REGULATORY ISSUES INVOLVING LONG-RANGE WEATHER OBSERVATION BY AEROSONDE AUTONOMOUS AIRCRAFT

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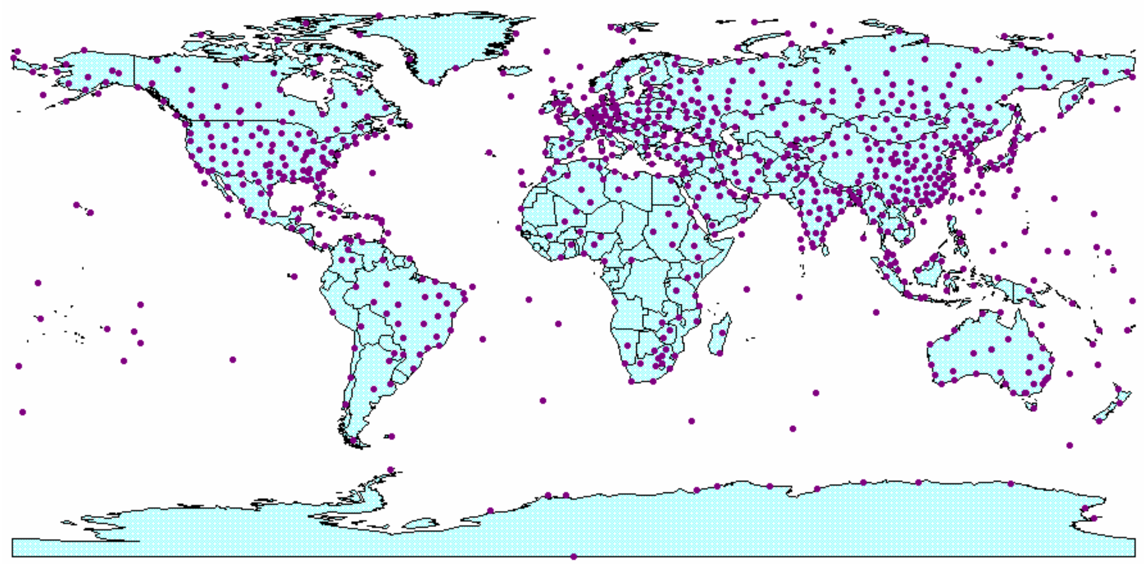


Figure 1. Balloon soundings of the atmosphere are made twice daily at about 1000 sites worldwide, and supply the lifeblood of numerical weather forecasting. However vertical sampling over oceans and remote areas is too sparse for effective model initialisation. Improved sampling in these areas requires a means to deploy instruments economically over long distances. Miniature autonomous aircraft, or *Aerosondes*, promise to meet this requirement, and similar needs in other earth-science disciplines.

The Aerosonde problem

We will discuss here a few prospective mission scenarios for weather reconnaissance by the Aerosonde miniature autonomous aircraft, as examples in the very diverse set of UAV applications to be considered in regulatory policy-making. We begin by reviewing the problem that the Aerosonde is designed to address.

Meteorologists are all-too-familiar with the chronic dearth of upper-air data over the world's oceans and remote areas. The skies over North America and other land masses are relatively replete with reports from radiosonde balloons, profilers, and airliners (Figure 1), but satellites are left to fill, incompletely, the voids between sparse *in situ* reports over the rest of the globe. The effect of the voids is sorely felt in forecasting, both directly and through a shortage of ongoing calibration data for satellite sampling algorithms.

