An Unmanned Aircraft for Dropwindsonde Deployment and Hurricane Reconnaissance

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Abstract

The prototype of a remotely piloted aircraft designed for research and operational reconnaissance of tropical cyclones has been developed and successfully test flown. Using modern aerodynamic and materials technology, the operational aircraft will by 1994 be capable of sustained operations at altitudes up to 20 km and of deploying large numbers of frangible dropwindsondes. We discuss the potential of such vehicles for making significant improvements of hurricane forecasts and for enhancing the database used in operational weather forecasts, atmospheric research, and climate monitoring.

1. Introduction

One of the most critical problems in weather forecasting is the prediction of hurricane motion and intensity. Of the United States' ten most costly insured catastrophes, five have been hurricanes (Brannigan and McQueen 1992); the widespread devastation of Hurricane Andrew has heightened public awareness of the problem. Not included in most hurricane damage reports are the large sums necessary to evacuate coastal populations. Large error margins in track forecasting result in the evacuation of many more people than is necessary in hindsight, resulting in high costs to and loss of credibility with the public.

Operational prediction of hurricane motion relies heavily on in situ measurements currently made by manned aircraft operated by NOAA and by the U.S. Air Force. Winds measured directly by such aircraft and by dropwindsondes (DWS) deployed from them can substantially increase the skill of track forecasts over those based on standard in situ and satellite-based observations (Franklin 1990).

While very effective, the value of such measurements is limited by the high costs of manned aircraft operation and by the restricted operating ceilings of the current fleet of reconnaissance aircraft. While the circulation of tropical cyclones extends upward of 18 km, the air force C-130's and NOAA WP-3D's are limited to altitudes below 10 km. Recent studies of hurricane motion using simplified baroclinic models (e.g., Wu and Emanuel 1992) suggest that the modification of upper-tropospheric potential vorticity distributions by hurricane outflow may have substantial effects on the evolution of the storm's motion.

Douglas (1990) has studied the costs and benefits of various dropwindsonde-equipped aircraft for operational forecasting applications. For each of eight candidate aircraft, he computed a "dropwindsonde efficiency" factor, which was determined by multiplying the speed (in kilometers per hour) by the atmospheric column depth beneath the aircraft (in millibars), then dividing this sampling area by the average hourly cost of the platform, and then normalizing to the current standard platform, the NOAA WP-3D. His results (repeated in part 1 of Table 1) suggest that significant improvements in dispensing efficiency are possible through the use of higher-altitude, higher-speed platforms. These increased efficiencies, he proposed, might in turn lead to operational applications of DWS-equipped aircraft, in addition to research uses. He estimates that a near-global DWS program, involving 75 manned aircraft operating from 22 bases, could achieve 500-km resolution with a 3-day revisit time over the global oceans north of 20°S and would cost about $80 million per year.

Unfortunately, the expense of current manned-aircraft operations has led to significant cutbacks in hurricane reconnaissance, including the cancellation of the U.S. reconnaissance operation in the western Pacific. This has occurred at a time when expanding coastal populations worldwide are making mankind increasingly vulnerable to tropical cyclones.

Douglas (1990) and others have based their assessments of future DWS-equipped aircraft on currently available manned aircraft designed and produced for other purposes. In recent years, major advances in composite materials, low–Reynolds number aerodynamics, global navigation systems, and microelectronics have combined to make hurricane reconnaissance by remotely piloted or autonomous aircraft an attractive alternative to manned operations. It now appears possible to build and operate auto-

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TABLE 1. Dropwindsonde efficiency factors.

Computed on the basis of direct cost (DOC) only:

Aircraft	**DWS alt (mb)**	**Speed (km/h)**	**Cost ($/h)**	**Douglas factor**	**DWS efficiency**
WP-3	400	555	$1800	185.00	1.00
DC-8	200	850	$5400	125.93	0.68
Gulfstream IV	150	850	$1200	602.08	3.25
Perseus B	50	430	$250	1634.00	8.83

Computed on the basis of total operating cost:

Aircraft	**DWS alt (mb)**	**Speed (km/h)**	**Cost ($/h)**	**Douglas factor**	**DWS efficiency**
Gulfstream IV	150	850	$4500	160.56	0.87
Perseus B	50	430	$1000	408.50	2.21
ER-2	50	583	$17,000	32.58	0.18

mated vehicles capable of sustained flights in the lower stratosphere. Modified internal combustion engines will allow for flights of 2–5 days' duration at these altitudes, while electric motors, powered by solar cells, may eventually make much longer flights possible. Operation above the major commercial aircraft flight levels, together with the extensive use of transponders based on the Global Positioning System (GPS) will minimize problems associated with air traffic control.

