of the wind field is preferred over radial extent of observations, while in the hurricane portion, the flight plan would be designed to get wavenumber 0 and 1 coverage of the hurricane out to the largest radius possible, rather then the highest time resolution of the eyewall winds. In all cases maximum spatial coverage is preferred over temporal resolution during one sortie.

Three-Dimensional Doppler Winds

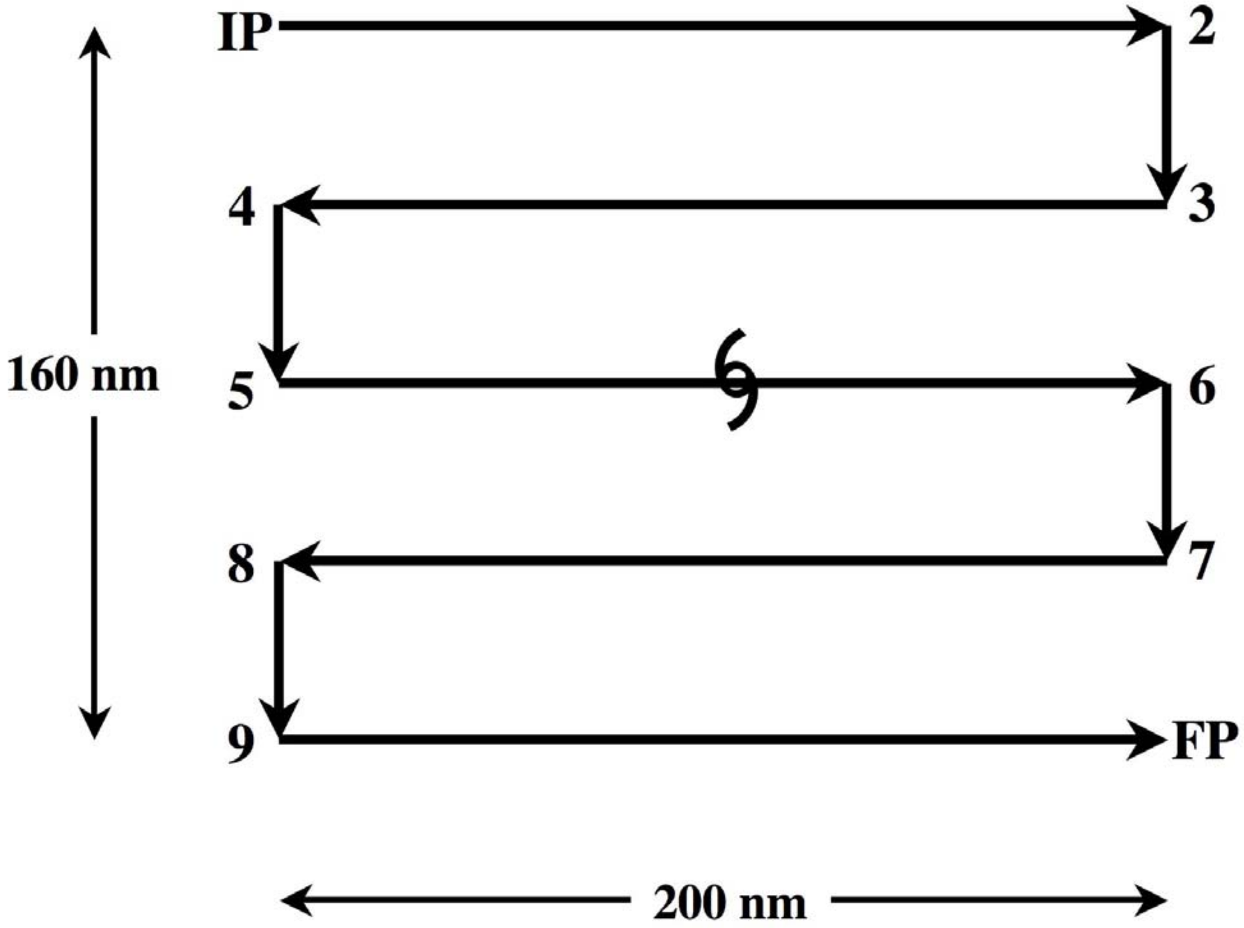


Figure TDDW-1. “Lawn Mower” Pattern A. Total flight distance as drawn is 1160 nm, and flight time is 4.8 h.

Note 1.	This is to be flown where even coverage is required, particularly in tropical depressions and tropical storms. Aircraft flies IP-2-3-4-5-6-7-8-9-FP. No attempt should be made to fix a center of circulation unless requested it is an operational request.
Note 2.	Doppler radars should be operated in single-PRF mode, at a PRF of 2400-3200. The default will be 2400 PRF. Radar scientist should verify this mode of operation with AOC engineers. If there is no assigned radar scientist, LPS should verify. *This is crucial for the testing and implementation of real-time quality control.*
Note 3.	Unless specifically requested by the LPS, both tail Doppler radars should be operated in fore/aft continuous scanning with a fore/aft angle of 20° relative to fuselage. French antenna automatically operates in fore/aft scanning, but it should be confirmed, nevertheless that the scanning is continuous, rather than sector scanning.
Note 4.	IP can be at any desired heading relative to storm center
Note 5.	To maximize sonde coverage aircraft should operate at highest altitudes that still minimize icing
Note 6.	If sondes are not dropped, aircraft can operate at any level below the melting level, with 10,000 ft preferred.
Note 7.	Dropsondes shown are not a required part of this flight plan and are optional.
Note 8.	Flight pattern should be centered around either the 18, 00, 06, or 12 GMT operational model analysis times.

Three-Dimensional Doppler Winds

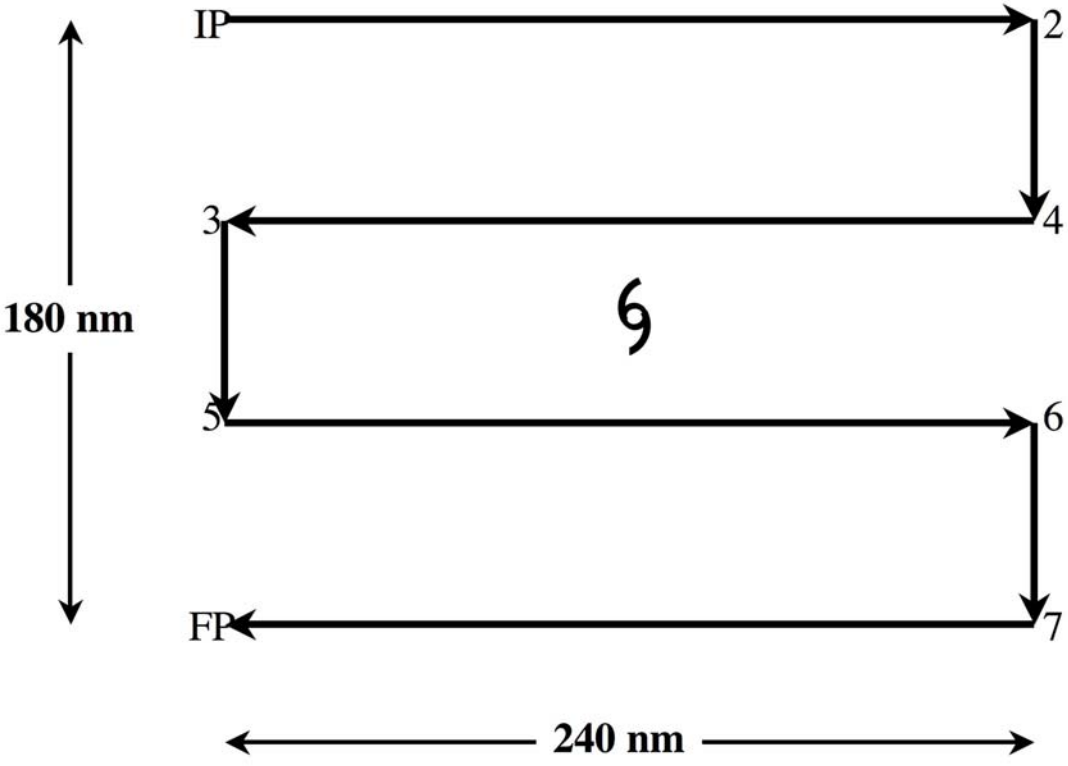


Figure TDDW-2. “Lawn Mower” Pattern B. Total flight distance as drawn is 1140 nm, and flight time is 4.75 h.

Note 1.	This is to be flown where even coverage is required, particularly in tropical depressions and tropical storms. Aircraft flies IP-2-3-4-5-6-7-FP. No attempt should be made to fix a center of circulation unless requested it is an operational request.
Note 2.	Doppler radars should be operated in single-PRF mode, at a PRF of 2400-3200. The default will be 2400 PRF. Radar scientist should verify this mode of operation with AOC engineers. If there is no assigned radar scientist, LPS should verify. *This is crucial for the testing and implementation of real-time quality control.*
Note 3.	Unless specifically requested by the LPS, both tail Doppler radars should be operated in fore/aft continuous scanning with a fore/aft angle of 20^o relative to fuselage. French antenna automatically operates in fore/aft scanning, but it should be confirmed, nevertheless that the scanning is continuous, rather than sector scanning.
Note 4.	IP can be at any desired heading relative to storm center
Note 5.	To maximize sonde coverage aircraft should operate at highest altitudes that still minimize icing
Note 6.	If sondes are not dropped, aircraft can operate at any level below the melting level, with 10,000 ft preferred.
Note 7.	Dropsondes shown are not a required part of this flight plan and are optional.
Note 8.	Flight pattern should be centered around either the 18, 00, 06, or 12 GMT operational model analysis times.

Three-Dimensional Doppler Winds

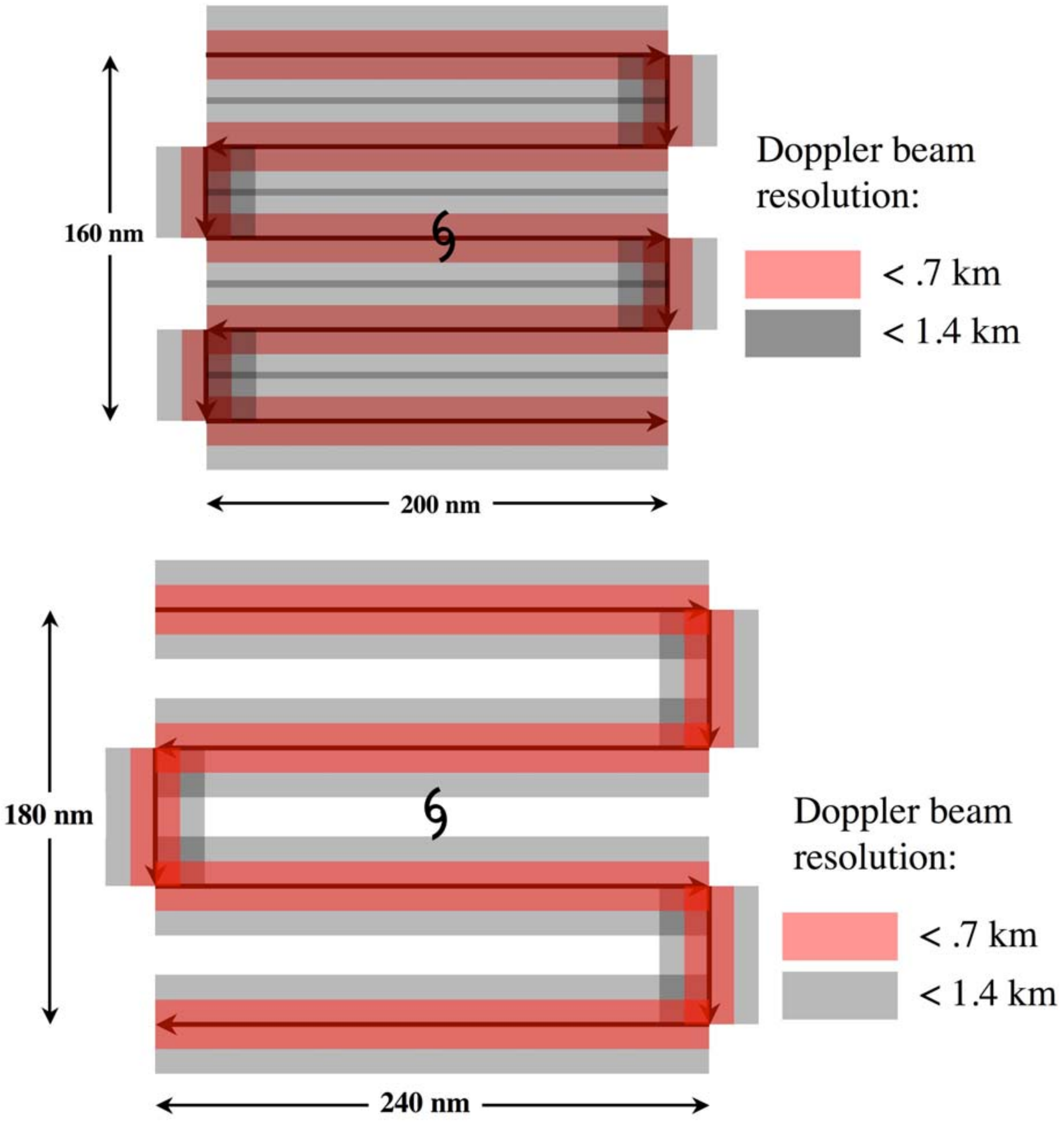


Figure TDDW-3. Display of Doppler coverage for A (upper panel) and B (lower panel) “lawn mower” patterns shown in Figs. TDDW-1 and TDDW-2. Pink region shows areas where vertical beam resolution is better than .7 km and gray regions delineate areas where vertical beam resolution is better than 1.4 km. Maximum extent of gray area is approximately 40 km from flight track, generally the maximum usable extent of reliable airborne Doppler radar coverage.

Three-Dimensional Doppler Winds

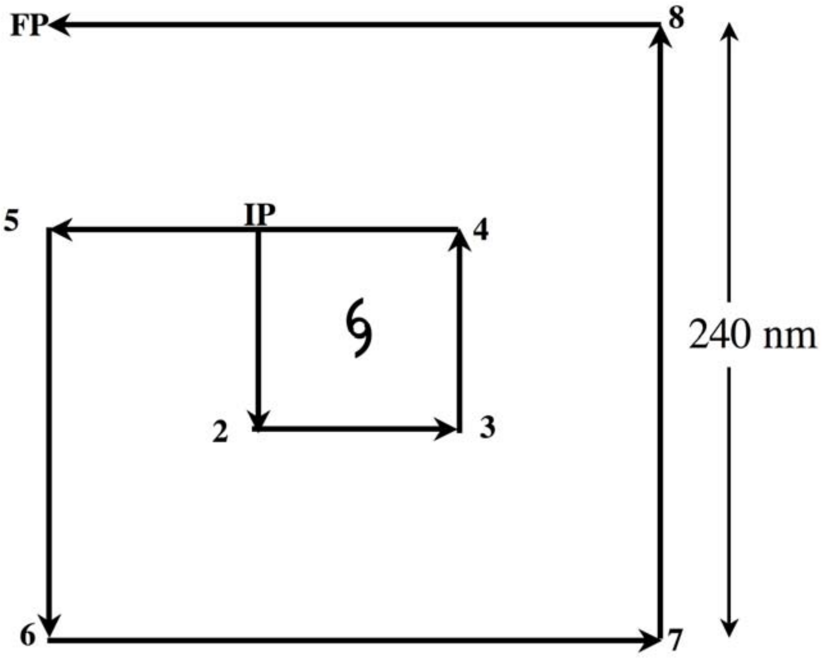


Figure TDDW-4. "Box Spiral" pattern A. Total flight distance as drawn is 1280 nm, and the flight time is 5.33 h.

Note 1.	This is to be flown where even coverage is required, particularly in tropical depressions and tropical storms. Aircraft flies IP-2-3-4-5-6-7-8-FP. No attempt should be made to fix a center of circulation unless requested it is an operational request.
Note 2.	Doppler radars should be operated in single-PRF mode, at a PRF of 2400-3200. The default will be 2400 PRF. Radar scientist should verify this mode of operation with AOC engineers. If there is no assigned radar scientist, LPS should verify. *This is crucial for the testing and implementation of real-time quality control.*
Note 3.	Unless specifically requested by the LPS, both tail Doppler radars should be operated in fore/aft continuous scanning with a fore/aft angle of 20^o relative to fuselage. French antenna automatically operates in fore/aft scanning, but it should be confirmed, nevertheless that the scanning is continuous, rather than sector scanning.
Note 4.	IP can be at any desired heading relative to storm center
Note 5.	To maximize sonde coverage aircraft should operate at highest altitudes that still minimize icing
Note 6.	If sondes are not dropped, aircraft can operate at any level below the melting level, with 10,000 ft preferred.
Note 7.	Dropsondes shown are not a required part of this flight plan and are optional.
Note 8.	Flight pattern should be centered around either the 18, 00, 06, or 12 GMT operational model analysis times.

Three-Dimensional Doppler Winds

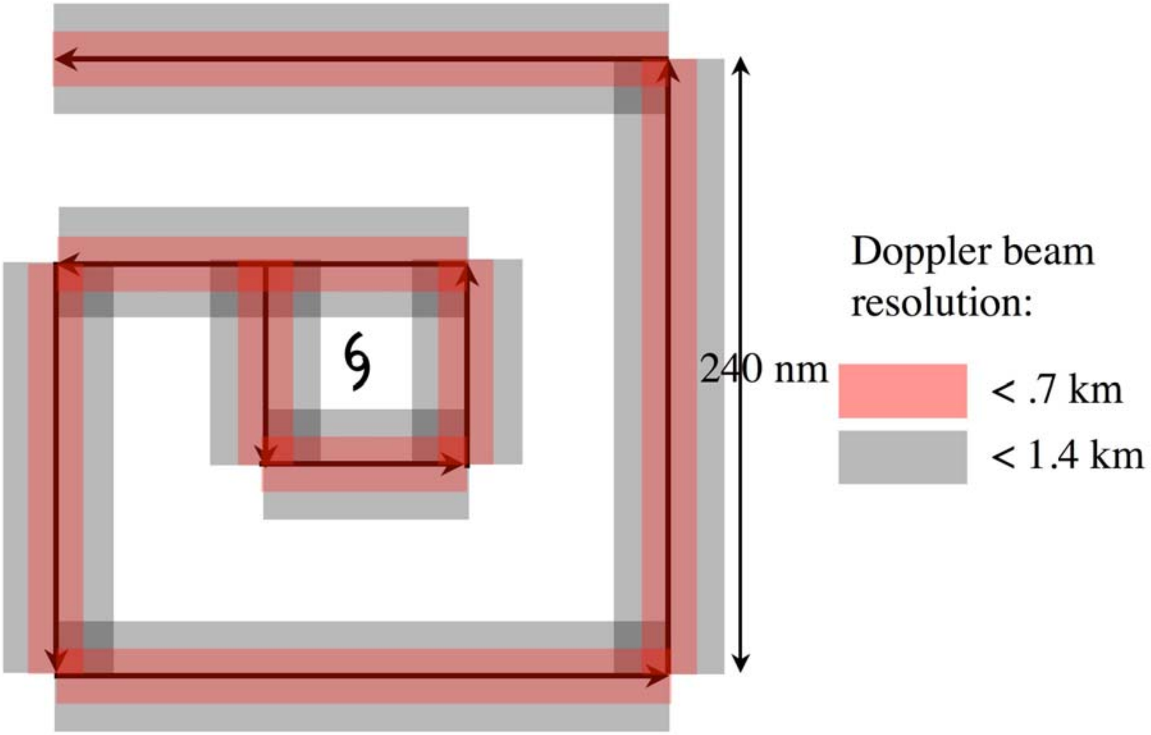


Figure TDDW-5. Doppler radar coverage for “Box Spiral” pattern A. Pink region shows areas where vertical beam resolution is better than .7 km and gray regions delineate areas where vertical beam resolution is better than 1.4 km. Maximum extent of gray area is approximately 40 km from flight track, approximately the maximum usable extent of reliable airborne Doppler radar coverage.

Three-Dimensional Doppler Winds

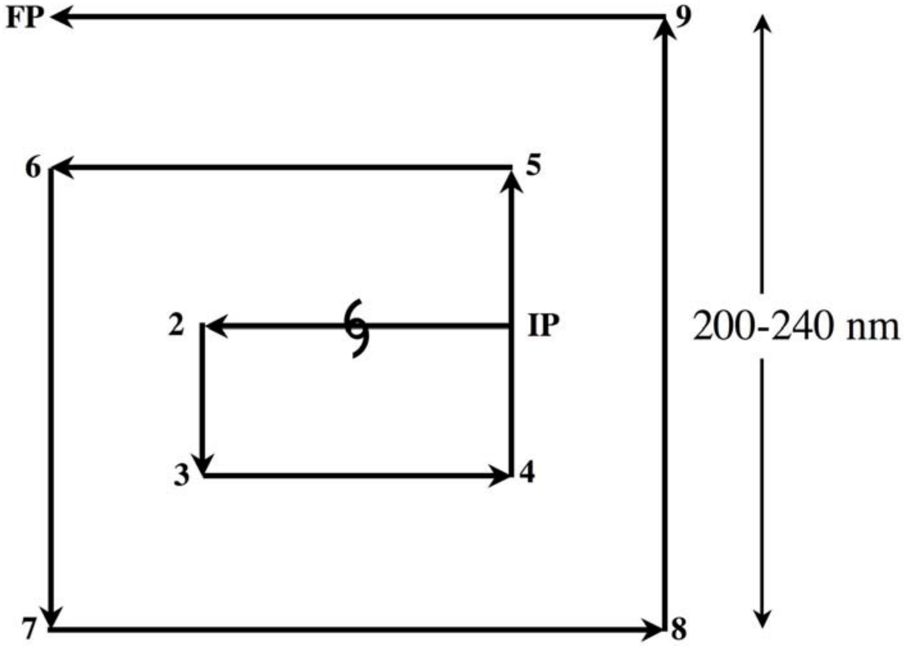


Figure TDDW-6. Box Spiral pattern B. Flight distance for 200 nm pattern is 1250 nm, while flight time is 5.2 h. Corresponding values for 240 nm pattern are 1500 nm and 6.25 h.

Note 1.	This is to be flown where even coverage is required, particularly in tropical depressions and tropical storms. Doppler radars should be operated in single-PRF mode, at a PRF of 2400-3200. The default will be 2400 PRF. Radar scientist should verify this mode of operation with AOC engineers. If there is no assigned radar scientist, LPS should verify. *This is crucial for the testing and implementation of real-time quality control.*
Note 2.	Unless specifically requested by the LPS, both tail Doppler radars should be operated in fore/aft continuous scanning with a fore/aft angle of 20° relative to fuselage.
Note 3.	IP can be at any desired heading relative to storm center
Note 4.	To maximize sonde coverage aircraft should operate at highest altitudes that still minimize icing
Note 5.	Shaded areas show airborne-Doppler radar coverage with a maximum flight radius of 100 nm
Note 6.	Maximum radius may be decreased or increased within operational constraints
Note 7.	Dropsondes shown are not a required part of this flight plan and are optional.
Note 8.	Flight pattern should be centered around either the 18, 00, 06, or 12 GMT operational model analysis times.
Note 9.	Maximum radius may be changed to meet operational needs while conforming to flight-length constraints.

Three-Dimensional Doppler Winds

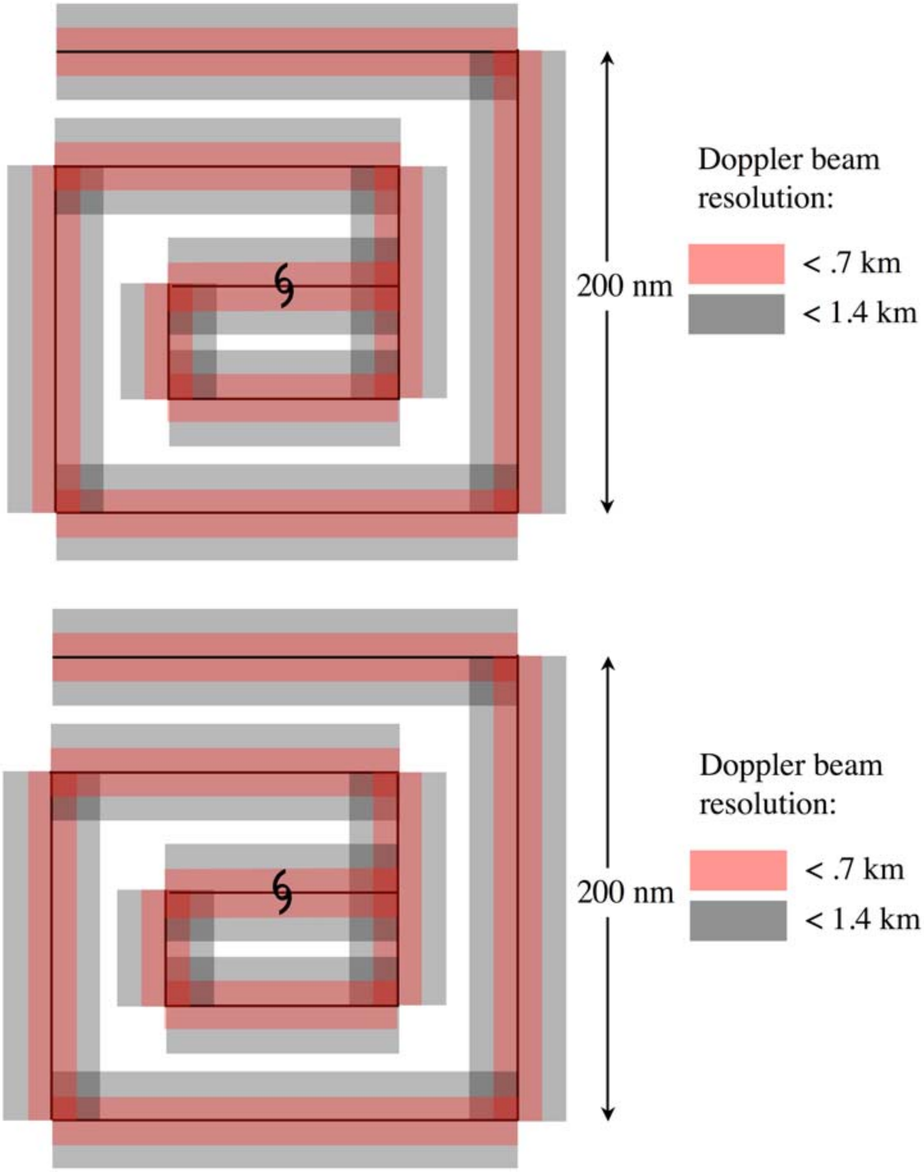


Figure TDDW-7. Doppler radar coverage for “Box Spiral” patterns B with flight pattern dimensions of 200 (upper panel) and 240 (lower panel) nm. Pink region shows areas where vertical beam resolution is better than .7 km and gray regions delineate areas where vertical beam resolution is better than 1.4 km. Maximum extent of gray area is approximately 40 km from flight track, approximately the maximum usable extent of reliable airborne Doppler radar coverage.