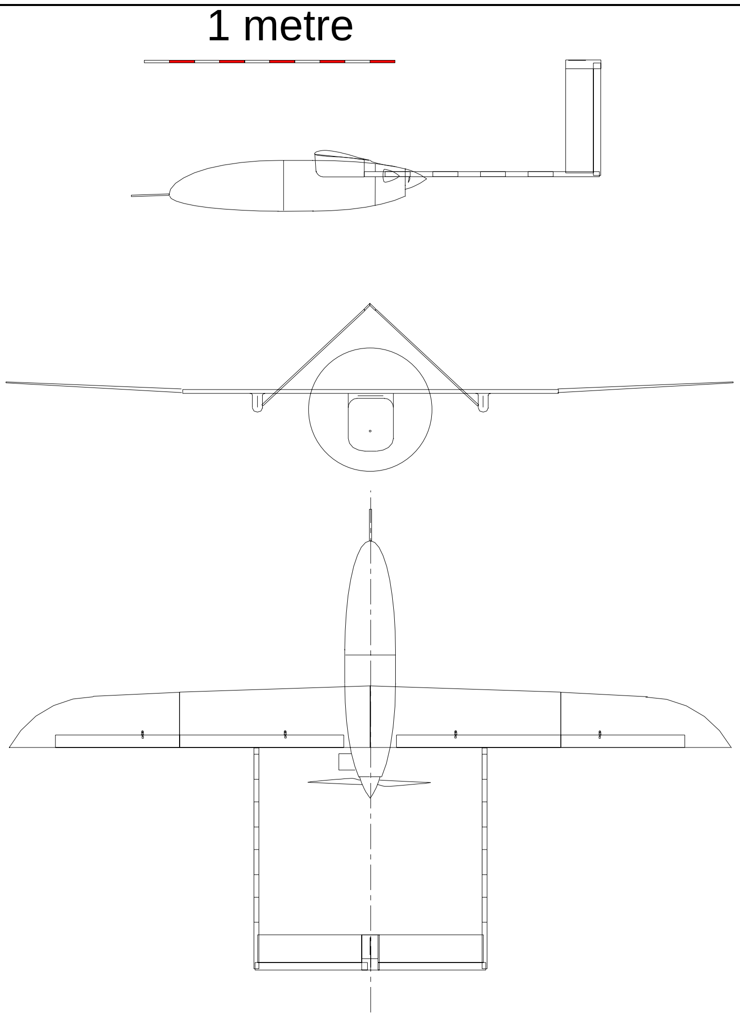


Figure 2. The Aerosonde: a small but long-range aircraft capable of autonomous weather reconnaissance over the oceans. In its present form the aircraft is capable of about 1400 nm still-air range, 36 hr endurance, and 14,000 ft ceiling. An improved version of about the same size will have about twofold higher range and endurance, and ceiling of 40,000 ft or so.

It is cost that prevents the voids being filled. While radiosonde balloons - which are generally regarded as the lifeblood of numerical weather prediction (NOAA 1992) - can be flown for about \$200 per sounding from convenient sites on land, the real cost for ship-based soundings is at least tenfold higher (*WMO Bulletin* 1991). Consequently it has never been possible to operate many weather ships, and indeed, in the modern fiscal climate, their ranks have dwindled away.

Meanwhile other methods of offshore data-gathering are even more expensive. The extreme example is the US hurricane-reconnaissance program in the Atlantic using *Hercules*, *Orions*, and now a *Gulfstream IV*, at a real cost of about $10,000 per flight-hour: no other country can afford costs at this level for weather observation.

The Aerosonde concept

Several years ago we proposed that an economical alternative would soon be possible in the form of miniature autonomous aircraft, small enough to fit on a tabletop, and yet capable of missions spanning thousands of kilometres and several days duration (McGeer 1991, Holland *et al.* 1992). The concept has four key features:

- **small size**, with attendant economies deriving from low costs of manufacture and use; easy shipment; assembly and operation by a single person; flexible basing; and independence of elaborate facilities;

- **long range and endurance**, sufficient to reach areas far offshore and to remain there for useful periods of time;

- **autonomy**, with automatic operation from take-off to landing, and only occasional messaging while en route;

- **attrition** that could be high (perhaps 10% of sorties flown) without making safety or economics unacceptable.

