Development of a Long Range and Light weight Autonomous Unmanned Aerial Vehicle (AUAV) and Instrument Platform for the Global Albedo Project (GAP)

A proposal to the National Science Foundation Major Research Instrumentation Program

Duration: July 1, 2003 to Dec. 31, 2004

Principal Investigators:
V. Ramanathan (Scripps Institution of Oceanography, UCSD)
J. Kosmatka (Department of Structural Engineering, UCSD)

Co-Investigators

G. Roberts (C4-SIO, UCSD)
E. Wilcox (C4-SIO, UCSD)
O. Lariviere (Ph.D. student, UCSD)
M. Robinson (Ph.D. student, UCSD)
R. McDonnell (M.S. student, UCSD)
A. Pham (Undergraduate student, UCSD)
J. Kuettner (Senior advisor, UCAR)

Industrial Partners

D. Baumgardner and W. Dawson (Droplet Measurement Technologies; Boulder, Colorado 80301)
R. Booth (Biospherical Instruments Inc.; San Diego, California 92110)
J. Panza (Optimum Solutions; San Diego, California 92093)

A. Project Summary

This proposal will create the next generation of affordable observing capability for atmospheric and environmental sciences. By focusing the development of this capability around a big-science research project of global interest, the AUAV will have a major impact on the education and training of engineers and atmospheric scientists in the UCSD campus, but our vision is that the AUAV developed under this MRI will also benefit the entire atmospheric sciences community.

The fundamental objective of GAP is to develop a sound observational base that will provide insights into how aerosols and clouds regulate the planetary albedo, with particular emphasis on how anthropogenic aerosols are modifying the albedo of cloudy skies (the so-called indirect effect). GAP's initial focus will be on exploring cloud systems in the Pacific Ocean with emphasis on how they are affected by air pollution from Asia and California. The first task is to generate a long term (covering an annual cycle) and a long-range (several thousand km) database with simultaneous in-situ observations of aerosols, cloud microphysical properties and cloud albedo. This requires AUAVs that have long duration (>1 day) and long range (about five thousand kilometers) with light instrument payloads (less than 5kg). Such AUAVs are currently not available; hence, if funded *this proposal will create new infrastructure for the American academic and research communities*. We propose the following systematic strategy to develop this capability.

a) Build an AUAV, hereafter referred to as, GAP-PT for GAP-Prototype 1 with a limited flight range of 100 to 200km; An NSF SGER proposal for $100 K has been submitted to NSF and we expect GAP-PT to be ready for flight-testing by June 2003.
b) Build GAP-FM1 (for Flight Model-1) through this MRI. GAP-FM1 will be similar to GAP-PT, but will have the full range of 5000 km required for flights from Southern California to Hawaii.
c) Develop lightweight instrument packages for GAP-PT and GAP-FM1.
d) Conduct testing and research flights with GAP-FM1 from Hawaii to La Jolla during July 2004 to December 2004.

The data gathered by GAP will be the first long term in-situ data on cloudy sky albedo, aerosols and cloud microphysics in a climatologically important region (the Pacific Ocean). Separate proposals will be submitted in July of 2004 to NSF, NOAA and NASA for conducting research with the data. GAP will open new doors into one of the most difficult areas of earth sciences, i.e., clouds and their feedback effects on climate. It will also provide new and unprecedented insights into how the cloudy sky albedo is regulated by human activities. The PI (VR) has extensive and demonstrated experience in conducting such interdisciplinary projects of big scope. The Co-PI (JK) has extensive experience in AUAV design and development and consults with leading builders of AUAVs including General Atomics, TRW and Northrop-Grumman. We are assembling a team of aircraft designers and builders, instrument experts and atmospheric physicists. The team consists of academics, post docs, graduate students, under graduate students as well as industrial partners. The unique platform and the scientific data gathered by the platform will attract a large number of engineering and physical science undergraduate and graduate students to the program and expose them to the exciting and fulfilling aspects of environmental research. Both SIO and the engineering departments will include the GAP platform design, operation and data gathering as part of their curriculum. The PIs will strive hard to enable strong student involvement and emphasize recruitment of qualified underrepresented students.

C. Project Description

Results from Prior NSF Support

Cloud condensation nucleus counter: Through a currently active NSF support to the PI (VR), we have designed a light-weight continuous-flow thermal gradient diffusion chamber to improve our measurements of cloud condensation nuclei (CCN) [*Roberts and Nenes*, 2003]. This instrument was developed for autonomous operation in airborne studies employing a novel technique of generating a supersaturation along the streamwise axis of the instrument. Although similar in design to CCN instruments developed by Hoppel et al. [1979], Leaitch and Megaw [1982] and Chuang et al. [2000], our instrument establishes a linear temperature profile along the streamwise axis to maintain a quasi-uniform supersaturation along the streamwise axis of the chamber. Model simulations suggest that direct measurements in the climatically important range of supersaturations of less than 0.1% are possible.

We have successfully tested the instrument during airborne experiments – Instrument Development and Education in Airborne Science (IDEAS) project at NCAR in April 2002 and the Cirrus Regional Study of Tropical Anvils and Cirrus Layers - Florida Area Cirrus Experiment (CRYSTAL-FACE) in July 2002. The results from the CRYSTAL-FACE campaign have yielded a remarkably good aerosol/CCN closure at 0.2 and 0.8% supersaturation, as shown in Figure 1. CCN concentrations were measured with a sampling resolution of 1Hz at a fixed supersaturation and compared to dry aerosol size distributions on one-minute intervals.

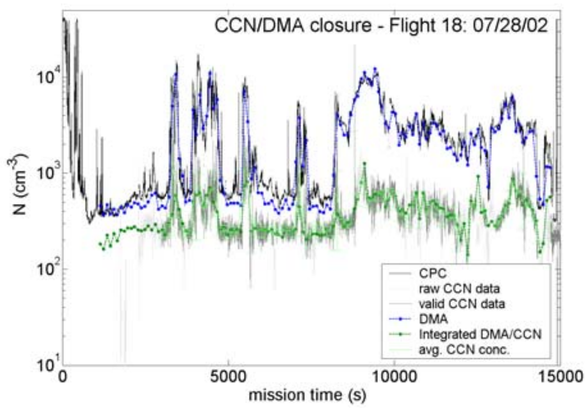

Figure 1: Time series of CCN and size distribution closure during a research flight on 28 July 2002 during CRYSTAL-FACE. The blue and black lines show the total aerosol concentration, and the green lines show the predicted and measured CCN concentrations assuming an ammonium bisulfate aerosol.

We have applied for a patent on this new design (Roberts, G., A Nenes; UCSD Disclosure #SD2002-186) and are working with Droplet Measurement Technologies in Boulder, CO to develop a commercial version of this instrument. Such an instrument will be vital in understanding the link between aerosols and cloud formation.