Three-Dimensional Doppler Winds

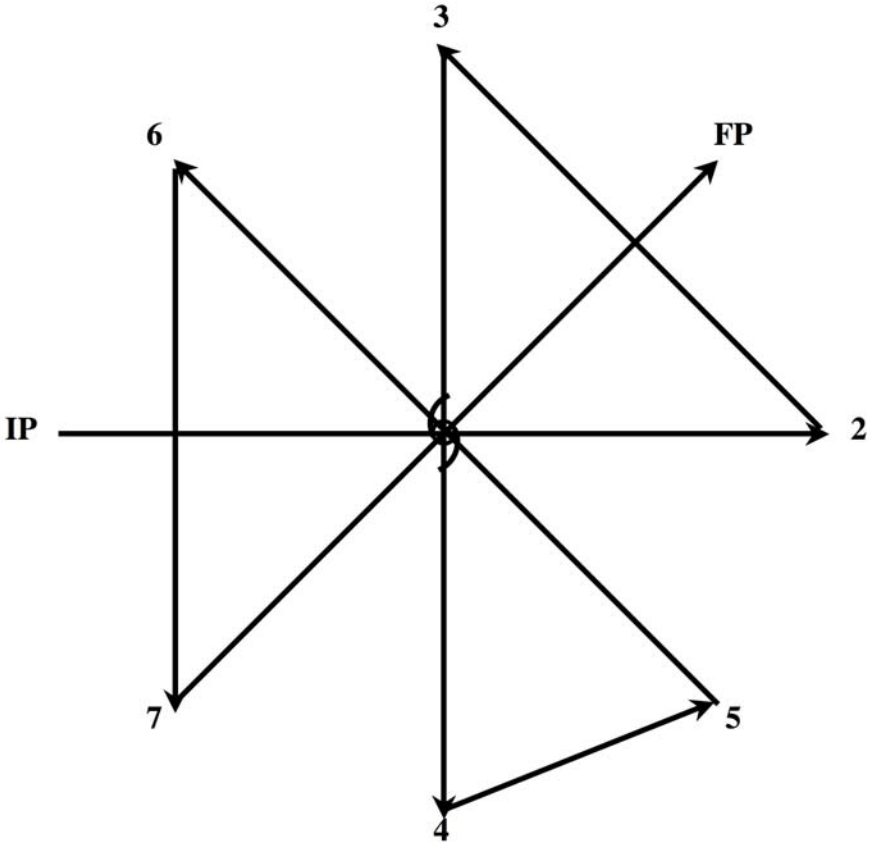


Figure TDDW-8. Rotating Figure 4 pattern. Flight distances for 100, 120 and 150 nm radial extents are 1160, 1395, and 1745 nm. Corresponding flight times are: 4.8, 5.8, and 7.3 h.

Note 1.	This pattern should be flown in strong tropical storms and hurricanes, where the circulation extends from 100 nm to 150 nm from the center. Doppler radars should be operated in single-PRF mode, at a PRF of 2400-3200. The default will be 2400 PRF. Radar scientist should verify this mode of operation with AOC engineers. If there is no assigned radar scientist, LPS should verify. *This is crucial for the testing and implementation of real-time quality control.*
Note 2.	Unless specifically requested by the LPS, both tail Doppler radars should be operated in fore/aft continuous scanning with a fore/aft angle of 20^o relative to fuselage.
Note 3.	IP can be at any desired heading relative to storm center
Note 4.	To maximize sonde coverage aircraft should operate at highest altitudes that still minimize icing
Note 5.	Shaded areas show airborne-Doppler radar coverage with a maximum flight radius of 100 nm
Note 6.	Maximum radius may be decreased or increased within operational constraints
Note 7.	Dropsondes shown are not a required part of this flight plan and are optional.
Note 8.	Flight pattern should be centered around either the 18, 00, 06, or 12 GMT operational model analysis times.
Note 9.	Maximum radius may be changed to meet operational needs while conforming to flight-length constraints.

Three-Dimensional Doppler Winds

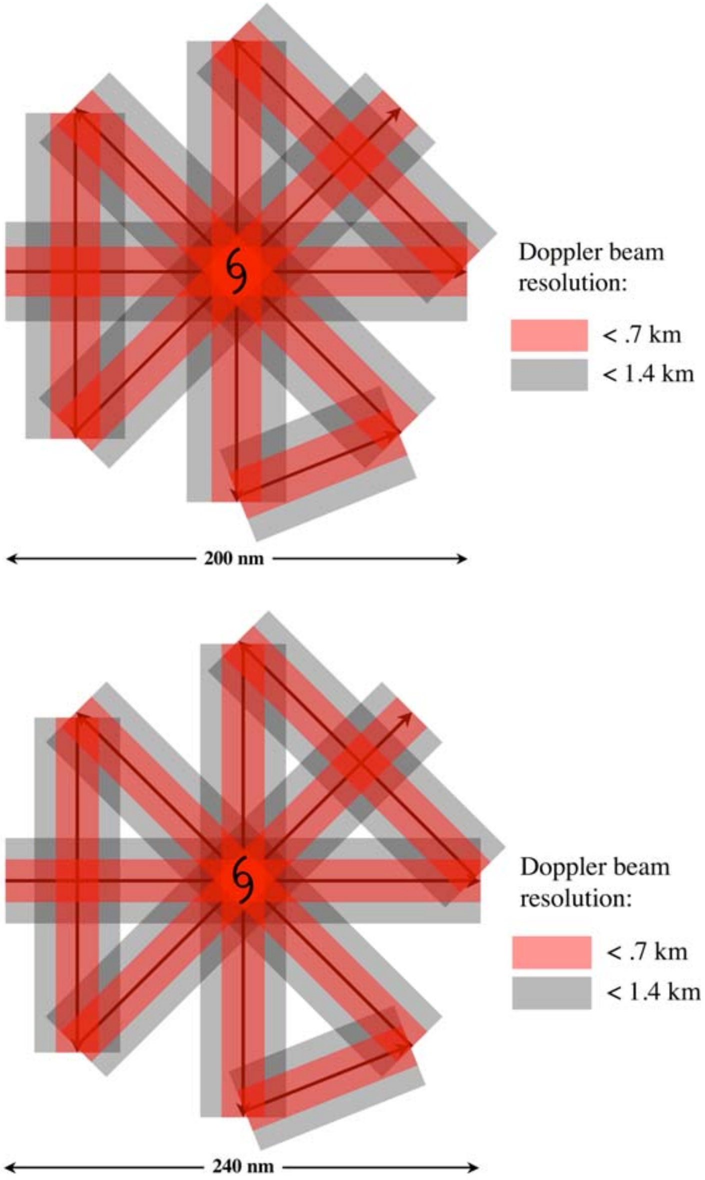


Figure TDDW-9. Doppler radar coverage for radial extents of 100 (top) and 120 (bottom) nm of the Rotation Figure 4 patterns. Pink region shows areas where vertical beam resolution is better than .7 km and gray regions delineate areas where vertical beam resolution is better than 1.4 km. Maximum extent of gray area is approximately 40 km from flight track, approximately the maximum usable extent of reliable airborne Doppler radar coverage.

Three-Dimensional Doppler Winds

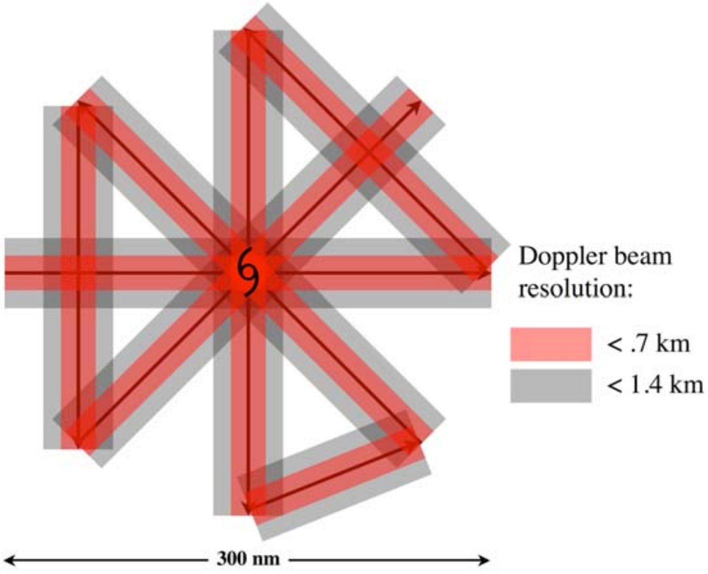


Figure TDDW-9 continued. Doppler radar coverage for radial extent of 150 nm of the Rotation Figure 4 patterns.

Three-Dimensional Doppler Winds

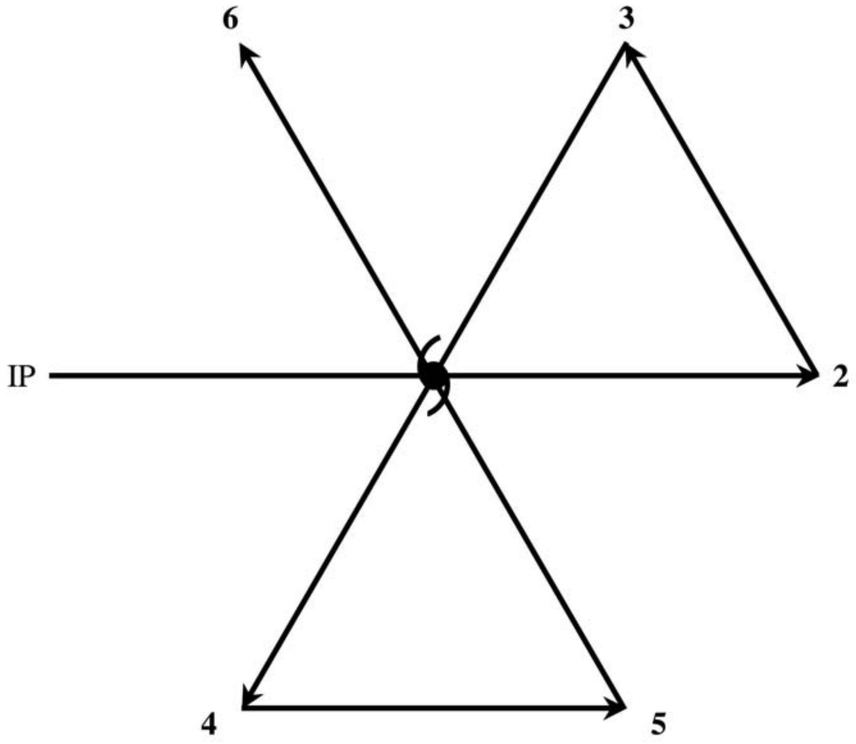


Figure TDDW-10. “Butterfly” Pattern. Flight distances for the patterns with 120 and 180 nm radials legs are 960 and 1440 nm. Corresponding flight durations are 4 and 6 h.

Note 1.	This pattern will be flown in large tropical storms, as well as hurricanes. Doppler radars should be operated in single-PRF mode, at a PRF of 2400-3200. The default will be 2400 PRF. Radar scientist should verify this mode of operation with AOC engineers. If there is no assigned radar scientist, LPS should verify. *This is crucial for the testing and implementation of real-time quality control.*
Note 2.	Unless specifically requested by the LPS, both tail Doppler radars should be operated in fore/aft continuous scanning with a fore/aft angle of 20^o relative to fuselage.
Note 3.	IP can be at any desired heading relative to storm center
Note 4.	To maximize sonde coverage aircraft should operate at highest altitudes that still minimize icing
Note 5.	Shaded areas show airborne-Doppler radar coverage with a maximum flight radius of 100 nm
Note 6.	Maximum radius may be decreased or increased within operational constraints
Note 7.	Dropsondes shown are not a required part of this flight plan and are optional.
Note 8.	Flight pattern should be centered around either the 18, 00, 06, or 12 GMT operational model analysis times.
Note 9.	Maximum radius may be changed to meet operational needs while conforming to flight-length constraints.

Three-Dimensional Doppler Winds

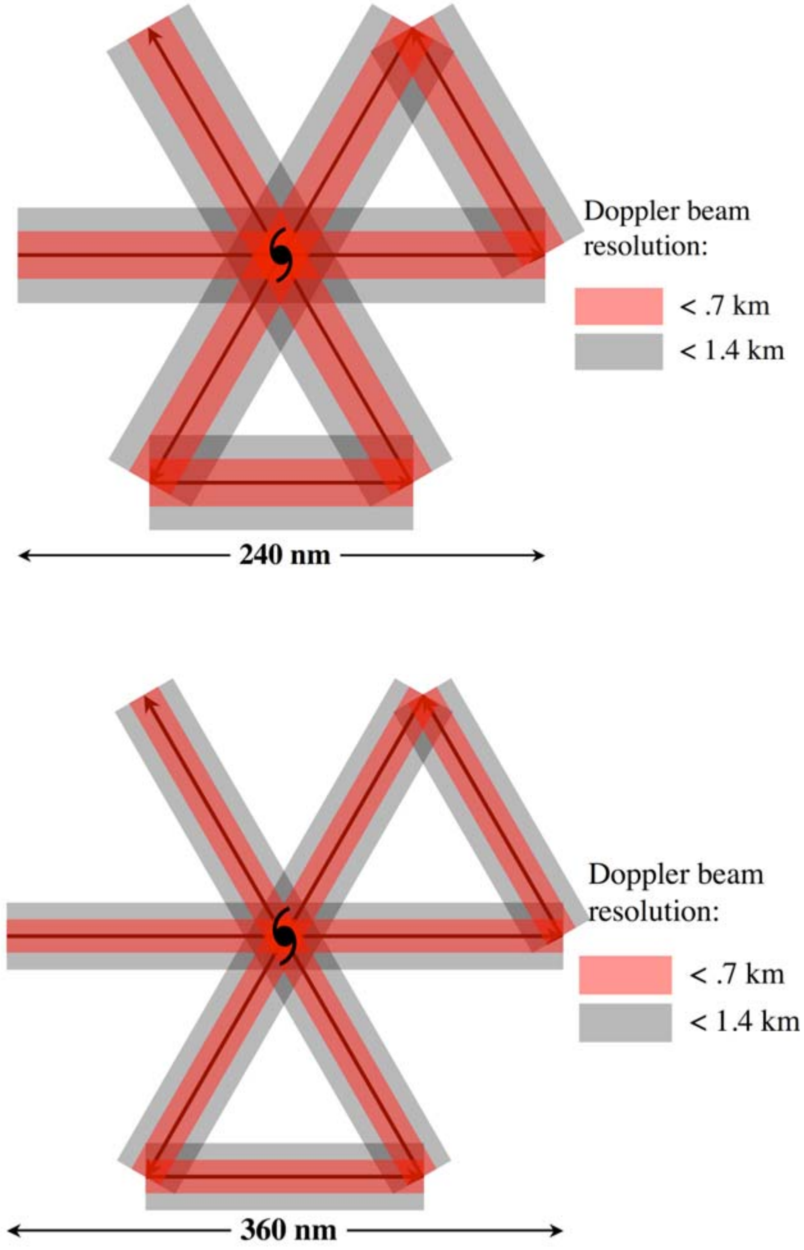


Figure TDDW-11. Doppler radar coverage for radial extents of 120 (top) and 180 (bottom) nm of the Butterfly pattern. Pink region shows areas where vertical beam resolution is better than .75 km and gray regions delineate areas where vertical beam resolution is better than 1.5 km. Maximum extent of gray area is approximately 40 km from flight track, approximately the maximum usable extent of reliable airborne Doppler radar coverage.

Three-Dimensional Doppler Winds

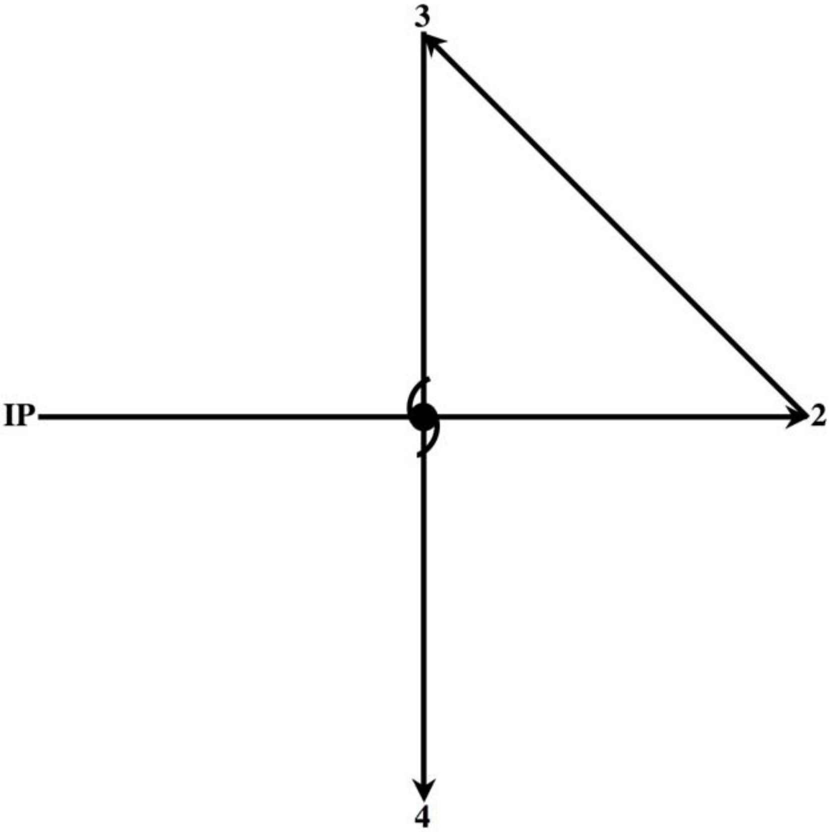


Figure TDDW-12. Single Figure 4 pattern. Flight distances for radial extents of 240 and 300 nm are 1300 and 1645 nm, respectively. Corresponding flight times are 5.4 and 6.8 h.

Note 1.	This pattern should be flown for large storms, to obtain as full a radial extent of observations of the full storm circulation as possible. Doppler radars should be operated in single-PRF mode, at a PRF of 2400-3200. The default will be 2400 PRF. Radar scientist should verify this mode of operation with AOC engineers. If there is no assigned radar scientist, LPS should verify. *This is crucial for the testing and implementation of real-time quality control.*
Note 2.	Unless specifically requested by the LPS, both tail Doppler radars should be operated in fore/aft continuous scanning with a fore/aft angle of 20^{o} relative to fuselage.
Note 3.	IP can be at any desired heading relative to storm center
Note 4.	To maximize sonde coverage aircraft should operate at highest altitudes that still minimize icing
Note 5.	Shaded areas show airborne-Doppler radar coverage with a maximum flight radius of 100 nm
Note 6.	Maximum radius may be decreased or increased within operational constraints
Note 7.	Dropsondes shown are not a required part of this flight plan and are optional.
Note 8.	Flight pattern should be centered around either the 18, 00, 06, or 12 GMT operational model analysis times.
Note 9.	Maximum radius may be changed to meet operational needs while conforming to flight-length constraints.

Three-Dimensional Doppler Winds

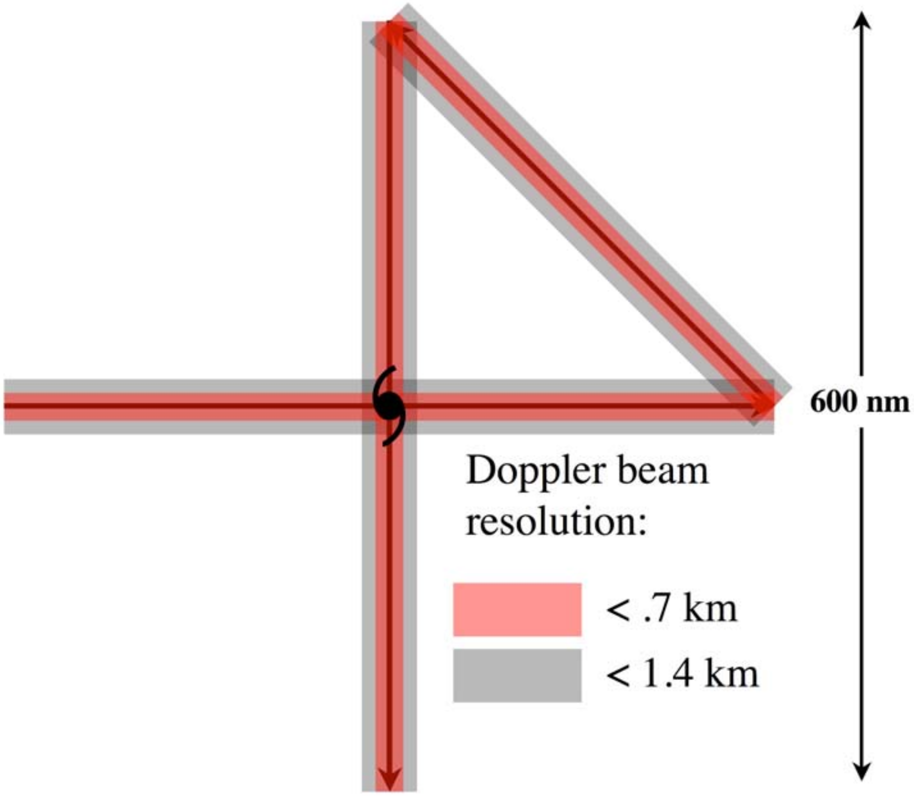


Figure TDDW-13. Doppler radar coverage for radial extents of 300 nm of the Single-Figure-4 pattern. Pink region shows areas where vertical beam resolution is better than .75 km and gray regions delineate areas where vertical beam resolution is better than 1.5 km. Maximum extent of gray area is approximately 40 km from flight track, approximately the maximum usable extent of reliable airborne Doppler radar coverage.

IFEX Missions Cont'd
Tropical Cyclone Landfall and Inland Decay

Program Significance: The lifecycle of a tropical cyclone often ends when it makes landfall and decays as it moves inland. During a hurricane threat, an average of 300 nm (550 km) of coastline is placed under a hurricane warning, which costs about $50 million in preparation per event. 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, and now one of the goals of HRD's Intensity Forecasting Experiment (IFEX) is to improve the accuracy of the surface wind fields in TCs, especially near and after landfall. Improvements in diagnosing surface wind fields could decrease the uncertainty of the size of the hurricane warning area thereby reducing the cost of preparing for a landfalling hurricane.

There are still uncertainties in deriving surface wind estimates from flight level and Stepped Frequency Microwave Radiometer (SFMR) windspeeds collected near the coast. Currents and changing bathymetry could change the breaking wave field, which could change both the roughness length at higher windspeeds as well as changing the microwave emissions. Evaluation of these effects may lead to adjustments to the operational surface windspeed algorithms. Data collected at the coast will also help to refine the Kaplan/DeMaria inland decay model that has been developed as part of a recently completed NOAA Joint Hurricane Test bed (JHT) project. Airborne Doppler radar data will be also be transmitted to TPC/NHC and EMC as part of another completed JHT project to assimilate radar data into the HWRF model.

Analysis of Doppler radar, GPS sonde, SFMR, flight-level and SRA or IWRAP data collected during hurricane flights can help achieve the Intensity Forecasting Experiment (IFEX) goals for the 2007 Hurricane Field Program. A major goal is to capture the lifecycle of a TC and while landfall is usually at the end of the lifecycle the same data collection strategies developed for mature hurricanes over the open ocean can also be applied at landfall. Subsets of the data collected can be transmitted to NHC and to EMC, for assimilation into HWRF. The Doppler and GPS sonde data can be analyzed to derive three-dimensional windfields to compare with output from the HWRF and data from the NASA Scanning Radar Altimeter (SRA) can be compared to HWRF wavefields. In addition to shear and heat flux from the ocean, hurricanes at landfall experience other conditions that may affect intensity change. These include change in ocean wave action in shallow waters, change in surface roughness, drier and cooler inflow from the land, and topography. Radar, sonde, and SFMR data can help define those conditions. Decay over land is also important and data collected during and shortly after landfall should help refine both operational statistical decay models (such as the Kaplan/DeMaria model) and 3-dimensional numerical models like HWRF.

HRD developed a real-time surface wind analysis system to aid the TPC/NHC in the preparation of warnings and advisories in TCs. The surface wind analyses are now used for post-storm damage assessment by emergency management officials and to validate and calibrate the Kaplan/DeMaria decay model. These wind analyses could also be used to initialize the operational storm surge model (SLOSH) in real-time.

As a TC approaches the coast, surface marine wind observations are normally only available in real-time from National Data Buoy Center (NDBC) moored buoys, C-MAN platforms, and a few ships. Surface wind estimates must therefore be based primarily on aircraft measurements. Low-level (<5,000 ft (1.5 km] altitude) NOAA and Air Force Reserve aircraft flight-level winds are adjusted to estimate surface winds. These adjusted winds, along with C-SCAT and SFMR wind estimates, are combined with actual surface observations to produce surface wind analyses. These surface wind analyses were initially completed after Hurricane Hugo's landfall in South Carolina and Hurricane Andrew's landfall in South Florida in support of post-landfall damage surveys conducted by FEMA. In recent years, these analyses have been produced in real-time for operational use by the NHC for many of the TCs that have affected the Western Atlantic basin, including such notable landfalling storms as Opal (1995), Fran (1996), Georges (1998), Bret and Floyd (1999), Isadore (2003) and Frances, Ivan and Jeanne (2004), and Dennis, Katrina, Rita and Wilma (2006).

Dual-Doppler analysis provides a more complete description of the wind field in the inner core. Recently the analysis techniques have been streamlined so real-time wind analyses can be computed aboard the aircraft and windfields at selected levels transmitted from the aircraft to NHC and NMC. These windffields are also quite useful for post-storm analysis. An observational study of Hurricane Norbert (1984), using a PDD analysis of airborne radar data to estimate the kinematic wind field, 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. Another study 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.

Recent GPS sondes dropped at and inside the flight-level radius of maximum winds (RMW) in strong hurricanes have shown remarkable variations of the wind with height. A common feature is a wind speed maximum at 300-500 m altitude. Theoretical and numerical modeling of the hurricane boundary layer suggests that the low-level jets are common features. The height of the jet varies by storm quadrant, and modeling indicates that this variation can be enhanced as a hurricane crosses land.

While collection of dual-Doppler radar data by aircraft alone requires two WP-3D aircraft flying in well-coordinated patterns, time series of dual-Doppler data sets have been 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, yielding true Dual-Doppler coverage. Starting in 1997 the Atlantic and Gulf coasts were 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-5 in the Appendix). Each radar transmits the base data (Level II) in near real-time to a central site. These data are subsequently archived at the National Climatic Data Center. In precipitation or severe weather mode the radars collect volume scans every 5-6 min.

If a significant tropical cyclone moves within 215 nm (440 km) of the coast of the Eastern or Southern United States, then (resources permitting) a WP-3D will obtain Doppler radar data to be combined with data from the closest WSR-88D radars in dual-Doppler analyses. The tail radar is tilted to point 20 deg forward and aft from the track during successive sweeps (the fore-aft canning mode: F/AST). 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 experiment is designed to obtain dual-Doppler analyses at intervals of 10-20 min in the inner core. The Doppler data will be augmented by dropping GPS-sondes near the coast, where knowledge of the boundary-layer structure is crucial for determining what happens to the wind field as a strong storm moves inland. GPS-sondes will also be dropped in the eye wall in different quadrants of the hurricane. To augment the inner core analyses, dual-Doppler data can also be collected in the outer portions of the storm, beyond the range of the WSR-88D, because the alternating forward and aft scans in F/AST mode intersect at 40 deg, sufficient for dual-Doppler synthesis of winds.

Objectives:

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

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

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

D) Measure the characteristics of the middle troposphere and the hurricane boundary layer with GPS-sondes.

Mission Description:
This experiment is a *multi-option, single-aircraft* experiment designed to study the changes in TC surface wind structure near and after landfall. The experiment has several modules that could also be incorporated into operational surveillance or reconnaissance missions. This experiment is designed to be conducted by flying one or two single aircraft missions with a NOAA WP-3D aircraft when a hurricane moves within 215 nm (400 km) of the U.S. coastline. The first of these 2 flights will typically consist of the real-time module followed by SFMR and/or Coastal Wind Profile modules. A second flight could complete the post-landfall module. If the storm either moves parallel to the coastline or moves slowly inland and resources permit, the experiment may be repeated with a second flight. While the storm's location relative to the coastline will dictate which combination of these modules will be flown, the real-time module will generally precede all of the other modules.

The aircraft must have working lower fuselage and tail radars. The HRD workstation should be on board, so we can ingest, analyze, and transmit radar and GPS sonde data back to TPC/NHC. The SFMR should be operated, to provide estimates of wind speed at the surface. If the IWRAP or C-SCAT is on the aircraft then it should also be operated to provide another estimate of the surface winds. If the NASA SRA is working it also should collect wave and sweep heights to characterize the storm surge and breaking wavefield near the coast.

If some of the portable Doppler radars (SMART-R and/or DOW), portable profilers and portable wind towers are deployed between ~65 and 130 km inland in the onshore flow regime as depicted in Fig. LF_1, this will provide valuable data for the inland decay model. If possible, one of the DOWs should be positioned relative to the nearest WSR-88D such that the dual-Doppler lobes cover the largest area of onshore flow possible. In the schematic shown in Fig. LF_1, one of the DOWs is positioned north-west of the Melbourne WSR-88D so that one dual-Doppler lobe is over the coastal waters and the other covers the inland region. The profiler is positioned in the inland dual-Doppler lobe to provide independent observations of the boundary layer to anchor the dual-Doppler analysis.

