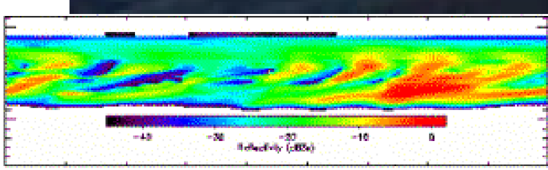
REVIEW OF
THE U.S. DEPARTMENT OF ENERGY'S
ATMOSPHERIC RADIATION MEASUREMENT (ARM)-
UNMANNED AEROSPACE VEHICLE (UAV) PROGRAM

FALL 2002 - Oklahoma



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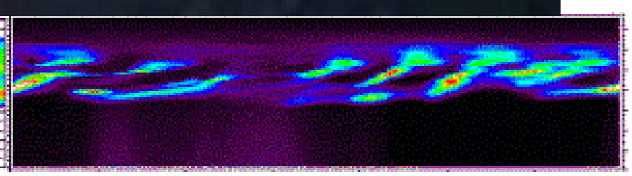

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December 2002

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Biological and Environmental Research
Advisory Committee

TABLE OF CONTENTS

EXECUTIVE SUMMARY

The Biological and Environmental Research Advisory Committee (BERAC) has a standing Subcommittee that oversees the DOE's involvement in the U.S. Global Change Research Program (USGCRP). This Subcommittee recommended in March 2001 that "the DOE management conduct an independent review of the usefulness and uniqueness of the Unmanned Aerospace Vehicle (UAV) compared with other methods of obtaining the same data." UAVs are one of the major observational components of the Atmospheric Radiation Measuring (ARM) Program that is a part of the USGCRP.

A special working group was convened on February 7-8, 2002, and charged with addressing the appropriateness of UAVs in supporting the scientific goals of ARM, its operational approach in making the needed measurements, and the reasonableness and appropriateness of the budget and adequacy of resources. Experts working in the field presented their views, reviewed the past work, and discussed future plans.

The working group concluded that UAVs are a very appropriate method of making the observations necessary to achieve the goals of ARM and that the operational approach in use is appropriate. The present budget is appropriate; however, the recommended merging of the ARM infrastructure and the ARM-UAV budgets should be carried out to provide additional flexibility.

The working group recommended that the UAV program be continued using its strategy of employing UAVs and UAV surrogates. The use of UAVs has to be made easier and less complicated in order to achieve maximum benefits from the vehicle. Increased availability through partnerships with other agencies, reduction in insurance costs, and increased accessibility to airspace would aid in this issue.

UAV data have to be used more widely and the subsequent analyses and data have to be brought to the attention of the community through increased publication of papers, attendance at broad general and specialized scientific meetings, and inclusion in ARM Science Team calls for proposals to use and analyze the UAV data.

Information regarding newly developed instrumentation and systems needs to be publicized and made available as soon as possible to potential users.

The ARM-UAV program needs to find a way to fund scientific researchers to make more effective use of ARM-UAV data. More funding should be made available to mission scientists and to the science team to make the results more useful and increase productivity. By merging support for ARM infrastructure and the ARM-UAV programs into a single category will provide the Program Manager with the necessary flexibility to carry out a unified program.

INTRODUCTION

The Atmospheric Radiation Measurement-Unmanned Aerospace Vehicle (ARM-UAV) Program is a multi-laboratory program funded by the Department of Energy's (DOE) Office of Biological and Environmental Research (BER). UAVs originally developed by the Department of Defense (DOD) for surveillance purposes are being used by the ARM Program as remotely piloted platforms for making surface and atmospheric measurements for climate applications.

UAVs offer significant advantages in that they can fly at high altitudes for long periods of time. These two features are important when studying changing cloud fields and their effects on the solar and thermal radiation balance of the atmosphere. The ARM-UAV Program also is trying to exploit the high altitude capability of UAVs to provide measurements that would allow calibration of satellite radiance products and validate their associated flux retrieval algorithms, but this is not the primary goal.

To accomplish the scientific goals necessitates the improvement and development of instrumentation and technology for observing radiative fluxes, cloud properties, and *in situ* water vapor. Instrumentation not only has to be designed and developed, but also miniaturized to fit into small spaces and also be lightweight. Not only is this program multi-disciplinary, but one that is evolving in time and also in its ability to make observations at higher altitudes.

The Earth's surface varies greatly over land and water. There are major differences between the poles and the tropics. In order to achieve some understanding of these differences, especially the effects of clouds and other atmospheric properties, the ARM Program has set up three intensively instrumented field sites referred to as Cloud and Radiation Testbeds (CART). The first and largest ARM-CART site is in the Southern Great Plains (SGP) (Oklahoma and Kansas), a second on the North Slope of Alaska (NSA) and the third in the Tropical Western Pacific (TWP). Data are collected in an operational mode and are made available in near real time. Thus, it is possible for scientists to participate in experiments from their home institutions rather than at the field sites. The use of this distributed facility allows many scientists to take part in the program, not only from the U.S., but also from locations outside the U.S.

