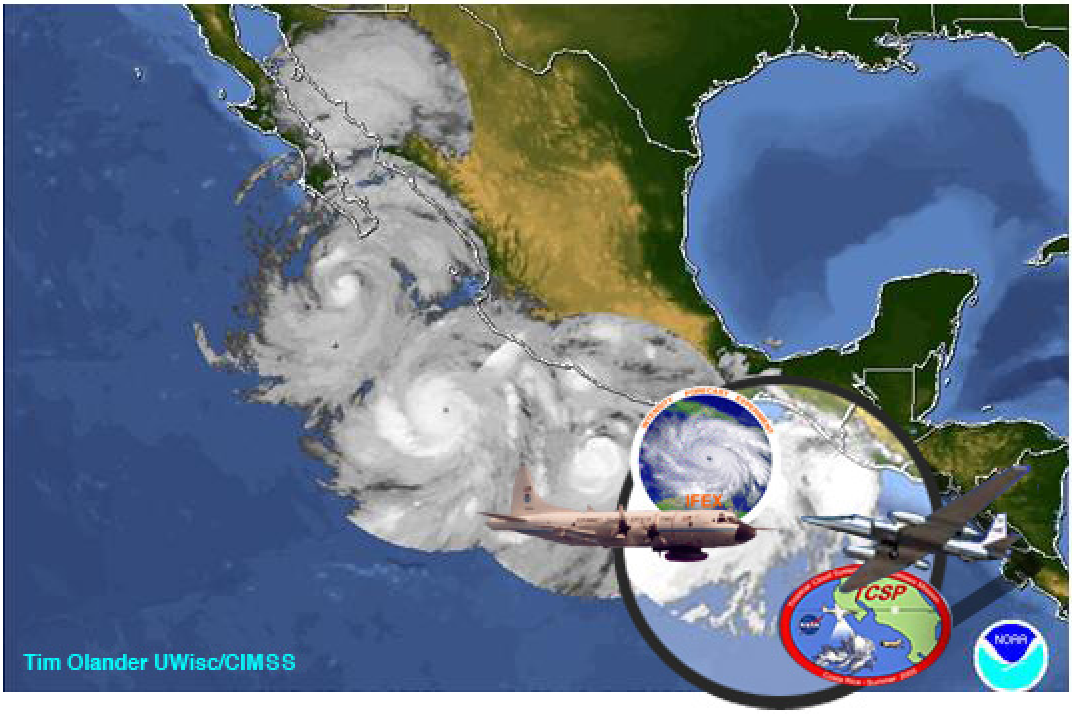
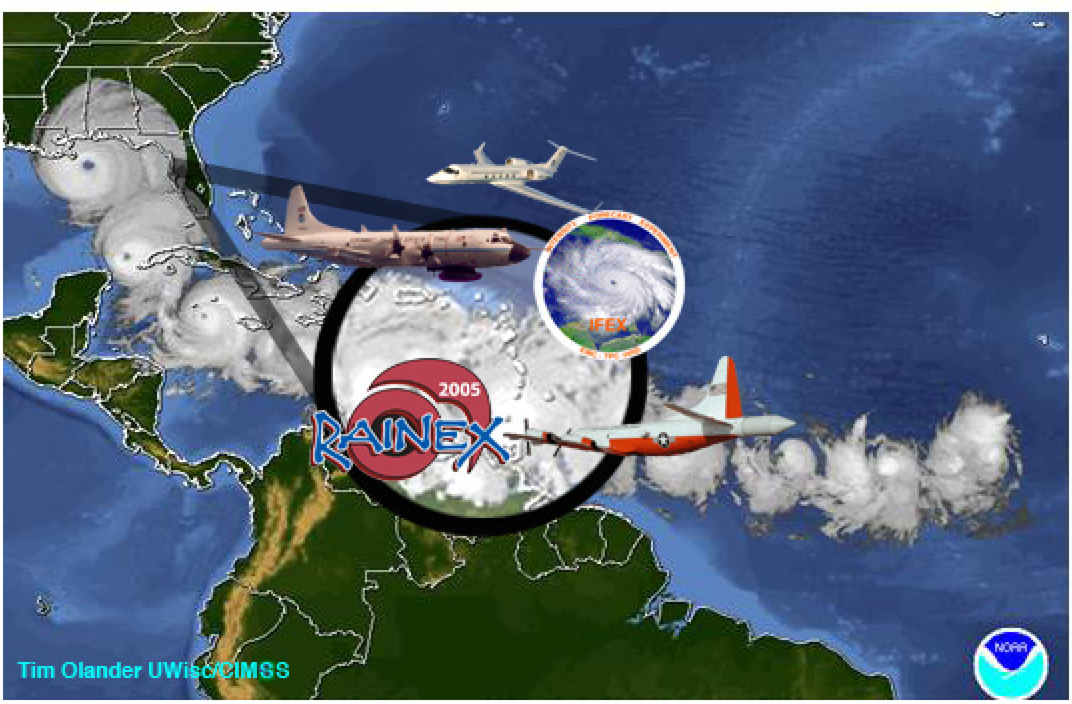
2005 HURRICANE FIELD PROGRAM Plan





NSF NASA NOAA

2005 Hurricane Field Program Plan

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Cover:

CONTENTS

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INTRODUCTION

National Oceanic and Atmospheric Administration
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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) Tropical Prediction Center (TPC) 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), TPC, 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:

1. Collect observations throughout the life cycle of a TC for the development of a 3-D variational assimilation of the hurricane core circulation.
2. Collect observations of the atmosphere and ocean in and around the storm scale circulation that can be used to develop an evaluation and validation package for the high resolution HWRF.
3. Collect observations in a variety of atmospheric/oceanic conditions (e.g. atmospheric shear and humidity environments, oceanic warm core eddies) to assess the influence of these features on observed and model TC intensity and structure changes.
4. Improve understanding and develop improved model representations of sea spray/surface flux effects on boundary layer structure and microphysics, especially in the core and rainbands. Develop techniques for evaluating ocean vertical mixing parameterizations against observed data.
5. Improve the understanding of the phase changes of moisture.
6. Determine the storm intensity and structure change during decay over cold water.

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. For example, the eastern North Pacific is an ideal location for genesis studies, since that region has the highest frequency of tropical cyclogenesis per unit area in the world. The western Atlantic, Caribbean Sea, and Gulf of Mexico are ideally suited for studying storms during their mature, landfalling, and extratropical transition stages of their lifecycle.

The field program presented here contains several flight experiments that are intended to be flown during the 2005 season. The flight patterns that comprise these experiments address various aspects of the tropical cyclone lifecycle, and they all specifically address IFEX goals. There is an experiment to investigate tropical cyclogenesis, an experiment to observe the structure of mature tropical cyclones, an experiment for decay over cold water, an experiment for sampling the tropical cyclone environment, and an experiment to measure the structural changes that accompany tropical cyclones at landfall. These experiments will be conducted with the NOAA/Aircraft Operations Center (AOC) WP-3D N43RF and N42RF and Gulfstream IV-SP aircraft. A summary of each experiment, along with which IFEX goals the experiment addresses, is included below. A more detailed description of each experiment follows, which includes a description of the scientific rationale for the experiment and flight patterns comprising the experiment.

(1) 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 will address IFEX goals #1 and 2 by taking measurements at the beginning of the life cycle of a TC for the development of a 3-D variational assimilation for incipient disturbances and to be used for evaluation and validation of the HWRF model. Measurements of microphysics quantities will improve our understanding of the phase changes of moisture (IFEX goal #5).

(2) Mature-Storms Experiment: This *multi-option*, *multi-aircraft* experiment is designed to provide data sets that improve our understanding of intensity and structure change in tropical cyclones that have already formed. In the Frequent-Monitoring experiment, particular emphasis is placed upon gathering data sets suitable for the initiation and validation of the Hurricane Weather Research and Forecasting (HWRF) model (IFEX goals #1 - 3). This *single-aircraft* or *dual-aircraft* module is repeated every 12 hours (depression to weak hurricane stage) or 24 hours (mature hurricane stage) to provide the maximum possible temporal resolution over the lifetime of the storm to evaluate the accuracy of the model, and provide a temporal stream of data to assimilate into the model. The NESDIS Ocean Winds and Rain Experiment is a *multi-option single-aircraft* experiment designed to improve understanding of microwave remote sensing of the ocean surface wind field in high-wind and heavy-rainfall conditions. Data are collected by the Integrated Wind and Rain Airborne Profiler (IWRAP), which operates as both a surface scatterometer and a high-resolution Doppler radar, and the UMASS Stepped Frequency Microwave radiometer (USFMR). These instruments provide a better understanding of the scatterometery characteristics in very high wind conditions. The Hurricane Rainband and Intensity Experiment (RAINEX) is a *dual- or multi-aircraft* experiment designed to collect dropsonde and airborne Doppler data simultaneously in the eyewall and rainbands to document the dynamic interaction between these features, and the role this interaction has on the evolution of the structure and intensity of the storm. A CBLAST option allows for low-altitudes measurements of temperature, humidity, winds, and turbulence to improve our understanding of the processes governing surface fluxes of heat, moisture, and momentum (IFEX goal #4). Another module that could be employed is high-resolution sampling of an intense hurricane eye/eyewall with patterns flown within the eye and supplemented by an array of GPS dropwindsondes in the eyewall. These modules could further our understanding of convective processes within the eyewall and mixing processes between the eye and eyewall, both of which are important components of hurricane intensity change associated with internal dynamics (IFEX goals #1,2 and 3).

(3) East Pacific Decay Experiment: The East Pacific decay experiment is designed to collect data in the lower troposphere and upper ocean while a storm is weakening under cooler sea-surface temperatures along the strong oceanic temperature gradient in the Eastern Pacific basin (IFEX goal #6). This module is sponsored by the NHC and hopes to address their needs of understanding the relation between vortex spin down and a resultant decay of surface winds.

(4) Tropical Cyclone Landfall Structure and Intensity 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 will address IFEX goals #2 and 3 by taking measurements at the end of the life cycle of a TC to be used for evaluation and validation of HWRF and by collecting observations in a variety of atmospheric/oceanic conditions to assess the influence of these features on observed and model TC intensity and structure changes.

(5) Hurricane Synoptic-Flow Experiment: Since the arrival of the new NOAA Gulfstream IV-SP high-altitude jet (G-IV), the HRD Hurricane Synoptic Flow Experiment has made the transition from a research program to operations. Beginning in 1997, the G-IV started conducting routine "hurricane surveillance" missions that are essentially HRD Synoptic Flow experiments. When coordinated with these operational G-IV flights, the HRD Synoptic Flow experiment now becomes a *single-option, multi-aircraft* experiment. As in previous years, the experiment seeks to obtain accurate, high-density wind and thermodynamic data sets from the environment and vortex regions of tropical cyclones (TC) that are within 72 h of potential landfall. The availability of the G-IV, however, greatly increases the amount of environment sampled. GPS-based dropwindsondes (GPS-sondes) deployed from the G-IV and the two NOAA/AOC WP-3D or Air Force C-130 aircraft provide these data over the normally data-void oceanic regions at distances up to 810 nm (1500 km) from the TC center. Mandatory and significant level GPS-sonde data, transmitted in real time, are used to prepare official forecasts at the Tropical Prediction Center/National Hurricane Center (TPC/NHC). These data are also incorporated into objective statistical and dynamical TC prediction models at TPC/NHC and the National Centers for Environmental Prediction (NCEP). In a research mode, these data help improve short and medium term (24-72 h) TC track predictions, study the influence of synoptic-scale fields on vortex track and intensity, and assess methods for obtaining satellite soundings (IFEX goal #3).

(6) Saharan Air Layer Experiment: This is a multi-option, single aircraft experiment which uses GPS dropwindsondes launched from the NOAA the G-IV (flying at ~200 mb/~41,000 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. The goal of this experiment is to better understand and predict how the SAL's dry air, mid-level easterly jet, and suspended mineral dust affect Atlantic TC intensity change (IFEX goals #3 and 5).

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. 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.

NASA has planned an experiment called Tropical Cloud Systems and Processes (TCSP), one of whose primary goals is to increase the overall understanding of tropical cyclone genesis, intensity change, motion, and rainfall by identifying remote sensing measurements and modeling requirements for improved hurricane predictability. They will be based in San Jose, Costa Rica during July 2005. HRD has committed to deploy to San Jose, Costa Rica and Acapulco, Mexico for up to 20 days during July 2005 to fly coordinated missions with the NASA DC-8 and ER-2 aircraft to study tropical cyclogenesis and, possibly, decay of mature storms over cooler water. An overview of this experiment can be found at:

http://research.hq.nasa.gov/code_y/nra/current/NNH04ZYS003N/index.html

Another experiment, the Hurricane Rainband and Intensity Change Experiment (RAINEX) funded by the National Science Fundation, will investigate the interactions between a tropical cyclone's inner core and outer rainbands and the role of these interactions in storm structure and intensity change. It will involve the two dual-Doppler equipped NOAA WP-3D aircraft plus the NRL P-3 with the NCAR ELDORA dual-Doppler system and GPS dropsondes to observe both the inner core and rainband structures simultaneously. This experiment will occur during August and September of 2005, and will use NOAA P-3 flight hours associated with IFEX and the NRL P-3 to conduct coordinated missions around rainbands and in the inner core of mature tropical cyclones. An overview of this experiment can be found at:

http://www.joss.ucar.edu/rainex/

OPERATIONS

1. Locations

Starting on or about July 1, the two NOAA P3 aircraft will be deployed to bases in San Jose, Costa Rica and Acapulco, Mexico for missions in the Western Caribbean, Gulf of Mexico, and Eastern Pacific basin. Starting about August 15, the primary base of operations for the NOAA aircraft will be Tampa, Florida, with provision for deployments to Bermuda, Barbados, and St. Croix for storms in the Atlantic basin (including the Atlantic Ocean and the Caribbean Sea).

The NOAA aircraft may deploy to U.S. coastal locations in the western Gulf of Mexico for suitable Gulf storms and to western Mexico for eastern Pacific storms. Occasionally, post mission recovery may be accomplished elsewhere.

The area of operations and associated primary bases are shown on the following set of maps. The range rings on the maps are 1000 km or 1500 km that represent approximately 2 and 3 hours of P3 ferry time, respectively.

2. Field Program Duration

The hurricane field research program will be conducted from 1 July through 31 October 2005. Active periods of operations which require both P3 aircraft will be from 1 July to 25 July and from about 15 August until 30 September 2005. One of the P3s should also be available for research opportunities during October of 2005.

3. Research Mission Operations

The decision and notification process for hurricane research missions is shown, in flow chart form, in Fig. A-1 (Appendix A in part II of the HFP). The names of those who are to receive primary notification at each decision/ notification point shown in Fig. A-1 are in Tables A-1 and A-2 (Appendix A in part II of the HFP). Contacts are also maintained each weekday among the directors of HRD/AOML, TPC/NHC, 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

Both NOAA/AOC WP-3D aircraft (N42RF, N43RF), equipped as shown in Table B (Appendix B in part II of the HFP), will be available for research operations throughout the 2005 Hurricane Field Program (on or about 1 July to 25 July and from about 15 August through 30 September). Also, the G-IV aircraft should be available, on a non-interference basis with operational surveillance or inner-core “tasked” flights, from about 1 July to 31 October 2005. The G-IV jet aircraft will be used for research flights during the Saharan Air-Layer Experiment.

5. Field Operations

5.1 Scientific Leadership Responsibilities

The implementation of the HRD 2005 Hurricane Field Program Plan is the responsibility of the field program director and, as designated, by the deputy director, who in turn, is responsible 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-2.10 (Appendix B in part II of the HFP) list the NOAA scientific crewmembers needed to conduct the 2005 hurricane field experiments. Actual named assignments may be adjusted on a case-by-case basis. Operations in 2005 will include completion of detailed records by each scientific member while on the aircraft. General checklists of NOAA science-related functions are included in E.2 through E.6 (Appendix E in part II 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 D.1 through D.12 (Appendix-D in part II 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 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 TCSP investigators, NSF-sponsored RAINEX investigators, and associated university or other Governmental partners.

RAINEX data will be accessible via the web through the JOSS Data Catalog.

All requests for NOAA data gathered during the 2005 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 P3 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 flight at the designated pre-take-off or "show" 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 in part II of the HFP (en-route calibration). 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).

EXPERIMENTS

1.Tropical Cyclogenesis Experiment

Program Significance and Background

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) is the collection of observations during all portions of a tropical cyclone's lifecycle. This emphasis on all stages of the lifecycle, including the genesis stage, will provide an opportunity to observe several genesis events and improve our understanding of this key process.

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 set of theories places primary focus on the dynamical fields as playing the dominant role in genesis. For example, observations of multiple midlevel vortices prior to genesis have led some to view the genesis process as a stochastic one whereby chance merger and axisymmetrization of these midlevel vortices leads to growth of the circulation to the surface (Ritchie et al 1997). Another theory emphasizes the role of a parent midlevel vortex in axisymmetrizing nearby low-level convectively-generated cyclonic vorticity, leading to spin-up of the surface circulation (Montgomery and Enagonio 1998; Davis and Bosart 2001; Montgomery et al 2004). Another set of theories emphasizes the importance of changes in the thermodynamic fields in explaining genesis. These theories focus on the reduction of the effective static stability to low values in the core of the incipient cyclone. 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. In another theory related to the role of downdrafts in determining genesis potential, downdrafts driven by evaporational cooling advect the vorticity of the midlevel vortex downward, enhancing convection and low-level vorticity production (Bister and Emanuel 1997). A third group of theories highlights the combined importance of the dynamic and thermodynamic fields by emphasizing the role the midlevel vortex and high midlevel humidity play 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 (Chen and Frank 1993; Rogers and Fritsch 2001). The purpose of the proposed experiment is to elucidate what role the dynamic (e.g., low- and mid-level vortices) and thermodynamic (e.g., static stability, humidity profiles) fields play in governing tropical cyclogenesis.

Recent observations from airborne Doppler radar have identified important processes on the mesoscale that contribute to tropical cyclogenesis. For example, results obtained from a WP-3D aircraft investigation of Dolly 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 P-3's will also enable a determination of the presence of saturation when scatterers are observed.

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.

Objectives

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

- Develop means for identifying likely candidates for tropical cyclogenesis and techniques for finding and tracking low- and mid-level vortices within these candidates.
- Investigate role, if any, that midlevel vortex plays in organizing deep convection.
- Document the development of low-level vorticity in the presence of a midlevel vortex center.
- Study the interactions between low- and mid-level vortices in pre-genesis environments.
- Determine the importance of static stability decreases through downdraft suppression in tropical cyclogenesis.
- Study the role of humidity profiles and static stability in governing downdraft morphology and vortex response to convective heating.

Mission Description

This experiment may be executed with aircraft from NOAA alone, or NOAA in cooperation with the NASA ER-2 aircraft flying into incipient tropical disturbances over the western Caribbean Sea, Gulf of Mexico, and tropical eastern North Pacific Ocean. The P-3's will be based in San Jose, Costa Rica and Acapulco, Mexico. For missions flown in conjunction with the NASA ER-2, the P-3's will operate out of San Jose. The systems flown here will primarily be incipient systems. If a system undergoes genesis and continues to develop, however, the P-3's my fly the system from San Jose and recover in Acapulco. Flights into the system will continue from Acapulco while it is still in range for the P-3's. When the system reaches its mature stage, it will fly the single-aircraft mature storm pattern (see Mature Storm Experiment in this Field Program Plan) out of Acapulco. If the system has the potential for decaying over the sea-surface temperature front in the East Pacific, the Decay Experiment will be flown (see Decay Experiment in this Field Program Plan).

The primary mission will require two WP-3Ds flying back-to-back missions. They 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 available, the G-IV aircraft would fly simultaneously at upper levels (42,000 ft or 175 mb) 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 Western Caribbean and there were indications of mid- or low-level dry air in the vicinity of the disturbance. The G-IV would operate coincident with the afternoon P-3 flight. The NASA ER-2 can fly at very high altitudes (around 65,000 ft or less than 100 mb), measuring Doppler vertical velocities, reflectivity, temperature, and humidity along flight legs sometimes coordinated with the P-3's.

The main aircraft for the mesoscale flights will be the two WP-3Ds. Doppler radar observations, GPS-sondes, and flight level observations obtained during these flights will help locate low- and mid-level vortices and help document their structures and life cycles. 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. We will also make use of the forecasting center that is being established by NASA in conjunction with Costa Rican meteorologists based in San Jose.

Staggered missions with the two 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-sonde data in the area of deep convection in order to map the evolution of the three-dimensional wind and thermodynamic structure of the deep convection and incipient vortex. 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. GEN-1) along the axis of an easterly wave. Leg lengths will be 150-200 nm (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. GEN-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. GEN-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. 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 (cf. Fig. GEN-3a and Fig. GEN-3b). The tail radar will operate in F/AST mode during the entirety of these patterns. For the P-3 using the NOAA antenna, the tail radar will operate in continuous mode for portions of the legs that are coordinated with the NASA

ER-2 and during modules where the aircraft is flying a coordinated pattern with the ER-2 (see Microphysics Module below).

The NASA ER-2 will fly primarily at night, concurrent with the nighttime P-3. The ER-2 patterns will largely mimic the P-3 patterns, with about a 5-10 nm (10-15 km) offset between the tracks. For portions of the pattern where the P-3 is circumnavigating convective features (cf. Microphysics and Convective burst modules), the ER-2 will perform racetrack or bowtie patterns. Some portions of these two modules, however, will require strict coordination between the two aircraft, with the ER-2 vertically aligned with the P-3 during these legs (see module descriptions and Figs. GEN-5 and GEN-6).

If available, the G-IV will be most beneficial flying a synoptic-scale pattern. It will fly at maximum altitude observing the upper and lower troposphere with GPS-sondes in the pre-genesis and incipient tropical disturbance environment. The G-IV will operate only if the system is in the western Caribbean and is interacting with a Saharan Air Layer (Fig. GEN-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 (primary experiment):**

The two NOAA WP-3D aircraft alone will fly, in the East Pacific, Gulf of Mexico, or western Caribbean basins, either diamond or square-spiral survey patterns to locate low- and mid-level vortices (Figs. GEN-1 or GEN-2). Once a persistent mid-level vortex is located, either rotating figure-4 (Fig. GEN-3) or square-spiral patterns will be flown over a 2-4 day period.

- **Option 2 (optimal experiments):**

A) Option 1 augmented with high-altitude measurements obtained by the NASA ER-2 aircraft operating out of San Jose, Costa Rica.
B) Option 2A augmented with large-scale upper- and lower-tropospheric observations obtained by the G-IV aircraft flying patterns similar to those given in Fig. GEN-4 in the western Caribbean basin.

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) Microphysics Module: This module can be flown as a combination P-3/ER-2 mission or by a P-3 alone. It is intended to collect both *in situ* and remotely-sensed microphysics data, including water and ice concentrations, reflectivity, and vertical and horizontal motion fields. While the primary pattern is flown, locations of active mesoscale convective systems are determined. Once the primary pattern is complete, the aircraft will target one mesoscale convective system, provided an extensive stratiform anvil is present. Due to the possibility of aircraft electrification, this module can only be performed after the primary pattern is completed. The P-3 will penetrate the stratiform rain region from the rear of the convective system at the +1 deg C isotherm (normally an altitude near 14,000 ft; Fig. GEN-5a). Once within the anvil, the aircraft will conduct a box-survey pattern, with the tail radar in Fore/Aft scanning mode. The dimensions of the box should be up to 40 nm, or whatever size will ensure the aircraft stays within the stratiform rain shield and does not reach the leading line of deep convective cores. Once the box is completed, the P-3 will head into the anvil, where it will begin a series of slanted ascents whose leg lengths should not exceed 15 nm (Fig. GEN-5b). The P-3 will climb by 1000 ft during each leg. At the end of each leg, the P-3 will turn 180 degrees, return to the point at the end of the previous leg, and begin the next slanted ascent. The P-3 will again turn 180 degrees and repeat the process up to an altitude of 4000 ft above the starting altitude (around the -3 to -4 deg C isotherm, or near 18,000 ft), traversing the melting level and collecting microphysical data and vertical motion data during the pattern. During these stepped ascents the tail radar should be in continuous mode to provide vertical incidence data. If the tail radar is not able to run in continuous mode, the stepped-ascent pattern should still be flown to collect the *in situ* measurements.

If available, the ER-2 will fly a pattern over the same system with the P-3. During the box survey the ER-2 will fly at altitude, conducting a racetrack or bowtie pattern over the system and collecting remotely-sensed data. When the P-3 is prepared to perform the slanted ascents, the ER-2 will fly an extended leg along the same axis as the P-3, so that a portion of the P-3 pattern will be coincident with the ER-2. Once the ER-2 completes the leg, it will turn 180 degrees, and fly back to the beginning point to get two periods of coincident passes with the P-3. At the end of the return leg the pattern will be complete.

(2) 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 fo convection or at the end of one of the survey patterns. The module can be flown independently with one of the P-3 aircraft or with a P-3 and the NASA ER-2 plane. Once a local area of intense convection is identified, the P-3 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 P-3 is near the original IP, two straight-line crossings of the convective area should be performed with the P-3 avoiding the strongest cores, as necessary for safety considerations. The P-3 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 P-3 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.

If the ER-2 is performing a coordinated mission with the P-3, the NASA aircraft can fly a series of racetracks or bowtie patterns over the convective burst while the P3- is flying the circumnavigation. During the convective crossing, however, the ER-2 should coordinate with the P-3 and perform the crossing vertically-aligned with the P-3 so that the planes are vertically-stacked at approximately the mid-point of the crossing.

Tropical Cyclogenesis Experiment

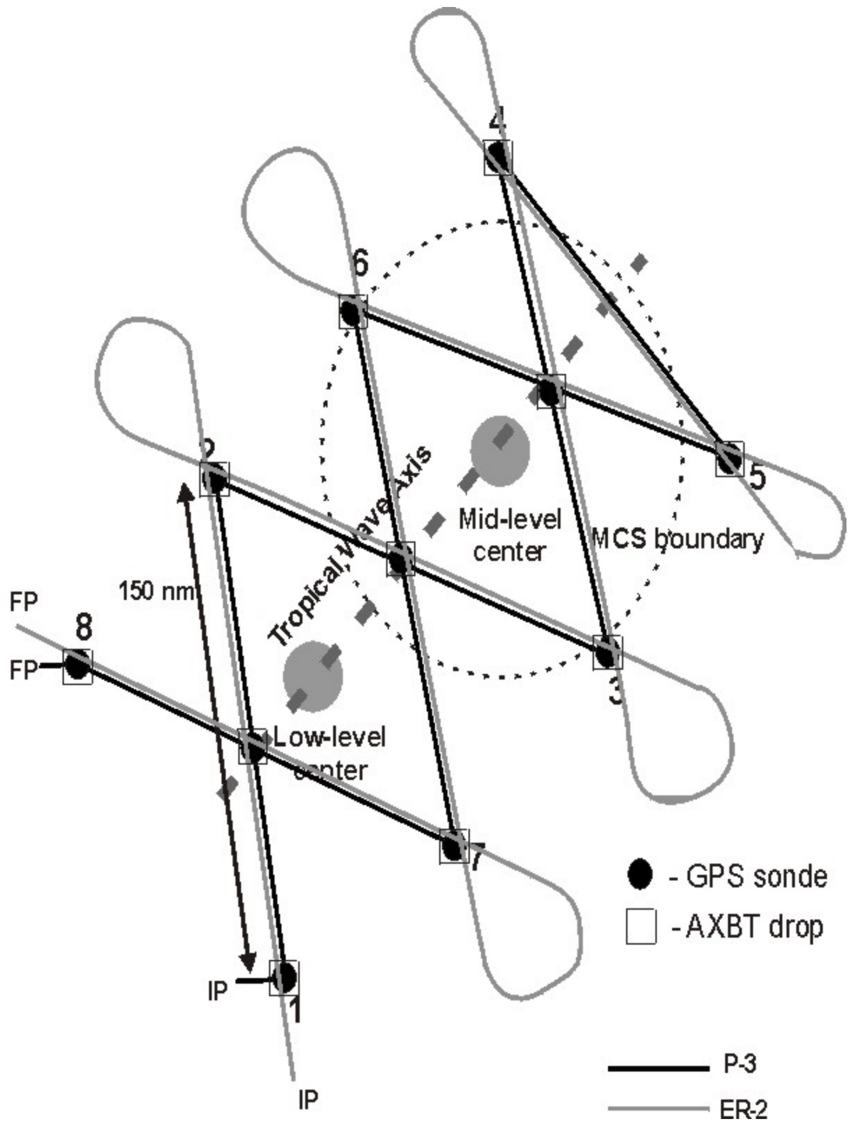


Figure GEN-1. P-3 Vortex survey pattern – Diamond pattern

- 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.
- Note 6. ER-2 track is offset 5-10 nm (10-15 km) from track of P-3.

