The Aerosonde Robotic Aircraft: A New Paradigm for Environmental Observations

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ABSTRACT

The Aerosonde is a small robotic aircraft designed for highly flexible and inexpensive operations. Missions are conducted in a completely robotic mode, with the aircraft under the command of a ground controller who monitors the mission. Here we provide an update on the Aerosonde development and operations and expand on the vision for the future, including instrument payloads, observational strategies, and platform capabilities. The aircraft was conceived in 1992 and developed to operational status in 1995–98, after a period of early prototyping. Continuing field operations and development since 1998 have led to the Aerosonde Mark 3, with ~2000 flight hours completed. A defined development path through to 2002 will enable the aircraft to become increasingly more robust with increased flexibility in the range and type of operations that can be achieved. An Aerosonde global reconnaissance facility is being developed that consists of launch and recovery sites dispersed around the globe. The use of satellite communications and internet technology enables an operation in which all aircraft around the globe are under the command of a single center. During operation, users will receive data at their home institution in near–real time via the virtual field environment, allowing the user to update the mission through interaction with the global command center. Sophisticated applications of the Aerosonde will be enabled by the development of a variety of interchangeable instrument payloads and the operation of Smart Aerosonde Clusters that allow a cluster of Aerosondes to interact intelligently in response to the data being collected.

1. Introduction

The Aerosonde is a small robotic aircraft designed to undertake a wide range of operations in a highly flexible and inexpensive mode. Holland et al. (1992) laid out the conceptual basis of an Aerosonde operation that would enable meteorological observations in remote and otherwise inaccessible regions. A prototype aircraft was first flown in 1993, demonstrating the viability of the platform and overall concept. By 1998, an intensive development program had led to the Mark 1 aircraft, which passed all requirements in a full operational trial by the Australian Bureau of Meteorology. Since 1998, a substantial research and development program has resulted in considerable improvements to the aircraft and its operational systems. These now extend well beyond the original concept.

The Aerosonde platform is proceeding along a well-defined development path over the period 1998–2002. The Mark 2 version entered operations in early 2000 and the Mark 3 aircraft is scheduled to enter operations in 2001. We have also participated in a number of international field programs and passed a significant milestone of 2000 flight hours in testing and operations by the end of 2000. These improvements and sustained testing under operational conditions are leading to aircraft that are more robust, able to operate over larger domains, and have increased flexibility in the range and type of operations that can be achieved.

Close contact has been maintained with user communities, inside and outside the field of meteorology,

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throughout the development of the Aerosonde. This interaction has brought forth a new vision for operations, instrument payloads, observational strategies, and platform design. A global Aerosonde reconnaissance facility is being developed that consists of a set of launch and recovery sites dispersed around the globe at locations defined by the aircraft capacity, regulatory issues, and the required missions. The use of satellite communications and internet technology enables an operation in which all aircraft around the globe are under the command of a single center. During operation, users will receive data at their home institution in near–real time via a virtual field environment framework, which allows the user to update or modify the mission through the global command center. Sophisticated applications of the Aerosonde will be enabled by the development of a variety of interchangeable instrument payloads and the operation of Smart Aerosonde Clusters (SMACS), whereby a cluster of Aerosondes interacts intelligently in response to the data sensed by the cluster.

In this paper, we provide an update on the Aerosonde development and operations and expand on the vision for future operations.

2. The Aerosonde operational system

Following initial development of the Aerosonde prototype, largely sponsored by the U.S. Office of Naval Research (ONR), a major development program was initiated in Australia in 1995. Environmental Systems and Services (ES&S) Pty Ltd., with support from the Australian Bureau of Meteorology, obtained Australian research and development syndication funds that were combined with continuing support from ONR to enable development of the aircraft and related systems. The Bureau of Meteorology and the U.S.-based Insitu Group were retained as subcontractors for the development program, which led to the Mark 1 Aerosonde in 1998. The Insitu Group left the consortium in 1999 and ES&S has provided an exclusive license to Aerosonde Robotic Aircraft for operations, production, and further development of the aircraft and related systems. All operations and development are now being undertaken by Aerosonde Ltd. and Aerosonde North America (which jointly trade as Aerosonde Robotic Aircraft), in association with several university partners in the United States and Australia. (Complete details of the aircraft, our collaborators, and past operations may be found at www.aerosonde.com.)

a. Description of the Aerosonde robotic aircraft

The aircraft resulting from the development program, designated Mark 1, was used in our initial operations during 1998 and early 1999. An extensive program of improvements to increase reliability, robustness, and operational capacity, has lead to the Mark 2 Aerosonde, which entered operations in early 2000, and the Mark 3, which is being prepared for operations in 2001. The Mark 3 aircraft is shown in Fig. 1 and the aircraft characteristics are described in Table 1. This includes airframe upgrades to reduce weight and drag, to enable increased maximum speed (up to 60 m s^{-1}), and to improve versatility in the mounting and positioning of hardware. We note here that the original plans for Aerosonde (Holland et al. 1992) described plans to develop a capability to fly to above 15 000 m. The Mark 3 will have a practical altitude ceiling of 7000 m. Because of the large number of lower-level applications for the Aerosonde that have been identified, we are not at present pursuing the development of an engine that would allow flight at higher levels.

The brain of the Aerosonde is the avionics set, which contains all components needed for its operations. The avionics hardware consists of a main flight computer based on a Motorola 68332 embedded processor, flight control sensors, including GPS, for waypoint navigation and wind measurements; piezoelectric rate gyros for stabilization and autopilot; air data sensors for airspeed and altitude measurement; engine sensors; and a payload computer currently used for meteorological measurements. A UHF radio and long-range radio frequency amplifier provide line-of-sight continuous telemetry up to about 180-km range, and a miniature satellite communicator provides over-the-horizon communications. The onboard flight software handles waypoint or specialized navigation, flight control, airspeed and altitude control, and basic health monitoring. The payload computer takes meteorological measurements from the meteorological sensors and computes winds from GPS and airspeed data. Several components of the ground station software provide command and control of the aircraft, a map display, graphic flight plan creation, data display, and real-time data injection into meteorological models and forecast systems. The ground station software includes UHF long-range communications capabilities by enabling multiple remote ground stations connected via telephone or the Internet. In May 2000, this capability was used when an Aerosonde flying in Bass Strait, Australia, was monitored and controlled for an

TABLE 1. Specifications and performance for the Mark 3 Aerosonde.