Indian Ocean Experiment (INDOEX) and the Kashidhoo Climate Observatory: We set up an aerosol-cloud-chemistry-radiation observatory in the Maldives [Satheesh et al. 1999 and Ramanathan et al. 2001a] and led INDOEX [Ramanathan et al. 2001a and 2001b].

Research Activities: The Global Albedo Project

Global Radiation Budget: On an annual-global mean basis, the planet receives about 342 ± 3 W m^{-2} solar radiation at the top of the atmosphere, and reflects about 30(±1.5)% or 102±5 W m^{-2} back to space. The percent reflected to space is referred to as the "Albedo". The balance of 240 W m^{-2} is absorbed by the surface-atmosphere system, which heats the planet and it gives off this energy as infrared (or long wave) radiation to space. The planet continues to warm until the absorbed solar radiation is balanced by IR emission to space (= 240 W m^{-2}).

Geochemical and Thermodynamic theories for the Atmospheric Greenhouse effect: The global-annual surface temperature is about 288 K and the surface IR emission is about 390 W m^{-2}. The absorption and emission of IR radiation by the atmosphere reduces it to 240 W m^{-2}. This reduction of IR radiation to space is referred to as the "Greenhouse Effect" and is mostly due to water vapor, CO_2, clouds and ozone. We have geo-chemical, thermodynamic and chemical theories for the atmospheric concentration of CO_2, water vapor and ozone, which can account for their greenhouse effect.

A Theory for the Global Albedo: We do not have any viable or testable theory for the planetary albedo and the main goal of GAP is to develop the observational foundation for such a theory (Figure 2). Towards this goal, GAP will address the following basic questions:

Figure 2: A Schematic of the GAP Project. The diagram shows the earth radiation budget and summarizes the key questions relevant to GAP.

Why is the global albedo about 30%? To understand why this is an important question, consider the following two examples. A global albedo of 33% would plunge the Earth into a climate similar to that of the last ice-age; while an albedo of 27% would be comparable to a five-fold increase in the CO_2 concentration [Ramanathan, 1998]. There is practically no theory for explaining how the cloudy sky albedos are determined or regulated. Given this state of the field, and given the fact that clouds exert a large global cooling effect (about –15 to 20 Wm^{-2}) as well as large regional cooling (Figure 3), we need a new approach to cut through the current impasse on this fundamental problem in climate dynamics. Numerous feedback and interactive processes involving surface conditions, sea surface temperatures, atmospheric dynamics and atmospheric aerosols (both natural and manmade) are involved in determining cloudy sky albedos. For example, the largest regional radiative cooling by clouds are found over the marine strato-cumulus regions (Figure 3) off the west coast of continents, because of the combination of the upwelling that brings colder water from below and the atmospheric subsidence above the shallow boundary layer (above these colder oceans) that caps these bright clouds.

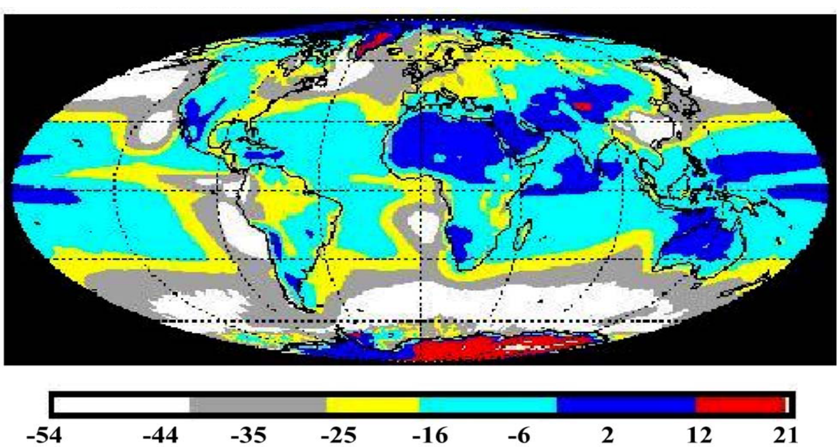

Figure 3: Observed annual mean Net Cloud Radiative forcing. The Net Cloud Radiative forcing is the effect of clouds on the net (solar plus longwave) radiative heating at the top-of-the atmosphere. Source: Ramanathan et al, 1989; Ramanathan, 1998; Harrison et al, 1990.

Another example of the feedbacks is illustrated by comparing Figure 4a with Figure 4b, which reveals the enormous impact of clouds in enhancing the low albedos of the rain forests in Africa and Amazon. Second, it is intriguing that the cloudy sky albedos of Africa and Amazon (with mean albedos between 30% to 38%) are comparable to the albedo (mean value of about 35%) of the Saharan desert. This is definitely not because the cloud albedos are limited to values between 30 to 38%, for the maximum albedos of the deep precipitating clouds over these regions are as high as 85%.

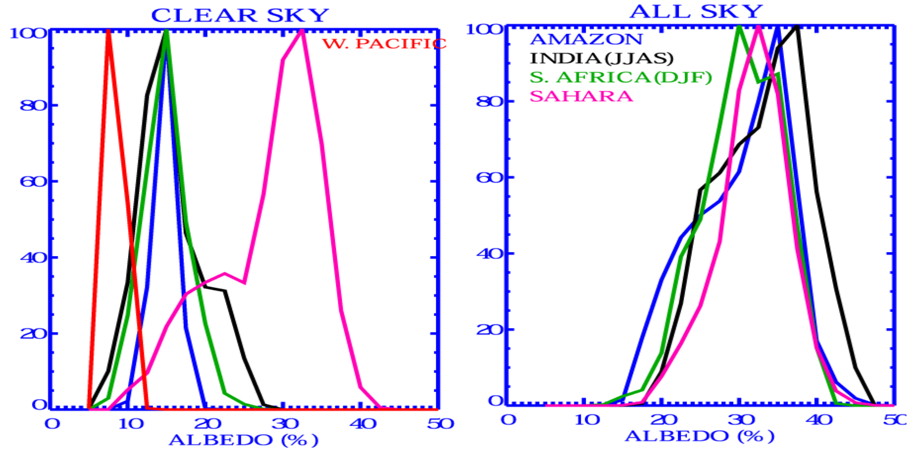

Figure 4: Frequency distribution of monthly mean albedos for clear sky (left panel) and all sky (clear plus clouds) for various climatological regions. Source: Earth Radiation Budget Experiment.

How do Aerosols and Clouds regulate the planetary albedo? The presence of clouds enhances the albedo of a cloud free earth by about a factor of two, from 15% to 30%. Atmospheric dynamics, chemistry and biology play critical roles in cloud formation. The atmospheric circulation determines the location, the spatial extent and the liquid or ice water content of clouds. Aerosols determine the size and number distribution of cloud drops and ice crystals. The aerosol properties are in turn determined by the chemistry (e.g. oxidation of sulfur dioxide) and the biology (e.g., emission of dimethyl sulfide and organic compounds by planktons and other marine life) of the planet. All of these parameters including the aerosol concentration and composition undergo significant temporal (minutes to years) and spatial (meters to planetary scales) variations. Yet it is remarkable that our GCMs are able to explain the observed temperature trends during the last century solely through variations in greenhouse gases, volcanoes and solar constant. This implies that the planetary albedo has not changed during the last 100 years by more than ±0.2%, out of 30%. Is the planetary albedo (and clouds by inference) indeed this stable? Or is it just an artifact of our models?