Tropical Cyclogenesis Experiment

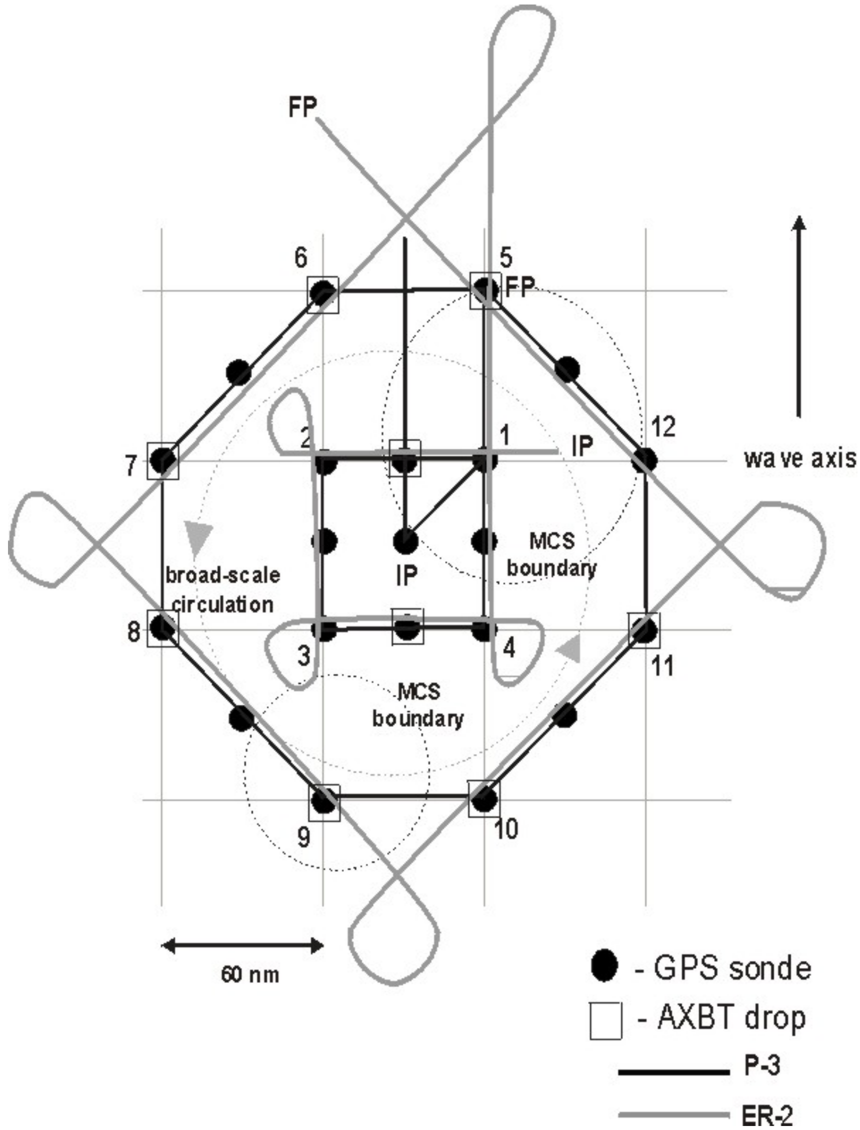


Figure GEN-2. P-3 Vortex survey pattern – Square-spiral pattern

- 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 sonde 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 P-3.

Tropical Cyclogenesis Experiment

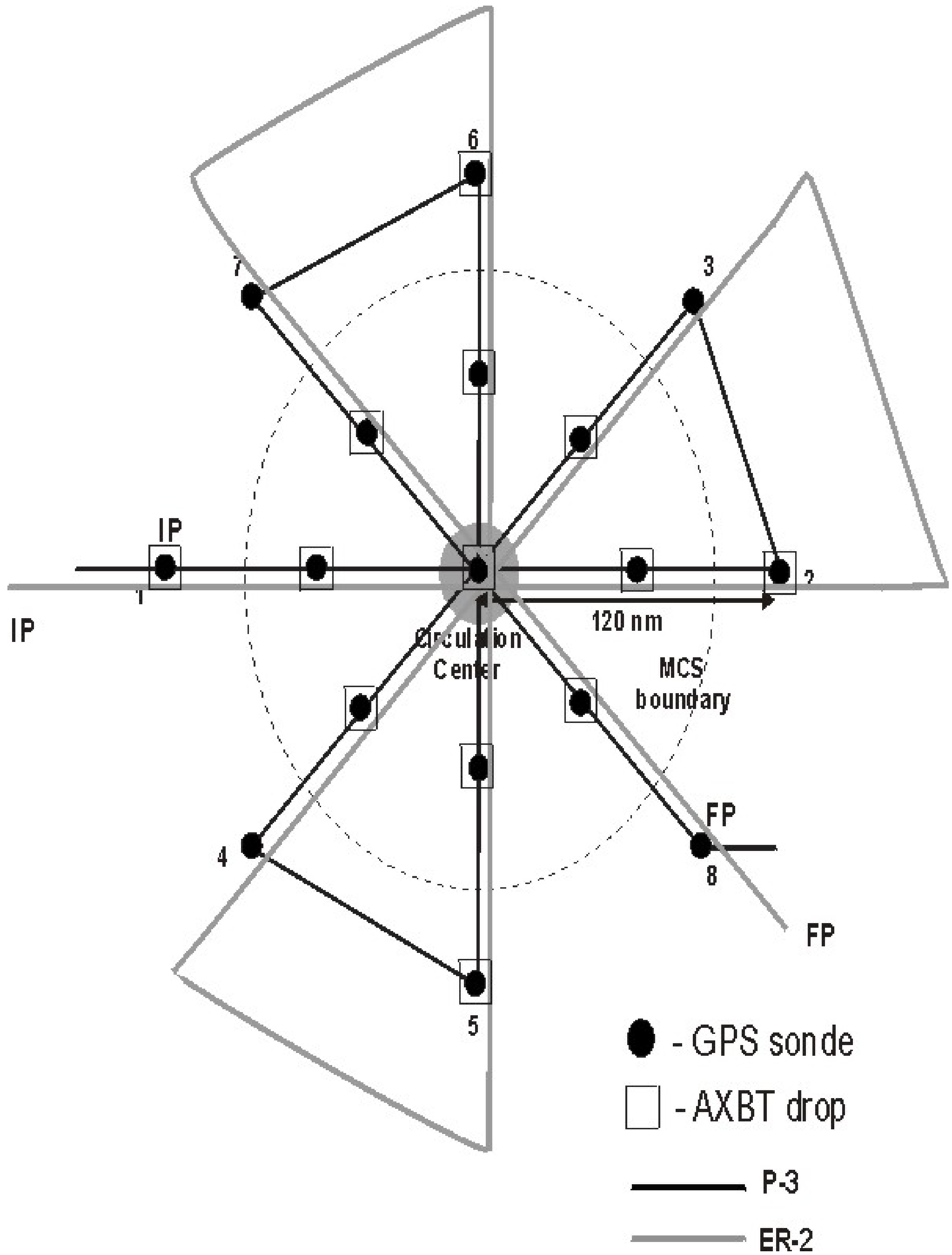


Figure GEN-3a. P-3 Rotating Figure-4 pattern – 8 leg

- 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 except for portions of those legs coordinated with NASA ER-2.
- Note 5. ER-2 track is offset 5-10 nm (10-15 km) from track of P-3.

Tropical Cyclogenesis Experiment

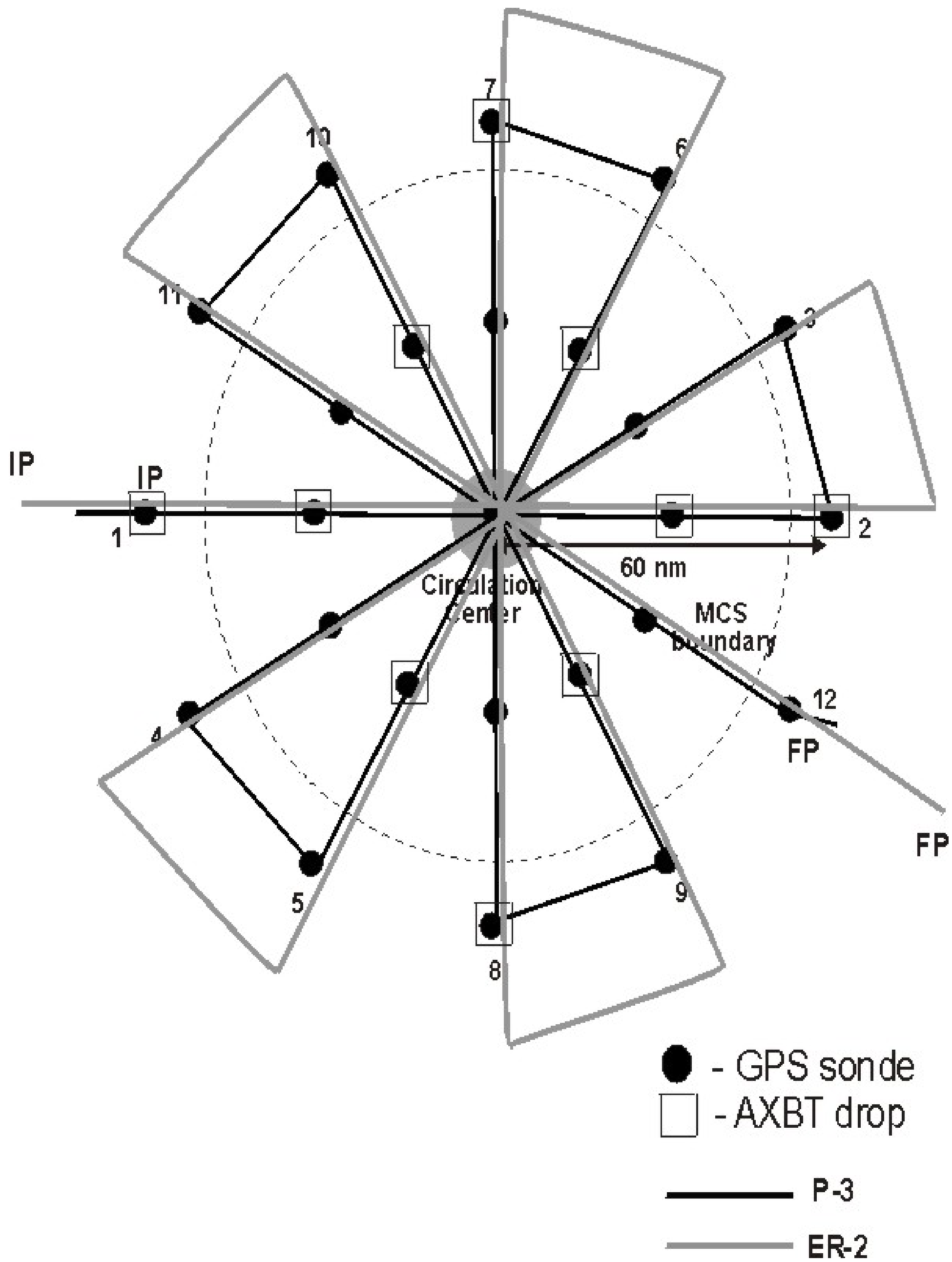


Figure GEN-3b. P-3 Rotating Figure-4 pattern – 12 leg

- Note 1: True airspeed calibration is required.
- Note 2. The pattern may be entered along any compass heading.
- Note 3. Fly 1-2-3-4-5-6-7-8-9-10-11-12 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 except for portions of those legs coordinated with NASA ER-2.
- Note 5. ER-2 track is offset 5-10 nm (10-15 km) from track of P-3.

Tropical Cyclogenesis Experiment

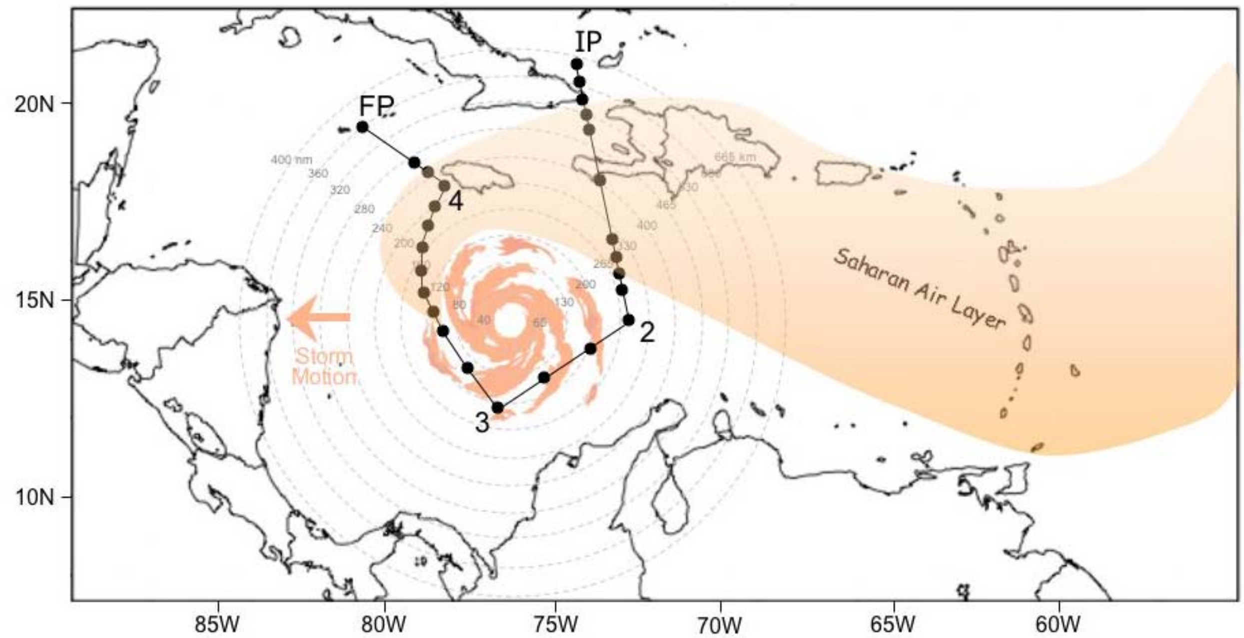


Figure GEN-4. Sample G-IV flight track for a TC embedded in the SAL for most or all of its lifecycle.

- Note 1: During the ferry to the IP, the G-IV should climb to ~200 mb (~41,000 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 (IP-2 and 4-FP).
- 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 (~20-45 kt at 700 mb/10,000 ft) may be evident from GPS dropwindsondes dropped near the SAL's southern boundary (IP-2).

Tropical Cyclogenesis Experiment

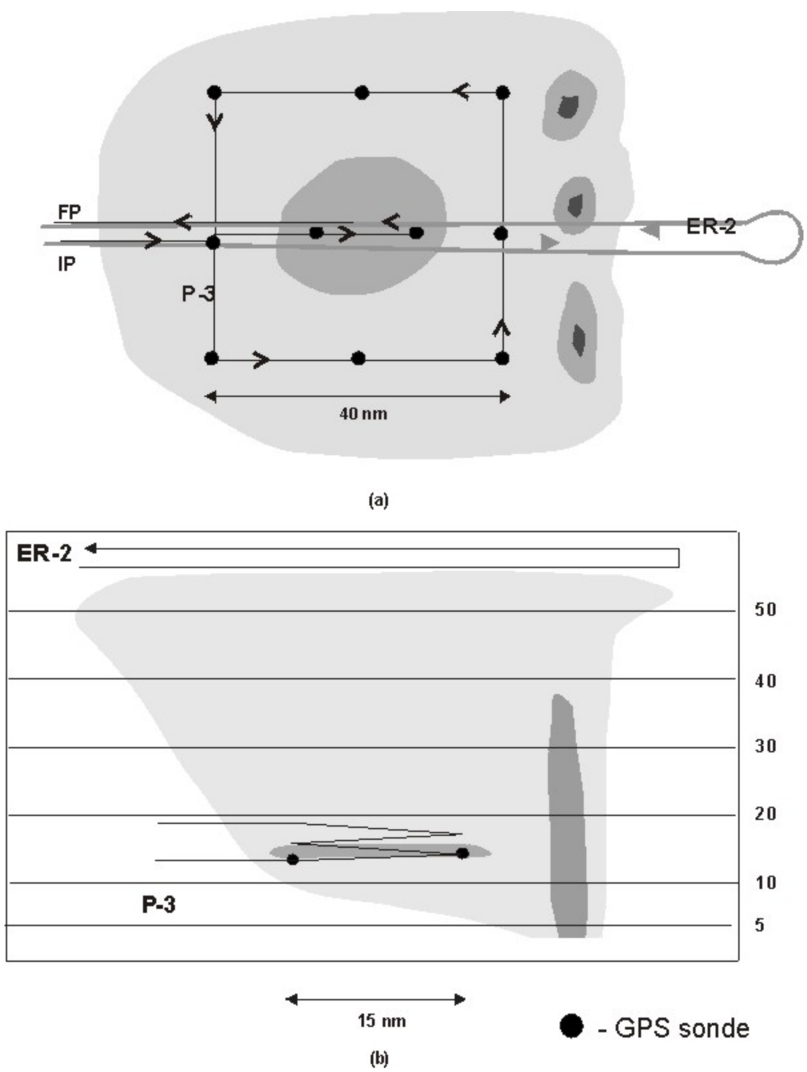


Figure GEN-5. Microphysics module

- Note 1: True airspeed calibration is required.
- Note 2. The pattern may be entered along any compass heading.
- Note 3. The P-3 flies box survey pattern at 14 kft, airborne Doppler set to scan F/AST. Shading denotes reflectivity features; darker shading means higher reflectivity.
- Note 4. At completion of survey pattern, change airborne Doppler to continuous mode, if possible, and head into anvil. Complete series of slanted ascents, beginning at +1 deg C isotherm (about 14 kft) and climbing 1 kft during each leg. Each leg not to exceed 15 nm. Stop ascents 4 kft above starting level (about -3 to -4 deg C isotherm or 18 kft).
- Note 5. ER-2 flies racetrack or butterfly pattern at altitude while P-3 conducts survey pattern, then flies leg back and forth aligned with P-3 during P-3 slanted ascents.

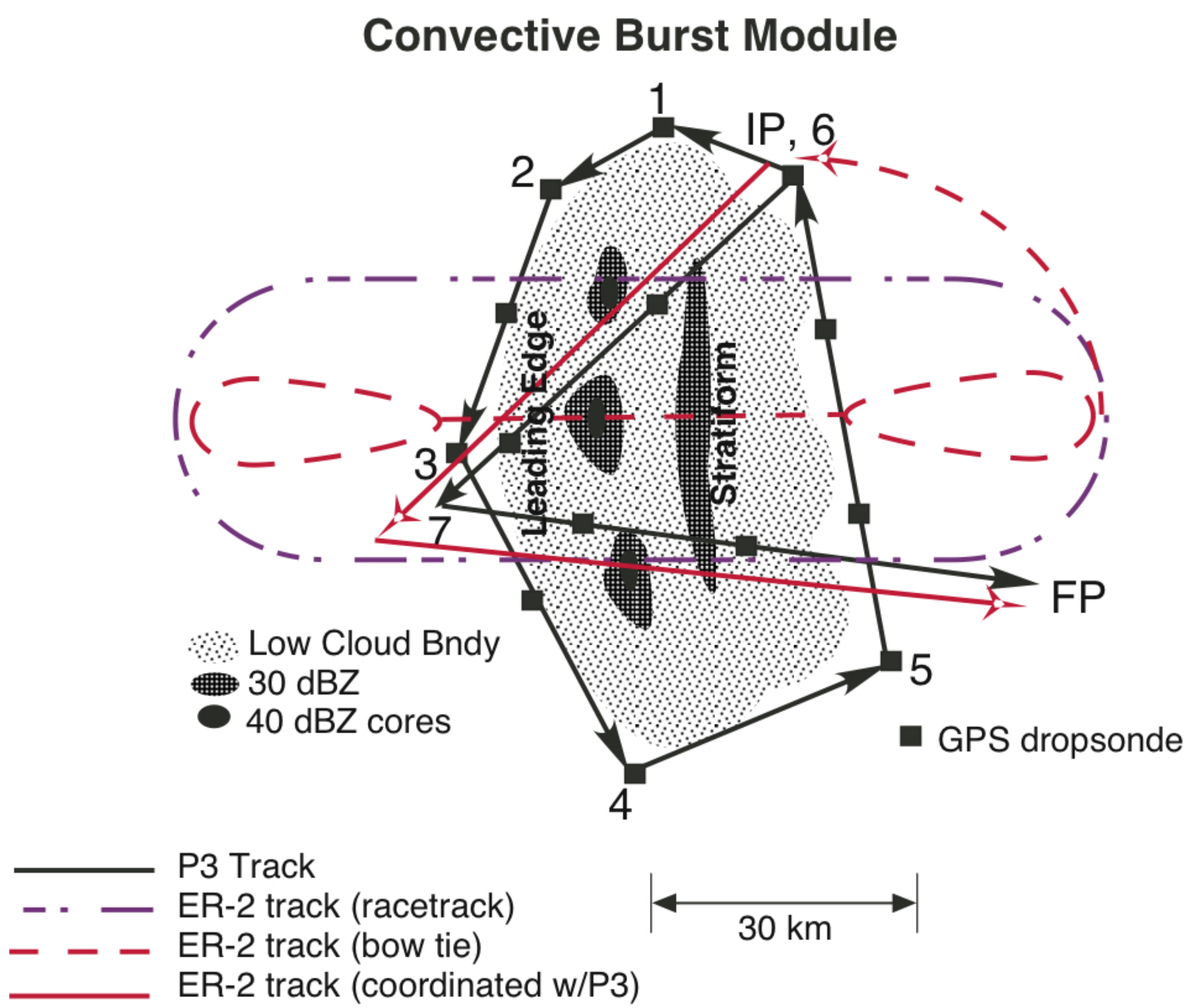


Figure GEN-6. Convective Burst module

- Note 1: True airspeed calibration is required.
- Note 2. Circumnavigation (IP to point 6) by single P-3 at 14 kft.
- Note 3. Convective crossing (6-7-FP) at 14 kft. or with optional steady ascents/descents
- 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 P-3 circumnavigation, flies vertically aligned with P-3 during convective crossing.

2. Mature Storms Experiment

Program significance: By "mature storm" we mean a tropical cyclone that has developed a closed circulation and a warm core. Thus this could include anything from a 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.

There are five main goals of this experiment this year: 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, 4) to develop rapid "real-time" communication of these observations to the National Centers for Environmental Prediction (NCEP) of the National Weather Service (NWS), and 5) to observe the hurricane core and rainbands simultaneously to understand the interactions between them and how that influences the evolution of storm intensity and structure.

Four different but complementary experiments comprise the overall Mature Storms Experiment. The first is the Frequent-Monitoring experiment, designed to obtain regular 12- or 24-h resolution airborne Doppler-radar observations of hurricanes, with optional GPS-sondes. The second is 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. The third is the Hurricane Rainband and Intensity Experiment (RAINEX), designed to collect nearly simultaneous wind and thermodynamic observations in the eye, eyewall, and rainbands of a hurricane to assess how the interaction between eyewall and rainbands influences the evolution of hurricane intensity and structure. The fourth experiment, the Coupled Boundary Layer Air-Sea Transfer (CBLAST) experiment, would operate mainly as a 1-2 hour vertical profiling in the "moat" region between rainbands or as an enhanced dropping of sondes during radial penetrations of the eyewall, but this year would be a module, while one of the other three experiments would be the overall experiment for the mission.

Frequent Monitoring: This experiment is designed specifically to answer 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 Frequent Monitoring experiment gets its name from its 12-24 hour monitoring schedule. 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 Frequent-Monitoring experiment to verify that the boundary-layer and surface winds produced in HWRF resemble those in observations. If sufficient sondes 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 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 P-3 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 N42 and N43 will each be equipped with dedicated globalstar satellite phones and computer systems 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.

Hurricane Rainband and Intensity Experiment (RAINEX):

The objectives of RAINEX are to document hurricane rainband and inner-core structures to gain insight into how they interact and, ultimately, affect hurricane intensity changes. Despite many years of hurricane studies, there is a general dearth of observations indicating how the hurricane outer rainbands interact with the storm's inner core, and hence with storm intensity changes. This problem will be addressed in RAINEX by Doppler radar observations. The coverage by Doppler radar in past studies has generally not been aimed at nearly simultaneous dual-Doppler observation of the rainbands outside the eyewall and of the eyewall itself. To address this observational gap, RAINEX will bring an additional Doppler radar aircraft (the NRL P3 with the ELDORA radar) to the 2005 Hurricane Field Program. The availability of three Doppler aircraft allows for simultaneous quadruple Doppler coverage of the principal rainband and continuous monitoring of the eyewall dynamics (see flight plan discussion above). With three Doppler radar aircraft, RAINEX will:

i. Document rainband and inner-core structures simultaneously by intensive multiple aircraft dual-Doppler radar. These airborne data will determine the evolution and structure of the rainbands relative to their environments and relative to the evolution of the inner-core region of the storm. The radar data will indicate which portions of rainbands are convective and stratiform. The patterns of divergence and vorticity associated with the convective and stratiform precipitation within the rainbands will be identified in the Doppler radar data and used to indicate the spatial configuration of fine-scale PV generation within the rainbands and eyewall.

ii. Describe the environments of the rainbands from the mid-troposphere down through the hurricane boundary layer by using GPS dropsonde data. These data will provide the thermodynamic framework for the dual-Doppler radar observations of rainband and eyewall structure and dynamics.

iii. Use a high-resolution, non-hydrostatic, and full physics model to investigate the interaction of rainbands and the inner-core region and the impact of this interaction on overall hurricane structure and evolution—particularly intensity changes. The aircraft Doppler radar and dropsonde observations will be used as constraints on what model output can or cannot be considered realistic. The subdivision of rainbands into convective and stratiform region will be examined in relation to the vertical profile of heating and PV generation on the sub-rainband scale. These small scale PV patterns related to latent heating profiles in the convective and stratiform regions will traced in the model through the axisymmetrization process, which is thought to be related to storm intensity change. The role of convectively induced gravity waves will also be examined in the model context and examined for consistency with the radar and dropsonde data.

It is the premise of RAINEX that extensive dual-Doppler data from multiple aircraft and dropsondes on the same aircraft missions can add substantially to the knowledge of the structure and evolution of the outer rainbands and concentric eyewalls, if they are directed toward simultaneously observing the rainbands and in the inner-core (eyewall) region. It is a further premise that simultaneous behavior of the rainband and eyewall regions relates to the rainband-inner core dynamical interactions and hence to understanding storm intensity changes.

Ideas to be tested in RAINEX

The vertical distribution of heating is different in convective and stratiform regions (Houze 1982, 1989, Mapes and Houze 1995, Houze 1997). The deep convective cores produce PV in a deep layer and maximum heating in the low-to-mid troposphere, whereas the PV is confined to the mid-troposphere with a maximum heating in the upper troposphere in stratiform rain areas. The experience of airborne scientists on hurricane flights has been to notice that radar observations tend to show rainbands having more deep convective cores on the upwind side of the storm, whereas stratiform precipitation dominates in the downwind part of the storm. This impression constitutes an important empirical working hypothesis: A bias toward convective structure on the upwind side versus stratiform structure on the downwind side would produce asymmetric heating and PV profiles around the storm. We would expect this asymmetry to affect the vortex dynamics and storm intensity. In this study we will measure this heating asymmetry and determine how it affects the interaction between the rainbands and hurricane mean vortex.

Hurricane rainbands are the major source of heating outside of the hurricane eyewall region. Convectively induced PV in the rainbands can be stretched into filaments that spiral inward along the bands toward the storm center. This process may increase PV in the inner core region when the rainbands evolve into a rainband pattern that includes a principal band (as defined by Willoughby et al. 1984). The complex of rainbands in the region outside the eyewall constitutes a relatively steady and stationary but asymmetric source of diabatic heating and PV production near the radius of maximum wind. Studies by Hack and Schubert (1986), Chen and Frank (1993), and Nolan and Grasso (2003) indicate that the intensification caused by such heating increases dramatically as the affected air moves closer to the center of the storm. The vertical structure of the heating in the stationary rainband complex is not known. Studies by Chen and Frank (1993), Bister and Emanuel (1997), and Ritchie et al. (2003) suggest that regions of stratiform rain in the center of a developing tropical storm favors intensification of the vortex. The vertical structure of the heating will be addressed in the research proposed here along with the horizontal pattern of rainband structure. We expect that that the heating will have a vertical structure of a more convective type farther from the storm in the tail of the principal band and of a more stratiform type in the part of the principal band that is close to and making contact with the eyewall.

Outside the hurricane inner core, PV is "axisymmetrized" by the shear of the symmetric vortex and may ultimately contribute further to intensification via the wave-mean flow interactions of associated vortex-Rossby waves (Montgomery and Kallenbach, 1997). Through this process, PV perturbations in rainbands can change the symmetric PV fields and thus the mean vortex itself. Since the vertical distribution of the heating (and hence the PV generation) in a rainband may depend on the rainband's structure and location relative to the hurricane center, as noted above, the vertical structure of the PV being axisymmetrized will be a function of the position of the rainband relative to the storm. The location of a rainband and its attendant convective and stratiform regions relative to the shear of the symmetric wind field may determine whether the PV of the rainband becomes axisymmetrized. By documenting the convective vs. stratiform structure of rainbands in various positions relative to the storm center, we will indicate the nature of the PV anomalies being axisymmetrized at different radii and azimuths relative to the storm center.

The proposed study will determine the asymmetry of the heating by using airborne Doppler radar to map the convective and stratiform echo structures in the rainbands and eyewall to determine the vertical structure of heating as a function of horizontal position relative to the storm. RAINEX will extend the analyses of the aircraft data by examining the implications of the observed heating patterns relative to the storm via numerical modeling. Detailed simulations will be made with a high-resolution, non-hydrostatic, full-physics numerical model (operated by Professor Chen at the UM) to determine the nature of the interactions between the mean vortex and convective and stratiform rainbands at different locations relative to the hurricane.

The pattern of rainbands, and in particular the *principal rainband* (PRB) identified by Willoughby et al. (1984), appear to be key dynamic elements and are usually readily identified in real time by the P3 lower-fuselage radar. The features are persistent and therefore amenable to performing aircraft penetrations of them, as directed by scientists on the aircraft. The data collected on RAINEX flight tracks can be organized relative to a composite storm with a characteristic pattern of eyewall and principal band. By real-time identification and targeted probing of these features by multiple dual-Doppler aircraft and dropsondes, we will obtain data that will constrain model simulations of the rainband/inner-core interactions. Our proposed experimental and modeling study will in this way focus on the principal band and other rainbands close to the inner core region and their dynamic connection with the inner core region of the storm.

Coupled Boundary Layer Air-Sea Transfer Experiment (CBLAST):

Missions dedicated to the high-wind component of the ONR-sponsored CBLAST experiment were flown during the 2003 and 2004 Hurricane Field Program. Successful missions were flown into Hurricanes Fabian and Isabel in 2003 but an abundance of operationally-tasked missions in 2004 prevented HRD from fully completing the mission goals in 2004. Components of the CBLAST program may be flown in 2005, albeit at a lower-priority with other HRD Field Program goals and only on a non-interference basis with operational or other research missions.

Mission Descriptions:

Frequent Monitoring: Three different options are possible with this experiment. These are 1) the dual-aircraft coordinated airborne Doppler pattern (Fig. FM-1), FM-2) the single-aircraft “rotating figure 4” (Fig. FM-2), and FM-3) the hexagonal pattern (Fig. FM-3). These three options permit the maximum flexibility at the time of the aircraft missions.