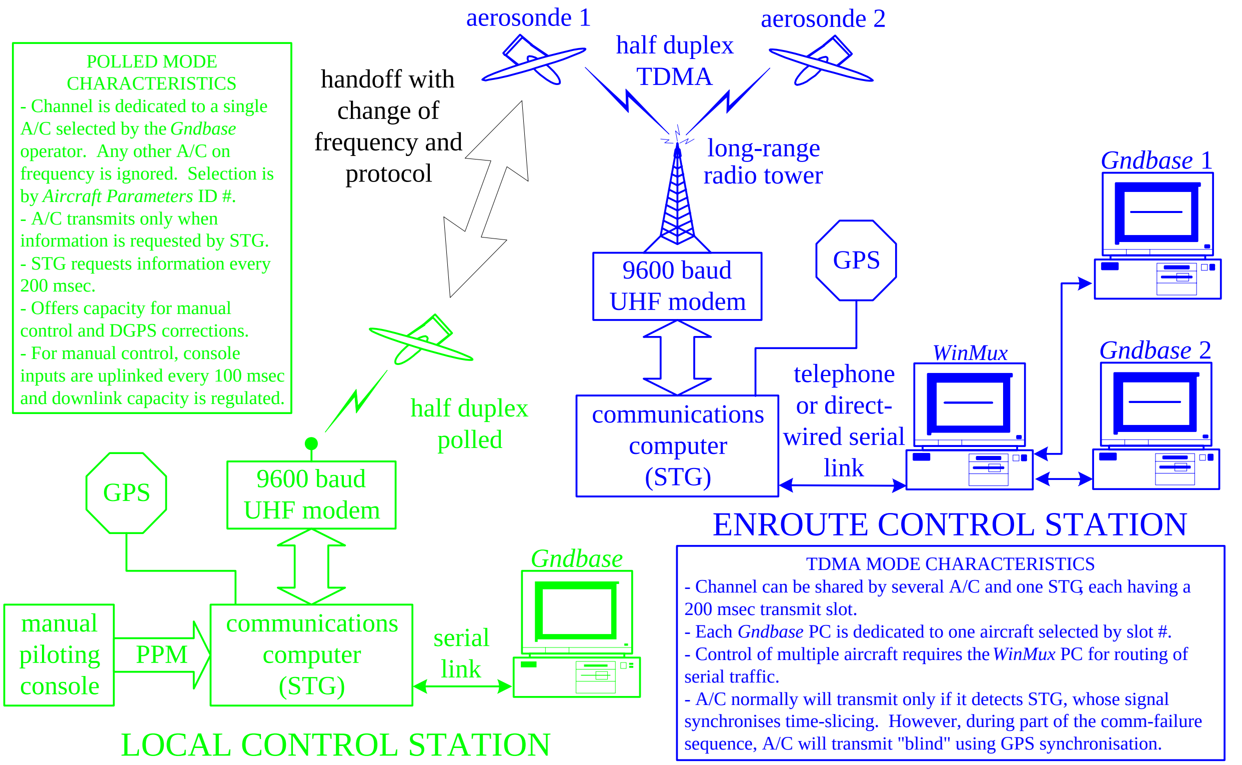
Aerosonde Milestones in 1998

- ~400 flight hours from January to August 1998 (~800 hr total since 1995)
- 5 flights >24 hr; longest 30.5 hr (actually 32 hr unrefuelled)
- flights in severe tropical thunderstorms (Western Australia; S. China Sea)
- flights in midlatitude icing (Vancouver Island)
- fully automatic flight from takeoff to landing
- inflight transfer among multiple ground stations, and enroute control-by-telephone from weather forecasting centres (Western Australia; Vancouver Island)
- first autonomous Atlantic crossing; 3270 km in 26h 45m from Newfoundland to Scotland (20-21 August)

Operations experience to date

Field trials with aircraft built according to this concept began in 1995, and have since been conducted in Australia, Canada, the United States, the South China Sea, and the North Atlantic (McGeer 1996, 1998; see also the Aerosonde web site). These operations have been based at coastal sites with light traffic, and mainly conducted over the sea, although some overland flights have been done in the Australian outback. Except for the transatlantic demonstration in August

1998, operations have been kept within the radio horizon of the ground station, *i.e.* typically 150 km. The normal ground-station arrangement is shown in Figure 3. (On the Atlantic crossing aircraft were out-of-contact except when near shore. An autonomous flight-termination system was in place to ensure that aircraft did not stray off-track.)



POLLED MODE CHARACTERISTICS

- Channel is dedicated to a single A/C selected by the *Gndbase* operator. Any other A/C on frequency is ignored. Selection is by *Aircraft Parameters* ID #.
- A/C transmits only when information is requested by STG.
- STG requests information every 200 msec.
- Offers capacity for manual control and DGPS corrections.
- For manual control, console inputs are uplinked every 100 msec and downlink capacity is regulated.

TDMA MODE CHARACTERISTICS

- Channel can be shared by several A/C and one STG, each having a 200 msec transmit slot.
- Each *Gndbase* PC is dedicated to one aircraft selected by slot #.
- Control of multiple aircraft requires the *WinMux* PC for routing of serial traffic.
- A/C normally will transmit only if it detects STG, whose signal synchronises time-slicing. However, during part of the comm-failure sequence, A/C will transmit "blind" using GPS synchronisation.

Operations usually require at least two ground stations, one for aircraft near the base, and another for aircraft en route. Enroute stations often have to be located on high ground away from the base to maximise communications range. To extend range further, the *WinMux* PC can access several ground stations simultaneously via telephone, and pass aircraft among them.

Figure 3. Most field programs flown to date have used the ground-station arrangement shown here. Upcoming changes include switching from manual to automatic takeoff and landing, and, for long-range missions, from a terrestrial UHF link to satellite relay for enroute control. With satellite relay, telemetry will be in the form of occasional on-demand messages rather than a continuous downlink stream.