RESPONSES TO THE CHARGE

The Working Group was requested to focus on the field component of the UAV program. It was asked to evaluate the program in three areas. A brief response is provided for each of the areas.

(1) The appropriateness of using a UAV to support the scientific goals of the Atmospheric Radiation Measurement Program.

After listening to the information presented during the meeting and reviewing the material available to the working group, there is little doubt that use of UAVs is a very appropriate method of making the observations necessary to achieve the goals of the ARM Program.

(2) Appropriateness of the UAV operational approach for making these measurements and/or investigating the related scientific questions.

The operational approach that is and has been used regarding UAVs is an appropriate way to make the necessary measurements and observations that are the basis of the investigations carried out by the ARM Program.

(3) Reasonableness and appropriateness of the budget and adequacy of the resources.

The ARM-UAV budget has essentially been level funded, at about $2.7 M, for each of the past 5 years. The current plans for a Grand Tour - SGP in FY 2003, NSA in FY 2004, and TWP in FY 2005 - are ambitious within this fixed budget. Nevertheless, it should be doable given the changes proposed by the Program – i.e., transition to an operational payload rather than a developmental payload and the use of a single high altitude aircraft rather than two aircraft (high and low altitude). The committee feels that the current budget is appropriate. The merging of the ARM-UAV and ARM infrastructure budgets will provide some flexibility at the margins. There are some suggestions made in the text that could lower costs and thus provide additional resources that could be used by the ARM-UAV Program.

RECOMMENDATIONS

1. The Unmanned Aerospace Vehicle (UAV) program should be continued as a component of the Atmospheric Radiation Measurement (ARM) program. UAVs are the best way to accomplish the science necessary to "close the box" at the top and sides of an atmospheric column to achieve ARM's goals and objectives. Should the data be useful to validate satellite observations, then that could be done, also.

2. The current strategy of using a mix of UAVs and UAV surrogates (e.g., the optionally piloted Proteus) is a good one and should be continued.

3. The use of UAVs has to be made less complicated if ARM is to receive maximum benefits from this unique vehicle. The program could benefit from:

    a. <u>Increased availability</u> – A working partnership with NASA should be established that would allow both DOE and NASA to have needed UAVs available when necessary. Relations with NASA already are very good so such a working relationship should be possible. ARM-UAV also should explore partnerships with other agencies that might have either an interest or a need. This would provide leverage for mutual efforts to develop appropriate architectures, standards, and technologies so UAVs will be able to operate in the National Air Space (NAS).
    b. <u>Reduced insurance costs</u> – If NASA or any government agency owned the UAV, the government would self indemnify thus significantly lowering the cost of operations.
    c. <u>Accessibility to air space</u> – Agreements for use of the air space are made on a case by case basis; however, the DOE needs to work closely with industry groups and the Federal Aviation Administration (FAA) to certify the UAVs and improve airspace access for them.

4. Information about newly developed instruments and systems now in use or soon to be used for the ARM-UAV program should be made available as soon as practical to other potential users.

5. UAV data needs to be more widely used by the scientific community. This implies more ARM analyses. It also means finding scientific researchers who will make more effective use of the data. At present data analyses have been done by a dedicated group of volunteers who have designed, developed, and carried out an extremely important and unique program. This activity is the foundation of an atmospheric radiation program that is seminal to the understanding of climate. Accompanying data need to be brought to the attention of the ARM Science Team as well as the broader scientific community. This can be accomplished through inclusion of ARM-UAV data analyses in ARM Science Team calls, published papers, attendance at broad scientific meetings as well as specialized meetings that are closely related to ARM science activities.

6. The ARM infrastructure and UAV programs should be components of a single budget category. They have been heretofore considered as separate entities when, in fact, the fiscal resources are drawn from the same source. The intent of the ARM-UAV program to fund mission scientists and of the ARM program to include analyses of data from Intensive Operational Periods (IOP) in future Science Team calls are significant steps in the right direction.

HISTORY OF THE PROGRAM

The concept of using Unmanned Aerial Vehicles (UAV) as platforms for carrying instruments to observe the atmosphere and its underlying surface has been considered for many years. In the early 1980's Boeing developed the *Condor* UAV for military use. Interest has increased in recent years owing to the increased use of such vehicles for military purposes and for civilian research programs such as those required for climate research. The potential for operations at high altitudes (above 20 km) for long periods of time (greater than 24 hrs.) and at low speeds has made UAVs desirable as observing platforms for atmospheric and remote sensing research.

