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Environmental Monitoring: Civilian Applications of Remote Sensing

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Abstract

This report documents the results of a Laboratory Directed Research and Development (LDRD) program to explore how best to utilize Sandia's defense-related sensing expertise to meet the Department of Energy's (DOE) ever-growing needs for environmental monitoring. In particular, we focused on two pressing DOE environmental needs: (1) reducing the uncertainties in global warming predictions, and (2) characterizing atmospheric effluents from a variety of sources. During the course of the study we formulated a concept for using unmanned aerospace vehicles (UAVs) for making key climate measurements; designed a highly accurate, compact, cloud radiometer to be flown on those UAVs; and established the feasibility of differential absorption lidar (DIAL) to measure atmospheric effluents from waste sites, manufacturing processes, and potential treaty violations. These concepts have had major impact since first being formulated in this study. The DOE has adopted, and DoD's Strategic Environmental Research Program has funded, much of the UAV work. And the ultraviolet DIAL techniques have already fed into a major DOE non-proliferation program.

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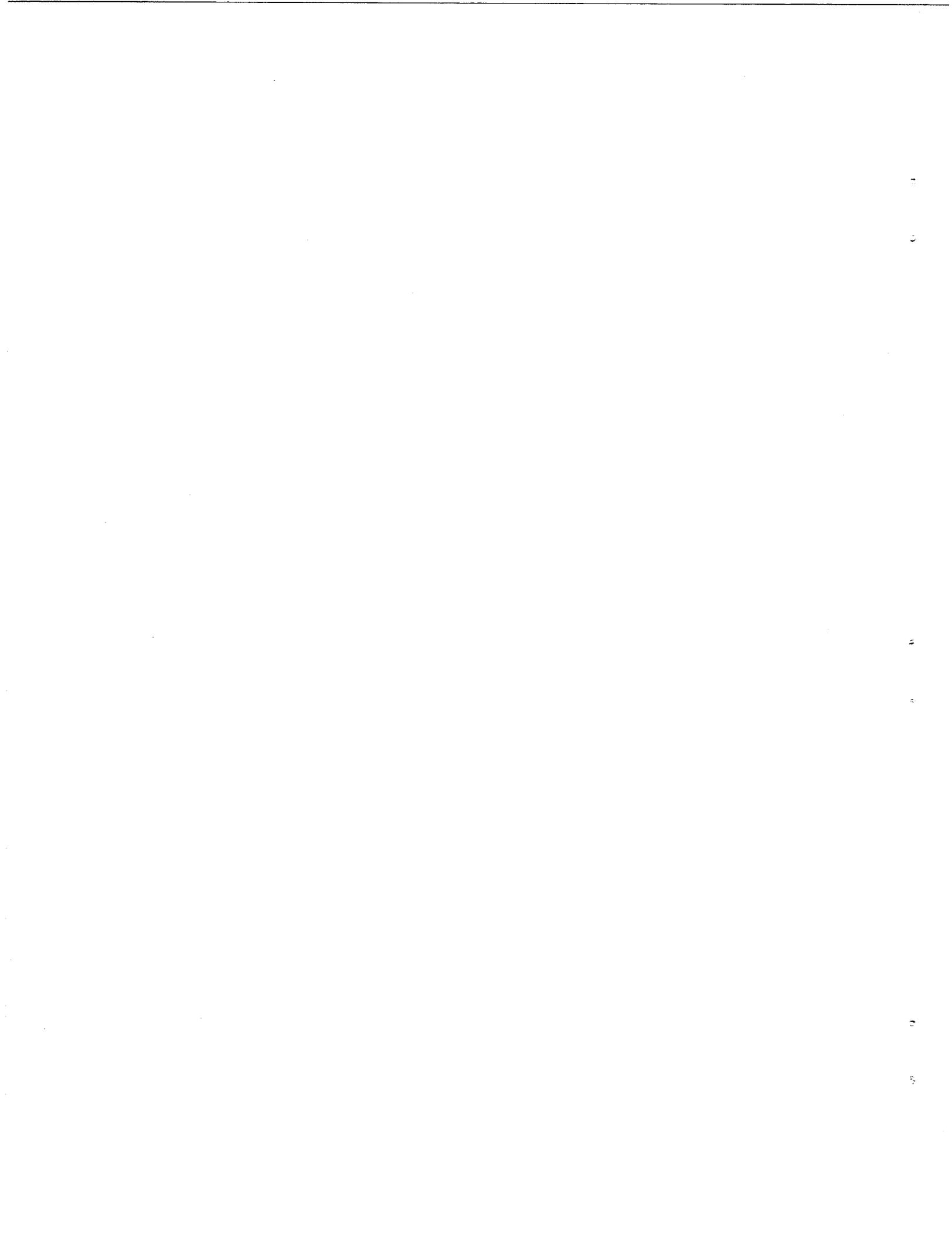
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1. Introduction and Executive Summary

