(2)

Low-Cost, Dual-Use Platforms for Environmental Sensing

A Phase I SBIR Report to the Office of Naval Research

Contract N00014-93-C-0037

Matthew G. Hutchison
John S. Langford
Charles S. Preston

Aurora Report AR-9305

Aurora Flight Sciences Corporation
10601 Observation Road
Manassas, Virginia 22111

phone: (703) 369-3633
fax: (703)369-0961

Aurora

Executive Summary

The combination of advances in microelectronics, structural materials technology and computational capability has enabled the development of a new class of aircraft, the unmanned aerial vehicle. Historically developed for and operated by the military, these aircraft are beginning to attract attention from the environmental and atmospheric-research communities because of their performance capabilities. In particular, their capacity for flights of extensive range and endurance may open up new prospects for research in the environmental sciences.

The key step in selecting missions suitable for UAV's is to identify characteristics that take special advantage of the aircraft's capabilities. In the report, we present 5 candidate missions specifically oriented to low-altitude flights in the marine environment. Though by no means an exhaustive list, this collection provides a useful basis from which desirable platform performance characteristics can be derived. Four aircraft were selected from those currently available as potential low-altitude research platforms: the General Atomic Gnat-750, the IAI/TRW Hunter, the Developmental Sciences SkyEye, and the Aurora Flight Sciences Perseus-C. Simply because the mission requirements do not conform to any currently funded military programs, only two of the above aircraft—the Gnat-750 and the Perseus-C—meet all of the performance goals.

These performance targets, though significant, are surpassed in difficulty by the requirement of low-cost operation. To estimate costs, an economic model was constructed to represent a small flight-service organization operating in one of two economic settings: as a small business or as part of a larger corporation. The results of the analysis indicate that achieving an operations-cost goal of $500 per hour is impossible for currently available platforms and actually would range from about $1,560 to over $4,000 per hour. In view of these figures, it is tempting to assume that the government could operate UAV's for research purposes more cheaply than could a private business (either large or small). Although it is quite true that a government-funded flight-service organization could charge a user whatever fee seemed appropriate (including $500 per hour), the *actual incurred costs* would, at best, be roughly equivalent to those estimated for a large corporation.

The observation that the performance requirements are not terribly demanding may allow an innovative solution for lowering the cost of operation by reducing the cost of acquisition. Rather than designing a vehicle from scratch to meet the specific demands of economical low-altitude science missions, we propose that converting an existing manned aircraft to unmanned use can accomplish the same scientific objectives at dramatically reduced cost. The ultimate promise of this approach—affordable, low-altitude scientific research—is sufficiently attractive to warrant further study. We therefore recommend that the Office of Naval Research consider funding a project in which one aircraft is converted for the purpose of technology evaluation and validation.

Table of Contents

1—Introduction

Recent advances in microelectronics, lightweight composite structures and computational fluid mechanics have made possible a new generation of semiautonomous, unmanned aircraft. Many of these unmanned aerial vehicles (UAVs) were originally conceived for purely military purposes, but the performance capabilities—in particular, the capacity for flights of extended range and endurance—have attracted the attention of the atmospheric and environmental research communities. While the application of UAVs to high-altitude research has been extensively investigated and documented, much less attention has been given to their potential role in low-altitude atmospheric studies.

This report focuses on the application of unmanned aircraft to environmental sensing at low altitudes in the marine environment. There appear to be a number of missions in which a suitable UAV platform could provide unique opportunities for data collection that would greatly expand the current understanding of this vital region of the atmosphere. In addition to scientific contributions, the information collected at low altitude would also be of significant interest to the U.S. Navy for purposes varying from calibration of weapons guidance systems to initialization of computational models.

In the next chapter, we present a collection of missions for which UAVs appear to be uniquely suited. In addition to a brief description of appropriate flight profiles, we enumerate appropriate instruments that would comprise mission payloads for each mission. Though far from an exhaustive set, these mission definitions serve their intended purpose: to identify desirable performance capabilities of a low-altitude platform.

In addition to identification of the scientific issues involved, an unexpected byproduct of a number of conversations with active researchers was the definition of acceptable operational costs. Although it is accurate to assume that UAVs are less expensive to operate than large, multi-engined research aircraft, it is somewhat surprising to find that they are unable to compete on a purely economic basis with small, single-engined aircraft. Clearly, keeping costs at a minimum is desirable, but it also appears that if costs stray much above about $500 per hour, many of the potential users of the aircraft would be unable to afford its operation, thus diminishing both its commercial and scientific value.

Using the desired performance capabilities as a guideline, in Chapter 4 we present four currently available aircraft that may be well suited for low-altitude environmental sensing. For the simple reason that the desired performance characteristics do not closely match those of any currently funded military program, the selection of appropriate platforms is limited.

In Chapter 5, we present a series of economic studies used to estimate the costs of operating the aircraft. For the investigation, we assumed that a number of UAVs would be operated by a small group of people dedicated to that purpose. Such an organization would focus on the supply of flight services and would expect an atmospheric-research customer to provide and support the appropriate instrument payload; it would cover its expenses by charging the customer on a per-flight or per-flight-hour basis. We view this organization in two different economic settings: as a small, independent business, and as part of a larger corporation. As is discussed in the chapter, each of these settings carries with it some important economic assumptions that affect the net operating cost significantly. These two scenarios establish approximate upper and lower bounds on the overall operating costs of a UAV system.

Suitable UAV platforms should not only meet the desired performance goals, but should do so at a reasonable cost. As the results of Chapter 5 suggest, the latter is the more formidable of the two requirements. An intriguing strategy for reducing flight costs calls for the adaptation of the flight-control hardware and software from a UAV to an existing manned aircraft, thereby converting it for unmanned operation. In Chapter 6, we elaborate on this concept and present the economic argument that motivates the discussion. In the final two chapters, we discuss several operational considerations facing the application of UAV's to low-altitude research and complete the report with some conclusions and recommendations for future action.

We are convinced that the concept of an unmanned aircraft operating at low altitude in support of environmental and atmospheric research has sound technical and scientific foundations. The principal obstacle facing the application of such a platform is not a performance requirement *per se*, but rather the expense of operating this class of aircraft. It may be that converting a manned aircraft to unmanned use will significantly reduce the expense of operation in comparison to currently available platforms. Such a cost reduction would be an important first step in allowing broad use of such a platform within the research community.

2—Measurements, Missions and Payloads

In this chapter, we review a number of measurements that could, potentially, be taken with an unmanned aircraft. We have included a brief description of the mission profiles associated with the measurements of interest, as well as the instruments that would make up suitable payloads. As we discuss in the next section, we envision that some common instruments would be included in every payload for basic meteorological data collection.

One of the goals for this study has been to identify measurement goals that are *best* met with a UAV—not merely those that *can* be met. We believe that four characteristics of some currently available UAV's make them attractive for low-altitude scientific missions: they are less expensive to operate than most large multi-engine research aircraft, at low altitudes they can be flown quite slowly (thereby increasing the resolution of the collected data), they can fly for extended periods of time, and they can fly at very low altitudes without risking a human pilot.

Common Instruments and Equipment for Mission Payloads

As we discuss in the following sections, individual measurements of interest require specific instrumentation suitable for that particular task. There are, however, a few instruments and equipment items that would be included in almost any mission's payload. Thus, one strategy for defining mission payloads (and the one we assume in the following discussion) uses a base collection of equipment and then incorporates special, mission-specific items as appropriate.

Table 2–1. Candidate instruments and equipment common to all mission payloads

Instrument/Equipment	Mass (*kg*)
AIR-FT-1A-T air temperature sensor	1
AIR-DB-3C air pressure sensor	1
AIR Dew-Point Hygrometer	5
(2) Eppley pyradiometers	4
MC68020-based VME-bus payload-control computer	10
Digital 8 *mm* tape data logger	4
Total	25

Nearly all measurement payloads would include instrumentation for measuring three basic meteorological quantities: atmospheric pressure, temperature and relative humidity. To this basic list, one might add the capability for broadband radiation measurement, largely because the pyradiometers required for the task are relatively inexpensive, compact and lightweight. A useful payload must incorporate some form of data-logging equipment and would nearly always require some form of payload-control computer. Table 2–1 summarizes the equipment we use to represent these basic functions.

Turbulence Measurements in the Marine Boundary Layer

Turbulence in the marine boundary layer (MABL) controls the mixing of a number of important physical including heat, moisture, momentum, and airborne aerosols. Physically, turbulent mixing accounts for several orders of magnitude more than that attributed to diffusion processes and thus is the primary mechanism of exchange between the ocean and the atmosphere. Turbulent processes are particularly important in the first 20-50 *m* above the surface, and at the top (or *inversion*) of the boundary layer.

Mission Profile. A typical mission profile suited for MABL turbulence measurements is illustrated in Figure 2–1. As shown, the flight profile consists of a repeating L-shaped pattern with legs ranging from 10 to 50 *km* in length. For a given mission, each L-shaped pattern would be flown at a constant altitude with measurements taken at a number of different altitudes over the course of a mission. To obtain statistically meaningful data, the mission would last as much as 24 hours and, ideally, the aircraft would adjust its flight path such that the pattern would be advected with the local wind.

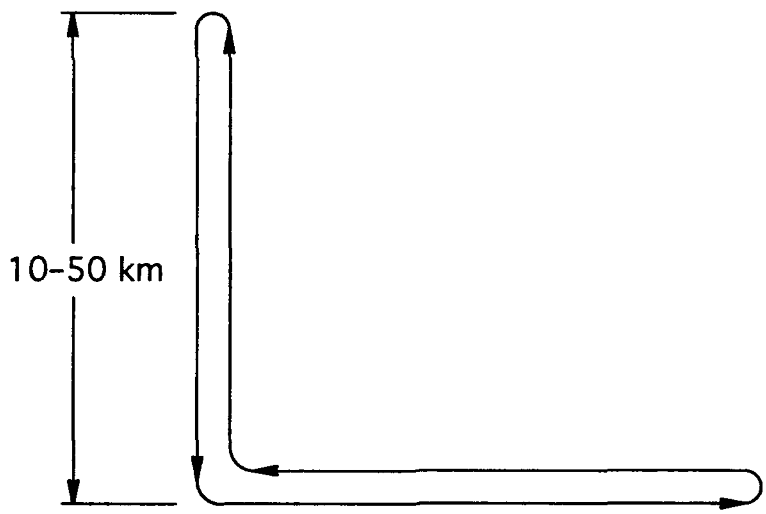

Figure 2–1. Mission profile for MABL turbulence measurements. Each leg of the mission would be flown repeatedly at a number of different altitudes.

Using a typical flight speed of 30 *m/s* for a UAV at low altitude, a turbulence-measurement mission could conceivably repeat the flight pattern 35 to 40 times (for 30 *km* legs) if the vehicle was capable of 24-hour on-station endurance.

Payload. The payload for this type of mission would feature an instrument suitable for measuring the motion of the air in which the aircraft travels. The National Center for Atmospheric Research (NCAR) has developed an instrument that measures atmospheric wind (and turbulence) by comparing—in a vector sense—the aircraft's inertial velocity with the aircraft's movement relative to the air. Inertial velocity is sensed with a combined inertial-navigation/GPS system, while the relative wind is measured with differential-pressure sensors used in conjunction with a five-hole wind probe. The instruments are listed in Table 2-2.

Table 2–2. Candidate instruments and equipment for a payload designed for turbulence measurements.

Instrument	Mass (*kg*)
NCAR air-motion sensor	40
Basic instrument/equipment suite	25
Total	65

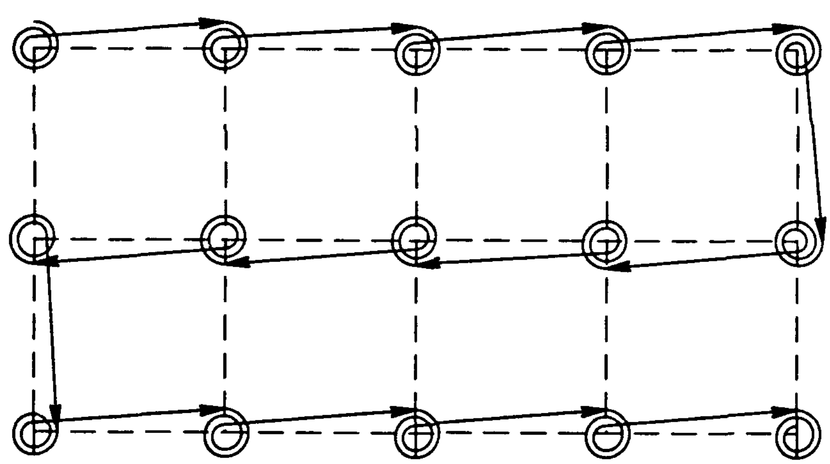

Figure 2–2. Mission profile for collecting air temperature and humidity profiles with altitude. At each grid point, the aircraft would spiral up (or down, as appropriate) from sea level to an altitude of about 1,000 *m*.

Low-Altitude Temperature and Humidity Gradients

The gradients of atmospheric temperature and humidity at low altitudes significantly affect the propagation of electromagnetic radiation, both in and out of the visible range. Typically, the computational models currently used for estimating these effects are based upon very limited data sets. The Navy has expressed interest in demonstrating an eventual tactical capability in which a UAV would be flown to initialize such computational models for use in weapons guidance-and-control systems. From a scientific perspective, long-duration flights over areas of interest would contribute significantly to this aspect of the limited existing knowledge of the marine atmosphere.