Several UAV-based research activities have been established and funded by agencies within the U.S., e.g., NASA and DOD/ONR. The DOE has established a UAV-based measurement component as an element of its Atmospheric Radiation Measurement (ARM) program. The evolution and development of these activities have been complementary to each other.

ARM-UAV was originally developed as a part of the Atmospheric Remote Sensing and Assessment Program (ARSAP) jointly with DOD. It was designed as a part of the global environmental change thrust of the Strategic Environmental Research and Development Program (SERDP). ARSAP was funded from FY 1991 through FY 1995 to develop improved measurements for studying the Earth's atmosphere. DOD focused on the stratosphere and the mesosphere while DOE focused on the troposphere. ARSAP's goal was to develop improved measurement techniques that could contribute to an enhanced understanding of the Earth's atmosphere and its role in global climate change.

The ARM-UAV program contributes to this goal in two major ways. First, by incorporating new instruments and data systems onto UAV platforms and adapting other instruments to the UAV environment. Second, by demonstrating that UAV platforms are able to operate under conditions that other aircraft cannot.

Four phases of activity were designed to meet the scientific and technological objectives. Phase I (1993) demonstrated the viability of making atmospheric profile measurements of clear air radiative fluxes and related atmospheric variables with a single UAV platform. Phase II (1995) showed that formation flight with a manned aircraft and a UAV platform and coordinating observations from both aircraft with surface and satellite observations was possible. Phase III (1999) extended the operational altitude of the UAV to 16 km while still acquiring scientific data. Phase IV (2003) will seek to provide measurements from a UAV up to altitudes of 20 km. Where necessary, manned-UAV-surrogates (the piloted Egrett and the optionally piloted Proteus) will be used until the necessary UAV capabilities are available.

Phases I to III have been successfully accomplished. Significant firsts include: first scientific flight of a UAV; stacked formation flying of a UAV over clouds and a manned aircraft under clouds; demonstration of continuous diurnal measurements in a 26 hour non-stop flight; and attainment of mission altitudes up to 55 kft (17 km). Necessary radiative flux and cloud property payloads have been developed and 8 scientific campaigns have been conducted. Attainment of 20 km altitudes is awaiting further UAV development outside the purview of this program.

A summary of details of the operation of the ARM-UAV program is available in an article titled, “The Department of Energy’s Atmospheric Radiation Measurement ARM) Unmanned Aerospace Vehicle (UAV) Program” published in the *Bulletin of the American Meteorological Society*, **81,** 2915-2937.

PREVIOUS REVIEWS

The subject of the ARM-UAV program has been discussed for many years as a part of the continuing review of DOE's participation in the U.S. Global Change Research Program (USGCRP). The Biological and Environmental Research Advisory Committee (BERAC) has a standing Subcommittee that was established in 1995 to oversee and review the DOE's participation in the USGCRP.

The first report of the Subcommittee noted that the ARM-UAV program "has great potential for innovative measurements that will complement ARM observations and other field research efforts. It appears to be moving closer to an operational phase with Department of Defense support. Support should be given, if possible, within present budget constraints. *It is a very important program."*

The Subcommittee in December 1998, while reviewing issues and discussing the budget of DOE's involvement in the USGCRP, commented on the ARM-UAV program. "The Unmanned Aerial Vehicle (UAV) program is an important part of the overall ARM program. The UAV provides scientists with a way to make observations that would otherwise be very difficult. This is shown in the tropical cirrus cloud work that already has been accomplished and whose analyses will be undertaken in FY 2000. Research aircraft, manned and unmanned, are an integral part of the ARM program, especially for sampling of aerosols and similar measurements. At present the major emphasis is on measurements of the lower and middle troposphere. The Subcommittee feels that there is additional need to obtain upper tropospheric water vapor measurements, as these will be important for understanding climate change issues . . . . The Subcommittee recommends that the DOE work with its federal partners within the USGCRP to find a means of addressing the important problem of measuring water vapor concentrations. In broader terms, the Subcommittee recommends that USGCRP agencies survey aircraft availability and needs across the interagency program and work together to obtain any additional needed capacity."

The JASONS reviewed the ARM Program during the Summer of 2000. Although the UAV component of the program was not discussed specifically, the review did discuss ARM observational programs, especially the ARM Enhanced Shortwave Experiments (ARESE I and ARESE II). It is implicit in the review that when aircraft are mentioned, as they are in the review, those aircraft would be principally UAVs and their surrogates as fielded in the ARM-UAV program. It is clear that the UAVs are very important to the experimental design and ultimately to the success of the field programs.