2. Perseus: A remotely piloted science aircraft

Although unmanned aircraft have existed for many years and there are a number of ongoing military programs, to date there has been no viable unmanned aircraft available for atmospheric science. Most military unmanned aircraft are designed for visual or infrared detection of targets on the ground, and are limited to altitudes of about 7 km or less. The one existing high-altitude unmanned aircraft, the Boeing Condor, is limited by its high costs [Watson et al. (1991) cites costs of $73 million to make the one existing Condor available for global change research, and $469 million to build two upgraded aircraft] and limited quantities (only one aircraft exists).

In 1988, a collaboration began between researchers at the Harvard Atmospheric Research Project and former members of the M.I.T. Daedalus human-powered flight team, with the goal of developing a new class of low-cost (relative to military platforms or manned aircraft) unmanned aircraft specifically dedicated to atmospheric science. This resulted in the formation of Aurora Flight Sciences in the spring of 1989. This group has subsequently identified several major areas of global climate-change research where fundamental measurement roadblocks exist between good science and sound public policy, and where an affordable unmanned aircraft may prove to be an enabling technology. These areas include studying stratosphere–troposphere exchange mechanisms, mapping the water vapor budget in the upper troposphere, providing data to initialize numerical weather prediction models, and conducting both research and operational forecasting for hurricanes and other severe storms.

To validate the concept of the unmanned science research aircraft, as well as to provide an engineering development testbed for the Perseus® program, a prototype aircraft known as the *Proof of Concept (POC)* was built. Between September 1989 and September 1991, approximately $1.5 million was invested in the *POC* program, with roughly equal shares coming from private investors, Harvard University, the National Institute for Global Environmental Change, the DuPont Company, and the National Science Foundation. The resulting aircraft, shown in Fig. 1, has a gross weight of 430 kg. Equipped with a commercial ultralight engine, it is capable of reaching altitudes up to approximately 7 km and durations up to about 8 h. The *POC* made its first flight at El Mirage, California, on 8 November 1991. The aircraft successfully completed a series of flight tests, during which it demonstrated ground-controlled flight, autonomous flight, and the deployment of dropsondes. It is now available as a testbed for future projects.

The Perseus A (see Fig. 2) is designed to carry 50- to 100-kg payloads to altitudes above 25 km for durations of approximately one hour, in support of stratospheric chemistry research. In order to achieve

FIG. 1. The Perseus *Proof of Concept* aircraft. The structural and electronics development testbed for the Perseus family, this aircraft completed its initial flight testing in November 1991. The plane has an 18-m wingspan and a gross weight of 430 kg.

this performance within a total program cost of about $4 million, Perseus A uses the tooling, structural design, and flight control system from the *POC* plus a unique closed-cycle engine. Rather than attempting to breathe ambient air to support combustion, Perseus A carries a tank of liquid oxygen on board. Aurora is presently under contract to NASA's High Speed Research Program/Atmospheric Effects of Stratospheric Aircraft (AESA) program to build, test, and deliver two Perseus A aircraft during 1993.

While the Perseus A offers unprecedented altitude capability, many members of the scientific community would gladly trade ceiling for longer range, heavier instrument capacity, and lower operating costs. Such an exchange is natural for the Perseus design. At lower altitudes, the aircraft can use a turbocharged engine rather than liquid oxygen, thereby dramatically reducing its fuel consumption. Furthermore, it can fly at higher weights, and so accommodate more fuel and payload. The result is a quantum jump in performance, shown in Fig. 3, and extraordinary new opportunities for atmospheric science. The technical risk of such a development is low, since it is based on the successful *Proof of Concept* program and the fully funded Perseus A program.

A single-staged turbocharged engine capable of powering Perseus to pressure altitudes of around 200 mb (about 12 km) has already been tested on a manned motorglider to altitudes of 11 km. A two-stage turbocharged version, capable of operations at pressures as low as about 50 mb, is under development and is expected to be ready by 1994. These power plants will provide affordable yet reliable means of placing 50–200-kg scientific payloads in the upper troposphere and lower stratosphere in the very near future.

