NEW AIRCRAFT PLATFORMS FOR EARTH SYSTEM SCIENCE: AN OPPORTUNITY FOR THE 1990s

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Abstract

The 1986 discovery of a massive ozone hole over Antarctica has focussed international scientific, political, and popular attention on the chemistry and dynamics of the middle atmosphere. During the 1990's the need for *in situ* data on this region will grow dramatically, in order to both complement and supplement various space- and ground-based observations. Recent advances in low Reynolds number aerodynamics, lightweight composite structures, microelectronics, and energy conversion systems offer the possibility of a new class of unmanned aircraft well suited to this purpose. This paper reviews some of the fundamental limits applicable to any very high-altitude subsonic design, and then reviews three projects under way at Aurora Flight Sciences. The first, designated Perseus, is an Antarctic ozone probe designed to carry 50 kg payloads to altitudes of approximately 25 km and return them for reuse during the austral spring of 1992. Theseus, the second program, is a larger platform designed to carry payloads of up to 250 kg at ranges greater than 20,000 km and to altitudes of up to 35 km. Odysseus is a solar-powered aircraft designed to carry 100 kg class payloads at altitudes of approximately 20 km for very long durations, measured in months or years. These platforms share not only a common technology base, but also a design philosophy that stresses scientific utility and reduced organizational and operational scale as the primary design drivers.

Background

The last decade of the twentieth century will be a unique, perhaps pivotal, time in terms of man's influence on the future of this planet's environment. Human activities under way for several decades have begun to produce a measurable impact on the global environment, and the very large inertias of the systems involved insure that this impact will continue (and probably accelerate) for many decades to come. Yet we have only begun to understand the processes that drive this change, and predictive capability is still beyond our grasp. Selecting the appropriate corrective actions, and assembling the political consensus that will be required to implement them, depends strongly on scientific understandings that are still in an embryonic state. We have perhaps ten years to understand the forces at work and to take corrective action.

Global environmental change is unique for the many areas of science and technology that it encompasses. The current emphasis in the nation's earth system science program is on remote sensing from space. To date, *in situ* observations at high altitudes have been provided primarily by the ER-2, a manned aircraft derived from the famous U-2 reconnaissance aircraft, and from balloons. The great utility of the ER-2 in recent research, particularly the 1987 Airborne Antarctic Ozone Experiment[1] and its 1988 sequel in the Arctic have led to interest in additional platforms that could extend ER-2-class capabilities to higher altitudes.[2] NASA-Ames and NASA-Dryden, in conjunction with the Lockheed Corporation (manufacturer and contract operator of the ER-2) have proposed the High Altitude Atmospheric Research Platform (HAARP) for this role.

The purpose of this paper is to propose an alternative strategy. Rather than purchasing a single, multi-function, manned aircraft, I will argue that it would be better to invest in a three-element program consisting of: 1) a new generation of miniaturized instruments; 2) a family of smaller, unmanned aircraft, each using appropriately advanced technology adapted to a specific mission; and 3) a set of coordinated, multidisciplinary experiments aimed at entraining and nurturing a new generation of researchers. These elements could be combined, for far less than the cost of developing a single new manned aircraft, in such a way as to significantly advance our understanding of global climate change while at the same time laying a firm foundation for atmospheric research in the next century.

Scientific Needs

Any rational examination of future platform and instrument needs must begin with a thorough understanding of the scientific issues which must be addressed. Together with Prof. James G. Anderson of Harvard University, the author has been engaged in a year-long survey of atmospheric science missions. To date ten key issues have been identified which could benefit from improved *in situ* sampling techniques.[3] These include:

- Atmospheric radiation measurements for prediction of global warming
- Polar ozone depletion
- Global sources and sinks of CO_2 and CH_4
- Stratosphere/troposphere exchange
- Heterogeneous and gas phase photochemistry of the tropical tropopause and lower stratosphere
- Hurricane research and forecasting
- Impact of high altitude supersonic aircraft flights on the stratosphere
- Tropical meteorology
- Operational meteorology
- Ground truth for UARS and EOS

Although a full discussion of these missions, their trajectory requirements, and candidate payloads is too lengthy to pursue here,[4] several conclusions emerge:

- The next ten years will require an increase of one to two orders of magnitude of *in situ* flight time to fully address these scientific problems.
- Existing systems such as satellites, ground-based remote sensors, balloons, and current aircraft cannot provide the scope of measurements needed.