The latest review of DOE's participation in the USGCRP was carried out by the Subcommittee in May 2001. In the section of the report devoted to accomplishments, the ARM-UAV program received the following comments:

"Operations: The ARM-UAV program conducted the first successful flight of a UAV in class A airspace and the first science measurements from a UAV were taken on station continuously for more than 24 hours. The program also made the first science measurements above 16 km. (The UAV platforms deployed under the auspices of the program are the Gnat-750, the Altus and

Altus-II UAVs provided by General Atomics Aeronautical Systems Inc.). The UAV program developed a mature data system that provides direct real-time downlink of the data to the instrument mentor during flight and an archive that provides access of the data by the general science community. The program developed aircraft operational *systems* that allow for the formation flying of multiple aircraft that enables close coordination of cloud observations from two or more aircraft.

Instrument development: The UAV program developed a versatile and powerful payload capacity that includes active systems such as millimeter (mm) radar and lidar as well as passive spectrometer and radiometer systems. The addition of these instruments provides a capacity to measure parameters such as water vapor and cloud properties at previously unattainable *in situ* resolutions.

Campaigns and fundamental physics: The program conducted several campaigns with findings important for testing and improving model parameterizations. In the two ARM Enhanced Short-wave Experiments, the program measured absorption by liquid water clouds using unique flight and sampling plans. These experiments led to: (a) a better appreciation of the role of clouds and radiative processes, (b) new approaches to experimental design, (c) improved instrumentation for measuring broadband and spectral radiation quantities, (d) unique data sets describing radiation absorption in clouds and other physical properties of clouds, and (e) advanced tests of the ability of climate models to calculate radiation absorption in clouds. Flights involving the Altus resulted in: (a) improved calibration of instrumentation on geostationary and polar orbiting satellites used for estimating the top of the atmosphere radiation budgets, (b) enhanced measurements of spectral albedo of different surfaces types at a wide range of solar zenith angles, and (c) new techniques for the sensing of cloud optical properties, all of which are important to reducing uncertainty in climate models."

In the recommendations section of the report, the following language was noted. "The Subcommittee heard about the use of the unmanned aerial vehicles (UAV) as another tool to carry out special measures in conjunction with other ARM measurement systems. The UAV can perform measurements that cannot be obtained by satellite and ground based *systems;* however, the Subcommittee was not convinced that the same measurements could not be obtained using manned aircraft at possibly lower cost."

"UAV Recommendations: The Subcommittee recommends that the DOE management conduct an independent review of the usefulness and uniqueness of the UAV compared with other methods of obtaining the same data."

SCIENTIFIC ASPECTS

The primary scientific focus of the ARM-UAV program is on radiation-cloud interactions. Uncertainties in how clouds interact with the Earth's solar and thermal radiation account for almost the entire factor-of-three variation in the predicted temperature rise for a doubling of carbon dioxide (CO_2). Some of these uncertainties can be addressed using ground-based measurements that are made routinely in the ARM program. Others need measurements from within the atmosphere.

The unique capabilities of UAVs offer excellent opportunities to meet the scientific goals of ARM. The pioneering contributions made by ARM researchers using UAVs have been recognized by the atmospheric science and radiation communities. The increased understanding of radiation processes resulting from ARM and ARM-UAV measurements already has allowed new parameterizations to be developed in GCMs used at the European Centre for Medium-Range Weather Forecasts (ECMWF) and Goddard Institute of Space Sciences (GISS).

At the SGP Site, a wide variety of surface-based *in situ* measurements provides a comprehensive characterization of the lower boundary of an imaginary column of the atmosphere that might represent a "grid box" in a numerical weather or climate model. Rawinsondes and surface-based remote sensing instruments provide limited information about the atmosphere within the column. This information can be compared with retrievals from satellites both to validate the satellite products and ultimately to extend information to regions where no conventional measurements exist. Unfortunately, however, satellites view the SOP site at an angle, thus the atmosphere and constituents within it (clouds, aerosols, etc) are actually not over the SGP site, which complicates the validation process. UAVs, by flying directly over the SGP site for extended and regular periods, can act as a local geostationary satellite and provide the information needed at the top of the column to close this side of the "grid box."

There have been two Atmospheric Radiation Measurement (ARM) Enhanced Shortwave Experiments (ARESE). These experiments were motivated by the need to know the amount and location of solar energy absorption. That is the key to understanding the general circulation of the oceans and the atmosphere and to an understanding and prediction of climate change. To have successful experiments necessitated a reexamination of the basic physics underlying the absorption of solar radiation within clouds, possible modification of climate models, and a change in remote sensing techniques.

The first measurement campaign, denoted ARESE I, was conducted from September 25 to November 1, 1995, at the ARM central and extended facilities in North Central Oklahoma. The overall objectives were to:

- directly measure the absorption of solar radiation by the clear and cloudy atmosphere and to place uncertainty bounds on those measurements and

- investigate the possible causes of absorption in excess of model predictions.

ARESE I did find solar absorption to be in excess of model predictions, but there were few samples and some inconsistencies between some of the measurements. This caused increased controversy in the community.