The flight envelope of the resulting aircraft (known

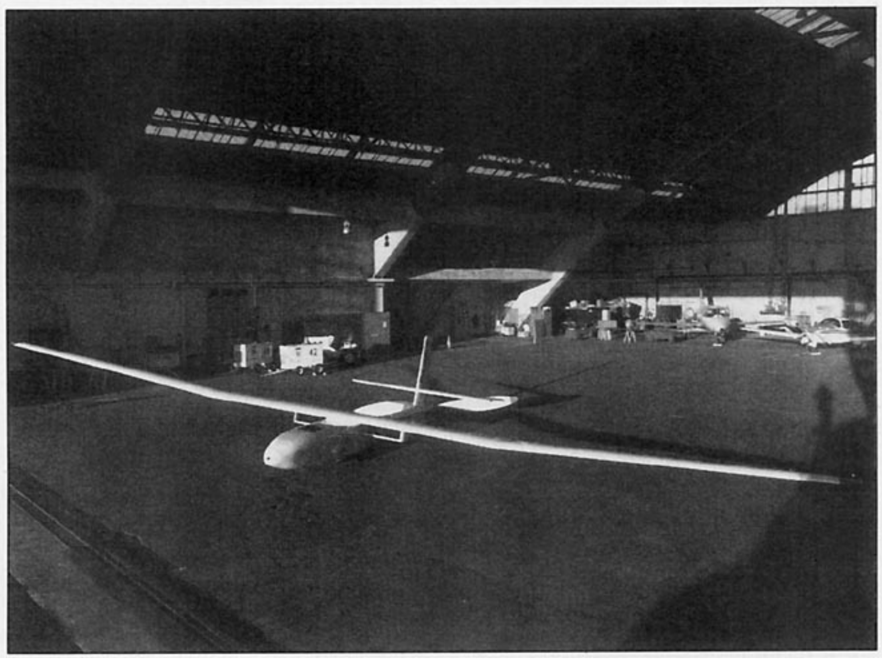

FIG. 2. The Perseus A is a high-altitude, short-duration version being developed for stratospheric chemistry research. This version carries 50-kg payloads to altitudes of almost 30 km.

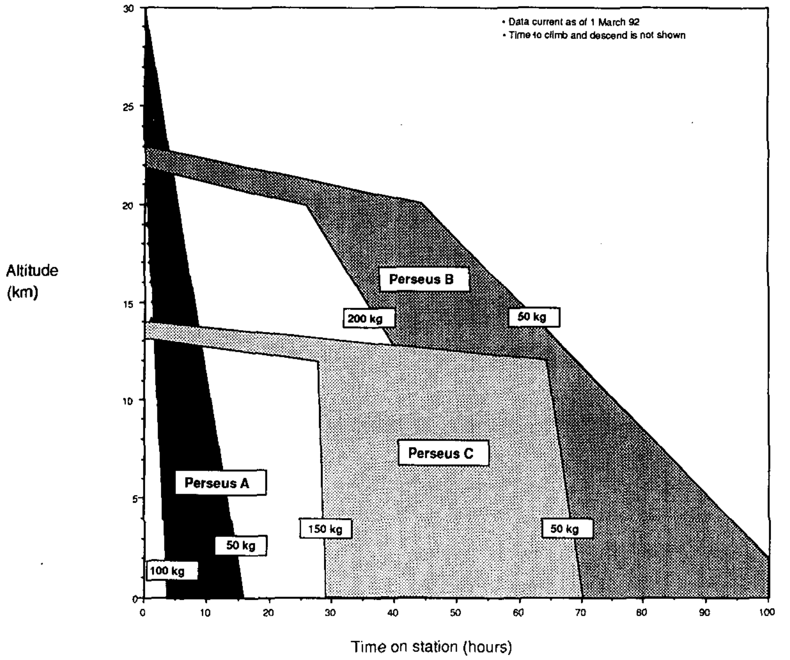

FIG. 3. Comparative performance of Perseus versions.

as Perseus B) is shown in Fig. 4. On the ground, the aircraft will be taxied and flown like a normal aircraft, except that the pilot will be flying the aircraft and communicating with air traffic control authorities from inside a ground control station rather than from inside the aircraft [a full instrument display, including a video out-the-window display, is provided in the ground station (see Fig. 5)]. Once a mission is under way, the aircraft can be flown manually, be programmed to follow a preplanned trajectory (which can be updated during flight), or be programmed to follow specific trajectories of interest (for example, a constant potential temperature contour). The basic aircraft is stressed to a load factor of 7 g's, which should be sufficient to enable it to handle severe turbulence, including that near tropical cyclones and convective storms. Although initial versions are not being designed for icing conditions, this feature can be included in subsequent versions if needed.

In addition to the Perseus platforms, Aurora is also developing (under sponsorship from the National Science Foundation) an autonomous dropwindsonde system suitable for deployment aboard unmanned aircraft. Building on the work of NCAR and existing radiosondes, an autonomous data-acquisition system onboard the unmanned aircraft will collect dropsonde data, process and compress it, and relay it back to the ground. One design under consideration is a simple autorotating design based on the maple seed. This is intended to increase packing density and eliminate packing and deployment complexity of current parachute systems (see Fig. 6). Another feature of great interest is wind-finding based on the Global Positioning Satellite (GPS) system. This allows high-accuracy wind measurements to be made anywhere in the world.