What is the impact of human activities on the Planetary Albedo? The link between aerosols and cloud albedo determines the so-called indirect effect of anthropogenic aerosols. Many models and some field observations (e.g., INDOEX and ACE-II) have shown that an increase in manmade aerosols can nucleate more cloud drops (Figure 5) and enhance the cloud albedo and lead to a cooling effect. The IPCC-2001 report shows that this cooling effect may be large enough to offset 50% to 100% of the radiative heating due to the build up in greenhouse gases. The understanding of the role of aerosols in cloud albedo constitute the first fundamental step of GAP. *The link between*

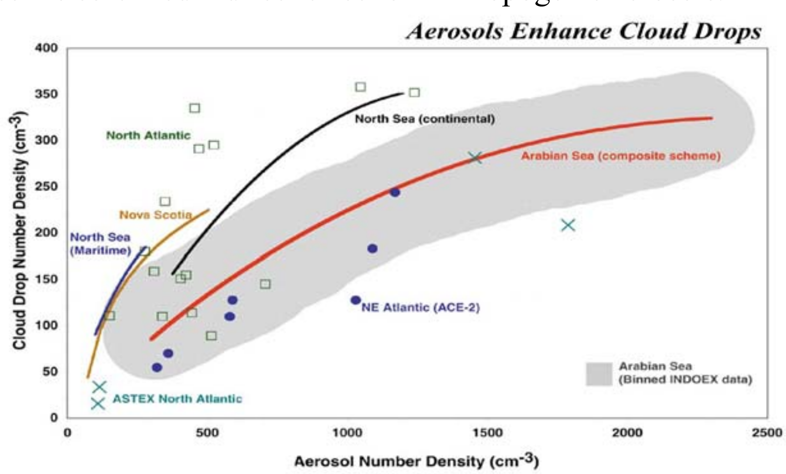

Figure 5: In-situ aircraft data showing the relationship between cloud drop number density and aerosol number density for various regions of the planet. The grey shaded region is the INDOEX data. Source: Ramanathan et al, 2001b.

aerosol and clouds can only be determined with in-situ data from airborne platforms and then extended to regional and global scales by integrating aircraft data with satellite observations of clouds and earth radiation budget. The large variability of aerosol and cloud properties dictate that we need to collect adequate samples of data under a variety of meteorological conditions and under varying aerosol concentrations ranging from pristine to highly polluted conditions. Available cloud physics data (e.g., Figure 5) are taken mainly from field campaigns with a typical duration limited to about 4 to 6 weeks and hence the field of cloud physics is severely sample limited. The AUAV platform provides a viable means for collecting the longer-term regional scale data for addressing the GAP objectives. Pioneering studies with AUAVs have already established their great potential for atmospheric sampling [Holland et al, 2001]. AUAVs are aircraft that are unmanned and not directly ground controlled. The complete vehicle and payload mission are defined and programmed into the vehicle during preflight set-up.

The AUAV mission includes take-off, cruise speed, destination or turn-about points from global positioning satellite (GPS) coordinates, loiter information, and landing coordinates. The payload mission can be either passive so that it does its job independent of the programmed vehicle mission, or it can be active, so that it alters the vehicle mission as needed. Military

Table 1: GAP instruments. Note that only a subset is included in this MRI.

GAP-FM1 Instrumentation	
Measurement	**Instrument**
Aircraft navigation	
Position	GPS
Meteorology	
Air temperature, pressure, humidity	Vaisala sensor
Wind speed and direction	Turbulent gust probe
Updraft velocity	Turbulent gust probe
Radiometers	
Total downwelling solar irradiance (0.200 to 3.6 μm)	modified CM22 pyranometer (Kipp & Zonen)
Cloud and surface albedo (reflected solar irradiance)	modified CM22 pyranometer (Kipp & Zonen) and Multi-Channel Airborne Radiometer (MCAR-4) (Biospherical Instruments, Inc.)
Multi-channel downwelling irradiance (405, 550, 875 nm, PAR)	MCAR-4 (Biospherical Instruments)
Transmitted solar radiation and cloud optical depth	MCAR-4 (Biospherical Instruments, Inc.)
Cloud and aerosol measurements	
Condensation nuclei concentration	Condensation particle counter (CPC) (TSI 3007)
Cloud condensation nuclei (0.13 to 3% S)	CCN counter (Scripps / Georgia Tech / DMT)
Aerosol size distribution (0.3 to 10 μm D_p)	Optical particle counter (MetOne)
Cloud droplet distribution (1 to 70 μm D_p)	Cloud droplet probe (CDP) (DMT)
Cloud liquid water content	infer from CDP (in-site; future development)
Cloud imaging	Video camera
Rain drop and drizzle size distribution	2D Probe (DMT; future development)
Gas measurements	
CO	(future development)
CO_2	(future development)
SO_2	(future development)
Volatile organic carbon compounds	(future development)

developed AUAVs, which cost $3M to $100M, can actively change their flight path based upon inputs from on-board sensors. But these military vehicles are much too expensive for nonmilitary applications. What is needed is an AUAV in the $20K to $75K range (finished replacement cost) that can be used by scientists performing atmospheric monitoring experiments. The AUAV presents a novel, observational approach to studies on the earth's atmosphere; yet, does not replace well-equipped research aircraft that provide the capability of many detailed measurements necessary for process studies (e.g., *Ramanathan et al.* [2001a], *Kaufman et al.* [1998], *Raes et al.* [2000]).

Figure 6: The GAP configuration for obtaining vertical structure of low clouds.

The GAP strategy for developing AUAVs is as follows: i) Focus first on low level clouds. Low clouds (cloud top altitude of 4 km or less) are the major contributors to the planetary albedo and they are also the major contributors to the aerosol indirect effect. It is much easier to design and build a platform with a focused objective. ii) Design and build AUAVs with a range of about 5000 km and a payload of about 5 kg. iii) Instead of requiring one AUAV to undertake vertical profiling as well as long range flying, deploy three aircraft flying in formation (Figure 6), with one above the cloud top to measure aerosol concentration and cloud albedo; one below the cloud base to measure aerosol concentration, cloud condensation nuclei and transmitted solar radiation; and one through the cloud to measure cloud properties. iv) Arrive at a minimum set of instruments that can help demonstrate the validity of the scientific thrusts of GAP as well as the validity of the AUAV concept for atmospheric sampling. Towards this goal, a set of instruments has been chosen for the initial phase of GAP (Table 1). The requests for MRI funding are included for acquiring, miniaturizing and adapting these instruments for the AUAV.