Specifications	
Weight	15 kg
Wing span	2.9 m
Engine	24 cc PULP, 1.25, fuel injected
Navigation	GPS, differential GPS (DGPS)
Performance	
Speed	Cruise 20–32 m s^{-1}; climb 4 m s^{-1}
Range	> 4000 km
Endurance	> 40 h
Altitude range	20–6000 m
Payload (max)	5 kg with 2 kg fuel

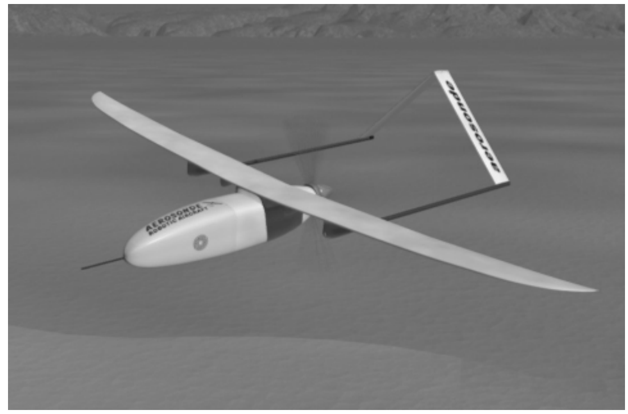


FIG. 1. A computer-generated image of the Mark 2 Aerosonde in flight.

extended period from Oregon, using a combination of radio, telephone, and Internet communications.

The basic configuration of the Aerosonde is as a "pusher," with the engine at the back. This design introduces some aeronautical limitations but has the major advantage of enabling instruments to be carried in pristine air, without fear of contamination by the engine heat and exhaust. Small engines capable of sustained operations over flights in excess of two days simply do not exist, and the development of such an engine has been one of our major development tasks. The resulting engine is considered to be the world's smallest fuel injected engine. The major components are a fuel injector, capable of delivering fuel accurately at 1–10 cc min^{-1}, a miniature engine management computer, a high-pressure fuel system, and a throttle body. The result is an impressive performance of well over 1 kW of power, flexibility to operate across a wide altitude range, and a fuel economy in excess of 2000 mpg.

Reliability is lower in the Aerosonde than in some larger and more sophisticated aircraft, due to its design as a partially disposable system, with virtually no redundant systems, to keep operational costs at a minimum. This lack of redundancy means that component failure can result in loss of the aircraft, particularly when it is several hundred kilometers out to sea. Great care has been taken to improve the reliability of critical components and to utilize extensive preflight checkout and testing to reduce the potential for component failure. For example, the new g-type engine has essentially eliminated early problems with engine failures. Operator training is also maintained at the highest levels to help remove human errors. However, losses will continue to occur, and the expected mean time to loss of an aircraft for the Mark 3 platform is 500 flight hours.

With components being improved, environmental factors are figuring more in aircraft losses. For example, several aircraft have been lost in recent years due to icing. A major research effort is underway with the University of Colorado to develop an active deicing system for the Aerosonde to help reduce this problem. An Aerosonde survived hail during recent missions for the Australian Bureau of Meteorology, indicating the strength and robustness of the airframe. No Aerosondes have been lost due to high-wind conditions, largely due to careful flight planning. While turbulence has not destroyed any aircraft (one Aerosonde survived over 6*g* turbulence in a flight into a microburst), the potential remains for losses in this area.

Because of specialized crew required to operate the Aerosonde, aircraft are not typically purchased; rather, the user purchases flight hours and data. The cost of Aerosonde operations per flight hour is highly competitive compared to alternative resources, and in many cases the Aerosonde can provide the only available means of gathering required data (e.g., in dangerous conditions). The advantage of the Aerosonde relative to manned aircraft is not just the cost; rather, the primary advantages are the capability of extended flight operations and the ability to fly under dangerous conditions that could not be feasibly flown with manned aircraft. High-risk flight plans are a feature of the Aerosonde capability, as loss of an aircraft in unpopulated regions is associated with little risk or cost. Examples of such high-risk flight programs include low-altitude operation in severe storms and sampling volcanic plumes.

b. Meteorological instrumentation

A thermodynamic and wind-observing capacity is standard on all Aerosondes. Temperature, pressure, and humidity elements consist of a set of Vaisala RSS901 radiosonde instruments trailing in the free airstream, where they are protected from rain and solar radiation by the aircraft wing. A fairing is located on the front of the set to protect the electronics and the pressure sensor. The reduction from the raw analog signal is done on board the aircraft and observations are routinely provided at 10-s intervals, with 1-s frequency available if required. A full ground check is undertaken at the start and finish of all missions to ensure instrument accuracy. The two sets of instruments are used to provide an internal calibration to ensure that observations are not contaminated by a faulty instrument and that missions can continue if one instrument fails. This is especially important for long flights of > 24 h. Comparison of the two sets of instruments over several missions indicates that they routinely are within 0.1 K, 0.2 hPa, and 2% relative humidity of each other.

Wind observations are obtained by a proprietary algorithm that uses a combination of Global Positioning System (GPS) ground speed, airspeed from a nose-mounted Pitot, and a short maneuver. Winds cannot be directly calculated from a vector difference between airspeed and ground speed, because only scalar airspeed is available, along with vector ground speed from GPS. The observation is therefore taken over the course of a turning maneuver, which gains more information on the vector airspeed and provides a best fit using an over-determined set of data. This wind maneuver can be an S turn, approximately 90° turn, or continuous circle, and typically requires 10–30 s for a wind solution to be obtained. The wind-finding process typically provides a horizontal wind resolution of 300 m. Inclusion of a compass would eliminate the need for the maneuver and increase horizontal resolution of the wind speeds; this is being considered for future versions of the aircraft.