Dual-aircraft option: If only 24-hour resolution is required, the dual-aircraft option may be chosen. This option provides the highest quality data possible from the airborne Doppler, radar. Radar geometry specifies that from a single airborne Doppler radar the integration of the continuity equation is unbounded, although other factors mitigate. When two aircraft fly simultaneously, any aircraft using a fore/aft scanning strategy will provide better boundary conditions for the other aircraft. Thus, Doppler winds near the aircraft are better bounded, and observations in many locations are over-determined, which also improves accuracy. Airborne Doppler data collected in these cases will be used to completely examine the probably accuracies of individual aircraft analyses, and to evaluate the role of improved boundary conditions. Such analyses would also be the most accurate for evaluating model output. The “quad-Doppler” regions would cover most of the region within 50 km of storm center, depending upon the distribution of precipitation and the radar sensitivity.
The initial positions for both aircraft will be determined to maximize the airborne-Doppler coverage of the hurricane core. Aircraft launches and trajectories should be coordinated so that both aircraft arrive at their respective IP’s at the same time. If sondes are to be dropped, the upper aircraft should fly at maximum altitude possible to avoid electrostatic charging (nominally 14,000 ft), and the lower aircraft should fly as high as is safe below the upper aircraft (nominally 12,000 ft). This will maximize the vertical coverage of the wind and thermodynamic data from the sondes. If sondes are not dropped, or it is determined that improved accuracy of the remote observations of surface and lower-boundary-layer winds take precedence, then flight altitudes of 7,000 and 5,000 ft would be preferred.

Single-aircraft options: In most cases temporal resolution is also important, for both initialization and verification. This has been verified in communication with EMC. At the time of this writing, the preferred mode of operation will be 12-hour turnaround with alternate P3 aircraft, launch times to be determined by HWRF assimilation needs, but within AOC operational and safety constraints. Figures FM-2 and FM-3 illustrate the proposed single-aircraft flight plans for this option. Complete “rotating figure 4” patterns, as shown in Fig. FM-2, provide the most complete coverage, but take longer to complete than the “hexagonal” patterns shown in Fig. FM-3.

RAINEX experiment: The flight track modules to be flown by the three Doppler radar aircraft in RAINEX are illustrated conceptually in Fig. RX-1.). These modules are designed to be simple and adaptable. They will obtain the desired dual-Doppler and dropsonde data with the minimal degree of complexity, and they are readily modified in real time to accommodate whatever eyewall/rainband configuration presents itself. The *Eyewall Module* is a figure-four, which will be rotated by approximately 45 deg each time it is repeated. The other two modules are designed to cover the PRB. The second module is flown back and forth on the inside edge of the PRB and will be designated as the *Inner PRB Module*. The third module is flown back and forth on the outside edge of the PRB and will be designated as the *Outer PRB Module*. All three modules will include dropsondes at intervals of 10-40 km along the track. The modules are designed such that each will give considerable useful information for RAINEX purposes, but they will have the greatest advantage when used in combination so as to give the best possible indication of the ongoing interaction between the eyewall and rainband components of the tropical cyclone. The dropsonde data will be assimilated into model simulations of the observed cases. The modules are geometrically simple and readily scalable by design, making it easier to adapt them to different storm scenarios. The simplicity and adaptability of the modules in Figure RX-1 will allow the data collected by the aircraft to be useful both in individual case studies and statistically. The cases with multiple aircraft coverage will be especially useful for case study analysis.

Figures RX-2-5 show how the Doppler radar aircraft will be deployed as a function of how many aircraft are available. Figure RX-2 provides an overview of the triple-Doppler-aircraft flight plan most sought after in RAINEX. This three-aircraft pattern provides contemporaneous quadruple Doppler coverage in the PRB and continuous figure-four monitoring of the eyewall. This is the ideal pattern for achieving the objective of understanding rainband-eyewall interactions. This is only possible by having three Doppler aircraft on-station for extended (i.e. >2-3 h) periods. Simultaneous Doppler radar coverage of the major rainband and of the eyewall are the ingredients required to satisfy the primary RAINEX science objectives. The coordination of three Doppler aircraft, made possible by NSF-supported involvement of the NRL P3, has not heretofore been possible, and thus constitutes a valuable opportunity unique to the 2005 hurricane season.

In this three-Doppler-aircraft plan, the #1 aircraft is the Eyewall Module aircraft. It is a NOAA P3 aircraft. It will arrive at the storm first and execute a figure-four in the inner core region and reconnoiter for the positioning of the second and third aircraft while performing this repeated survey. The #2 aircraft is the second NOAA P3, and it will perform the Inner PRF Module, repeatedly going back and forth along the inside edge of the PRB. It will arrive after the #1 aircraft has completed the initial figure-four, and it will be guided by the #1 aircraft into a position on the inside edge of the principal rainband (as described by Willoughby et al. 1984), or whatever rainband appears to be most significant at the time). Once in position, the #2 aircraft will guide the #3 aircraft into position. The #3 aircraft will be the NRL P3, and it will arrive a short time after the #2 aircraft to perform the Outer PRB Module, flying back and forth parallel to the outer edge of the PRB. The #2 aircraft will guide the NRL P3 into position on the outside edge of the rainband. The #1 aircraft will continue to do figure-four patterns in the inner core, progressively rotating their orientations by ~45 deg, while the #2 and #3 aircraft will fly back and forth on the inside and outside edge of the rainband, respectively, for the duration of the mission. The #2 and #3 aircraft will attempt to coordinate their legs so that quadruple Doppler coverage can be obtained in the rainband. If the rainband diminishes after the patterns have begun, the #2 aircraft will select another rainband and direct itself and the #3 aircraft to the new rainband and resume flying coordinated reciprocal tracks on the inside and outside edges of the rainband for the duration of the mission. Figure RX-3 illustrates how a three-Doppler-aircraft mission of the type described in Fig. RX-2 could be applied to a rather typical hurricane, as seen on a NOAA P3 lower-fuselage radar display. Note that the NRL P3 will be restricted to fly in echo <35 dBZ. It is shown in the example to be avoiding intense portions of the outer rainbands (if present) by utilizing gaps between cells of higher reflectivity (depicted both by its nose radar and frequent updates of the telemetered NOAA LF reflectivity pattern) and ultimately positioning itself so as to begin its first Outer PRB Module.

If only two P3 aircraft are available, the RAINEX objectives will be pursued with two Doppler aircraft, but compromises will be required. Figures RX-4 and RX-5 show two ways that the RAINEX goals can be accomplished, depending on which two Doppler aircraft participate and on which compromise is made. Figure RX-4 shows the case in which the mission is flown by either the NRL P3 with one NOAA P3 or by two NOAA P3's. In this option, continuous coverage of the eyewall is sacrificed to maintain more intensive (quadruple) Doppler coverage of the PRB. The #1 aircraft is a NOAA P3 aircraft, and it begins the mission as the Eyewall Module aircraft. It arrives at the storm first and does one or two figure-fours in the inner core region and reconnoiters for the location of the PRB and for the positioning of the second aircraft relative to the PRB. After completing its figure-four survey, the #1 aircraft assumes the role of Inner PRB Module aircraft and begins to fly in tandem with and directing the #2 aircraft. The #2 aircraft is the NRL P3. It will arrive after the #1 aircraft has completed the initial figure-four, and it will be guided by the #1 aircraft into a position on the outside edge of the PRB and fly the Outer PRB Module. It will fly in tandem with the #1 aircraft, which will be flying the Inner PRB Module. The two aircraft will coordinate their legs so that quadruple Doppler coverage can be obtained in the PRB. If the PRB diminishes after the patterns have begun, the #1 aircraft will select another rainband and direct itself and the #2 aircraft to the new rainband and resume flying reciprocal tracks on the inside and outside edges of that rainband for the duration of the mission. The #1 aircraft may perform a final figure-four in the eyewall at the end of the mission.

Figure RX-5 shows another choice for the case in which only two Doppler aircraft are available. In this case, quadruple Doppler coverage is sacrificed to maintain continuous monitoring of the eyewall region. This option is available only when the two aircraft are both NOAA P3s, because the NRL P3 cannot fly the Inner PRB module. In this option, the #1 aircraft arrives first and flies the rotating figure-four Eyewall Module repeatedly for the entire mission, to provide continuous coverage in the eyewall. During its first figure-four pattern, it reconnoiters for the positioning of the second aircraft. The #2 aircraft is the second NOAA P3. It will arrive after the #1 aircraft has completed the initial figure-four, and it will be guided by the #1 aircraft into a position on the inside edge of the principal rainband, where it will fly a racetrack pattern consisting of an Inner PRB Module followed by an Outer PRB Module. The racetrack is repeated as often as possible. In this pattern (just as in the case of PRB tracks shown in Figs. RX-2 and RX-4), some upwind legs are unavoidable, but will be balanced by intervening downwind legs. By flying the Inner PRB Module upwind the net distance upwind will be minimized. If the PRB diminishes after the patterns have begun, the #2 aircraft will select another rainband and commence flying the racetrack around the new rainband.

Figures RX-6-8 show dropsonde modules to be executed via the NOAA GIV jet. Ideally the dropsonde modules should be contemporaneous with the Doppler modules, but in real operations they may have to be separated in time.

Figures RX-6 and RX-7 illustrate the RAINEX flight track modules for obtaining GIV dropsondes to support analysis of the PRB. The lead P3 aircraft (see above) will guide the GIV to the PRB, and the GIV will fly a racetrack pattern around the entire rainband (Fig. RX-6) or around a selected segment of the rainband (Fig. RX-7).

Figure RX-8 illustrates the RAINEX flight track module for obtaining GIV dropsondes to support the inner-core analysis. The GIV will fly a racetrack pattern around the eyewall, and at the discretion of the GIV flight crew may occasionally make transects across the eye.

Mature Storms Experiment Flight Planning Approach:

During phase II of the 2005 Hurricane Field Program, from 15 August until 30 September, 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. . A subset of these goals will be accomplished in the context of the Mature Storms Experiment, with flight patterns that involve one or both NOAA P3s in the frequent monitoring modules and with multiple aircraft including the NRL P3 flying with the NOAA P3s in joint NOAA and NSF-sponsored RAINEX missions.

Conducting three-P3 (2 NOAA P3s and the NRL P3) dedicated RAINEX missions in mature storms is a top priority. The presence of the NRL P3 in the 2005 Hurricane Field Program is a unique opportunity to obtain this type of dataset. Attaining RAINEX missions will be subject to constraints on available opportunities, flight-hours, and operational constraints. Two-P3 RAINEX missions (1 NOAA P3 and the NRL P3) may be flown when all three P3 aircraft are not available, either as dedicated missions, as part of other research missions, or as part of operationally-tasked missions.

In addition to the RAINEX flights, HRD will conduct a set of frequent monitoring missions over several days encompassing as much of a particular storm’s life cycle as possible. This would entail using the NOAA P3s on back-to-back flights on a 12-hour schedule when the system is at depression or tropical storm strength, followed by single NOAA P3 sorties every 24 hours once the TC is nearing hurricane status (55-60 knot max winds). The aircraft flying the 24 hour cycle could multi-task with a RAINEX mission involving the 2nd NOAA P3 and/or the NRL P3, provided there is not any additional operational tasking.

At times, one set of flights may take precedence over others depending on factors such as storm strength and location, operational tasking, and aircraft availability. Two general scenarios could likely occur that illustrate how the mission planning is determined:

1) 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 HRD priority would be to start the set of frequent-monitoring flights, first at 12-hour intervals with single NOAA P3 missions while the TC is below hurricane strength, followed by single or dual NOAA P3 missions at 24-hour intervals until the system is out of range or makes landfall. During the 24-h-interval portion of this scenario, the flight plan for the "inner P3" would be designed to get wavenumber 0 and 1 coverage of the hurricane out to the largest radius possible, rather than the highest time resolution of the eyewall winds. The 2nd NOAA P3 and the NRL P3 could fly in the RAINEX mode, with the 2nd

NOAA P3 flying along the inner side of the principal rainband and the NRL P3 flying along the outer side of the principal rainband.

2) A TC, not previously flown by NOAA, is at or near hurricane strength and is within range of an operational base. In this case, the highest HRD research priority would be the three Doppler aircraft RAINEX missions. This mission could be flown on one or more days depending on aircraft range limitations and any operational constraints. For these missions, the inner P3 will emphasize achieving high time resolution of the eyewall winds.

Mature Storms Auxiliary Modules:

These modules are designed to be flown as opportunities arise and on a non-interference basis with flight patterns previously described or with operational mission requirements

USAF Alpha Pattern:
This pattern is the typical pattern that the USAF routinely performs on NHC-tasked operational missions. Altitudes are usually 5,000 ft or below for weak systems and 10,000 ft in intense hurricanes. HRD, in coordination with RAINEX investigators, would request through NHC and CARCAH, that the USAF release additional dropsondes along their route at the designated locations in Fig. RX-9.

CBLAST Eyewall Module:
This module (Fig. CBLAST-1) is a carryover from CBLAST missions flown in 2002-2004. It is intended to gather high-resolution sampling of the eyewall with GPS sondes (the new UBLOX versions) in an intense (Cat. 3-5) hurricane with a well-developed eyewall. The module should only be flown on a non-interference basis with other missions and can be performed with one or both P3s during selected radial penetrations in conjunction with another mission or as a separate module. The number of sondes deployed along each radial leg will be 4, 8 or 12, depending on which aircraft or combination of aircraft is used.

CBLAST Stepped-descent module:
This module is also a carryover from CBLAST missions of previous years. It is intended to be flown on a non-interference basis with other existing or planned missions. Since AOC now requires an engine wash after any low-level flying in strong winds, this module can only be performed if no operational or research missions are planned for the following day. The module is designed to be flown by N43RF with N42RF providing sonde coverage above the area of the stepped-descent but the module may be performed by N43RF alone.

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

Eye mixing module:
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 tropical cyclones, 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 tropical cyclones.

For this module, a Category 4 or 5 tropical cyclone with a clearly-defined eye and eyewall and an eye diameter of at least 25 nm is needed. The P-3 will penetrate the eyewall at the altitude proposed for the rest of the experiment. Once inside the eye, the P-3 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 2.0 nm from the edge of the eyewall. Upon completion of the descent, the P-3 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.

Ocean Winds experiment/module:
This option (Fig. OW-1) consists of a series of pie-shaped wedges originating in the eye and extending outward to just beyond the eyewall and high wind inner core nominally 50 km (37 nm), and which rotate downwind with time. These pie slices will be concentrated in the high wind right and front quadrants of the storm and be flown with the two WP-3D aircraft flying ‘in trail’, maintaining same lateral and vertical spacing.

CBLAST Turbulence Calibration Module: If the BAT probe is utilized during a mission, a calibration of the BAT probe should be executed at least once, whenever possible during the field program. The following maneuvers are requested for turbulence sensor calibration:

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

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

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

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

Mature Storms Experiment

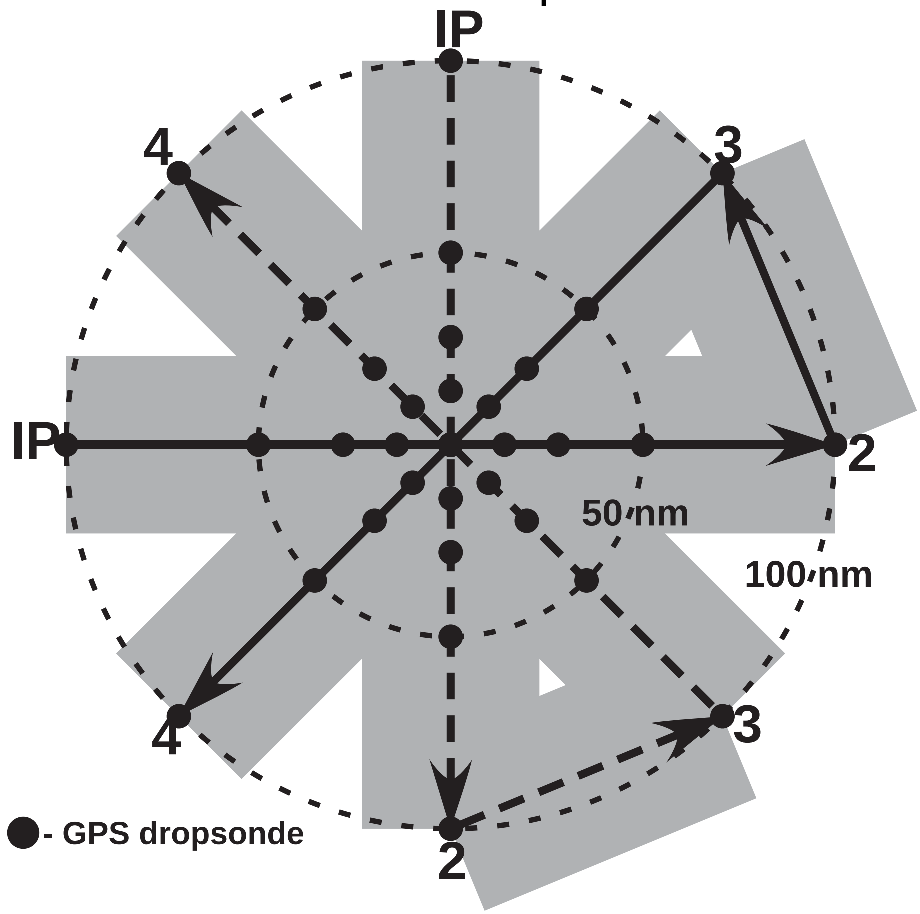


Figure FM-1. Dual-aircraft coordinated Doppler pattern

Note 1.	Doppler radars should be operated in single-PRF mode, at a PRF of 2400-3200. The default will be 2800 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.	Aircraft should be launched and/or coordinated to reach their respective IP's at the same time.

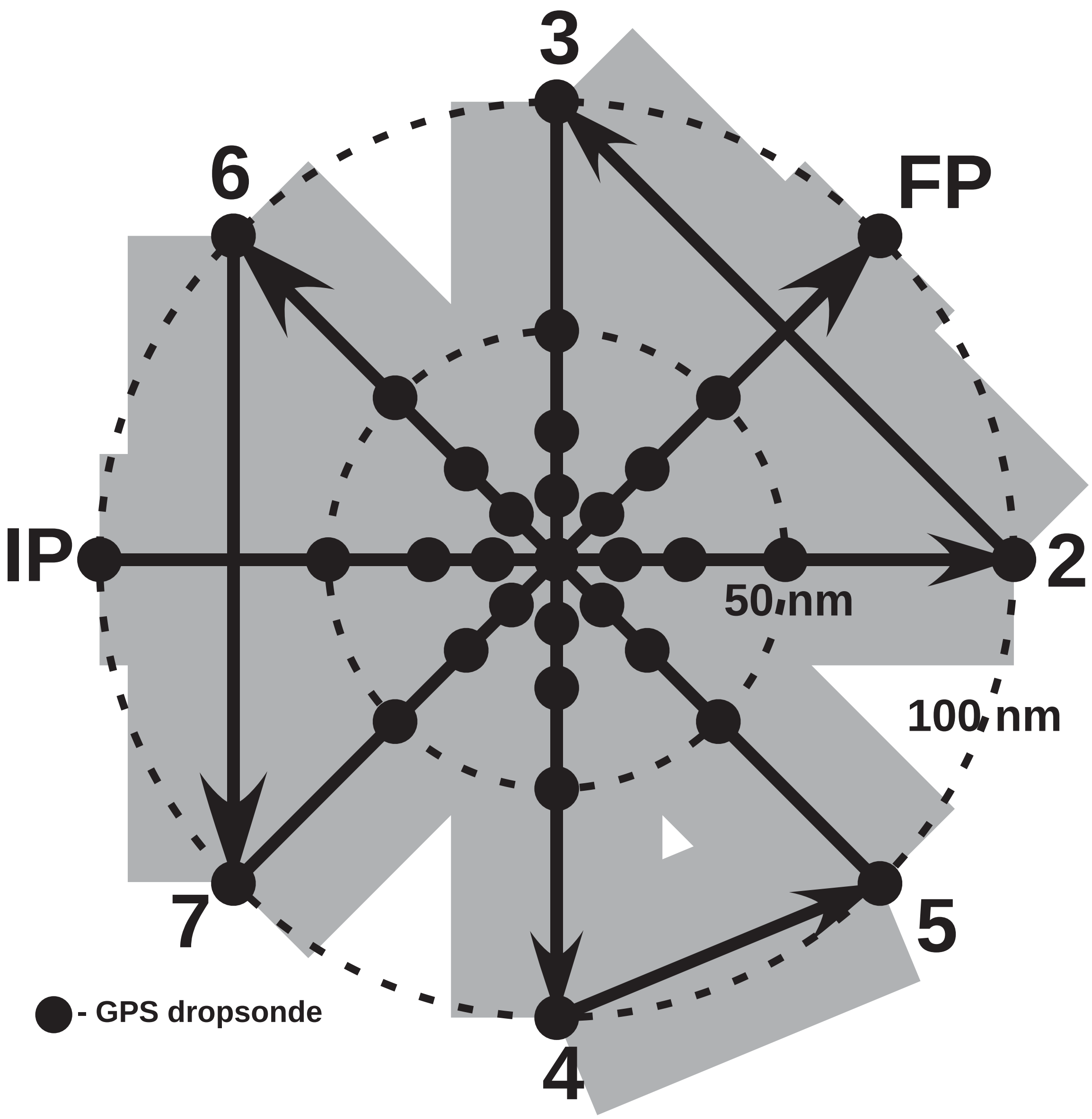


Figure FM-2a. Single-aircraft "rotating figure 4" pattern (100 nm maximum radius)

Note 1.	Doppler radars should be operated in single-PRF mode, at a PRF of 2400-3200. The default will be 2800 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

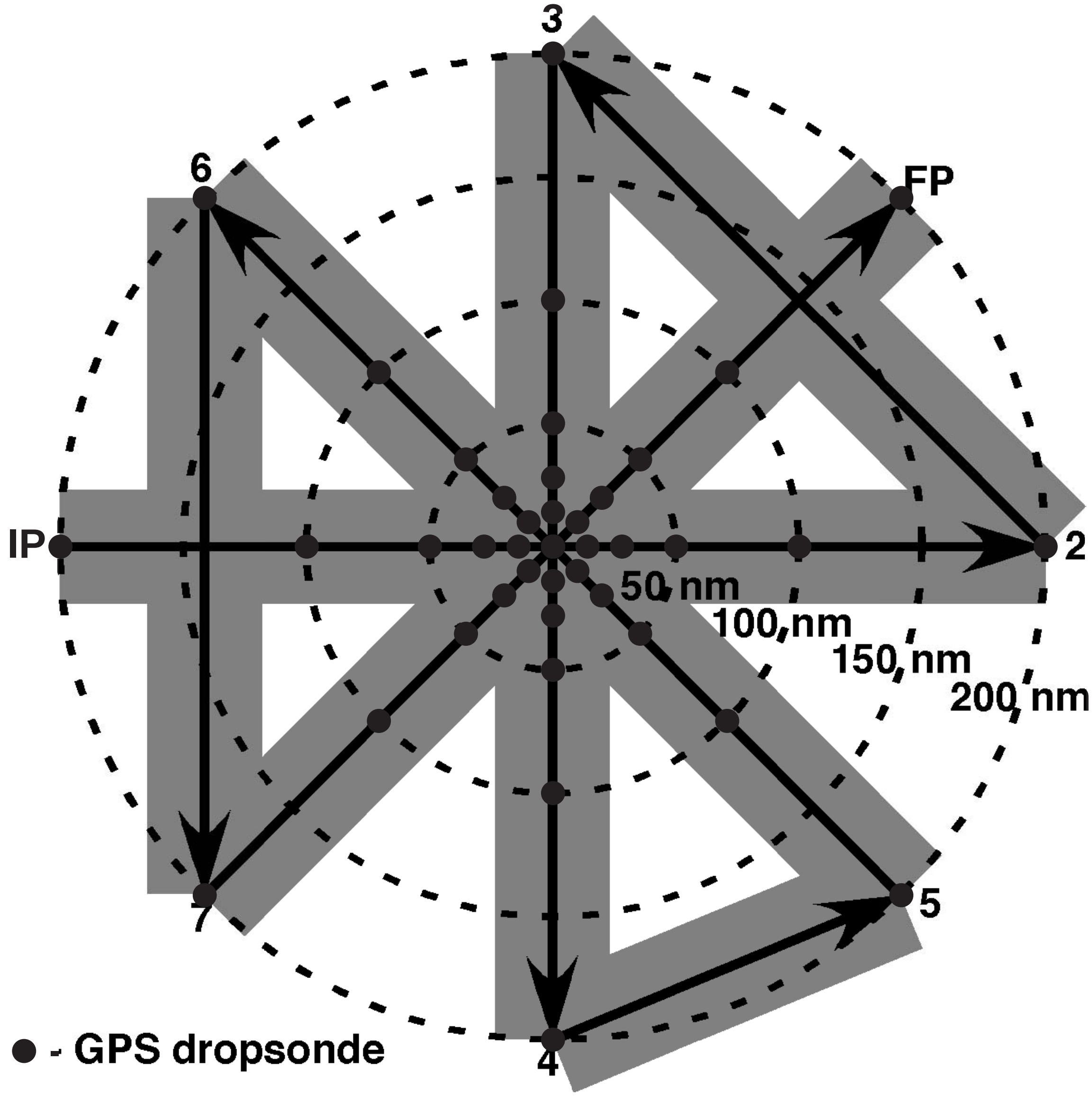


Figure FM-2b. Single-aircraft "rotating figure 4" pattern (200 nm maximum radius)

Note 1.	Doppler radars should be operated in single-PRF mode, at a PRF of 2400-3200. The default will be 2800 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 200 nm
Note 6.	Maximum radius may be decreased or increased within operational constraints

Mature Storms Experiment

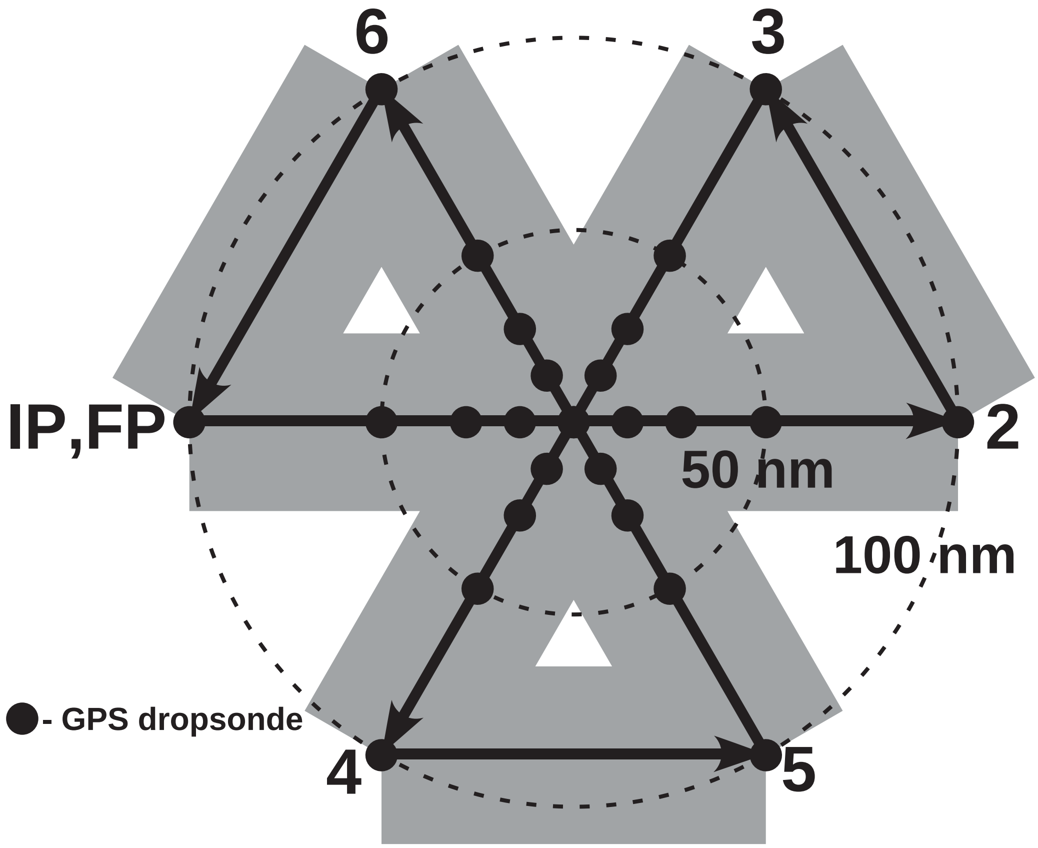


Figure FM-3a. Single-aircraft "Hexagonal flight pattern" (100 nm maximum radius)

Note 1.	Doppler radars should be operated in single-PRF mode, at a PRF of 2400-3200. The default will be 2800 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 200 nm
Note 6.	Maximum radius may be decreased or increased within operational constraints

Mature Storms Experiment

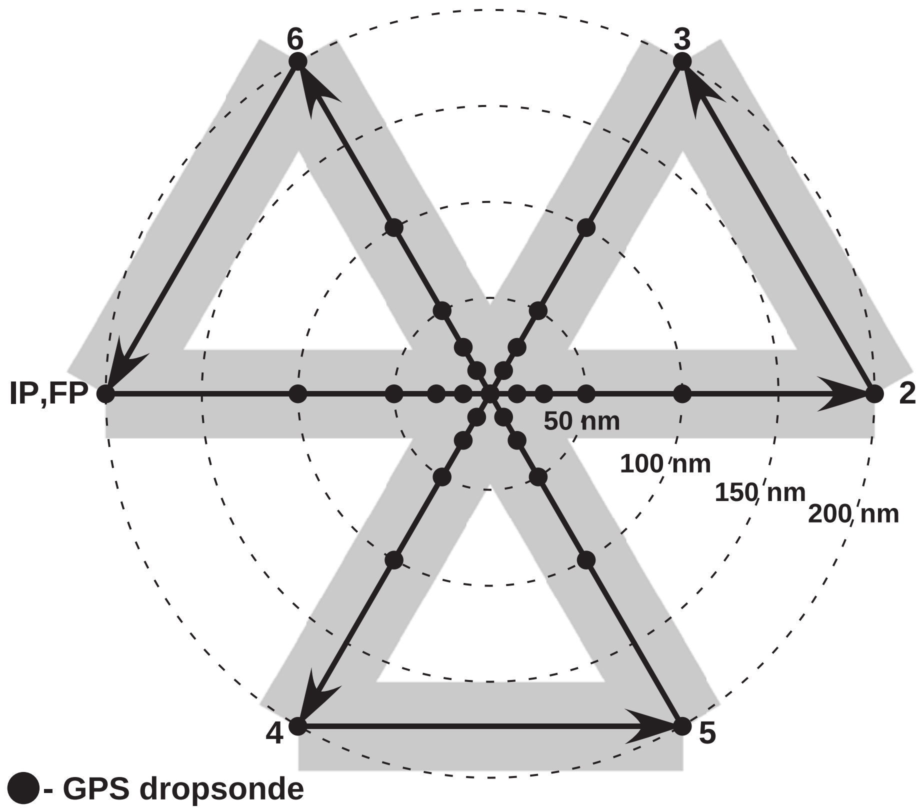


Figure FM-3b. Single-aircraft "Hexagonal" pattern (200 nm maximum radius)