Each of these operations has been done under *ad hoc* procedures worked out with the responsible aviation authorities, and formalised in an appropriate document (Notification of Exemption by CASA in Australia; Certificate of Authorization by the FAA in the US; Special Flight Operations Certificate by MoT in Canada). These have specified areas of operations (and in the US and Canada, precise transit routes from base out to sea); altitude restrictions; notifications to be given to flight service and ATC, and to other aircraft by VHF from the Aerosonde ground station; and procedures in the event that the ground station loses communication with the aircraft. A NOTAM was also issued for each field program.

Our experience with these special arrangements has been good. Regulatory and ATC staff have been conscientious and flexible, and the agreed procedures have allowed us to operate safely and to accomplish the objectives of the trials. However we look forward to removal of some restrictions - for example, restriction to special-use WA and CYR airspace off the west coast of North America - and to standardisation. We will discuss associated issues presently.

Mission characteristics in routine service

We envision that, in routine weather reconnaissance over the oceans, Aerosondes would fly about 10^6 flight-hours per year worldwide. The annual cost would be several tens of millions of dollars, which is fiscally realistic compared with current weather-balloon spending of about $100m, and would provide resolution over the oceans comparable with that currently obtained over land. At a loss rate of, say, one aircraft every ten missions, there would be about 100 Aerosondes flying weather reconnaissance at any given time. Likely characteristics of these missions are as follows.

- **supervisory control from a remote station via a low-rate data link**
  In routine oceanic operations, the current line-of-sight link for enroute control (Figure 3) would be replaced by a low-rate satellite link, *e.g. Iridium*. Data would be routed by telephone from satellite gateways to a central station, which would be responsible for supervisory control of many aircraft simultaneously. This station would link position and other data to air-traffic services, and weather data to users. Data would be in the form of brief messages sent a few times per hour, or otherwise when triggered by events on the aircraft or by the need for a command from the ground.

- **round-robin basing**
  Aerosondes are slow, with a cruise speed of 40 kt or so, and consequently can cover much more ground when routed downwind than otherwise. Consider for example reconnaissance in the NE Pacific, which is of considerable interest to the US National Weather Service. Aircraft flying out-and-return from the west coast would usually face strong headwinds on the outbound leg, and so be relatively limited in operating radius. A more attractive possibility would be to circulate aircraft among bases on the west coast, Hawaii, and the Aleutians. Typical winds are such that the whole NE Pacific would usually be within reach of aircraft flying this circuit; out-and-return and reverse-circulation missions would only be used infrequently.

- **automatically-generated diverse routings**
  Areas of most interest to forecasters vary from day to day. Contemporary forecast models can calculate the sensitivity of a forecast to data from any given area, and Aerosonde routes would be varied from day to day to maximise the value of data return. We envision that these routes would be planned automatically (on the ground), using optimisation algorithms accounting for forecast sensitivities, aircraft performance, icing, and air-traffic constraints.

- **altitude cycling**
  To afford a significant forecast benefit, Aerosondes would have to collect data through the atmospheric column rather than at a single level. Hence flight profiles would often

involve continuous cycling from minimum altitude (say 200 ft to stay clear of ship masts, icebergs, *etc.*) to 20,000 ft or so, and in some applications to more than 40,000 ft. These cycles would be constrained by air traffic and icing.

- **autonomous re-routing (within specified bounds)**
  Aircraft would have some limited ability autonomously to adjust routes, for example upon encountering icing or a strong headwind. In the case of icing, the re-routing would entail some combination of a backtrack and altitude change before proceeding en route.

  Another routing problem of great interest to some weather services is tropical-cyclone reconnaissance. Aircraft flying cyclone reconnaissance would be programmed to keep station relative to the storm using their onboard wind measurements. Stationkeeping might be done in the eye or while orbiting the storm at some radius.

- **the "Aerosonde rain"**
  We noted earlier that high attrition would be expected in routine service, that is, most aircraft would be lost at sea after a few missions (mainly due to icing, we suppose). One would have to ensure that the associated hazard to ships, *etc.*, would be acceptably small. It turns out (McGeer 1994) that, with a "rain" of 1000 Aerosondes per year, the collision rate with ships in the open sea would be about one every 200 years or so. This seems acceptably small relative to other oceangoing hazards.

New regulatory issues involving unmanned aircraft

The concept of acceptably small risk is, in our view, a point of departure for regulatory policy. Our familiar regulation of manned aircraft is designed essentially to achieve an acceptable level of risk to people and property

- onboard the aircraft;
- in other aircraft;
- on the surface.