Typical Mission Profile. One likely mission profile for examining these effects is illustrated in Figure 2–2. As shown, a grid would overlay the area of interest and the measurement aircraft would travel from grid point to grid point. At each point, the aircraft would spiral up (or down, as appropriate) from near sea level up to approximately 1,000 *m* of altitude. Along each vertical traverse, the aircraft would collect temperature and humidity data.

As with the turbulence-measurement mission, the diurnal time scales are of significant interest and, thus, the platform's on-station endurance capability should be about 24 hours. To avoid excessive time spent during the spiral climbs, the aircraft's climb rate should be reasonable; for example, if the aircraft were capable of climbing at least 2.5 *m/s* (about 500 *ft/min*), it would take less than 7 minutes to reach 1,000 *m*.

Payload. There are no instruments required for this mission beyond those included in the basic payload; see Table 2–1.

Water Color, Temperature and Salinity for Monitoring Estuaries

Remote sensing offers a unique opportunity to observe and monitor entire estuaries synoptically and compare them to other estuaries. Due to the tidal influences and small features which need to be detected, estuaries place demanding temporal and spatial resolution requirements on sensing systems as resolution requirements on sensing systems as compared to open ocean or land applications (Ref. 1). Recent developments in instrumentation technology have allowed the integration of a relatively small payload package suitable for use on a small aircraft. This package would be capable of remotely measuring water color in several spectral bands, surface temperature, and water salinity.

Table 2–3. Candidate instruments and equipment for a payload designed for monitoring estuaries.

Instrument	Mass (*kg*)
Xybion MSC-02 multispectral video camera (and associated equipment)	10
Barnes PRT-5 radiation thermometer	13
Quadrant Engineering scanning low-frequency microwave radiometer	100
Basic instrument/equipment suite	25
Total	148

Typical Mission Profile. The principle advantage of a UAV for this application is that it would allow continuous observation of coastal areas for an entire tidal cycle (the principal time scale of interest), we assume roughly 12 hour endurance.

The altitude at which such a mission would be flown depends primarily upon the desired filed of view from the onboard instrumentation, but would probably vary from about 100 to 1,500 *m*. The track flown by the aircraft would be defined by the coastal area of interest and would not vary with time.

Payload. As mentioned above, a payload suitable for this application would measure water color, temperature and salinity; the instruments are listed in Table 2-3.

In-Situ Ocean Measurements using Deployable Microbouys

Aurora Flight Sciences has teamed with Neptune Sciences, Inc. to investigate the feasibility of lightweight, expendable microbouys for oceanographic research. The capability to collect *in-situ* oceanographic data with such buoys would complement other types of measurements including satellite remote sensing, use of moored or drifting instrumentation, and ship surveys. The concept would utilize the Global Positioning Satellite (GPS) System to determine buoy position and would relay data via the ORBCOMM satellite system; Figure 2–3 illustrates the system architecture.

Typical Mission Profile. As shown below, a 95 *kg* payload would be expected to contain about 50 microbouys. The frequency at which the buoys would be dropped would vary with mission objectives, but might be expected to occur at 25 *km* intervals. This assumption implies a 1,250 *km* mission radius, or a total range of about 2,500 *km*.

Payload. The anticipated mass of a buoy-deployment payload is summarized in Table 2–4.

Table 2–4. Candidate instruments and equipment for a microbuoy-deployment payload.

Instruments and Equipment	Mass (*kg*)
(50) Neptune Sciences deployable microbouys	60
Dispensing mechanism	20
Basic instrument/equipment suite	25
Total	95

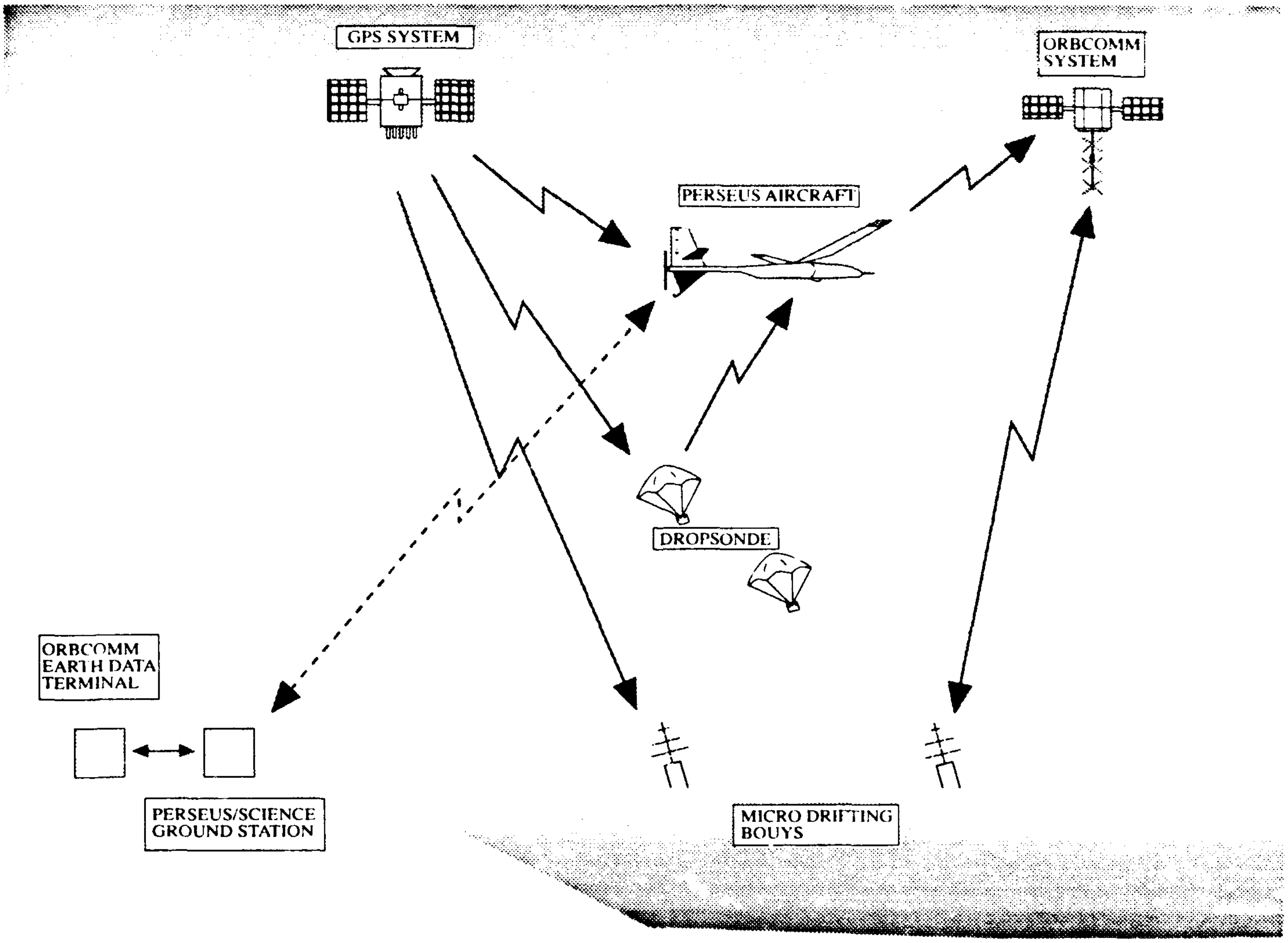

Figure 2–3. Proposed system architecture for deployable microbouys. The buoys would be deployed by an unmanned aircraft (the Aurora Perseus is shown) and would relay data via satellite.

Properties of Aerosols

As noted in Ref. 2, the scattering of electromagnetic radiation by aerosols is important not only in terms of visibility and signal propagation, but also in terms of global energy balance and climate. It has been shown that the direct radiation effect of aerosols could be of the same order of magnitude as the so-called greenhouse effect, but opposite in sign. The effect of aerosol backscatter would likely be most important over the oceans, due to the low albedo of the sea surface relative to land or ice.

One particularly important area of research in which a UAV could provide vital data would be ground-truth verification of satellite-derived scattering measurements. It is currently unclear whether the measurements obtained from satellites represent the optical nature of aerosol backscatter at sea level, or higher in the marine atmosphere. A platform which could obtain high-resolution vertical profiles of aerosol light-scattering characteristics in conjunction with satellite observation would significantly improve the interpretation of available satellite data.

Typical Mission Profile. A mission dedicated to collecting data on aerosols would be flown using the same profile as was illustrated in Figure 2–2. Again, the diurnal variation is considered to be very important, and would require aircraft on-station endurance capability of about 24 hours.

Payload. In addition to the basic instrument suite, an aerosol-measurement payload would likely consist of one or more particulate measurement probes. We assume that 3 would provide a broad measurement capability; see Table 2–5.

Table 2–5. Candidate instruments and equipment for a n aerosol-measurement payload.

Instruments and Equipment	Mass (*kg*)
(3) PMS OAP-230X optical array probes	60
Basic instrument/equipment suite	25
Total	85

This list of mission and equipment, though far from exhaustive, provides a useful basis from which desirable performance characteristics can be derived. In the next two chapters, we summarize the performance requirements and identify platforms that meet some or all of the mission objectives presented here.

3—Desired Performance Capabilities

To summarize the results of the previous chapter, it appears that a UAV platform with the following characteristics would meet the requirements of a large spectrum of low-altitude, science missions.

- **Range.** The aircraft should be able to fly as much as 2,500 *km*.
- **Endurance.** To examine the diurnal variation of various quantities of interest, greater than 24-hour endurance is desirable.
- **Payload.** It appears that a platform should be capable of carrying up to 150 *kg* of instruments and equipment.
- **Flight Speed.** One characteristic of UAV's that is attractive to the research community is their low airspeeds. This feature allows for greater measurement resolution that is possible with many manned aircraft. As a baseline performance target, it appears that typical cruise flight speeds should be less than about 50 *m/s*.
- **Sea-Level Climb Rate.** To allow reasonably rapid traverses through the marine boundary layer (not to mention flight safety considerations), a suitable UAV should be capable of climbing at a rate of at least 2.5 *m/s* at sea level.

In addition to the physical performance capabilities, an unmanned aircraft suitable for use in environmental sensing must be able to operate economically. For comparison, examination of the flight costs for manned aircraft shows that they fall into two basic groups that are widely separated. At the upper end are the large, multi-engined, turbine-powered aircraft operated, typically, by federally-funded organizations. The National Center for Atmospheric Research, for example, operates a fleet of aircraft that range in size from the Beechcraft King Air to the Lockheed Electra; the cost to the user ranges from about $3,000 to $5,000 per flight hour for these aircraft. On the other end of the price scale, there are a number of organizations that operate small, single-engine, piston-powered aircraft for scientific research (Cessna 182's and DeHavilland Beaver aircraft are popular platforms). For safety reasons, this class of aircraft is typically restricted to flight relatively close to shore, but offers a dramatic reduction in cost; typically, one can be hired at a rate of less than $200 per flight hour.

Many people accurately assume that unmanned aircraft are less expensive to operate than the larger manned aircraft, but it comes as a surprise that they are unable to compete on a purely economic basis with small single-engined aircraft. Clearly, UAV operation costs should be held to a practical minimum, but it can be difficult to quantify an actual cost. In a number of conversations with scientists, an initial target cost of $500 per flight hour was discussed. Although we originally regarded this figure only as a starting point, it subsequently became apparent that $500 per hour is a practical *upper limit* for the many in the research community.

For this reason, we have concluded that if a low-altitude UAV cannot be operated at or below this cost level, it immediately eliminates a large fraction of the potential flight-service customer base. As we show later in the report, a key factor in keeping flight costs at a minimum is maximum utilization rate. If the flight costs were to stray much above $500 per hour, the customer base would rapidly erode with a consequent decrease in utilization rate. This reduction in turn would drive the flight costs up and, very quickly, much of the attraction of unmanned aircraft is lost. It should be noted that there are users—especially the military—for whom operational cost is a secondary consideration. For the large majority of the environmental and atmospheric research community, however, acceptably low operating costs are a nearly indispensable characteristic of a useful UAV system. As we show in Chapter 5, this economic requirement is much more challenging than any of the aforementioned performance requirements.

4—Available Platforms

Using the desired performance characteristics described in the previous chapter as a guideline, we reviewed the UAV systems that are currently available to select candidate platforms for low-altitude scientific research. As with so many aviation technologies, the large majority of UAV's that have been (or are being) developed were conceived for military applications. Consequently, most unmanned aircraft are designed to meet some very specific mission requirements that generally do not resemble those defined by science research needs.

The U.S. Department of Defense has defined four different operational missions for use in defining UAV performance specifications. They are the Close-Range, the Short-Range, the Mid-Range, and the Intercontinental missions. The Close-Range mission calls for platforms with an operational radius of up to 50 *km* , 3 hour endurance (plus reserve), with a 50 *lb* payload capacity. Similarly, the Short-Range mission requirements specify an operational radius of 300 *km* , 8 *hr* endurance and a payload weight of more than 100 *lb*. This ambiguous payload requirement stems from the fact that the aircraft are assumed to carry significant imaging equipment (visual and infrared cameras, at least) to meet other mission requirements, but the weight of these items is not included in the payload weight accounting. Thus, the actual payload capacity of aircraft designed for this role is significantly more than 100 *lb*, though how much depends on the specific model. The Close and Short-Range programs are currently funded under the auspices of the U.S. Army and Marine Corps.