We initially tested the instrument accuracy by attaching an Aerosonde under the wing of a Grob 109 aircraft operated by Airborne Research Australia and comparing the observations with those from the highly sophisticated onboard research instrumentation. Further comparisons have been conducted with radiosonde ascents in Alaska and Australia. A complete intercomparison is being prepared for separate publication.

c. Launch and recovery

A major design requirement for Aerosonde launch and recovery is that they can be operated from a wide variety of sites, including regular airports, local fields, sandy beaches, and roads. It is also required that the operation be portable and able to be established in remote and inhospitable environments.

At present, the Aerosonde is launched from a launch system consisting of a roof rack that can be fitted to any full-size car. The base of the rack is fixed to the car and the upper section is connected to the base at the front, enabling free rotation in a vertical plane aligned with the direction of travel. Initially, the aircraft lies tail down in the cradle. As the car accelerates, the aircraft assumes a flight attitude, then at the rotation, or takeoff, speed of 18 m s^{-1} the aircraft lifts up, the cradle constraining straps are automatically released, and the aircraft is launched. An alternative launch system from a catapult has been designed and is being built. As the system develops, the catapult may become the preferred launch mode, as it requires only one operator and launch is feasible from ships and ice sheets.

Recovery of the aircraft is achieved by a belly landing. This "goony bird" mode has been very successful. The lack of undercarriage is no impediment to the landing process and enables landings on rough surfaces that would be unsuitable for an undercarriage. The absence of an undercarriage also provides a substantial reduction in drag, weight, and complexity, and thus an increase in operational range and endurance. (Pictures and movies of the launch and recovery process are provided at www.aerosonde.com.)

For launch and recovery, communications with ground command are accomplished by UHF radio, communicating through a proprietary ground base, as indicated in the bottom right of Fig. 2. Autonomous launch and recovery has been demonstrated and is accomplished by using differential GPS. Currently we use a trained operator for launch and recovery, and the autonomous mode is only used for emergencies. However, autonomous launch and recovery is being developed for routine use.

d. Undertaking a mission

Once an aircraft has been launched and fully checked out, the mission is assigned and command is transferred to the command site, which is typically remote from the mission area. During operations, the Aerosonde is fully robotic, flying under the control of an onboard autopilot.

Flight monitoring occurs by communications through a combination of one or more of radio, satellite, telephone, and Internet connections, as illustrated in Fig. 2. The preferred mode is a combination of Low Earth Orbit (LEO) satellite and Internet communications. In addition to observational data, information on the power plant (revolutions, engine temperatures, voltage, etc.), flight control (pitch, roll, airspeed, etc.), and avionics bay (temperature) is communicated to the command center. Fuel and oil use is modeled to provide estimates of available endurance and to adjust autopilot sensitivity.

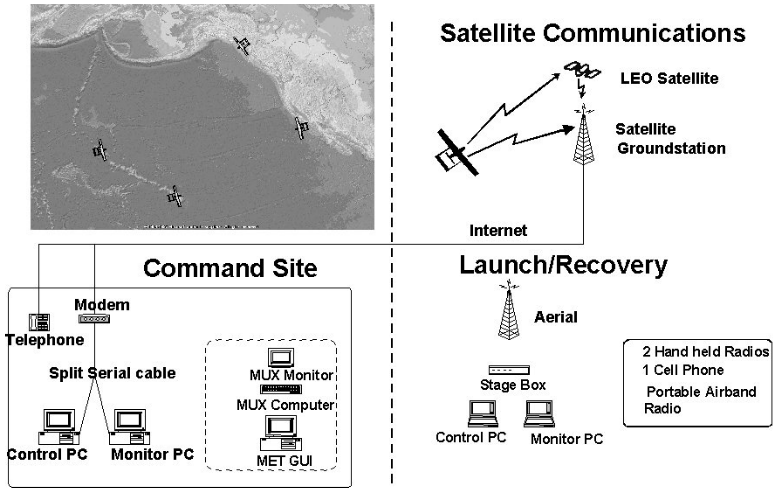


FIG. 2. The in-flight communications and command system for the Aerosonde robotic aircraft operating as part of a global reconnaissance facility. (bottom right) The launch/recovery site, (top right) the aircraft communicating with LEO satellites, and (bottom left) the ground command site.

Flight command is exercised by uploading revised flight plans to the aircraft. The flight plans normally consist of a series of waypoints (latitude, longitude, and altitude). Autonomous programs are also available; for example, the aircraft can follow autonomously a sea-breeze front and conduct a specified monitoring mission. We envision that autonomous missions, where the aircraft makes internal decisions based on its own observations, will become a significant component of all operations.

e. Regulatory and safety issues

The regulatory environment for aircraft operations has evolved on the basis of manned flights, and the increasing use of Unmanned Aerial Vehicles (UAVs) creates challenges for ensuring safety and minimal disruption to established traffic. One of the greatest challenges to UAV operations is obtaining clearance for flight in civil airspace. This issue is extremely complex in terms of defining what operational procedures, qualifications, and capabilities must be required for safety on manned and unmanned aircraft operating in the same airspace. The issue is further complicated by the lack of coordination among aviation regulatory groups, even within the same country.

Because of its small size, the Aerosonde is having an easier time than other larger and more complex UAVs in obtaining permission to fly. Aerosonde has never been refused permission to fly operations, although occasional undesired restrictions have been placed on operations. Aerosonde has systematically worked through issues with regulatory authorities to establish benchmarks and operating procedures. A major advantage is both the small size of the aircraft and the fact that the operations are mostly in remote regions. In Australia, the regulatory environment is already changing to accommodate Aerosonde-class aircraft and we are confident that our work with the Federal Aviation Administration will result in similar changes.

Safety is maintained by 1) not utilizing the aircraft in situations where, for example, loss of an engine can lead to injury or property damage; and 2) limiting damage liability through the use of a light-weight, relatively slow aircraft. All Aerosonde operations are conducted with liability insurance coverage. The Aerosonde group has developed high safety standards for operations and the approach has been to start slowly and work up to higher levels of difficulty and requirements. The Aerosonde has an unblemished safety record during 2000 h of flight operations. Each Aerosonde operational crew is trained to the highest standard in all aspects of flight operations, regulatory requirements, and safety and this training is now being accepted by aviation authorities.