Note 1.	Doppler radars should be operated in single-PRF mode, at a PRF of 2400-3200. The default will be 2800 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 200 nm
Note 6.	Maximum radius may be decreased or increased within operational constraints

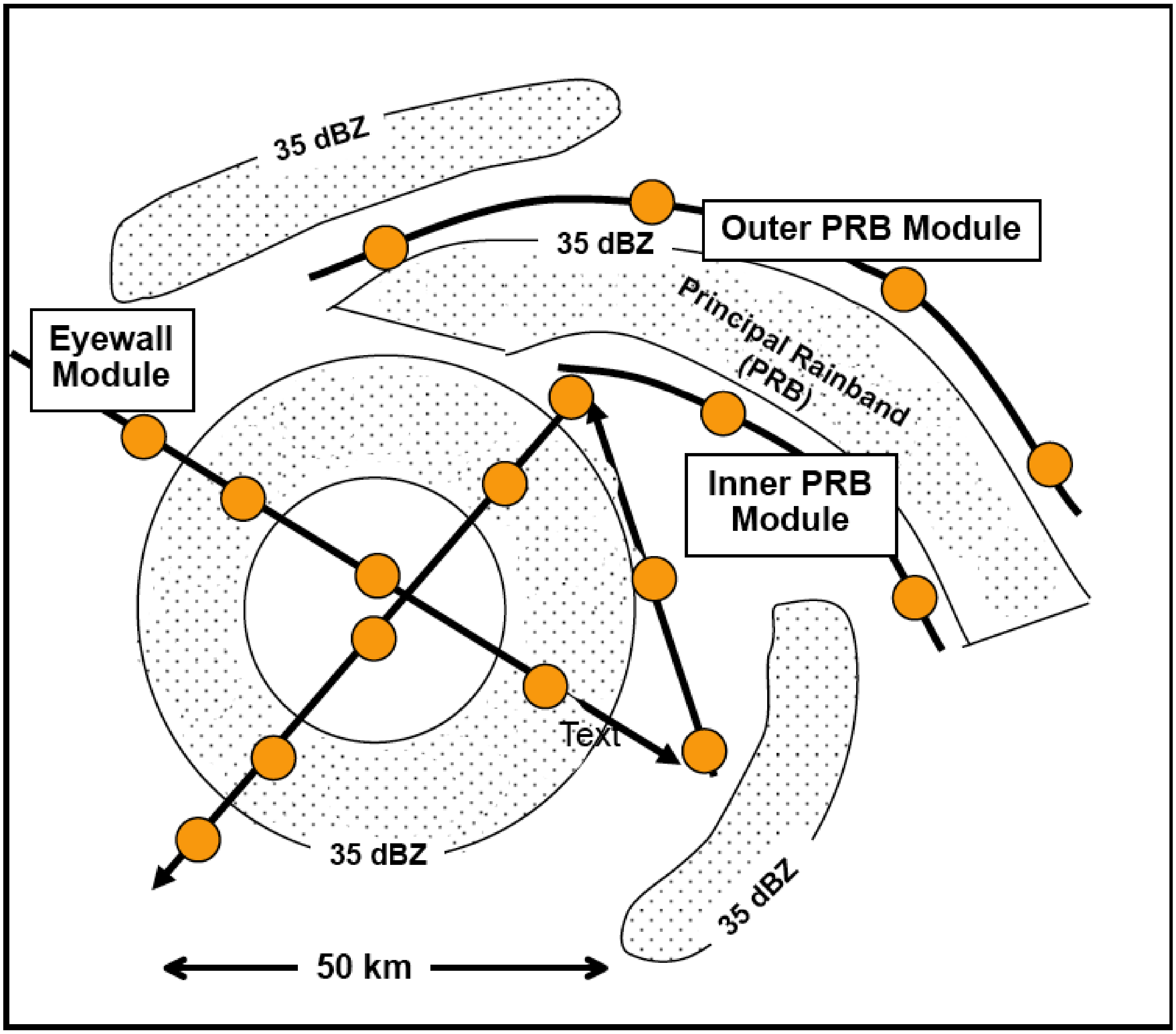


Figure RX-1. Doppler radar module nomenclature. Dots indicate possible dropsonde locations, to be adjusted depending on scale of storm features. The Eyewall module will be flown repeatedly, rotating its orientation by increments of ~45 deg. The Inner and Outer PRB Modules will be flown in tandem for quadruple Doppler coverage, and they will be flown a few km outside the 35 dBZ contour.

Note 1.	Doppler radars should be operated in single-PRF mode, at a PRF of 2400-3200. The default will be 2800 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 NOAA-P3 Doppler radars should be operated in fore/aft continuous scanning with a fore/aft angle of 20^{o} relative to fuselage.

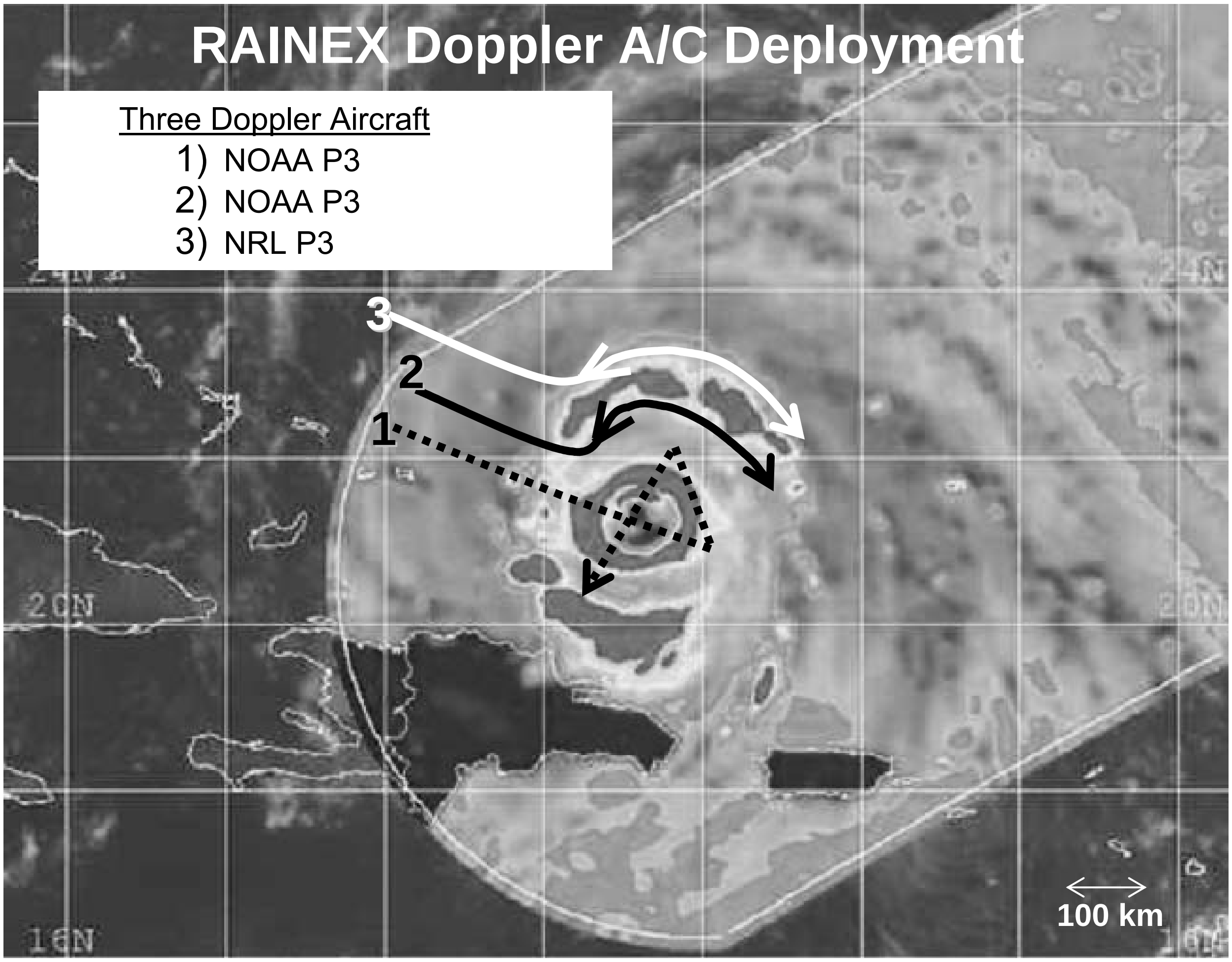


Figure RX-2. RAINEX Doppler radar aircraft modules for NRL P3 and two NOAA P3 Doppler aircraft. Aircraft 1 arrives first, reconnoiters, and executes a rotating figure-four Eyewall Module for the duration of the mission. Aircraft 2 enters under the guidance of Aircraft 1 and flies reciprocal Inner PRB modules. Aircraft 3 enters under the guidance of Aircraft 2 and flies reciprocal Outer PRB Modules.

Note 1.	Doppler radars should be operated in single-PRF mode, at a PRF of 2400-3200. The default will be 2800 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 NOAA-P3 Doppler radars should be operated in fore/aft continuous scanning with a fore/aft angle of 20^{o} relative to fuselage.

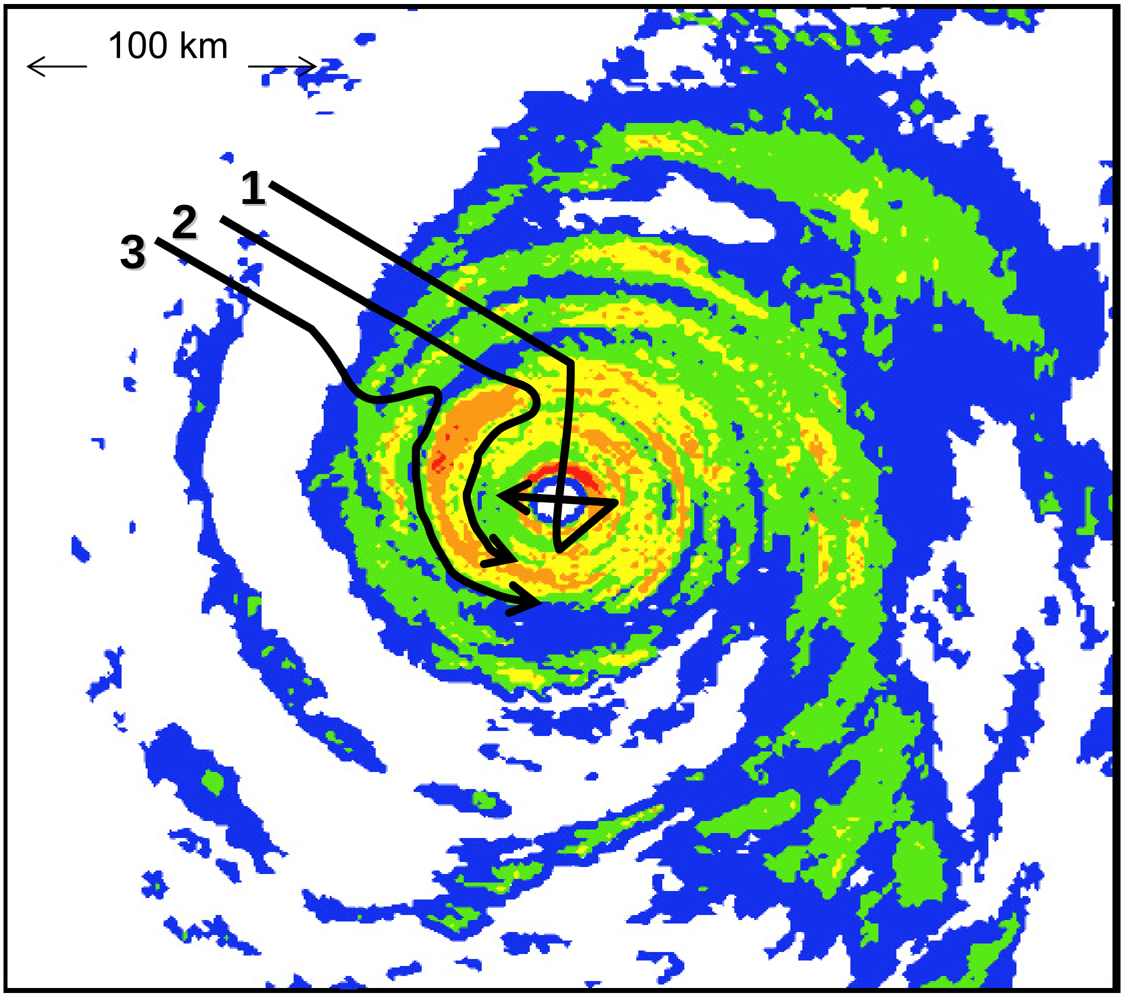


Figure RX-3. RAINEX Doppler radar example. Reflectivity thresholds are for 27 (blue), 31(green), 35 (yellow), 38 (brown), and 44 (red) dBZ. The aircraft tracks are numbered 1, 2 and 3 as in Fig. 1. The #1 aircraft executes a repeating Eyewall Module. The #2 aircraft executes the Inner PRB Module. The #3 aircraft is the NRL P3, which must fly in rain with echo intensity <35 dBZ. This schematic shows #3 flying through gaps between cells to get in position to do the Outer PRB Module in tandem with the #2 aircraft. Module nomenclature is defined in Fig. 1.

Note 1.	Doppler radars should be operated in single-PRF mode, at a PRF of 2400-3200. The default will be 2800 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 NOAA-P3 Doppler radars should be operated in fore/aft continuous scanning with a fore/aft angle of 20° relative to fuselage.

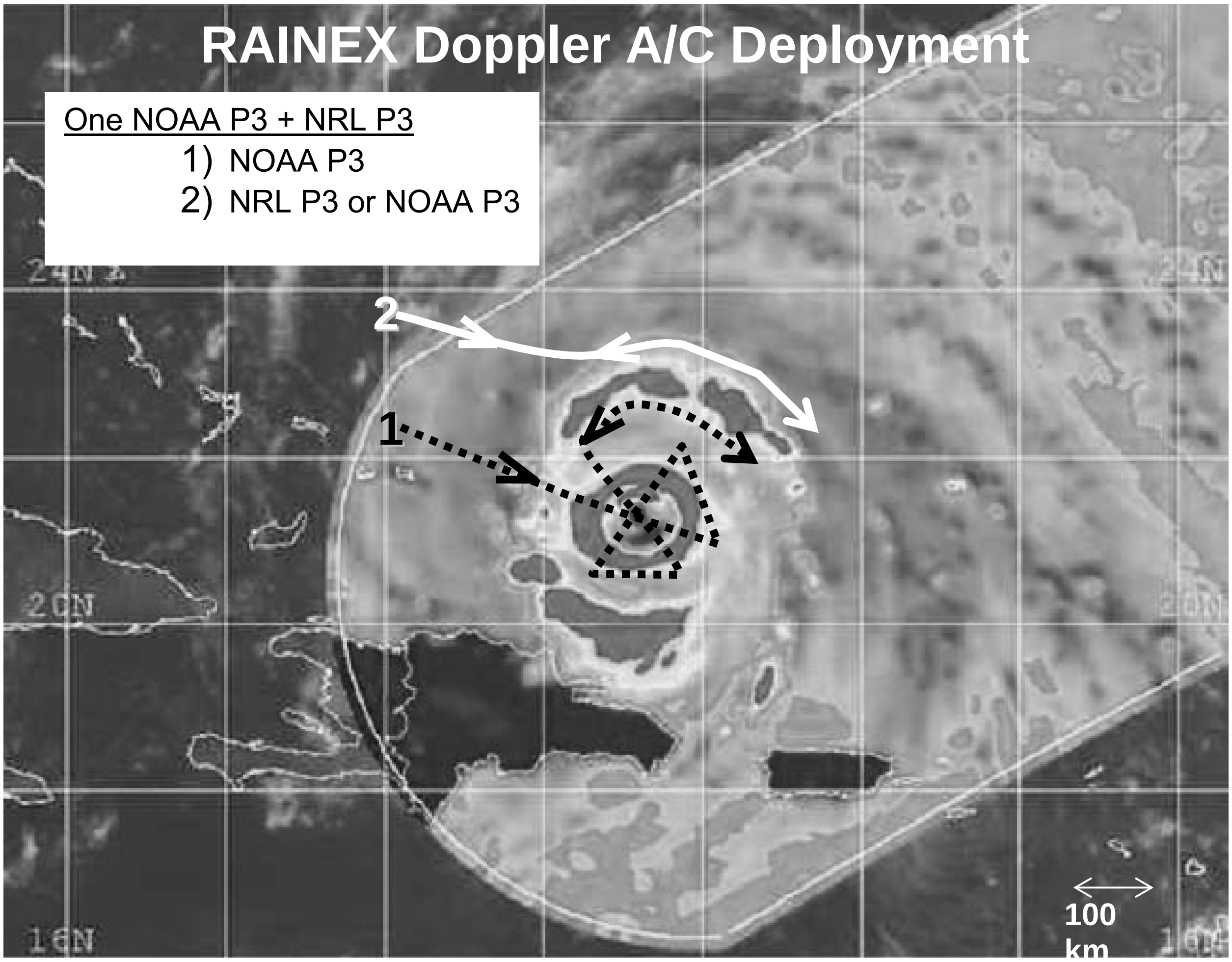


Figure RX-4. RAINEX Doppler radar aircraft pattern for two P3 aircraft. Aircraft 1 must be a NOAA P3. Aircraft 2 is either the NRL P3 or a NOAA P3. Aircraft 1first flies a figure-four Eyewall Module pattern, then when Aircraft 2 arrives, Aircraft 1 flies a quadruple Doppler track in tandem with Aircraft 1. The quadruple Doppler track entails Aircraft 1 and 2 flying reciprocal tracks of the Inner and Outer PRB Modules, respectively. At the end of the mission, Aircraft 1 may fly an additional Eyewall Module. See Fig. 1 for Module nomenclature. This option for two Doppler radar aircraft sacrifices continuous coverage of the eyewall region in favor of quadruple Doppler coverage in the PRB.

Note 1.	Doppler radars should be operated in single-PRF mode, at a PRF of 2400-3200. The default will be 2800 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 NOAA-P3 Doppler radars should be operated in fore/aft continuous scanning with a fore/aft angle of 20^{o} relative to fuselage.

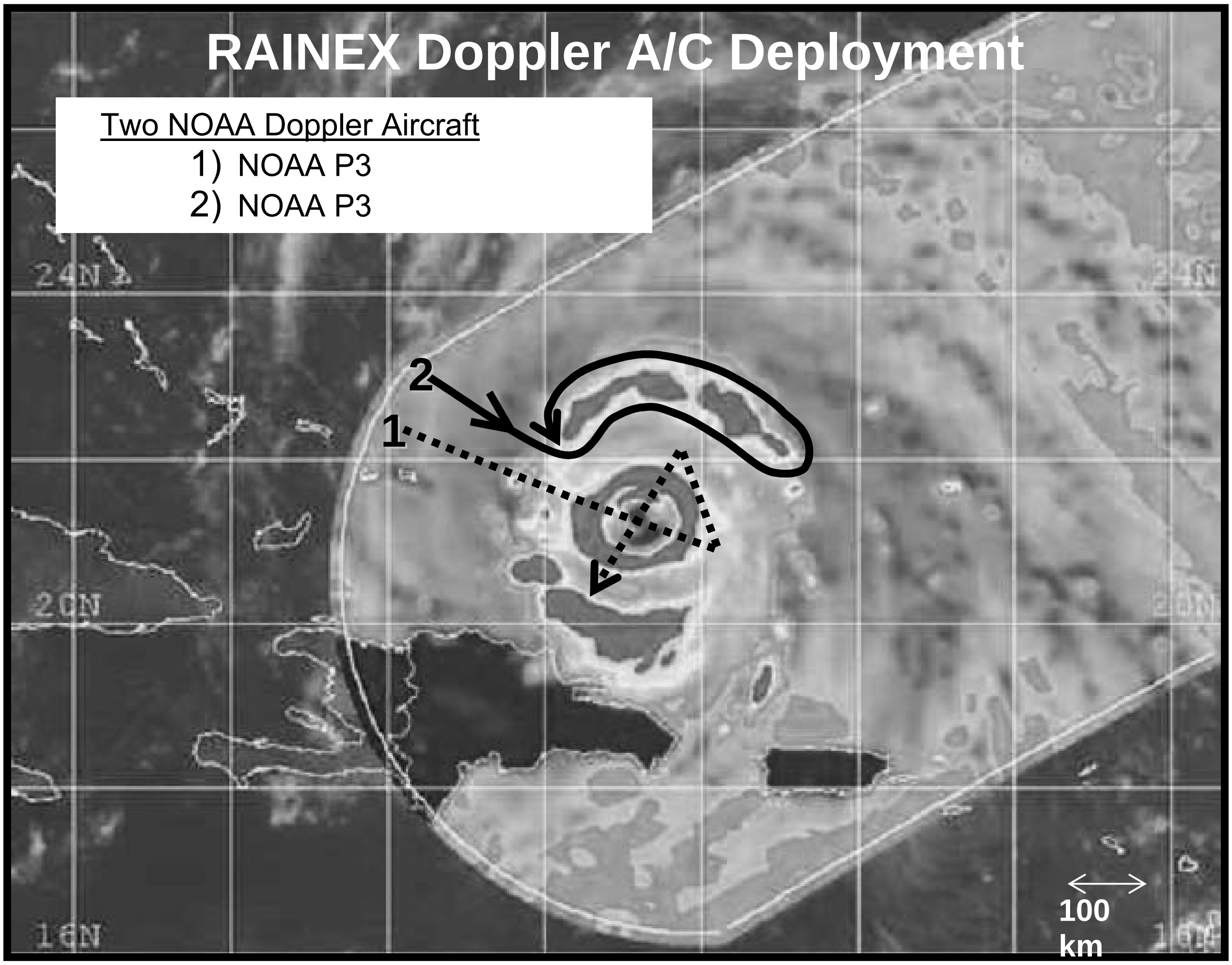


Figure RX-5. Alternate RAINEX Doppler radar aircraft modules for two NOAA P3 aircraft. Aircraft 1 arrives first, reconnoiters, and executes a rotating figure-four Eyewall Module for the duration of the mission. Aircraft 2 enters and flies an upwind Inner PRB module, goes around the end of the PRB and flies a downwind Outer PRB module. Then Aircraft 2 repeats the racetrack around the PRB for the duration of the mission. The racetrack could be flow in the opposite direction, but would be slower overall since it would have longer upwind leg. This alternate can be used only when the NRL P3 is not participating since the NRL PE may fly only the outer PRB Modules. This option for two Doppler radar aircraft sacrifices quadruple Doppler coverage of the PRB in favor of continuous coverage in the eyewall region.

Note 1.	Doppler radars should be operated in single-PRF mode, at a PRF of 2400-3200. The default will be 2800 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 NOAA-P3 Doppler radars should be operated in fore/aft continuous scanning with a fore/aft angle of 20^{o} relative to fuselage.

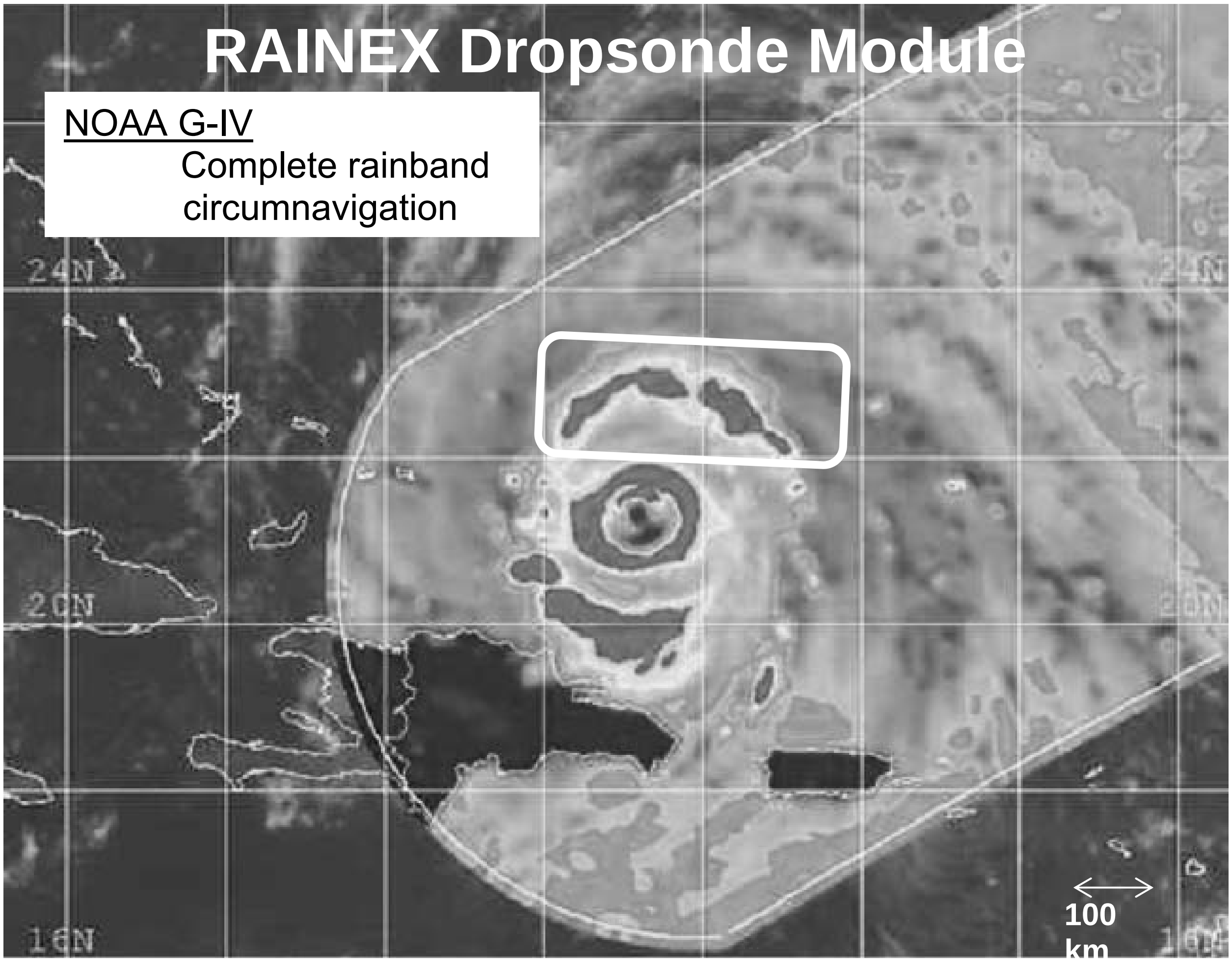


Figure RX-6. RAINEX dropsonde track for NOAA G-IV aircraft circumnavigating a major rainband.

Note 1.	Doppler radars should be operated in single-PRF mode, at a PRF of 2400-3200. The default will be 2800 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 NOAA-P3 Doppler radars should be operated in fore/aft continuous scanning with a fore/aft angle of 20° relative to fuselage.

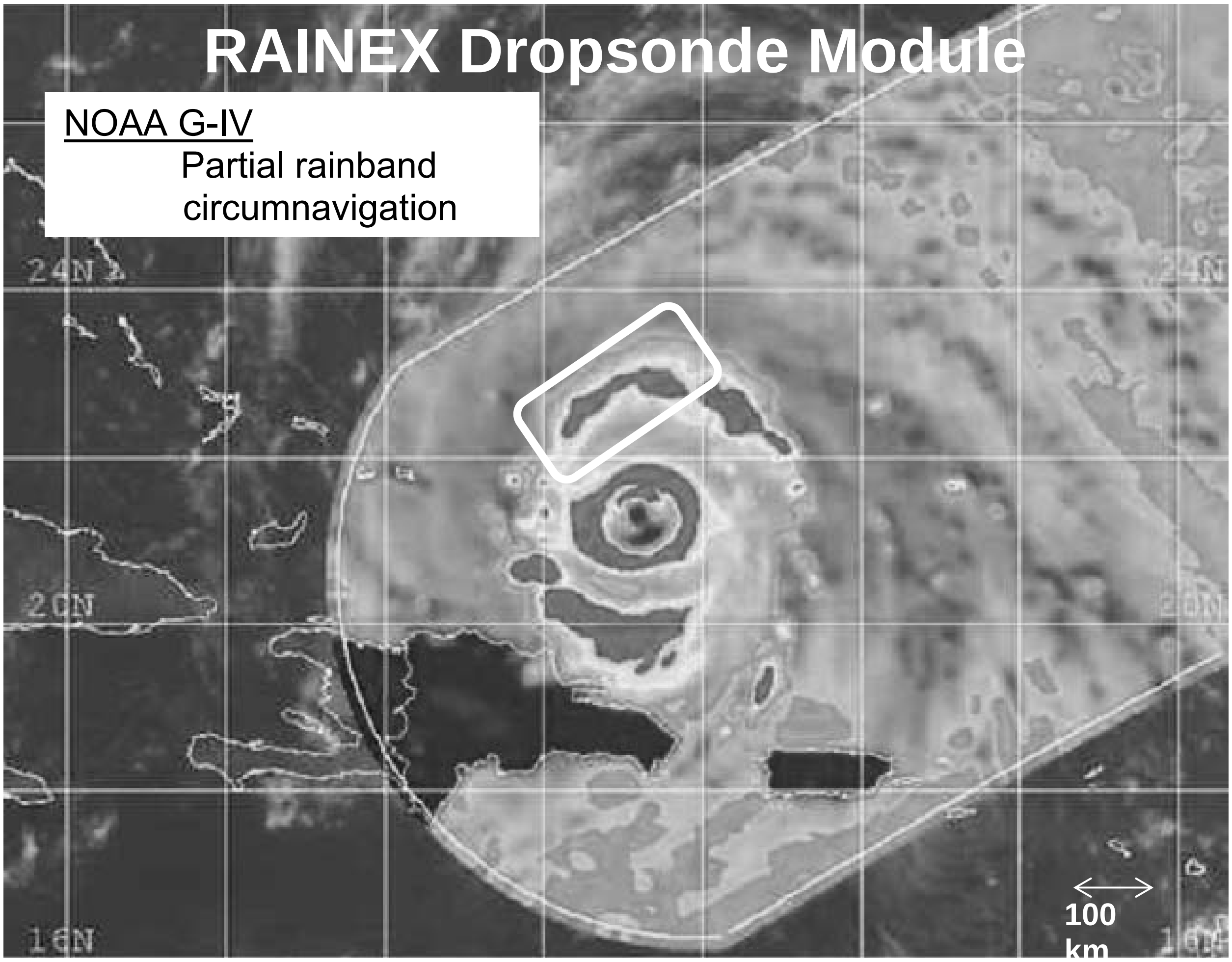


Figure RX-7. RAINEX dropsonde track for NOAA G-IV aircraft circumnavigating a portion of major rainband.