The Mid-Range program calls for aircraft platforms capable of operating out to a radius of 700 *km*. and was supported by the U.S. Navy during the 1980's; since then, funding for the program has been cut off. The Intercontinental mission refers to platforms with a radius of operation of greater than 700 *km* and has historically been regarded as the purview of the U.S. Air Force. The Air Force has interpreted this mission to apply to cruise-missile programs and has not supported the development of unmanned aircraft, *per se*.

The end result of this stratification of missions—and the current status of the Mid-Range and Intercontinental programs—is a paucity of UAV's that meet all of the performance figures described in the previous chapter. For this reason, we adopted a strategy of identifying aircraft that meet *most* or all of the science-mission requirements; 4 platforms have been identified:

- The General Atomics Gnat-750,
- The TRW/IAI Hunter,
- The Developmental Sciences SkyEye, and
- The Aurora Flight Sciences Perseus-C.

Each of these aircraft is discussed in more detail below.

For each, we have included a table of physical and performance characteristics. Where available, data for the aircraft's performance was obtained from the producer's literature; in some cases, a quantity of interest was not available and was calculated using simple, first-order analysis techniques. The strategy employed in this process was to estimate the aircraft's aerodynamic and propulsion parameters by adjusting them within reasonable limits to match the known performance figures. Having determined appropriate values for these parameters, unknown performance quantities could then be estimated with a reasonable degree of confidence.

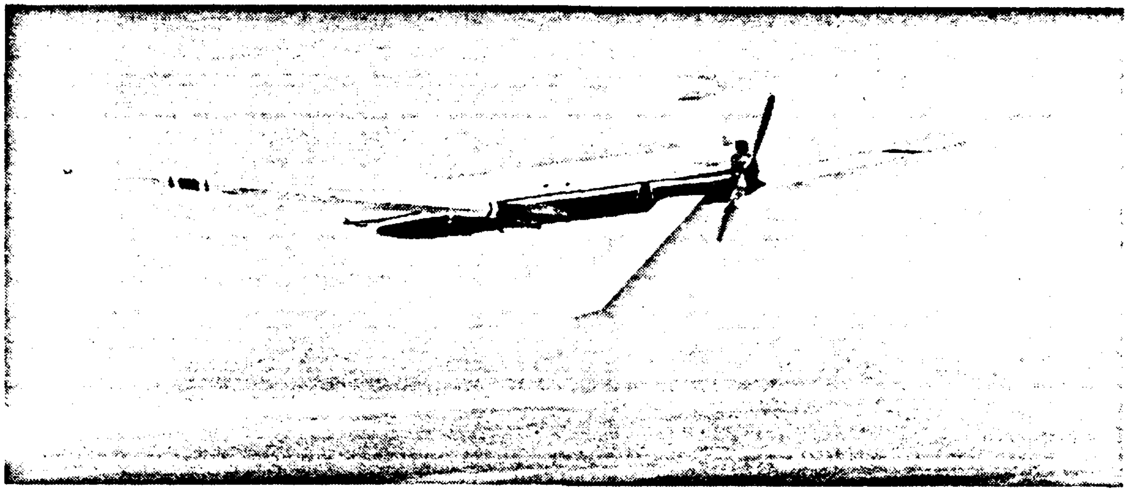

Figure 4–1 The Gnat-750 in flight.

Table 4–1 General Atomics Gnat-750 physical and performance characteristics.

Wing Span	10.74 *m*	35.25 *ft*
Wing Area	6.11 *sq. m*	65.8 *sq. ft.*
Gross Weight	517 *kg*	1140 *lbs*
Payload Weight	210 *kg*	462 *lb*
Fuel Weight	108 *kg*	237 *lb*
Engine Power	48.5 *kW*	65 *hp*
Number of Engines	1	
Endurance	48 *hrs*	
Range	5,370 *km*	2,900 *n.mi..*
Service Ceiling	8,080 *m*	26,500 *ft*
Sea-Level Climb Rate	5.9 *m/s*	1,165 *ft/min*
Flight Speed for Max. Endurance	27.3 *m/s*	53 *kts*
Flight Speed for Max. Range	35.5 *m/s*	69 *kts*

The General Atomics Gnat-750

In the mid 1980's, the U.S. Navy and DARPA supported the development of an unmanned aircraft known as the Amber to meet the requirements of what would subsequently be called the Mid-Range UAV mission. Following the cancellation of the program, the company which designed and built the Amber—Leading Systems, Incorporated—declared bankruptcy and its assets were acquired by General Atomics.

General Atomics used much of the Amber technology to develop a less-complex derivative, the Gnat-750. Figure 4–1 shows the aircraft in flight and Table 4–1 summarizes its physical and performance characteristics. As the tabulated data shows, the vehicle exceeds the desired performance requirements outlined in Chapter 3.

The TRW/IAI Hunter

To compete for the Department of Defense Short-Range UAV System contract, Israeli Aircraft Industries (IAI) teamed with TRW to produce an aircraft known as the Hunter; see Figure 4–2. The design proved successful in the contract competition and is currently undergoing operational testing preparatory to deployment.

Table 4–2 summarizes the physical and performance characteristics of the Hunter. Unfortunately, the differences between the Short-Range mission requirements and those of the science missions of interest here are apparent. Although the aircraft meets the payload, climb-rate and flight-speed goals, it falls short in terms of both range and endurance.

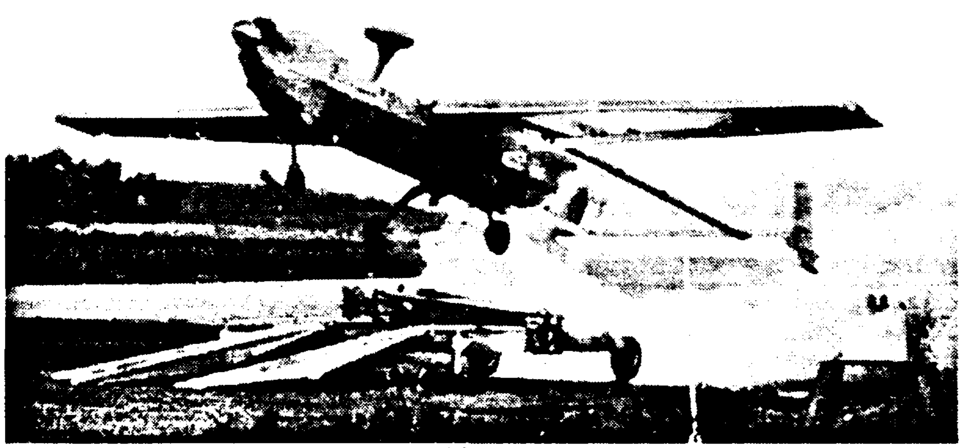

Figure 4–2. Rocket-assisted launch of the IAI/TRW Hunter

Table 4–2. IAI/TRW Hunter physical and performance characteristics.

Wing Span	8.84 *m*	29 *ft*
Wing Area	7.90 *sq. m*	85 *sq. ft.*
Gross Weight	726 *kg*	1600 *lbs*
Payload Weight	113 *kg*	250 *lb*
Fuel Weight	136 *kg*	300 *lb*
Engine Power	51 *kW*	68 *hp*
Number of Engines	2	
Endurance	12 *hrs*	
Range	1,460 *km*	790 *n.mi..*
Service Ceiling	4,820 *m*	15,800 *ft*
Sea-Level Climb Rate	4.88 *m/s*	960 *ft/min*
Flight Speed for Max. Endurance	28.8 *m/s*	56 *kts*
Flight Speed for Max. Range	38.1 *m/s*	74 *kts*

The Developmental Sciences SkyEye

As a second entrant in the Short-Range contract competition, Developmental Sciences Corporation teamed with the McDonnell Douglas Corporation to produce the SkyEye; see Figure 4–3. Though unsuccessful in this competition, the aircraft is currently in production and has been sold to a number of overseas customers.

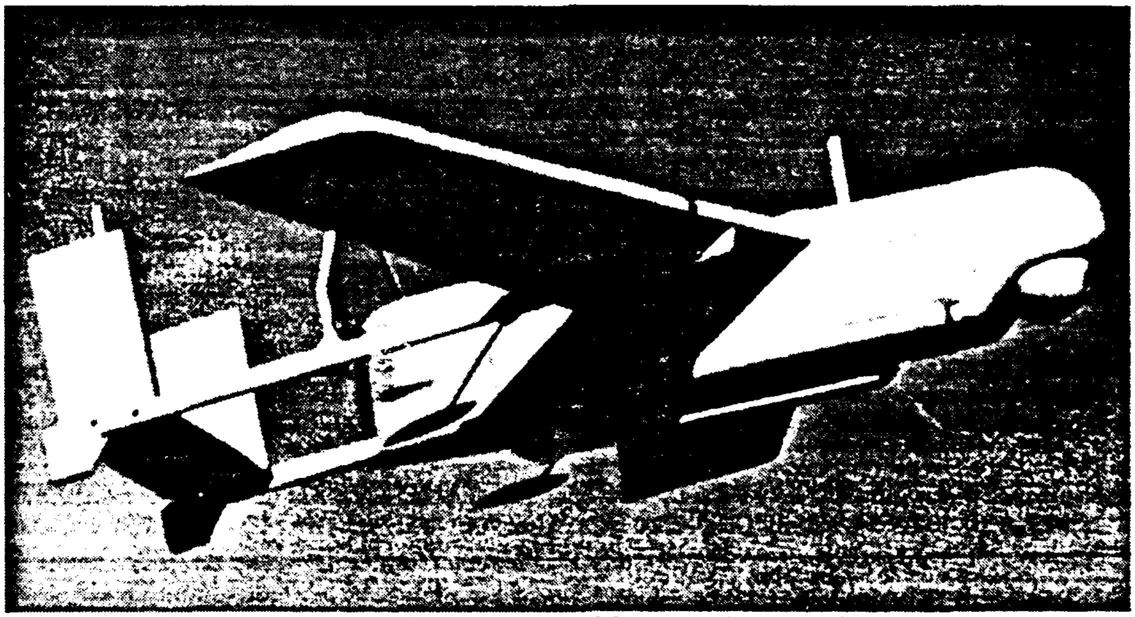

Figure 4–3. The Developmental Sciences SkyEye in flight.

Table 4–3 summarizes the vehicle's physical characteristics and performance capabilities. As with the Hunter, the SkyEye falls short in several performance areas because of the disparity in requirements between the Short-Range mission and those of the present study. Specifically, the SkyEye meets the climb-rate and flight-speed targets, but is limited in its payload, range and endurance capabilities.

Table 4–3. Developmental Sciences SkyEye physical and performance characteristics.

Wing Span	6.10 *m*	20 *ft*
Wing Area	5.30 *sq. m*	57 *sq. ft.*
Gross Weight	354 *kg*	780 *lbs*
Payload Weight	79 *kg*	175 *lb*
Fuel Weight	45 *kg*	100 *lb*
Engine Power	34.3 *kW*	46 *hp*
Number of Engines	1	
Endurance	12 *hrs*	
Range	1,410 *km*	760 *n.mi..*
Service Ceiling	5,330 *m*	17,500 *ft*
Sea-Level Climb Rate	5.0 *m/s*	975 *ft/min*
Flight Speed for Max. Endurance	28.8 *m/s*	56 *kts*
Flight Speed for Max. Range	37.6 *m/s*	73 *kts*

The Aurora Flight Sciences Perseus-C

In contrast to the previous 4 vehicles, the Perseus family of aircraft was, from its inception, designed to suit the needs of the atmospheric-science research community. The first member of the family, the Perseus-A, is designed for relatively short flights at extreme altitudes (approximately 25 *km*). The second, the Perseus-B, trades maximum altitude for greater endurance to achieve flight durations in excess of 24 hours at altitudes of 20 *km*. Currently, the Perseus-A is undergoing initial flight tests and the Perseus-B is in full-scale development. The design concept for Perseus-C would replace the propulsion systems required for flights in the mid-stratosphere with a simple, normally-aspirated engine and fixed-pitch propeller. Because it combines the same airframe and flight-control system of the Perseus-A with an off-the-shelf engine/propeller combination, the aircraft—though not currently in production—could readily meet the requirements of low-altitude science missions. The aircraft would closely resemble the Perseus proof-of-concept aircraft shown in Figure 4–4.

Table 4–4 lists the physical and performance characteristics of the Perseus-C. The fact that its airframe was originally designed for flight at extreme altitudes accounts for its generous capabilities; it surpasses all the of the performance goals.