The Pacific Ocean between equator and 45^{o}N is chosen as our natural experimental area. It contains cloud systems with the largest radiative cooling effect (Figure 3). It contains a range of aerosol conditions with highly polluted airmasses from Asia and northern California (Figure 7), as well as pristine marine airmasses. Depending on the weather conditions and available cloud systems, we will fly one-way trips routinely between La Jolla and Hawaii, or out and return trips anywhere within the range from La Jolla or from Hawaii (see circled domains in Figure 8) to sample a variety of stratocumulus, trade cumulus and shallow to moderately deep (tops around 4 kilometers) cumulus clouds under pristine (low aerosol loading) and polluted

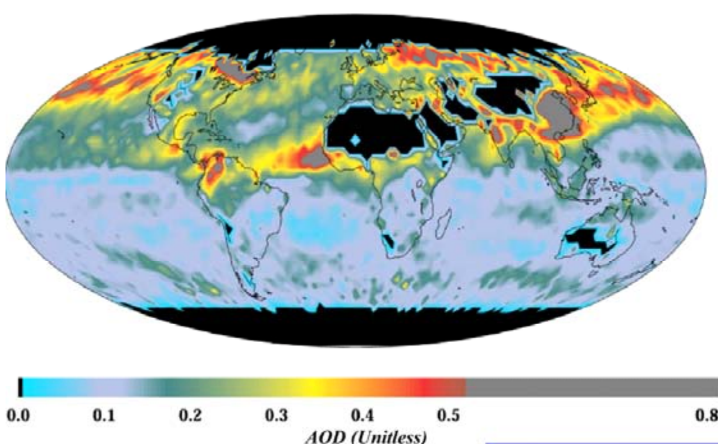

Figure 7: Aerosol optical depth for April 2001 as obtained from Terra satellite (Kaufman et al, 2002).

conditions (high aerosol loading). An important objective of the flights is also to sample clouds subject to Asian or Californian aerosols (see Figs. 7 and 9).

We will carry out about one round trip flight mission every 10 days for an entire year, collecting about forty samples of about 4000 km each (roughly the air-distance between La Jolla and Hawaii) in one year. The aircraft data will be collocated with TERRA and AQUA satellites, and data for aerosols, cloud and radiation budget from these satellites will be used to extrapolate the aircraft results to larger regional scale cloud systems in the Pacific Ocean. We will adopt the following conservative path to the operational flight goals of the three low altitude aircraft:

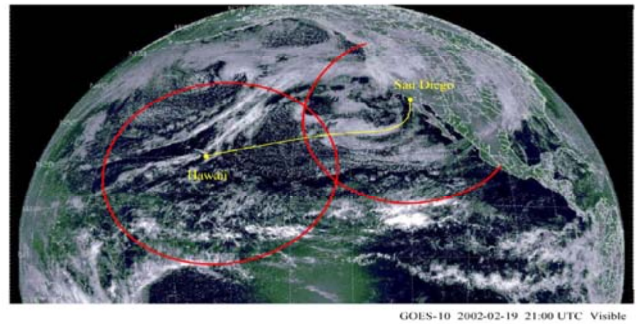

Figure 8: Possible flight tracks of GAP-FM1. The yellow line shows the La Jolla to Hawaii flight. The red circle is the 2250 km radius from La Jolla and Hawaii within which GAP-FM1 can perform out and return sampling.

Step 1 (January to July 2003): Design and build GAP-PT with 5 kg payload but limited range of 100km to 200km for limited sampling along the Southern California coast.

Step 2 (March to December 2003): Acquire and integrate the instruments with the GAP-PT and conduct limited science flights along the coast. In addition, some of the instruments have to be miniaturized to fit within the 5 kg payload. Single aircraft fights along the coast, at cloud base and in-cloud flying below 1.9 km, the currently allowed ceiling by FAA. We will also have to develop jointly with the FAA operational procedures with respect to controlled airspace.

Step 3 (July 2003 to June 2004): Design and build the GAP Flight Model 1 (GAP-FM1) that will fly between La Jolla and Hawaii with a payload of 5 kg.

Step 4 (January 2004 to December 2004), develop and integrate instruments with FM-1 and conduct research flights in a single aircraft configuration. These research flights will be between La Jolla and Hawaii and will be restricted to a single aircraft configuration.

Subsequent Steps: The success of the above MRI-funded efforts will be used to seek funding for the three aircraft operational flights.

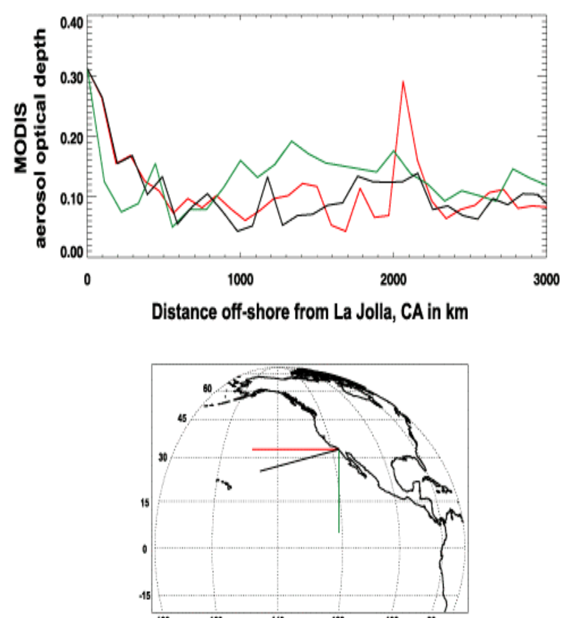

Figure 9: Variation of aerosol optical depth (AOD) as a function of distance along the three straight lines shown in the bottom panel for July 2002. The AOD is obtained from the MODIS instrument on TERRA. The high values close to the coast are the impact of Californian air pollution.

Description of the Research Instrumentation and Needs

Aircraft Development: GAP-AUAV: The success of this project depends upon the development of a low-cost fully autonomous AUAV that can be programmed to fly long-range (5000 km) missions including San Diego to Hawaii and carry up to 5 kg of instrumentation in the nose of the fuselage. This vehicle (GAP-FM1) requires sophisticated avionics software and instrumentation so that its complete flight plan (take-off, climb, cruise, loiter, and land) can be programmed into the aircraft. Moreover, it is important to keep in contact with the aircraft during its flight so that either the mission can be altered or the measured data can be examined.

Existing AUAVs are either too expensive to purchase and operate (e.g., military sponsored vehicles such as the General Atomics Predator or Northrop-Grumman Global Hawk) or do not have the range and avionics sophistication needed to complete our planned mission (e.g., Aerosonde). Currently, UCSD and Optimum Solutions are developing a low-cost AUAV, with NSF support that is capable of carrying up to five kilograms of GAP instruments on short (200 km) missions off the southern California coast. See Figure 10 for a sketch of the aircraft, GAP-PT (prototype) where the forward third of the fuselage (blue component) is designed to be interchangeable so that it can carry each GAP instrument, the mid-region of the fuselage holds the autopilot, avionics computers, fuel tank, ballistic parachute and homing device, and in the aft-fuselage a four-stroke gas engine and propeller (red) are mounted (pusher design). UCSD is concentrating on vehicle design, structural concerns and construction. Optimum Solutions, which includes mechanical and aerospace engineers that are responsible for many of the systems on the General Atomics Predator aircraft, will concentrate on vehicle design, avionics, flight control software (autopilot), and landing gear design.