The minimum payload for meteorological studies consists of some number of dropwindsondes, their dispensers, a data receiving and processing system, a storage and/or relay system, and instruments for high-precision on-board measurements of basic thermodynamic properties (temperature, pressure, humidity, and winds). Additional instruments to measure radiative, microphysical, and dynamic properties are desirable for research but probably not necessary for operational purposes. A candidate payload section is shown in Table 2, with a schematic installation in the Perseus payload section shown in Fig. 7. The total weight of this system, which includes 24 dropsondes, a cryogenic frost-point hygrometer, PMS cloud probes, broadband radiometers, an ozone instrument, cloud-imaging video, a gust probe, a data-acquisition system and data logger, a low-bandwidth satellite data link, and an emergency parachute system, is about 150 kg.

This weight could be reduced substantially by eliminating or miniaturizing the radiometers and the cloud particle probes. It seems reasonable to assume that 50 kg is an approximate lower limit for payload weight. On the upper side, payloads can of course grow as large as they are allowed. Since there is a minimum (approximately) 10:1 mass ratio between the platform and the payload, and since modern aircraft and instruments have approximately the same ratio of cost to weight, the minimum-cost solution to any sampling problem is strongly biased toward reducing payload

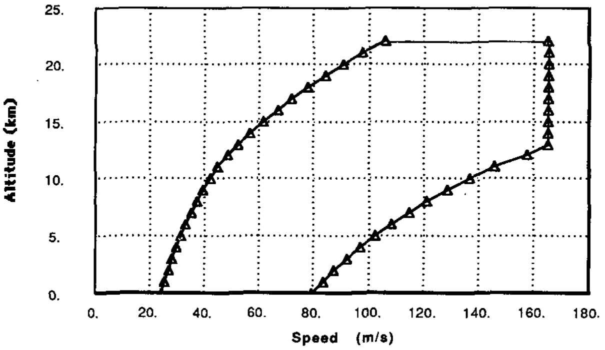

FIG. 4. Flight envelope for the Perseus B with a 1000-kg gross takeoff mass.

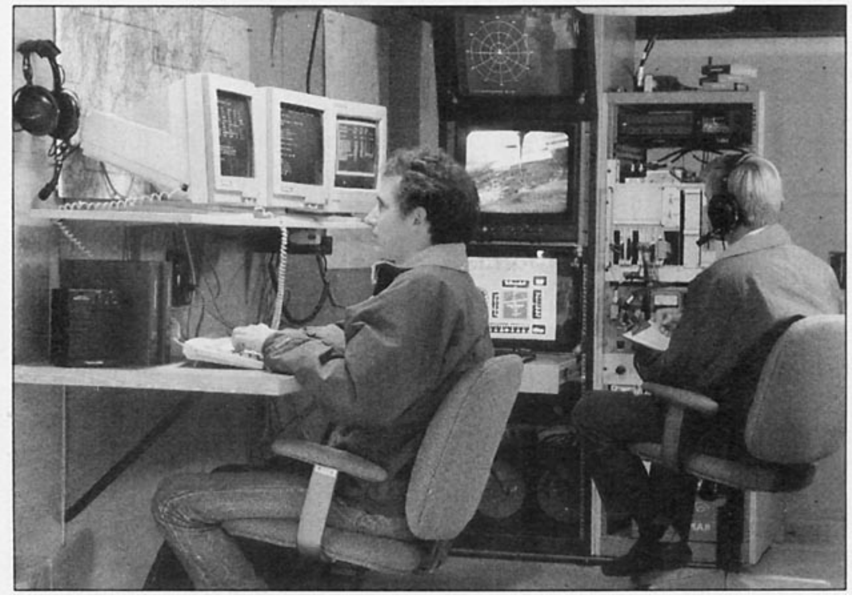

FIG. 5. View inside the Perseus ground station. Stations for payload scientist and flight engineers are at left, pilot station is in center. Pilot station has control console plus instrument display (lower), video display (center), and map display (top).

weight whenever a new platform is to be acquired or, especially, developed. Extensive studies conducted by Aurora for the National Science Foundation by McGeer et al. (1990) suggest that 220 kg is a reasonable upper limit for almost all of the pressing issues related to global change research. At the other extreme, it may be possible that an aircraft weighing tens, rather than hundreds, of kilograms may someday be available for basic meteorological observations. The idea is to place the sensors from a single radiosonde onto a completely autonomous model airplane-sized vehicle, which would then make repeated vertical profiles over many hours. Aurora initiated a project known as AeroSonde® to study this concept during the fall of 1990. Although the theoretical performance predictions are impressive, the concept has severe problems associated with 1) performance degradation due to turbulence, 2) air traffic–control and safety issues, 3) ground safety issues (an AeroSonde would have as much kinetic energy as a small car; semirandom, fully autonomous landings pose severe liability issues), and 4) high costs associated with miniaturization. Solving these problems is a significant development effort; even if it is possible, the AeroSonde is well beyond Perseus in terms of operational availability.