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- No single platform is likely ever to satisfy all the demands. Some experiments require samples to 35 or even 40 km, while others require long durations at or near the tropopause (15-18 km), while still others require extended flights only a few meters above the sea's surface.
- There are important institutional questions that must be addressed in order to provide responsiveness and flexibility.

The conclusion that existing platforms are inadequate is sufficiently important that the next section will explore it in more detail. The next two sections take a fundamental look at some constraints and some technological opportunities that apply to any high-altitude platform that relies on dynamic lift.

Current Platforms and Their Limits

Balloons. The primary method for carrying large scientific payloads (1000 kg and greater) to extreme altitudes (up to 40 km) are large scientific balloons. For missions requiring large payloads and extreme altitudes, balloons will remain the only viable launch platform for the foreseeable future. Balloons suffer a number of operational problems, however, including:

- they provide very little control over the time and place at which measurements are taken. Once launched, balloons follow prevailing winds.
- they are difficult to launch, since they require calm conditions. The requirement to wait for suitable launch conditions is a major driver of the cost and duration of many balloon campaigns.
- Since they are free-flying, balloons are a serious safety hazard to both air traffic and to persons and property on the ground. Balloons are tracked within the national airspace system, but other traffic must be steered around them. Balloon payloads descend under parachutes, and to date have avoided a serious ground incidents on landing, but concern over potential liability is one of the factors that have curtailed major balloon flights from over 100 flights per year a decade ago to a few dozen flights per year now.
- Although the balloons themselves are relatively inexpensive (ranging from a few tens of thousands of dollars to something over $100,000 for the largest), they are not recoverable. Although the payloads are recoverable, and the recovery rate in the U.S. is very high, payloads are sometimes damaged during landing. Recovery rates in areas such as Antarctica are significantly lower. Since payloads are frequently very expensive, this is a major limitation on multiple-flight balloon campaigns.

Satellites. In the atmospheric sciences, the primary U.S. development program is the Upper Atmosphere Research Satellite (UARS), an $800 million vehicle targeted for launch in the fall of 1991. UARS will be capable of measuring temperature, pressure, winds, and most (but not all) significant chemical constituents during its 32 month mission. A follow-on system, the Earth Observing System (EOS) is proposed for deployment late in the 1990s.

Space-based measurements are complemented by an array of increasingly sophisticated ground-based tools, primarily laser radars (LIDARs). Nonetheless, *in situ* measurements will remain important because: 1) "ground truth" measurements are needed for remote sensor calibration and verification, 2) greater temporal or spatial resolution is needed than the remote sensors can provide, and 3) some key components such as the hydroxyl radicals cannot be measured remotely. Thus, rather than replacing *in situ* measurements, programs like UARS and EOS will significantly *increase* the need for them.

The ER-2. The primary high-altitude research aircraft in the U.S. inventory is the ER-2, a derivative of the Lockheed TR-1/U-2R. With its large payload (1179 kg, 2600 lbs) and high altitude capability, the ER-2 is the mainstay of the NASA High Altitude Missions Branch and has proved its value in many roles and many missions. Nonetheless, the ER-2 has a number of limitations which are important to the discussion here:

- its altitude is limited to 20-22 km. This is not sufficient for many of the experiments that must be undertaken.
- duration is limited to about 8 hours.
- as a manned platform with a single engine, the flight regime is limited in the interest of safety. NASA does not allow its aircraft to fly further than gliding range from an available landing strip, does not allow night flying, limits cross winds to approximately 15 knots, and limits durations to approximately 8 hours.
- the aircraft is very expensive to operate. Through the Lockheed operating contract, the government pays approximately $8500 per flight hour. Since this excludes depreciation and the NASA share of costs, this number significantly understates the true cost of operating the ER-2.

The Boeing Condor. Boeing has developed a tested the Condor, a large unmanned aircraft, which many have suggested would be applicable to high altitude scientific research.[5] Condor has a wing area of about 100m^2 (1100 ft^2) and a wingspan of just over 60m (200 ft). Although its precise performance remains classified, it appears that Condor can carry a payload approaching 1000 kg to altitudes of about 20 km and sustain durations of several days. Although Condor appears to be well suited for some of the long-duration missions of interest here, it too has some important limitations:

- At the present time, there is one flyable vehicle. This is apparently controlled by DARPA, which at the time of this writing had made no decisions requiring future utilization of the aircraft.
- Future platforms are likely to be expensive. Numbers between $100-$320m have been reported as the development costs, and figures of $20m per copy (in large quantities) have been reported.[6]
- Condor apparently cannot reach altitudes greater than approximately 21 km in its present configuration. With three stages of turbocharging (not a simple or inexpensive proposition) it could conceivably achieve altitudes of 27 km (90,000').