Several onboard components are designed to prevent untoward incidents from happening. For example, in case of a communications failure, the aircraft proceeds to a predefined flight plan, which has been agreed to with aviation authorities beforehand. The communications failure point is generally a defined safe landing site with execution of an autonomous landing.

3. Highlights of Aerosonde operations

The Aerosonde has been developed with a strong focus on operations, and an extensive series of field missions were programmed into the overall development effort. As a result, over 1500 h of Aerosonde flight operations have been undertaken in Australia, the United States, Canada, and East Asia since 1995 (Fig. 3). These have included system testing and development, and missions for a variety of international field programs. The latter programs have provided a valuable experience base for establishment of the Aerosonde operational facility. Three such missions are described in some detail: the Port Hedland trial for the Australian Bureau of Meteorology in 1998, the record flight across the North Atlantic, and operations for the U.S. Navy in North Carolina.

a. Port Hedland trial

The intensive development program from 1995–98 included a requirement that the resulting aircraft and related systems pass a trial sponsored by the Australian Bureau of Meteorology. In this trial, during January and February 1998, Aerosondes flew multiple missions from a launch and recovery site at the Cargill saltworks, including over 150 h of operations and individual flights of up to 31-h endurance. After launch, Aerosonde command was passed to the Perth Regional Forecasting Centre (approximately 1300 km from the launch site), which was responsible for the conduct of all missions. In addition, a temporary command site was established in the Bureau of Meteorology Research Centre in Melbourne (over 3000 km from the launch site), with communications undertaken over the Internet. The routine operations mainly focused on a series of sea-breeze flights and offshore monitoring, at the request of the Perth Regional Forecasting Centre. Significant weather experienced during the program consisted of a microburst encounter, occasional thunderstorm squall lines, and a flight into the outer circulation of severe Tropical Cyclone Tiffany. We describe the microburst encounter as an example of aircraft operations in severe conditions.

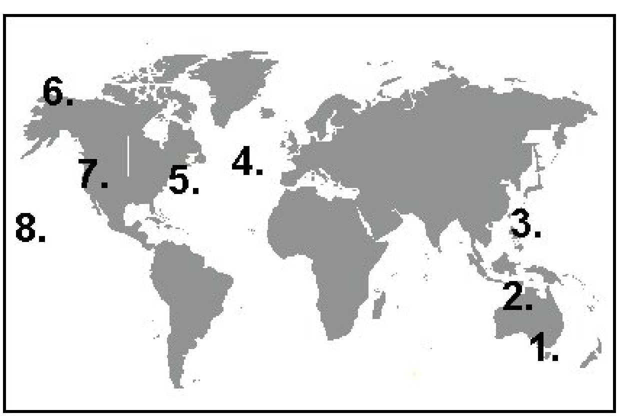


FIG. 3. Aerosonde missions 1995–2000.

On Saturday, 24 January 1998, the Aerosonde sampled the environment of moderate convective cells that had developed along the sea-breeze front and moved into the area from the southeast. The sea breeze was quite strong, with vertical wind shear at the top of the landward gravity current of around 20 m s^{-1} over 100–200 m. The Aerosonde encountered moderate to severe turbulence in this layer, and Kelvin–Helmholtz billows were observed to grow into long roll clouds on occasions. During the mission, a small convective cell developed rapidly over Cargill, with heavy rain experienced for several minutes. The control site was then hit by a classic wet microburst, with winds in excess of 35 m s^{-1}. The Aerosonde flew into a downdraft of around 12 m s^{-1} at approximately the same time, which we have associated with the roll vortex at the leading edge of the microburst (Fig. 4). Forced descent occurred to an altitude of 250 m, where the aircraft experienced a massive acceleration as it descended into the main microburst outflow. The lateral acceleration exceeded 4*g*, with a 30 m s^{-1} change in aircraft speed in 1.5 s. This acceleration occurred as the aircraft descended into the main outdraft, pitched forward, and rapidly adjusted to the outflowing air. The vertical shear at the top of the outdraft therefore exceeded 30 m s^{-1} in 20 m, which indicates a vertical vorticity of > 1 s^{-1}!

b. Record transatlantic flight

During August 1998, the Aerosonde *Laima* flew from Newfoundland to the Outer Herbrides to become the first robotic aircraft to cross the North Atlantic Ocean. *Laima* was launched from Bell Island Airport, Newfoundland, at 0959 UTC 20 August 1998 (Fig. 5). There were no satellite communications available at that time, and *Laima* moved out of UHF range and proceeded to complete its mission completely in robotic mode. The specified flight plan consisted of a series of waypoints for a route that went slightly south of a great circle (shortest distance) to the landing site at DERA Range in the Outer Hebrides.

Before launch, complete flight simulations had been made using winds provided by the National Oceanic and Atmospheric Administration/National Weather Service National Centers for Environmental Prediction

(NCEP) model to provide approximate times at each waypoint. The flight track took *Laima* across a weak cold front and along an occluded frontal zone (Fig. 5a), and moderate to heavy rain was experienced for 14–18 h, or well over half the entire flight. *Laima* contacted the landing crew at the DERA range at 1215 UTC, and was brought in to land under manual control at 1244 UTC. The landing was within 15 min of schedule, after a flight of 3270 km in a time of 26 h 45 min. Approximately 4 kg of fuel was used, giving a fuel economy of over 570 m L^{-1} (1350 mpg). The wind observations for the flight compared very well with the associated NCEP analysis (Fig. 5b). The only significant differences were where the aircraft recorded details of the frontal zone that were below the model resolution.

Laima was developed and manufactured by ES&S (precursor to Aerosonde Robotic Aircraft) in Australia and purchased by the University of Washington with a grant from the U.S. Office of Naval Research. The flight was organized by The Insitu Group and the University of Washington and conducted with support from ES&S. The aircraft *Laima* now hangs in the Seattle Museum of Flight.

c. *Operations for the U.S. Navy*

Demonstration flights were conducted in North Carolina (Fig. 6) during 22–25 February 1999, in support of an exercise by the Naval Second Fleet. The goals were to demonstrate that Aerosondes could provide meteorological data in support of fleet operations. Launch and recovery was undertaken from Atlantic Field and remote command was maintained from Naval Meteorology and Oceanography (NAVMETOC) in Norfolk, Virginia. All data collected were transferred to the NAVMETOC Web site, to Naval Research Laboratory Monterey, and to the fleet.