Costs are critical to the successful implementation of unmanned technology. Table 3 illustrates the expected costs of the Perseus aircraft, and compares them to other commonly considered high-altitude platforms: the Gulfstream IV, the Lockheed ER-2, and the Boeing Condor. In keeping with commercial airline practice, we have divided total operating costs (TOC) into three components: 1) direct operating costs (DOC), which essentially are the marginal cost to fly one additional hour of aircraft time; 2) depreciation costs, whereby the original acquisition costs of the vehicle are amortized over its useful life; and 3) indirect operating costs (IOC), which include all costs related to the operation of the aircraft but which are invariant with the number of flight hours. Note that with many government assets, prices are set at DOC, with all acquisition costs written off and indirect costs ignored (typically, they are funded through different portions of a government organization's budget). The costs used in Douglas (1990) appear to include DOC only; this methodology severely understates the true cost of flying an aircraft.

When the Douglas "DWS efficiency" is calculated for Perseus B on the basis of direct operating cost, it is seen to compare very favorably with manned-aircraft options (Perseus B scores 8.8, versus 3.25 for the Gulfstream IV and 1.0 for the WP-3D). When total operating costs are used, this advantage is even more pronounced. The Gulfstream is now actually less effective than the WP-3D, since the Gulfstream must be purchased and amortized, whereas the WP-3D is

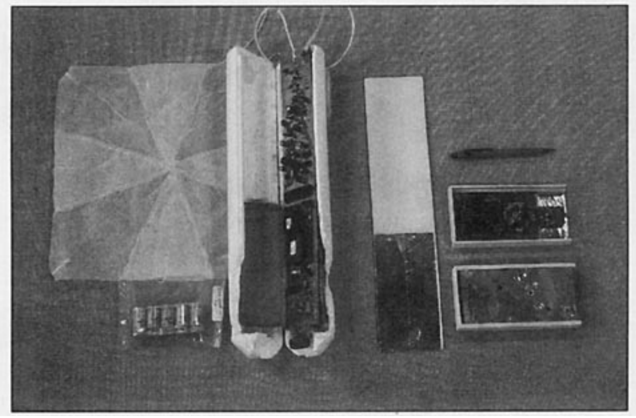

FIG. 6. Lightweight dropsondes are one of the key technologies being developed for use with unmanned aircraft. The NCAR Lightweight Loran Digital Dropsonde (left) and the Aurora Gyrosonde (right) each weigh about 250 g and can be deployed from Perseus.

an existing, fully depreciated asset. Even though it must be procured, the Perseus B scores 2.2.

3. Hurricane reconnaissance and beyond

Unmanned aircraft used for hurricane research and reconnaissance will bring direct economic benefits to the nation in three ways. First, they will help improve our understanding of how hurricanes form and when they are likely to form. An improved understanding of the physics and thermodynamics behind cyclogenesis will allow longer advance warning of potentially dangerous storms such as Andrew, which formed relatively close to land. The unmanned aircraft will revolutionize cyclogenesis studies by allowing systematic measurements of potential vorticity and other parameters over large time and distance scales. Second, unmanned aircraft will help improve our understanding and predictive capability of how these storms intensify. They will do this by monitoring emerging storms on a continuous basis, beginning long before they are classed as hurricanes, and continuing throughout their entire life cycle. Third, and of perhaps the most immediate consequence, these aircraft can improve our track prediction forecasts by conducting sustained in situ measurements above a storm system. Rather than penetrating the eyewall at low levels, as is done in current manned aircraft, unmanned aircraft will probably fly above the storm, measuring the upper-level steering winds with aircraft-based instruments and sea-surface conditions with remote-sensing instruments and obtaining regular vertical profiles of both the atmosphere and the ocean mixing layer by releasing dropwindsondes and sea-surface drifting buoys. An ideal national system for later in this decade might include advanced satellites for imaging and remote sounding; a fleet of unmanned aircraft for research, synoptic-scale measurements, and continuous storm tracking; and a small number of manned aircraft where direct eyewall penetration is deemed necessary. The unmanned aircraft would be the least expensive component of this triad, by far.