Thus it appears that at the present time there are no platforms in the existing inventory that can meet the needs of an expanded atmospheric science program. Before turning to what such platforms might look like, it is appropriate to review some first principles that will govern any very-high altitude subsonic platform that relies on dynamic lift.

Fundamental Constraints of High-altitude Subsonic Flight

The fundamental constraint on dynamic flight at high altitudes is the rapid drop in air density in the stratosphere. This limits both the lifting capability of a wing and the propulsive capability of air-breathing combustion engines. For steady-state flight, the lift produced (L) must equal the vehicle weight (W). Lift is a product of air density (ρ), velocity (V), lift coefficient (C_L) and wing area (S):

$$L \approx W \approx 1/2\, \rho\, V^2\, C_L\, S$$

With ρ defined by altitude, V constrained by the need to remain subsonic (in order to avoid passing the chemical constituents through a shock wave before sampling), and C_L constrained to values of about 1.5 (to obtain good lift-to-drag properties)[7], weight becomes the primary determinant of aircraft size. Weight and size together are the primary determinants of cost. The ratio of weight to size (known as wing loading) is the primary determinant of the aircraft's overall robustness:

$$W/S = 1/2 \rho V^2 C_L$$

Typical transports such as the 747 have wing loadings exceeding 7000 N/m^2 (150 lbs/ft^2); that of the ER-2 or the Boeing Condor are about 1000-2000 N/m^2 (roughly 20-40 lbs/ft^2). As shown in Figure 1, the combination of low density and low speed means that any very high-altitude scientific aircraft will have *very* low wing loadings; at 40 km, the wing loading cannot exceed about 100 N/m^2, or roughly 2 lbs/ft^2 -- more within the range of a human-powered aircraft than any other operational vehicle.

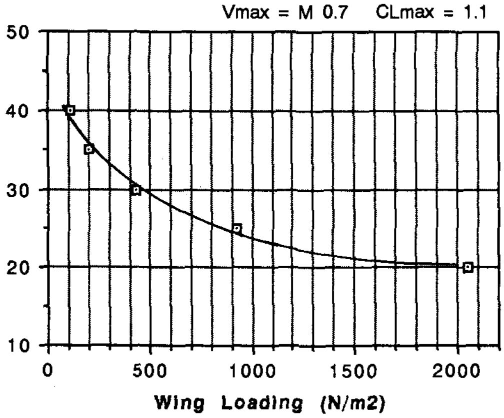

Figure 1. Maximum allowable wing loading as a function of altitude for different Mach limits. The actual speed allowable depends on propeller and airfoil performance. A lift coefficient of 1.1 is assumed for this plot. (1 lb/ft^2 $\approx$ 50 N/m^2)

For a given payload weight, the aircraft's size is determined by its wing loading and its payload fraction (that is, ratio of payload weight to gross weight). Achievable payload fractions depend on many things (among them mission requirements, level of structural technology, desired safety factors, etc) but in general it is extremely difficult to achieve payload fractions greater than about 30% in any practical aircraft. The ER-2 has a payload fraction of about 6.5% at takeoff and about 15% at landing. Figure 2 shows the required aircraft size as a function of payload weight assuming a 15% payload fraction. If the achievable payload fraction is lower, these areas will increase proportionally. For comparison, the wing area of the ER-2 is about 93 m^2 (1000 ft^2), that of the 747 is about 510m^2 (5500 ft^2). Carrying an ER-2 payload to 40 km will require an aircraft larger than a 747 but only 1/70th the weight.

From this simple analysis it is clear that building subsonic, very-high altitude aircraft will place a premium on reducing payload weight, particularly of the payload. There are two immediate implications of this conclusion. The first is that very-high altitude platforms should probably be unmanned. A human pilot adds at least 300 pounds to any design, which is (or should be) a significant fraction of the payloads at issue here. Further, a manned aircraft requires higher levels of safety and redundancy than an unmanned aircraft, with consequent increases in cost, complexity, and weight. The recent experiences of Voyager spacecraft, of the Soviet *Buran* shuttle, and the underwater robots *Jason* and *Nemo* provide ample testimony that unmanned platforms are capable of achieving missions that would be far more costly, or even impossible, to achieve with manned platforms.