Note 1.	Doppler radars should be operated in single-PRF mode, at a PRF of 2400-3200. The default will be 2800 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 NOAA-P3 Doppler radars should be operated in fore/aft continuous scanning with a fore/aft angle of 20^o relative to fuselage.

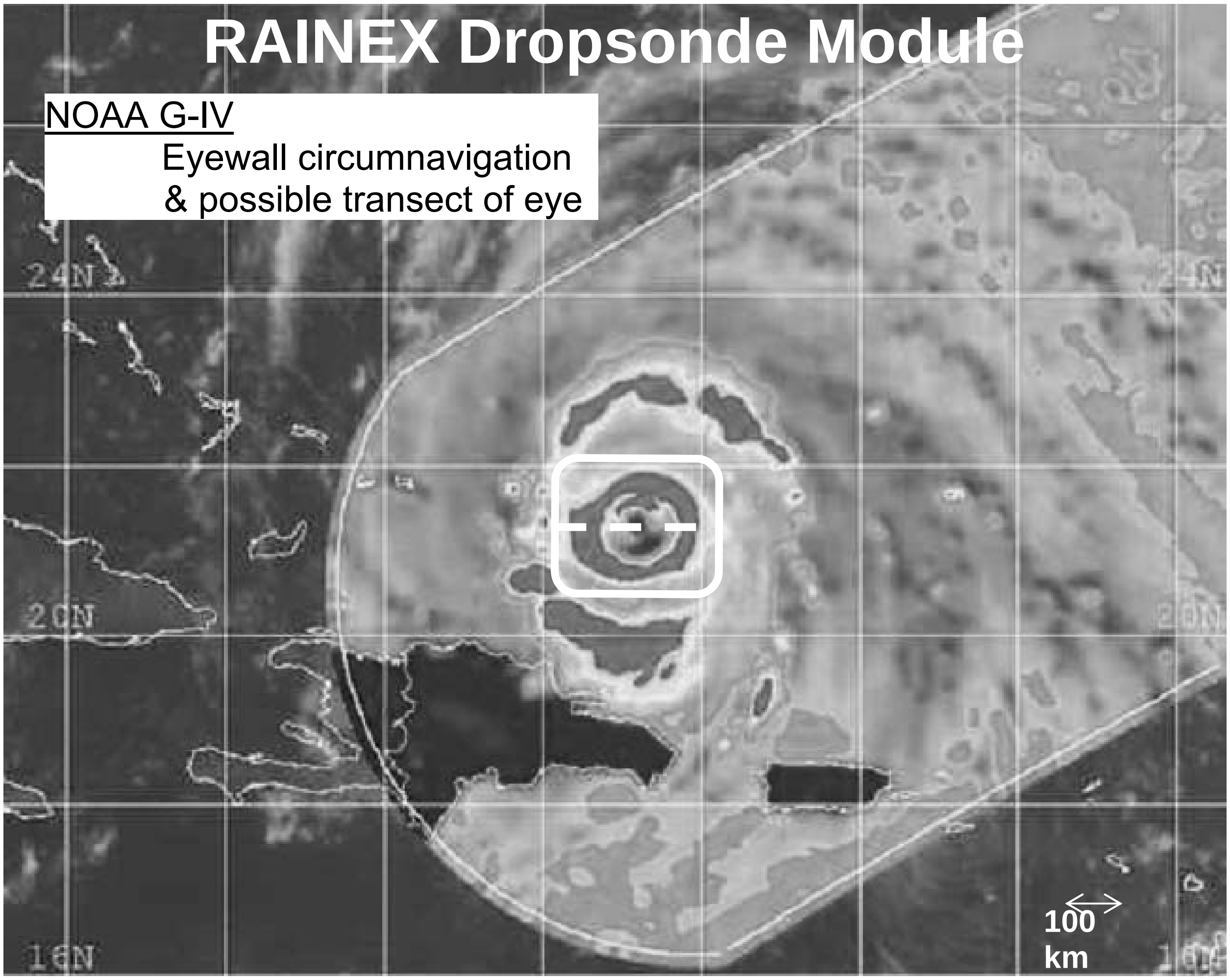


Figure RX-8. RAINEX dropsonde track for NOAA G-IV aircraft circumnavigating the eyewall. Dashed track indicates an optional transect of the eye.

Note 1.	Doppler radars should be operated in single-PRF mode, at a PRF of 2400-3200. The default will be 2800 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 NOAA-P3 Doppler radars should be operated in fore/aft continuous scanning with a fore/aft angle of 20^{o} relative to fuselage.

Mature Storms Experiment

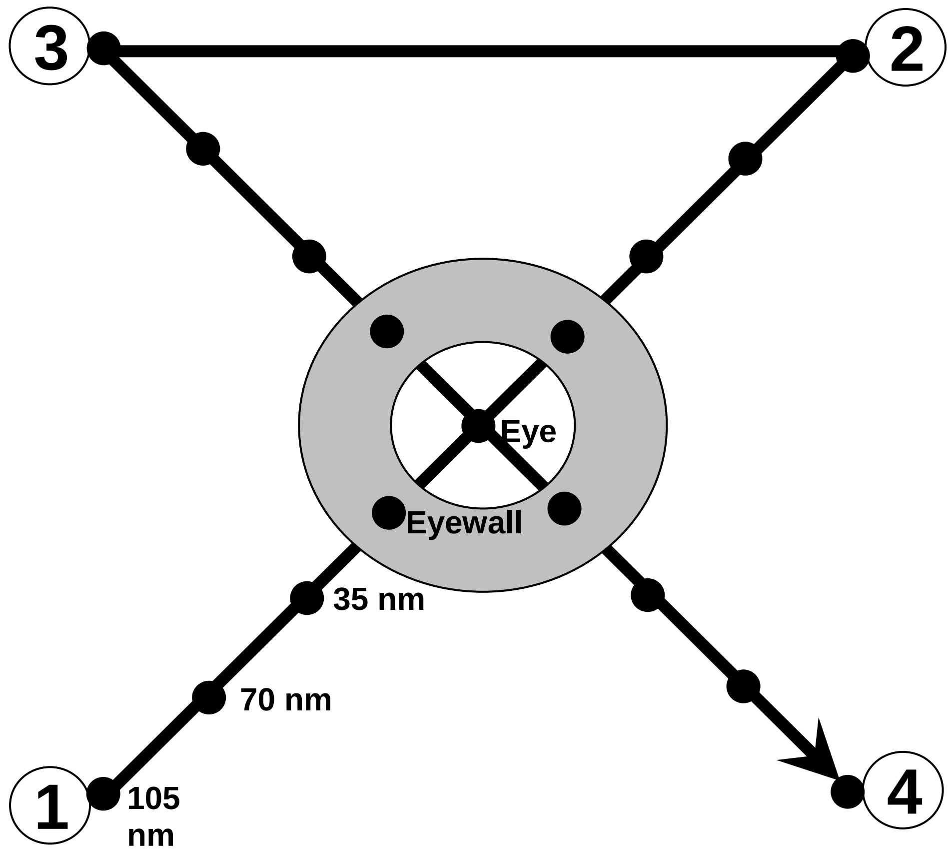


Figure RX-9. RAINEX USAF Flight Pattern ALPHA. Numbers in circles indicate way points. Dots are proposed dropsonde locations when flight altitude is 700 mb or higher.

Mature Storms Experiment

CBLAST EYEWALL MODULE

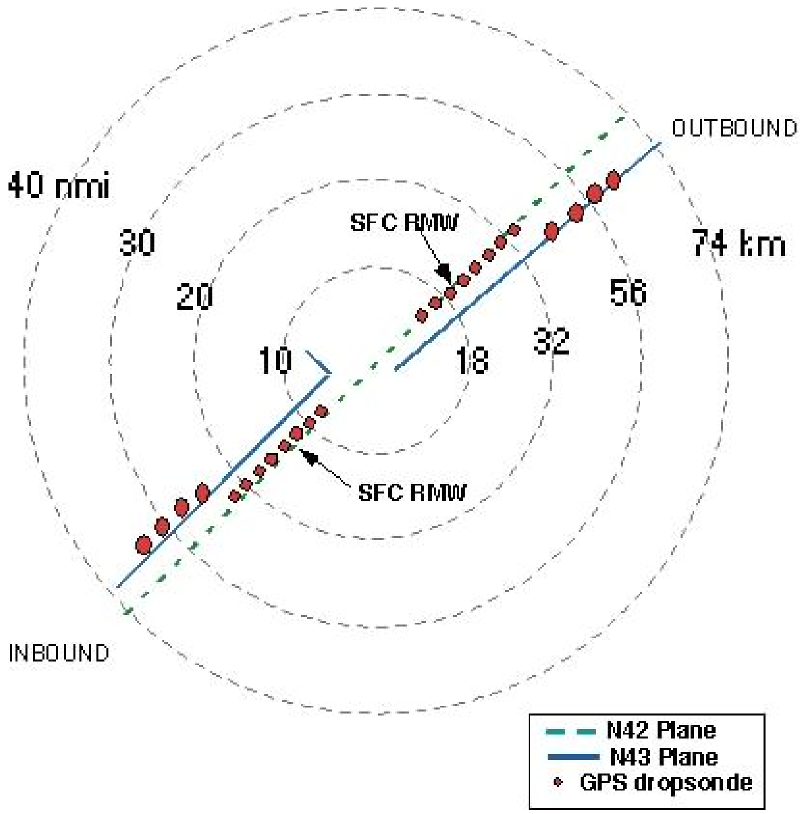


Figure. CBLAST-1. CBLAST eyewall sonde module.

• Note 1.	The pattern can be flown by one or both P3's along planned radial transits of the eye or as a separate module by one or both P3s.
• Note 2.	If both P3s are available, the lower WP-3D will commence a sequence of four near-eyewall drops on inbound legs at approximately $2R_{MAX}$ or twice the eyewall thickness radially-outward. High-level aircraft should commence series of 8 eyewall drops 30 s after end of low plane drops, ending at inner edge of eyewall. Orbit in the center until all drops have cleared. Reverse the sequence on the outbound legs.
• Note 3.	If only a single P3 is available, the dropsonde sequence should start near the flight-level RMW on the inbound leg and just before the surface RMW on the outbound leg.
• Note 4.	Operate NOAA 43 Tail Doppler in continuous mode on all coordinated legs.

Mature Storms Experiment

CBLAST Stepped-Descent Module

CBLAST
Along Wind Pattern

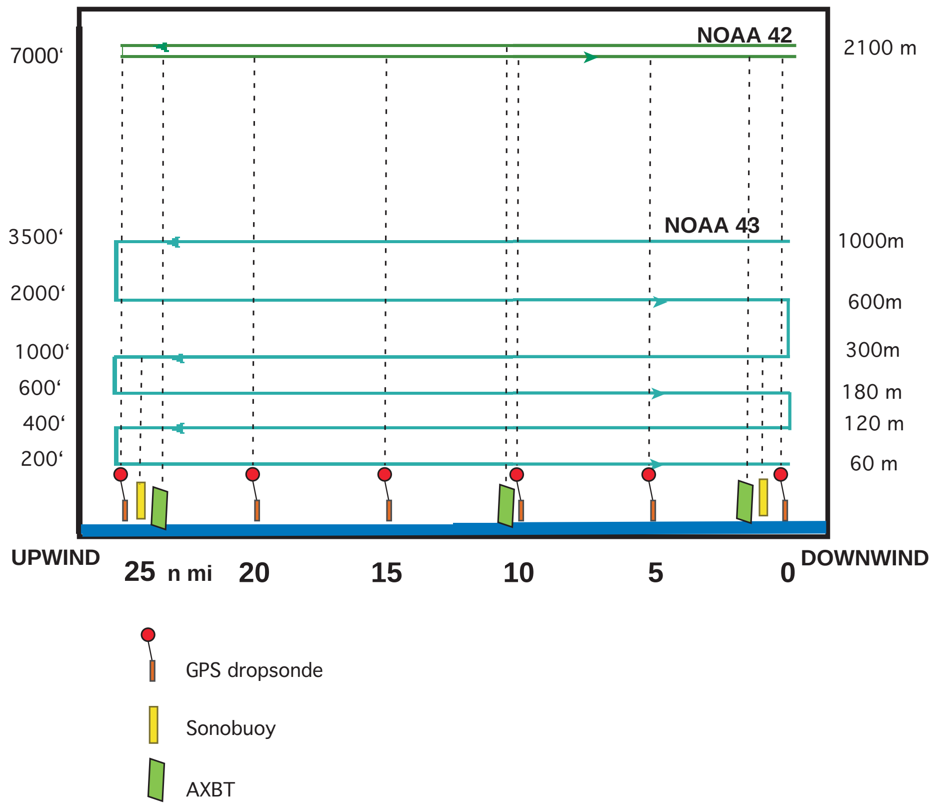


Figure CBLAST-2. CBLAST stepped descent pattern (racetracks) in upwind/downwind direction.

• Note 1.	If available, the high P3 flies at 7,000 ft deploying six sondes along the track of the low WP-3D for the first leg. The low P3 leads and orbits past the endpoint until the last sonde has splashed.
• Note 2.	A spiral descent is executed at the end of each leg.
• Note 3.	27 n mi legs will require 6 min downwind and 9 min upwind in 34-50 kt (17-26 m s^{-1}) winds (5 min down wind, 11 min upwind in 64-80 kt (33-41 m s^{-1}) winds).
• Note 4.	This module can only be performed if the following day is a hard-down day for any other research or operational flights

Mature Storms Experiment

Eye Module

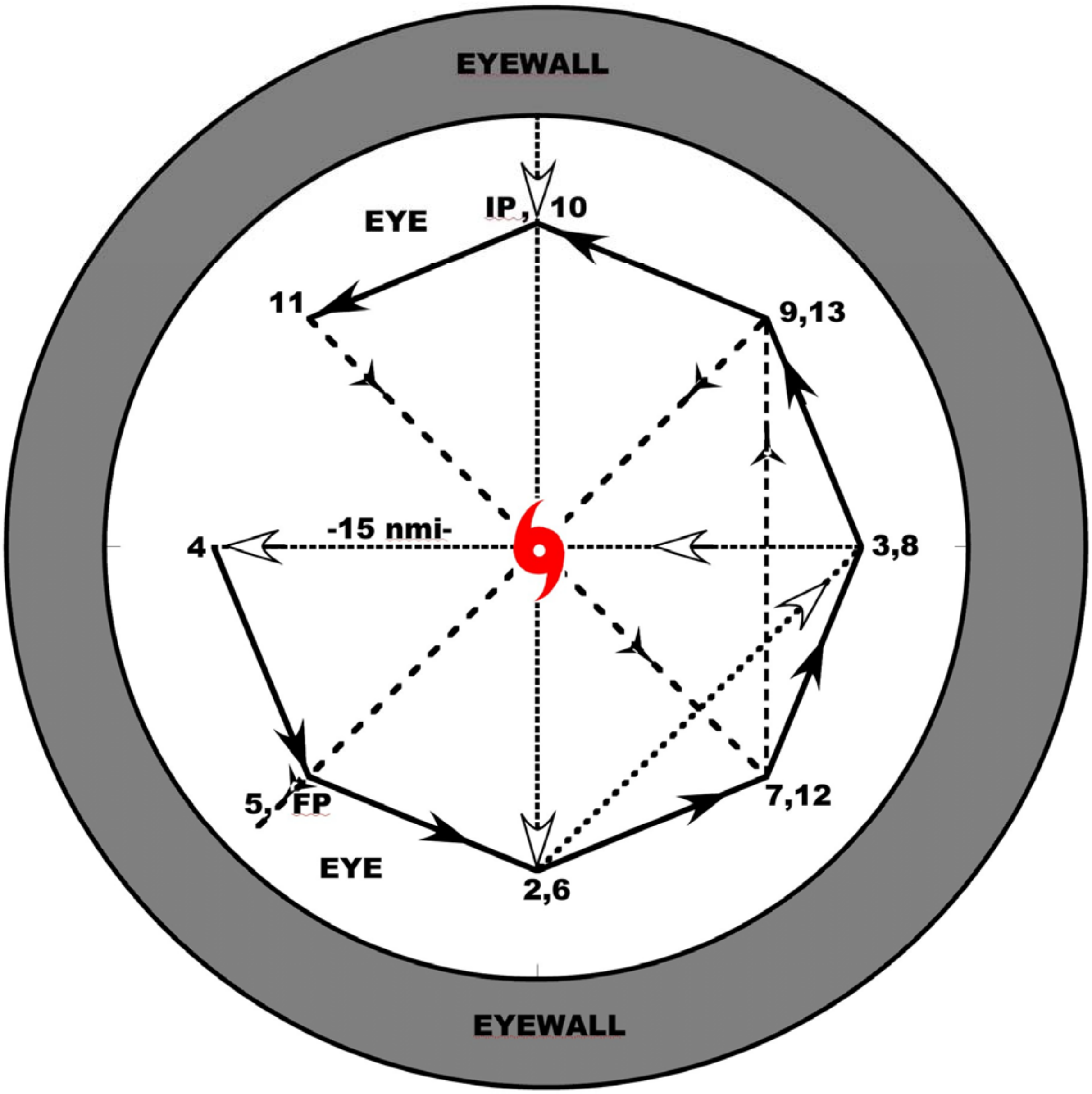


Figure EYE-1. Mature Storm Eye Module. The P-3 approaches from the north, penetrates the eyewall into the eye, and descends below the inversion to 2500 ft while performing a figure-4 (dotted line) in the eye. The P-3 circumnavigates the eye in an octagon or pentagon (solid line), and then ascends while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

Mature Storms Experiment
OCEAN WINDS EXPERIMENT/MODULE

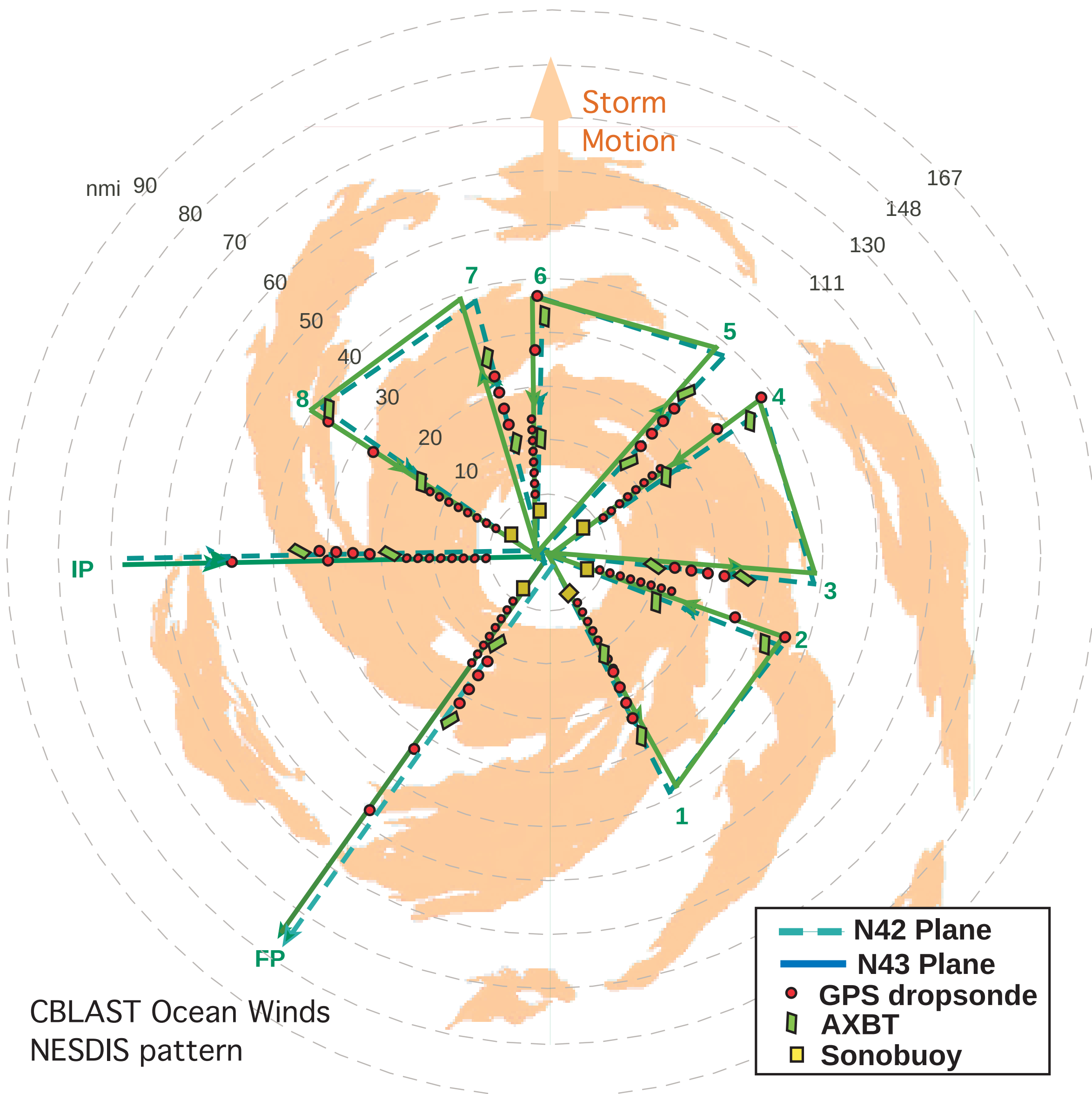


Figure OW-1. Ocean Winds Pattern

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

3. East Pacific Decay Experiment

Motivation

In-situ observations are rarely, if ever, available in eastern North Pacific tropical cyclones decaying over cooler waters. The intensity of these systems is typically estimated by the Dvorak technique, supplemented by QuikSCAT observations, however, there is some evidence that the Dvorak technique overestimates the intensity of weakening systems, thus overstating the hazard to marine interests. The purpose of this experiment is to obtain in-situ observations of decaying tropical cyclones to better calibrate existing methods of estimating tropical cyclone intensity over cold water.

Objectives

The observational objective is to obtain SST and flight-level, surface, and profile wind observations in tropical cyclones over several days during the decay process over cold water. Observations must be sufficient to obtain a reliable estimate of the cyclone's maximum sustained surface wind.

Flight Strategy

The flight strategy is to obtain two standard (105 n mi radius) alpha patterns (rotated) on each of 3 flights over a 3-4 day period (Fig. EPAC-1). Each flight requires the SFMR, three AXBTs and about 10 dropsondes. AXBTs would be used on the inbound and outbound legs most perpendicular to the SST gradient, one at each end and one in (near) the center to get a general idea of the SST. Drops would be made at the corner points of one alpha pattern and in the max wind band of two of the four penetrations of each alpha pattern. In addition, a center drop would be made during each penetration to provide surface pressure. If the storm were too far away to do two, one alpha pattern would be acceptable. SFMR is almost critical for the success of the mission, but should it fail or be otherwise unavailable a mission could be conducted with a significantly enhanced number of dropsondes.

Three flights would occur over a 3-4 day period. First flight is in a hurricane just prior to reaching the SST gradient. Second flight is in the gradient (presumably now TC is a TS), and last flight is over the cold water as the TS is decaying toward TD status. Depending on forward speed, flights would occur on consecutive days, or perhaps there would be a down day. If possible, flight levels should be constant over the course of the flights - 850 mb is the preferred level.

East Pacific Decay Experiment

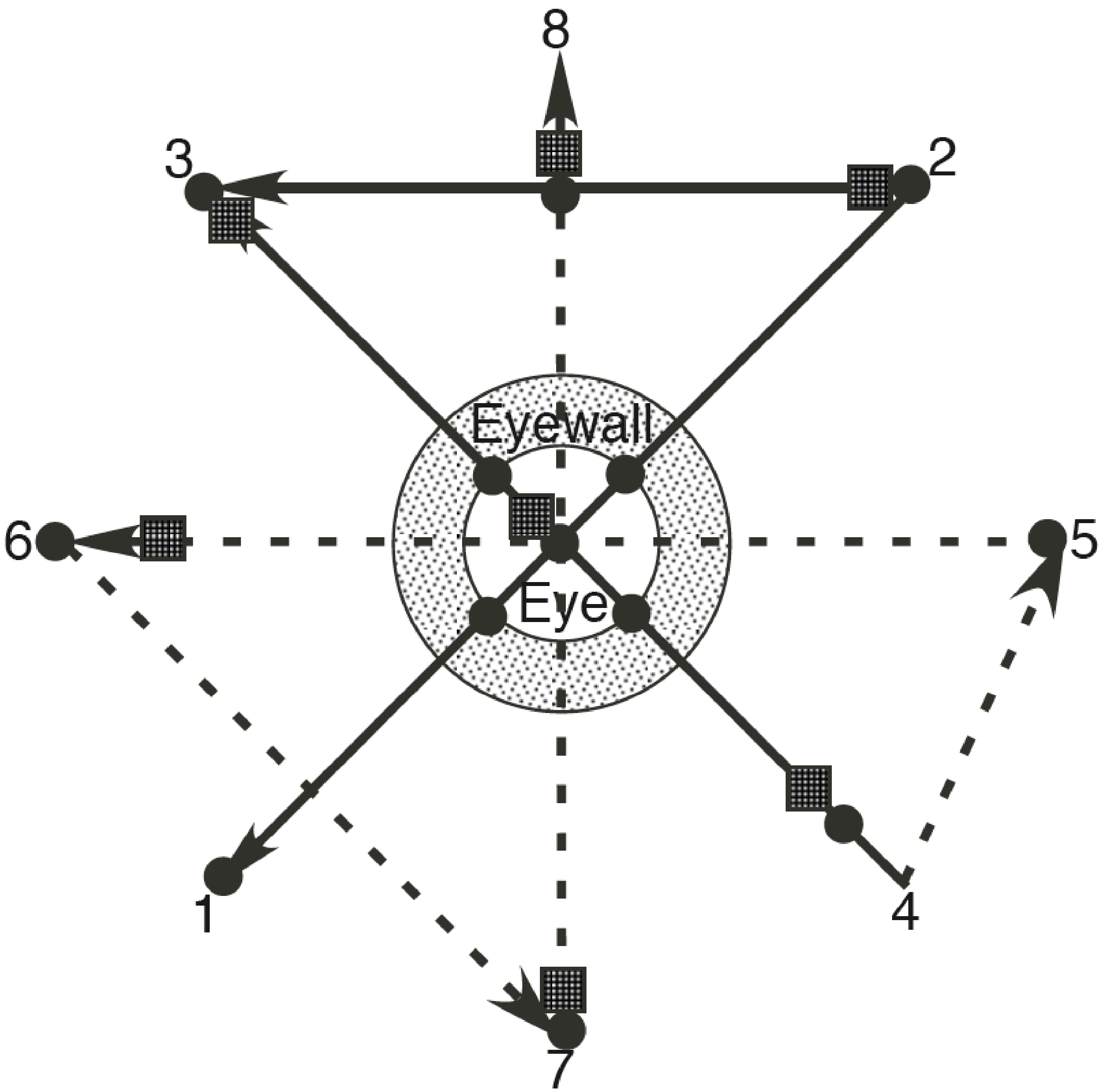


Figure EPAC-1. Rotating alpha pattern

• Note 1.	Alpha pattern leg lengths of 105 nm flown at 850 mb.
• Note 2.	Repeat initial Alpha pattern (5-8) time permitting
• Note 3.	Supplemental dropsondes and AXBTS may be requested

4. Tropical Cyclone Wind Fields at Landfall Experiment

Program Significance: An accurate real-time description of the TC surface wind field near and after landfall is important for warning, preparedness, recovery efforts, and post-storm analysis. 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, but now there is an opportunity to improve the accuracy of the surface wind fields in TCs, especially near landfall. Improvements in diagnosing surface wind fields could reduce uncertainties in the size of hurricane warning areas.

There are still uncertainties in deriving surface wind estimates from flight level and Stepped Frequency Microwave Radiometer (SFMR) wind speeds collected near the coast. Currents and changing bathymetry could change the breaking wave field, which could change both the roughness length at higher wind speeds as well as changing the microwave emissions. Evaluation of these effects may lead to adjustments to the operational surface wind speed algorithms. Data collected at the coast will also help to refine the inland decay model being developed and evaluated in the Joint Hurricane Testbed (JHT). Airborne Doppler radar data will be transmitted to TPC/NHC and EMC as part of another 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 2005 Field Program. A major goal is to capture the lifecycle of a TC and landfall is usually at the end of the lifecycle. 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 wind fields to compare with output from the HWRF. SRA data can be compared to HWRF wave fields. 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. Data collected during and shortly after landfall should help refine operational statistical decay models as well as provide validation for 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. The surface wind analyses are also used to validate and calibrate an operational inland wind forecast model that HRD has developed under Federal Emergency Management Agency (FEMA) sponsorship. The operational storm surge model (SLOSH) could also be run in real-time with initial data from the surface wind analysis.