These missions clearly demonstrated the capacity of Aerosondes to obtain observations of mesoscale features in any region of interest. This is illustrated by the flight on 24 February, which proceeded to the operations area in a moderate northwesterly flow of 5–10 m s^{-1} and relatively warm temperatures of 1°–2°C (Fig. 7). Once inside the operations region, a descent to 750 ft was initiated to commence the sounding cycle. This brought the aircraft into wet, cold air trapped against the coast and ranges. Freezing temperatures and 100% humidity caused the aircraft to develop icing problems and it was ordered to ascend. After transiting the dry/warm zone of northwesterly

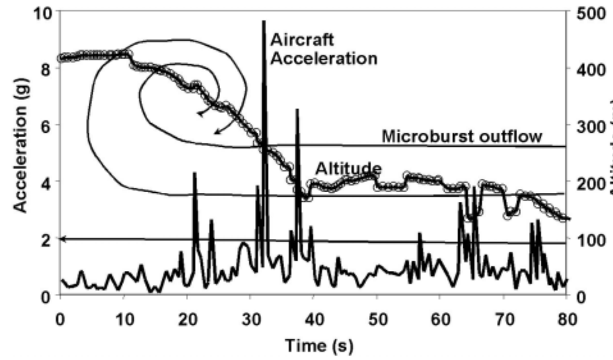
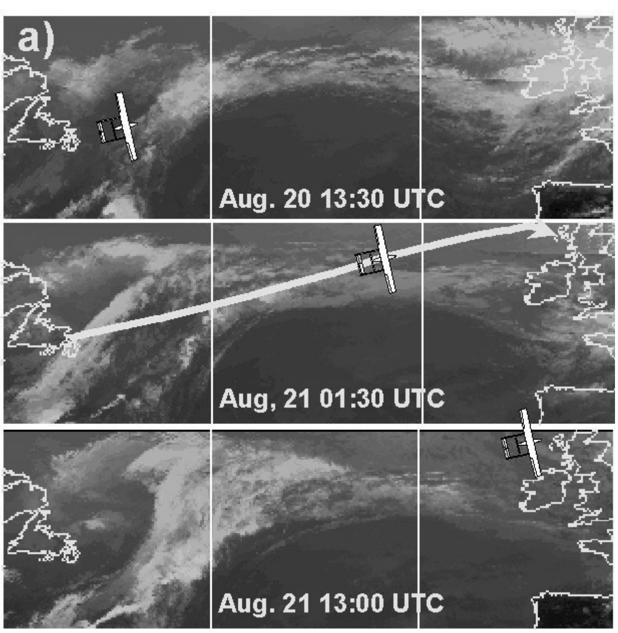


FIG. 4. Summary of the encounter of an Aerosonde with a microburst at Port Hedland. A schematic of the microburst outflow is overlain on Aerosonde altitude and acceleration plots.



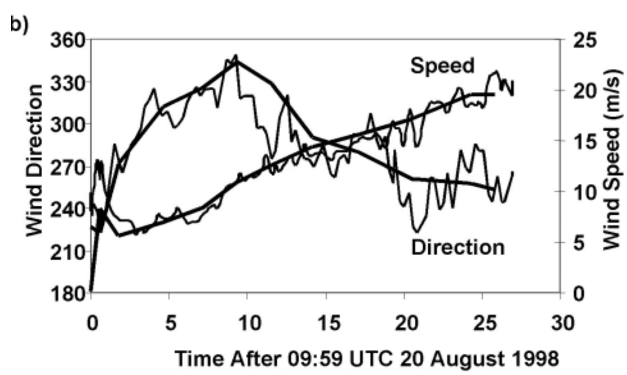


FIG. 5. Flight of Aerosonde *Laima,* first robotic aircraft to cross the North Atlantic Ocean. (a) Flight track superimposed on satellite imagery with the logo showing the Aerosonde location at satellite observation time. (b) Comparison of Aerosonde wind observations (thin lines) with those from the NCEP analyses (heavy lines).

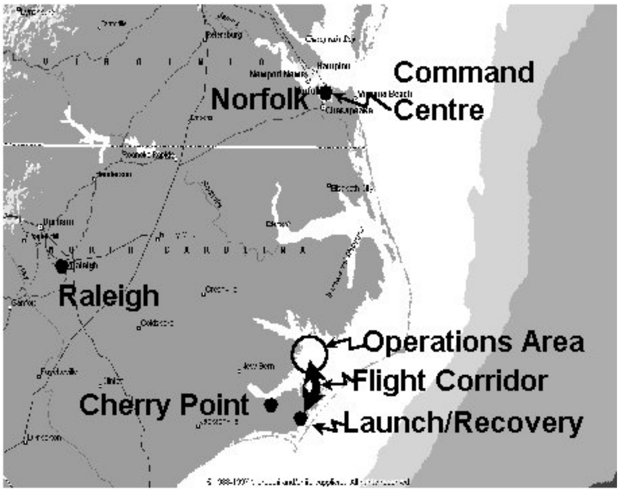


FIG. 6. Operations area for the U.S. Navy in Feb 1999.

flow, the Aerosonde ascended into a region of moist upslope in southwesterly flow. Radar imagery for the time showed a marked mesoscale band of precipitation moving through the region. Above 800 hPa, icing buildup on the airframe reduced control, and a slow descent was commanded to provide high-resolution observations. The Aerosonde returned to base in the relatively warm and dry northwesterly flow.

These data clearly show the variety of conditions that can be experienced in a small region. The low-level icing had not been forecast, and the Aerosonde observations resulted in cancellation of a mission that could have otherwise caused combat aircraft difficulties.