All of the modules support real-time and post-storm surface wind analyses. The flight patterns will depend on the location and strength of the storm relative to surface observing platforms and coastal radars. The first two modules could be easily incorporated into a tasked operational mission. The other three modules are more suited to research missions, where the patterns are not constrained by fix or gale force wind radii requirements.

Real-time module:
The real-time module combines passes over marine surface platforms with one or more figure four patterns in the core of the hurricane (Fig. LF_1.) 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. Note that if the storm is outside of WSR-88D Doppler range then the figure-4 pattern could be repeated before returning home.

The landfall flight pattern should take advantage of buoys or C-MAN sites nearby, if those platforms are expected to experience winds > 25 m/s. The aircraft descends at the initial point and begins a low-level figure-4 pattern, possibly modifying the legs to fly over the buoys (Fig. LF_1). The radar will be in F/AST mode. If time permits the aircraft would make one more pass through the eye and then fly the dual-Doppler option. In this example, the pattern would be completed in about 2.5 h. GPS-sondes would be dropped near the buoys or C-MAN sites, and additional sondes will be dropped at or just inside the flight level radius of maximum winds (RMW).

Note that the optimal volume scans for this pattern will be obtained when the storm is 32-80 nm (60-150 km) from the radar, because beyond 80 nm (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 nm (60 km) the volume scan will be incomplete, because the WSR-88D does not scan above 19.5 deg. It is essential that these passes be flown as straight as possible, because turns to fix the eye will degrade the Doppler radar coverage.

Coastal Survey module:

When the hurricane is making landfall, this module will provide information about the boundary layer in the onshore and offshore flow regimes. FigureLF_2 shows an example for a hurricane making landfall near Melbourne, Florida. On the first coastal pass the WP-3D would fly parallel 10-15 km offshore to obtain SFMR surface winds (1-2 in Fig. LF_2). The track should be adjusted so that the SFMR footprint is out of the surf zone. The second pass should as close to the coast as safety permits, to sample the boundary layer transitions at the coast in onshore and offshore flow (3-4 in Fig. LF_2). The first pass should be at 5,000 ft (1.5 km) or less, and the aircraft could climb to higher altitudes for the second pass. On both of these passes the aircraft should fly to 150 km or the radius of gale-force winds and drop GPS-sondes at the RMW and at intervals of 12.5, 25, 50, 75 and 100 or 125 km on either side of the storm track, to sample both onshore and offshore flow regimes. Finally, to better sample the adjustment of the off shore flow from land to ocean a short leg would be flown from the coast spiraling towards the storm center. 3-4 sondes would be dropped quite near the coast, followed by 3-4 sondes spaced every 20-30 km along the trajectory. The Doppler radar will 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 ~2 h.

SFMR Evaluation Module:

This module is similar to the Coastal Survey module, except that it concentrates on the region with hurricane force winds and is designed to collect data to evaluate the performance of the SFMR in varying ocean conditions near landfall where strong oceanic currents (like the Gulf Stream) and shallower bathymetry could cause changes to the breaking wave field that would cause changes in microwave emissions, besides those changes that correlate directly to windspeed. As shown in Fig. LF_3, the aircraft would fly a leg toward the coast, preferably at 1200' above MSL, to gather high resolution SRA data to define the wave field. A sequence of combined AXBT and GPS sonde drops will map out the thermodynamic and boundary layer windspeeds. This leg is followed by a run along the coast to the maximum offshore flow, where the plane turns and flies offshore, dropping a further sequence of AXBTs and sondes. The final leg of the pattern, in this example, is parallel to the Gulf Stream back to the onshore flow region. From here the module could be repeated or the aircraft could execute the next module.

Onshore Wind Profile Evaluation Module:

In this module, the aircraft will collect vertical profiles of windspeed in various near shore environments to test the hypothesis that near the coast surface windspeeds may be lower than the operational flight level wind reduction would suggest. Data collected will help evaluate various effects. For example, roughness lengths may change, especially in higher wind speeds. The boundary layer changes at the coast; sonde data will help indicate whether there are similar changes from open ocean to coastal waters.

To evaluate the adjustment of winds from normal reconnaissance altitude to the surface in near-shore conditions, the aircraft should fly this module at 700 mb (10000', ~3000 m). The aircraft follows the flow to the coast (Fig. LF_4), deploying GPS sondes every 5-10 nmi. Then the aircraft turns and flies into the center of the storm, back off shore, and then upwind to a point to start a new onshore profile, where each sequence of sondes is closer to the radius of maximum winds. The last sequence could be along the inside edge of the eye wall. To maintain good SFMR, tail Doppler radar, SRA and IWRAP data collection, the onshore flow segments should be flown in short straight segments with quick turns rather than smooth curves.

Post Landfall Module:
This module is designed to collect kinematic and thermodynamic data ~1-2 h prior to and up to 6 h after a hurricane makes landfall. It is essential that ground based measurements are obtained in conjunction with those that are being made by aircraft, since the primary goal of this module is to determine the kinematic and thermodynamic changes that occur after a hurricane makes landfall throughout the depth of the lower troposphere.

The WP-3D will fly a coastal survey pattern followed by a figure-4 pattern (Fig. LF_5) over land with leg lengths ~150 km at an altitude of ~15,000 ft (5 km). The WP-3D tail radar should be in F/AST mode. These data will aid in rainfall estimation and will help document the changes in vortex and rain band structure over land that are crucial to understanding the environment that supports tornado and mesovortex development.

Over land, available portable wind towers, mesonet stations, profilers and DOW radars should be deployed along the path of the landfalling hurricane to identify the changes in storm structure as the hurricane moves inland. The wind towers and mesonet stations will obtain high-resolution surface wind, temperature, pressure, relative humidity, and perhaps rainfall measurements. If available, a profiler could be placed at the center of each line of mesonet stations. The profilers and RASS sounder will provide wind and temperature measurements within the lowest 3 and 1 km, respectively. Rain gauges should be located at each profiler and DOW radar site to obtain high-resolution rainfall measurements, both for calibrating the radar rainfall algorithms and for documentation of storm rainfall.

The first set of towers and mesonet stations should be placed as close as possible to the coastline (<10 km) to enable accurate documentation of the surface wind field just after landfall. Other towers or mesonet stations should be placed ~65 and 135 km inland respectively; however, these distances will vary depending upon the intensity and speed of motion of the landfalling storm as well as safety considerations. Fig. LF_6 shows the estimated time after landfall that is required for the TC winds to decay to various wind threshold levels as determined using the Kaplan/DeMaria inland decay model. The spacing between the mesonet stations located within each group should be ~30 nm (50 km) perpendicular to the track to maximize the likelihood that one of the mesonet stations will be located near the radius of maximum wind of the landfalling storm.

If the inland profilers are mobile, it will be possible to follow severe weather producing rainbands if safety and logistical considerations allow. The DOW Doppler radars should be placed roughly halfway between the two rear lines of mesonet and profiler stations. The DOW radars in combination with the profilers with RASS will aid in documenting the changes in kinematic and thermodynamic structure of the hurricane after landfall. An accurate analysis of such changes is crucial to learning more about the development of mesovortices and/or tornadoes spawned by landfalling hurricanes. They will also help document the changes in winds within the PBL of a landfalling hurricane. Finally, the radars will aid in the measurement of the rainfall associated with the landfalling hurricane.

TROPICAL CYCLONE LANDFALL WINDFIELDS EXPERIMENT

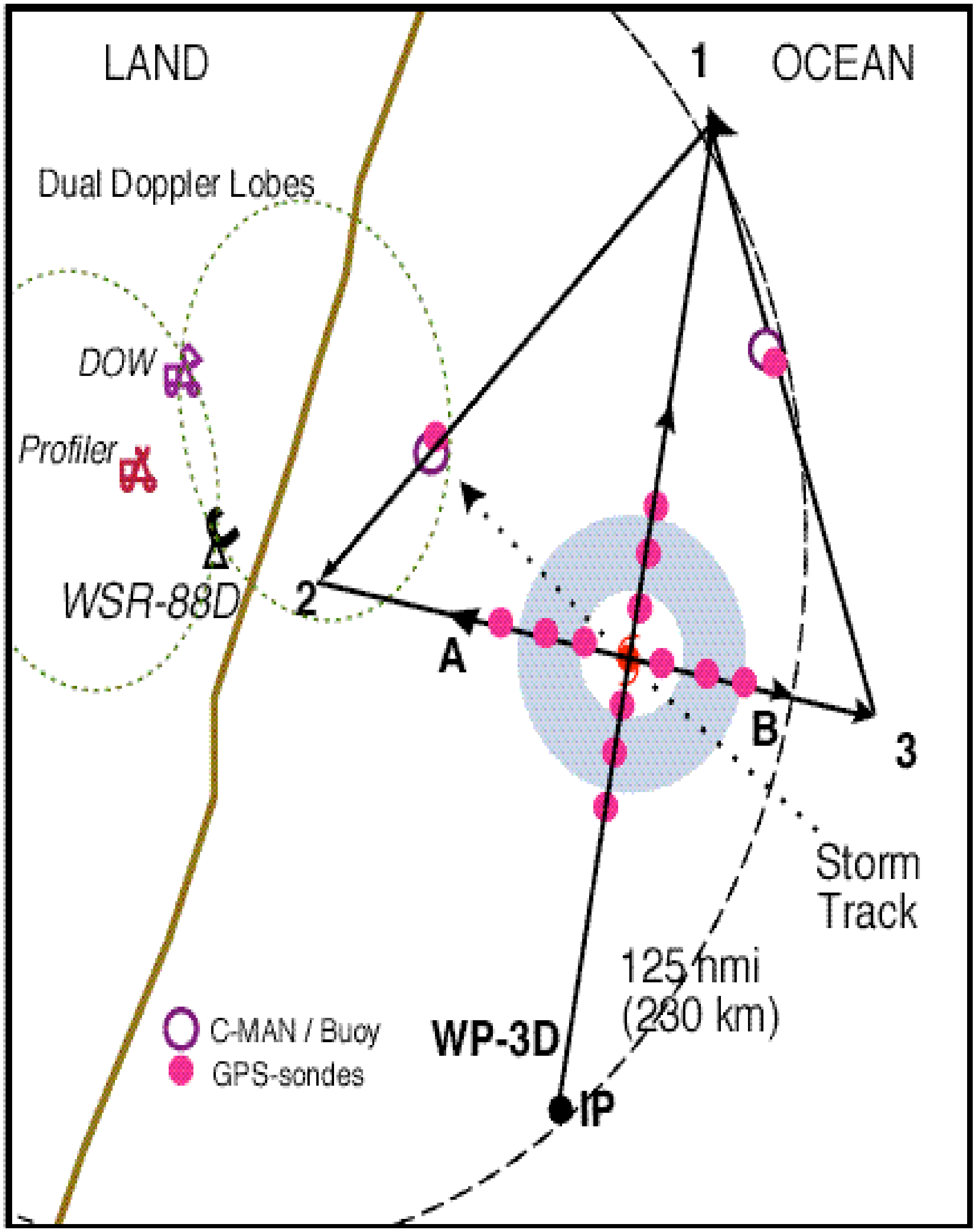


Figure LF_1. Real-time module

True airspeed calibration required. 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 nm (185 km) from the storm center. Downwind legs may be adjusted to pass over buoys.

WP-3D should fly legs along the WSR-88D radials.

Set airborne Doppler radar to F/AST scanning on all legs. Aircraft should avoid penetration of intense reflectivity regions (particularly those over land).

Wind center penetrations are optional

TROPICAL CYCLONE LANDFALL WINDFIELDS EXPERIMENT

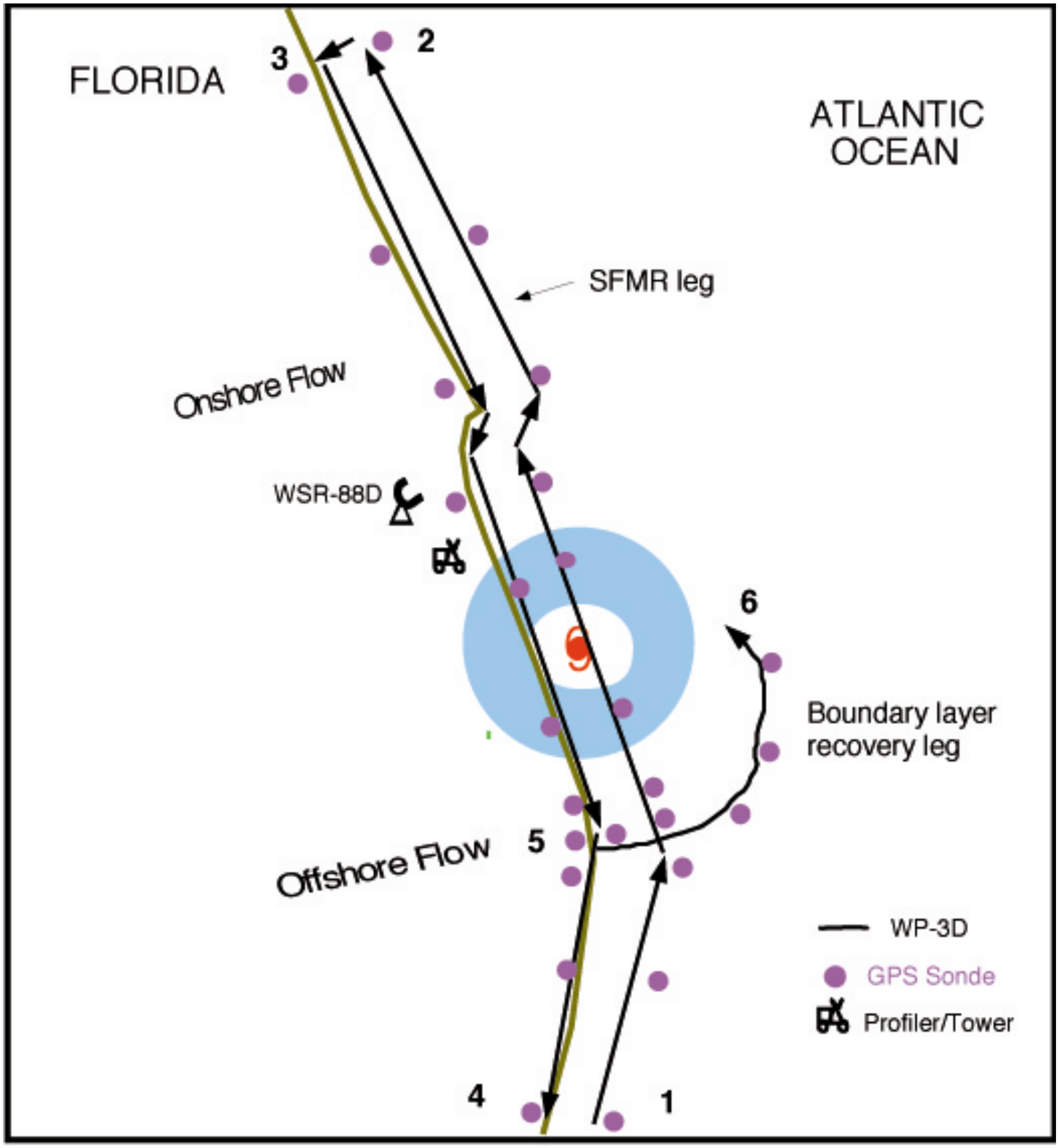


Figure LF_2 Coastal Survey pattern.
.First pass starts 150 km from center or radius of gale-force winds, whichever is closer. Pass from **1-2** should be 10-15 km offshore for optimum SFMR measurements. Drop sondes at RMW, and 12.5, 25, 50, 75 and 100 or 125 km from RMW on ether side of storm in legs **1-2** and **3-4**. Sondes should be deployed quickly at start of leg **5-6**, and then every 10-15 km hereafter.
Set airborne Doppler to scan in F/AST scanning on all legs, with single PRF > 2400 and 20% tilt. Aircraft should avoid penetration of intense reflectivity regions (particularly those over land).

TROPICAL CYCLONE LANDFALL WINDFIELDS EXPERIMENT

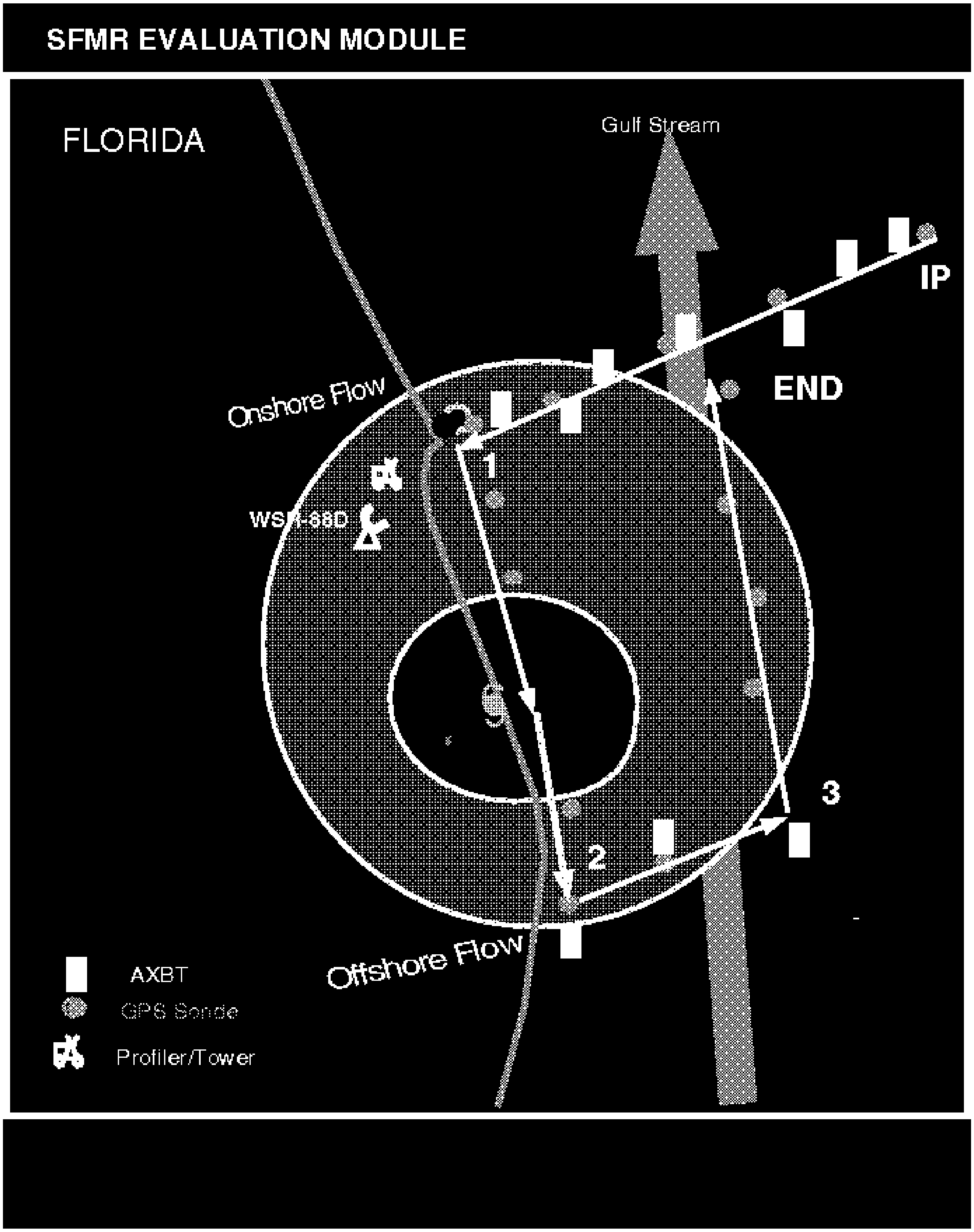


Figure LF_3. SFMR Evaluation Module.
Gray area encloses hurricane inner core with winds > hurricane force.
True airspeed calibration is required. The legs are at 1500-3000 ft (500 - 1000 m) altitude.
Set airborne Doppler radar to F/AST mode at a single PRF 2400 and 20° tilt on all legs.
Aircraft should avoid penetration of intense reflectivity regions (particularly those over land).
Wind center penetrations are optional.

TROPICAL CYCLONE LANDFALL WINDFIELDS EXPERIMENT

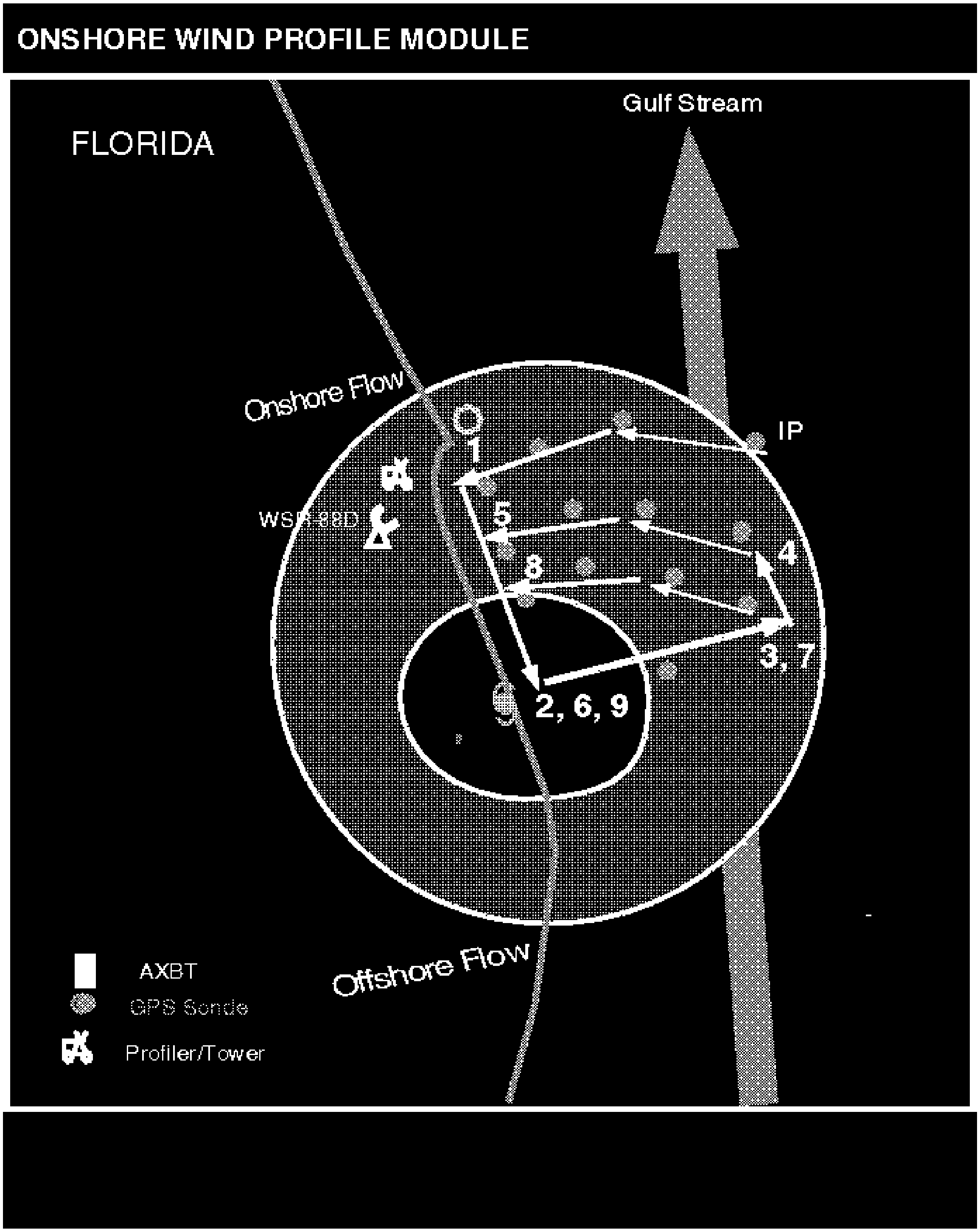


Figure LF_4. Coastal Windspeed Profile Evaluation Module.

True airspeed calibration is required. The legs are at 700 mb (10000 ft, 3000 m) altitude.
Set airborne Doppler radar to F/AST mode at a single PRF 2400 and 20° tilt on all legs.
Aircraft should avoid penetration of intense reflectivity regions (particularly those over land).
Wind center penetrations are optional.

TROPICAL CYCLONE LANDFALL WINDFIELDS EXPERIMENT

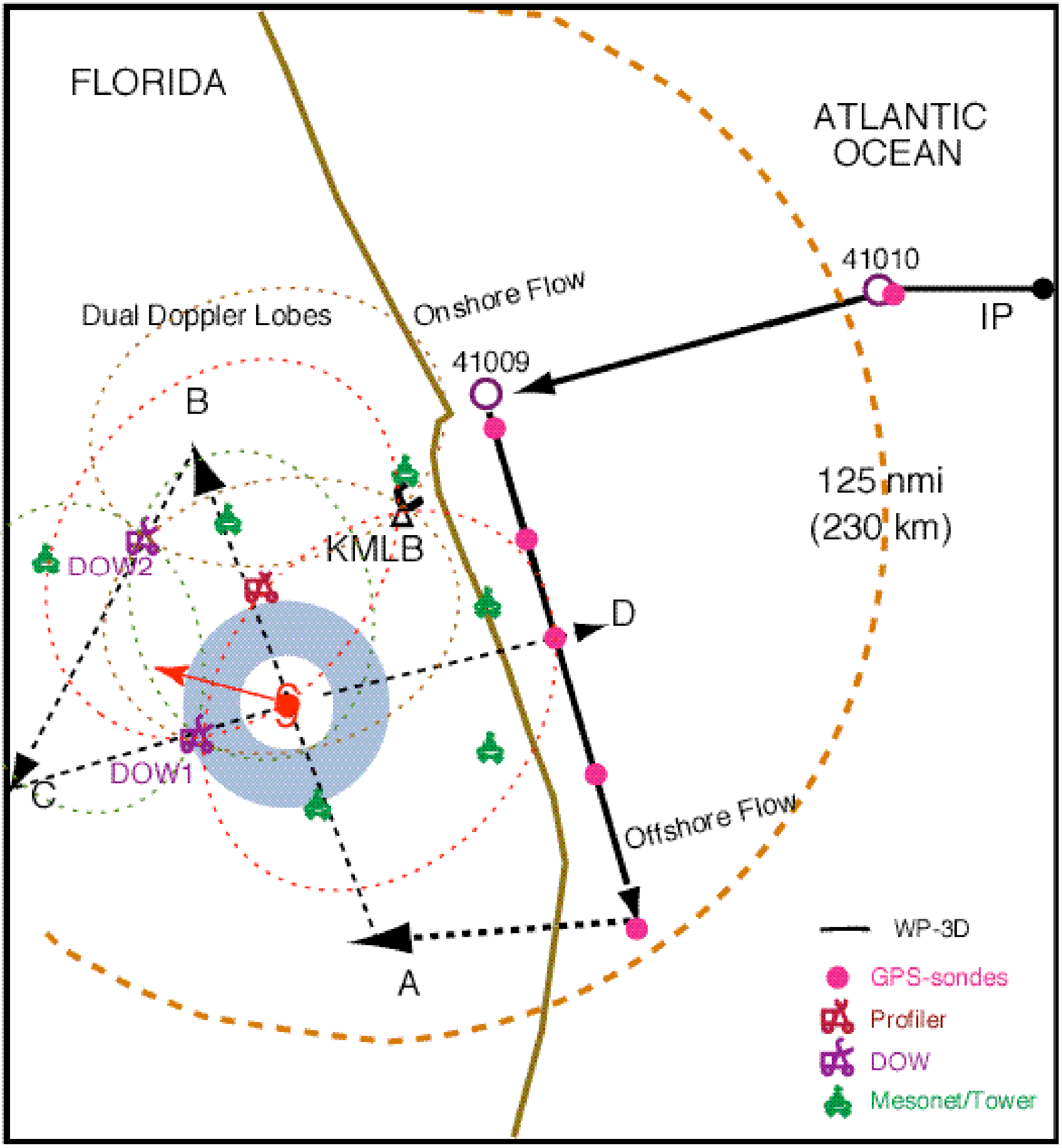


Figure LF_5. Post landfall module flight pattern.