Over the years, Sandia National Laboratories has developed an impressive array of sensing technology and expertise in support of its defense-related missions. These capabilities include a wide range of rugged, compact, space, air, and ground-based sensors; extensive experience in design and execution of field tests; and a considerable expertise in laser-based sensing. The purpose of the "Environmental Monitoring" Laboratory Directed Research and Development (LDRD) program described in this report was to explore how best to utilize this defense-related technology to meet the Department of Energy's (DOE) ever-growing needs for environmental monitoring. In particular, we focused on two pressing DOE environmental needs: (1) reducing the uncertainties in global warming predictions, and (2) characterizing atmospheric effluents from a variety of sources.

1.1 Global Warming

DOE is a major participant in the United States Global Change Research Program (USGCRP) and has focused much of its attention on understanding how sunlight and thermal energy interact with clouds to heat the atmosphere. Uncertainties in this radiation-cloud interaction are the dominant uncertainty in existing climate models, accounting for almost the entire factor of three uncertainty in the predicted temperature rise for a doubling of CO₂. It is for this reason that radiation-cloud interactions is rated as the top scientific priority by the USGCRP and has become the focus of the DOE's Atmospheric Radiation Measurement (ARM) program. While ARM, with its ground-based measurements was addressing some of the key measurement needs, other key needs—most notably for measuring radiative fluxes *in the atmosphere*, for measuring upper tropospheric water vapor, and for measuring cloud top properties—were going unmet because of the need to make these measurements to high altitudes and for long durations. In this LDRD, we formulated a plan for using Unmanned Aerospace Vehicles (UAVs) for making the high-altitude, long-endurance measurements; developed a design for a compact wide field-of-view cloud radiometer to be flown on a UAV; and laid the basis for a multi-laboratory (SNL, LANL, LLNL, and PNNL) implementation strategy.

The UAV Systems Concept

The UAV systems concept is shown schematically in Figure 1.1 and detailed in Chapter 2. The essential idea is to fly the UAV at the tropopause (45 to 65 kft) above the DOE climate site(s) for multiple days (24-48 hours) thereby in effect creating a geostationary satellite at the tropopause. Data would be collected by the instruments on board the UAV and then telemetered to the ground for near real-time processing. If multiple UAVs are available, it would be possible to provide quasi-continuous coverage. The UAV payload would consist of broad-band radiometers for measuring the solar and thermal fluxes, spectral radiometers for measuring cloud properties and atmospheric physics, a cloud lidar for detecting and profiling thin clouds, and a meteorological package for characterizing the state of the atmosphere. A preliminary packaging study indicated that such a payload could be accommodated within the 150 kg, 0.5 m³ payload capability projected for such UAVs. However, significant development would be required to miniaturize the instruments, provide for the 1-2% accuracy typically required for climate measurements and allow for sustained unattended operation.