4. The future

The principal developments for future operations that are planned include the following. A global Aerosonde reconnaissance facility is being developed that consists of a set of launch and recovery sites dispersed around the globe. The use of satellite communications and internet technology enables an operation in which all aircraft around the globe are under the command of a single center. During operation, users will receive data at their home institution in near–real time via the virtual field environment. Sophisticated applications of the Aerosonde are being enabled by the development of a variety of interchangeable instrument payloads and the operation of SMACS. Details on these planned developments are provided below.

a. Aerosonde global operation

Imagine a robotic airline operating from a distributed set of launch and recovery sites, which can be located in almost any reasonably flat and clear area, with a global command center undertaking all of the scheduling and in-flight command, and a virtual field environment to provide all relevant information to users. This is made possible by the enormous range and flexibility of the Aerosonde, with its GPS navigation, straightforward launch and recovery, and LEO/Internet communications.

The basic concept is illustrated in Fig. 8. An Aerosonde flying in the western North Pacific communicates via an LEO satellite to a ground station in Japan. The signal is transferred to the Internet and routed to the global command center located in Melbourne, Australia. Relevant information is then relayed via the Internet to the virtual field environment established at the user's home site. The user utilizes the virtual field environment to respond with requests for Aerosonde mission changes.

The command center can be located anywhere with good communications capacity and only one is re-

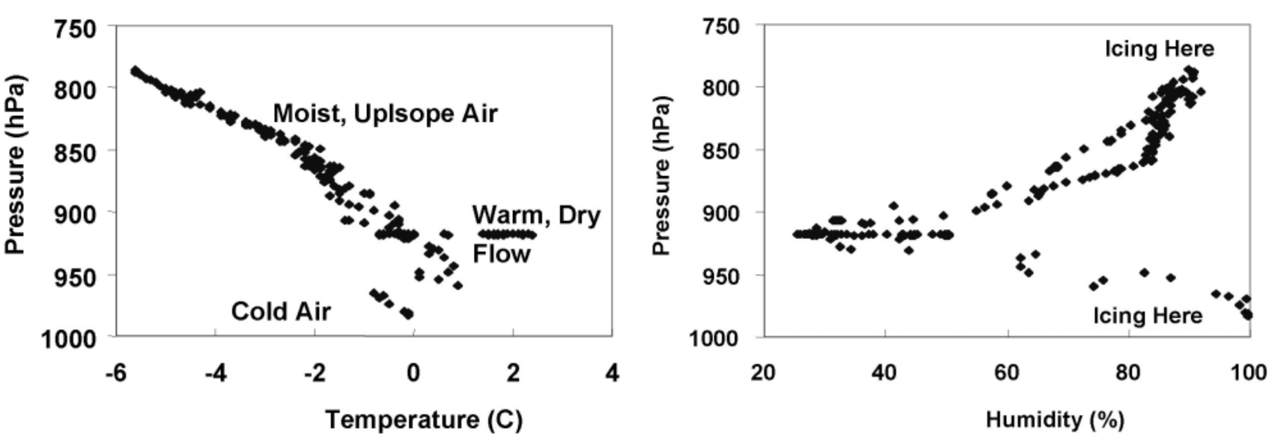


FIG. 7. Temperature and moisture observations from the flight on 24 Feb 1999.

quired, in principle, to service the entire globe. We estimate that around 20 launch/recovery sites will provide sufficient coverage for operations over 90% of the globe. These sites will be strategically located to take advantage of available infrastructure, while accounting for the impacts of local wind regimes on Aerosonde operations. The operations will occur through the Aerosonde global reconnaissance facility, which will consist of a global command center, a virtual field environment, a distributed set of launch/recovery sites, and a field services unit.

The Aerosonde global command center will be responsible for all aircraft operations, including:

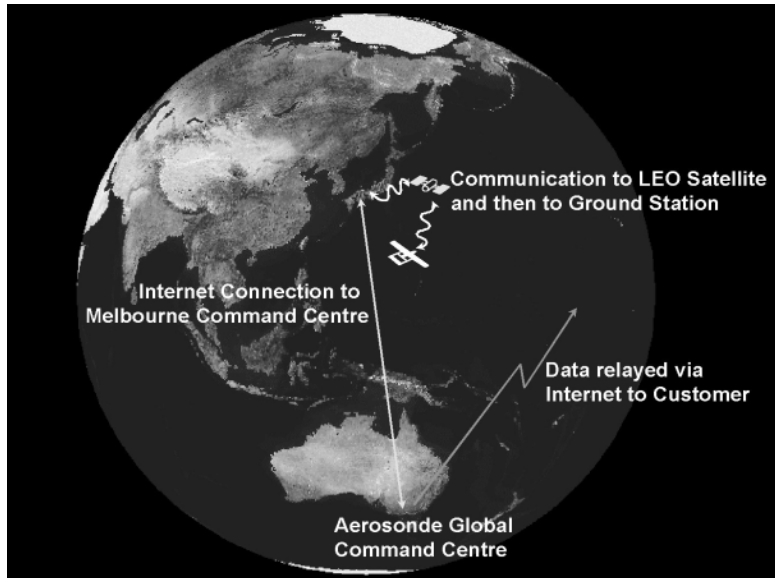


FIG. 8. Schematic of the manner in which global Aerosonde operations will occur.

- scheduling of regular Aerosonde operations, including aircraft transport and logistics;
- monitoring the deployed Aerosonde fleet and taking action as required by air traffic considerations, changing weather conditions, aircraft emergencies, changing user requirements, and the like;
- ensuring data are relayed to customers; and
- responding to mission requests from users.

The Aerosonde virtual field environment is a Web-based real-time data display system that allows users to monitor the observations in near–real time and interact with the global command center to modify the mission. The idea is to provide users, sitting at their office workstations in a location remote from the flights, with the same level of control over the mission as if the user were flying in a manned research aircraft, with data displayed in near–real time in a manner analogous to that provided during flights on National Center for Atmospheric Research research aircraft. The Aerosonde data are downloaded via satellite to the global command center, where it is ingested into a Web-based data display system. Users are connected by the Internet to enable them to examine the data from their desktop workstation and modify a mission in response to the observations. The data display system will allow considerable flexibility in plotting the data in multiple simultaneous data windows, using a menu point-and-click system. Sample data display formats include time traces, vertical profiles, contour plots, histograms, and imagery, and can be tailored to the user's requirements. Additionally, satellite and other weather data can be displayed, including combinations of flight and satellite data (e.g., the aircraft flight track plotted over a satellite image). The software can also prompt the user for input on predefined mission decision points, such as confirming identification of an object under surveillance. The virtual field environment thus enables users to fully interact with the aircraft mission without leaving their office, forwarding mission change requests to the global command center for implementation.