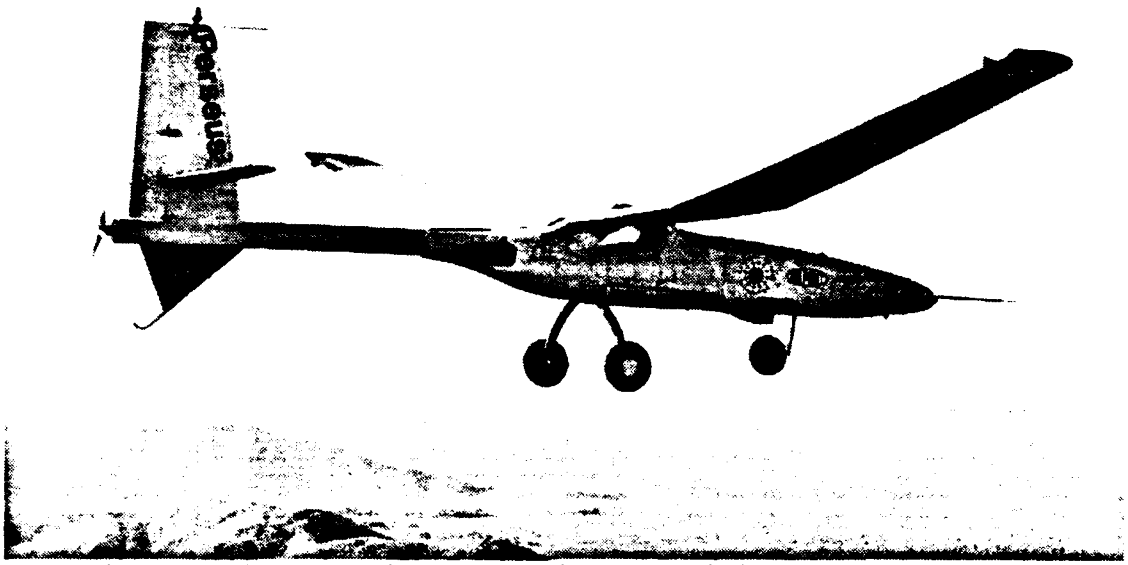

Figure 4–4. The Aurora Flight Sciences Perseus proof-of-concept aircraft in flight. The Perseus-C would closely resemble this aircraft.

Table 4–4. Aurora Flight Sciences Perseus-C aircraft physical and performance characteristics.

Wing Span	18 *m*	59 *ft*
Wing Area	16 *sq. m*	172 *sq. ft.*
Gross Weight	850 *kg*	1,875 *lbs*
Payload Weight	200 *kg*	442 *lb*
Fuel Weight	200 *kg*	442 *lb*
Engine Power	56 *kW*	75 *hp*
Number of Engines	1	
Endurance	90 *hrs*	
Range	8,020 *km*	4,330 *n.mi..*
Service Ceiling	8,040 *m*	26,400 *ft*
Sea-Level Climb Rate	4.5 *m/s*	890 *ft/min*
Flight Speed for Max. Endurance	30.9 *m/s*	60 *kts*
Flight Speed for Max. Range	40.7 *m/s*	79 *kts*

For the simple reason that the desired performance capabilities of a UAV applied to low-altitude environmental sensing do not match any currently funded military program requirements, the selection of suitable UAV platforms is limited. Of the four aircraft identified in our research, only two—the General Atomics Gnat-750 and the Aurora Flight Sciences Perseus-C—meet or exceed the performance objectives enumerated in the previous chapter.

5—Economic Analysis

In this portion of the report, we describe the economic model used to estimate operating costs for a small fleet of UAV's applied to low-altitude, environmental sensing. For the discussion, we have assumed that a number of UAV's would be operated by a small group of people dedicated to that purpose. Such an organization would focus on the supply of flight services and would expect the science-research customer to provide and support the appropriate instrument payloads; it would cover its expenses by charging the customer on a per-flight or per-hour basis. We assume that this organization would include a modicum of maintenance and technical-support capability to keep the aircraft in flyable condition, but would not be involved with the vehicle's ongoing development. We view this organization in two different economic settings: as a small, independent business, and as part of a larger corporation. As will be seen, each of these settings carries with it some important economic assumptions that affect the net operating cost significantly and serve to establish approximate upper and lower bounds on the overall operating costs of a UAV system.

Many of the assumptions used in this chapter represent optimistic assessments of actual expenses and, for this reason, the bottom-line costs presented here should be interpreted as targets toward which an efficient, well-managed organization would strive. It is likely that a flight-service organization would experience significantly higher costs during an initial, startup phase.

For the simple reason that a UAV without a ground-control station (GCS) is unusable, most manufacturers refer to their products as UAV *systems*, which include one or more aircraft, a GCS and all required ground-support equipment. We have adopted the same terminology and, in the following, assume that the system is composed of 3 aircraft, one GCS and all support equipment.

This chapter is divided into 6 sections. In the first, we discuss the indirect operating costs; that is, the salaries of the employees, fringe benefits, overhead costs and general-and-administrative expenses. Second, we examine the amortization of initial acquisition costs over the expected life of the vehicles. In the third section, we discuss the costs related directly to operation. Fourth, we describe our baseline assumptions on the utilization and lifetime of the aircraft. In the fifth section, we present and discuss the results of our analysis and, in the final section, we examine several parametric variations in the model. These provide some justification for several assumptions (in particular, that 3 aircraft comprise the system) and which also illustrate some important strategies for reducing the overall operating cost.

Indirect Operating Costs

In this discussion, the indirect operating costs (IOC) include those costs related to the operation of the aircraft which are invariant with the number of hours flown, and exclude the amortized acquisition costs. In short, the IOC equates to the salaries and associated additional costs of the personnel composing a flight-service organization. The number of people required is largely defined by two primary factors: the broad cross-section of skills required to operate and maintain the aircraft, and the desired capability in terms of mission duration.

Aircraft (A & P) Mechanic. To cover normal mechanical maintenance tasks on several UAV's, a flight-service group must include at least one licensed Airframe and Powerplant (A & P) mechanic. Although he would likely be paid on an hourly basis, a typical equivalent annual salary for such a mechanic would be approximately $30,000.

Electronics Technician. UAV's and their GCS are highly dependent upon the operation of a large number of electrical and electronic devices, including computers, transducers and sensors, radios, and video equipment. Even if one were to rely upon the manufacturer for major maintenance, the rigors of day-to-day operation demand a technician capable of, for example, isolating a failed sensor and repairing or replacing it. We assume a qualified technician would be paid an equivalent annual rate of about $30,000.

Pilot. The first member of the UAV flight crew would be the pilot. Human-factors considerations dictate that a pilot cannot be expected to safely operate an aircraft—even a nearly autonomous one—for more than about 8 hours in any 24-hour period. Although the issue is complicated by consideration of duty time *vs.* flight time, 1-day, 3-day and 7-day limitations, and environmental factors, this figure is consistent with both FAA and DOD rules of operation. Given that many of the science missions of interest require more than 24 hours of endurance, this clearly requires that 3 pilots be employed. Annual salaries vary widely with experience and license ratings, but we have assumed that qualified individuals could be employed for about $35,000 per year.

Flight/Support Engineer. An engineer, the second member of the flight crew, would be responsible for monitoring the health of onboard systems, data links, the payload, *etc.* during flight operations. For the same reasons as outlined above, 3 engineers would be required. In addition to their flight-operations duties, we have assumed that the engineers would be available to assist and guide the mechanic and technician in day-to-day troubleshooting and maintenance tasks. These apparently disparate tasks are actually quite consistent with one another, in that both require detailed knowledge of the various aircraft and groundstation systems and equipment. In the current market, degreed engineers with some level of experience earn salaries of roughly $35,000 per year.

Mission Coordinator. While the pilot and engineer would be concerned primarily with the safe operation of the aircraft, the mission coordinator would have the role of ensuring that it is flown in such a way as to collect the specific science data of interest. In this capacity, he would serve as the interface between the flight crew and the science principal investigators and would, therefore, have to be cognizant of both the technical aspects of aircraft operation and the mission requirements from a scientific perspective.

During flight operations, this individual would act, in military parlance, as the mission commander. As with the flight engineer, the mission coordinator would have responsibilities beyond those required during flight operations, including such items as logistical planning, coordination of airspace requirements and flight planning, and issuance of data-link radio frequencies. We have assumed that 2 flight coordinators would be required to support 24-hour missions, and that qualified individuals would be paid approximately $40,000 per year.

Director of Flight Operations. The director of flight operations would be expected to manage the flight-services organization. He would be responsible for scheduling, logistical and long-term planning, customer relations, and strategic decision making. During flight operations, the director would serve as a third mission coordinator. He would be expected to have some level of experience in each of the disciplines described above; that is, he would likely be a qualified pilot that is also familiar with aircraft system-engineering considerations and research-flying issues. Because of the necessary technical and managerial experience, a person qualified for this position would command an annual salary of roughly $50,000.

To summarize, we estimate that a small, well-managed flight services organization would require the following positions:

(1) A & P Mechanic	$30,000
(1) Electronics Technician	$30,000
(3) Pilots	$35,000
(3) Flight/Support Engineer	$35,000
(2) Mission Coordinator	$40,000
(1) Director of Flight Ops.	$50,000
(11) Total	$400,000

In comparison, the U.S. Army currently estimates that it will require 96 people to operate the Short-Range UAV System in the field at an approximate cost (salary only) of $3.84 million. This figure allows for the simultaneous operation of 2 aircraft (with the associated GCS) and includes a significant number of soldiers whose roles relate primarily to transporting the system from point to point. One would expect that a UAV system of only 3 aircraft operated in a much less strenuous environment would require far fewer people—by our estimation as few as 11—but we reiterate that our projections are assumed to be best-case estimates of actual needs and therefore represent a *minimum* required staffing level.

Fringe, Overhead and General-and-Administrative Costs. For this discussion, we have included 3 additional indirect costs categories related to direct labor charges: fringe, overhead, and general-and-administrative (G & A) costs. Fringe costs refer to those expense carried by the employer that are associated with health insurance, savings-and-securities programs, retirement benefits, *etc.* Across a range of private and public employers they average about 28% the cost of direct labor.

The second catagory, overhead, is often calculated as a percentage rate that is applied to the total of labor and fringe costs. Overhead costs may be thought of as the cost of the infrastructure required to do business and thus include facility rental, facility maintenance and repair, utilities, secretarial and administrative support, *etc.* Clearly, these costs vary widely with the type of industry, the size of the company and the efficiency of the organization. One of the principal means by which a small business remains competitive is by paring these costs to an absolute minimum. A carefully run, well-managed, small business might be expected to keep overhead costs (in this accounting scheme) as low as 60% of the cost of direct labor and fringe.

By contrast, most large corporations incur much higher overhead rates simply because the cost of performing their business is often dramatically increased. For example, the facilities and equipment that Boeing requires to manufacture a commercial jet transport—a task at which it has been remarkably successful—are vastly more expensive (in a percentage sense) than those found in most small businesses. As a conservative estimate, we have assumed that a large corporation incurs approximately 200% the cost of labor plus fringe.

The third category of indirect costs are G & A expenditures. In Manual 7640.1 6–606.4, the Defense Contract Audit Agency defines G & A expenses as "any management, financial and other expense which are incurred by or allocated to a business unit and which are for general management and administration of the business as a whole." G & A thus refers to activities such as corporate officer functions, legal services, accounting, and marketing efforts. It is typical—though by no means universal—to apply G & A costs as a percentage of the total direct (discussed later) and indirect costs; this is the method used here. For a small business, rates as low as 18% are possible; for a larger corporation, one would expect to see rates on the order of 30%.

We note here that our estimates for fringe, overhead and G & A costs are just that—estimates. For any given company, these rates are considered to be sensitive, proprietary information and are jealously guarded simply because they relate so closely to the cost of performing a function in a competitive environment. Consequently, these figures should be regarded as accurate *representative* values but not as precise data.

Amortized Acquisition Costs

In a business setting, the capital investment required to acquire a UAV system would be amortized over the expected life of the vehicles. For this discussion, we assume an equal payment series to recover the initial capital investment, which is given by

$$A = P\left[\frac{i(1+i)^T}{(1+i)^T - 1}\right],$$

where A is the annual payment on the initial investment P, i is the interest rate (*i.e.*, cost of capital) and T is the system's life given by

$$T = \frac{N_u L_u}{u}.$$

Here, N_u is the number of aircraft in the system, L_u is the anticipated life (in flight hours) of a single aircraft and u is the utilization rate in flight hours per year.

Table 5–1 is a list of approximate acquisition costs of a 3-aircraft system for each of the currently available platforms identified in Chapter 4.

Table 5–1 Estimated acquisition costs for 3-aircraft system; the vehicles are those identified as those that are currently available and appropriate for low-altitude research objectives.

Vehicle	GCS /Support	Aircraft	Total
Perseus-C	$1,000k	$800k	$3,400k
Gnat-750	$1,000k	$1,600k	$5,800k
SkyEye	$3,000k	$800k	$5,400k
Hunter	$2,500k	$2,500k	$10,000k

We note that the figures listed in Table 5–1 are reasonably accurate but are, at best, only representative of actual system costs. Because UAV's are produced principally to meet the requirements of a specific order, the vehicles can be extensively customized to meet individual requirements which in turn affects the net sales price. Further, the data was collected from a variety of sources including trade-journal articles, published literature, and conversations with sales representatives; without exception, the manufacturers went to some length to explain that the estimates were approximate at best.* Finally, our assumption that there are 3 UAV's per system is not necessarily the "normal" configuration marketed by the manufacturer. For example, the Hunter system, as sold to the U.S. Army, consists of 8 aircraft, two groundstations and all required support equipment; converting the acquisition cost of such a system to one that represents the system we have assumed necessarily introduces some level of uncertainty. In short, these figures are assumed to be accurate representative, but not exact, costs.

Direct Operating Costs

The direct operating cost (DOC) is essentially the marginal expense of operating an aircraft for one additional hour of flight time. We assume that the DOC is composed of 3 items: the maintenance-material cost, the cost of mission fuel, and the hull insurance premiums on the aircraft.