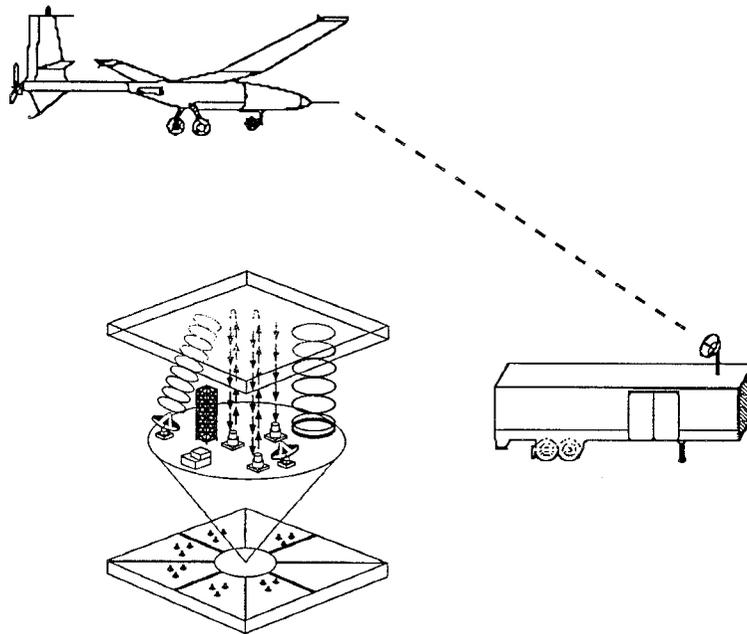


Figure 1.1: A high-altitude, long-endurance UAV can act as a “geostationary satellite at the tropopause” above the DOE's Cloud and Radiation Testbed (CART) sites.

MPIR, a Compact Cloud Radiometer

We next turned our attention to one of those key instruments: a compact, wide field-of-view cloud radiometer that would allow retrieval of cloud optical properties (e.g. reflectivity, ice/water phase, effective droplet size) as well as provide “climate-level” calibration for measurements aboard existing weather satellites. The resulting instrument is shown in Figure 1.2 and is known as MPIR, the Multispectral Pushbroom Imaging Radiometer.

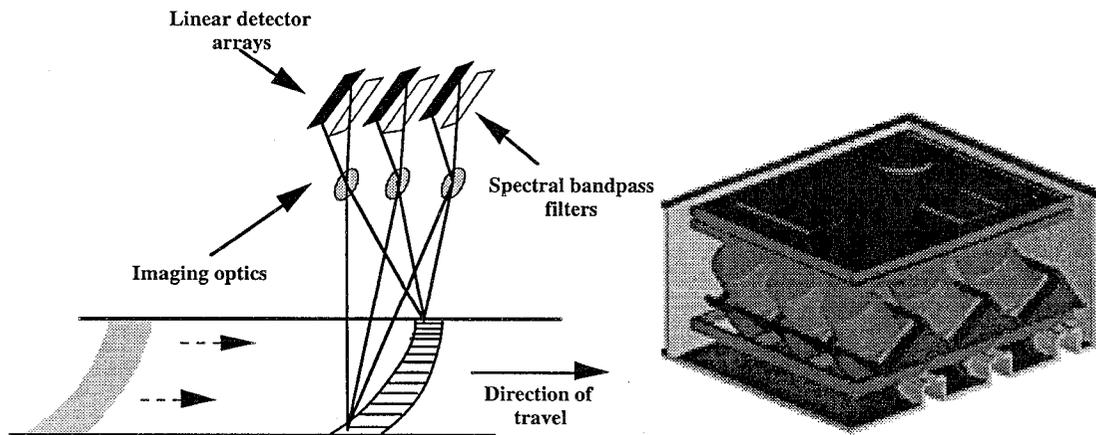


Figure 1.2: MPIR, the Multispectral Pushbroom Imaging Radiometer

MPIR has 9 spectral channels distributed between 0.6 and 11.5 microns. Each channel consists of a 256 or 512 element linear array detector mounted in a so-called pushbroom geometry, i.e. transverse to the flight path so that the UAVs motion sweeps out the other dimension of the image. This configuration results in a much more compact instrument than a conventional “flying spot” radiometer which uses a large rotating mirror to sweep out the scene on a single element detector. MPIR will weigh less than 25 kg and draw less than 50 W while providing a full ± 40 degree field-of-view (FOV) with a 6-8 mrad instantaneous FOV. Furthermore, the MPIR design is highly modular, consisting of nine identical modules differing only in the detector array and filter. Thus, changing channels to accommodate other applications is a straightforward process of changing out a module, making MPIR a highly flexible instrument. Designed from the outset with calibration in mind, on board black bodies are used to ensure calibration accuracy between pre- and post-flight calibrations.

1.2 Atmospheric Effluents

The Department of Energy also has significant interest in detecting and monitoring atmospheric effluents, whether for waste site monitoring (Environmental Restoration and Waste Management), or for environmentally conscious manufacturing (Defense Programs) or for treaty verification (National Security and Non-proliferation). Though the end uses differ widely, the detection requirements for all three are rather similar, i.e. ppm level sensitivities to selected species at standoff distances of hundreds of meters to tens of kilometers. A laser technique know as DIAL, differential absorption lidar, has demonstrated this kind of capability but has remained largely a research tool. However, recent advances in lasers have resulted in more robust lasers operating over broader spectral ranges, thereby making DIAL a real contender for a robust field monitoring tool.