Aerosonde launch and recovery sites provide launch and recovery services on request. Their tasks include:

- maintenance of a store of Aerosondes and spare parts;
- assembly and launch of aircraft on demand (including full system checkout), and recovery, packing, and return of used aircraft as required; and
- minor field maintenance and system health checking.

Launch and recovery sites are being selected for both their suitability for Aerosonde operations and their geographic location. Currently, sites in Alaska, Canada, Australia, Taiwan, and Japan are under review, or in the process of implementation. A hierarchy of sites will be established, with some sites providing major operations capacity, while others are used for specialist programs or emergencies.

The Aerosonde field service unit provides a wide range of support for the global operations, including

- undertaking all establishment and training for the full operation,
- holding a reserve of Aerosondes for operations and ensuring that aircraft are deployed as required,
- maintaining and updating the Aerosonde fleet, and
- undertaking specialist user operations on contract.

A full operational test of the concept has been conducted in collaboration with the Australian Bureau of Meteorology, from March to June 2000 (Fig. 9). The major goal was to demonstrate the capabilities of, and gather experience in the establishment and operation of, an Aerosonde global reconnaissance facility. This was accomplished by establishing a prototype command center in the Victorian Regional Forecast Centre and a launch recovery site at Sale Royal Australian Airforce Base (Fig. 9). Operations were conducted in eastern Bass Strait and over the adjacent land, subject to regulatory and safety requirements. Over 250 h of flights in the Bass Strait region were then conducted during a series of 1-week intensive campaigns. During overnight operations Aerosonde command was transferred to the offices of Cloud Cap Technology in Oregon, very effectively demonstrating the feasibility of the global concept. The meteorological data obtained via the Aerosonde also were passed into the real-time system and assimilated into the Bureau forecast process, including the numerical modeling suite.

b. Smart Aerosonde Clusters

The advanced technology and relatively low cost make possible unique experimental designs that use clusters of Aerosondes to collectively undertake a variety of missions. We have called this an operation of SMACS, in which a group of Aerosondes communicate with each other and make independent decisions on how to arrange themselves to conduct a defined mission.

A simple example is use of a Smart Aerosonde Cluster to obtain observations in hurricanes that cannot be obtained by, and are complementary to those currently available from, satellites and manned aircraft. One aircraft proceeds to the cyclone center, navigating itself relative to the winds and derived surface pressures. Once there it maintains station autonomously, observing the cyclone location and central pressure, together with making eye soundings as required. A cluster of Aerosondes then commences operations to undertake defined missions in the tropical cyclone, navigating directly from the observations passed by the first aircraft. Missions that can be accomplished in this manner include circling in the maximum wind region while monitoring the wind intensity, mapping the boundary layer structure, and collecting observations of the near environmental conditions for use in numerical modeling.

More complex missions for Smart Aerosonde Clusters include operating a grid search for a ship at sea, using advanced search techniques. Whenever one aircraft finds a likely candidate, it would withdraw from the search, hold position, and pass information back to the command site. The remaining aircraft can then autonomously adjust their search pattern. In all SMAC operations, the defining feature will be the capacity for the aircraft to operate together to undertake a mission defined at the macro level. Human beings remain in overall command, but do not in general dictate the details of the operation.

c. Instrument payloads

Largely motivated by our interactions with a variety of potential users of the Aerosonde, a new avionics package for the Aerosonde is being designed so that instrument payloads can easily be interchanged. Selection of instruments for the Aerosonde is constrained by the following:

- weight and size (maximum instrument payload is 5 kg; smaller payloads for extended range),
- power requirements (maximum power for instrument payload is 50–60 W sustained power usage), and
- cost (the total cost of payload should be minimized in case the aircraft is lost in hazardous flight conditions).

Table 2 describes candidate instruments for the Aerosonde. These measurements and instruments have

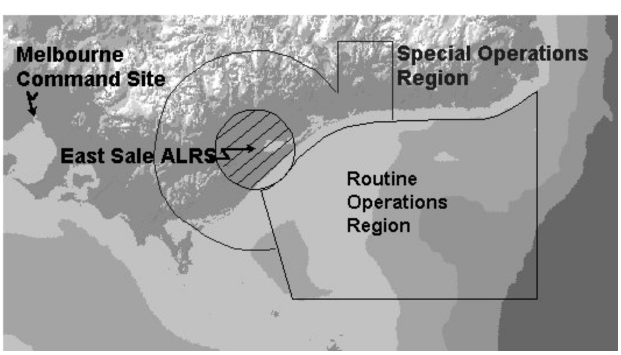


FIG. 9. Basic components of the Aerosonde operational system for the Australian Bureau of Meteorology trial in Jan–Mar 1998.

been selected in response to interactions with current and potential users of the Aerosonde. The radiometric and remote sensing observations have stringent requirements for high-frequency sensing of aircraft position and attitude in three planes and flight stability augmentation; such development is underway in support of these instrument payloads.

The technology for small instruments is rapidly developing in response to the needs of kites, balloons, satellites, and small robotic aircraft. Promising technologies for gas measurements include tunable diode lasers, cascade quantum lasers, and fiber chemical sensing.

d. Applications

A variety of different applications for the Aerosonde are funded, proposed, and under consideration. An illustrative sample of current and planned Aerosonde applications is described below.

1) Adaptive observations

Aerosondes can provide meteorological observations in remote regions that are lacking radiosonde measurements. Aerosonde observations are being made available to the meteorological community over the Global Telecommunications System. To maximize the impact of Aerosonde observations on weather forecasts, an adaptive observing strategy for Aerosondes is being developed. Numerical weather prediction centers conduct ensemble forecasts from which instability calculations are performed. Singular vectors identify the regions of maximum dynamical instability, where small initial errors could strongly amplify and destroy forecast skill. Using Aerosondes in an observing strategy targeted at instability regions identified by the singular vectors (or other techniques) could reduce uncertainties in initial conditions in these critical regions. Aerosonde Robotic Aircraft has commenced collaborations with both NCEP and the European Centre for Medium-Range Weather Forecasts to perform adaptive observations. The first test of the Aerosonde in this capacity will be conducted during The Hemispheric Observing System Research and Predictability Experiment.