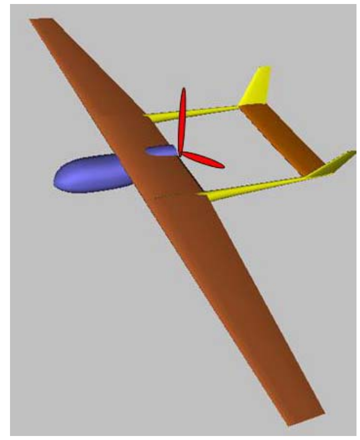

Figure 10: GAP-PT

The GAP-PT aircraft is being constructed entirely of composite materials to reduce the aircraft weight, where an autoclave and pre-preg graphite/epoxy materials are used to fabricate all primary structural components and low-cost vacuum assisted techniques are used for many of the secondary structural components. See Figure 11 for autoclave in the UCSD Composite Aerospace Structures Laboratory (CASL). The wing and stabilizer sections are fabricated in three pieces (upper skin, lower skin, internal spar) using matched mold tooling and then bonded together to produce a lightweight low-cost structure. These molds can be reused to easily make additional wing sections. A three-point retractable landing gear is included, where the nose landing gear is mounted in the nose and retracts into the fuselage, whereas the main landing gear is mounted between wing spars (central wing) and retracts into the central wing. The inclusion of the landing gear (less than 1 kg) allows one to program the aircraft to take-off and smoothly land on paved runways, as opposed to the Aerosonde AUAV which doesn't have landing gear and is considered semi-autonomous since the vehicle take-off and landing are pilot controlled. The Aerosonde is released from the top of a car traveling at 10 m/sec, then is programmed for flight, and on landing, the vehicle skids to a stop on its fuselage belly. This skidding would be detrimental to our instrument package. Another feature of our GAP-PT aircraft is its modular design, where depending upon the flight mission, one can change the wing span, landing gear, the engine and the instrument pod on the front of the fuselage. Initial flight tests are planned for late spring of 2003. The fabricated aircraft will be devoted only to the GAP program and basic autonomous flight research during the GAP grant period.

Figure 11: UCSD CASL

Table 2: *Comparison of proposed GAP-FM1 AUAV with the Insitu Group, Inc. Aerosonde*

Specifications	Insitu Aerosonde	GAP-FM1
Wing span	2.9 m	6.2 m
Weight		
empty (dry)	7 kg	8.5 kg
maximum	15 kg	21.5 kg
Fuel tank	1.75 gal	2.8 gal
Fuel weight (max)	5 kg	8 kg
Payload range	2-5 kg	5-11 kg
Engine	Insitu 4-stroke	MECOA 4-stroke
power	1.4 Hp	4.4 Hp
weight	1.9 kg	2.6 kg
Performance		
V_{stall}		6.5 m/sec
V_{cruise}	20-32 m/sec	36 m/sec
V_{max}	42 m/sec	
Altitude	< 6000 m	< 5000 m
Range		
at designed payload	3000 km / 2 kg	5000 km / 5 kg
at 2 kg payload	3000 km	6800 km
at 5 kg payload	1200 km	5000 km

In the current proposal, a long range (5000 km) low-cost AUAV (called GAP-FM1) will be developed based upon the low-cost modular design of GAP-PT and making use of the various forward fuselages that are specifically designed for the different GAP instruments. This development will require (1) acquiring and performance testing of a larger commercially available four-cycle engine, (2) increasing the size of the fuel tank, propeller, and fuselage rear portion, (3) increasing the wing span to support the increase in aircraft weight, (4) extending the fuselage booms to maintain our static and dynamic stability margins, (5) adding needed long-range flight safety hardware, (6) adding an instrument stabilization platform, (7) development of an improved autopilot and avionics system, and (8) adding a ballistic parachute, radio transponder, and homing beacon to locate the aircraft if it should go down during its mission. The GAP-FM1 aircraft will look essentially the same as GAP-PT (Figure 10) with a much larger wing span, slightly longer empennage booms, and a larger engine and fuel tank. A comparison of the specifications for our GAP-FM1 aircraft design and the existing Aerosonde (Insitu Group) is shown in Table 2, where our vehicle is designed to carry larger and heavier payloads (5 kg vs. 2 kg) for a much longer distance. This results in a larger engine, fuel tank, and structure. For example, the Aerosonde is designed to carry 2 kg of payload and 5 kg of fuel, thus to carry 5 kg of instruments, the aircraft could only carry 2 kg of fuel resulting in a limiting range of 1200 km. This is much less than the needed range of 5000 km of our aircraft. If our instrumentation minimization is successful so that we were able to reduce payload to 2 kg, then the fuel tank of GAP-FM1 can be expanded to 11 kg, resulting in a range of 6800 km.

Clearly, the success of this aircraft development involves using a reliable light-weight four-stroke engine with a minimum of four horsepower. The MECOA Kavan is one of the most outstanding engines available (Figure 12). It has a power to weight ratio (1.69 hp/kg) that is much better than almost any engine on the market including the Aerosonde motor (0.74). It is an opposed two-cylinder design that is virtually vibration free. A two magnet electronic pick up system was developed for advancing and retarding of spark which greatly improves the fuel efficiency for long-range low rpm cruising to Hawaii. It is the only mini-engine made with a "wet sump" oil system with an internal oil pump. Additional work will involve heating the incoming air by passing it over the

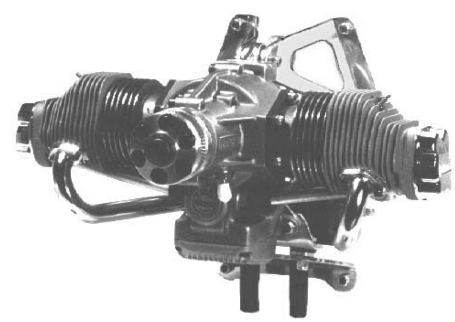

Figure 12: MECOA Kavan 4-stroke engine.

exhaust manifold to eliminate the potential of icing at high altitudes.