Coastal survey pattern (sold line) at an altitude of ~10,000-15,000 ft (3-4 km) dropping GPS sondes near buoys of opportunity and within 10-20 km of the shore in both the onshore and offshore flow

Inland figure-4 pattern (dashed line) centered on the storm with leg lengths of ~80 nm (150 km) at an altitude of ~15,000 ft (5 km).

WP-3D should fly legs along the WSR-88D radials.

Set airborne Doppler radar to F/AST scanning on all legs.

Aircraft should avoid penetration of intense reflectivity regions (particularly those over land).

Wind center penetrations are optional.

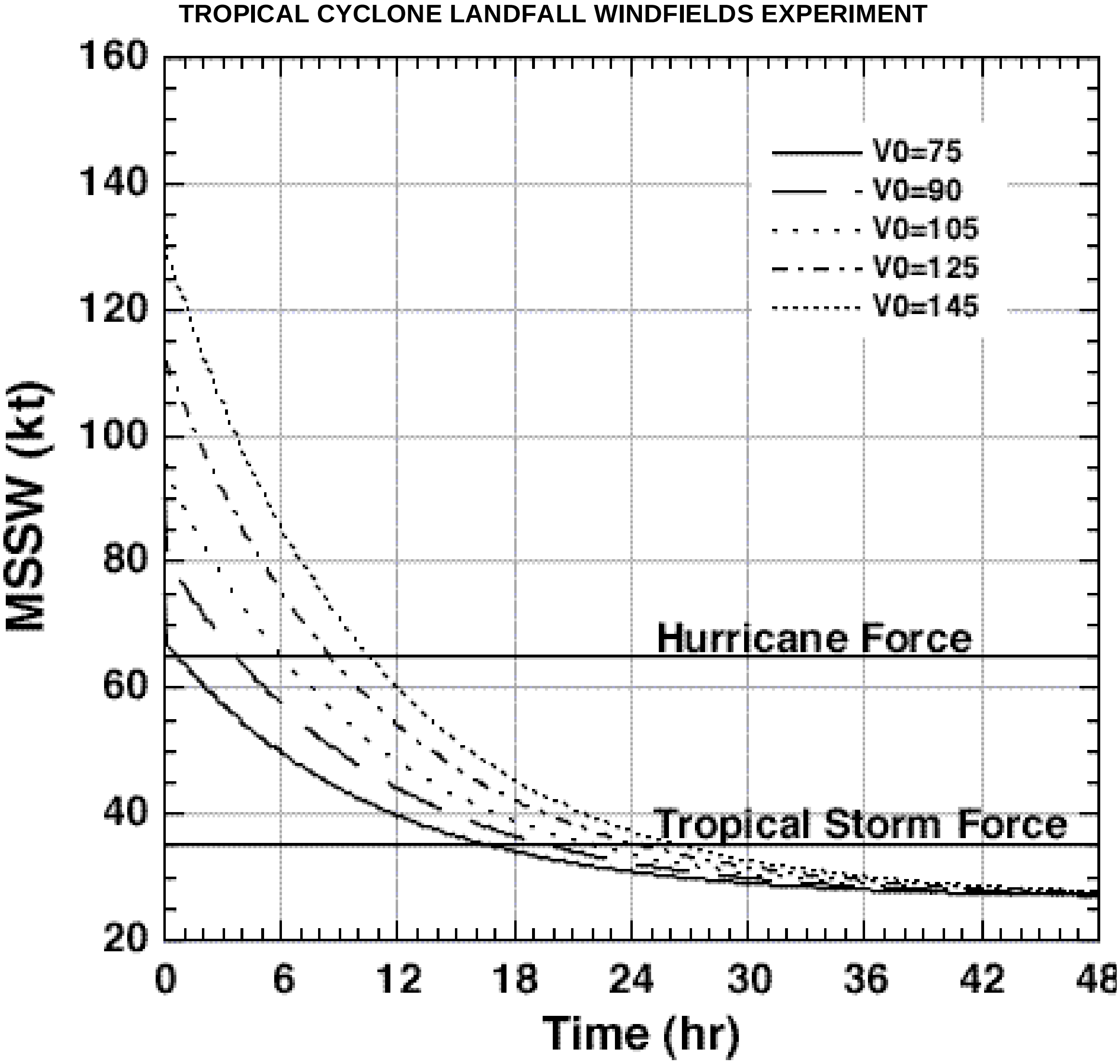


Figure LF_6. Maximum sustained surface winds (MSSW) after landfall estimated using the Kaplan/DeMaria (1995) inland decay model for TCs with landfall intensities (V0) of 75, 90,105,120, and 145 kt.

IFEX MISSIONS (CONT'D)

3. Aerosonde Tropical Cyclone Inflow Experiment

Hurricanes and tropical storms cause many deaths and average billions of dollars in damages each year. More than 1000 lives were lost in Hurricane Katrina (2005) alone, and the financial impact on the U.S. economy has already exceeded $200 Billion. Improved forecasts and warnings also reduce the costs inherent in responding to the hurricane threat. The devastating impacts of Hurricanes like Katrina or Wilma (2005) require that we make the best possible and most authoritative information available to decision-makers to help them determine whether to implement mandatory evacuations and other costly actions for approaching hurricanes.

NOAA is working with its international and domestic partners to cost-effectively increase the number, breadth, accuracy, and availability of observation systems. As part of this effort, NOAA is investing in new technologies, such as Unmanned Aircraft Systems (UAS) in order to improve the accuracy and timeliness of our Nation's existing weather observation and forecast system. This experiment plans to demonstrate the capabilities of the versatile Aerosonde UAS within the context of low-level hurricane reconnaissance. It will also build upon recent NOAA UAS success (Ophelia 2005) and directly tie into one of the GoM CI major themes (Coastal Hazards).

Ultimately, the value of this proposed work will be measured in lives saved and money not spent from improved understanding, forecasts and preparation. Specific benefits that directly link to NOAA's stated strategies within the Weather and Water mission goal include detailed documentation of the rarely-observed hurricane boundary layer environment (*Monitor and Observe*), an improved physical understanding of this critically important region (*Understand and Describe*), and enhanced observations that directly lead to improved future forecasts of tropical cyclone intensity change (*Assess and Predict*).

The Aerosonde UAS

The Aerosonde UAS is fully summarized in Holland et al (2000). It has been undertaking civilian operations since 1995, was the first UAV to cross the Atlantic Ocean and has an impressive endurance record of over 32 hrs. It has a sophisticated command and control system and the flexibility to be deployed and commanded from virtually any location. Initially developed for meteorological and environmental applications in remote and dangerous conditions, the Aerosonde has been specifically designed for all-weather operations under harsh conditions and is well suited to the hurricane reconnaissance role. The aircraft has evolved through to the current Mark 4 version and its relevant specifications are provided in Table 1.

Table 1. Specifications of Mark 3 Aerosonde UAV

Specifications	
Weight, wing span	26-30 lb, 10 ft
Engine	24 cc, Fuel Injected engine using unleaded petrol
Navigation	GPS
Operation	
Staff for Launch and Recovery	3 staff: Controller, Engineer, Pilot/Maintenance
Ground Equipment	Proprietary Staging Box, Personal Computer, GPS, Radio Antennae and Iridium Satellite modem
Flight	Fully autonomous, under Base Command
Launch and Recovery	Launch from car roof rack, or catapult, land on belly. Able to operate from remote and unprepared surfaces
Ground & air communications	UHF or Satcoms to Aerosonde, VHF to field staff and other aircraft, internet or phone to command center and users.
Performance	
Speed, Climb	Speed 35-80 kt, Climb 3 m/s at sea level
Endurance, Range	20 to >30 h, up to 3000 km (depending on payload weight and configuration)

Aerosonde Payload

A range of payloads are operational or under development for the Aerosonde. Those that are relevant to the hurricane boundary layer mission are listed in Table 2

Table 2. Operational Aerosonde instruments of relevance to boundary layer monitoring.

Measurement	**Instrument**	**Manufacturer**	**Technical**	**Comments**
Air temp, press., hum.	Vaisala RSS901 sensor	Vaisala	P<.5 hPa, T<.2K, RH<2% 0.1 hz standard, capable of 1 hertz	Standard met observations
Winds	Proprietary	AeNA	u,v < .5 m/s	Standard met observations
Surface temperature	IR KT11	Heitronics	SST < 0.5K	Surface ocean and land temperatures.
	IR KT15	Heitronics	SST < 0.5K	
Liquid water content and ice crystal concentration	Heymsfield VIPS	NCAR	Video recording of impacts on oiled plastic	Cloud physics and potential spray/ salt distributions
Sea state, ocean surface winds, soil moisture	GPS reflectance	NASA	<10 m resolution. Accuracy unknown	Detailed observations of surface conditions
Surface visible imaging	Digital still camera Olympus 5050	Olympus	5 megapixel 3x Optical zoom	High resolution surface imaging
Surface visible imaging	Sony 555 Video camera, fixed mount	Sony		Video of surface conditions
Infrared imaging	Indigo Omega camera	Indigo Systems	8-12 micron IR imaging	IR surface imagery

Aerosonde Launch, Command and Control

Aerosonde command and control is accomplished by:

- UHF command for LOS up to 120 miles, which may be back to a launch site or can be transferred to a mobile or other site as required;
- Iridium Satcom for OH command to any location on earth.

The required equipment is a lap top computer, a small staging box (briefcase size) and relevant antennae. AeNA has often operated from a vehicle and has transferred control to ships and other sites under operational conditions. All Aerosonde commanders and technicians are fully qualified under Australian Civil Air Operator Certificate Number VT585156-U-01, issued to Aerosonde on 30 May 2003. This is the only current Aviation Authority Certification in the world.

Use of the Aerosonde UAS for Hurricane Reconnaissance

While recent composite analyses from Cione et al (2000) and Cione and Uhlhorn (2003) have led to new insights regarding structural details of the hurricane air-sea interface, sustained and comprehensive observations of the thermodynamic (temperature and moisture) and kinematic (wind) structure of the near-surface hurricane environment have never been undertaken. Yet this environment, where the atmosphere meets the sea, is critically important:

- This is where the critical oceanic energy supply is transferred to the atmosphere
- Here we find the strongest winds in a hurricane and especially those that are most critical for forecasts and warnings

Improved observations in this region will lead to better understanding, and improved capacity for forecasting tropical cyclone intensity change. A major uncertainty in forecasting landfall intensity is the potential for rapid intensification or decay in the critical 24 h period when major response decisions have been already made. Enhancing this predictive capability would save our economy billions of dollars and help reduce the risk of death and injury for vulnerable populations

Successful utilization of the WP-3D Orion and Gulfstream IV-SP aircraft have made NOAA a global leader in the area of hurricane aircraft surveillance and reconnaissance. However, the danger of near-surface operations in the extreme hurricane conditions has precluded comprehensive monitoring of this critical region. Satellites are also unable to monitor this region, so we are currently left with scattered local observations from dropsondes. We propose to use the unique low-flying capacity of the Aerosonde UAS platform to address this significant observational shortcoming. The Aerosonde is capable of flying at altitudes of 500 feet or less within the high-wind hurricane eyewall environment. This is thousands of feet lower than any manned aircraft is able to operate.

We consider that the payoff for using the Aerosonde platform within the hurricane environment would be both significant and immediate. The benefits would include detailed documentation of a heretofore poorly observed region of the tropical cyclone (*Monitor and Observe*) together with providing real-time, high-resolution, low-level wind observations of the hurricane maximum winds in support of NOAA's Tropical Prediction Center's (TPC) forecasting requirements (*Assess and Predict*). In addition, the low flying Aerosonde would greatly enhance our physical understanding of the rarely observed hurricane air-sea interface (*Understand and Describe*). Ultimately, this will lead to improved forecasts of tropical cyclone intensity change by enhancing today's boundary layer parameterization schemes and providing invaluable initialization and verification data sets for numerical models (*Assess and Predict*). The data also will provide ground truth for aircraft and satellite derived remote measurements.

These observations and related benefits can be obtained at a cost that is quite low by normal hurricane reconnaissance costing standards.

The potential importance of this UAS role in hurricane reconnaissance is emphasized by the findings of the Hurricane Intensity Research Working Group established by the NOAA Science Advisory Board. There preliminary recommendation, presented to the last meeting of the SAB, is that:

"Low and Slow" Unmanned Aircraft Systems (UAS) have demonstrated a capacity to operate in hurricane conditions last season. A full demonstration program should be instituted in 2006 to assess their ability to provide low altitude in situ observations in a critical region where manned aircraft satellite observations are lacking.

Links to IFEX: This experiment supports the following NOAA IFEX goals:

- **Goal 1**: Collect observations that span the TC lifecycle in a variety of environments;
- **Goal 2**: Develop and refine measurement technologies that provide improved real-time monitoring of TC intensity, structure, and environment;
- **Goal 3**: Improve our understanding of the physical processes important in intensity change for a TC at all stages of its lifecycle;

Summary of Relevant Prior Research and Results

On September 16th 2005, NOAA, NASA and Aerosonde partners successfully flew into tropical storm Ophelia. This landmark event marked the first time an autonomous vehicle was flown into the core of a mature tropical system (see http://www.noaanews.noaa.gov/stories2005/s2508.htm and http://www.magazine.noaa.gov/stories/mag193.htm). At the time, Ophelia was a 55kt tropical storm and was located off the North Carolina coastline (Figure 1). Winds were reported in near-real time to NOAA's National Hurricane Center and directly impacted NHC operational forecasts for the tropical system at that time.

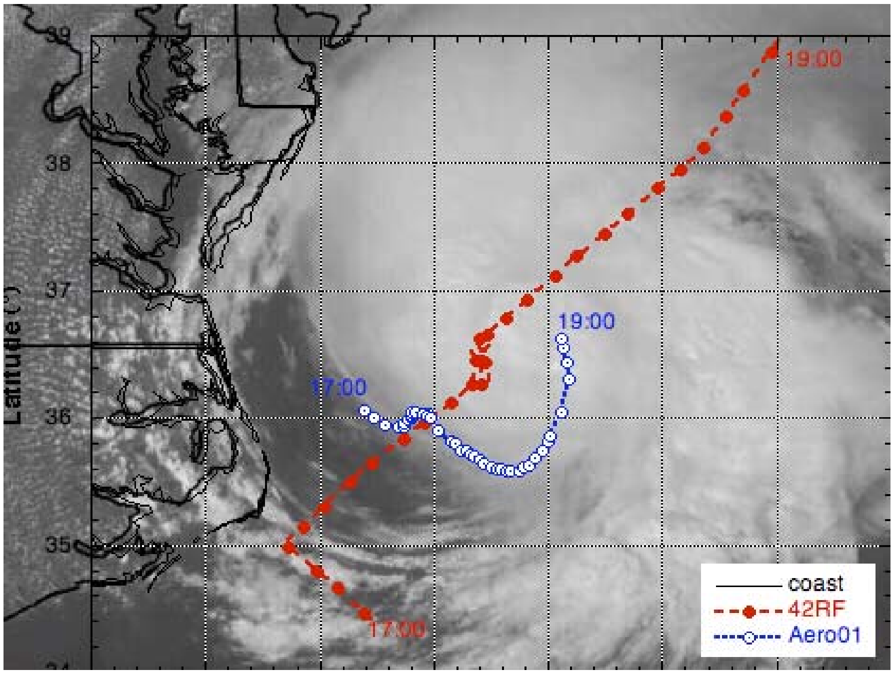


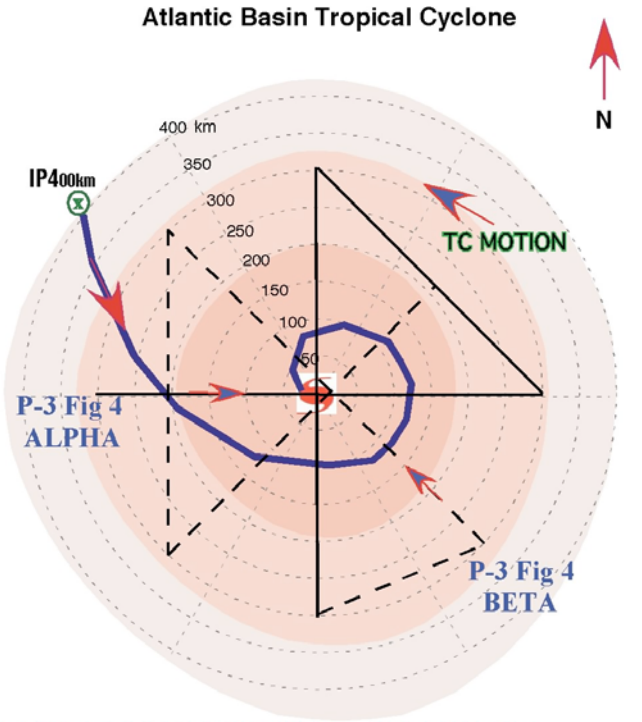
Fig. 1: *Aerosonde (blue) and WP-3D (red) flight tracks into tropical storm Ophelia on September 16th 2005. This mission marked the* ***first-ever successful unmanned flight*** *into a tropical cyclone. Storm intensity at the time was 55kts.*

This experiment is designed to build on the success and strong momentum attained in 2005. Using the experience gained from the Ophelia mission, it is believed that the time is right for a focused and concerted effort to fly additional missions into stronger storms (hurricanes) at lower altitudes. We also feel that we can build upon recent operational success and continue to transmit critical data to NOAA's operational centers (NHC and EMC) that might otherwise go un-sampled. With additional support, significant improvements to data quality, quantity, resolution and transmission efficiency are all possible in the very near future. It is also believed that the scientific insights and benefits gained by conducting additional low-level Aerosonde missions into the rarely observed, yet critically important hurricane boundary layer environment are potentially very significant.

Mission Description

The primary objective of this experiment is fully demonstrate and utilize the unique capabilities of the Aerosonde platform to document areas of the tropical cyclone environment that would otherwise be either impossible or impractical to observe. It is planned that this effort will be based somewhere on the east coast of the Florida peninsula or possible within the Florida Keys. The immediate focus of this experiment is to document and significantly improve our understanding of the rarely-observed tropical cyclone boundary layer and undertake detailed comparisons between in-situ and remote-sensing observations obtained from manned aircraft (NOAA WP-3D and AFRES C-130) and satellite based platforms. In addition, a primary objective of this effort is to provide real-time, near-surface wind observations to the National Hurricane Center in direct support of NOAA operational requirements. These unique data will also be made available to EMC for both data initialization and forecast verification purposes.

The NOAA WP-3D (flying initially at 5000ft) GPS dropwindsonde and AXBT drop points will be regularly spaced (see notes below). Only mature tropical systems positioned offshore the SE US coast that are of at least tropical storm intensity would be considered viable candidates for this mission. When possible, Aerosonde Tropical Cyclone Inflow Experiment missions will be coordinated with the TC Landfall and Inland Decay Experiment. This coordination will involve the WP-3D and be executed on a case-by-case basis.



TC AEROSONDE INFLOW EXPERIMENT
Estimated Aerosonde Flight Time: 16-22h
Aerosonde avg Airspeed: 25ms (expect add'l speed from TC inflow - Vr)
Inflow Ange Assumed: 20 deg
TC Init Intensity Range: TS - Cat 5
TC Rmax Assumed: 25km
TC motion: Assumed 5m/s at 300 degrees

Fig. 2: TC Inflow Experiment flight tracks for both the AEROSONDE and WP-3D Aircraft.

- Note 1: AEROSONDE Take-off/Recovery: East Coast US (Florida)
- Note 2: Pre-IP: AEROSONDE-Coastal Buoy/C-Man 150m comparisons (SST,Ta,Td,P,V)
- Note 3: AEROSONDE IP: 400km from TC center (Initial IP flight level: 750m)
- Note 4: AEROSONDE Descend to 150m (IR SST retrieval). Remain at 150m until 350km. At 350km, ascend to 700m, remain at 700m until 300km
- Note 5: AEROSONDE Descend to 150m, remain at 150m until 250km. At 250km, ascend to 700m, and remain at 700m until 200km.
- Note 6: **When the AEROSONDE is ~200km from the TC center: BEGIN WP-3D Figure 4 ALPHA Pattern.**
- Note 7: WP-3D will fly at 5000 ft and drop co-located AXBT and GPS pairs every 100 km between 300-100km from the center (and every 50km from 0-100km from the TC center). For non-penetration legs, an additional AXBT/GPS drop will be launched at the leg mid-point.
- Note 8: **After completing the ALPHA pattern, the WP-3D will begin pattern BETA by climbing to 10000 ft and repeating the identical drop pattern conducted during the ALPHA pattern. A total of 38 AXBT and GPS expendables are required for this mission.**
- Note 9: Post storm-comparisons with WP-3D Doppler radar winds and SFMR are desired so both instruments will need to be fully functional.
- Note 10: At 250km, AEROSONDE ascend to 700m, and remain at 700m until 200km. From 200-100km, continuous 700m-150m soundings (briefly below 150m if possible)
- Note 11: At 100km, AEROSONDE ascend from 150m to 500m for eyewall penetration (~40-50km from center). In eye, AEROSONDE descend to 100-150m (IR SST retrieval) then corkscrew eye sounding to 3km
- Note 12: AEROSONDE Begin final eyewall penetration at 3km altitude (if no manned aircraft in storm)
- Note 13: **IF AFRES C-130 PRESENT NO EYE SOUNDINGS WILL BE CONDUCTED**
- Note 14: **RETURN TO AEROSONDE BASE OF OPERATIONS**

IFEX MISSIONS (CONT'D)

4. Tropical Cyclogenesis Experiment

Motivation

While forecasts of tropical cyclone track have shown significant improvements in recent years (Aberson 2001), corresponding improvements in forecasts of tropical cyclone intensity have been much slower (DeMaria and Gross 2003). The lack of improvement in intensity forecasting is the result of deficiencies in the numerical models (e.g., resolution limitation and parameterization inadequacies), deficiencies in the observations, and deficiencies in our basic understanding of the physical processes involved. The problem becomes even more acute for forecasting tropical cyclogenesis. While global models have shown some skill in recent years in predicting tropical cyclogenesis, our understanding of the physical processes involved remains limited, largely because observing genesis events is a difficult task. However, a key aspect of the NOAA Intensity Forecasting Experiment (IFEX; Rogers et al. 2006) is the collection of observations during all portions of a tropical cyclone's lifecycle, particularly on the early lifecycle stages. This emphasis on the early stages of the lifecycle will provide an opportunity to observe several genesis events and improve our understanding of this key process, leading to better predictions of tropical cyclogenesis, organization, and intensification.

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 collection of three-dimensional data at all stages in a tropical cyclone's lifecycle is one of the key requirements for NCEP as a part of the IFEX experiment. Such data will provide information that will guide the development of balance assumptions and error covariance matrices important in the development of data assimilation schemes for models (i.e., HWRF) that will be used in these environments. They will also provide important datasets for evaluating the performance of HWRF. 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 and East Pacific. 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.

Background

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. One of the key aspects differentiating these hypotheses centers on whether the lower-tropospheric cyclonic vorticity begins in the mid-levels and develops downward to the surface or begins in the lower troposphere and builds upward to the middle troposphere – the so-called "top-down" vs. "bottom-up" mechanisms. Prominent "top-down" theories include one study which showed observations of multiple midlevel vortices prior to genesis in the West Pacific (Ritchie et al. 1997) that led them 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 by increasing the Rossby-Prandtl-Burger penetration depth of potential vorticity anomalies associated with the vortices. Another study supporting the "top-down" approach showed observations of genesis in the East Pacific (Bister and Emanuel 1997) and hypothesized that downdrafts driven by evaporational cooling advected the vorticity of the midlevel vortex downward, enhancing convection and low-level vorticity production.

The set of hypotheses supporting the "bottom-up" approach generally describes the genesis process as being driven by low-level convergence that increases cyclonic vorticity near the surface through vortex stretching. One such "bottom-up" hypothesis emphasizes the role of a parent midlevel vortex in axisymmetrizing nearby low-level convectively-generated cyclonic vorticity, called vortical hot towers, that leads to the spin-up of the surface circulation (e.g., Montgomery and Enagonio 1998; Davis and Bosart 2001; Montgomery et al 2004). A similar hypothesis was advanced by Rogers and Fritsch (2001) and Chen and Frank (1993) who emphasized the role of the midlevel vortex and high midlevel humidity 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. Another set of theories focuses on the reduction of the lower tropospheric effective static stability to low values in the core of incipient cyclones. Suppression of convectively-induced downdrafts is one means of accomplishing this (Emanuel 1995; Raymond, Lopez, and Lopez 1998). Eliminating low-level outflows produced by the downdrafts allows the inflow of updraft air to spin up the low-level circulation, leading to the development of the warm-core characteristic of the tropical cyclone.

Objectives

With the above background in mind, the objectives of this experiment are defined as follows:

1. Test prevailing hypotheses relating to top-down vs. bottom-up development

   This objective will be addressed by documenting the development of low-level vorticity in the presence of a midlevel vortex center, and vice versa. It will also be addressed by documenting the interactions between low- and mid-level vortices in pre-genesis environments.

2. Document aspects of mesoscale and synoptic-scale environment of incipient disturbances to identify characteristics necessary in genesis

   Key tasks in addressing this objective involve assessing the importance of pre-existing vorticity and broad areas of high humidity and determining the importance of their spatial and temporal distribution in tropical cyclogenesis. Another important question to address is the role, if any, that a midlevel vortex plays in governing the distribution and magnitude of deep convection, and to determine the importance of downdraft suppression in limiting boundary layer stabilization. A final task is to examine hypotheses relating humidity and static stability profiles to downdraft morphology and the vortex response to convective heating.

Links to IFEX: This experiment supports the following NOAA IFEX goals:

- **Goal 1**: Collect observations that span the TC lifecycle in a variety of environments;
- **Goal 3**: Improve our understanding of the physical processes important in intensity change for a TC at all stages of its lifecycle;

Experiment Description

The physical processes that are important in tropical cyclogenesis span a wide spectrum of temporal and spatial scales, with time scales ranging from minutes to days and space scales ranging from mm to hundreds of km. Furthermore, many of the processes are highly nonlinear and transient. For these reasons, an experimental approach that combines observations and numerical modeling is required to adequately address the questions posed above. When possible, GenEx missions will be coordinated with the HRD Saharan Air Layer Experiment (SALEX). This coordination will involve the WP-3D and/or G-IV and be executed on a case-by-case basis.

Observational component

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 in 1996 (Reasor et al. 2005) 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 these vortices, it is vital that they be sampled in their entirety (which will invariably depend on the distribution of precipitation scatterers) and with a temporal resolution that allows time continuity of the vortices to be established when possible.

In addition to the wind and rainfall measurements provided by the Doppler radars, measurements of temperature and moisture are vital to address the thermodynamic issues described above. Dropsondes released in a regular grid will enable the determination of thermodynamic fields in the vicinity of the incipient system, as well as enable the calculation of mean divergence and vorticity fields around the system, important in determining the strength and depth of the downdrafts (provided time aliasing is minimized). The dropsondes should be released from as high an altitude as possible to provide observations of mid-level humidity and winds where scatterers are not present. The tail radars on the WP-3D's will also enable a determination of the presence of saturation when scatterers are observed.

This experiment may be executed with the NOAA WP-3D alone, but optimally it will involve the participation of the NOAA G-IV aircraft as well. Flights will occur into incipient tropical disturbances over the western Caribbean Sea, Gulf of Mexico, and tropical Atlantic Ocean. For these missions the WP-3D will be based primarily in Barbados, though operations can also occur from St. Croix and Tampa. The systems flown here will primarily be incipient systems. If a system undergoes genesis and continues to develop, however, the WP-3D's will continue to fly the system using flight patterns from the Frequent-Monitoring Experiment (in this Field Program Plan).

The primary mission will require the WP-3D flying back-to-back missions. It will fly mesoscale survey patterns designed to document any suspected low- and mid-level vortices and sample any changes in the low- and mid-level thermodynamic fields associated with the incipient systems. 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 midnight (12 AM) local and again on station at noon (12 PM) local. If it is not possible to fly the WP-3D at 12-h staggering, then 24-h staggering will be performed. If available, the G-IV aircraft would fly simultaneously at upper levels (42,000 ft or 175 hPa) and collect observations to a distance of ~1500 km from the center of the disturbance. This G-IV mission would only occur if operations happened in the tropical Atlantic or Western Caribbean and there were indications of mid- or low-level dry air in the vicinity of the disturbance.