The majority of existing regulation addresses the safety of people onboard, and in taking care of them it pretty much takes care of those on the surface as well. But with autonomous aircraft the onboard problem vanishes, and consequently a lot more diversity is possible than with manned aircraft. That is, with a manned aircraft you have to build to the same standard no matter what is underneath you, but among unmanned aircraft, acceptable safety for flights exclusively over oceans can be achieved with rather more rickety machines than would be fit to fly over a city. Hence the abundance of possibilities which everyone recognises and is struggling to manage.

Diversity calls into question the conventional approach of mandating specific design techniques, load cases, redundancy levels, equipment, and so forth. An alternative might be to specify instead acceptable *levels of risk*, and being receptive to diverse solutions for achieving those levels. The authorities in Canada[1] and Australia[2] have circulated preliminary ideas consistent with this concept. Over the next few months, we contemplate developing a thorough risk analysis for Aerosondes to serve as a test case and model. This analysis would aim to define limits on density of aircraft and surface "targets", below which operations could be conducted with acceptable safety.

Elementary midair collision risk and mitigation

We have mentioned a surface-hazard result from an elementary risk analysis. We can also add some elementary midair collision results (McGeer 1994). It turns out that if Aerosondes were distributed through some region at the density of radiosonde balloons now flying over the continental US - and distributed *at random*, that is, with absolutely no effort at separation - then from the point of view of a transiting aircraft the collision probability would be (as it is now for radiosondes) about 10^{-8} per flight-hour. Meanwhile for transport-category aircraft a catastrophic-failure probability worse than 10^{-9} per flight-hour is generally considered unsatisfactory, so
10^{-8}/flight-hour collision risk is too high - but only by an order of magnitude. The necessary order-of-magnitude improvement - plus several orders of magnitude more - can readily be achieved by making the Aerosonde distribution non-random.

The basis for effective separation is precise knowledge of aircraft position, which is continuously determined onboard by GPS. At present it is also reported continuously to the ground station. Reporting will be reduced to several short messages per hour on long-range missions with satellite relay (*cf.* Figure 3), but then the ground-station software will run an estimator during the intervals between messages. Flexibility of operation will depend upon how effectively the position information is applied. We foresee application in three levels:

- **Avoidance of busy airspace**

Aerosondes are primarily required over oceanic and remote areas, where low-altitude traffic is essentially nil, and high-altitude traffic operates on well-defined IFR routes. These routes can be avoided reliably, without undue complication or restriction in flight planning. Operations near coastal bases are likely to be more constrained, but, as in our work to date, bases can be sited where activity is light and transit corridors easily arranged.

- **Data communication with ATC**

A real-time data link for position reports and traffic advisories can be established between the Aerosonde ground station and the ATC computer network. Aerosondes could then be controlled much like manned aircraft, and separation reliably maintained in areas wherever ATC tracks the large majority of traffic.

- **Independent surveillance**

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[1] Minutes of Non-Piloted Aircraft meeting chaired by Arlo Speer, Chief, Recreational Aviation & Special Flight Operations, Transport Canada, Ottawa, 22 May 1998.

[2] *Guidance for unmanned aerial vehicle (UAV) operations, design specification, maintenance and training of human resources.* Civil Aviation Safety Authority draft, September 1998.

The definitive technical solution will be active collision avoidance independent of ground control. A Swedish system has demonstrated mutual avoidance based on local broadcasting of GPS position (Nilsson 1992), and the technical and economic strengths of such an approach make a compelling case for universal adoption. (The cost might be a few hundred dollars per aircraft, and arguably it would be economical for government, or industry, to pay for installation on every aircraft flying rather than to spend large sums on developing an alternative system.) In any case such a system will not be operational before the next century, but once in place it should allow operations almost everywhere.

Safety benefits from wide-scale use

In weighing an acceptable level of risk for Aerosonde operations, one must also consider the risk of *not* doing operations. In particular, we are now suffering a safety penalty - not least in aviation, but also in many other fields - through lack of offshore data for weather forecasting. Thus if, for example, it was proposed to exclude Aerosondes from some oceanic airspace due to some potential for traffic conflict, the risk of conflict would have to be compared with the risk associated with loss of forecast data from that region. Similarly, if a regulatory proposal were made with implications for higher costs (and hence reduced operations) then again it would be necessary to compare the effects on collision risk and forecast quality. We look forward to discussion of how to draw these lines as the policy process proceeds.

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