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), Isidore (2002) and Frances, Ivan and Jeanne (2004).

Dual-Doppler analysis provides a more complete description of the wind field in the inner core. While these techniques are still too computationally intensive for real-time wind analysis, the data are quite useful for post-storm analysis. 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 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% 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 eyewall 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%, 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 through utilization of GPS-sonde data.

E) Obtain a remote sensing database suitable for evaluation and improvement of satellite and ground validation rainfall estimation algorithms for landfalling TCs.

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 transmit GPS sonde and radar back to TPC/NHC. Microphysical data should be collected, to compare rainfall rates with those used in the WSR-88D precipitation products. The SFMR should be operated, to provide estimates of wind speed at the surface. If the IWRAP or C-SCAT is on the aircraft then it should also be operated to provide another estimate of the surface winds.

If the portable Doppler radars (SNART-R and/or DOW), portable profilers and portable wind towers are able to participate in the experiment then they should be deployed between ~65 and 130 km inland in the onshore flow regime as depicted in Fig. LF-1. 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 northwest 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 will 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 ms^{-1}. 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. 15). 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%. 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. Figure LF-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 wind speed. 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 wind speeds. 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 wind speed n various near shore environments to test the hypothesis that near the coast surface wind speeds 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 nm. Then the aircraft turns and flies into the center of the storm, back offshore, 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 eyewall. 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 rainband 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. A profiler will 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. 20 shows the estimated time after landfall that is required for the TC winds to decay to various wind threshold levels as determined using the HRD empirical inland wind 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.

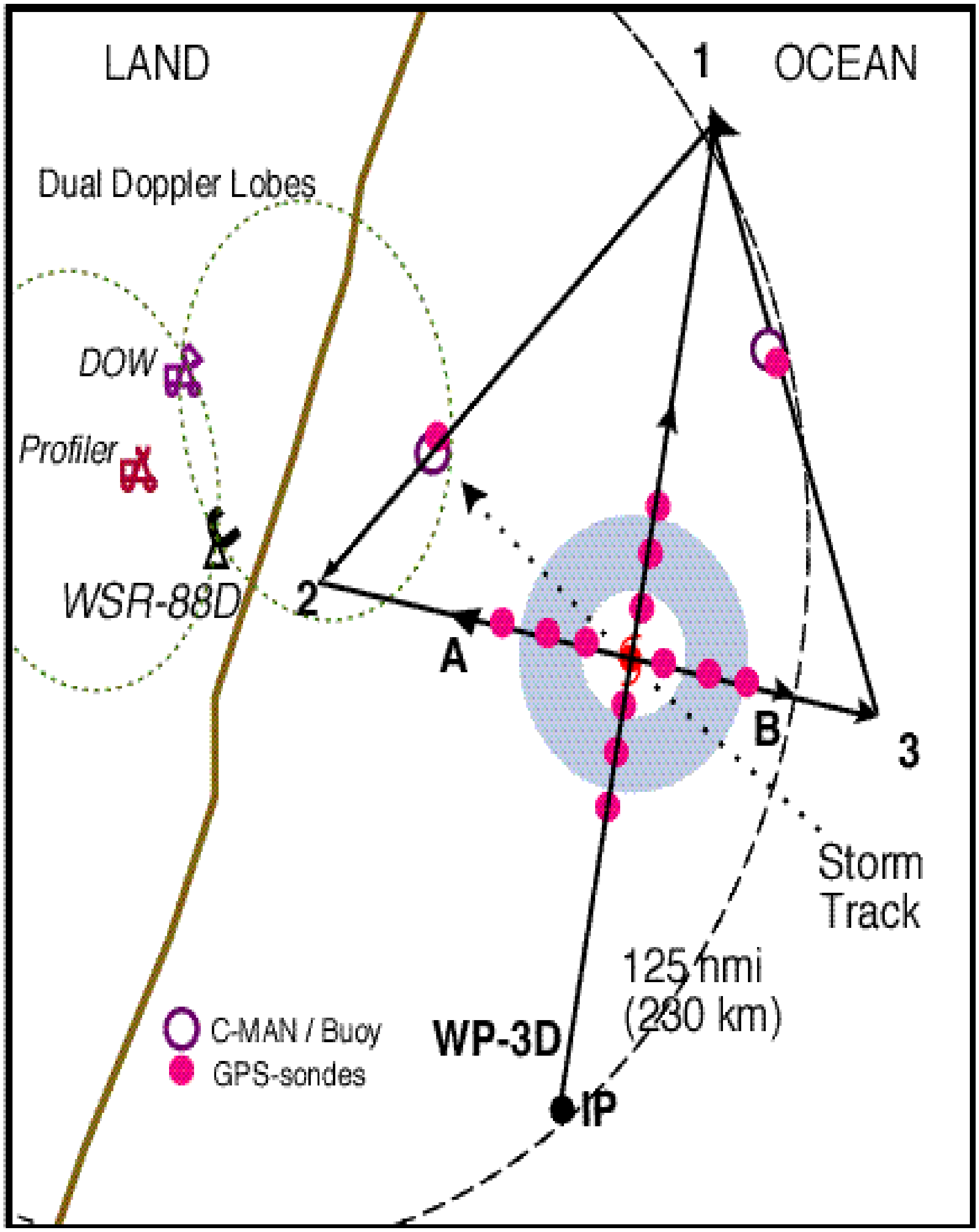


Figure LF-1. Real-time module

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.

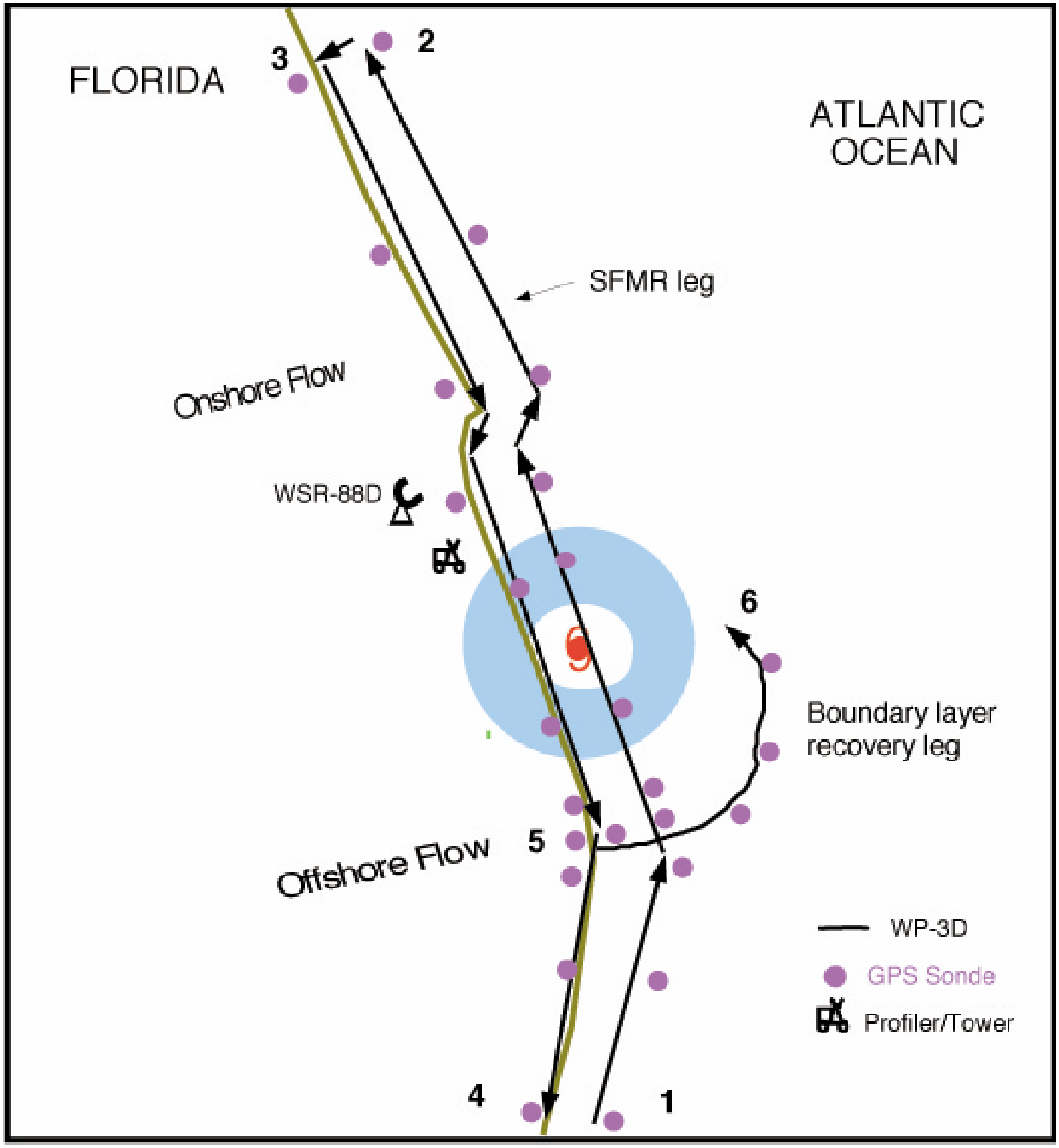


Figure LF-2 Coastal Survey pattern.
First pass starts 150 km from center or radius of gale-force winds, whichever is closer. Pass from **1-2** should be 10-15 km offshore for optimum SFMR measurements. Drop sondes at RMW, and 12.5, 25, 50, 75 and 100 or 125 km from RMW on ether side of storm in legs **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).

SFMR EVALUATION MODULE

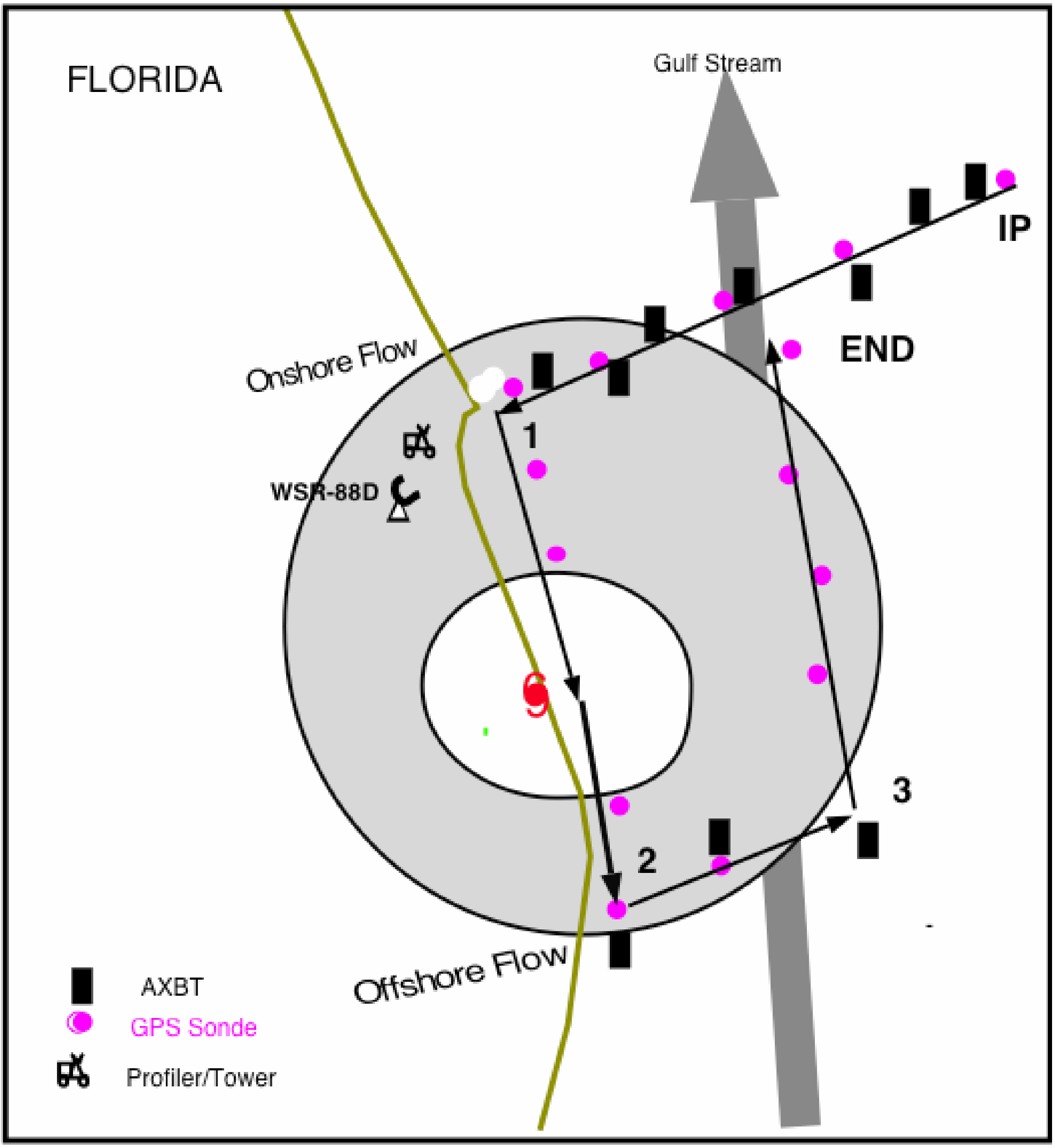


Figure LF-3. SFMR Evaluation Module. Gray area encloses hurricane inner core with winds > hurricane force. True airspeed calibration is required. The legs are at 1500-3000 ft (500 - 1000 m) altitude. Set airborne Doppler radar to F/AST mode at a single PRF 2400 and 20° tilt on all legs. Aircraft should avoid penetration of intense reflectivity regions (particularly those over land). Wind center penetrations are optional.

ONSHORE WIND PROFILE MODULE

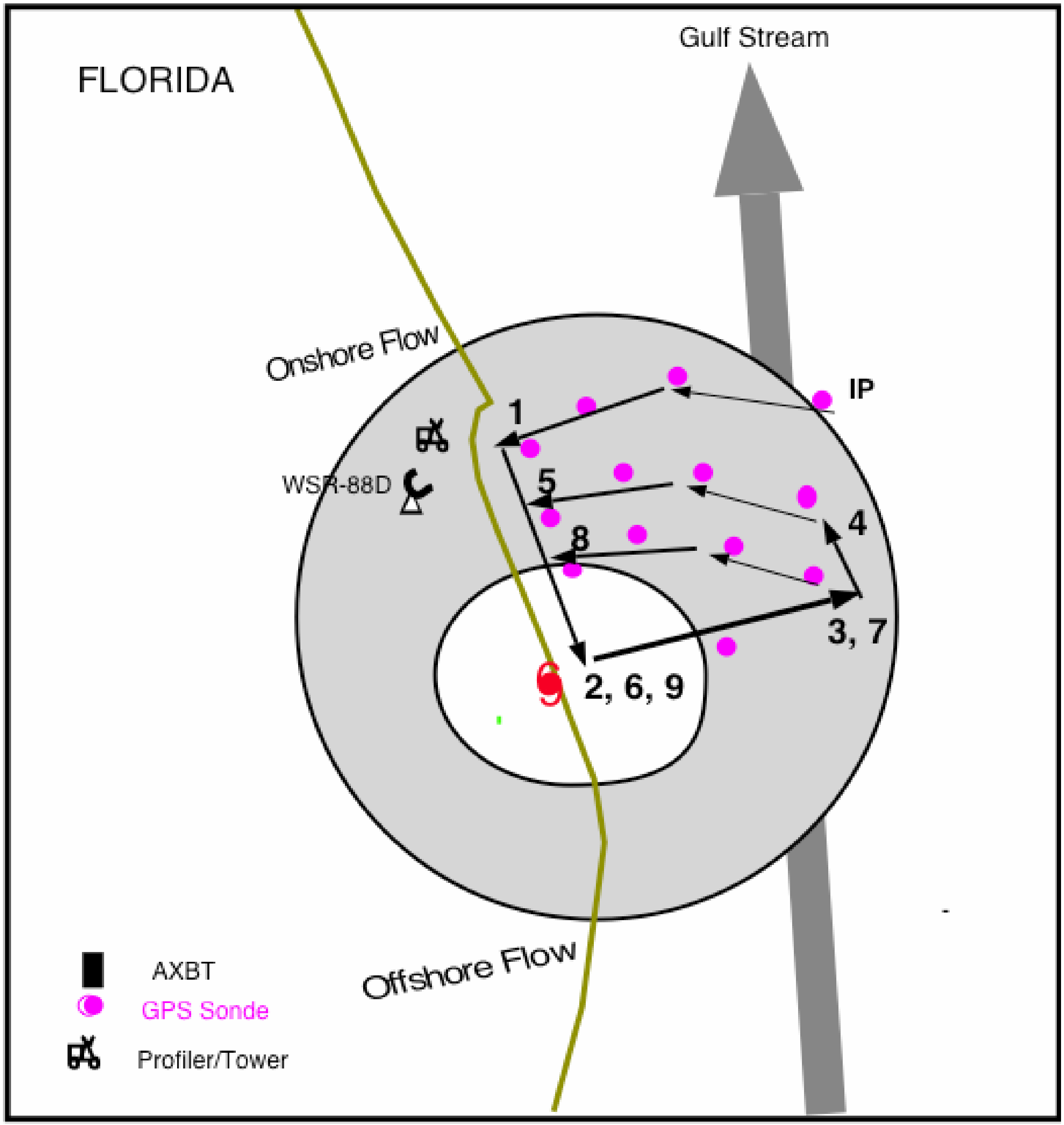


Figure LF-4. Coastal Windspeed Profile Evaluation Module.
True airspeed calibration is required. The legs are at 700 mb (10000 ft, 3000 m) altitude.
Set airborne Doppler radar to F/AST mode at a single PRF 2400 and 20° tilt on all legs.
Aircraft should avoid penetration of intense reflectivity regions (particularly those over land).
Wind center penetrations are optional.

TROPICAL CYCLONE LANDFALL WINDFIELDS EXPERIMENT

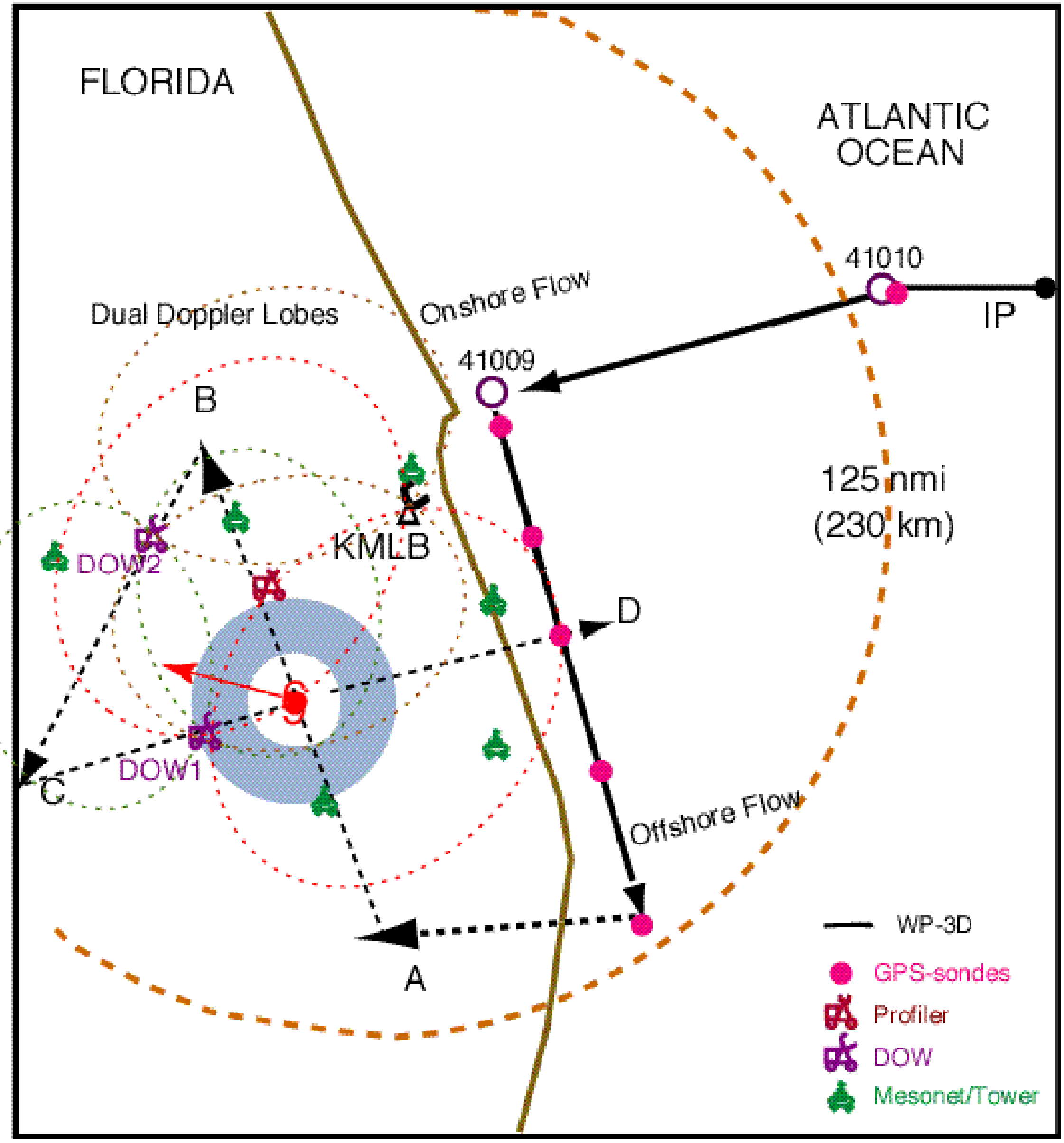


Figure LF-5. Post landfall module flight pattern.

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.

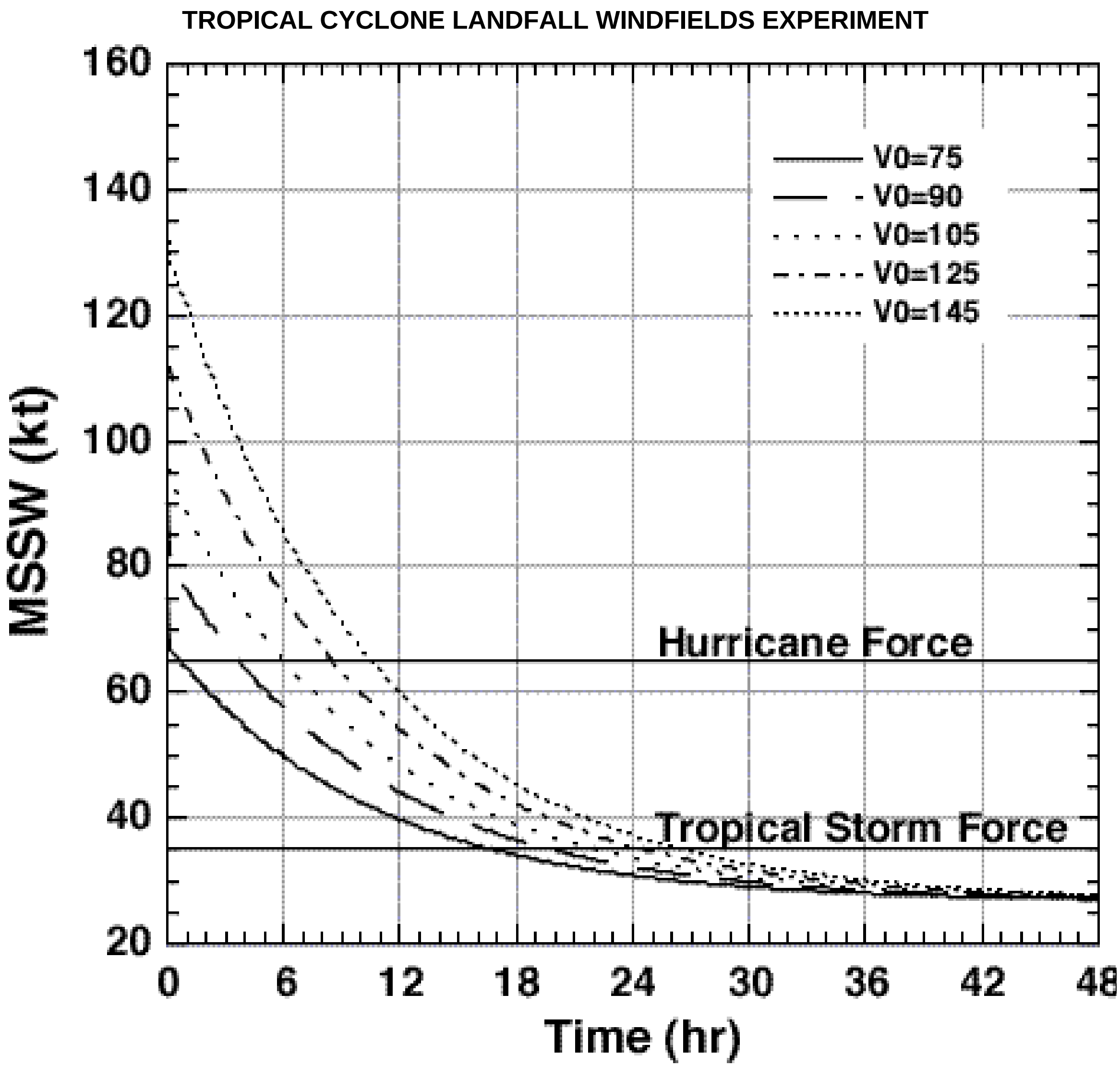


Figure LF-6. Maximum sustained surface winds after landfall.
Maximum sustained surface winds (MSSW) after landfall estimated using the Kaplan/DeMaria inland wind decay model for TCs with landfall intensities (V0) of 75,90,105,120, and 145 kt.

5. 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 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.

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 2005, it is unlikely HRD will to perform the synoptic flow missions with the P-3 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 P3s only on a non-interference basis with other research or operationally-tasked missions.

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-mb 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.*

GPS-sondes are released in one of two modes. Beyond 80 nm (150 km) from the storm center, drops are made at pre-assigned locations, generally every 25 min or 120 nm (222 km). These drop locations are provided with the particular mission flight tracks 2 h before departure. Within 80 nm (150 km) of the TC's center, drop locations are specified relative to the center's position (e.g., 40 nm (75 km) north of the eye). During in-storm portions of the mission, drops will be made with possible spacing <8 min or 40 nm (75 km).

If a NOAA-P3 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 0530 or 1730 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

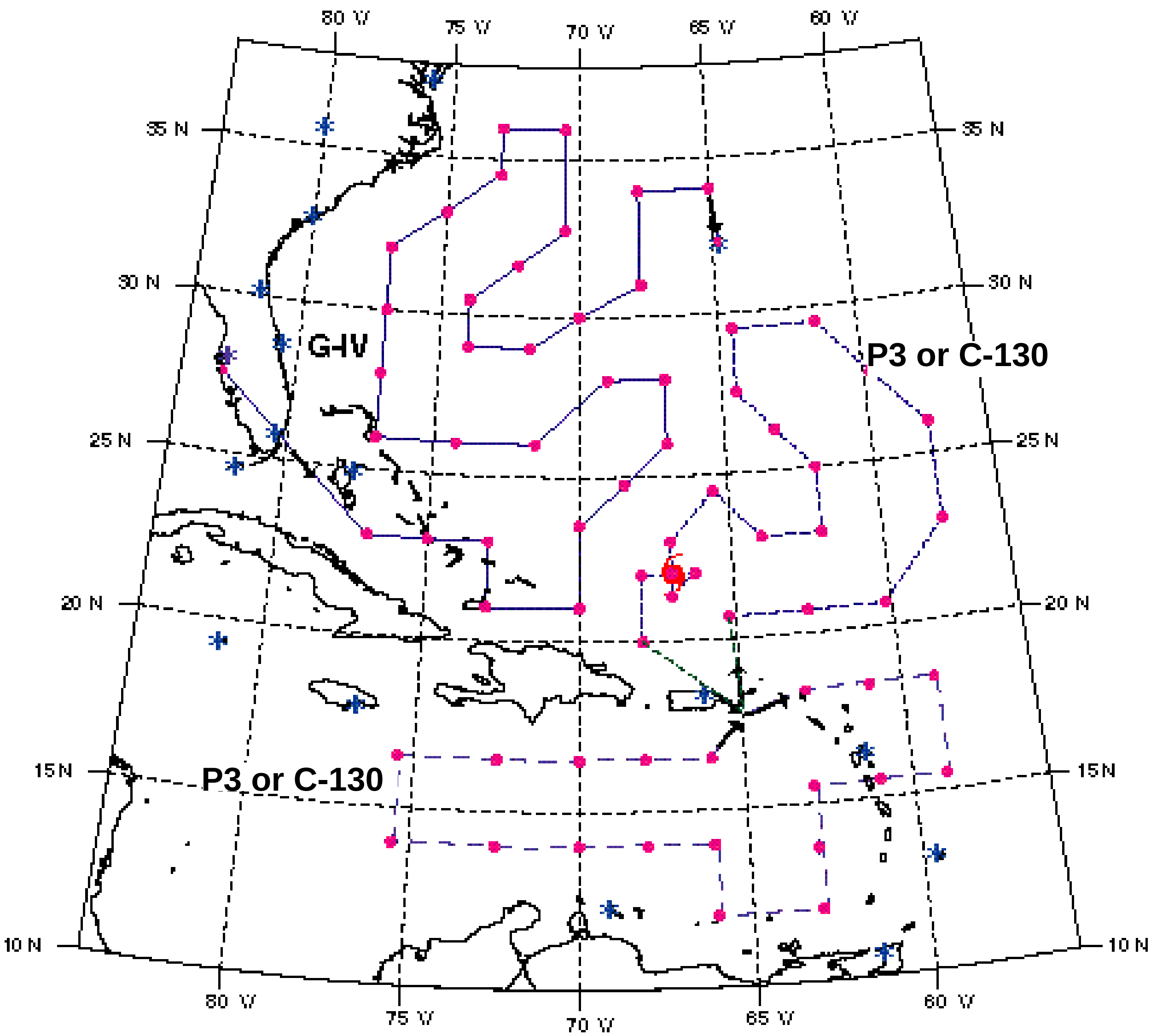


Figure. SYN-1 Sample Environmental Patterns

• Note 1.	During the ferry to the **IP**, the WP-3D or C-130 aircraft will climb to the 500 mb level (about FL 180). The 400 mb level (about FL 250) should be reached as soon as possible and maintained throughout the remainder of the pattern, unless icing or electrical conditions require a lower altitude.
• Note 2.	During the ferry to the **IP**, The G-IV should climb to the 41,000 ft (200 mb) as soon as possible and climb as feasible to maintain the highest altitude for the duration of the pattern.