The main aircraft for the mesoscale flights will be the WP-3D. 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. Primary aspects of this experiment will be to observe the complete life cycle and interaction of low- and mid-level vortices, understand how these vortices are influenced by the diurnal cycle of convection, and observe the evolution of the thermodynamic fields as the incipient system evolves. The location of persistent areas of deep convection and candidate vortices will be determined using high-resolution visible and infrared GOES-winds produced available online, supplemented by NASA TRMM imagery when available. Additionally, favorable 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, also available online.

Staggered missions with the WP-3D aircraft will begin with the aircraft flying one of two survey patterns at 14,000 ft (4 km). The primary purpose of these patterns will be to collect F/AST Doppler radar and GPS dropsonde 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. Two possible patterns can be flown, with the decision of which pattern determined by the degree of organization of the system. For incipient systems that are relatively disorganized, a sawtooth pattern is flown (Fig. 1) along the axis of an easterly wave. Leg lengths will be 150-200 nmi (250-300 km), with some variability dependent on the size of the system and the time available on station. The pattern will be centered approximately on any discernible circulation, if identifiable, or on a dominant area of convective activity. After the circulation center or convective area is passed, the sawtooth pattern is mirrored and the aircraft completes a return trip, creating a series of diamond shapes to complete the pattern. This return trip will provide some greater temporal continuity to the observations.

As a system becomes better organized, a second survey pattern is flown (Fig. 2), consisting of a square-spiral configuration centered on a broad low- or mid-level circulation center. If multiple mesoscale convective systems exist embedded within a parent circulation, the pattern will be centered on the parent circulation. Dropsondes are released at regular intervals to create a near uniform grid covering the circulation and including any MCS's, if possible. The spacing between the outer spiral and the inner box pattern is nominally set for 60 nm (111 km), but it can be varied to ensure optimal representation of the convective and mesoscale features.

Once a persistent low-level vortex is identified, subsequent missions will fly a pattern centered on the vortex. This pattern will be a rotating figure-4 pattern (Fig. 3). Flight legs for the figure-4 pattern will be 60-120 nm (111-225 km) to allow for the collection of data with high temporal and spatial resolution in the vicinity of the vortex center. The length of these flight legs is designed to completely include the low-level vortex and convection associated with it. Depending on the leg lengths and the time available on station, the pattern may consist of higher azimuthal resolution. The tail radar will operate in F/AST mode during the entirety of these patterns. For the WP-3D using the NOAA antenna, the tail radar will operate in continuous mode during the Microphysics Module.

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 dropsondes in the pre-genesis and incipient tropical disturbance environment. The most likely scenario calls for the G-IV to fly a Saharan Air Layer Experiment (SALEX) pattern as the system is interacting with a Saharan Air Layer (Fig. 4).

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 (Optimal experiment):**

The NOAA WP-3D aircraft will fly in the tropical Atlantic, Gulf of Mexico, or western Caribbean basins, either diamond or square-spiral survey patterns to locate low- and mid-level vortices (Figs. 1 or 2). These flights will be flown in coordination with the G-IV aircraft, providing synoptic-scale measurements of upper- and lower-tropospheric observations around the incipient disturbance. Once a persistent mid-level vortex is located, the WP-3D will fly either rotating figure-4 (Fig. 3) or square-spiral patterns.

- **Option 2 (Lesser experiment):**

Option 1 but with only the WP-3D aircraft.

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

(1) Convective Burst Module: The objectives of the convective burst module are to obtain quantitative description of the kinematic, thermodynamic, and electrical properties of intense convective systems (bursts) and the nearby environment to examine their role in the cyclogenesis process. This module can be flown separately within a mission designed to study local areas of convection or at the end of one of the survey patterns. The module can be flown independently with one of the WP-3D aircraft or with a WP-3D and the NASA ER-2 plane (Fig. 4). Once a local area of intense convection is identified, the WP-3D will transit at altitude (14,000 ft.) to the nearest point just outside of the convective cores and fly a circumnavigation of the convective area. The circumnavigation will consist of a series of straight legs just outside of the main convection. The tail radar should be operated in F/AST sector scan and regularly spaced dropsondes (10-20 km apart) will be released during this time. Once the circumnavigation is completed, and the WP-3D is near the original IP, two straight-line crossings of the convective area should be performed with the WP-3D avoiding the strongest cores, as necessary for safety considerations. The WP-3D can fly at either at a constant radar altitude of 14,000 ft. or, if conditions warrant, to perform a slanted ascent through the melting layer on the first pass and a slanted descent on the return pass. If time permits, the WP-3D should descend to the lowest safe altitude and perform another circumnavigation (or partial one) of the convective burst. No dropsondes will be released during the low-level run.

Modeling component

A modeling component is a necessary complement to the observational component because it provides spatial and temporal continuity to the dynamics and thermodynamics fields in incipient systems. It also provides a framework for testing the various hypotheses regarding the structure and environment of the incipient vortex that is undergoing tropical cyclogenesis. For the tests to be conducted here, a high-resolution numerical model (grid length < 2 km) is necessary to adequately resolve the deep convective towers that are key to the genesis process. A variety of models are available to suit this need; initially the MM5 mesoscale model will be used, which is a well-tested model that provides a variety of options for physical parameterizations. In addition, the WRF-ARW model can be used. Ultimately, the desired model will be the WRF-NMM model, otherwise known as the HWRF model. The HWRF model will be the NOAA operational model, so it is desirable to perform research using this model once it has the capability of being run at sufficiently high resolution.

A variety of experiments can be run with such a modeling framework. Simulations of observed genesis cases can be performed to test the performance of the model and evaluate the importance of the various physical processes observed by the aircraft. Vorticity, heat, and moisture budgets can be calculated from the model and compared with comparable budgets from the Doppler radar and GPS dropsonde data. The statistical properties (e.g., means, distributions, correlations) of various fields and their variation with time and altitude can be compared between the model and the observations to gain a better understanding of the structural evolution of incipient systems and how well they are reproduced in the model. Observing system simulation experiments (OSSEs) can also be performed to determine the optimal flight tracks for initializing HWRF for incipient systems.

To complement the real-data simulations, idealized simulations can be performed that will better be able to isolate specific physical processes important in tropical cyclogenesis. For example, tests could be run that vary the amplitude and altitude of the initial midlevel vortex and the humidity of the synoptic and mesoscale environment of the incipient system. The observations could be used to guide the formulation of idealized experiments by providing a physically realistic range for specifying the structures of the system and its environment and evaluating the performance of the idealized simulations.

Tropical Cyclogenesis Experiment

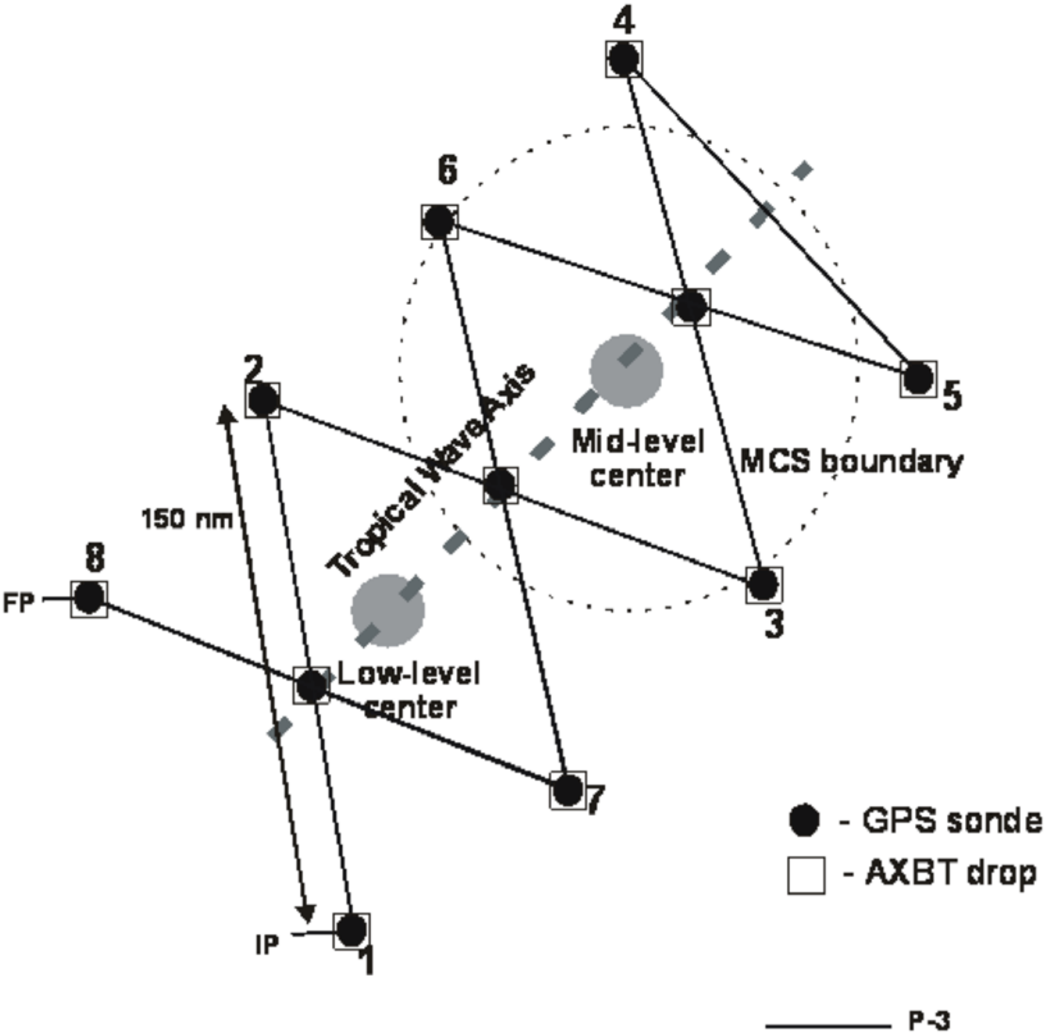


Figure 1: WP-3D Pre-genesis early organization vortex survey pattern – Diamond pattern

- 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. Length of pattern (axis parallel to wave axis) should cover both low- and mid-level vortices, leg lengths range from 150 – 200 nm (275-375 km).
- Note 4. Fly 1-2-3-4-5-6-7-8 at 14,000 ft (4 km) altitude, dropping sondes at all locations denoted by black circles.
- Note 5. Set airborne Doppler radar to scan F/AST on all legs.

Tropical Cyclogenesis Experiment

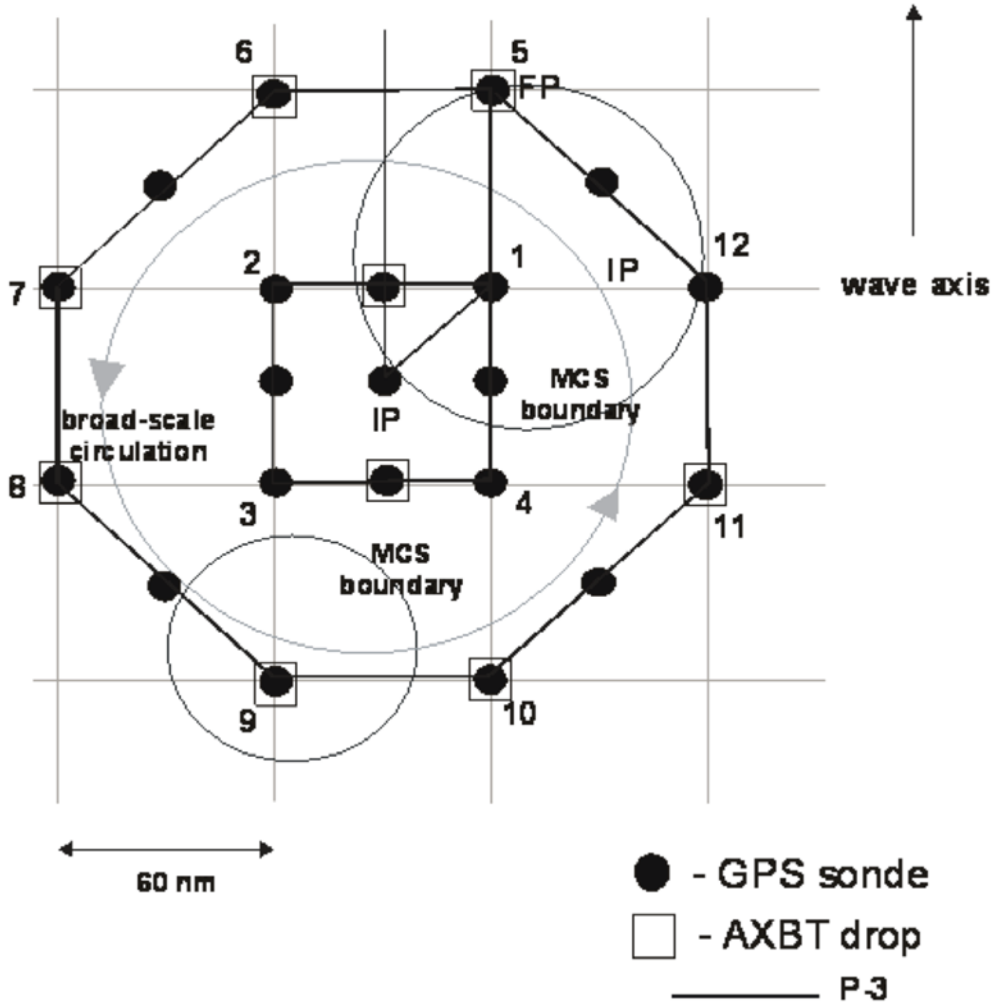


Figure 2: WP-3D Pre-genesis late organization vortex survey pattern – Square-spiral pattern

- 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. Drop sondes at all numbered points. Drops at intermediate points can be omitted if dropsonde supply is insufficient.
- Note 4. The spacing between the outer spiral and inner box (nominally set to 60 nm (111 km)) can be increased or decreased depending on the size of the disturbance.
- Note 5. Fly 1-2-3-4-5-6-7-8-9-10-11-12 at 14,000 ft (4.0 km) altitude.
- Note 6. Set airborne Doppler radar to scan F/AST on all legs.
- Note 7. ER-2 track is offset 5-10 nm (10-15 km) from track of WP-3D.

Tropical Cyclogenesis Experiment

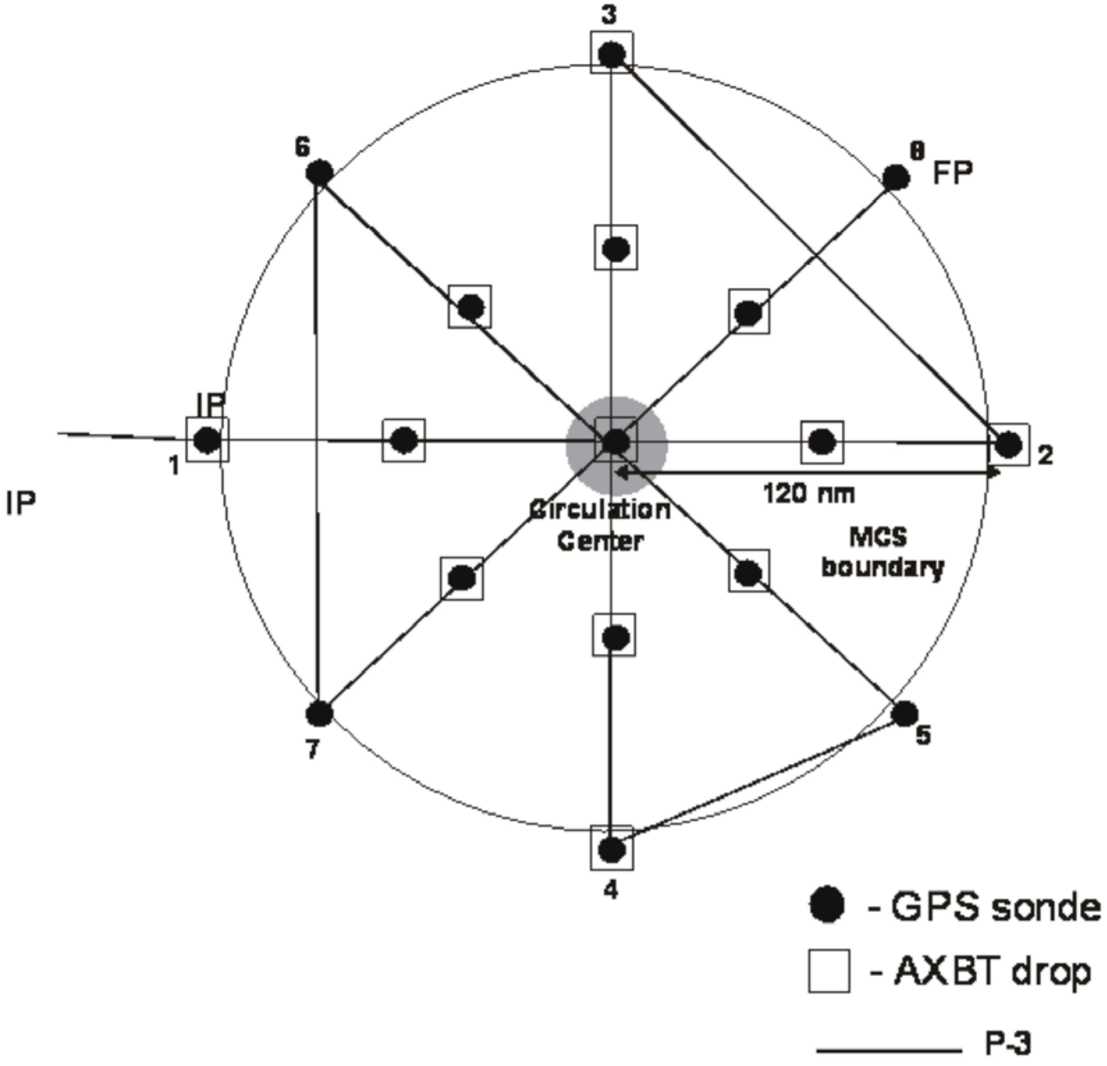


Figure 3: WP-3D Post-genesis rotating Figure-4 pattern

- Note 1: True airspeed calibration is required.
- Note 2. The pattern may be entered along any compass heading.
- Note 3. Fly 1-2-3-4-5-6-7-8 at 14,000 ft altitude, 60-120 nm (111-225 km) leg length.
- Note 4 Set airborne Doppler radar to scan F/AST on all legs.

Tropical Cyclogenesis Experiment

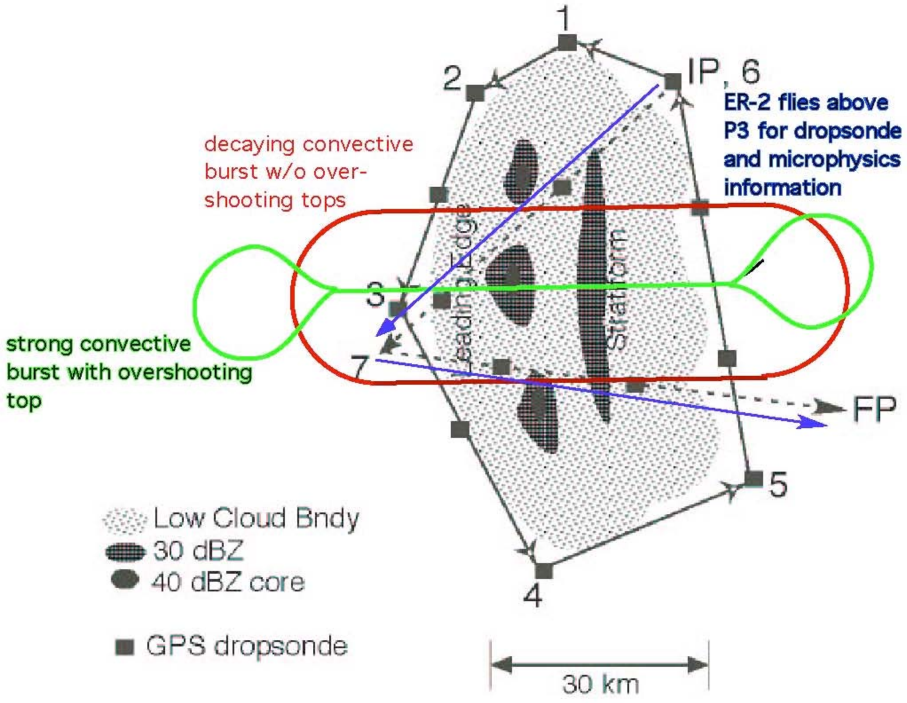


Figure 4: Convective Burst module

- Note 1: True airspeed calibration is required.
- Note 2: Circumnavigation (IP to point 6) by single WP-3D at 14 kft.
- Note 3: Convective crossing (6-7-FP) at 14 kft.
- Note 4: Repeat circumnavigation (time permitting) at low altitude (200 ft in day, 1000 ft at night).
- Note 5: No GPS sondes for low-altitude option.
- Note 6: ER-2 flies either racetrack or bowtie pattern during WP-3D circumnavigation, flies vertically aligned with WP-3D during convective crossing.

IFEX Experiment Cont'd
5. Tropical Cyclone Eye Mixing Module

Program Significance: Eyewall mesovortices have been hypothesized to mix high entropy air from the eye into the eyewall, thus increasing the amount of energy available to the hurricane. Signatures of such mesovortices have been seen in cloud formations within the eyes of very strong TCs, and from above during aircraft penetrations. Observations within the eye below the inversion can allow for the study of the dynamic and thermodynamic structures of these mesovortices and improve our knowledge of small-scale features and intensity changes in very strong TCs.

Objectives: The main objective of the Eye Mixing Module is to:

- Collect observations within the eye below the inversion to investigate the dynamic and thermodynamic structures of these mesovortices and improve our knowledge of small-scale features and intensity changes in very strong TCs.

Links to IFEX: This experiment supports the following NOAA IFEX goals:

- **Goal 3**: Improve our understanding of the physical processes important in intensity change for a TC at all stages of its lifecycle;

Mission Description: Although this WP-3D research module is not a standalone experiment it could be included as a module within any of the following HRD research missions: Saharan Air Layer Experiment, Aerosonde Experiment, or TC Landfall and Inland Decay Experiment. For this module, a Category 4 or 5 TC with a clearly-defined eye and eyewall and an eye diameter of at least 25 nm is needed (Fig. EYE-1). The WP-3D will penetrate the eyewall at the altitude proposed for the rest of the experiment. Once inside the eye, the WP-3D will descend from that altitude to a safe altitude below the inversion (about 2500 ft) while performing a figure-4 pattern. The leg lengths will be determined by the eye diameter, with the ends of the legs at least 2 nm from the edge of the eyewall. Upon completion of the descent, the WP-3D will circumnavigate the eye about 2 nm from the edge of the eyewall in the shape of a pentagon or hexagon. Time permitting; another figure-4 will be performed during ascent to the original flight level. Depending upon the size of the eye, this pattern should take between 0.5 and 1 h.

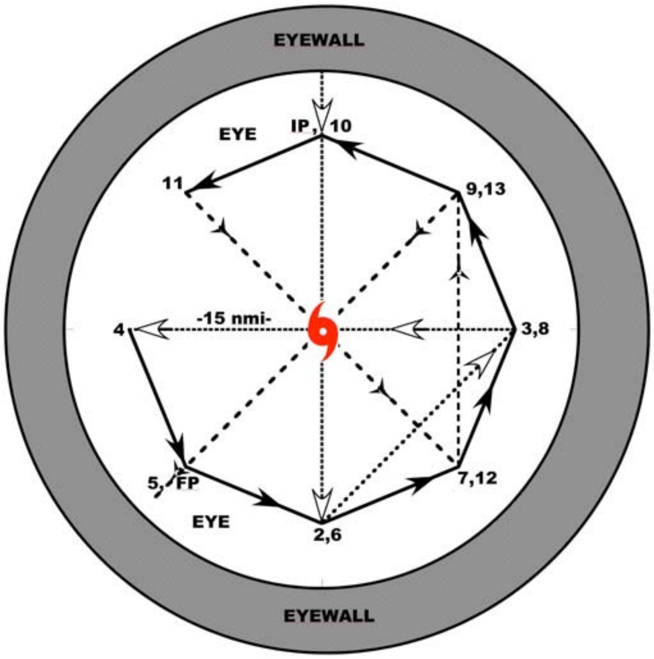


Figure EYE-1 (Mature Storm Eye Module): The WP-3D approaches from the north, penetrates the eyewall into the eye, and descends below the inversion to 2500 ft while performing a figure-4 (dotted line) in the eye. The WP-3D circumnavigates the eye in an octagon or pentagon (solid line), and then ascends while conducting another figure-4 (time permitting) rotated 45 degrees from the original (dashed line).

IFEX Experiment Cont'd
6. Eyewall Sampling and Intensity Change Experiment

Hypothesis: Hurricane intensity, defined by either minimum sea-level pressure in the eye or maximum sustained winds in the eyewall, is determined by processes in the inner core (radial distance < 100 km). These processes include, but are not limited to, enhanced sea to air fluxes near and under the eyewall, eye-eyewall mixing, convective outbreaks in the eyewall, increased mass and moisture inflow to the eyewall, contraction of the eyewall, and the interaction of the upper level flow with the eyewall.

To more fully understand these processes the research community needs detailed monitoring of the inner core for several hurricanes. The observations collected during the proposed experimental module can also serve some real-time needs of NHC.

What we obtain:

The primary raw data includes the GPS sondes, reflectivity, Doppler derived winds, and in-situ aircraft observations.

a. GPS sondes spaced equally around eye wall

The GPS sondes, when combined with the TC track, will allow us to calculate storm relative variables. Each sonde will provide estimates of inflow rate and depth, and energy content. These profiles are then assembled to construct an azimuth-height (Φ-z) surface that extends from a few hundred meters below aircraft altitude to the sea surface around the eye wall. The Φ-z surface allows us to estimate fluxes of mass, moisture, and energy flux to the eyewall for the entire inflow.

If the experiment is repeated at other radii (e.g., 100 km or just inside the eye wall) we can determine net vertical transports through a given altitude, or net fluxes through the sea surface. Here we are simply exploiting an established method – using divergence to infer processes between the two surfaces. The surface fluxes may be solved as a residual or estimated using the data collected at 10 m by the sonde. Mixing across the top surface remains an issue, but if the aircraft is equipped with turbulence sensors we can estimate this exchange.

b. Reflectivity observations from the tail and lower fuselage radars

The plan views of the eye wall region from the lower fuselage radar are used to estimate net latent heat release (LHR). As the aircraft moves around the eyewall it will get views of each quadrant. These quadrants are assembled for a complete view of the eye wall region that limits beam filling or attenuation issues. A Z-R relationship is then applied to this map of reflectivity to estimate LHR. LHR can be compared to other standard measures of TC intensity such as MSLP and maximum sustained winds estimated from the aircraft. LHR has the advantage that it does not rely on a single pass or reading, instead it is the integration of the net latent heat release from the entire eye wall region. The lower fuselage radar also reveals if the eyewall consists of one or more Cbs, is more mesoscale, or is asymmetric.

The tail radar provides estimates of echo top, and echo slope. These also serve as measures of TC intensity – higher, less sloped systems expected for higher category TCs.

c. Doppler winds from the F/AST sampling strategy

As the aircraft circumnavigates the eye wall the fore/aft scanning technique (F/AST) can be applied. F/AST provides approximately 2 km horizontal resolution where ever there are scatterers. Continuity applied to these wind fields results in an estimate of the vertical velocity field. The GPS sondes provide data that can be used as an initial condition for the lowest 500 m where sea clutter may contaminate the Doppler wind estimates.

Experiment design: This is an economical experiment with a single NOAA WP-3D that consumes less than 45 minutes and can be a piggy-back experiment with the standard reconnaissance flights required by NHC or in conjunction with other experiments by NOAA/AOML/HRD. It combines resources form NOAA/AOML/HRD, NOAA-AOC and potentially NSF (NSF may fund expendables and analysis). The flight pattern is easy to execute and does not entail any maneuvers that differ from standard practices. The pattern utilizes GPS sondes, AXBTs, reflectivity and Doppler wind measurements to obtain detailed views of the eye wall of a hurricane.