Because of the reported magnitude of the enhanced cloudy sky absorption and its potential impact on climate modeling, ARESE II was planned and carried out between February 15 and April 15, 2000, also at the SGP site. It focused on the same scientific questions as ARESE I, but was structured to:

- provide more observational cases,
- have two or more independent instruments measuring each of the key parameters
- provide extensive pre- and post-mission calibrations.

The major conclusions from the experiment were that observed absorption is somewhat greater than calculated, but the observed discrepancies were smaller than for ARESE I. Why these differences exist is not known; however, the problems are being addressed by the scientific community.

Another experiment known as the Kauai Experiment was conducted in the Spring of 1999 focusing on sub-tropical cirrus clouds. Cirrus clouds cover a large area of the Earth and dramatically affect the atmosphere's radiation budget. In addition they are a fundamental component of the water budget of the upper troposphere and produce feedbacks in the climate system whose effects are highly uncertain.

The Kauai-99 experiment obtained measurements that provided a way of relating radiative properties to cloud properties and a way of testing surface and satellite methods for obtaining this information.

<u>Enhancement of Cloud and Radiation Testbed (CART) Site Data Sets</u>:

A major challenge for global climate modelers is to extend the data gained from the vertically-resolved single-column sampling above the CART sites to knowledge of the parameters and processes in an extended volume surrounding that column. A UAV orbiting the boundaries of a defined volume would aid this effort by making measurements from which the horizontal fluxes of heat, moisture, and condensed water could be calculated.

With measurements from the larger atmospheric field surrounding the column above the CART site, predictions of cloud fields could be more accurate. Sampling of cirrus properties in a broad area above a CART site would greatly aid in the understanding of radiances. If a high-altitude UAV in a tight orbit above an area of interest is thought of as a low-altitude geostationary satellite, there is then the opportunity for parallax-free cloud field measurements from the actual top of the column. This would greatly aid in local calculations of radiation budget. A UAVs ability to fly precise and repeatable flight tracks offers an opportunity for intensive sampling of cloud properties.

Many of these ideas and concepts already have been tested or are planned to be tested. Although much of the text material above deals only with scientific objectives and findings, it is crucial to acknowledge that none of this would be possible without the instrumentation that has been developed and without the aerial platforms to carry that instrumentation. In many of the experiments, UAVs have played major roles while in others only manned aircraft have been used. More commonly, a mixture of manned and unmanned aircraft has been used.

Science Opportunities at the CART Sites:

Planning continues at all the CART Sites. An experiment is planned at the SGP site during the Fall of 2002. Its goals are to close the top of the column's radiation budget, observe condensed water advection in and out of the column, observe cloud properties, remotely sense their boundaries, and make *in situ* measurements of microphysical properties. This experiment will be conducted together with an Intensive Operating Period (IOP) looking at single-column models.

At the NSA site, a campaign will be held in April-May 2003 that will focus on interplay between clouds, radiative heating, and changing surface albedo during the rapid onset of snowmelt.

Since the TWP site at Nauru is beyond the range of instrumented conventional aircraft, UAVs have to be used that are flown from small airfields on that or nearby islands. To aid in attaining the objectives of ARM in the tropics, a fourth site has been built at Darwin, Australia with the help of the Australian Bureau of Meteorology (BOM). That site opened on July 30, 2002. The Australian BOM will maintain that station as well as the two stations that make up the TWP site. A joint campaign to be held over the Darwin site is being planned for 2004.

Worldwide Sampling:

With the increased duration and higher altitudes realizable by UAVs over conventional aircraft, long-term, routine monitoring of atmospheric parameters at or above the tropopause becomes possible. Long-duration monitoring from tropopause altitudes can be further exploited either for a selected small area (station keeping by a slower vehicle) or for large areas (with a faster platform), say across an ocean or a continent.

Support of field campaigns:

For the reasons stated above, UAVs should be included as an integral component of any proposed site. Sondes dropped from an overflying UAV would greatly enhance the data set from any CART site, existing or proposed. Portable "fly-away" CART-like instrument packages should be developed to be used in conjunction with UAVs. These would be small stand-alone instrument packages similar to those used at CART sites. They could be suitable for flying unattended on UAVs or other aircraft thus providing ground-based and air-based measurements using similar if not identical instruments.

A UAV could be a viable part of a wide variety of field campaigns in atmospheric research. Because the crew requirements could be far less demanding than for conventional aircraft, the number of days in the field as well as more efficient use could be greatly increased. Use of a UAV with short-field capability would allow extension of field campaigns into areas where only short runways are available. A UAV might be flown in certain atmospheric conditions that would be too risky for an inhabited aircraft. Among these are measurements in fields of high electrical potential, plumes containing toxic substances, and standard measurements around tornadoes and hurricanes. Interagency cooperation should be exploited, with a view toward campaigns that would benefit from the unique capabilities of a UAV.