HURRICANE SYNOPTIC FLOW EXPERIMENT

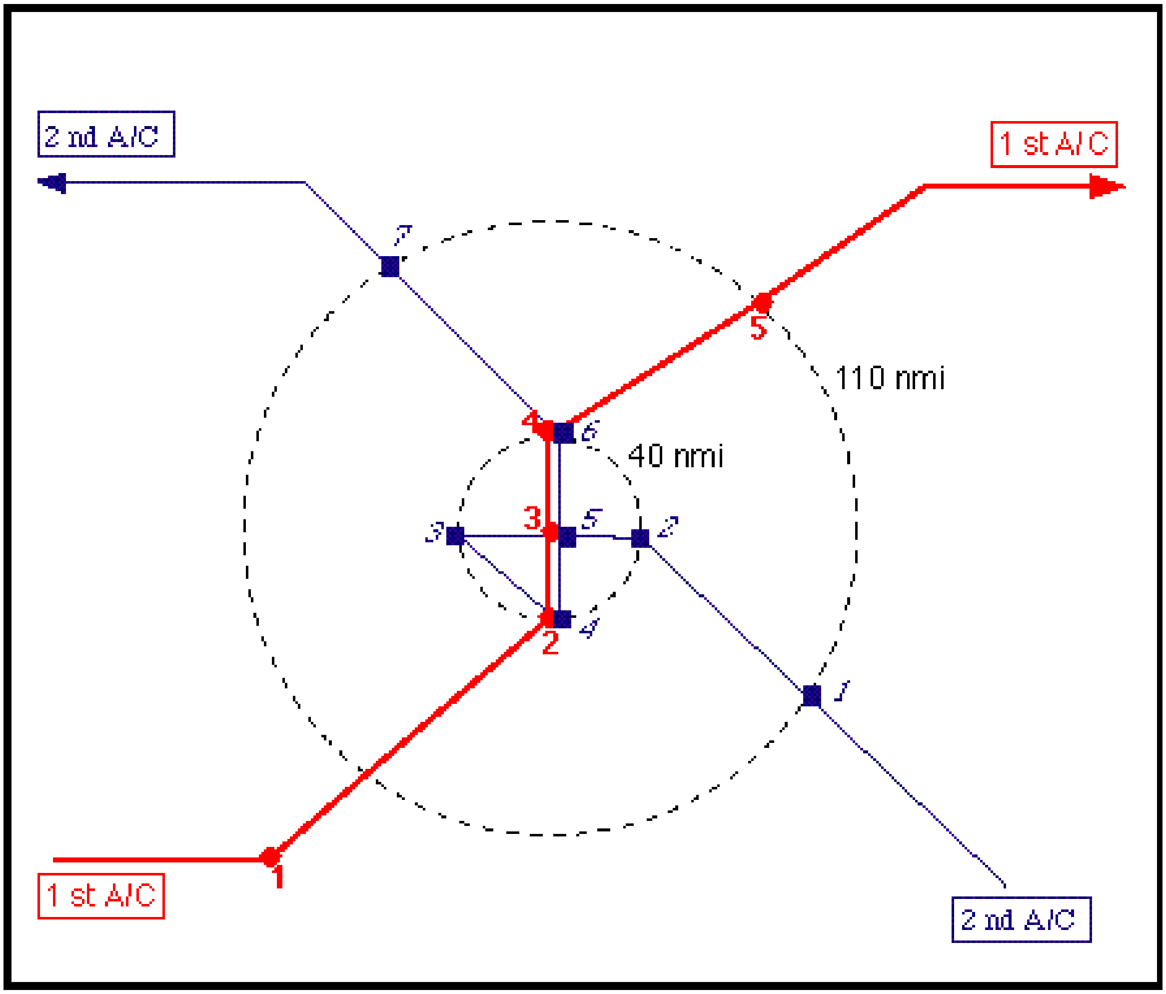


Figure. SYN-2 In-Storm Patterns

- 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 (υ, ν) reflect scheduled drops for each aircraft.
- Note 4. Drop #5 in the "figure-4" pattern occurs on the second pass through the eye.
- Note 5. A/C 1 should collect vertical incidence Doppler data during storm penetration.
- Note 6. If missions are not repeated, then block times may exceed 9 h. In addition to the GPS-sonde data, *3-4 RECCO's h^{-1} should be transmitted during each mission.*

Special Notes: Missions similar to the Synoptic Flow missions may be flown in non-hurricane conditions to collect GPS-sonde 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. 22) 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: GPS dropwindsondes will be launched from the G-IV (flying at ~200 mb/~41,000 ft) or the WP-3D (flying at ~500 mb/~20,000 ft) along the operational Synoptic Surveillance flight pattern. These additional drop locations 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 (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.

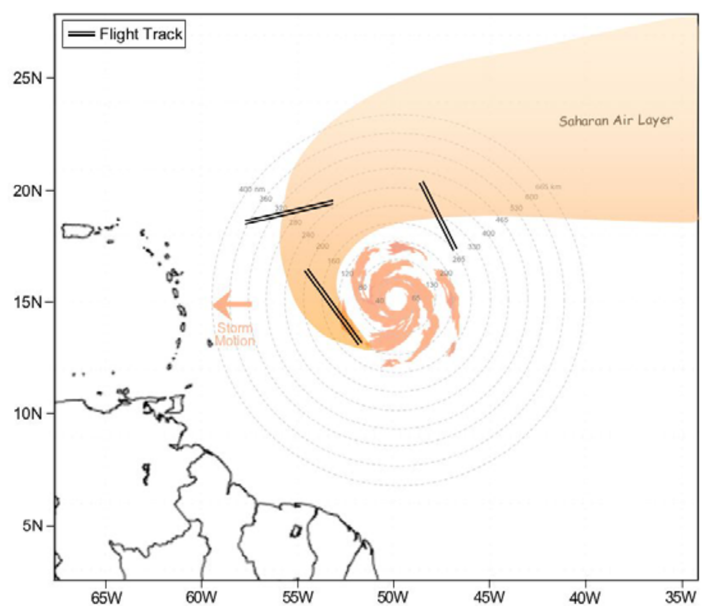


Figure SYN-3: Sample flight track for a TC positioned along the SAL's southern boundary.

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.

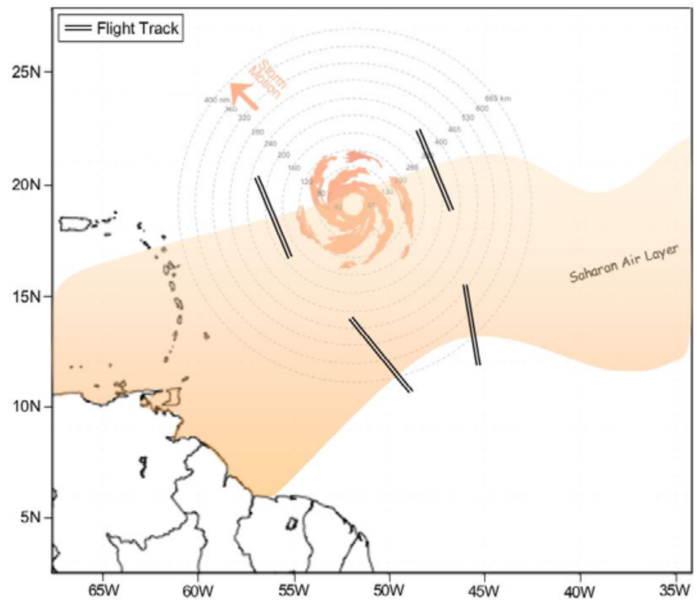


Figure. SYN-4: Sample flight track for a TC emerging from the SAL.

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.

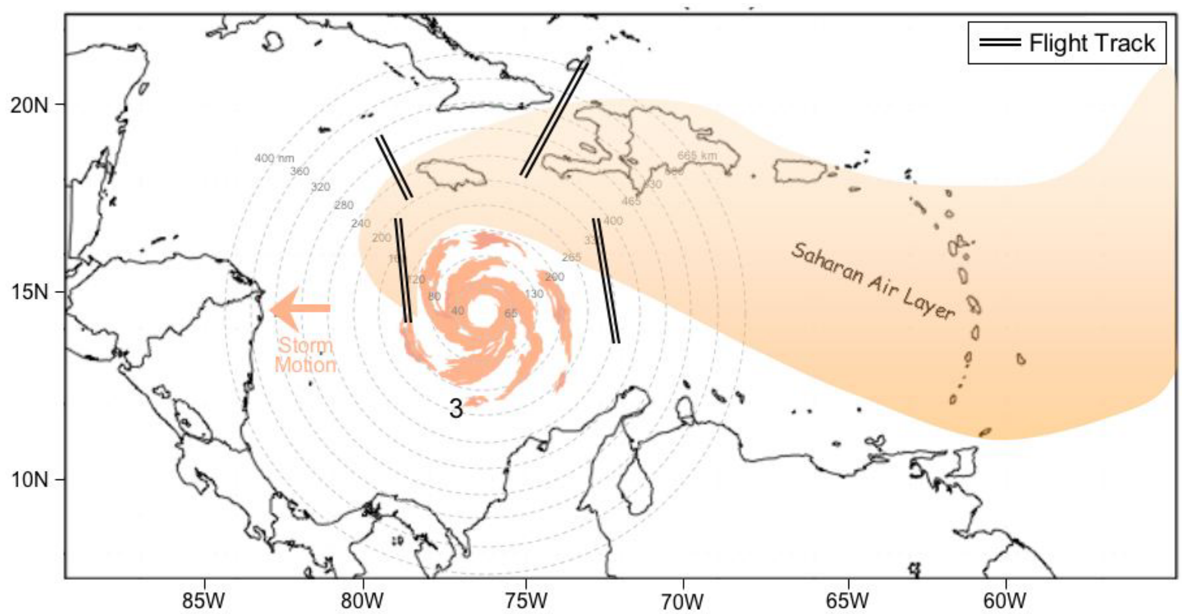


Figure SYN-5: Sample flight track for a TC embedded in the SAL for most or all of its lifecycle.

- Note 1. During the ferry to the **IP**, the WP-3D aircraft will climb to the ~500 mb level (~20,000 ft). The 400 mb 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 mb (~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.

6. Saharan Air Layer Experiment (SALEX)

Program Significance: The Saharan Air Layer (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 mb (~20,000 ft) over the African continent. This air mass is extremely warm and dry, with temperatures that are markedly warmer (~0.5-1.0^{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 mb (~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 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:
- Collect observations of the atmosphere and ocean in and around the storm scale circulation that can be used to develop an evaluation and validation package for the high resolution HWRF.
- Collect observations in a variety of atmospheric/oceanic conditions (e.g. atmospheric shear and humidity environments, oceanic warm core eddies) to assess the influence of these features on observed and modeled TC intensity and structure changes.

Mission Description: The NOAA G-IV (flying at ~200 mb/~41,000 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, and the immediate surrounding moist tropical environment. Several SAL/TC interaction scenarios are candidates for this mission:

<u>Option 1:</u>
Single TC located along the southern edge of the SAL (Fig. SAL-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). The **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 low humidity and wind shear (produced by 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**).

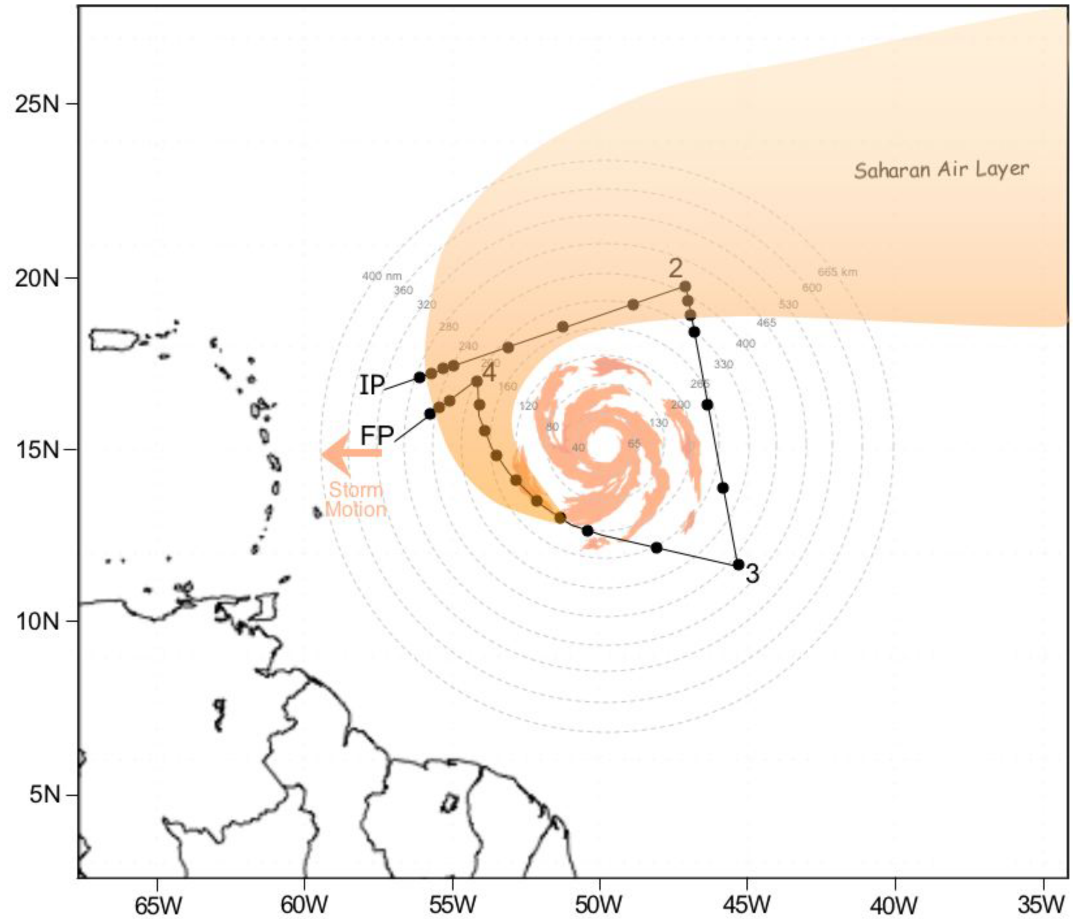


Figure. SAL-1: Sample G-IV flight track for a TC positioned along the southern edge of the SAL.

- Note 1: During the ferry to the **IP**, The G-IV should climb to ~200 mb (~41,000 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 (**IP-2**, **2-3**, and **4-FP**).
- Note 3: The SAL's mid-level easterly jet (~20-45 kt at 700 mb/10,000 ft) may be evident from GPS dropwindsondes dropped near the SAL's southern boundary (**IP-2** and **2-3**).

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

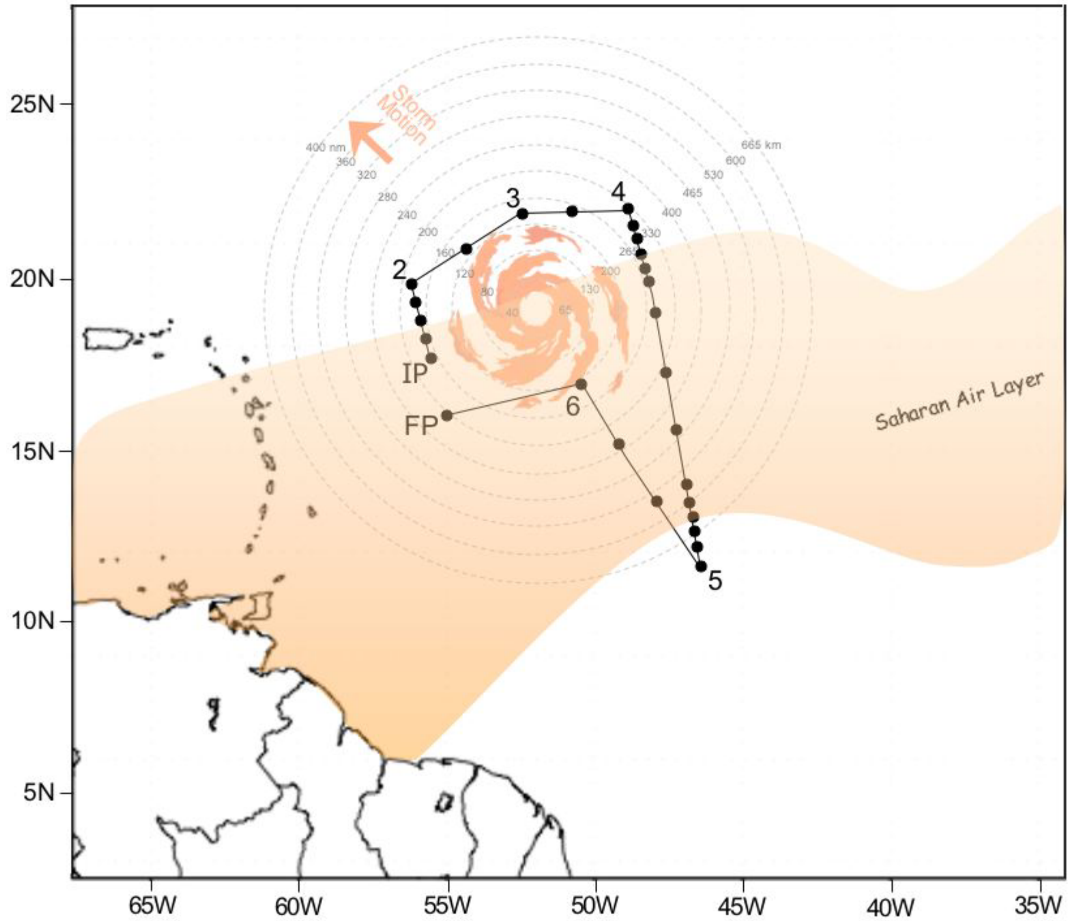


Figure. SAL-2: Sample G-IV flight track for a TC emerging from the SAL.

- Note 1: During the ferry to the **IP**, the G-IV should climb to ~200 mb (~41,000 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 (**IP-2** and **4-5**).
- Note 4: The SAL's mid-level easterly jet (~20-45 kt at 700 mb/10,000 ft) may be evident from GPS dropwindsondes dropped near the SAL's southern boundary (**4-5** and **5-6**).

Option 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 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). 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. 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.

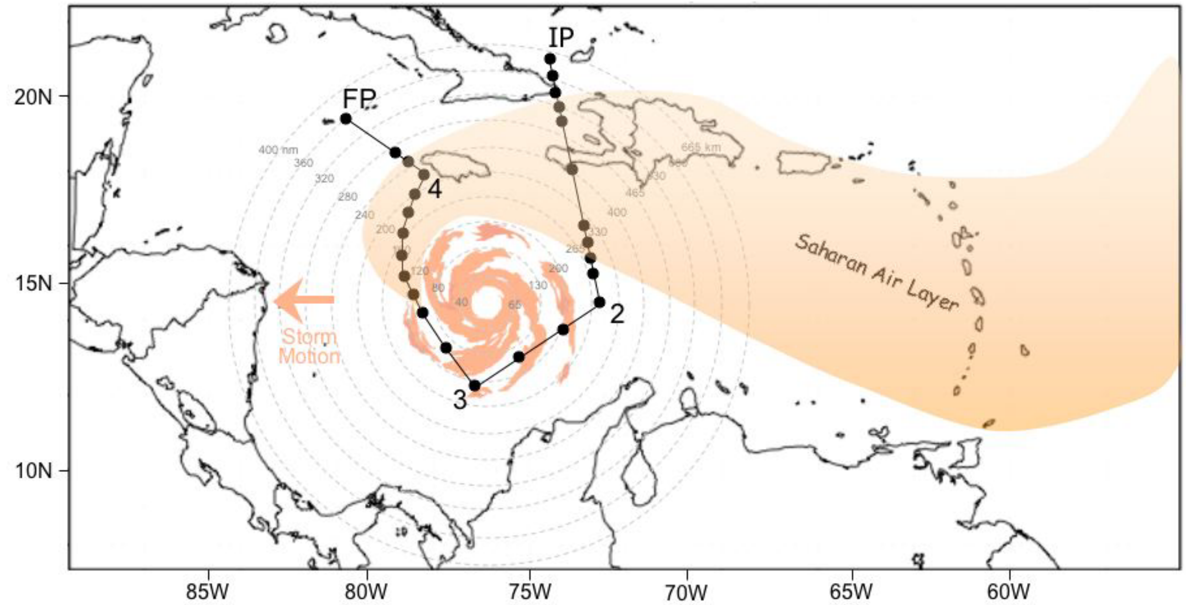


Figure. SAL-3: Sample G-IV flight track for a TC embedded in the SAL for most or all of its lifecycle.

- Note 1: During the ferry to the **IP**, The G-IV should climb to ~200 mb (~41,000 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 (**IP**-**2** and **4**-**FP**).
- 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 (~20-45 kt at 700 mb/10,000 ft) may be evident from GPS dropwindsondes dropped near the SAL's southern boundary (**IP-2**).

SALEX Hurricane Rainband and Intensity Change Experiment (RAINEX)
G-IV Module:

Mission Description: The G-IV (flying at ~200 mb/~41,000 ft) will temporarily deviate from the SALEX flight pattern to carry out one partial or complete circumnavigation (preferably anticyclonic) of a TC rainband of interest. GPS dropwindsonde points will be selected by RAINEX scientists and dropwindsondes will be supplied through RAINEX. GPS dropwindsonde spacing will be ~100 km around the rainband (~3-4 dropwindsondes per band edge; ~6-8 total) and will take ~45 min. to 1 hr to complete. After the completion of the rainband circumnavigation, the SALEX flight pattern will resume. This module supports the following RAINEX goals:

1. *Use airborne observations to examine simultaneously the dynamic and thermodynamic structures of the hurricane inner core and outer rainband regions where the positive potential vorticity associated with deep convective cores are located.*
2. *Use numerical models to investigate the interactions of the rainbands and primary hurricane vortex circulation and their role in hurricane intensity change.*

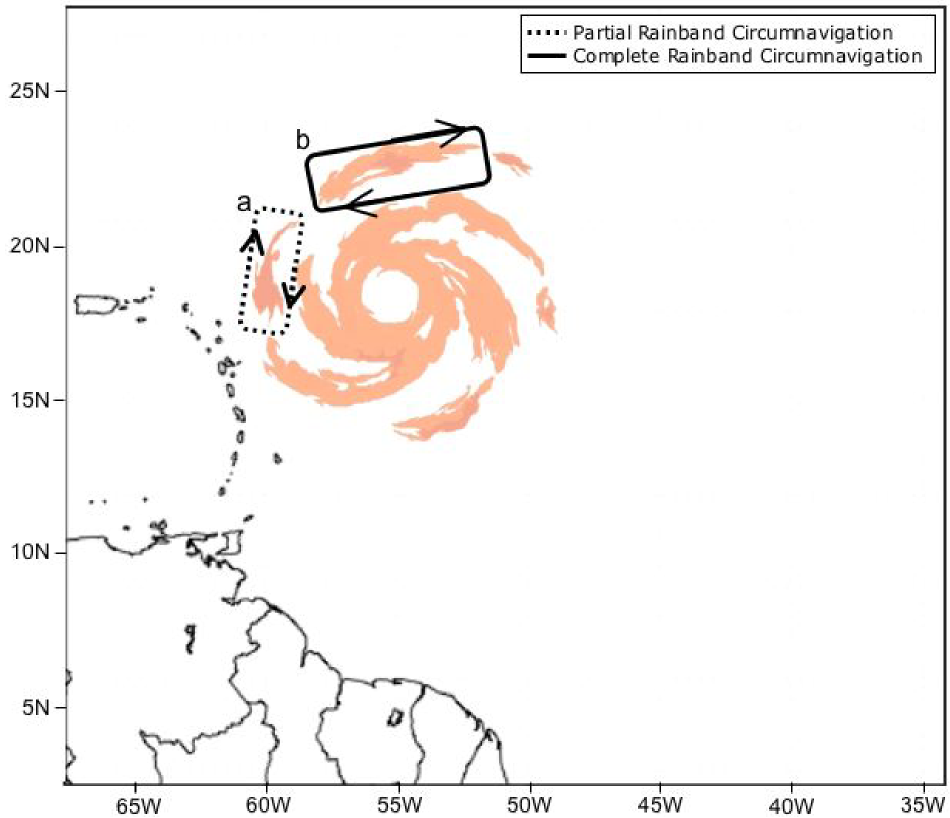
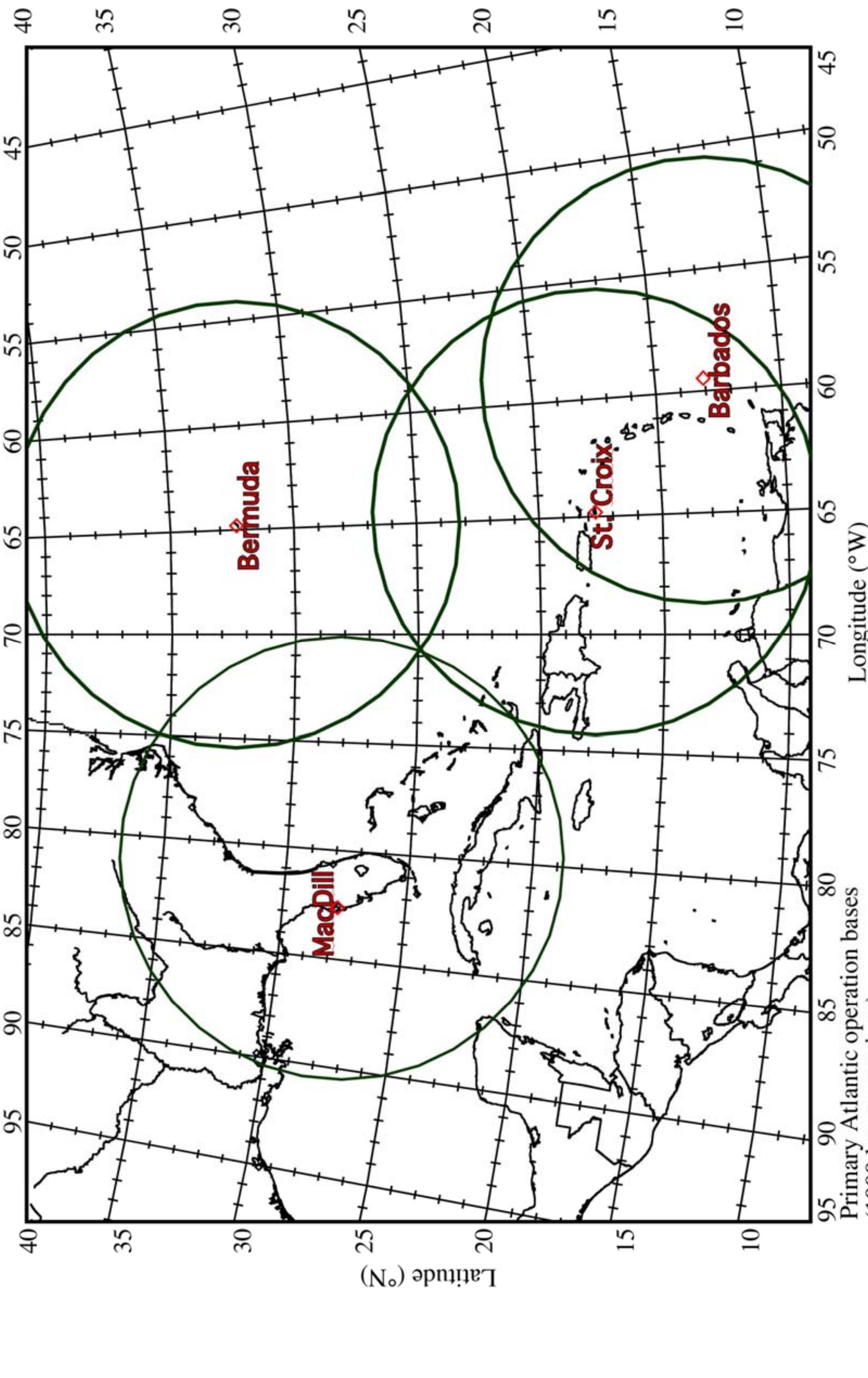
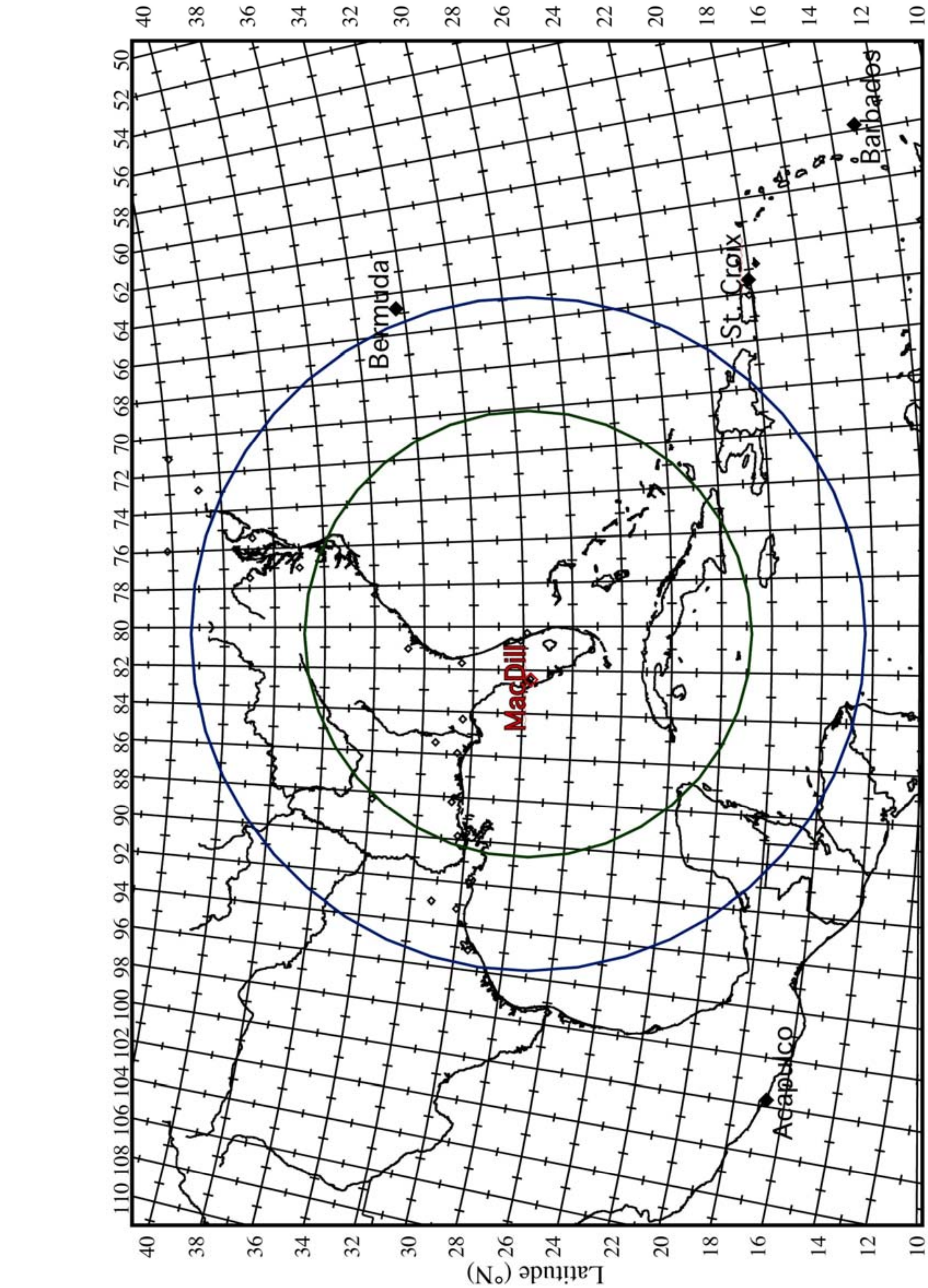


Figure. SAL-4: SALEX RAINEX Module showing a G-IV flight pattern for a (a) partial and (b) complete rainband circumnavigation.