Maintenance Material. As a starting point for estimating the material costs of maintaining the aircraft, we employed the Airline Transport Association's statis-

* In fact, General Atomics declined a specific request for cost information. The figures shown in the table for the Gnat-750 are, therefore, estimates based on references in the published literature.

tical cost models described in Ref. 3. The airframe material costs are assumed to be broken into per-flight-cycle costs given by

$$C_{fc} = 6.24 \frac{C_a}{10^6},$$

and the per-flight-hour costs given by

$$C_{fh} = 3.08 \frac{C_a}{10^6},$$

where C_a is the acquisition cost of the aircraft.

The applicability of these expressions to this class of aircraft is, at best, questionable since they were derived for a class of aircraft—civil transports—which are designed from a very early stage to keep maintenance costs at a practical minimum. Nevertheless, we used the models for two simple reasons. First, they agree favorably with the general-aviation figures shown in Ref. 4 and thus are, in some sense, at an approximately correct order of magnitude. Second and more important, the results of the following section show that the material costs are so small relative to the overall cost of operation that were they to increase by a factor of three or four, the effect on the net cost would be minimal.

Mission Fuel. The mission fuel is estimated by dividing the utilization rate (in hours per year) by the maximum endurance and multiplying the result by the maximum fuel capacity. The cost of aviation fuel is assumed to be $0.35/*lb*.

Insurance. Our model for insurance costs is a very simple one, given by

$$C_{ins} = r_{ins} N_a C_a,$$

where r_{ins} is some fixed, annual insurance rate and the remaining parameters are as above. Although we assume that the cost of insurance is fixed for a given year, we have included it as a direct cost because the overall insurance expenditure is proportional to the life of the UAV system which, in turn, depends on the yearly utilization rate. A typical starting value for the insurance rate would be 3–5%, although if one (or more) aircraft were to be lost earlier than their projected lifetime this rate would be expected to increase dramatically.

Utilization Rate and Aircraft Lifetime

It is a simple matter to show that the minimum hourly cost of operation is achieved by maximizing both the yearly utilization rate and the lifetime of the aircraft. Establishing appropriate upper limits for these parameters is a much more challenging task.

From a practical standpoint, it appears that a flight-services organization would have to operate at some rate above about 1,000 hours per year; much below this level the indirect and acquisition costs rapidly become oppressive. We believe that about 2,000 hours per year is an absolute, theoretical upper limit that would be virtually impossible to achieve in practice. (Note that 2,000 hours of operation is 40 hours *per week* over an entire year, allowing for 2 weeks of downtime.)

Choosing a middle ground between these two extremes, we assume a baseline utilization rate of 1,500 hours per year. This value represents a very aggressive flight schedule of 30 hours per week; even if the missions flown were lengthy and this value could be accumulated over only 1 or 2 days, this still would be a grueling schedule with little slack available to accommodate the realities of weather delays, maintenance downtime and personnel absences.

The lifetime of a UAV is defined principally by the anticipated loss rate. Most of the statistical data currently available was accumulated by the Department of Defense in the time period leading up to and during the Persian Gulf War. The data is therefore skewed heavily towards very high loss rates (*i.e.*, low expected lifetimes) and is not considered to be especially applicable to predicting the lifetimes of research UAV's. As an alternate baseline for comparison, we have turned to data available for the U.S. Army's Short-Range UAV System (the Hunter), which is currently in the operational testing phase of development. The Short-Range UAV Program Office in Huntsville, Alabama projects a *normal, peacetime-operation* loss rate of 1 aircraft every 1,200 flight hours. Deploying the system in a combat situation is expected to dramatically increase this loss rate.

One would hope that this figure could be improved upon by establishing high standards of maintenance and flight-crew training and, further, that the lifetime could be increased by operating the aircraft conservatively with regard to weather hazards. Note, however, that the latter strategy would adversely affect the utilization rate and could thereby negate a perceived benefit in operations cost obtained by increased life.

One of the most important factors in estimating a UAV's lifetime for low-altitude applications is the inherent hazards found in this flight regime. A major system failure—particularly when operating over water—almost guarantees the loss of the vehicle because there is little margin available for corrective action or, in the event of an engine failure, little flexibility in choice of an emergency landing site (by contrast, an aerodynamically efficient aircraft which lost its engine at an altitude of, say, 50,000 *ft* could easily glide for more than 100 miles). Statistically, engine reliability has been an Achilles heel for UAV systems—according to Department of Defense records, fully 50% of all UAV losses have been caused by engine failures.

For these reasons, we believe that an assumed lifetime of 2,000 flight hours is an appropriate baseline that *may* be achievable in practice. Implicitly, we have assumed that the U.S. Army's lifetime estimates for the Short-Range system can be improved by 67% through the implementation of high crew-training and maintenance standards. Though appealing, projected lifetimes of 3,000 to 5,000 hours for unmanned aircraft, especially for low-altitude, over-water missions, do not seem to be reasonable in view of the currently available data.

Analysis Results

As we stated earlier, we have investigated two different economic settings which we refer to as the small-business and large-corporation scenarios. Calculated costs for each are presented in this section.

For the small-business setting, we used a fringe rate of 28%, an overhead rate of 60% and a G & A rate of 18%. The cost of capital was assumed to be 10%, the annual insurance rate 3%, and the company is expected to charge a fee of 10% above its own costs. The tabulated and plotted results are shown in Figures 5–1 and 5–2. As shown, we estimate hourly costs of about $1,560 to $3,240 per hour. Note that the indirect costs alone (labor, fringe, overhead and G & A) exceed the $500 per hour cost target and, for the cheapest platform, are of nearly the same order as the amortized acquisition costs.

For the large-corporation setting, we again used a fringe rate of 28% but increased the overhead rate to 200% and the G & A rate to 30% for the reasons discussed earlier. Again we used 10%, 3% and 10% for the cost of capital, insurance rate and fee, respectively. The tabulated and plotted results are shown in Figures 5–3 and 5–4. It seems apparent that with hourly costs ranging from over $2,300 to $4,000 a large corporation is not likely to operate a UAV flight-service organization both profitably and economically.

(Figures shown on following pages.)

Basic Data		
Lifetime (hrs)	2,000	
Utilization (hrs/yr)	1,500	
No of years	4 00	
Fringe	28 00%	
Overhead	60 00%	
G & A	18 00%	
Number of aircraft	3	
Cost of capital	10 00%	
Fuel Cost ($/lb)	$0 35	
Insurance Rate	3 00%	
Fee	10 00%	
Personnel	**Number**	**Annual Salary**
A & P Mechanic	1	$30,000
Electronics Technician	1	$30,000
Pilot	3	$35,000
Flight/Support Engineer	3	$35,000
Dir of Flight Ops	1	$50,000
Mission Coordinator	2	$40,000
Total Direct Labor	11	$400,000
	Fringe	$112,000
	Overhead	$307,200
	Total	**$819,200**

	Perseus-C	Gnat-750	SkyEye	Hunter
Acquisition Cost Data				
Aircraft	$800,000	$1,300,000	$800,000	$2,500,000
Groundstation & Support Equipment	$1,000,000	$1,100,000	$3,000,000	$2,500,000
Total Acquisition	$3,400,000	$5,000,000	$5,400,000	$10,000,000
Supplemental Data				
Fuel Weight (lbs)	442	237	100	300
Endurance (hrs)	90	48	12	12
Maintenance Materials				
Materials, per flight cycle	$4 99	$8 11	$4 99	$15 60
Materials per flight hour	$2 46	$4 00	$2 46	$7 70
Direct Costs				
Fuel	$2,578	$2,592	$4,375	$13,125
Maintenance Materials	$3,779	$6,260	$4,320	$13,500
Insurance	$72,000	$117,000	$72,000	$225,000
Total, per year	$78,358	$125,852	$80,695	$251,625
Total Direct and Indirect, per year	$897,558	$945,052	$899,895	$1,070,825
G & A, per year	$161,560	$170,109	$161,981	$192,749
Amortized Acquisition, per year	$1,072,601	$1,577,354	$1,703,542	$3,154,708
Total Costs	$2,131,719	$2,692,515	$2,765,418	$4,418,282
Fee	$213,172	$269,252	$276,542	$44[illegible] 828
Total Op. Cost, per year	$2,344,890	$2,961,767	$3,041,960	$4,860,110
Total Op. Cost, per flight hour	**$1,563**	**$1,975**	**$2,028**	**$3,240**

Figure 5–1. Economic analysis results of costs to operate available UAV systems. The assumptions used here are those outlined for the *small-business* economic setting.

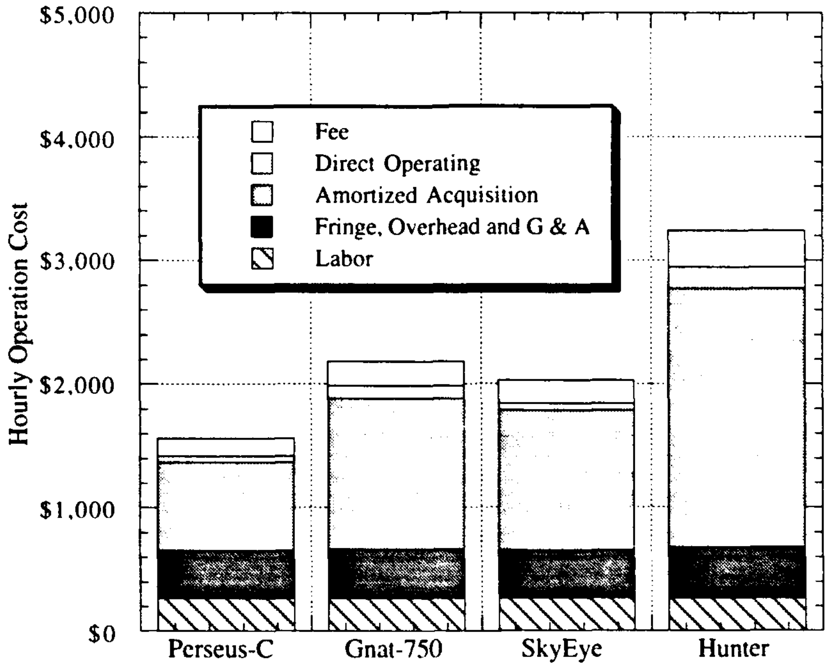

Figure 5–2. Hourly cost comparison for the *small-business* economic scenario.

Basic Data	
Lifetime (hrs)	2,000
Utilization (hrs/yr)	1,500
No of years	4 00
Fringe	28 00%
Overhead	200 00%
G & A	30 00%
Number of aircraft	3
Cost of capital	10 00%
Fuel Cost ($/lb)	$0 35
Insurance Rate	3 00%
Fee	10 00%

Personnel	Number	Annual Salary
A & P Mechanic	1	$30,000
Electronics Technician	1	$30,000
Pilot	3	$35,000
Flight/Support Engineer	3	$35,000
Dir of Flight Ops	1	$50,000
Mission Coordinator	2	$40,000
Total Direct Labor	11	$400,000
	Fringe	$112,000
	Overhead	$1,024,000
	Total	$1,536,000

	Perseus-C	Gnat-750	SkyEye	Hunter
Acquisition Cost Data				
Aircraft	$800,000	$1,300,000	$800,000	$2,500,000
Groundstation & Support Equipment	$1,000,000	$1,100,000	$3,000,000	$2,500,000
Total, Acquisition	$3,400,000	$5,000,000	$5,400,000	$10,000,000
Supplemental Data				
Fuel Weight (lbs)	442	237	100	300
Endurance (hrs)	90	48	12	12
Maintenance Materials				
Materials, per flight cycle	$4 99	$8 11	$4 99	$15 60
Materials, per flight hour	$2 46	$4 00	$2 46	$7 70
Direct Costs				
Fuel	$2,578	$2,592	$4,375	$13,125
Maintenance Materials	$3,779	$6,260	$4,320	$13,500
Insurance	$72,000	$117,000	$72,000	$225,000
Total, per year	$78,358	$125,852	$80,695	$251,625
Total Direct and Indirect, per year	$1,614,358	$1,661,852	$1,616,695	$1,787,625
G & A, per year	$484,307	$498,556	$485,009	$536,288
Amortized Acquisition, per year	$1,0[illegible]2,601	$1,577,354	$1,703,542	$3,[illegible]54,708
Total Costs	$3,171,266	$3,737,761	$3,805,246	$5,478,621
Fee	$317,127	$373,776	$380,525	$547,862
Total Op. Cost, per year	$3,488,392	$4,111,537	$4,185,770	$6,026,483
Total Op. Cost, per flight hour	$2,326	$2,741	$2,791	$4,018

Figure 5–3. Economic analysis results of costs to operate available UAV systems. The assumptions used here are those outlined for the *large-corporation* economic setting.