The programmable avionic software (autopilot), which is being developed for GAP-PT and GAP-FM1 by Optimum Solutions, results in a completely autonomous aircraft, where the complete mission can be preprogrammed using GPS navigation coordinates, including take-off, climb, cruise, loiter, and landing. The aircraft can be programmed for altitude and airspeed hold with coordinated turn rate (20 degree/sec) capabilities, or manual ground control override for mission changes or aborts. The system for GAP-FM1 will also include an onboard Motorola satellite telephone that is connected to the modem on the aircraft flight computer. The telephone is on the Iridium Satellite network (Figure 13), which offers complete coverage of the Earth (including all oceans and Polar regions, except the countries of Poland, Hungary, North Korea, and North Sri Lanka) through a constellation of 66 low-earth orbiting satellites. Each satellite covers a region of 4000 km and the network constellation revolves around the earth once per hour, so that calls are handed from one pair of satellites to another pair. Thus one can phone the airplane anywhere on a world mission from the San Diego ground station, so that its mission can be altered or experimental data downloaded at rate of 2.4 Kbps.

Fig 13: Iridium Network

Professor John B. Kosmatka of the University of California, San Diego (UCSD) has been involved with developing lightweight composite aircraft structures for the past 20 years. These efforts have been sponsored continuously by NASA, Air Force, U.S. Army, DARPA, and industry partners (Boeing, TRW, and General Atomics). During the past four years he has been concentrating his efforts on aeroelastic stability issues related to the General Atomics Predator AUAV as well as developing new light-weight low-cost AUAVs. This new aircraft development has involved looking at a wide range of designs for different payloads, and different structural manufacturing options to reduce cost. The aircraft have been built and flown in international university competitions. In the past three years, the UCSD aircraft have taken 6th, 4th, and 1st place in these competitions. The UCSD team has received valuable assistance from a wide variety of local aerospace engineering and R/C aircraft experts.

Aircraft Development Schedule: The proposed effort will follow:

(1) Aircraft Development: An AUAV aircraft will be developed for longer-range missions (one-way nonstop from San Diego to Hawaii) based upon the low-cost approach of our short-range AUAV. This design and analysis effort involves increasing the wing span and fuselage booms based upon increased engine size, and added fuel weight.

(2) Propulsion System: Three commercially available air-cooled four-stroke engines will be purchased for the project. The first engine will be instrumented and bench tested as a function of temperature. Horsepower and thrust as a function of engine rpm and temperature will be measured to get efficiencies. A 100-hour test will be preformed to insure reliability. The air intake plumbing will be routed over the exhaust manifold to preheat the incoming air to eliminate the potential for icing at higher altitudes. The two remaining engines will be used in the flight vehicles.

(3) Aircraft Instrumentation: An instrumentation stabilization platform to remove aircraft jitter from the GAP instrumentation will be developed. Satellite cellular telephone capabilities will be added and connected to the aircraft flight computers so that the airplane can be phoned during flight.

(4) Aircraft Fabrication: The aircraft structure will be constructed of advanced composite (graphite/epoxy) materials using existing materials, tools, and fabrication (autoclave) equipment at UCSD. Initially, a foam mock-up of the complete aircraft will be constructed to use in the design process so that its low-cost and modular features can be incorporated. It is planned that four aircraft structures will be built during the program. The first fuselage will be used for static proof testing and modal (vibration) testing to correlate the experimental results to the analytical finite element models. This aircraft will be tested to ultimate and then failure to make sure all safety margins are positive. The second aircraft structure will be used for initial flight testing without the autopilot and GAP instrumentation. Aircraft performance and stability margins will be measured. Fuselages three and four will be used for flight testing with the autopilot followed by the GAP instruments. A primary and secondary aircraft will be designated.

(5) Auto-Pilot Development, Calibration, and Training: The auto-pilot development will be installed and checked-out using one of the aircraft structures doing long-range (200-5000 km) flight testing in the California high desert and off the coast of Southern California.

(6) Scientific Mission: After completion of the flight tests, the vehicle will be delivered to Hawaii and flown to San Diego. This flight direction is selected to benefit from the prevailing westerly winds. The particular flight path will be presented to the FAA. No formal FAA approval is required since the aircraft is flying over at low altitudes in an uncontrolled airspace.

Instrument Development and Deployment:

The GAP-PT and GAP-FM1 will be equipped using the instruments and configurations outlined in Table 3. The platforms include an above-, in- and below cloud vehicle; an illustration depicting the flight formation is shown in Figure 6. The above-cloud aircraft measures aerosol concentration solar irradiation, and cloud and surface albedo; the in-cloud aircraft measures aerosol concentration and droplet distribution; the below-cloud aircraft aerosol concentration, cloud condensation nuclei and transmitted solar radiation. Table 3 also estimates weight and power requirements for the instruments and each platform.

The proposed MRI effort will focus on miniaturization and integration of aerosol and cloud instruments for deployment on the GAP-FM1 aircraft. The specific goals are to: 1) integrate aerosol instrumentation (CPC, CCN, OPC, inlet) into aircraft; 2) develop and test aerosol inlet; 3) miniaturization and testing of CCN counter, CM22-A pyranometer and MCAR-4 radiometer for airborne deployment; 4) integrate CDP into aircraft; 5) demonstrate autonomous operation of the instruments employing a PC-104 based data acquisition system.

Instrument Development Schedule: Our initial efforts will focus on the integration of instruments that are readily available, relatively cheap and easily deployed on the aircraft. These instruments include the CPC, OPC, aerosol inlet, CM22-A and data acquisition system. In the first phase of the project, the above-cloud platform will be developed (minus the MCAR-4) and tested on the AUAV. During this period, miniaturization of the MCAR-4, CDP and CCN will be achieved and integrated into the aircraft payload.

Obtaining unbiased aerosol samples requires a well-designed inlet suited for the airborne platform. The aerosol inlet will extend from the nose of the aircraft to obtain isokinetic and isoaxial samples outside the influences of the aircraft. Design calculations support a shrouded inlet design [*Brock and Wilson,* 1993*; McFarland et al.*, 1989]. A flow splitter will be attached to the inlet on the inside of the fuselage cage to allow sampling from each of the aerosol instruments. The splitter is necessary for instrument comparison between the CPC, CCN and

OPC, without biasing the aerosol concentration or size distribution. Smooth flow transitions and small bend angles prevent inadvertent impaction of the sample aerosol. Aerosol instruments are connected to each port of the splitter. For the in-cloud platform, an aft-facing aerosol inlet may be installed to avoid collection of cloud droplets and flooding of the instruments. This inlet will measure interstitial aerosol and its cutoff will be several micron diameter.

To maintain easy, unobstructed access to equipment inside the fuselage, a removable cage will house the aerosol instruments (i.e., CPC, CCN, OPC), camera, supporting electronics for the CDP, the data acquisition system, and the navigational system. The aerosol inlet and nose of the aircraft will be fixed to one end of this cage and slide out of the fuselage of the aircraft as a single unit. The CM22-A, MCAR-4 and CDP (radiometric and cloud instruments) are all mounted externally as close to the fuselage as possible or possibly on the fuselage itself. If possible, a gust probe will be mounted on the nose of the in- or below-cloud aircraft to measure updraft velocity. Extensive modeling simulations and wind tunnel testing will be performed to optimize placement and performance of the instruments.