The pattern is a circumnavigation around the eye wall with the WP-3D flying counterclockwise to exploit strong tailwinds (Fig. 1). The aircraft would maintain a ~10 km separation from the eye wall that places the aircraft in an excellent position to obtain tail radar data for both reflectivity and Doppler wind measurements. Altitude may be 8500 feet to 11,500 feet (750 to 650 hPa). Circumnavigation around the eyewall can be done relatively quickly, on the order of a half an hour, for an eye wall radius of about 35 km. About 12 GPS sondes would be deployed during circumnavigation that provides estimates of the depth, rate and thermodynamics of the inflow. AXBTs should also be deployed at points 1, 5, 8, and 11. The circumnavigation can be done as part of the standard “figure 4” pattern used routinely during reconnaissance missions and often at the start and finish of research missions.

The approximate cost of the GPS sondes and a few AXBTs is about $12k. The trade-off in deployment is that the aircraft is spending more time near the eyewall and less time on the periphery of the circulation determining the extent of the gale force winds. Over the course of a several hurricane seasons we might obtain 20 datasets with similar characteristics for comparison.

There are several possible variations on this experiment. More GPS sondes could be jettisoned in the eyewall in rapid succession, akin to the CBLAST experiment. It would also be possible to do multiple rings. For hurricanes with a large eyewall a circumnavigation along the inner edge of the eyewall would be possible to ascertain more about the interaction of the eye and eyewall. More distant circumnavigations allow for an assessment of where the inflow is gaining or losing energy as the inflow approaches the eyewall. Complementary sampling could be done with the aerosonde at more distant radii.

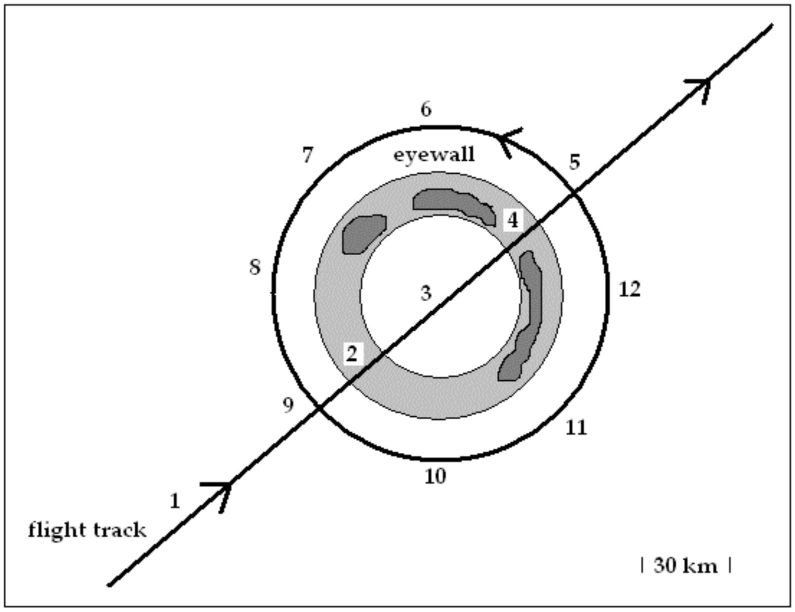


Fig. 1: WP-3D track (bold line), eyewall (gray region), and GPs sondes (numbered).

IFEX Missions Cont'd
7. Canted SFMR MODULE

1. RATIONALE

The Hurricane Imaging Radiometer, HIRad, is currently under development by NASA and NOAA and is intended to follow the SFMR and extend its spatial coverage by providing a wide swath measurement. It is intended to be the next-generation scanning SFMR intended to reduce surface wind uncertainty by extending the SFMR measurement swath in the cross –track direction. In order to design HIRad and to retrieve wind speed and rain rate over its full swath, an ocean surface emissivity model is required that covers wind speeds over the full SFMR range of greater than 70 m/sec and over the full HIRad swath of approximately ± 60 deg incidence angle. Existing models cover high winds at nadir only (SFMR) and cover large incidence angles only during turns at less than hurricane force. Therefore, a new surface emissivity model is being developed under the HIRad project to meet future needs in radiative transfer analyses.

The HIRad surface emissivity model is being developed using SFMR algorithms for nadir incidence and using SFMR brightness temperature measurements in aircraft banks and turns for off-nadir modeling. Aircraft turns in past hurricane flights have typically produced maximum bank angles of 30 – 35 deg. or less. Therefore, there is a critical need for brightness temperature data in hurricane force winds at incidence angles greater than 35 deg. in order to complete the HIRad surface emissivity model. The Nadir Off-Set SFMR Experiment is intended to fill this need.

A further rationale for this flight module is to provide off nadir SFMR measurements to Remote Sensing Solutions for an experiment to develop an SFMR SST algorithm using dual nadir and off-nadir, nearly collocated SFMR observations with the objective of leveraging crucial flight resources. This application does not require circle flights. It's objective could be achieve with the nadir and canted SFMR's flying straight and level flight legs.

2. FLIGHT PATTERN DESCRIPTION

This experiment will include an SFMR instrument installed on one of the P-3 aircraft with the antenna canted off-nadir by 45 deg. in the roll plane. This will put the aircraft roll angle in the plane of incidence, and aircraft roll will add directly to the 45 deg. off-set angle of the SFMR. In this way, incidence angles as high as 75 deg. will be achievable. This will allow for antenna pattern corrections required to estimate emissivity out to the 60 deg. swath edge for HIRad. Examples of proposed flight maneuvers are described in the following figure and table.

It is important throughout this pattern for the rolls to be accomplished during the aircraft turns to be at constant pitch insofar as possible. Changes in pitch will translate to changes in canted SFMR polarization. For a given hurricane, straight and level passes through the eye-wall region will provide the highest winds at approximately 45 deg. incidence, and circle maneuvers just outside the eye-wall at various bank angles would provide data at the highest incidence angles and highest possible wind speeds.

When executing these rolls it is important to perform a left upwind (CCW) turn during inbound flight legs in order to maintain station-keeping in high winds and to also acquire the higher incidence angle data from the canted SFMR, which will be mounted on the right wing, inboard hard points. During outbound legs, a right upwind (CW) turn is to be executed to obtain data between the 45 deg canting angle and the lower angles where turn data has already been obtained at lower wind speeds. These patterns are to be flown when situation and time dictate. Over the course of a season, it is anticipated that a series of inbound and outbound circle flights could be obtained at approximately 4 separate wind speed ranges: 20-25 m/s, 30-35 m/s, 40-45 m/s and 50-55 m/s. It is likely that data may need to be stratified also by storm quadrant relative to storm motion, a goal that may prove difficult in one season.

The examples in the table indicate a need, at each wind speed interval, for measurements at 35, 60 and 75 deg. incidence angle in the circle maneuvers and 45 deg along the return legs in level flight with approximately 10 minutes of data each. We suggest two left upwind (CCW) bank angles on the inbound legs at 15 and 30 deg roll angles for the 60 and 75 deg incidence angle measurements, as indicated in the table, repeating each series of circles three times. Then on the outbound leg, one right upwind (CW) bank at 10 deg roll angle would accomplish the 35 deg incidence angle measurement. These maneuvers are estimated to occupy a total of approximately 45 minutes of flight time.

Both horizontal and vertical polarization measurements are required. To maintain constant polarization during banks, the aircraft should maintain constant pitch while executing the roll insofar as possible. The two separate polarization measurements would need to be accomplished on separate flights, which would require the antenna to be rotated between flights to switch the observed polarization.

In summary, a full series of circles at four wind speed intervals, 3 incidence angles, two polarizations and three circles per case would require 72 circles. If stratification by storm quadrant were to be attempted, four times this or 288 circles would be required, an effort likely spanning several seasons.

Concurrent standard SFMR nadir viewing measurements are needed for wind speed surface truth during each flight, and measurements around surface buoys are needed for calibration after installation and at the end of the experiment.

(As of 14 May, the figure below and table need to be redrawn to reflect upwind turns and inbound and outbound flight legs.)

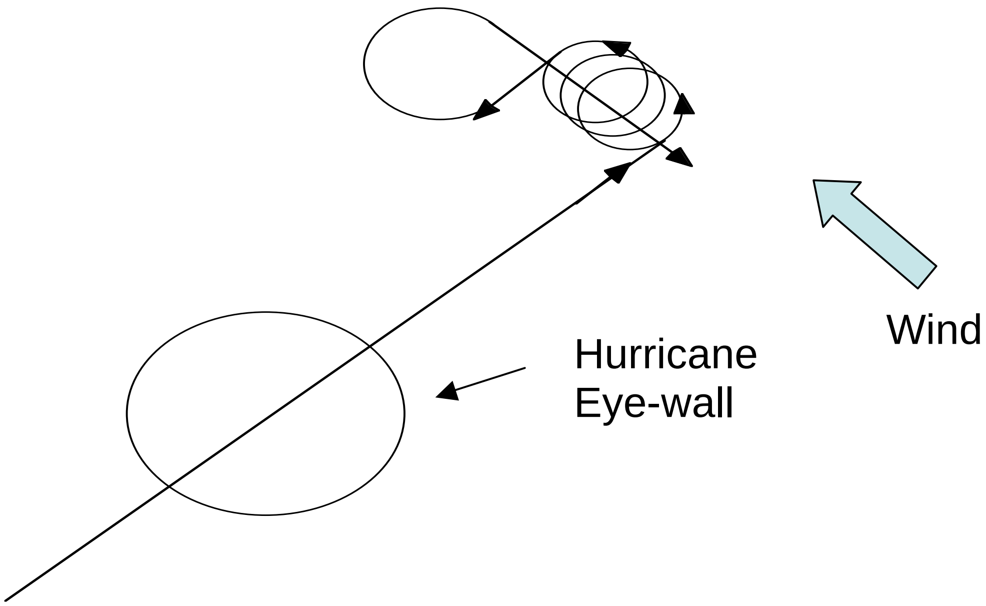


Figure 1. Example of flight lines penetrating eye-wall region and circle patterns outside of eye-wall region..

Maneuver	**Bank Angle**	**# Turns**	**Time, min.**
CCW bank	30°	3 x 360°	10
Upwind leg	0°		10
CCW bank	15°	2 x 360°	12
Upwind leg	0°		10
CW bank	-10	1 x 360°	9

Figure 2. Examples of circles patterns and return legs at selected bank angles.

IFEX Missions Cont'd
8. SFMR-Bathymetry Flight Module

Background

In the annual report from the first year of this project and in subsequent technical reports, higher than expected SFMR wind speed retrievals have been reported in regions where the water depth is less than 50 m. Several mechanisms may be the cause of these anomalies, but the largest is believed to be enhanced wave breaking of both swell and local sea wave components due to shoaling, i.e. when the water depth approaches the dominant ocean swell and local sea wavelength (200-300 m and 50 – 80 m, respectively). As ocean waves enter shallower water their height increases as their speed and length decrease. At the point where the ocean wavelength and depth become approximately equal, the wave becomes unstable and begins to plunge forward and break. The normal wave breaking criteria of wave slope (ratio of wave height to wave length) exceeding 1/7 changes in shallow water and alters frequency of wave breaking and hence the foam and whitecap coverage that SFMR senses. Since this foam is not directly generated by the local wind, but by a shoaling bottom, and the ocean surface emission is dependent on the amount of foam, the SFMR retrieval process may over estimate the wind speed in these conditions. Therefore, the gradient in the water depth, the direction of the waves, the complexity of the wave field and other parameters may all affect this process. To begin to understand and characterize these effects, SFMR observations and "in situ" ocean surface wind observations in different water depths, ocean states and wind conditions are required.

Objective

To develop recommended flight modules that will obtain ocean surface wind observations collocated with the SFMR observations in water depths ranging from 50 m to 10 m, and in conditions of onshore and offshore wind to delineate the effect of long period ocean swell. Potential wind observations from ocean wind scatterometry may not suffer from the same effects, and thus ocean surface backscatter observations collected by the IWRAP system should also be obtained. If analysis of the IWRAP data shows no dependence on bathymetry, the IWRAP ocean wind estimates could be used in future flights to determine the bathymetry effects on the SFMR wind retrievals. Utilizing IWRAP for this purpose has the advantage of requiring less resources since GPS dropsondes would not be needed and IWRAP would provide continuous wind observations rather than point observations that are obtained with the GPS dropsondes. In addition, dual aircraft modules are proposed to obtain colocated surface wave spectra, including swell and local sea components, from the new Operational Scanning Radar altimeter (OSRA) which will be mounted on N43RF, a different WP-3D from N42RF, where IWRAP is be mounted. Both aircraft will have operational OC SFMR systems.

Proposed Bathymetry Flight Module

The objective of the bathymetry flight modules is to obtain collocated SFMR and GPS dropsonde estimates of the 10 m wind speed measurements at different water depths (less than 50 m). In addition to the SFMR, IWRAP and OSRA observations are desired. Below, flight modules for single and dual aircraft are described. These modules need to be executed for different wind and bathymetry conditions. Ideally the flight module(s) should be executed at water depths of 10 m, 20 m, 30 m, 40 m and 50 m under gale, storm and hurricane force winds. Each flight module is designed to obtain in situ measurements of the 10 m wind speed that are collocated within approximately 200 hundred meters of the center point in the SFMR footprint. Because the wind and bathymetry might be changing spatially and because the SFMR observations are time sequenced and its beamwidths are finite, each module executes orthogonal cross patterns over the GPS dropsonde splash point. This will allow the effects of bathymetry on the SFMR to be separated from spatial gradients in the wind field and bathymetry.

In the case where the wind is onshore or offshore and the bathymetry does not change by more than a couple of meters per kilometer, an additional simplified flight module would simply fly the available aircraft, or the two WP-3d aircraft in tandem, downwind for a flight segment beginning at the 60-m isobath and continuing to the 10-m isobath while deploying a sequence of 8 sondes (from a single aircraft) or 12 sondes from the two aircraft in tandem. Care would need to be taken to fly parallel to the surface wind so that the aircraft would fly over the dropsonde splash point. This would be executed at the wind speed regemes indicated above for onshore and offshore winds.

Single Aircraft

Required Instruments

NOAA AOC SFMR and GPS dropsondes are required for this flight module. IWRAP is desired but not required. Ocean wave measurements from the Operational Scanning Radar Altimeter (SRA) and/or from buoys are also desired but not required. Wind measurements from buoys are desirable but not required.

Single Aircraft Bathymetry Flight Module

Figure 1 presents a proposed flight track pattern for a single aircraft mission. Below is a description:

1. Aircraft enters pattern heading in the direction of the bathymetry gradient (increasing or decreasing water depth). If the bathymetry gradient is not known, this pattern is still recommended as the orthogonal cross pattern will allow us to determine if the bathymetry was changing and in which direction.

2. At time t = 0 seconds, GPS dropsonde (Drop 1) is launched. Aircraft maintains a level flight.

3. GPS dropsonde 2 (Drop 2) is launched 2 minutes later (t = 120 seconds).

4. Aircraft maintains level flight until the splash location of the Drop 1 is determined. At 5000 ft altitude, the dropsonde will take approximately 150 seconds to fall to the surface.

5. With the splash location known, the aircraft executes a series of three 90 degree turns to align for a pass over the splash location of Drop 1. Each turn should be sharp (30 degree bank) to minimize turning time and non-level flight. Between turns the aircraft should maintain level flight. This will maximize the amount of valid observations collected with the SFMR (and IWRAP).

6. An 8 km level flight leg centered on the Drop 1 splash location is executed. The heading of this leg should be orthogonal to the original flight track as depicted in the figure.

7. By this time the splash location of Drop 2 should be known. The aircraft should execute two 90 degree turns (30 degree bank angle) to align for the pass over the second splash location. Once again, between turns the aircraft should maintain level flight.

8. An 8 km level flight leg centered on the Drop 2 splash location is executed. Again, the heading of this leg should be orthogonal to the original flight track as depicted in the figure.

9. After this leg, the aircraft can exit this flight module.

This flight track module can be embedded in another flight track module as a sub module or part of a flight track dedicated to analyzing bathymetry effects on the SFMR. For the latter, the aircraft should be heading in the direction of increasing or decreasing water depth. Figure 2 illustrates the flight track for a dedicated flight.

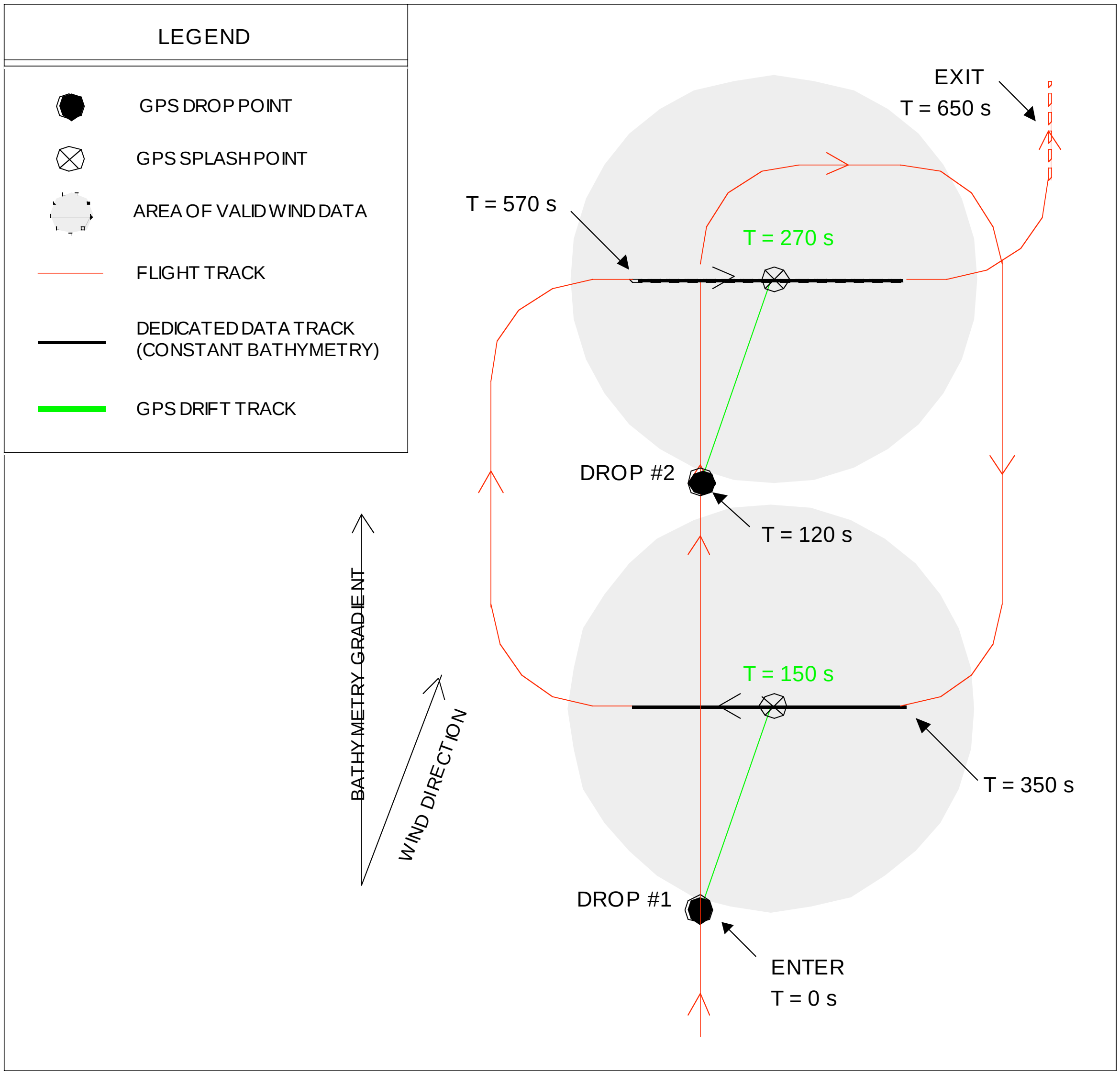


Figure 1: Proposed single aircraft flight module designed to collect the necessary observations for determining the impact bathymetry has on the SFMR retrievals.

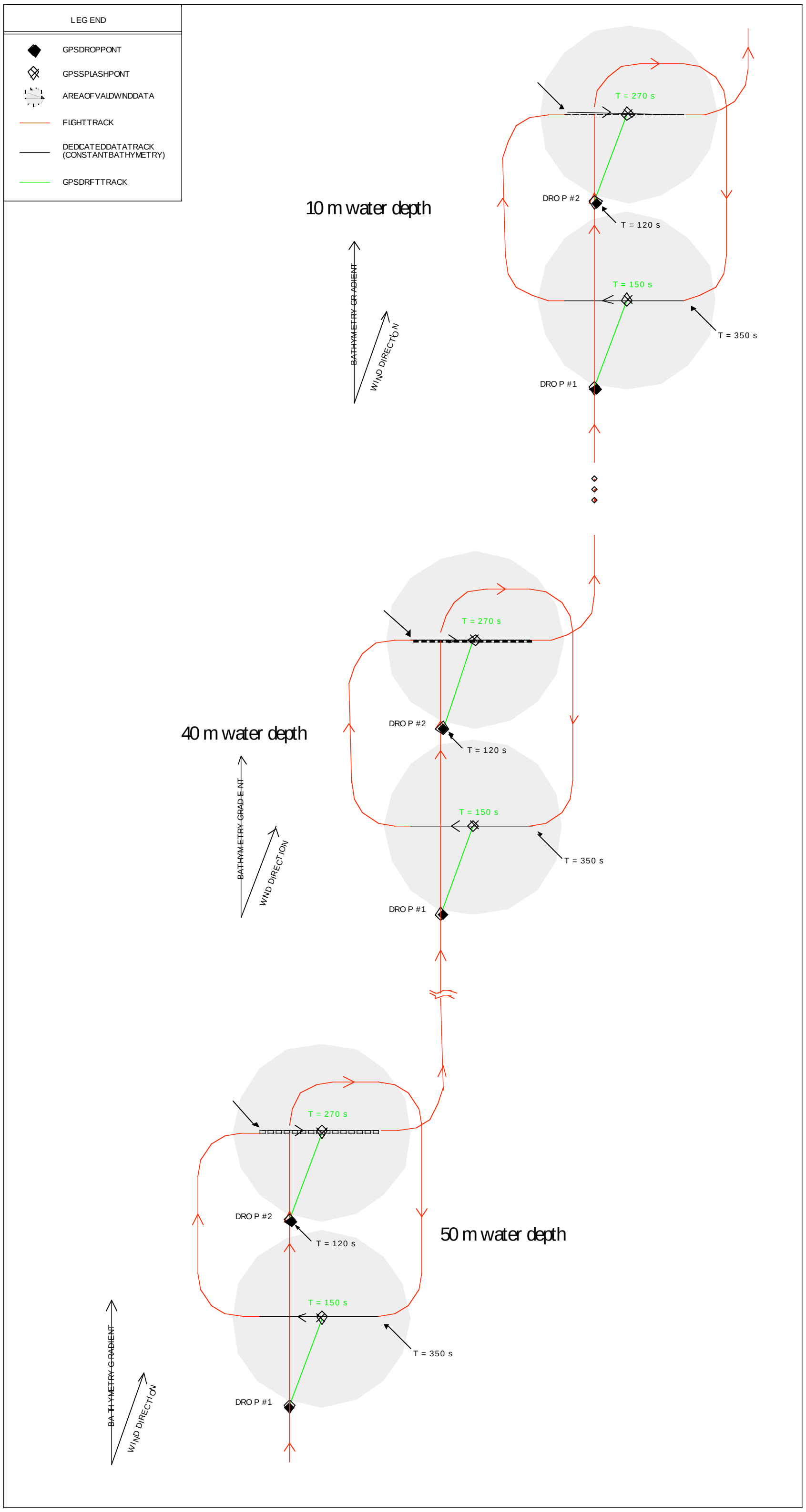


Figure 2: Single aircraft dedicated bathymetry flight track is shown. Each submodule (figure 1) is executed at water depths of approximately 50 m, 40 m, 30 m, 20 m and 10 m.

Multi-Aircraft

Required Instruments

NOAA AOC SFMR and GPS dropsondes are required for this flight module. IWRAP is desired but not required. Ocean wave measurements from the scanning radar altimeter (SRA) and/or from buoys are also desired but not required. Wind measurements from buoys are desirable but not required.

Dual Aircraft Bathymetry Flight Module

Figure 3 presents the dual aircraft bathymetry flight module. The orthogonal cross patterns over the splash locations of each dropsonde are achieved by flying orthogonal legs with the two aircraft rather than each aircraft. This reduces the total flight time to execute the pattern and simplifies the pattern of the higher altitude aircraft. Below is a description.

Low Aircraft (5000 feet):

1. Aircraft enters pattern heading in the direction of the bathymetry gradient (increasing or decreasing water depth). If the bathymetry gradient is not known, this pattern is still recommended as the orthogonal cross pattern will allow us to determine if the bathymetry was changing and in which direction.

2. At time t = 0 seconds the aircraft executes a 90 degree turn (30 deg bank) and then holds level flight. At time t = 90 seconds GPS dropsonde 1 is launched (Drop 1).

3. GPS dropsonde 2 (Drop 2) is launched 2 minutes later (t = 210 seconds).

4. Aircraft maintains level flight until the splash location of the Drop 1 is determined (~ t = 270 seconds). The aircraft executes a 180 degree turn to over fly splash location of Drops 1 and 2. Splash location of Drop 2 is estimated from splash location of Drop 1. Since the drop points are separated by approximately 12 to 15 km, both drops should advect similarly.

5. The aircraft maintains level flight as it over flies the splash locations of Drop 2 and Drop 1 at approximately t = 390 seconds and t = 510 seconds, respectively. After flying a minimum of 4 km past the splash location of Drop 1, the aircraft then executes a 90 degree turn to resume the original flight track exiting this flight module at t = 580 seconds.

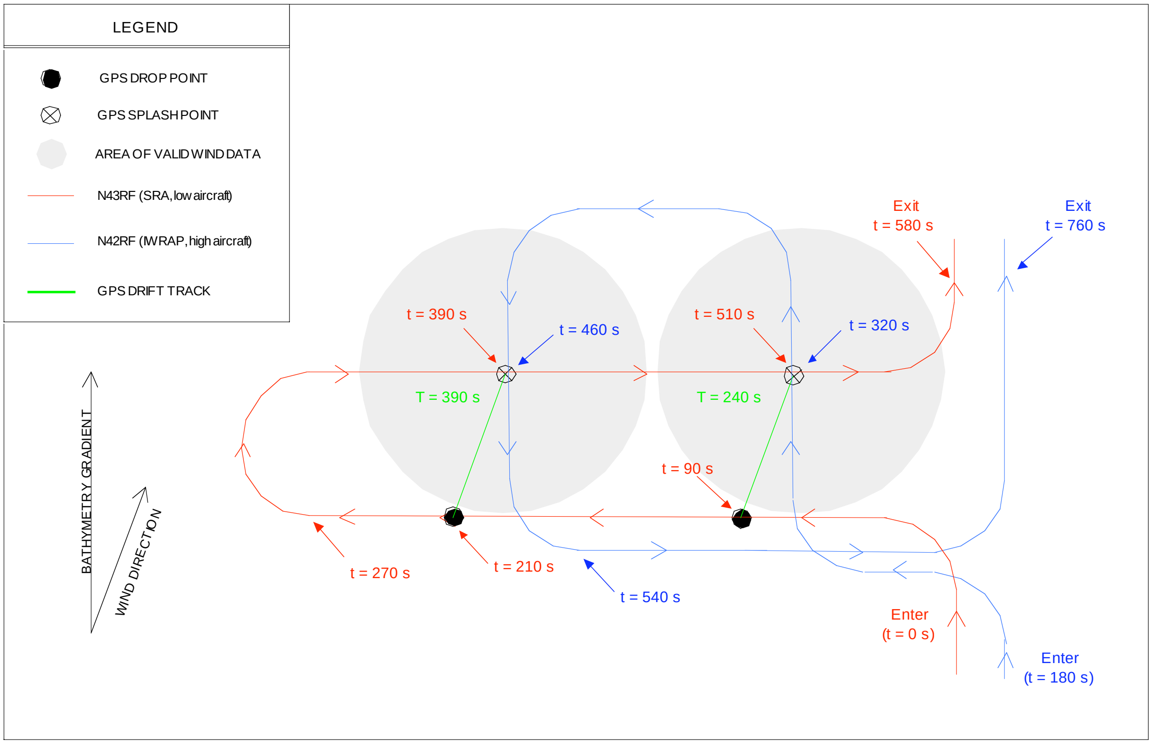


Figure 3: Dual aircraft bathymetry flight module 1.