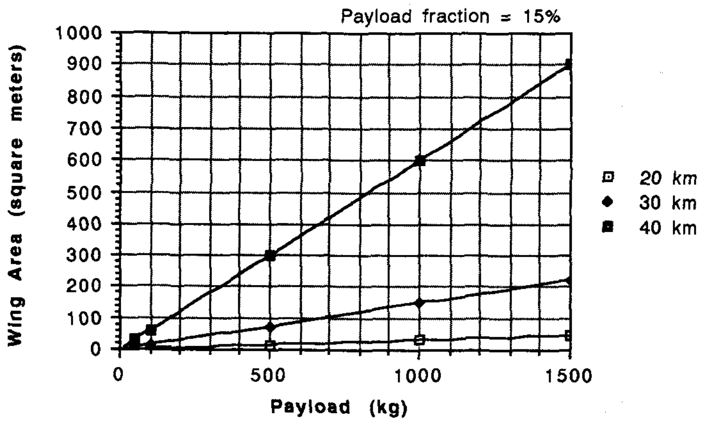

Figure 2. Required wing area for sustained flight as a function of payload weight, assuming a payload weight fraction of 15% -- a reasonable value for a short duration mission, but quite optimistic for a long duration one.

The second conclusion is that a significant fraction of the available resources should be devoted to minimizing the payload weight. Thus while it may be tempting to initially specify that any future aircraft be able to carry the same instruments as the ER-2, this may in fact be a far from optimal approach. A detailed study is required to determine the appropriate division between resources devoted to the platform and those devoted towards miniaturizing the payload. Some indication of the magnitude of weight reduction possible can be found in Harvard University's experience developing payloads for stratospheric measurement of chlorine monoxide and bromine monoxide. The first instruments, developed for balloon launches in the late 1970s, weighed over 2000 pounds. A second generation version, flown aboard the ER-2, weighs about 400 pounds. A third generation version, now under development for the Perseus unmanned aircraft (described below) will weigh only 50 kg (110 lb), including an ozone measuring instrument and self-contained data logging and power supplies. This capability has not been obtained with spacecraft-level expenditures: each generation has cost around $500,000 to develop. Our experience visiting various research laboratories have convinced us that similar dramatic reductions are possible in most other instrument systems.

New Technological Opportunities

There are, of course, many technical complications to building a very-high altitude science aircraft besides reducing payload size. In the past decade, however, three trends have occurred which can be combined to have a major impact on the design of future vehicles:

1) Major technical advances have occurred in low-speed aerodynamics and lightweight structures, as illustrated by the successes of Daedalus and Voyager. The advent of computational fluid dynamics has made possible a new realm of low-speed aerodynamics not dependent on expensive facilities such as wind tunnels. Similarly, composite materials have made high-strength and high-stiffness structures possible and practical. Both of these technologies have relatively low barriers to entry and thus are available to small enterprises. The Daedalus Project, for example, recently tripled the world record for flight under human power with a 116 km (72 mile) flight between Crete and Santorini in April 1988. The December, 1986 flight of the Voyager doubled the distance record for flight with an internal combustion engine. Both these aircraft used composite materials and computer-based aerodynamics, and both were built by small teams without government sponsorship for approximately $1 million. The Reynolds number regime in which Daedalus operated is surprisingly similar to that in which the high-altitude aircraft proposed herein must operate, allowing direct transfer of experience and technology.

2. Energy conversion technologies such as batteries, solar cells and fuel cells continue to mature. During the 1960s the space program fostered the development of new energy technologies such as solar cells (which convert sunlight into electricity) and fuel cells (which electrochemically combine fuel and oxidizer such as hydrogen and oxygen to produce electricity). During the 1970s these systems were further developed for terrestrial use as a response to the 1973 oil embargo. Continued steady progress has been made throughout the 1980s, and during the 1990s many of these technologies will reach commercial status. Thin-film solar cells made from amorphous silicon or epitaxially grown gallium arsenide offer sufficiently high power-to-weight ratios that propulsion of lightweight airframes is now a possibility. Fuel cells have reached the point where they, too, may be considered either as primary propulsion for aircraft or as extremely efficient batteries, to store energy for nighttime operations of solar-powered aircraft. This will continue to be an area of rapid progress in the coming decade, and will make the concepts proposed here, already plausible with current technology, even more attractive.