OPERATIONAL ASPECTS

The appropriateness of the ARM-UAV operational approach for making measurements and/or investigating related scientific questions deserves to be examined from several perspectives.

Measurement Challenges

Remote sensing and *in situ* measurements are required to characterize the solar and IR radiation environment driving the Earth's climate system. Evolving science questions drive the measurement objectives, and define the experimental approach (sensors, flight profiles, etc) to meet those objectives. ARM-UAV scientists and operational support groups, working in concert with the broader ARM and atmospheric science community, defined an experimental approach that requires access to the top of the atmosphere (TOA) in order to measure the incident, reflected, and emitted energy as well as the effect of clouds on the radiative balance. This requires the ability to make measurements from the surface to perhaps as high as 55,000 feet (16.8 km) in the tropics and as far north as the North Slope of Alaska (NSA). Flights extending over one to several diurnal cycles are highly desirable. Slow flight speeds are needed to match the airborne measurements to the scale of complementary ground measurements.

Sensors, aggregated to payloads, are defined by the experimental approach. They are constrained by budget and aircraft performance capabilities (payload volume, weight, power, aircraft configuration, etc.). The need for sensor operations across a wide range of environmental conditions (temperatures and pressures) for extended times brings new engineering challenges similar to space-borne payloads. The evolution of technology, mission measurement requirements, and programmatic constraints requires flexible platform, payload, and mission architectures.

Candidate Platforms

The experimental approach, typical of ARM-UAV missions to date and those expected in the foreseeable future, require specialized platforms that are capable of making measurements to altitudes in excess of 50,000 ft for long periods of time and at slow speeds. The few civilian platforms that can meet these requirements are listed in the table below along with comments on operational considerations. Nominal maximum values are provided in the table.

Platform	Altitude (ft)	Duration (hr)	Speed (mph)	Payload (lbs.)	Comments
ER-2	65,000	8	300	2000	NASA owned & operated
WB57	55,000	8	500	2000	NASA owned & operated
Altus II UAV	55,000	24	200	330	ARM-UAV payload
Pathfinder+ UAV	80,000	16	30	100	Tech development platform
Proteus	55,000	8	350	2000	Tech development platform
Balloons	110,000	24+	wind	1000	Vertical profile only

The ER-2, WB-57, Proteus and Pathfinder have limited duration that precludes diurnal measurements. The Pathfinder + is a technology demonstrator (extreme duration) not suitable for present ARM-UAV payloads. The Proteus aircraft was developed as a UAV subsystem and as a commercial communications technology demonstrator has supported airborne science missions for NASA. Balloons designed for vertical profiling have the altitude and payload capability, but lack the trajectory control required for the science requirements that have been identified. The Altus II UAV is best matched to the needs of the ARM-UAV missions and the ARM-UAV team has had considerable experience with this vehicle. The availability of the NASA platforms is limited, however, arrangements can be coordinated through the Earth Science Enterprise Suborbital Science Program Manager.

General Atomics/Aeronautical Systems Inc., the manufacturer of the Altus UAV platform, is developing with NASA a next-generation Altair UAV that will have 30-40 hour duration, 55,000 ft ceiling, a certified power-plant, over-the-horizon (OTH) ability for operations, and an enhanced payload capability leading to a reliable and flexible science platform that will be well suited to the ARM-UAV measurement requirements. This vehicle is expected to demonstrate a meaningful science capability in the next year. If as expected, the DOD utilizes the military variant, the logistics chain will be developed to make this platform operational, thus providing a platform capable of meeting the ARM-UAV measurement requirements over the next decade.

AeroVironment is developing a long-duration concept of the Pathfinder + UAV (Helios) that would be capable of multi-day (months) flight for commercial communications and remote sensing applications.

The working group sees the Altus UAV as the best match for the present ARM-UAV measurement requirements. It is encouraged by the development of the new Altair and Helios platforms to meet longer-term operational needs.

Operational Challenges

UAVs offer the potential to be the workhorse for airborne science. They come with operational challenges that deserve special considerations. The platform technology is an extension of extensive work for conventional aircraft, however the regulatory environment has been slow to establish a framework for operations in the National Air Space (NAS). The FAA, NASA and the DOD are working to develop NAS architecture, certification standards, and subsystem technologies (such as communications, see and avoid, etc.) for this new class of aircraft. While it is not clear when the FAA standards will be codified, UAVs now operate under a Certificate of Authorization (COA) that will meet the near-term needs of ARM-UAV missions. This does require that a Government sponsor certify that the aircraft is airworthy. DOE will need to see that this sponsorship is provided, either internally or through a partner such as NASA or DOD. The working group recommends that ARM-UAV explore a partnership with NASA in order to leverage their mutual ongoing efforts to develop appropriate architectures, standards, and technologies to operate UAVs in the NAS.