High Aircraft (IWRAP, 7000 to 10,000 feet):

1. The high altitude aircraft enters pattern at the same location as the low aircraft but delayed by 180 seconds. It may be offset slightly so that it is over flying the splash locations of GPS dropsondes launched by the lower aircraft.
2. With knowledge of the splash location of Drop 1, a box pattern is executed to over fly the splash locations of Drops 1 and 2. Each leg over each drop splash location is a minimum of 8 km centered on the splash location. The length can be extended in order to keep the timing of both aircraft aligned at the exit of the flight pattern. During the 8 km legs, the aircraft must maintain level flight. Note that in this case the splash location of Drop 2 will already be known and therefore does not need to be estimated.
3. After completing the box pattern the aircraft executes a 90 degree turn to resume the original track with the lower aircraft.

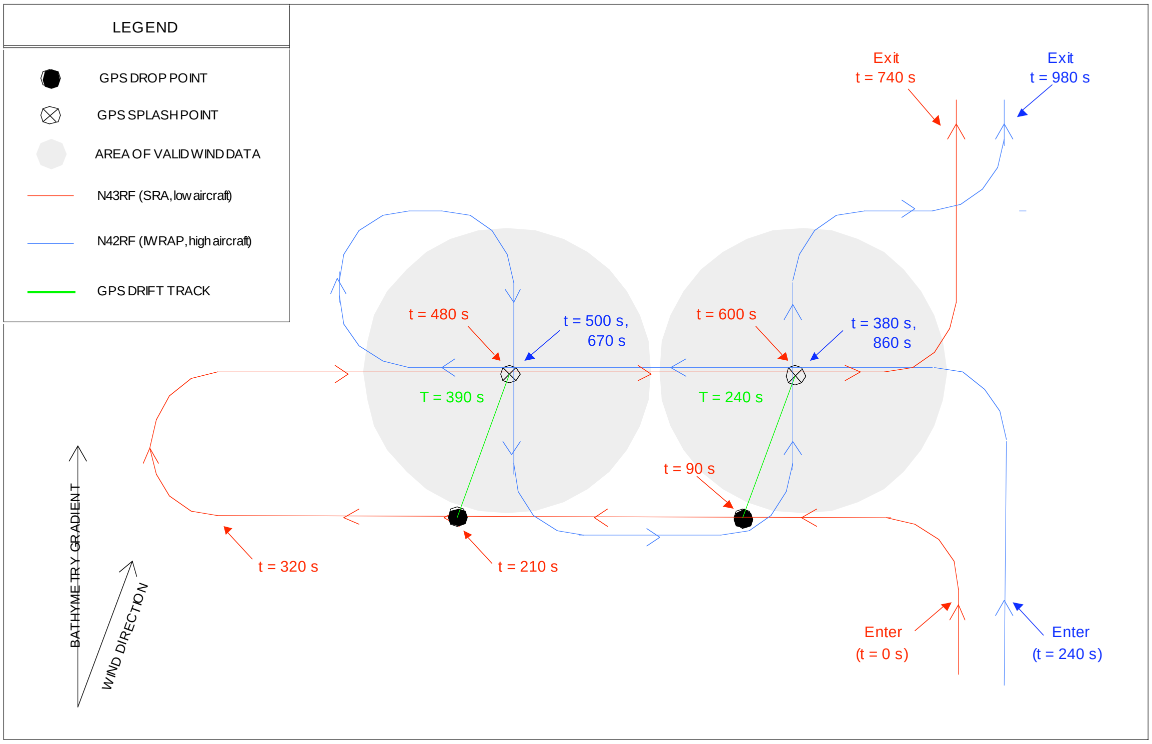


Figure 4: Dual Aircraft bathymetry flight module 2.

An alternative flight pattern is shown in Figure 4. With this pattern, the higher altitude aircraft executes orthogonal cross patterns over each location and over flies the same track as the lower aircraft as it over flies the two splash locations. This pattern has several advantages:

- Small calibration biases between the two SFMR units on the lower and higher altitude aircraft can be calculated since the two aircraft over fly the same track between the splash locations of Drops 1 and 2.
- The orthogonal legs are executed by the same aircraft, and thus measurement uncertainty caused by calibration biases between instruments is removed.
- More observations in the presence of the splash locations are collected by the additional passes of the higher altitude aircraft and by the coincident legs between the splash locations. This reduces the statistical uncertainty in the analysis.
- The splash location of Drop 2 does not need to be estimated since the track of the lower aircraft is extended giving the lower aircraft more time to determine the splash location.

The tradeoff is that this pattern is slightly more complex for the higher altitude aircraft (albeit probably attractive to the pilots) and the total flight module takes 2 minutes longer to execute.

IFEX MISSIONS (CONT'D)
9. Saharan Air Layer Experiment (SALEX)

INTRODUCTION

Saharan Air Layer Experiment: This is a multi-option, multi-aircraft experiment which uses GPS dropwindsondes launched from the NOAA G-IV (flying at ~175-200 hPa/~45,000-41,000 ft) and NOAA WP-3D (flying at ~500-700 hPa/18,000-10,000 ft) to examine the thermodynamic and kinematic structure of the Saharan Air Layer (SAL) and its potential impact on tropical cyclone (TC) genesis and intensity change. The GPS dropwindsonde drop points will be selected using real-time GOES SAL tracking imagery from UW-CIMSS and mosaics of SSM/I total precipitable water from the Naval Research Laboratory. Specific effort will be made to gather atmospheric information within the Saharan Air Layer as well as regions of high moisture gradients across its boundaries and the region of its embedded mid-level easterly jet. The goals of this experiment are to better understand and predict how the SAL's dry air, mid-level easterly jet, and suspended mineral dust affect Atlantic TC intensity change and to assess how well these components of the SAL are being represented in forecast models.

Program Significance: The Saharan SAL has been investigated fairly extensively during the past several decades, buts its role in influencing Atlantic TCs has not been thoroughly examined. The SAL is characterized by a well-mixed layer that originates over the arid regions of the Sahara and often extends up to ~500 hPa (~18,000 ft) over the African continent. This air mass is extremely warm and dry, with temperatures that are markedly warmer (~0.5-5.0^{o}C in the western North Atlantic and ~5-10^{o}C in the eastern North Atlantic) than a typical tropical sounding. Additionally, the RH (mixing ratio) in the SAL is ~30-35% (~3 g kg^{-1}) drier than a typical moist tropical sounding. The SAL is often associated with a mid-level easterly jet centered at about 700 hPa (~10,000 ft) and concentrated along its southern boundary.

SAL outbreaks typically move westward off the western coast of North Africa every 3-5 days during the summer months. There are several characteristics of these frequent outbreaks that can act to suppress Atlantic TC formation:

1) The SAL contains **dry, stable air** that can diminish local convection by promoting convectively driven downdrafts in the TC environment.
2) The SAL contains a **mid-level easterly jet** that can significantly increase the local vertical wind shear. The low-level circulations of TCs under the influence of this jet tend to race out ahead of their mid and upper-level convection, decoupling the storm and weakening it.
3) **Mineral dust** suspended within the SAL absorbs solar energy and subsequently releases longwave infrared energy. These thermal emissions act to warm the SAL and can re-enforce the tropical inversion that already exists in the tropical North Atlantic. This warming helps to stabilize the environment and also limits vertical mixing through the SAL, allowing it to maintain its distinctive low humidity for extended periods of time (several days) and over long distances (1000s of km)

Objectives: The main objectives of SALEX are to:
- Better understand how the SAL's dry air, mid-level easterly jet, and suspended mineral dust affect Atlantic TC intensity change.
- Include the moisture information from the GPS dropwindsondes in operational parallel runs of the NOAA Global Forecast System (GFS) model. The impact of this data on the GFS (and GFDL) initial/forecast humidity fields and its forecasts of TC track and intensity will be assessed.

Links to IFEX: This experiment supports the following NOAA IFEX goals:
- **Goal 1**: Collect observations that span the TC lifecycle in a variety of environments;
- **Goal 3**: Improve our understanding of the physical processes important in intensity change for a TC at all stages of its lifecycle;

Mission Description: The NOAA G-IV (flying at ~175-200 hPa/~45,000-41,000 ft) and NOAA WP-3D (flying at ~500-700 hPa/~18,000-10,000 ft) GPS dropwindsonde drop points will be based on a flight pattern selected using information from the UW-CIMSS/HRD GOES SAL tracking product and mosaics of SSM/I

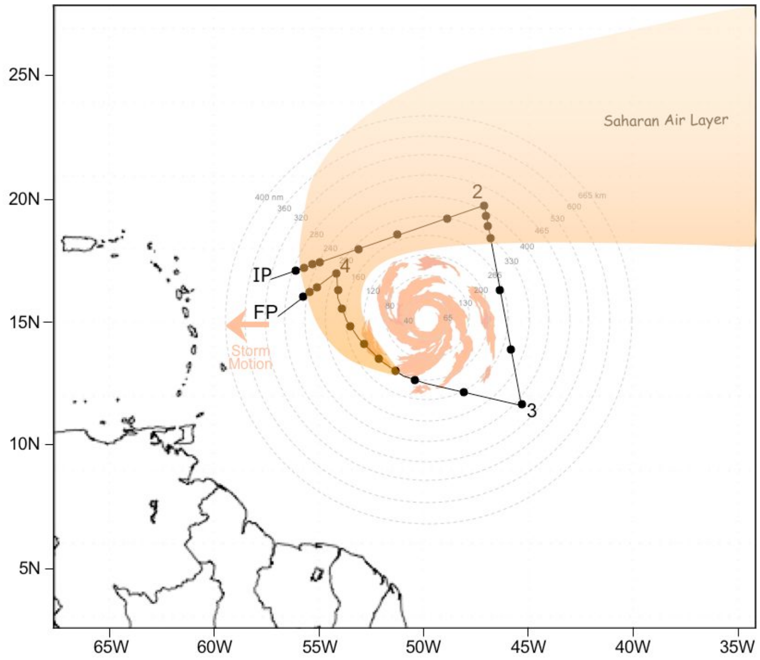
TPW from NRL Monterey. Specific effort will be made to gather atmospheric information within the SAL, the transitional environment (regions with high gradients of humidity) across its boundaries, its embedded mid-level easterly jet, and the immediate surrounding moist tropical environment. When possible, SALEX missions will be coordinated with the HRD Tropical Cyclone Genesis Experiment (GenEx). This coordination will involve the WP-3D and/or G-IV and be executed on a case-by-case basis. Several SAL/TC interaction scenarios are candidates for SALEX missions:

Option 1:

Single TC located along the southern edge of the SAL (Fig. 1). Depending on the proximity of these two features, the SAL's dry air may be wrapping into the TC's low-level circulation (western semicircle).

G-IV: The G-IV **IP** will be in the NW quadrant of the TC (preferably west of the SAL's leading edge) and the initial portion of the 1st leg (**IP-2**) will focus a GPS dropwindsonde sequence across the high gradient region of humidity at the SAL's leading edge. There will be intermittent GPS dropwindsondes along the remainder of the first leg (**IP-2**), with higher density sequences along pre-determined regions of interest (e.g. dry SAL air). The 2nd leg (**2-3**) will focus a GPS dropwindsonde sequence across the SAL's southern boundary to capture gradients of humidity and wind shear (associated with the SAL's mid-level easterly jet). Subsequent intermittent drops will be made along this leg (**2-3**) to sample the ambient moist tropical environment. The 3rd leg (**3-4**) will include a GPS dropwindsonde sequence that will be focused along the dry air inflow region on the west semicircle of the TC. This drop sequence will focus on sampling the intrusion of low humidity SAL air into the TC circulation and how the SAL's vertical structure and moisture content modify as it advects closer to the TC inner core. The SAL's leading edge ("rooster tail") will be sampled by a GPS dropwindsonde sequence during the final leg (**4-FP**).

WP-3D: The WP-3D **IP** will be in the SW quadrant of the TC and the initial portion of the 1st leg (**IP-2**) will focus on sampling the ambient moist tropical environment south of the TC. The 2nd leg (**2-3**) will include sampling the ambient moist tropical environment east of the TC as well as focusing a GPS dropwindsonde sequence across the SAL's southern boundary to capture gradients of humidity and wind shear (associated with the SAL's mid-level easterly jet). The 3rd leg (**3-4**) will include a GPS dropwindsonde sequence that will be focused along the dry air inflow region on the west semicircle of the TC. This drop sequence will focus on sampling the intrusion of low humidity SAL air into the TC circulation and how the SAL's vertical structure and moisture content modify as it advects closer to the TC inner core. The final leg (**4-FP**) will include a penetration of the TC center of circulation followed by GPS dropwindsonde sequences targeting the SAL west of the TC. The final GPS dropwindsonde sequence will sample the SAL's leading edge ("rooster tail") west of the TC.



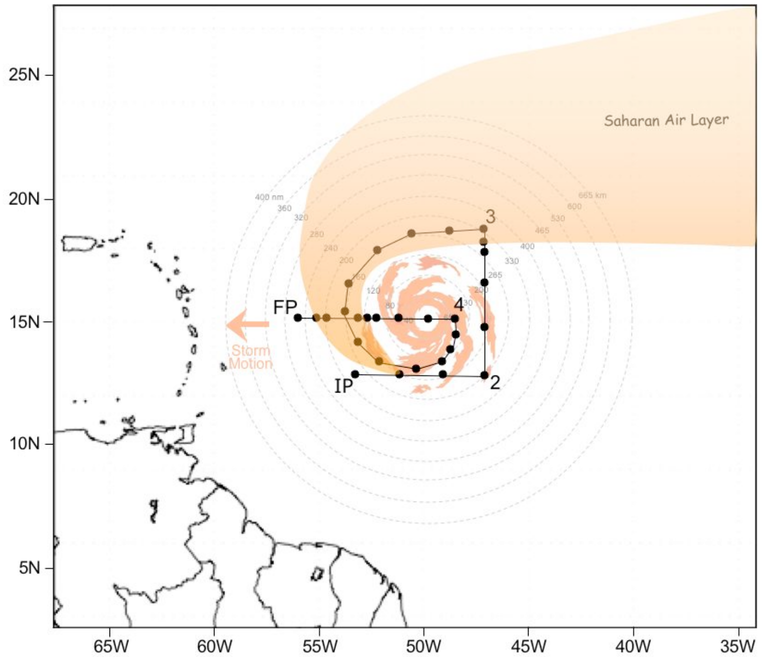


Fig. 1: Sample G-IV (top) and WP-3D (bottom) flight tracks for a TC positioned along the southern edge of the SAL

- Note 1: During the ferry to the **IP**, the G-IV (WP-3D) should climb to ~200 hPa/41,000 ft (500 hPa/18,000 ft) as soon as possible and climb as feasible to maintain the highest altitude for the duration of the pattern.
- Note 2: In order to capture the SAL's horizontal/vertical structure, particular attention should be paid to regions of high moisture gradients across its boundaries (G-IV: **IP-2**, **2-3**, and **4-FP**; WP-3D: **2-3**, and **4-FP**).
- Note 3: The SAL's mid-level easterly jet (~20-50 kt at 600-700 hPa/12,000-15,000 ft) may be evident from GPS dropwindsondes dropped near the SAL's southern boundary (G-IV: **IP-2** and **2-3;** WP-3D: **2-3** and **3-4**).

Option 2: Single TC is embedded within the SAL and intensifies upon emerging. These systems are often candidates for rapid intensification.

G-IV: The G-IV **IP** will be west of the TC and preferably within the SAL. The 1st leg (**IP-2**) will include a GPS dropwindsonde transect across the northern boundary of the SAL. This dropwindsonde sequence will focus on sampling the large humidity gradients across the northern edge of the SAL. The 2nd (**2-3**) and 3rd (**3-4**) legs of the flight pattern will intermittently sample the moist tropical environment out ahead of the TC and north of the SAL. The 4th leg (**4-5**) will include a GPS dropwindsonde transect across the northern boundary of the SAL (NE of the TC), intermittent GPS dropwindsondes within the SAL (in the middle of the flight leg), and a GPS dropwindsonde transect across the southern boundary of the SAL (southeast of the TC). The northern and southern dropwindsonde sequences will focus on sampling the large humidity gradients along the SAL's boundaries. The intermittent dropwindsondes and southern dropwindsonde sequence will concentrate on sampling the SAL's mid-level easterly jet. The 5th (**5-6**) and 6th (**6-FP**) flight legs will include intermittent GPS dropwindsondes that will help identify how the SAL's vertical structure and moisture content are being modified by the TC circulation closer to the storm.

WP-3D: The WP-3D **IP** will be west of the TC and preferably within the SAL. The 1st leg (**IP-2**) will include a GPS dropwindsonde transect across the northern boundary of the SAL. This dropwindsonde sequence will focus on sampling the large humidity gradients across the northern edge of the SAL. The 2nd leg (**2-3**) of the flight pattern will sample the boundary between moist tropical air north of the TC center and the SAL to the south and will include a penetration of the TC center of circulation. Particular attention will be focused on sampling dry SAL air near the TC inner core. The 3rd leg (**3-4**) will include a GPS dropwindsonde transect across the northern boundary of the SAL to sample the humidity gradients at the

SAL's northern boundary. The 4th leg (**4-FP**) will sample the boundary between moist tropical air north of the TC center and the SAL to the south and will include a penetration of the TC center of circulation. Particular attention will be focused on sampling dry SAL air near the TC inner core.

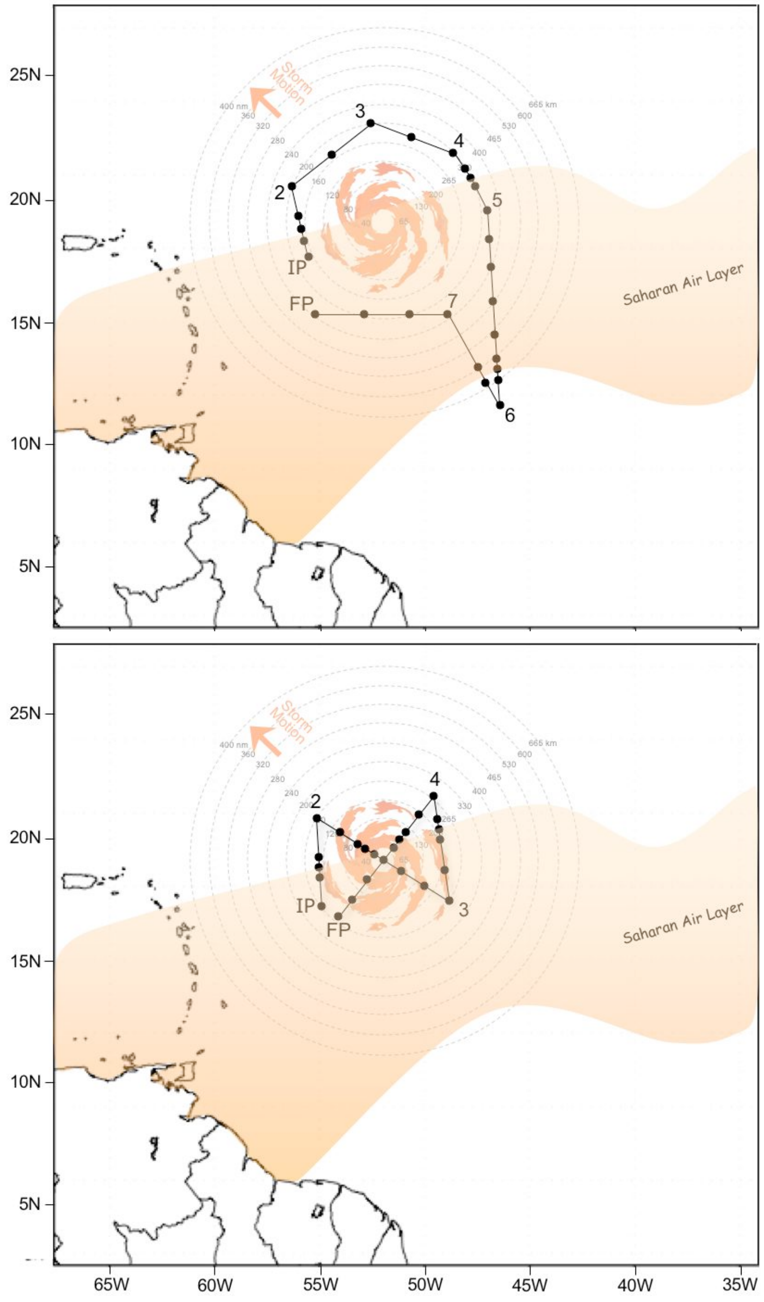


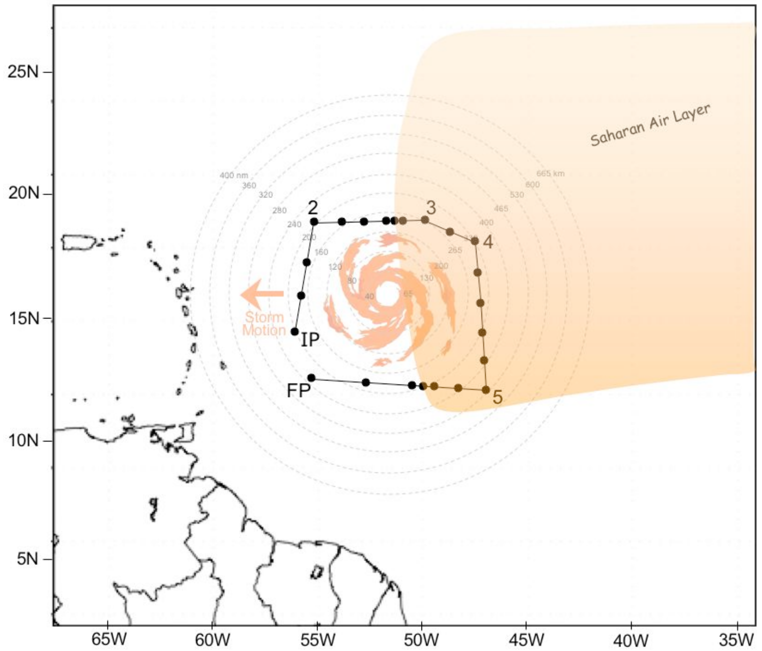
Fig. 2: Sample G-IV (top) and WP-3D (bottom) flight tracks for a TC emerging from the SAL.

- Note 1: During the ferry to the **IP**, the G-IV (WP-3D) should climb to ~200 hPa/41,000 ft (500 hPa/18,000 ft) as soon as possible and climb as feasible to maintain the highest altitude for the duration of the pattern.
- Note 2: The TC may undergo a period of rapid intensification as it emerges from the SAL.
- Note 3: In order to capture the SAL's horizontal/vertical structure, particular attention should be paid to regions of high moisture gradients across its boundaries (G-IV: **IP-2** and **4-5;** WP-3D: **IP-2** and **3-4**).
- Note 4: The SAL's mid-level easterly jet (~20-50 kt at 600-700 hPa/12,000-10,000 ft) may be evident from GPS dropwindsondes dropped near the SAL's southern boundary (G-IV: **5-6** and **6-7**).

<u>Option 3:</u> Single TC embedded located along the leading edge of the SAL. These systems are often struggle to intensify as they are overtaken by the SAL surge, but do occasionally separate from the SAL and intensify. These systems are often characterized by their low-level circulations racing out ahead (west) of their mid-level convection.

G-IV: The G-IV **IP** will be west of the TC. The 1st leg (**IP-2**) will include intermittent GPS dropwindsonde sampling of the moist tropical environment out ahead of the TC and west of the SAL. The 2nd (**2-3**) leg will sample the moist tropical environment north of the TC and west of the SAL followed by a GPS dropwindsonde transect across the leading edge of the SAL (north of the TC). The 3rd (**3-4**) and 4th (**4-5**) legs of the flight pattern will intermittently sample the SAL with specific focus on sampling the gradients associated SAL's mid-level easterly jet (typical located along the southern edge of the SAL). The 5th (**5-IP**) flight leg will include intermittent GPS dropwindsonde sampling of the SAL, followed by a transect across the SAL's leading edge, followed by intermittent GPS dropwindsonde sampling of the moist tropical environment out ahead of the TC and west of the SAL.

WP-3D: The WP-3D **IP** will be west of the TC. The 1st leg (**IP-2**) will include intermittent GPS dropwindsonde sampling of the moist tropical environment out ahead of the TC and west of the SAL. The 2nd leg (**2-3**) of the flight pattern will sample the boundary between moist tropical air north of the TC center and the SAL to the south and will include a penetration of the TC center of circulation. Particular attention will be focused on sampling dry SAL air near the TC inner core. The 3rd leg (**3-4**) will include intermittent GPS dropwindsonde sampling within the SAL with specific focus on sampling the gradients associated SAL's mid-level easterly jet (typical located along the southern edge of the SAL). The 4th leg (**4-FP**) will sample the boundary between moist tropical air west of the TC center and the SAL to the east and will include a penetration of the TC center of circulation. Particular attention will be focused on sampling dry SAL air near the TC inner core.



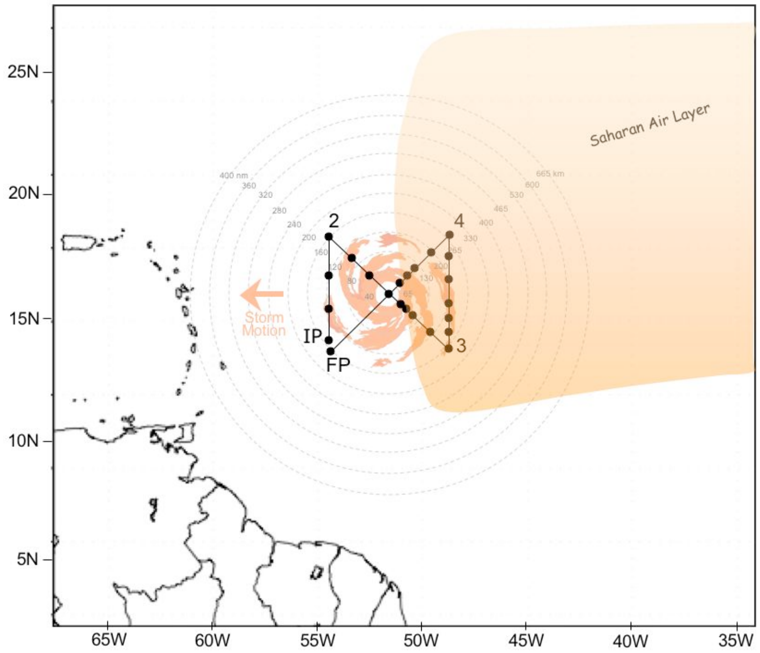


Fig. 3: Sample G-IV (top) and WP-3D (bottom) flight tracks for a TC along the leading edge of the SAL.

- Note 1: During the ferry to the **IP**, the G-IV (WP-3D) should climb to ~200 hPa/41,000 ft (500 hPa/18,000 ft) as soon as possible and climb as feasible to maintain the highest altitude for the duration of the pattern.
- Note 2: The TC will likely struggle to intensify as it is overtaken by the SAL. Slow intensification is possible if the TC is able to separate from the SAL.
- Note 3: In order to capture the SAL's horizontal/vertical structure, particular attention should be paid to regions of high moisture gradients across its boundaries (G-IV: **2-3** and **5-FP**; WP-3D: **2-3** and **4-FP**).
- Note 4: The SAL's mid-level easterly jet (~20-50 kt at 600-700 hPa/12,000-10,000 ft) may be evident from GPS dropwindsondes dropped near the SAL's southern boundary (G-IV: **4-5** and **5-FP**; WP-3D: **2-3** and **3-4**).

Option 4: Single TC embedded within the SAL throughout most or all of its lifecycle. These systems struggle to intensify and are often characterized by their low-level circulations racing out ahead (west) of their mid-level convection. Depending on the proximity of these features, the SAL's dry air may be wrapping into the TC's low-level circulation (western semicircle).