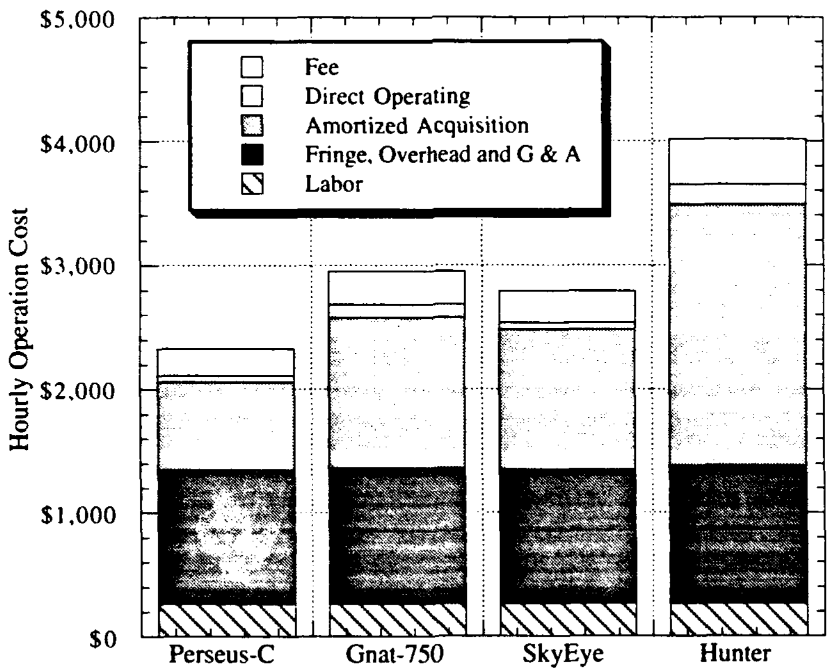

Figure 5–4 Hourly cost comparison for the *large-corporation* economic scenario.

Parametric Studies

In this section, we present the results obtained from our economic model by varying specific parameters and examining the resulting variations in hourly operational cost. The economic setting we chose for this exercise was that of a small business operating the UAV flight-services organization. Earlier in this chapter, we made the assertion that the UAV system should be composed of 3 aircraft (plus GCS and support equipment); the calculation results presented here provide some justification for this number.

Figure 5–5 shows the variation of net hourly cost with aircraft acquisition cost for a system composed of 2, 4, or 6 aircraft. Not surprisingly, the hourly cost increases linearly with the purchase price, but this increase occurs at a rate that differs with the number of aircraft in the system. For this calculation, in which we assumed an aircraft lifetime of 2,000 hours, a utilization rate of 1,500 hours per year, and a $1 million price for the GCS and support equipment, the lowest hourly rate for aircraft prices below about $400,000 occurs with a 6-aircraft system. At the other end of the spectrum, acquisition costs greater than about $1.1 million imply that the least-cost system is composed of only 2 aircraft.

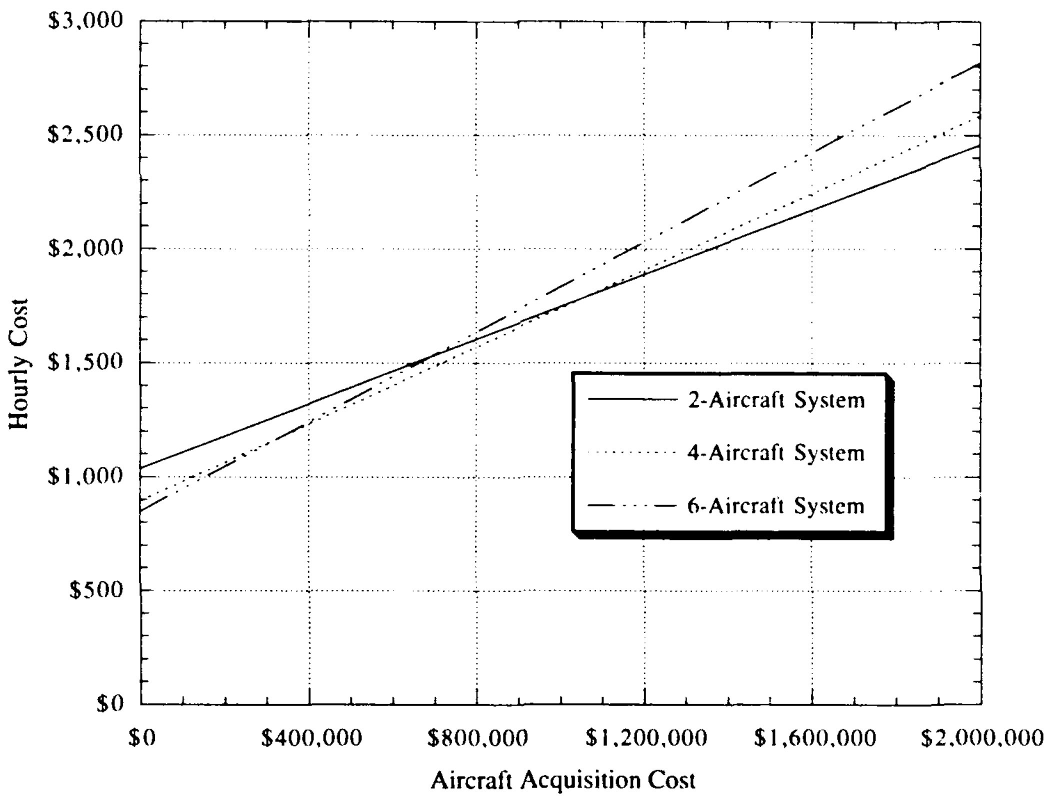

Figure 5–5. Hourly cost as a function of aircraft acquisition cost.

In Figure 5–6, we show the variation in hourly cost with utilization rate (here the aircraft acquisition cost was fixed at $1 million and the lifetime at 2,000 hours).

Obviously, the hourly cost decreases rapidly with increasing utilization, but we again see that the least-cost number of aircraft in the system also changes with the utilization rate. Over the entire practical range of utilization, 2 and 4-aircraft systems are more economical than one composed of 6 aircraft, but for rates lower than about 1,400 hours per year, the 2-aircraft option is slightly cheaper , and above this value the 4-aircraft system has a small advantage.

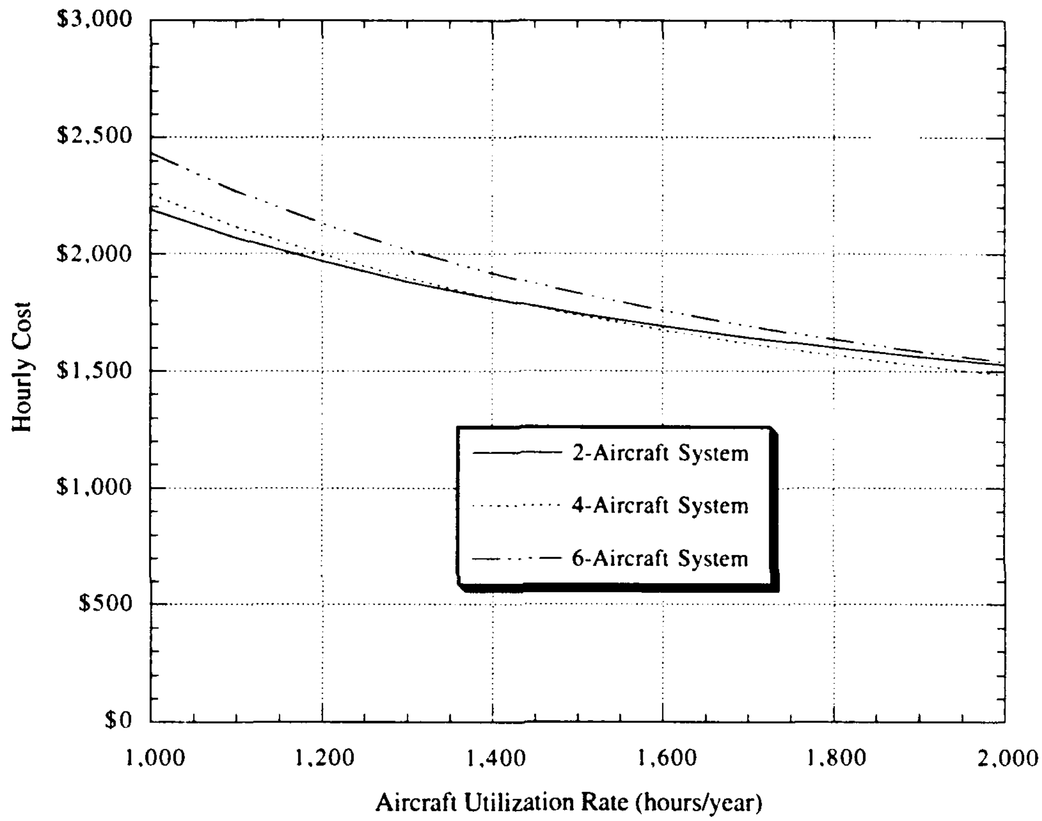

Figure 5–6. Hourly cost as a function of aircraft utilization rate .

Finally, in Figure 5–7 we show how hourly costs behave with variations in aircraft lifetime. Once again, the anticipated result—decreased cost for increased lifetime—is apparent, with similar behavior in the least-cost number of aircraft. The data presented in these three figures suggests that a 3-aircraft system is a good least-cost compromise over a broad range of aircraft prices, lifetime and utilization rates.

There is no question that the lowest hourly cost is achieved by combining minimum acquisition costs with maximum aircraft utilization and lifetime. A more subtle implication comes in the form of trades between these quantities. For example with a 3-aircraft system, a 10% reduction in acquisition cost yields a 4.5% reduction in hourly cost, an increase of 10% in the life of the aircraft produces only a 4.0% decrease in the hourly cost, but a 10% increase in utilization produces a 5.0% decrease in cost. Thus, one might accept a decrease in aircraft life by flying in marginal (more hazardous) weather conditions if that in turn implied a proportional increase in utilization rate. By the same token, an increase in cost that carries with it a proportional increase in lifetime is a losing proposition—from the above results, this would result in a net *increase* in operational cost.

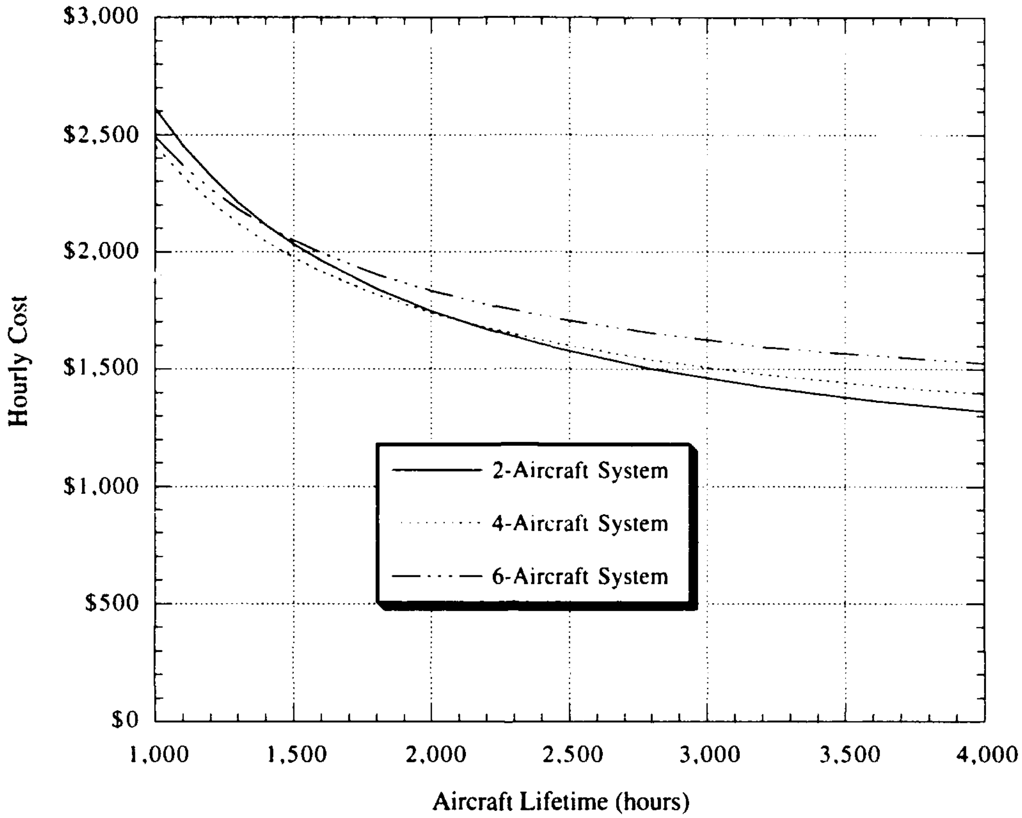

Figure 5–7. Hourly cost as a function of aircraft lifetime.

To summarize the principal result of this chapter, meeting the operational-cost objective of $500 per flight hour is impossible with currently available UAV platforms. The combined indirect, direct, and amortized acquisition costs drive the expense of operation well above this target value, even without the addition of a modest profit margin.

The parametric studies indicate that a UAV system should be composed of about 3 aircraft for minimum cost over a broad range of acquisition costs, vehicle lifetimes and utilization rates. Given our baseline assumptions that the life of an individual UAV is about 2,000 hours and that the system utilization rate is about 1,500 hour per year, it appears that increasing utilization rate has a more significant effect on operating costs than does increased vehicle lifetime.

6—A Low-Cost Alternative

The results of the previous chapter suggest that reaching the operations-cost goal of $500 per hour is impossible for currently available UAV's. As stated in Chapter 3, it appears that this significantly reduces the current applicability of the UAV to low-altitude environmental and atmospheric research. Fundamentally, the operations cost is driven by two nearly equal factors: the expense of the personnel required to operate a flight-service organization and the expense of the UAV system itself; as we saw in Chapter 5, the direct operating costs are relatively unimportant. Thus, an attack on the cost problem should be two-sided: first, every effort should be made to reduce the number of people required to operate the system, and second, the acquisition cost must be reduced. Unfortunately, we believe that the personnel requirements of the previous chapter, though achievable, are actually *optimistic* projections and, until operational data is available to the contrary, are already at a practical minimum. In contrast, there may be an attractive alternative that addresses the second consideration.