Comments on the ARM-UAV Approach

The ARM UAV team has pioneered the use of UAVs in airborne science. They have anticipated the need for a high-altitude, long-endurance (HALE) capability thus meeting their mission requirement to make diurnal measurements at the tropopause. The UAV industry has kept pace It now is developing third-generation platforms with certified power plants capable of flying at high altitudes and at thousands of miles from ground controllers. The insightful modular payload/data monitoring approach provides the ability to monitor data quality as well as dynamically modify the flight to ensure mission success. The ARM-UAV team has done an outstanding job.

OTHER FINDINGS

The ARM-UAV Program as a whole, as well as its links with the goals of ARM and global change science, is unique and unparalleled in the world. The design is based on the synergy of not only a variety of instruments on a single platform, but also the combination *of in situ* surface observations, retrievals from surface-based remote sensing devices, satellite data, *in situ* and remote observations from aircraft, and numerical models. This synergy among observations and modeling provides a powerful tool that exceeds the capability of any of these components individually for addressing many of the important science questions that are outstanding in atmospheric research today. This is particularly apropos to ARM in its endeavor to improve numerical weather prediction, identify causes for disagreement among climate models, and develop new parameterizations that align model products with reality. Although weather prediction is not a DOE mission, data from the ARM program have enabled improvements in numerical weather models. Results from the ARM and ARM-UAV programs already have instigated changes in the most recent NCAR climate model (CCM3), the GISS model, and in the ECMWF forecast model. In addition to benefits of improved simulations of atmospheric processes for understanding climate change and weather, homeland security also may benefit from improved predictions of atmospheric transport of airborne hazardous materials.

The UAV platforms, together with their innovative instrument development and data management advances, have made substantial progress to ARM science goals. They also provide new measurement techniques that can be transferred to other platforms that require the reduced size, weight, and power consumption of instruments developed for UAVs. These smaller instruments allow for additional correlative measurements to be made simultaneously, thereby unraveling complex interactions among a variety of atmospheric and surface processes.

Several unique attributes of the UAV itself contribute substantially to the overall success, both past and potential, of the ARM-UAV program. While piloted aircraft can achieve some of the performance characteristics of the UAV, none of them can duplicate the UAVs capabilities.

- Altitude range - Recent UAV designs can sustain flight at levels between the boundary layer and above the tropopause (0.5 to 20 km).

- Long endurance - Some UAVs can remain airborne for several days.

- Slow flight speed - Accurate measurements of many cloud and aerosol properties and chemical constituents require flight speeds well below most available piloted research aircraft.

- Stable horizontal platform - One of the ongoing problems in analyzing data from aircraft is removing effects caused by aircraft pitch and roll. The UAVs stability greatly reduces this problem.

- Precise flight tracks - The accurate navigation and control system of the UAV allows precise flight tracks to be flown, and these patterns can be preprogrammed for a particular objective or geophysical feature.

- Coordination with other aircraft - Owing to the slow speeds and precise flight control UAVs can fly in formation with other aircraft in a variety of configurations, such as side-by-side and stacked. In past research campaigns with piloted aircraft, this has been difficult to achieve. The ARM-UAV test flights have demonstrated the capability with great success.

The unique capabilities of UAVs for research open the door to a number of important applications that have been heretofore difficult or impossible to achieve, some of which have prevented the ARM science program (and others) from fully reaching its objectives of characterizing the physics and processes in anatmospheric column. Applications are numerous. A sampling of ARM-related ones is outlined here.

- The total energy and mass budget of the grid box is determined by fluxes of energy and mass along all faces of the atmospheric column. One component that is virtually unknown at present is the flux of condensed water and ice into the sides of the column. The UAV can provide measurements along the upwind side to estimate this flux. Further, ARM seeks to find out whether radiative transfer models can accurately calculate fluxes in the column if all the state variables and cloud properties are known.

In addition to applications that relate specifically to the ARM program, UAVs can:

- provide measurements that are difficult and/or dangerous for piloted aircraft to reach. These might include flying into a plume that is hazardous to human health (toxic, biologically hazardous) and over regions where rescue would be difficult or impossible (over sea ice, above severe storms over the ocean),

- measure upper tropospheric humidity above areas where strong interactions are suspected, such as tall cumulus towers, strong frontal systems, high cirrus, etc.,

- provide the capability to follow the evolution of a feature throughout its lifetime, such as a cirrus feature, convective complex, tropical storm, atmospheric pollution, and

- map the diurnal cycle of surface features, such as the bidirectional reflectance distribution function, albedo, soil moisture, sea ice melt or freeze, ice motion, etc.