A new technology, such as the unmanned aircraft, must be extensively proven before being implemented as an operational system. We propose a three-phased program that begins with one or more demonstrations, moves then to use for research purposes, and finally to operational use. The demonstrations, which will serve to uncover and solve problems as well as to

TABLE 2. Preliminary payload design.

Quantity measured/function	Instrument	Weight (kg)	Power (W)
Cloud droplets and aerosols	PMS optical array probe	21	100
Ice and precipitation	PMS 2-D probe	21	100
Radiation—visible	Epply pyradiometer (2)	3.5 (each)	—
Radiation—IR	Epply pyradiometer (2)	3.5 (each)	—
Horizontal winds	GPS	2	20
Gusts	Gust probe	5	50
Humidity	Cryogenic frost-point hygrometer	20	150
Ozone (tracer)	Harvard UV absorbtion	10	10
Air temperature	AIR	1	5
Air pressure	AIR	1	1
Scene image	Low-rate video	5	20
Vertical T, P, RH, winds	Dropwindsondes	0.4 (each)	10
Other payload elements:			
Data-acquisition system	VME bus 68020	10	20
Data logger	8-mm tape	3.3	30
Dropsonde dispenser		10	20
Satellite data link	ORBCOMM	5	10
Emergency flight termination	Mortar-launched parachute	15	0
Total:		147	656 W

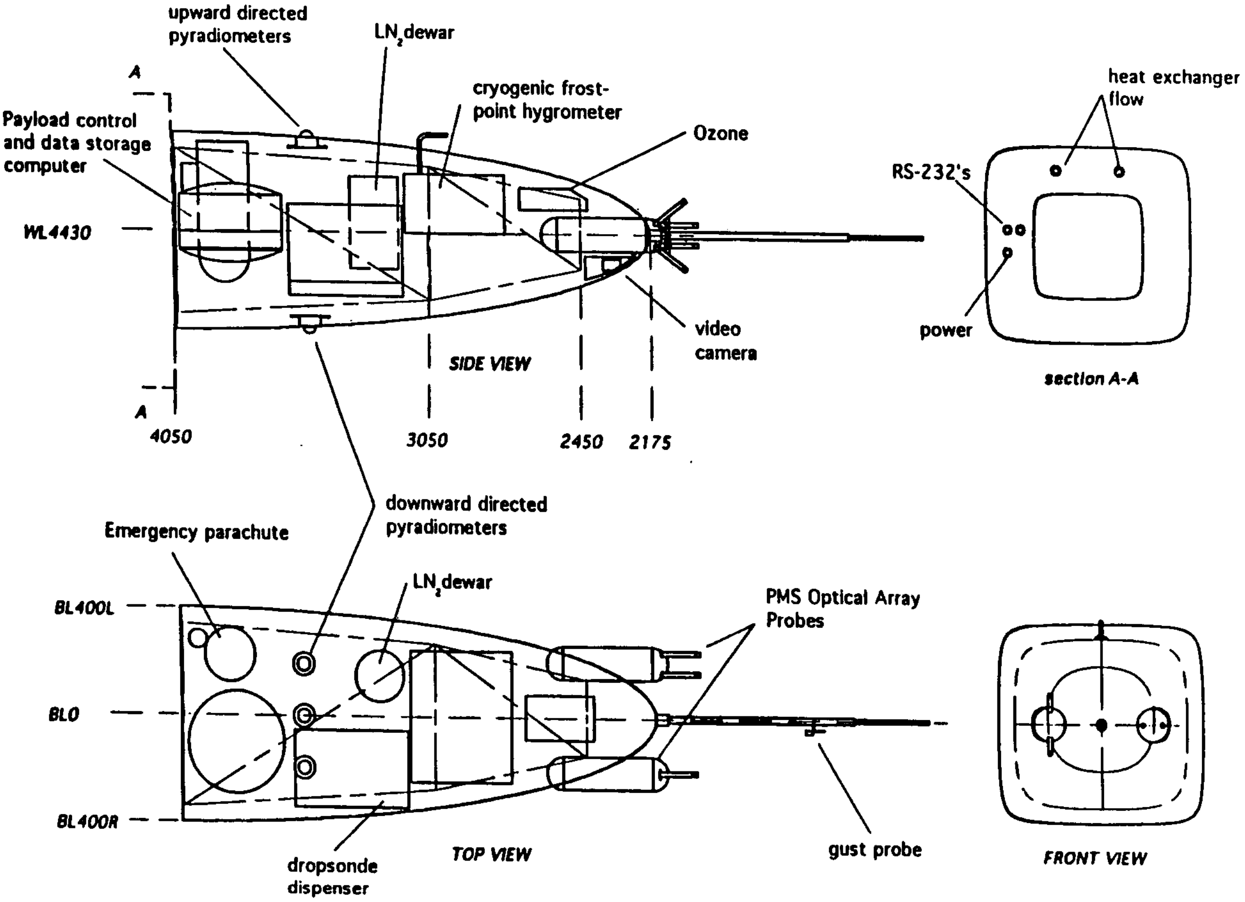

FIG. 7. Candidate payload installation for research payload.