Simple calculations reveal that the performance requirements summarized in Chapter 3 do not place any particularly extreme demands on the airframe itself. We believe that this observation may open up an intriguing possibility for developing a UAV that can achieve significantly reduced operational expense. Rather than designing a vehicle from scratch to meet the specific demands of economical low-altitude science missions—a task which appears to be nearly impossible—we propose that converting an existing, manned aircraft to unmanned use can accomplish the same scientific objectives at dramatically reduced cost. This conversion would consist largely of adapting the flight-control hardware (radios, servos, computers, *etc.*) and software from an *existing* UAV to an appropriate manned aircraft.

We see four primary advantages to this strategy. First, many types of aircraft are available on the used market for remarkably low cost and, thus, the expense of fabricating and integrating the UAV airframe and powerplant would be effectively eliminated. Second, the integration of flight-control hardware and software to an existing airframe, though challenging, would be simplified by the fact that only the servos that manipulate the engine controls and aerodynamic surfaces must be placed in specific physical locations; the remaining components could be placed essentially wherever was simplest. This consideration is further ameliorated by the existence of many commercially available autopilots which have servo configurations designed for many civil aircraft; such equipment could, potentially, be adapted to this purpose. The necessary software modifications would consist primarily of updating the aerodynamic data (stability derivatives, principally) to represent a new platform, and recalculating feedback gains in the control algorithms, while the basic structure of the software would remain essentially unchanged.

The third advantage we see with this approach is that it would employ an airframe and powerplant that are FAA certified for flight and are, therefore, fully developed and highly reliable systems. As noted in the previous chapter, statistical evidence reveals that a large fraction of UAV losses are directly attributable to engine failures; thus, utilizing a certified engine in combination with a certified airframe may be an inexpensive means of significantly extending the anticipated life of the platform. Finally, utilizing an existing manned aircraft could allow the vehicle to be flown either remotely or with a pilot onboard in some circumstances. Provided that the safety of an onboard pilot could be ensured, this strategy would allow the same aircraft to be used for flights in airspace inaccessible to UAVs, thus expanding its research utility.

Basic Data	
Lifetime (hrs):	2,500
Utilization (hrs/yr):	1,500
No. of years:	5.00
Fringe:	28.00%
Overhead:	60.00%
G & A:	18.00%
Number of aircraft:	3
Cost of capital:	10.00%
Fuel Cost ($/lb):	$0.35
Insurance Rate:	3.00%
Fee:	10.00%

Personnel	**Number**	**Annual Salary**
A & P Mechanic	1	$30,000
Electronics Technician	1	$30,000
Pilot	3	$35,000
Flight/Support Engineer	3	$35,000
Dir. of Flight Ops.	1	$50,000
Mission Coordinator	2	$40,000
Total Direct Labor	11	$400,000
	Fringe	$112,000
	Overhead	$307,200
	Total	**$819,200**

	Manned/Unmanned Conversion
Acquisition Cost Data	
Aircraft	$500,000
Groundstation & Support Equipment	$300,000
Total, Acquisition	$1,800,000
Supplemental Data	
Fuel Weight (lbs)	442
Endurance (hrs)	90
Maintenance Materials	
Materials, per flight cycle	$3.12
Materials, per flight hour	$1.54
Direct Costs	
Fuel	$2,578
Maintenance Materials	$2,362
Insurance	$45,000
Total, per year	$49,940
Total Direct and Indirect, per year	$869,140
G & A, per year	$156,445
Amortized Acquisition, per year	$474,835
Total Costs	$1,500,421
Fee	$150,042
Total Op. Cost, per year	$1,650,463
Total Op. Cost, per flight hour	**$1,100**

Figure 6–1. Economic analysis of the acquisition costs required to achieve total operation costs of $1,100 per hour.

To assess the financial constraints under which such an aircraft would be developed, we utilized the economic model described previously. As Figure 6–1 indicates, it appears that a 3-aircraft UAV system could be operated by a small business at a cost of $1,100 per flight hour if the aircraft could be purchased at a cost of $500,000 each, and the GCS and support equipment for $300,000. Note that we have allowed for an increase in the expected lifetime from 2,000 hours to 2,500 hours to reflect the presumed increase in reliability found in a certified engine. This would represent a 30% reduction in cost from the *least* expensive system described in the previous chapter.

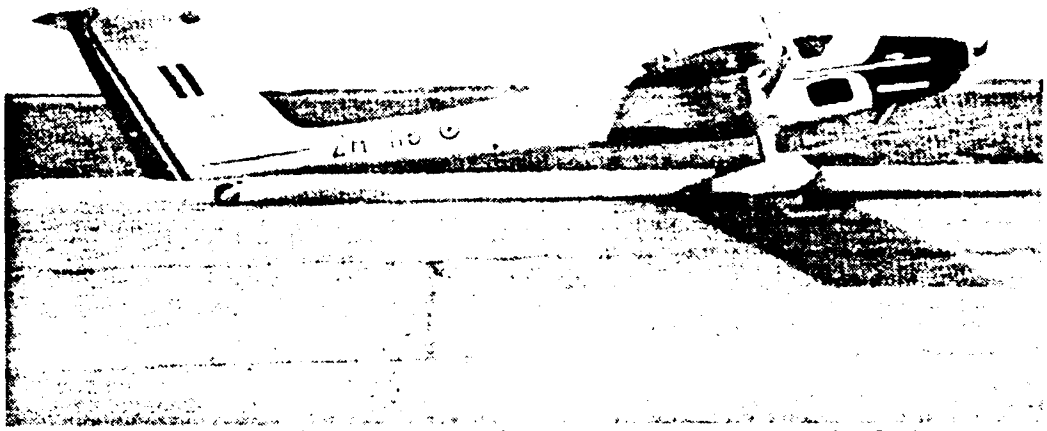

Figure 6–2. One candidate for manned-to-unmanned conversion: the Grob 109B.

Table 6–1. Estimated physical and performance characteristics of a Grob 109B converted from manned to unmanned operation.

Wing Span	16.6 *m*	54.45 *ft*
Wing Area	20.4 *sq. m*	219.6 *sq. ft.*
Gross Weight	826 *kg*	1,820 *lbs*
Payload Weight	113 *kg*	250 *lb*
Fuel Weight	113 *kg*	250 *lb*
Engine Power	59.7 *kW*	80 *hp*
Number of Engines	1	
Endurance	27 *hrs*	
Range	2,800 *km*	1,510 *n.mi..*
Service Ceiling	6,100 *m*	20,000 *ft*
Sea-Level Climb Rate	2.8 *m/s*	550 *ft/min*
Fligh' Speed for Max. Endurance	25.2 *m/s*	49 *kts*
Flight Speed for Max. Range	33.5 *m/s*	65 *kts*

To investigate the performance capabilities of such an aircraft, we have selected two candidates for conversion that represent opposite ends of the spectrum of possibilities. The first, a Grob 109B, is a small sport aircraft that falls in the class known collectively as *motorgliders,* which are designed to operate as self-launching sailplanes. The aircraft, shown in Figure 6–2, employs an 85 *hp* Limbach engine.

The physical characteristics and performance capabilities of the aircraft are presented in Table 6–1. Note that to estimate the performance of the aircraft operated as a UAV, we have assumed that weight normally attributed to pilot, passenger and fuel is redistributed between payload and fuel (the empty weight and gross weight were fixed at their published values). The analysis models alluded to in Chapter 4 were employed to estimate the performance figures in the table. For the simple reason that the payloads of interest weigh less than a pilot, passenger, and luggage the fuel weight can be increased to allow significant gains in both endurance and range.

The second aircraft, a Cessna 337 Skymaster, is a twin-engined, business-class aircraft; see Figure 6–3. Much larger than the Grob, it is powered by two 210 *hp* engines located fore and aft on the fuselage centerline. This configuration was of interest primarily because the two engines offer redundancy in the event of an engine failure and further, would not challenge the autopilot system with strong yawing tendencies in an engine-out situation. The physical and estimated performance characteristics of the Cessna converted to unmanned use are summarized in Table 6–2.

Note that both of these aircraft meet or exceed most of the desired performance capabilities outlined in Chapter 3; the Grob 109B falls somewhat short in payload capacity, and the Cessna's estimated endurance is one hour short of the 24-hour target, but the remaining performance targets are surpassed. The more challenging requirement is that of keeping the acquisition cost below $500,000 per aircraft. Roughly speaking, this cost would be divided into three main categories: that required to procure the aircraft, the purchase cost of the flight-control system hardware, and the engineering cost of modifying the software and adapting the hardware of an existing UAV for another aircraft. A Grob 109B commands a price of between $20,000 and $30,000 while a Cessna Skymaster in good condition could be purchased for about twice that amount. Using the Perseus hardware as a baseline, we estimate that the flight-control hardware would cost no more than about $200,000. Thus, approximately $240,000 to $280,000 would be available to perform the engineering and manual tasks required for the conversion (roughly 3 to 4 man-years).

There is no question that these economic and technical issues must be investigated much more thoroughly before any UAV manufacturer could reasonably make a large-scale commitment to this strategy. An appropriate first step would be to convert a single aircraft to unmanned use in a technology verification and demonstration program. We feel that the ultimate promise of the approach—reduced-cost, low-altitude scientific research—is undeniably attractive.

(Figures follow.)

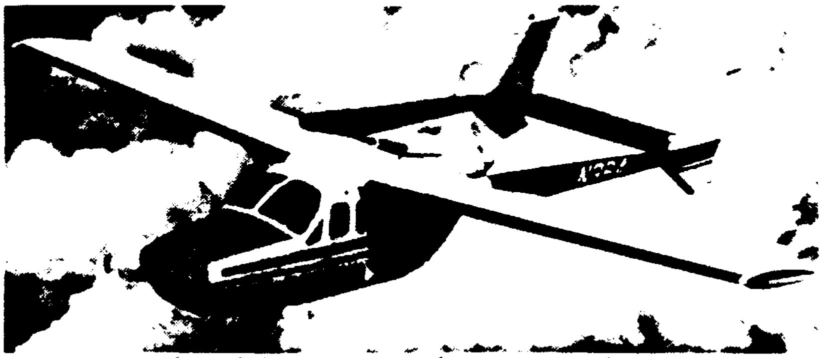

Figure 6–3. A second candidate for manned-to-unmanned conversion: the Cessna 337 Skymaster.

Table 6–2. Estimated physical and performance characteristics of a Cessna 337 Skymaster converted from manned to unmanned operation.

Wing Span	11.9 *m*	39 *ft*
Wing Area	23.2 *sq. m*	250 *sq. ft.*
Gross Weight	1,996 *kg*	4,400 *lbs*
Payload Weight	150 *kg*	330 *lb*
Fuel Weight	621 *kg*	1,370 *lb*
Engine Power	157 *kW*	210 *hp*
Number of Engines	2	
Endurance	23 *hrs*	
Range	3,240 *km*	1,750 *n.mi..*
Service Ceiling	5,640 *m*	18,500 *ft*
Sea-Level Climb Rate	6.3 *m/s*	1,250 *ft/min*
Flight Speed for Max. Endurance	34.0 *m/s*	66 *kts*
Flight Speed for Max. Range	43.8 *m/s*	85 *kts*

7—Operational Considerations

In addition to the driving economic factors, there are at least two important operational considerations that must enter into any discussion of low-altitude UAV applications. The first is the issue of communicating with the aircraft while it is operating over the horizon from the GCS, and the second is the safety of operating a UAV where it could pose a hazard to aircraft or marine traffic.

For the former, we can estimate the distance to the horizon (ignoring diffraction effects) from

$$d = \sqrt{h^2 + 2Rh} \ ,$$

where h is the height above ground level, d is the distance to the horizon, and R is the radius of the earth ($R \approx 2.112 \times 10^7 \ ft$). For a UAV controlled from a groundstation, one simply sums the distance to the horizon allowed by the GCS antenna height with the contribution from the aircraft's operating altitude; Figure 7–1 illustrates such a scenario.

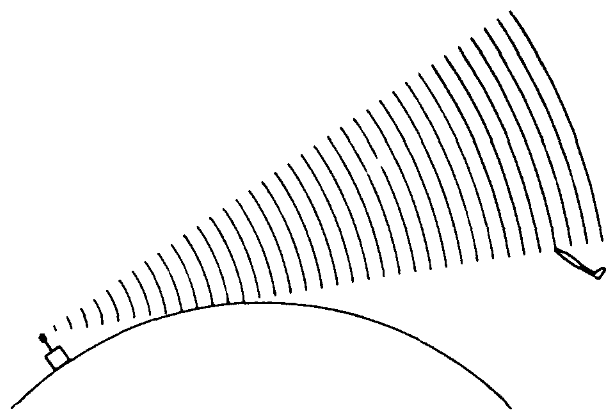

Figure 7–1. The radius of operation of a UAV is limited by the earth's horizon. At low altitude, this becomes a significant limitation.