G-IV: The **IP** will be north of the TC and preferably north of the SAL. The 1st leg (**IP-2**) will include a GPS dropwindsonde transect across the northern and southern boundaries of the SAL. These dropwindsonde sequences will focus on sampling the large humidity gradients across the SAL boundaries as well as the SAL's mid-level easterly jet (typical located along the southern edge of the SAL). These scenarios (TC embedded within the SAL) are typically cases where the TC is under the influence of a strong SAL easterly jet. The 2nd leg (**2-3**) of the flight pattern will intermittently sample the moist tropical environment south of the SAL. The 3rd leg (**3-4**) will include a GPS dropwindsonde sequence that will be focused along the dry air inflow region on the west semicircle of the TC. This drop sequence will sample the intrusion of low humidity SAL air into the TC circulation and help to define how the SAL's vertical structure and moisture content modify as it advects closer to the TC inner core. A final GPS dropwindsonde transect (**4-FP**) will be made across the area of high moisture gradients at the SAL's northern boundary and in the relatively moister tropical environment north and northwest of the SAL.

WP-3D: The **IP** will be NW of the TC and preferably north of the SAL. The 1st leg (**IP-2**) will include a GPS dropwindsonde transect across the northern boundary of the SAL. This dropwindsonde sequences will focus on sampling the large humidity gradients across the SAL. The 2nd leg (**2-3**) of the flight pattern will intermittently sample the moist tropical environment south of the SAL and will include a GPS dropwindsonde transect across the southern boundary of the SAL as well as the SAL's mid-level easterly jet (typical located along the southern edge of the SAL). The 3rd (**3-4**) and 4th (**4-5**) legs will include a GPS dropwindsonde sequence that will be focused along the dry air inflow region on the west semicircle of the TC. This drop sequence will sample the intrusion of low humidity SAL air into the TC circulation and help to define how the SAL's vertical structure and moisture content modify as it advects closer to the TC inner core. The final leg (**4-FP**) will sample the boundary between moist tropical air west of the TC center and the SAL to the east and will include a penetration of the TC center of circulation. Particular attention will be focused on sampling dry SAL air near the TC inner core.

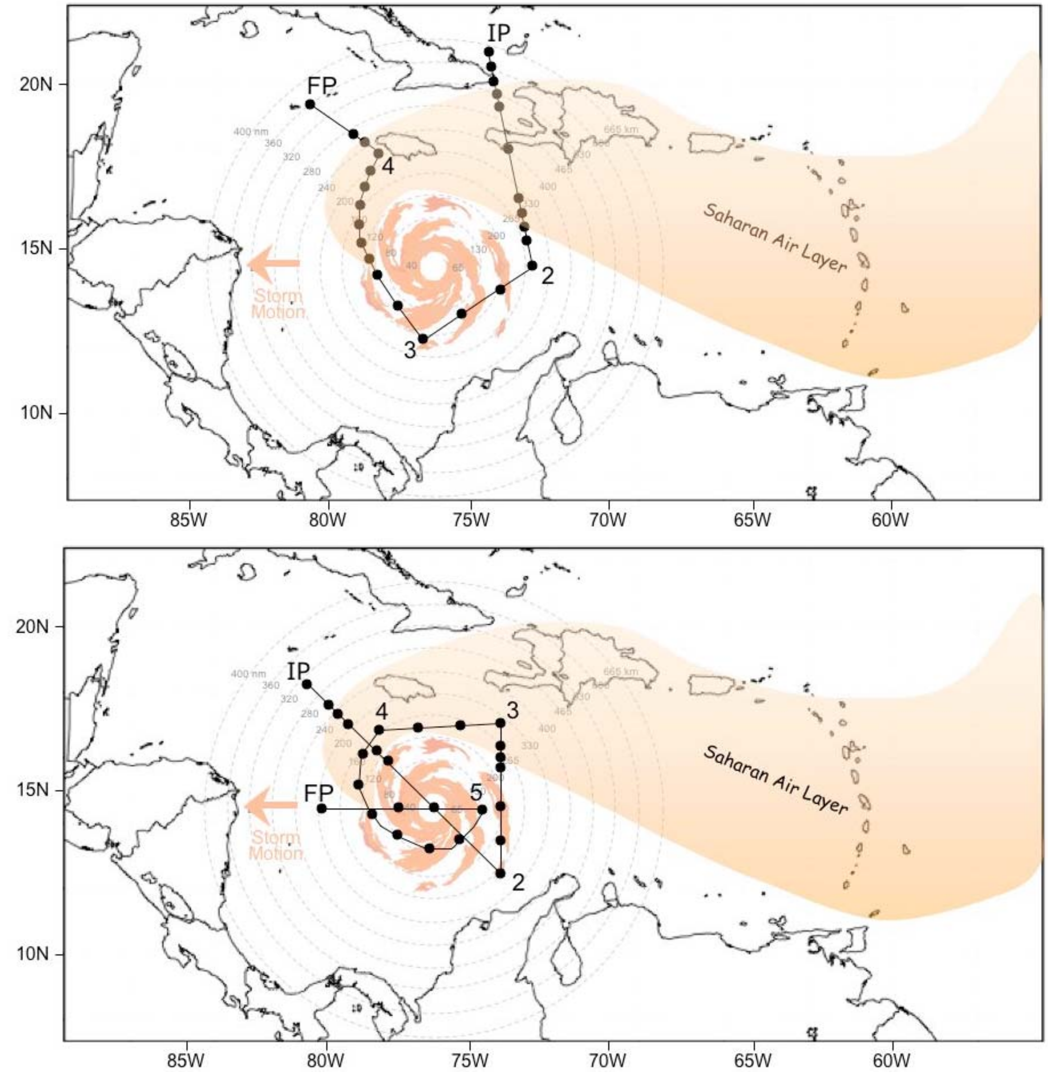


Fig. 4: Sample G-IV (top) and WP-3D (bottom) flight track for a TC embedded in the SAL for most or all of its lifecycle.

- Note 1: During the ferry to the **IP**, The G-IV (WP-3D) should climb to ~200 hPa/~41,000 ft (500 hPa/18,000 ft) as soon as possible and climb as feasible to maintain the highest altitude for the duration of the pattern.
- Note 2: In order to capture the SAL structure, particular attention should be paid to regions of high moisture gradients across its boundaries (G-IV: **IP-2** and **4-FP**; WP-3D: **IP-2** and **2-3**).
- Note 3: The TC's low-level circulation may race ahead of its mid-level convection due to the influence of the SAL's mid-level easterly jet.
- Note 4: The SAL's mid-level easterly jet (~20-50 kt at 600-700 hPa/15,000-10,000 ft) may be evident from GPS dropwindsondes dropped near the SAL's southern boundary (G-IV: **IP-2**; WP-3D: **2-3**).

IFEX MISSIONS (CONT'D
10. Hurricane Synoptic-Flow Experiment

Program Significance: Accurate numerical TC forecasts require the representation of meteorological fields on a variety of scales, and the assimilation of the data into realistic models. Omega dropwindsonde (ODW) observations from WP-3D aircraft obtained between 1982 and 1996 during the Hurricane Synoptic Flow Experiment produced significant improvement in the guidance for official track forecasts. Since 1997, more than 130 operational "Synoptic Surveillance" missions have been flown with the NOAA G-IV jet in the environments of TCs threatening the United States coastline; some of these have been supplemented with dropwindsonde observations from one or two WP-3D or USAF C-130 aircraft. An improved dropwindsonde based on the Global Positioning System has been developed by the National Center for Atmospheric Research and has replaced the ODW. With further operational use of the G-IV aircraft, and as other mobile observing platforms become available, optimal sampling and utilization techniques must be devised to provide the greatest possible improvement in initial condition specification.

Objectives: The goal of the NHC/HRD synoptic flow experiment is to improve landfall predictions of TCs by releasing dropwindsondes in the environment of the TC center. These data will be used by TPC/NHC and NCEP to prepare objective analyses and official forecasts through their assimilation into operational numerical prediction models. Because the atmosphere is known to be chaotic, very small perturbations to initial conditions in some locations can amplify with time. However, in other locations, perturbations may result in only small differences in subsequent forecasts. Therefore, targeting locations in which the initial conditions have errors that grow most rapidly may lead to the largest possible forecast improvements. Locating these regions that impact the particular forecast is necessary. When such regions are sampled at regularly spaced intervals the impact is most positive. The optimal targeting and sampling strategies is an ongoing area of research.

A number of methods to find targets have been investigated, mainly in the wintertime extratropics. Potential vorticity diagnosis can help to find the cause of forecast failure. Singular vectors of the linearized equations of motion can estimate the growth of small perturbations in the model. This method is relatively expensive, and full implementation in the Tropics where adiabatic processes dominate has proven difficult, and the linear assumption tends to break down at the 72 h forecast time necessary for the posting of hurricane watches and warnings. Related strategies involve the sensitivity vector, and quasi-inverse linear method. All these methods may depend on the accuracy of the initial conditions determined without the supplemental data.

A fully nonlinear technique uses the breeding method, the operational NCEP perturbation technique in which initially random perturbations are repeatedly evolved and rescaled over a relatively short cycling time. These vectors are related to local Lyapunov vectors and, therefore, define the fastest growing modes of the system. Changes to initial conditions due to dropwindsonde data obtained from operational synoptic surveillance missions during the 1997 and 1998 hurricane seasons grow (decay) in regions of large (small) perturbation in the operational NCEP Ensemble Forecasting System. Therefore, these bred-modes provide a good estimate of the locations in which supplemental observations are likely to have the most impact. However, though the breeding method can find locations of probable error growth in the model globally, it does not distinguish those locations, which impact the particular forecast from those which do not.

A more generalized method which can use any dynamical ensemble forecast system is the ensemble transform. This method transforms an ensemble of forecasts appropriate for one observational network into one appropriate for other observational networks. Ensemble forecasts corresponding to adaptations of the standard observational network are computed, and the expected prediction error variance at the observation time is computed for each potential network. The prediction error variance is calculated using the distances between the forecast tracks from all ensemble members and the ensemble mean. These last two methods are currently undergoing testing with Observing System Experiments to discern an optimal targeting technique.

Links to IFEX: This experiment supports the following NOAA IFEX goals:

- **Goal 1**: Collect observations that span the TC lifecycle in a variety of environments;

Mission Description: To assess targeting strategies a relatively uniform distribution of dropwindsondes will be released over a minimum period by various aircraft operating *simultaneously.* 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.

In 2006, it is unlikely NHC/HRD will perform synoptic flow missions with the WP-3D aircraft unless NOAA is tasked by NHC to do so. The flight patterns described here can be adopted for implementation by the USAF C-130 aircraft on tasked surveillance missions which could be augmented by one of the NOAA WP-3Ds only on a non-interference basis with other research or operationally-tasked missions. A current goal is to obtain oversampled datasets with which to study the effectiveness of the various targeting techniques described above. This goal usually requires the deployment of more than one aircraft during a particular mission.

A sample mission is shown in Fig. SYN-1. The two WP-3D or C-130 aircraft and the G-IV will begin their missions at the same time. Subject to safety and operational constraints, each WP-3D or C-130 will climb to the 500 hPa level (about 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.*

Beyond 60 nm (111 km) from the storm center, drops are made at pre-assigned locations, generally every 120 nm (222 km). These drop locations are provided with the particular mission flight tracks 24 h before departure and may potentially be modified in-flight. Since dropwindsonde data within 60 nm (111 km) of the storm center are automatically rejected by the operational data assimilation schemes, such observations are not made unless requested as part of other tasking requirements.

If a NOAA WP-3D aircraft is involved in the missions, at least one will fly through the TC center and execute a figure-4 pattern. This aircraft's Doppler radar 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. SYN-2, although the actual orientation of these tracks may be rotated.

Of paramount importance is the transmission of the dropwindsonde data to NCEP and TPC/NHC for timely incorporation into operational analyses, models, forecasts, and warnings. Operational constraints dictate an 0600 or 1800 UTC departure time, so that most of 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 TPC/NHC's analysis and forecasting schedules.

HURRICANE SYNOPTIC FLOW EXPERIMENT

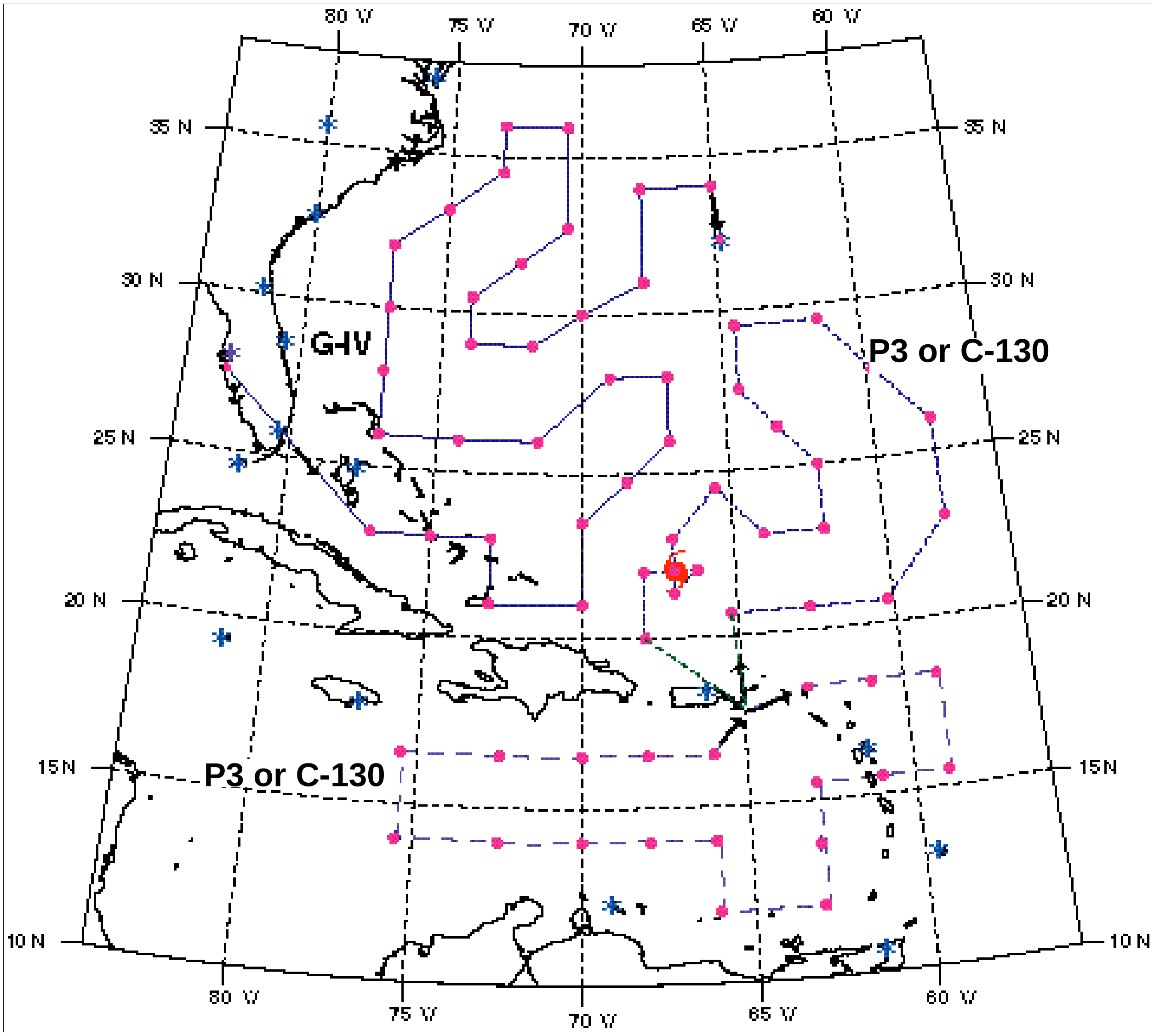


Figure SYN-1: Sample Environmental Patterns

• Note 1:	During the ferry to the **IP**, the WP-3D or C-130 aircraft will climb to the 500 hPa level (about FL 180). The 400 hPa 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 hPa) as soon as possible and climb as feasible to maintain the highest altitude for the duration of the pattern.

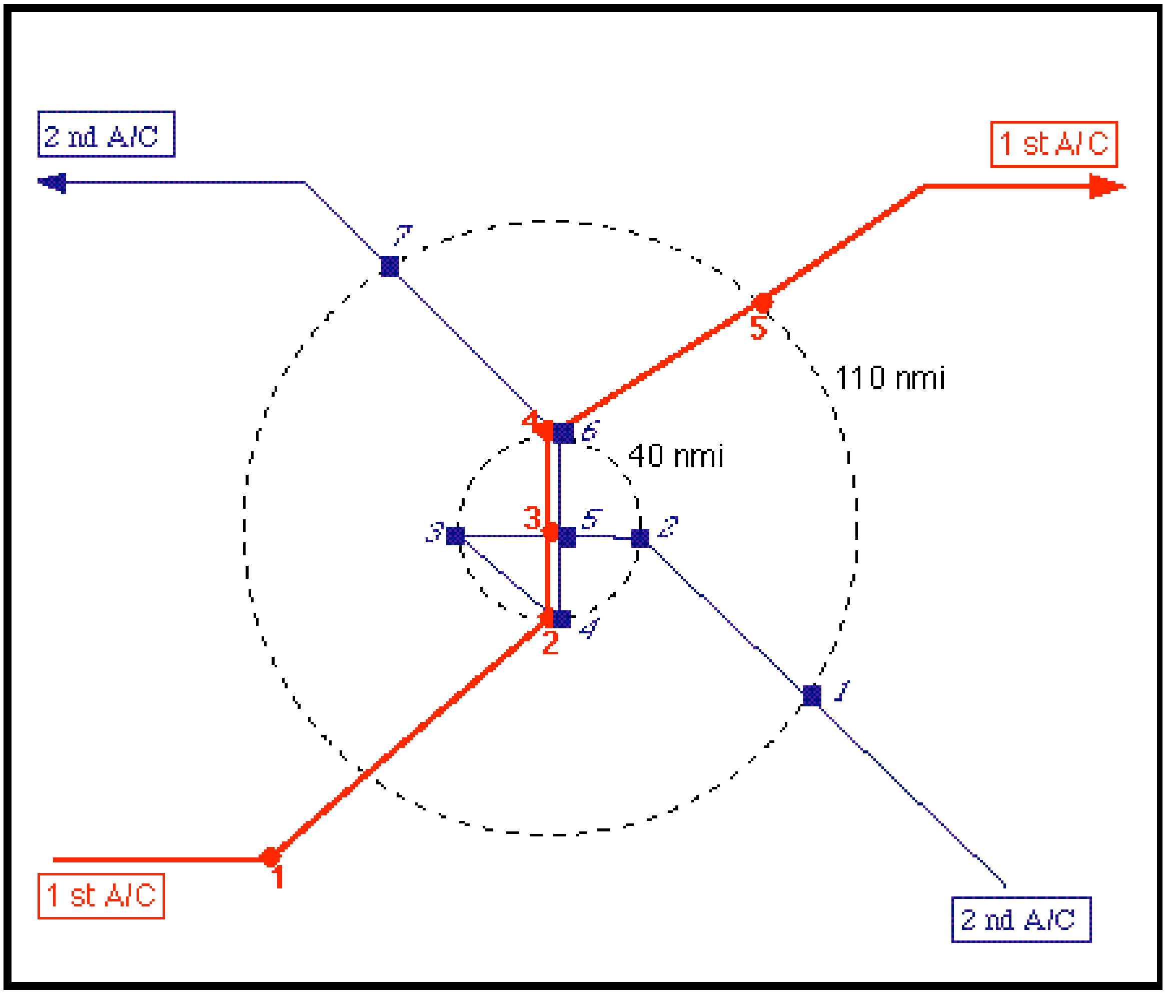


Figure SYN-2: In-Storm Patterns

• Note 1:	Within the 40 nm (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 dropsonde data, 3-4 RECCO's h^{-1} should be transmitted during each mission.

Special Notes: Missions similar to the Synoptic Flow missions may be flown in non-hurricane conditions to collect GPS dropsonde data sets for satellite sounding evaluations. These missions differ from the normal experiment as follows:

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

Saharan Air Layer - Synoptic Surveillance Follow-on

Mission Description: This follow-on module will be executed by HRD, using HRD resources and will be carried out within the constraints of the pre-determined operational flight track. Additional intermediate GPS dropwindsondes (HRD supplied) may be requested along the flight track to target specific areas of interest. GPS dropwindsondes will be launched from the G-IV (flying at ~200 hPa/~41,000 ft) or the WP-3D (flying at ~500 hPa/~20,000 ft) along the operational Synoptic Surveillance flight pattern. These additional drop locations will be selected using real-time GOES Saharan Air Layer (SAL) tracking imagery from UW-CIMSS and mosaics of SSM/I total precipitable water from the Naval Research Laboratory. Specific effort will be made to gather atmospheric information within the SAL as well as regions of high moisture gradients across its boundaries. The main goals of this experiment are to:

- Better understand how the SAL's dry air, mid-level easterly jet, and suspended mineral dust affect Atlantic TC intensity change.
- Include the moisture information from the GPS dropwindsondes in operational parallel runs of the NOAA Global Forecast System (GFS) model. The impact of this data on the GFS initial/forecast humidity fields and its forecasts of TC track and intensity will be assessed.

Several SAL/TC interaction scenarios are candidates for this follow on mission:

1) Single tropical cyclone (TC) located along the southern edge of the SAL. Depending on the proximity of these two features, the SAL's dry air may be wrapping into the TC's low-level circulation (western quadrants). GPS dropwindsonde sequences will be focused along this dry air inflow region (west of the TC), across regions of high moisture gradients at the SAL's leading edge (northwest of the TC), and across the southern boundary of the SAL (north and northeast of the TC). The SAL's mid-level jet will also be sampled in the region of the latter transect.

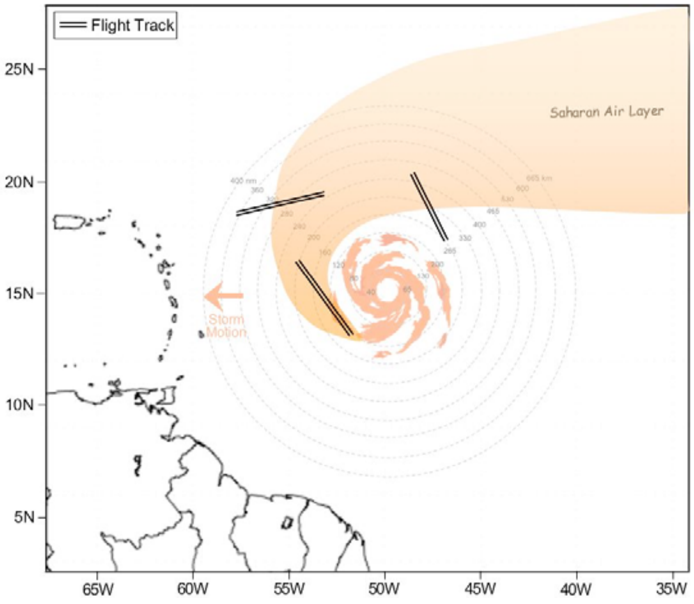


Figure SYN-3: Sample flight track for a TC positioned along the SAL's southern boundary.

2) Single TC is embedded within the SAL and intensifies upon emerging. These systems are often candidates for rapid intensification. GPS dropwindsonde transects perpendicular to the northern boundary of the SAL and near to possible points of the TC's emergence from the SAL are desirable. Additional transects will be focused along the SAL's southern boundary (south of the TC). The SAL's mid-level jet will also be sampled, particularly along those transects on the eastern sides of the TC.

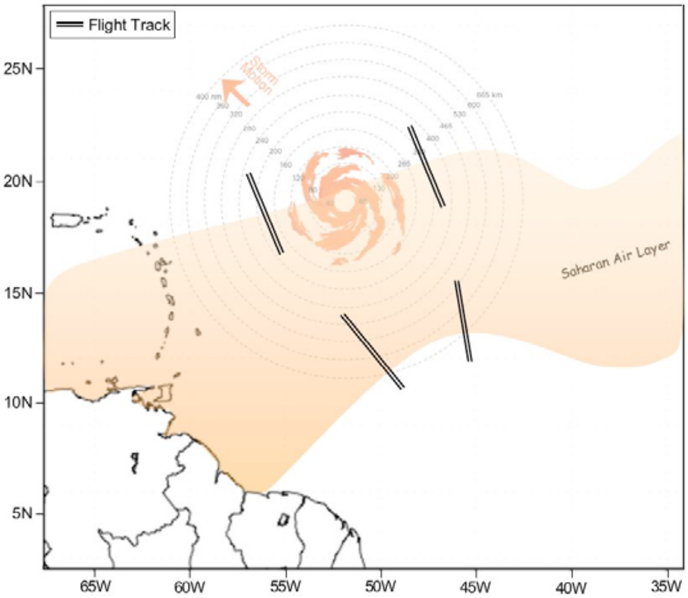


Figure SYN-4: Sample flight track for a TC emerging from the SAL.

3) Single TC embedded within the SAL throughout most or all of its lifecycle. These systems struggle to intensify and are often characterized by their low-level circulation racing out ahead (west) of their mid-level convection. Depending on the TC's proximity to the SAL, the SAL's dry air may be wrapping into its low-level circulation (western semicircle). GPS dropwindsonde sequences will be focused along this dry air inflow region (west of the TC), across regions of high moisture gradients at the SAL's northern boundary (north of the TC), and across regions of high moisture gradients at the SAL's southern boundary (east of the TC). The SAL's mid-level jet will also be sampled, particularly in the region of the latter transect.

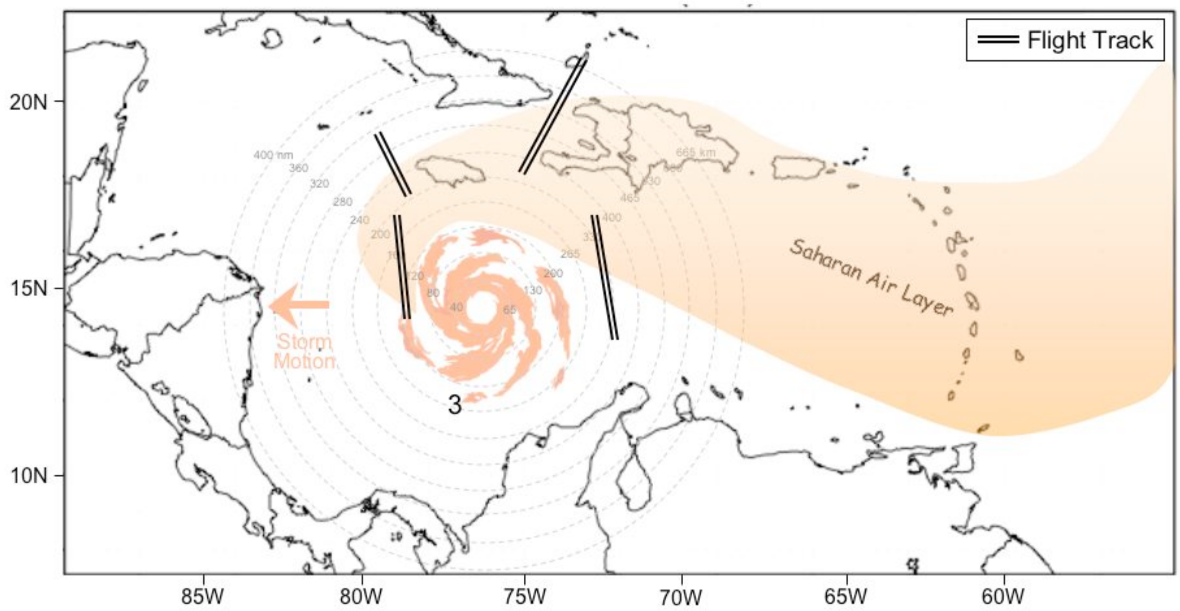


Figure SYN-5: Sample flight track for a TC embedded in the SAL for most or all of its lifecycle.

- Note 1: During the ferry to the **IP**, the WP-3D aircraft will climb to the ~500 hPa level (~20,000 ft). The 400 hPa level (~25,000 ft) 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 ~200 hPa (~41,000 ft) as soon as possible and climb as feasible to maintain the highest altitude for the duration of the pattern.
- Note 3: In order to capture the SAL's horizontal/vertical structure, particular attention should be paid to regions of high moisture gradients across its boundaries.