increase awareness of the potential uses of unmanned aircraft, could begin as early as 1994. One such demonstration, which could be conducted off the north coast of Puerto Rico, is illustrated in Fig. 8. The campaign would have two scientific objectives and one engineering objective. The primary science mission would be to use lightweight dropwindsondes dropped from the aircraft and a high-resolution water vapor instrument on board the aircraft to produce a comprehensive dataset on the distribution of water vapor in the troposphere. The second scientific objective would be hurricane tracking on a "target of opportunity" basis. In the event that a tropical cyclone formed in or passed through or near the experiment area, we would expect to redeploy the Perseus in such a manner as to fly a sampling pattern around the storm region (we do not propose core penetration or overflight as part of this experiment). The engineering objective of the experiment would be to demonstrate the unmanned aircraft in a field campaign, including the first cooperation with manned aircraft such as the NOAA WP-3D, and intercomparison between the two platforms.

A successful demonstration would allow the unmanned aircraft to move into more routine use for research purposes during 1995 and 1996. With a payload of about 150 kg, it will be possible to carry instrumentation for measuring quantities not measured (or not measured with enough accuracy) by dropwindsondes. Perseus could, for example, carry instrumentation designed to measure with high accuracy the low absolute water vapor contents of the upper-tropical troposphere. Such measurements are crucial for understanding the water vapor and high cloud feedbacks in global climate change (Lindzen 1990). The low cost of operating Perseus will also make it possible to conduct maritime field experiments on a much larger scale than heretofore has been practical. Experiments aimed at studying cyclogenesis, such as the role of potential vorticity (see Montgomery and Farrell 1993), will now be possible. A dedicated fleet of three aircraft (one spare plus two operational), perhaps assigned to NOAA's Hurricane Research Division, would probably be adequate for this role.