3. Lightweight, low power electronics allow "intelligent" or autonomous operation. The same revolution that personal computers brought to computing during the 1980's is being brought to control systems in the 1990s. Computer systems have already replaced flight engineers in new commercial aircraft, while in advanced military aircraft, the human pilot is already the limiting factor in terms of survivability, maneuverability, and endurance. Remotely piloted vehicles, where the pilot in the cockpit is replaced by a pilot on the ground, have been under development for many years and are now in production and operation on a limited scale. Autonomous aircraft have already been demonstrated. Several space-based systems are already available for data relay to and from remote platforms, and more are in development. The possibility exists for "satellite-type" operations, where a central ground facility monitors aircraft operation and gives overall guidance but leaves specific local decisions to on-board systems. Another opportunity is to reduce the operational complexity of short-duration platforms. Scientific platforms could be operated by the research teams actually performing the experiment, rather than dedicated vehicle teams.

Examples of New Platforms

I turn now to illustrating the range of new alternatives that are potentially available.

Perseus. In an effort to place the philosophies espoused above into practice, Harvard University and Aurora Flight Sciences are jointly developing a system called Perseus to measure ozone, chlorine monoxide, and bromine monoxide with high temporal and spatial control at altitudes up to 25 km. The initial Perseus has a gross weight of approximately 300 kg of which 50 kg is instruments. To minimize development costs, Perseus uses an electric propulsion system based on a 20 kW brushless motor and 32 kW-hr of lithium thionyl chloride reserve batteries. With a wingspan of 17 m and a wing area of 16m^2, two Perseus vehicles can be shipped in a single commercial M-2 container, and three Perseus vehicles plus all ground control facilities can be transported in a single C-130. The first planned use of Perseus is in a campaign from McMurdo Station, Antarctica in the austral spring of 1992. Because of the time urgency in its development and the need for absolute minimum cost, initial development of Perseus was undertaken using funds secured from the private sector.

Though Perseus will be a flexible platform in its baseline configuration, even greater potential is offered by derivative versions. One version under study will use a small internal combustion engine with two stages of turbocharging. With a reinforced structure, this Perseus "B" could carry payloads as large as 150 kg at altitudes up to 18 km. Durations of over 100 hours would be possible at slightly lower altitudes. Another version of Perseus could be equipped with a solid polymer electrolyte fuel cell operating on liquid hydrogen fuel. This has the potential to double durations achieved by an internal combustion version.

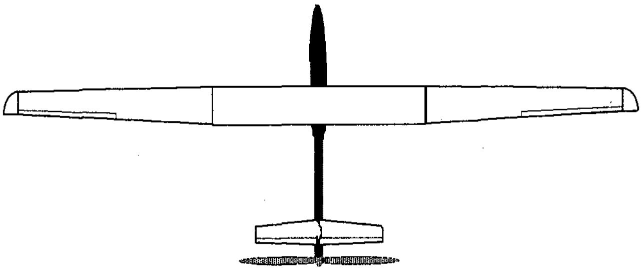

Figure 3. The Perseus Antarctic ozone probe, presently under development by the Aurora Flight Sciences Corporation of Alexandria, Virginia.

Theseus. Many missions require higher performance than achievable by the low-cost Perseus. Studies conducted by Aurora for the National Science Foundation (NSF) indicate a need for a platform with an instrument capacity of about 250 kg (550 lbs), for which we propose a larger, more versatile aircraft known as Theseus. As currently envisioned, Theseus would have a gross weight of about 1800 kg (3900 lbs), a wing area of 106 m^2 (1141 ft^2), and a span of 56 m (185 ft). It would be able to cruise 19,500 km (10,500 nm) at 25 km, with a derivative version capable of making multiple pop-ups to 35 km. Theseus would be powered by a proprietary fuel-cell based system known as Arion. The platform would be designed for transportation in a single C-130 aircraft, with subsequent field assembly and operation with a team of less than a dozen people. We believe that Theseus could be operational within three years at a cost of about $25 million, and that subsequent vehicles would cost about $5 million each with direct operating costs of about $2000/flight-hour (excluding depreciation).