One significant difficulty associated with operating at very low altitudes is the fact that the horizon is rather close. In Figure 7–2, we show the line-of-sight distance from the aircraft to a groundstation of 10 *ft* elevation as a function of aircraft flight altitude. As an example, a mission flown at 30 *ft* for, say, marine-boundary-layer turbulence measurements can operate no further than about 10 miles from the groundstation before the horizon would obscure radio transmissions.

To extend this radius of operation, some form of relay station must be employed. At least 3 options are available including airborne or ground-based relay stations and satellite communications. Utilizing an airborne relay station in the form of a second UAV is unattractive simply because it would immediately double the support staff. Although in some sense the cost per flight hour of two aircraft (one collecting data, one acting as a relay station) would be constant, the cost to the flight-service customer would have to double to cover the expense of the second aircraft.

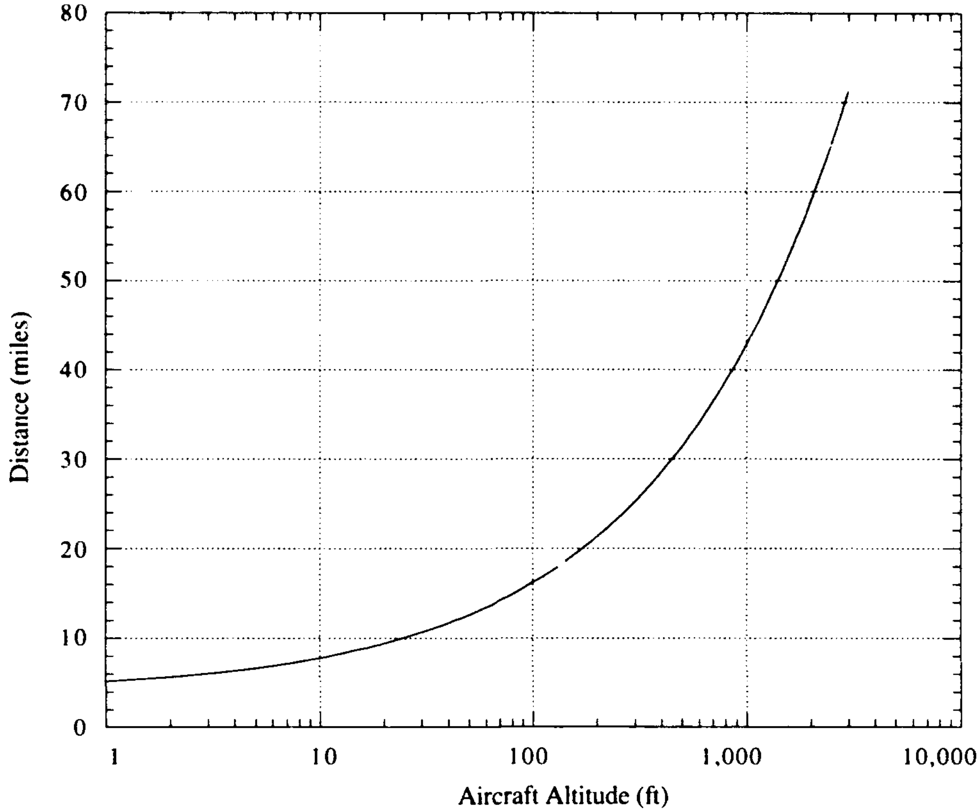

Figure 7–2. The line of sight distance from a 10 *ft* elevation GCS to a UAV flying at low altitude as a function of flight altitude.

Satellite communications may offer an alternative to airborne data relay, but are not currently available at acceptably low cost. The ORBCOMM system, currently under development, will be composed of 26 MicroStar™ satellites circling the earth in low orbit that operate in concert with one or more Gateway ground stations. Once the system is fully operational (by late 1994 to early 1995, according to company projections), communication rates of up to 2,400 *bps* should be available nearly continuously at near-zero latency. It is conceivable that this data rate could successfully support over-the-horizon operation of a UAV and its payload, though it implies a relatively high level of autonomous capability on the UAV's part, and would preclude any form of live video (low-rate video obtained using frame-grabbing technology might still be an option).

The principal attractions of the ORBCOMM system are its low cost and lack of satellite tracking requirements. The system's transmitters are anticipated to cost roughly $500 to $1,000, and to weigh less than 5 *kg*, and communications costs are expected to be well under 1¢ per byte for volume customers. Although this cost is superior to that of other, existing satellite systems, simple calculations reveal that a continuous data rate of 2,400 *bps* would add very significantly to the operational cost. Nevertheless, when this and other competitive systems become fully operational, they may be attractive for over-the-horizon communications.

The concept of a ground-based relay station operating between the UAV and its GCS is appealing because of the system's simplicity, availability and low cost. If, for example, the GCS employed a 100 *ft* radio mast and a relay station did the same, the radius of operation would, for a UAV operating at an altitude of 30 *ft*, increase from 19 miles to over 31 miles with the addition of the relay station. Increasing the height of the radio masts further would be an inexpensive means of extending the range, though the ability to transport the system would be degraded. Since no low-altitude UAV flight-service organization currently exists, it seems likely that this latter approach—as opposed to airborne or satellite relay—would be the most attractive in the initial stages of operation.

A second, perhaps more restrictive, consideration is that of flight safety. The vast majority of airspace in the United States, including that extending offshore, is available for flight under Visual Flight Rules (weather permitting). Because an aircraft operating VFR is not under the positive direction of any controlling agency, there is no existing system which could guarantee the safe separation of a UAV and civil aircraft. The FAA is only now beginning to grapple with the safety and control issues of UAV operation and it is likely that in the near future flight will be limited to airspace that is designated as *special-use* or *restricted*. Through the Notice-to-Airmen system, the FAA can notify pilots that unusual activity (such as UAV operation) will be taking place in such airspace blocks and that entering the area is either prohibited or to be done with extreme caution. Fortunately, a number of special-use airspace areas would, potentially, be available for low-altitude research; for example, NASA's Wallops Island facility, and the Stennis Naval Research Laboratory on the Gulf coast might be appropriate locations for initial flight operations.

Though legal requirements have yet to be defined, it would seem prudent that a UAV operating at low altitude have some form of live, or near-live, video capability. The pilot flying the aircraft would then be able to see and avoid obstacles. The technical challenge of transmitting live video relates fundamentally to the bandwidth of the communication link between the UAV and the GCS; as distances increase, the transmission power required increases rapidly. One strategy that may reduce the bandwidth requirement would employ a low-rate video system that utilizes frame-grabbing technology to send video images at a rate lower than the normal 30 frames per second. If the rate were reduced by a factor of 10 from the normal speed, the communications power required would decrease by a proportional amount. At a flight speed of 30 *m/s*, the pilot would still be given visual updates every 10 *m* along the flight path which would be sufficient to see and avoid obstacles in the UAV's flight path.

To summarize, there are at least two operational challenges that a successful low-altitude UAV system would have to address: the limitation of over-the-horizon operation and flight safety considerations at low flight altitudes. An inexpensive solution to the first would employ ground-based (or water-based) relay stations to extend the UAV's radius of operation. This approach is regarded as an interim strategy that could, hopefully, be supplanted by a low-cost satellite communications system. The issue of flight safety appears to mandate operation within airspace that can be utilized exclusively for that purpose; that is, special-use or restricted airspace. From a technological standpoint, the hazard posed by a UAV to other low-flying aircraft would be reduced through the use of some form of onboard video system. The low flight speeds of a UAV operating near sea level may allow the use of low-rate video technology to reduce communications power requirements.

8—Summary and Conclusions

The combination of advances in microelectronics, structural materials technology and computational capability has enabled the development of a new class of aircraft, the unmanned aerial vehicle. Historically developed for and operated by the military, these aircraft are beginning to attract attention from the environmental and atmospheric-research communities because of their performance capabilities. In particular, their capacity for flights of extensive range and endurance may open up new prospects for research in the environmental sciences.

The key step in selecting missions suitable for UAV's is to identify characteristics that take special advantage of the aircraft's capabilities. In Chapter 2 we presented 5 candidate missions that are specifically oriented to low-altitude flights in the marine environment: turbulence measurements in the boundary layer, measurements of humidity and temperature gradients, sensing water color, temperature and salinity for monitoring estuaries, deployment of microbouys for *in-situ* ocean data collection, and measurements of the physical characteristics of aerosols. Though by no means an exhaustive list, this collection provides a useful basis from which desirable platform performance characteristics can be derived. Specifically, it appears that a UAV capable of the following would be applicable to a broad range of research efforts:

- Range of 2,500 *km*,
- Endurance of 24 hours,
- Payload capacity of 150 *kg*,
- Flight speed at low altitudes of less than 50 *m/s*, and
- Sea-level climb rate of greater than 2.5 *m/s*.

In addition to their physical requirements, UAV's suitable for scientific research must operate economically. Conversations with a number of active researchers produced a target cost figure of $500 per hour.

Using the above list of desired performance capabilities, 4 aircraft were selected from those currently available as potential low-altitude research platforms: the General Atomic Gnat-750, the IAI/TRW Hunter, the Developmental Sciences SkyEye, and the Aurora Flight Sciences Perseus-C. Simply because the mission requirements do not conform to any currently funded military programs, only two of the above aircraft—the Gnat-750 and the Perseus-C—met all of the performance goals.

The performance goals, though significant, are surpassed in difficulty by the operations-cost goal. In Chapter 5 we described an economic model used to estimate the hourly cost of operating each of the 4 aircraft. The model was constructed to represent a small flight-service organization operating in one of two economic settings: as a small business or as part of a larger corporation. As discussed, these settings carry certain implications for the cost of overhead and general-and-administrative support that significantly affect the net operating expense. The results of the analysis indicate that achieving the operations-cost goal of $500 per hour is impossible for currently available platforms. The cheapest aircraft operated in a small business setting is expected to cost $1,563 per hour. At the other end of the spectrum, the most expensive aircraft is estimated to cost about $4,020 per hour if operated by a large corporation.

It is tempting to assume that the government could operate UAV's for research purposes more cheaply than could a private business (either large or small). Although it is quite true that a government-funded flight-service organization could charge a user whatever fee seemed appropriate (including $500 per hour), the *actual incurred costs* would, at best, be roughly equivalent to those estimated for a large corporation. Historically, flight costs of government-operated aircraft have frequently been assumed to consist solely of direct operating expenses and have not included the costs of required support personnel, facilities, *etc*. As the analysis results indicate, the direct costs are often only a small fraction of those actually incurred. Moreover, there is the concern that government operation of UAV's in support of environmental and atmospheric research would constitute a commercial activity. As noted in Ref. 5, "it has been and continues to be the general policy of the government to rely on commercial sources to supply the products and services the government needs".

The analysis suggests that any strategy intended to reduce these costs have two parts: first, reduce the number of people required for operation and second, reduce the system's acquisition cost. With regard to the former, the estimate of personnel requirements in the economic discussion already appears to be at a practical minimum and, until data is available to the contrary, is not expected to decrease. The observation that the performance requirements are not terribly demanding, however, may allow an innovative solution for reducing the purchase costs. Rather than designing a vehicle from scratch to meet the specific demands of economical low-altitude science missions, we propose that converting an existing manned aircraft to unmanned use can accomplish the same scientific objectives at dramatically reduced cost. Such a conversion would consist largely of adapting the flight-control hardware (radios, servos, computers, *etc*.) and software from an existing UAV to an appropriate manned aircraft. Potentially, this strategy could allow for a 30% reduction in cost from the least expensive of the currently available platforms. For illustration purposes, two candidates for conversion were investigated: a small sportplane and a larger, twin-engined aircraft.

In the last chapter, we discussed several operational challenges that a successful, low-altitude platform must overcome, including over-the-horizon communications and safe operation in airspace shared with small, manned aircraft. An inexpensive solution to the first would employ ground-based (or water-based) relay stations to extend the UAV's radius of operation. This approach is regarded as an interim strategy that could, hopefully, be supplanted by a low-cost satellite communications system. The second concern appears to mandate operation within airspace that can be utilized exclusively for that purpose; that is, special-use or restricted airspace. From a technological standpoint, the hazard posed by a

UAV to other low-flying aircraft would be reduced through the use of some form of onboard video system.

As with so many emerging technologies, the unmanned aircraft may eventually find application across a wide variety of commercial and scientific fields but, at this stage in their development, the cost of operation represents a significant barrier to many potential users. One of the most important contributors to this cost is the purchase price of the UAV system. An intriguing strategy for reducing this cost would be to convert a manned aircraft to unmanned use; the ultimate promise of this approach—affordable, low-altitude scientific research—is sufficiently attractive to warrant further study. We therefore recommend that the Office of Naval Research consider funding a project in which one aircraft was converted for the purpose of technology evaluation and validation. Such a program would be a vital first step towards the eventual goal of economical research flight operations.

References

1) "Remote Sensing of Estuaries", proceedings of a workshop, V. Klemas, J.P. Thomas and J.B. Zaitzeff, editors, NOAA, Washington, D.C., June 1987.

2) "A Naval RPA Research Facility", R. Bluth, *et al.*, Office of Naval Research, 1993.

3) "Standard Method of Estimating Comparative Direct Operating Costs of Turbine-Powered Transport Airplanes", Air Transport Association of America, December 1967.

4) "Aircraft Operating Costs", D. Weeghman, *The Aviation Consumer*, November 1, 1992.

5) "Performance of Commercial Activities", Circular No. A-76 (revised), Office of Management and Budget, August 1983.