The proposed instrument development plan has the following steps: 1. The CPC and OPC are readily available and relatively easy to integrate into the aircraft design. They need to be repackaged in a light-weight holder, which will be mounted in the aircraft fuselage. 2. An aerosol inlet will be mounted on the nose to allow unbiased sampling of aerosol concentrations and size distributions, and will be modeled and tested to characterize its performance before deployment. 3. The radiation instruments (i.e., the CM22-A and MCAR-4) need to be miniaturized and tested before deployment. The airborne version of the pyranometer (CM22-A) will be designed, modeled, and tested at Scripps Institution of Oceanography with CAD software to provide an aerodynamic package that can be externally mounted. Biospherical Instruments Inc. will miniaturize the electronics and repackage their commercially available multi-channel radiometer. 4. The performance of the aerosol inlet and instruments will be tested in a wind tunnel to ensure proper performance. The wind tunnel facilities will be fitted with aerosol generators and samplers to ensure proper performance. All instruments will also need to be calibrated periodically. 5. Flight missions will test the autonomous operation and validity of the data

Table 3. Instrumentation for the autonomous unmanned aircraft (GAP-FM1).

Instrument	***ID***	***Est. weight (kg)***	***Power (W)***	***Data acquisition***
Condensation Particle Counter	CPC	0.75	15.0	RS-232
Optical Particle Counter	OPC	0.30	5.4	RS-232
Cloud Droplet Probe	CDP	1.6	14.0	RS-232
Pyranometer	CM22	0.40	NA	datalogger
Multi-Channel Airborne Radiometer (405, 550, 875, PAR)	MCAR	0.30	0.1	RS-232
Cloud Condensation Nucleus Counter	CCN	3.00	25.0	RS-232
digital video camera	DC	0.50	0.1	Flash card
data acquisition system	DAQ	0.50	10	--
aerosol inlet	AI	0.30	NA	--

Estimated payload for each platform	***Payload (kg)***	***Power (W)***	***Instrumentation***
above-cloud	3.75	30.7	AI, DAQ, CPC, 2*CM22, OPC, 2*MCAR, DC
in-cloud	3.85	45.4	AI, DAQ, CPC, CDP, OPC
below-cloud	4.85	50.1	AI, DAQ, CPC, CCN, MCAR, OPC

obtained from the aerosol and cloud instruments. Post-flight information will be used to evaluate instrument performance and expose necessary modifications.

A description of the instrumentation, their function in achieving the GAP objectives, miniaturization and deployment is outlined below.

1. Condensation Particle Counter (CPC) – TSI Model 3007

Description: The CPC measures total aerosol concentrations (N) between 0 and 10^5 cm^{-3} in the diameter range (0.01 μm < D< 1.0 μm). The CPC serves as a reference for N for comparison to other aerosol measurements, and as an indicator for clean versus polluted regimes.

Miniaturization: The Model 3007 is TSI's smallest CPC (at 1.7 kg) and can be readily integrated into the fuselage of the AUAV with minimal effort. To reduce weight and volume by nearly half of the commercial version, the external case and LCD display will be removed, exposing the CPC engine (i.e., optical block and saturator) and supporting electronics, pumps and filters. The deployed package will weigh 0.75 kg.

Deployment in aircraft: The CPC engine, electronics, filters and pumps will be repackaged into a lightweight enclosure, mounted in the fuselage, with the sample line attached to the aerosol inlet. The CPC engine will be arranged such that the optics block is pointing towards the nose of the aircraft and mounted as upright as possible. This is to prevent flooding of the optics chamber during take off and landing. Depending on flight duration, a separate isopropyl alcohol bottle may be attached to the CPC to maintain a wetted column; this will require slight modification to the commercial version. The RS-232 output will relay aerosol number concentrations to the aircraft's onboard data acquisition system.

2. Cloud Condensation Nuclei Counter (CCN)

Description: Measurements of CCN are fundamental for providing the link between cloud microphysics and the physical and chemical properties of aerosol. It is this liaison that is essential to improving our understanding of the first indirect effect of aerosols. We have developed a cylindrical continuous-flow thermal gradient diffusion chamber for autonomous operation in airborne studies employing a novel technique of generating a supersaturation along the vertical, streamwise axis of the instrument [*Roberts and Nenes*, 2003].

Miniaturization: We propose to transform our current design, which weighs 10 kg (5 kg chamber and 5 kg electronics) to a compact, automated instrument that can be deployed on the AUAV platform. The finished product shall weigh no more than 3 kg and be able to autonomously measure CCN concentrations at 1 Hz at a single supersaturation between 0.13% and 2%. Based on model simulations and laboratory studies, important aspects of the instrument, such as the sensors, column dimensions and control electronics must be optimized to provide a robust, automated package. Groups at Scripps Institution of Oceanography, Georgia Institute of Technology, and Droplet Measurement Technologies will work together to achieve miniaturization of the CCN instrument.

Deployment in aircraft: The CCN instrument will be mounted in the fuselage, with sample line attached to the aerosol inlet. Currently, the CCN instrument is arranged vertically to avoid gravitational losses. Model simulations and laboratory testing will be conducted to assess the performance of the instrument in an angled or horizontal configuration. If the height of the CCN instrument exceeds the dimensions of the fuselage, an aerodynamic cover will be placed over the protruding section of the instrument.

3. Optical Particle Counter (OPC) – MetOne Model 9012

Description: The OPC measures ambient aerosol size distributions between 0.3 and 10 μm diameter. A high sample rate (> 1 lpm) improves counting statistics and increases the sensitivity for ambient aircraft measurements and the aerosol distribution may be recorded at 1 Hz.

Miniaturization: The optical detector is rugged and low cost and may easily be integrated into the platform. However, the commercial electronics provide only six channels; hence, we will utilize the small detector and modify the electronics processor to achieve measurements of the size distribution at a higher resolution.

Deployment in aircraft: The OPC sensor, electronics and pumps will be mounted in the fuselage cage. The sensor will be connected directly to the aerosol inlet to minimize biases to the aerosol size distribution.

4. Cloud Droplet Probe (CDP) – Droplet Measurement Technologies

Description: Droplet Measurement Technologies (DMT) has designed a miniature CDP based on the popular technique of collecting and measuring light that is scattered when a particle passes through a laser beam and will provide *in-situ* measurements of droplet size distributions for non-precipitating clouds [*Baumgardner et al.*, 1992; *Knollenberg*, 1981]. The CDP measures particle concentrations (up to 10^4 cm^{-3}) for diameters between 1 and 70 μm. The classification of particle sizes is possible in resolutions up to 256 bins at 1 Hz, from which cloud liquid water content can also be derived.

Miniaturization: The CDP developed by DMT may readily be incorporated on the aircraft. The electronics have also been miniaturized onto a single card using Field Programmable Gate Array Technology and will be integrated into the fuselage of the aircraft. The current probe mounting system may not by the best choice for this aircraft and may be slightly modified to better fit the CDP to the AUAV.