2) Arctic Long-Term Observations

The Mark 1 Aerosonde was flown in the Arctic (based from Barrow, Alaska) in April 1999, in support of the U.S. Department of Energy Atmospheric Radiation Measurement Program. Operations were hampered significantly by aircraft icing, which is common in the Arctic, where field measurements are typically

Table 2. Aerosonde instrumentation.

Measurement	Instrument
Aircraft navigation and operations	
Position	GPS, DGPS
Aircraft icing	Icing rate detector
Meteorology	
Air temperature, pressure, humidity	Vaisala RSS901 sensor
Winds	Proprietary
3D water vapor fields	GPS
High frequency winds, temperature, pressure, humidity	(Under investigation)
Gas measurements	
H_2O and CO_2	Infrared gas analyzer
O_3	UV ozonesonde
CO	Conductometric detector
CO_2	Conductometric detector
SO_2	Electrochemical detector
Radiometers	
Shortwave flux	Pyranometer
Ultraviolet (UV) radiation	Pyranometer (UV)
Infrared flux	Pyrgeometer
Surface temperature	Pyrometer
Cloud and aerosol	
Liquid water content	Hot-wire probe
Ice crystal concentration	(Under investigation)
Condensation nuclei concentration	(Under investigation)
Surface remote sensing	
Altitude	Laser altimeter (spot)
Topographic mapping	Scanning laser altimeter
Surface visible imaging	Camera, video camera
Infrared imaging	Infrared camera
Ocean surface winds, waves	GPS reflectance
Geomagnetic survey	Total field and directional magnetometers

expensive, logistically difficult, and hazardous. The National Science Foundation (NSF) Office of Polar Programs has recently funded the establishment of an observing system using the Aerosonde at Barrow under its Arctic Long-Term Observations Program. The goals of this NSF effort are to

- adapt the Aerosonde to make environmental observations in the extreme Arctic environment;
- adapt and integrate miniature instrumentation for deployment on the Aerosonde in the Arctic to do remote sensing of cryospheric surfaces (melt ponds, sea ice thickness distribution, topographic mapping of glaciers, ice stream velocity);
- establish a facility at Barrow for deployment and reconnaissance of Aerosondes;
- coordinate with numerical weather prediction and sea ice modeling centers to assimilate the Aerosonde data into their predictive models; and
- coordinate with U.S. and international field programs in the Chukchi/Beaufort sectors of the Arctic to support their scientific efforts and evaluate the Aerosonde measurements.

Initial flights using the Mark 2 Aerosonde were conducted from Barrow during August 2000, including tests of a variety of icing mitigation strategies and sea ice monitoring using an onboard camera.

The Australian Bureau of Meteorology is planning to utilize Aerosondes in a variety of operations. The environment around the Cape Grim Baseline Air Pollution Station in Tasmania will be monitored to provide the meteorological context for the extensive atmospheric chemistry data that are collected there. In addition, Aerosondes will be fitted with chemical instrumentation to provide a spread of observations around the core observing site. Australia also does not have a capacity for manned reconnaissance of tropical cyclones, and Aerosondes are to be deployed to provide observations of cyclone location, intensity, and environmental features of importance to the forecast process. Additional applications of the Aerosonde that are being pursued include the following:

- surveillance with cameras and a laser altimeter, for scientific, civil, and military applications;
- geomagnetic surveys, where the aircraft measure micromagnetic and microelectrical changes that can be used to find mineral deposits;
- wide agricultural surveys covering vegetation types, growth rates, and stress;
- air pollution source identification and dispersion;
- air–sea interaction studies, including measurement of turbulent fluxes, studies of cloud–aerosol interactions, and measurements of surface energy balance components;
- validation of satellite remote sensing products in remote regions, coastal mapping, and erosion monitoring; and
- atmospheric chemistry observations, including trace gases and volcanic plumes.

5. Conclusions

The Aerosonde introduces new technology that extends the forefront of environmental observational capabilities. Its capacity to operate continuously for 2 days and in excess of 4000 km provides a highly flexible and relatively inexpensive platform from which a wide variety of environmental observations can be obtained. The Aerosonde provides a complementary component of the atmospheric observing system, with its capacity to operate over long periods of time and a wide range, and to work in dangerous and debilitating conditions. It can do some of what manned aircraft are already doing in a more cost-effective and risk-free manner. There are no constraints from consideration of crew safety and the aircraft can operate in hazardous conditions (including nighttime operations). Aerosondes can operate under cloud and in conditions that negate effective remote sensing from satellites, and the combination of direct wind and thermal observations has been shown to be a powerful combination for numerical model assimilation.

Based on a combination of satellite and Internet communications, Aerosondes will generally operate under a global command center, which can take responsibility for all aircraft operating anywhere on earth. Aircraft deployment will occur from launch recovery sites located around the globe in a configuration that enables required operations to occur. Users of Aerosonde technology will utilize a virtual field environment, running on their local personal computer, which provides both aircraft flight information in real time and the capacity to define new mission profiles for passing to the global command center. The deployment flexibility offered by these advances will be substantially enhanced by use of Smart Aerosonde Clusters, in which a group of aircraft operates cooperatively to conduct a defined mission, with minimal external interaction.

In combination with these aircraft developments, a wide variety of instruments are being adapted, or are planned for the Aerosonde. Current developments are listed in Table 2.

We are pleased to report that the original concept for the Aerosonde, by Holland et al. (1992), has been validated by ~2000 flight hours flown in support of scientific and operational missions. The next stages are to improve reliability and performance, to extend the aircraft capacity, particularly with sophisticated instrument suites, and to introduce global operations, which minimize costs and maximize range and flexibility of operation. (Further information about the Aerosonde, and ongoing developments and operations, can be found at www.aerosonde.com.)

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