There is great potential for a strong ARM-UAV program that makes important contributions to questions related to climate change, numerical weather prediction, atmospheric chemistry and pollution issues, and homeland security. The working group feels that the capabilities of the UAV program could be leveraged and enhanced through collaboration with other programs and campaigns. In turn those programs stand to benefit substantially by incorporating UAV measurements into their efforts. This platform offers the research community an unprecedented resource. Efforts should be mounted to maximize their contributions.

There already has been use made of ARM-UAV developed instrumentation by other agencies and as pointed out above, there really is a great deal more that can and should be done. Instrument improvements developed by the ARM-UAV Program to support future flight deployments have attracted interest from several organizations including NASA, the U.S. Navy, and NOAA in addition to potential commercialization. For example, NASA Ames will fly modified radiometers developed under ARM-UAV as a part of their "Crystal" campaign that will be conducted in central Florida during July of 2002. The U.S. Navy's Center for Interdisciplinary Remotely Piloted Aircraft Studies also has interests. The instrument improvements involve modification of commercial radiometers normally used for ground-based measurements to make them suitable for airborne use and development of a compact, solid state data acquisition and storage device for use with the radiometers and other flight instruments.

The ARM-UAV Program recently provided data acquisition hardware support for nuclear weapons-related test activity. Results of the experiment will assist in data analysis in end-event wide-band testing for re-entry vehicle systems. ARM-UAV provided two data acquisitions modules that are being developed to support atmospheric research flights. These solid-state storage modules will provide primary flight data on board ARM-UAV aircraft. This test activity provided an early opportunity for ARM-UAV to confirm proper operation in flight and field conditions as well as providing the needed data for test activities.

BUDGET AND OTHER RESOURCES

The ARM infrastructure budget actually consists of four components - engineering, operations, data management, and UAV. The UAV budget has been kept separate since the program began. It is not clear why that happened. The following table shows the financial support for the UAV component of the budget for the most recent 5 years.

Fiscal Year	Dollars (in millions)
1998	2.624
1999	2.843
2000	2.527
2001	2.721
2002	2.718

The program has been nearly level funded. Since the entire ARM infrastructure and ARM-UAV are controlled by the same Program Officer within the Climate Change Research Program of BER, it would make a great deal of sense to merge the two budgets so they could be supportive of one another and provide some flexibility "at the margins".

The various science teams that have developed science and experiment plans and oversaw their implementation have never had funds of their own with which they could operate. Instead all members had to take funds out of their own individual ARM grants or contracts. Science teams need to have some funds to ensure that members attend meetings, to enable the team to gather and communicate when needed, and to write and publish reports. Such a fund also could be used to provide small amounts of support if some very urgent, but unfunded matter came to light and had to receive funds quickly.

There are some budget items that deserve attention, although it is recognized that not all of these issues are under the control of the ARM program or even DOE. One of these is the ownership of the UAVs. At present, the UAVs are commercially owned. They are rented by DOE to carry out the ARM program. If the UAVs were government owned, costs could be reduced. The Federal government self indemnifies so there would be no insurance costs. There also would be no debt service or cost of capital, no taxes, and no profits, all of which are paid as a part of the rental fee. Since NASA, DOD and DOE all use UAVs, it would seem to be in the best interest of the government to have one of those agencies purchase UAVs for interagency use.

As UAVs are used more often and increased flight experience is gained, costs can be lowered by reducing field personnel, spreading fixed costs over more flight hours, and allowing other agencies such as DOD to develop and improve the needed technologies.

A major advantage that the DOE has in supporting the ARM-UAV program is the resources of the National Laboratories that can be brought to bear on problems. Without the instrument expertise available from Sandia, Lawrence Livermore, Los Alamos, and Brookhaven as well as other government laboratories such as NASA Ames and NASA Langley plus universities such as

Scripps, Wisconsin, CSU, and U Mass, it would have been impossible to do what has been done so well for the ARM-UAV program. Although the ARM-UAV program has supported these activities, the availability of the expertise and the synergy involved has proven to be exceptional and only available through a national laboratory system working in conjunction with other agency and university laboratories.

Appendix A - Members of the Working Group

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Appendix B - Meeting Agenda

February 7, 2002

8:30 - Continental breakfast

9:00 - The Vision and Implementation Strategy - An Overview
J. Vitko

9:30 - Impact for ARM
T. Ackerman

9:50 - New capabilities - Instruments & Techniques
T. Tooman

10:30 - Break

10:45 - Science: Overview & Case Studies
Cloud Properties (Kauai 99)
G. Stephens

11:30 - Radiation Budget Strategies (ARESE II)
R. Ellingson

12:15 - Lunch

1:15 - Operational considerations & Comparisons
W. Bolton

2:15 - Questions and Open Discussion
All

3:30 - Closed Session
Review Panel and DOE representatives

February 8, 2002

8:30 - Continental breakfast

9:00 - Closed Session - Review Comment Preparation
Working Group

12:00 - Adjourn