Deployment in aircraft: The CDP will be externally mounted on the wing or fuselage such that the probe measures outside the influence of the aircraft to avoid biasing the particle size distribution. Power and data acquisition cables connect the probe to the electronic processor in the fuselage.

5. CM22-A Pyranometer – Kipp & Zonen

Description: The CM22 pyranometer accurately measures total hemispherical solar irradiance for a broad spectral range between 0.200 – 3.6 μm. Downward solar irradiance is the fundamental quantity from which the earth obtains its energy and is measured by an upward-facing horizontal pyranometer. Conversely, a downward-facing horizontal pyranometer measures the amount of downward solar irradiance reflected by clouds or the earth's surface – the ratio of upward and downward solar irradiance yields the albedo of the clouds or earth's surface.

Miniaturization: The commercial instrument (CM22) weighs 0.85 kg will be repackaged in a smaller, aerodynamic housing to reduce the total weight of the instrument to ca. 0.3 kg (CM22-A) and mounted in the airstream above and below the center of the wing. Researchers at Scripps Institution are currently redesigning the sensor housing to achieve a smaller, aerodynamic design to be externally mounted in the airstream to ensure thermal equilibrium between the sensor and housing. Instrument performance and stability will be tested using computer modeling and experiments in a wind tunnel. A temperature sensor will be mounted to the CM22-A for temperature compensation..

Deployment in aircraft: Upward and downward facing sensors will be mounted horizontally on the fuselage or wings. Our goal is to mount the radiometers on a gyrostabilized platform to maintain a horizontal platform parallel to the earth's surface. Data will be recorded via a datalogger.

6. Multi-Channel Airborne Radiometer (MCAR-4) – Biospherical Instruments, Inc.

Description: The multi-channel airborne radiometer measures irradiance with center wavelengths at:

- 405 nm where ozone absorption is zero to measure aerosol scattering.
- 550 nm for comparisons with satellites (i.e., MODIS)
- PAR (400 to 700 nm) to measure photosynthetically active radiation
- 875 nm where water absorption is small to measure aerosol scattering.

Upward-facing sensors will measure total irradiance to allow comparison with satellites.

Miniaturization: Biospherical Instruments will redesign and miniaturize their commercial instrument, which weighs 0.85 kg, into smaller housing to reduce the total weight of the instrument to ca. 0.3 kg. Scientists at Scripps Institution will work with Biospherical Instruments to repackage and integrate the radiometer into the AUAV platform.

Deployment in aircraft: Upward and downward facing sensors will be mounted on the wings and on the gyrostabilizers with the pyranometer.

Impact of Infrastructure Projects

This multi-disciplinary project will integrate research with education at three different levels. First, students from both the disciplines of atmospheric science and aeronautical engineering will be engaged in the development of the aircraft and the instrumentation. One undergraduate student is presently employed in generating CAD drawings of the proposed miniaturized versions of the aerosol, cloud and radiation instrumentation, and two undergraduate aerospace engineering students will be involved in the design and testing of the AUAV aircraft. One SIO graduate student and two engineering graduate students will also be directly involved in the development project. Following the initiation of research flights, graduate students will be involved in both the flight operations and the analysis of the resulting data sets as a part of their dissertation research. Furthermore, a formal undergraduate teaching and training program will be developed in conjunction with the flight operations. The program will allow undergraduate students to gain hand-on experience with the aircraft platform, the sampling instrumentation and will play a role in operations of research flights. Following their participation in a research flight, students participating in the undergraduate program will receive an introduction to the atmospheric sciences through directed research projects involving analysis of data from the flights. The undergraduate program will be coordinated with the Scripps Institution of Oceanography Undergraduate Research Fellowship (SURF) program, which provides funding to introduce underrepresented undergraduate students to research in the marine and Earth sciences.

Second, this project provides a unique opportunity to develop a world-class graduate-level three-course focus sequence that concentrates on; (1) Design and Development of Autonomous Unmanned Aircraft, (2) Atmospheric Research using AUAVs, and (3) Autonomous Vehicle Design and Build Laboratory. UCSD science and engineering students that take this sequence will be uniquely qualified as leaders in this exciting research field of using AUAVs as instrument platforms for performing monitoring science in extreme environments (altitude, climate, location, etc). No other university educates students in this multi-disciplinary field, which will get more exciting as sensors get smaller, and vehicles become cheaper, smaller, and more reliable.

Third, and most importantly, the scientific data and the flight data that is recorded during these flights will be shared, via a UCSD internet site, with the research community, as well as with younger pre-college students to introduce them to the exciting fields of atmospheric science, global research, and aircraft design. The site will be regularly updated with development and design information, up-to-date status of research flights and research results. The site will be maintained by the graduate and undergraduate students involved the research activities, and therefore serve as an educational tool through their development of materials for the site while providing a vehicle for communicating the results of their activities to the research community. Furthermore, the site will serve as a recruitment tool for both undergraduate and graduate students by advertising opportunities to participate in the research activities.

Development of the AUAV platform and demonstration of its applicability to atmospheric environmental sampling will pave the way for expanded academic/industry partnerships through the production of AUAVs as part of a global observing system. As a result, the platforms and instruments developed under this MRI will be used by faculty and students from many atmospheric sciences departments in the US, in addition to faculty and students within SIO and engineering departments within UCSD. The development project supported by this MRI initiative will occur in collaboration with several industrial partners: Optimum Solutions in AUAV development, Biospherical Instruments and Droplet Measurement Technologies in the miniaturization of the narrowband radiometer and cloud droplet probe. Following the successful demonstration of the AUAV platform for cloud sampling, further funding will be sought for the production and deployment of additional instrumented AUAVs. This will occur in tandem with the commercialization of the miniaturized cloud-aerosol-climate sampling instruments, thus making low-cost AUAV atmospheric sampling available to the atmospheric sciences community.

Project Management Plans

V. Ramanathan will serve as the overall PI of the project. The PI has extensive experience with the management of large multi-institutional and multi-disciplinary experimental projects such as CEPEX and INDOEX. J. Kosmatka will have the primary responsibility for the development of the AUAV. V. Ramanathan will have the primary responsibility for the instrument miniaturization and integration part of the proposal assisted by Dr. Greg Roberts, a researcher in Ramanathan's lab, who will be the scientist in-charge of the instrument effort. The miniaturization of the CCN instrument and the adaptation of the pyranometer, the CPC and the OPC for the AUAV will be undertaken at SIO. The cloud droplet spectrometer development will be the responsibility of W. Dawson of Droplet measurement Technologies, Boulder, Colorado. Once a month we will have a design review team meeting between Kosmatka's group, Optimum solutions and Ramanathan's laboratory. These meetings will serve to document the design of aircraft, changes as they are made and development of aircraft-instrument integration packages. The first meeting (to be held in fourth to fifth week of January) will be used to confirm the agreed upon plan and make a detailed schedule for the developmental activities. Changes to the agreed upon design and instrument packages will be made only after getting written approval from the PIs. After successful test flights, the PIs will initiate the education and research training activities within the campus.

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