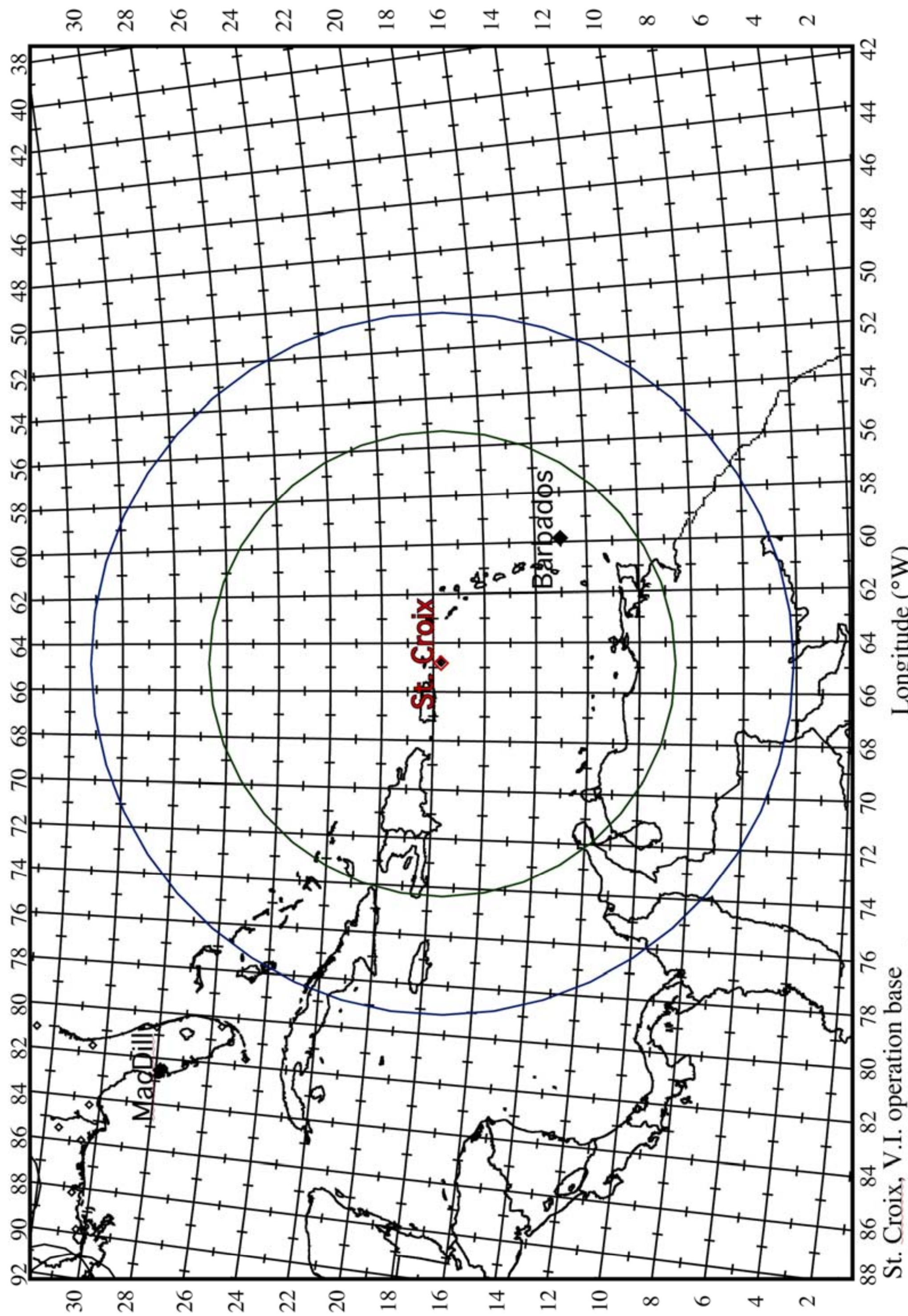
- Note 1: The SALEX flight pattern will dictate the ideal approach to the rainband of interest and will be coordinated on a case-by-case basis.
- Note 2: Coordination is required to clear the airspace below the G-IV during the rainband circumnavigation.
- Note 3: The ideal (most efficient) G-IV flight pattern is an anticyclonic circumnavigation around the rainband of interest.
- Note 4: The dropwindsonde spacing will be ~100 km around the rainband of interest. This equates to ~3-4 (~6-8 total) dropwindsondes on each side of the rainband.

Supplemental: Operational base maps

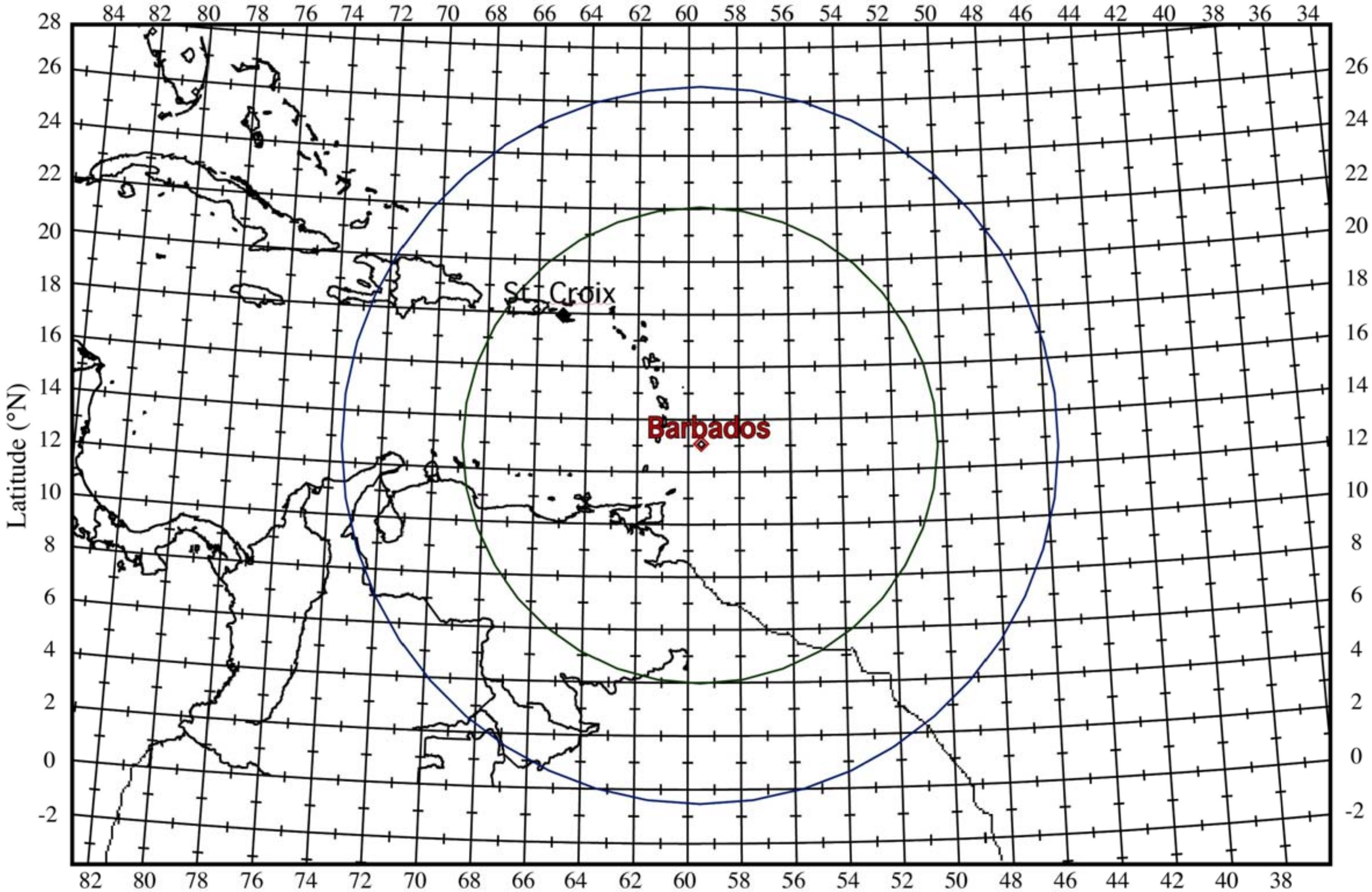




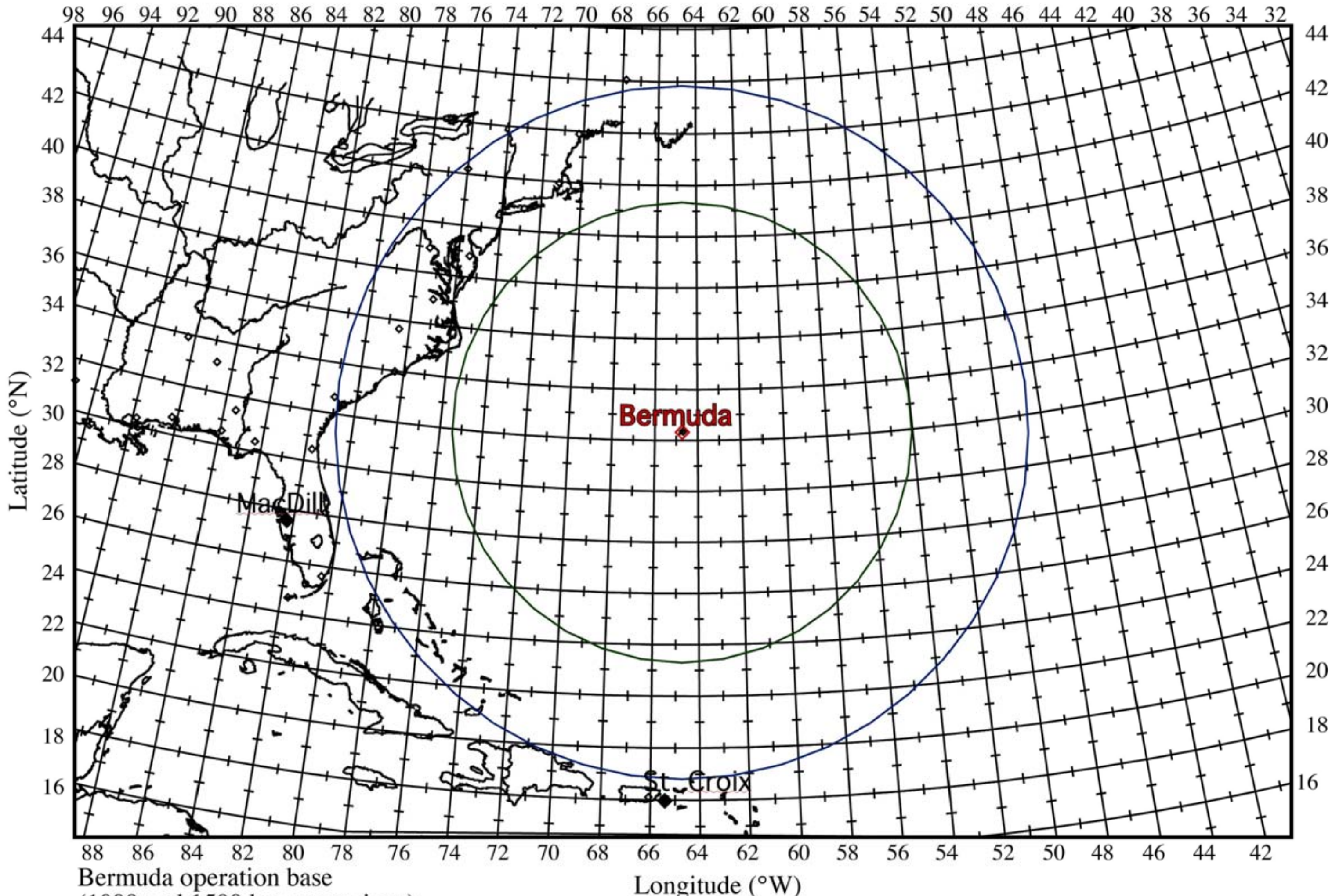
MacDill AFB, FL operation base
(1000 and 1500 km range rings)



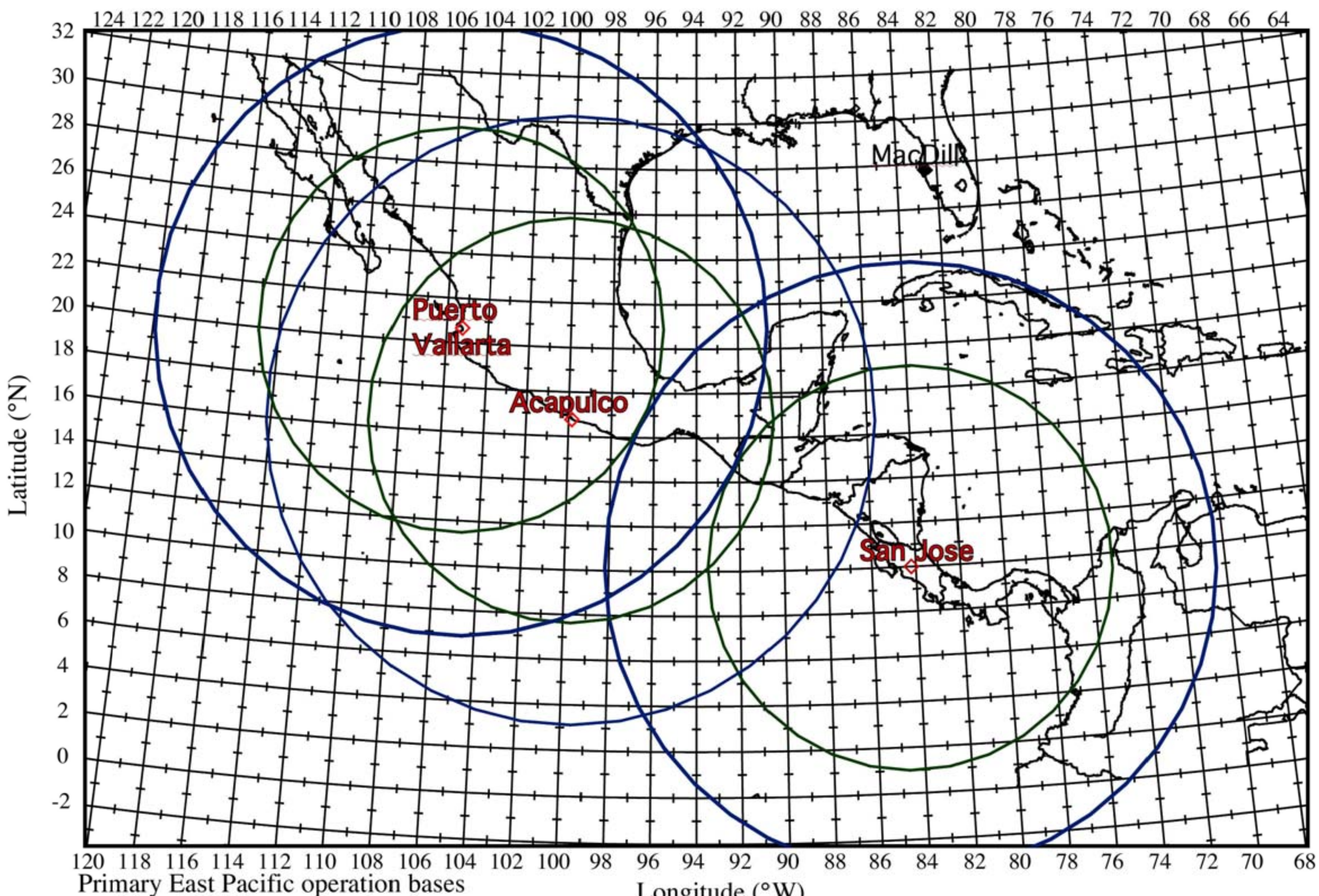
St. Croix, V.I. operation base
(1000 and 1500 km range rings)



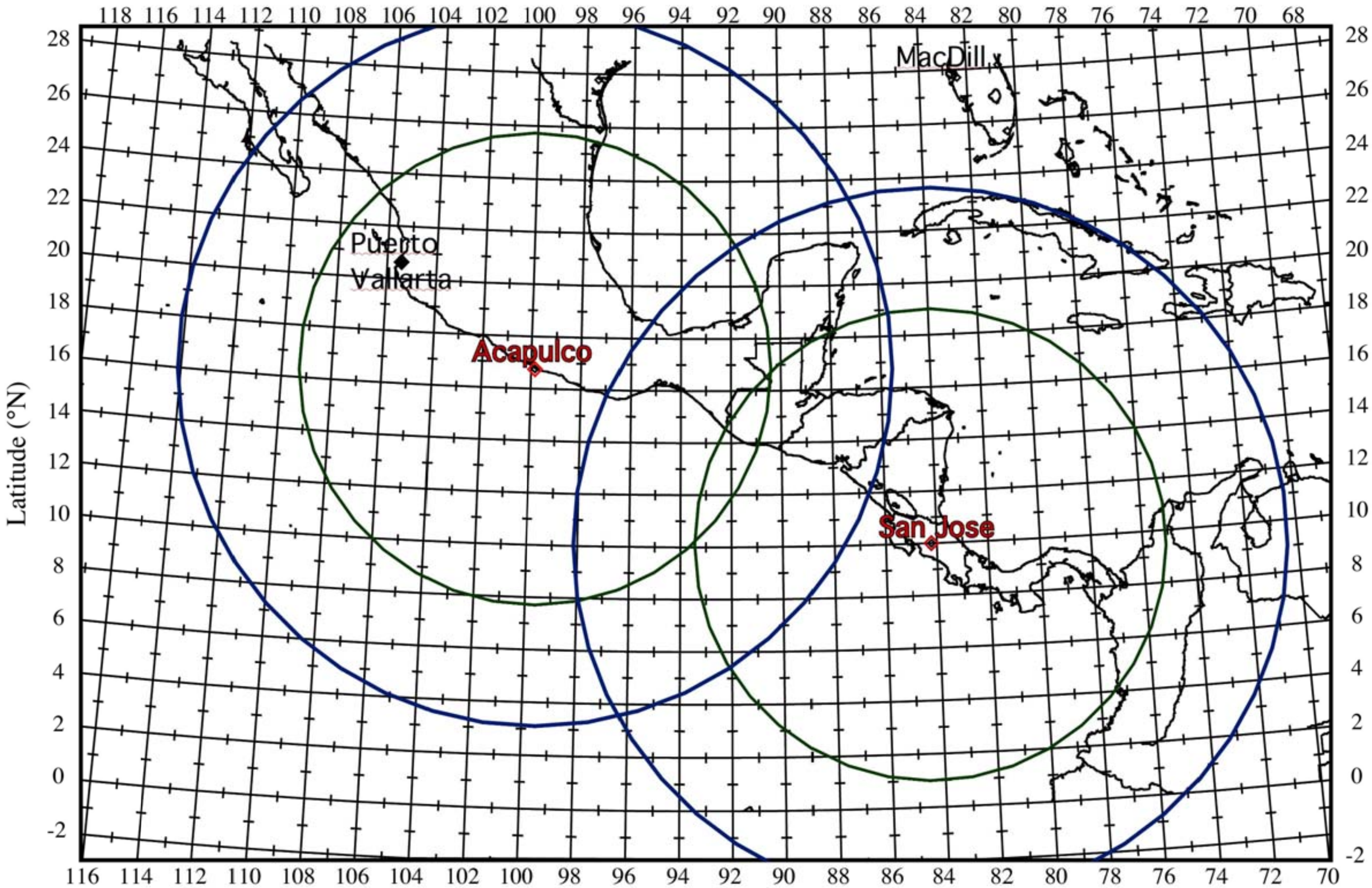
Barbados operation base
(1000 and 1500 km range rings)



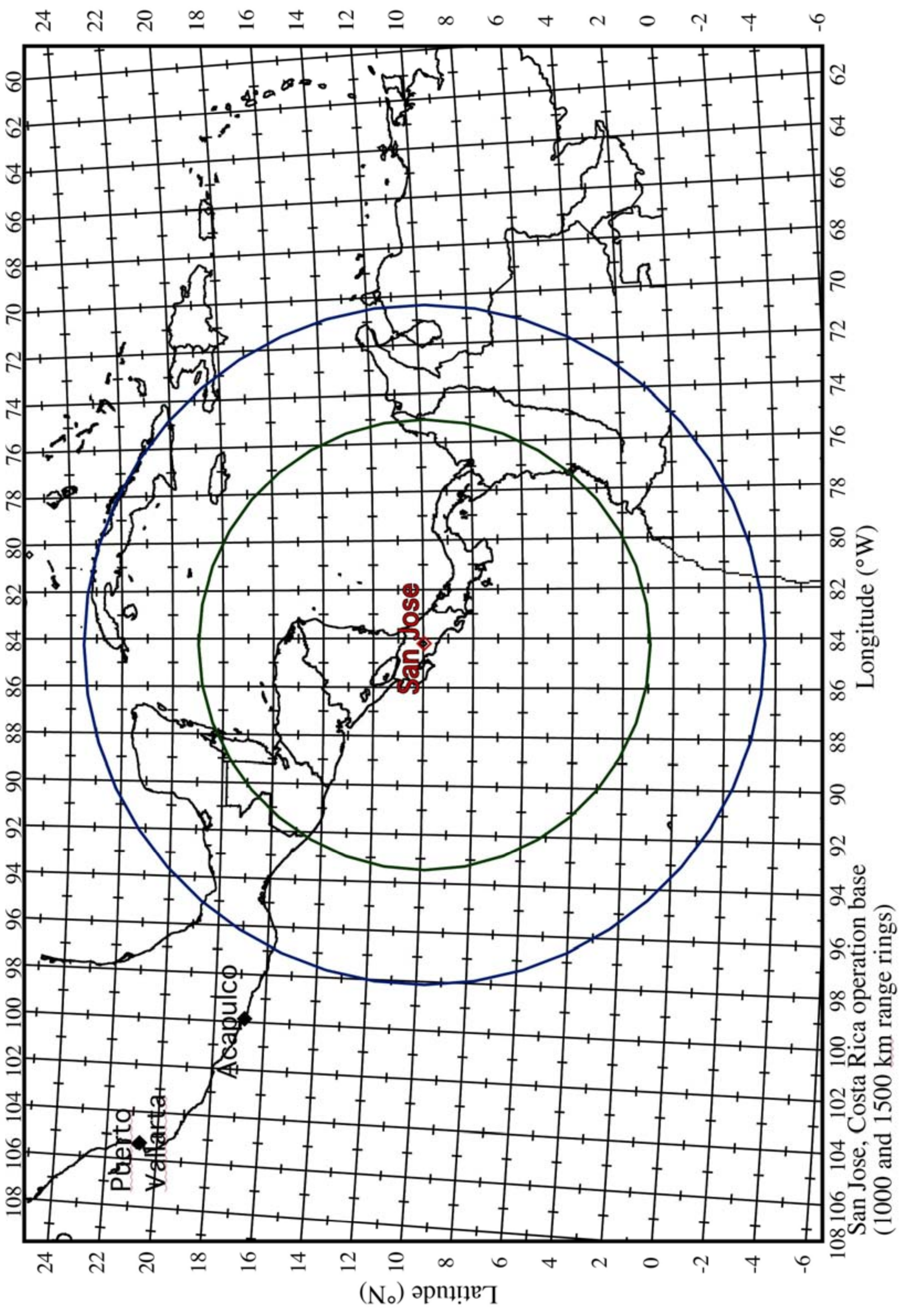
Bermuda operation base
(1000 and 1500 km range rings)



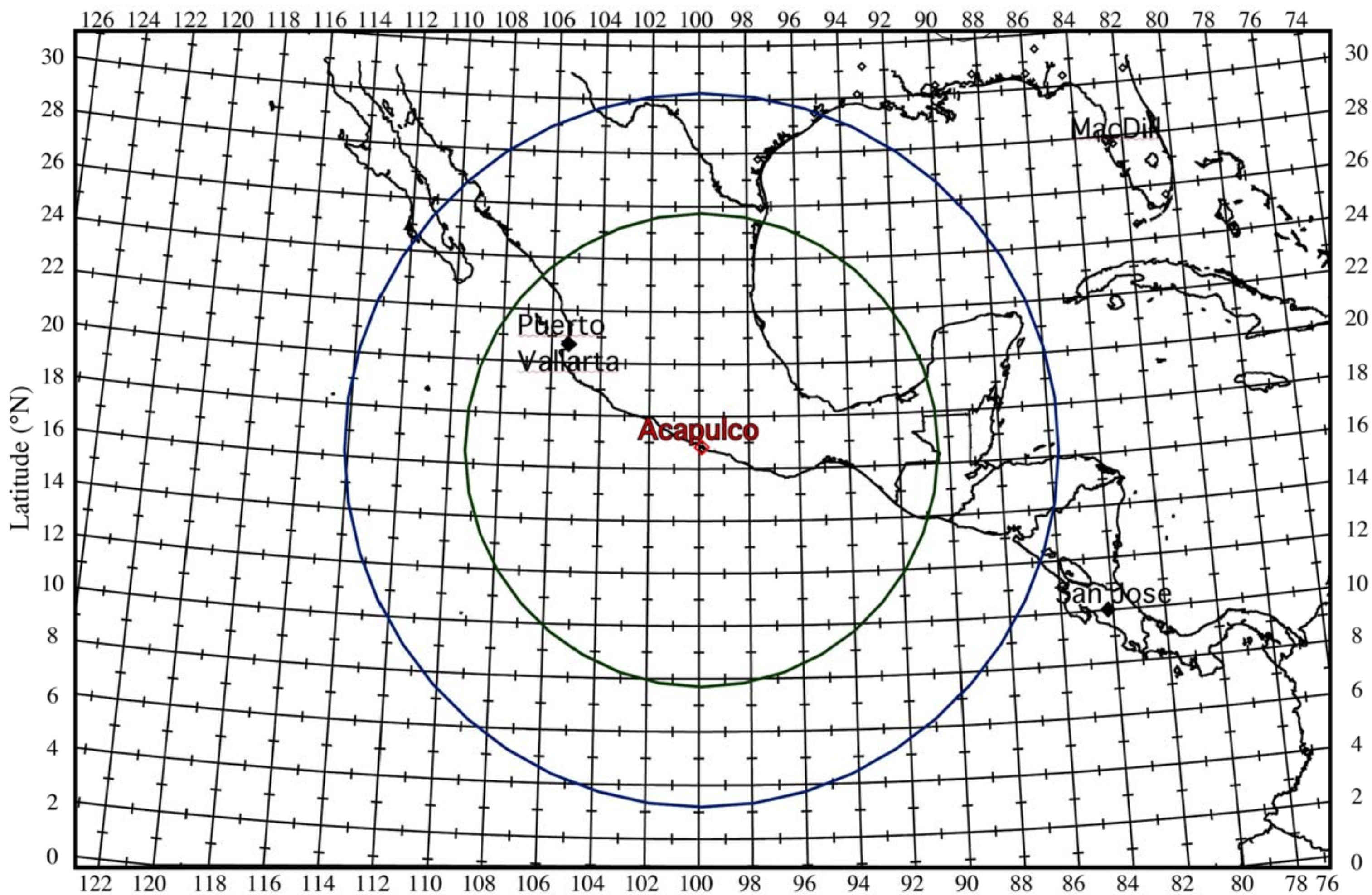
Primary East Pacific operation bases
(1000 and 1500 km range rings)



San Jose and Acapulco operation bases
(1000 and 1500 km range rings)



San Jose, Costa Rica operation base
(1000 and 1500 km range rings)



Acapulco, Mexico operation base
(1000 and 1500 km range rings)

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