Ultimately, weather forecasting (including but not

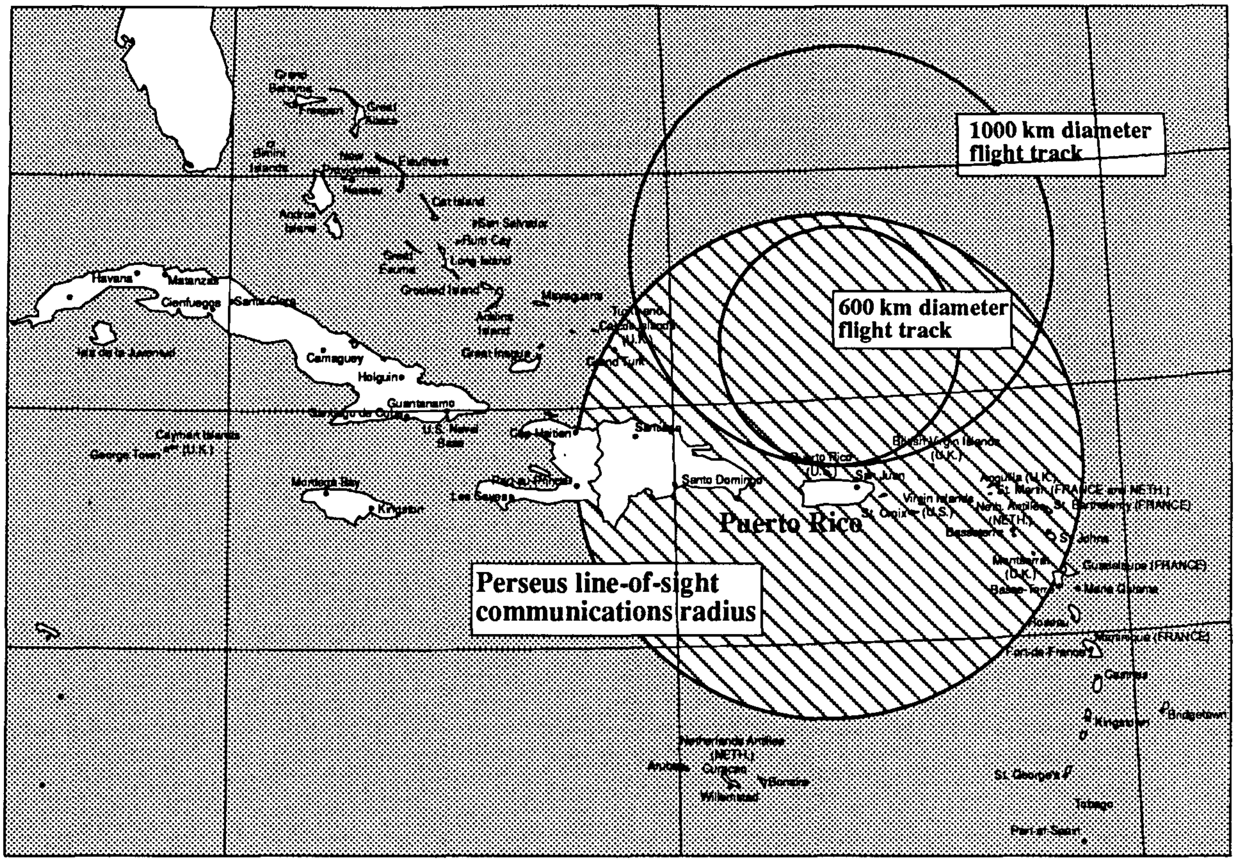

FIG. 8. Demonstration area north of Puerto Rico. The Perseus B would fly a gentle sinusoidal track between 400- and 50-mb altitude, releasing sondes at approximately 300-km spacing. The area covered is comparable to 1974 GATE array.

limited to severe storms) will also benefit from the advent of pilotless aircraft. Measurements made from dropwindsondes deployed from such vehicles would help close the major data gap that now exists over the oceans. Our calculations suggest that DWS soundings from unmanned aircraft on an operational scale will be comparable to present costs for rawinsonde soundings from land. By making routine measurements on a uniform global grid, far less-aliased assessments of global climate change could be made. We believe that an operational system could be in place by 1997 or 1998; provided that proper planning is undertaken today toward this objective. Equipped with a fleet of ten or so aircraft, the NOAA Aircraft Operations Center could provide synoptic coverage throughout the Atlantic area of operations from its base in Miami. Figure 9 illustrates the coverage the Perseus B would have; additional time on station could be obtained by forward basing of the aircraft, perhaps in the Windward Islands.

TABLE 3. Comparative cost estimates for high-altitude aircraft.

	Perseus B	ER-2	Gulfstream IV	Condor
Unit cost ($ million)	1.5	20	25	50
Lifetime (h)	6000	30 000	30 000	12 000
Utilization (h/yr)	1000	300	1000	1000
DOC ($/h)	250	2500	2000	1700
Depreciation ($/h)	250	700	850	4200
IOC ($/h)	300	14 000	1500	6200
Total $/flt-h	800	17 200	4350	12 100

Source: Aurora estimates based on AFSC/ATA common costing model. Costs are for comparable operating scenarios and assume "airline style" operations from a fixed base.

4. Conclusions

In situ measurements continue to play a vital role in atmospheric research, operational weather forecasting, and climate monitoring. Unmanned aircraft such as Perseus offer a new and cost-effective means of obtaining needed measurements, especially over the oceans. Demonstrations are under way for an initial research capability within the next year. In order to realize the benefits of this new technology, however, planning must begin now for its inclusion in the long-range plans of cognizant agencies and organizations.

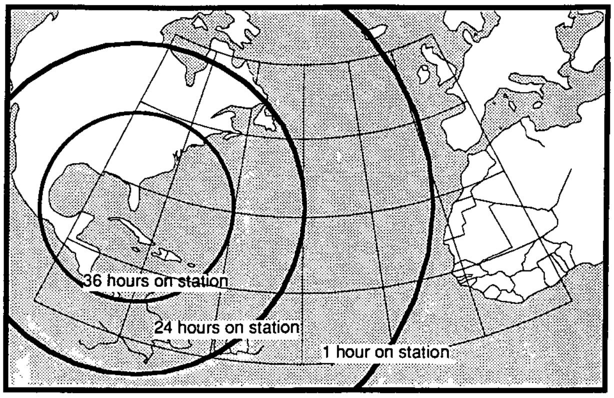

FIG. 9. Operating radius of the Perseus B from Miami, Florida, with a 100-kg payload at an altitude of 50 mb (about 20 km). For ranges beyond its radio line of site, the aircraft flies in an autonomous mode and communicates through an HF or satellite data link.

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