Odysseus. Some of the scientific issues at hand, such as the measurement of radiation fluxes in the stratosphere, require measurements accumulated over very long periods of time -- months or even years. Using thin-film solar cells made of amorphous silicon and technology developed from the Daedalus human-powered aircraft, we believe that a solar-powered aircraft can be built and flown within 3 years. The specific power of current energy storage systems (needed if such an aircraft is to sustain flight throughout a nighttime period) mandates that such platforms will have extremely low wing loading, on the order of 50-100 N/m^2. Thus, practical aircraft will have limited payloads and ascent or descent through the troposphere must be planned and carefully controlled. A conceptual aircraft that can carry a 100 kg payload year-round at latitudes of up to 35° is shown in Figure 4. Such a platform has greater altitude (or payload) capability during summertime at higher latitudes, as illustrated by the performance map shown in Figure 5.

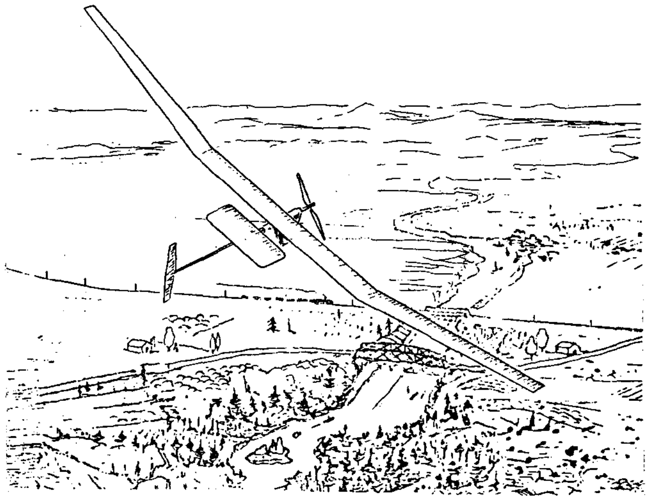

Figure 4. Conceptual view of Aurora's proposed Odysseus solar-powered aircraft.

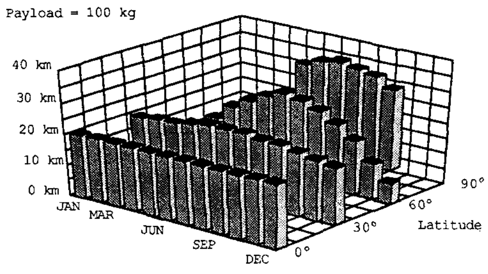

Figure 5. Performance map of the Odysseus, showing sustainable altitude with a 100 kg payload as a function of latitude and time of year.

These platforms are not proposed as separate, totally independent efforts, but rather as a family of vehicles that share common technology and are linked together on an evolutionary path. Perseus is a modest introductory step, that illustrates the power of the concepts proposed here while still providing significant science benefits. Perseus' tooling, instrumentation, and flight control system will be used in derivative versions that use more advanced power plants such as fuel cells. These propulsion systems will then be incorporated into larger vehicles -- as presently conceived, for example, Theseus will use three Perseus fuel cell powerplants. Odysseus will use one scaled-down Perseus fuel cell operating in a regenerative mode. Aerodynamic analysis codes and construction techniques will be shared throughout.

Summary

The next decade will be a critical period in terms of public policy regarding atmospheric science. At the present time the atmosphere is severely undersampled. Providing an adequate observational base to support modeling and ultimately, policy decisions and regulation will require an increase of one to two orders of magnitude of flight time, in addition to significant increases in platform performance. Providing this experimental capability within foreseeable budget constraints is a difficult challenge. A new family of lightweight, low cost unmanned platforms is proposed, along with a coordinated instrument development program and an experimental program designed to rebuild the scientific infrastructure in the atmospheric science community. Three platforms are currently under study and development at Aurora Flight Sciences. These platforms can meet many of the needs projected for the coming decade, and serve as steppingstones to future, more advanced systems.

Acknowledgements

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[7] Flight at low Reynolds numbers and high Mach numbers is a relatively unexplored aerodynamic regime, which requires additional fundamental research. Prof. Mark Drela has undertaken preliminary work in this area, which will be reported in a forthcoming Aurora report to the National Science Foundation entitled *Theseus: A New Platform for High-altitude Atmospheric Science.*