With this in mind, we explored the feasibility of constructing a ultraviolet (UV) DIAL system to address the broad range of DOE applications. We surveyed available laser and detector technology, developed a conceptual design for a fieldable DIAL system, and performed an end-to-end simulation, including atmospheric transmission calculations, to evaluate its performance. Figure 1.3 shows the representative performance for such a system.

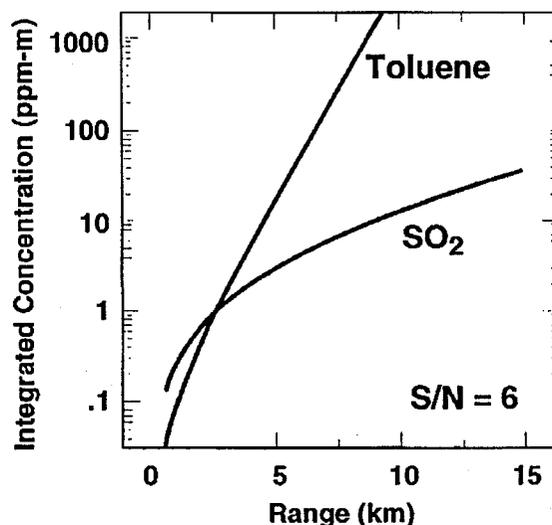


Figure 1.3: Calculated DIAL performance vs. range. (75 mJ/60 Hz laser, operating at 267 nm for toluene and 300 nm for SO₂)

With recently available lasers (75 mJ at 60 Hz rep rate) and a reasonable sized telescope (0.5m) one should be able to detect a variety of species out to distances of 5 km or greater with a sensitivity approaching 10 ppm-m (i.e. 1 ppm with 10 m resolution or 0.1 ppm with 100 m resolution). See Chapter 3 for additional details.

1.3 Impact

Since the time of its inception, this LDRD has already had major impact. DOE's Office of Health and Environmental Research (OHER) adopted the proposed ARM-UAV program. DoD's Strategic Environmental Research and Development Program (SERDP) provided the funding for developing the necessary UAV instrumentation and for demonstrating the proposed measurement techniques aboard rented UAVs. In April of 1994, a Sandia-led multi-laboratory team demonstrated the first-ever climate-relevant measurements from a UAV, conducting eight science flights at the DOE Cloud and Radiation Testbed (CART site) in Oklahoma. In the words of the leader in the field, Dr. Francisco Valero, this is a unique data set on clear sky fluxes and is unprecedented in its accuracy and its quality. Three advanced UAV instruments, including MPIR are nearing completion, and will likely be on-board a major cloudy-sky mission in the Fall of 1995. Collectively, this work will:

- reduce uncertainty in greenhouse warming predictions
- leverage existing satellites for climate measurements
- develop several instruments that are readily adaptable to small satellites, and
- will also benefit weather prediction for defense applications, be they troop movements or cloud backgrounds for smart weapons.

The laser work has also had an impact. The UV-DIAL concepts have already fed into a DOE non-proliferation program known as CALIOPE, Chemical Analysis by Laser Interrogation of Proliferation Effluents. A Sandia developed UV DIAL performed well in the first CALIOPE ground test—easily detecting and spatially resolving a toluene plume at distances of 0.5 km. Succeeding field tests will be conducted at ever-increasing distances to characterize the ultimate performance of the system. In addition to these non-proliferation applications, the DIAL work is currently feeding into other areas. The UV DIAL has great potential for spatially mapping ozone, SO₂, and other atmospheric pollutants important to regional air quality. Such measurements are critically needed to test and refine the computational Air-shed Quality Models that are currently the basis for much of our regulatory requirements. Another “spin-off” is in the area of waste management. Here we are developing a mid-infrared DIAL system for use in a small van to monitor volatile organic compounds (VOCs) at waste sites. This van with its DIAL and open-path FTIR (Fourier Transform Infra-Red) systems will be available shortly and will be at the “cutting edge” in VOC detection.

1.4 The Rest of this Report

The rest of this report provides a detailed description of three key aspects of this LDRD study as they stood at the end of the LDRD in September 1993. Chapter 2 delves into the scientific needs, aircraft and payload considerations that gave rise to the UAV program. Chapter 3 gives the detailed design considerations that led to our novel approach for a highly accurate, compact, UAV-compatible, cloud radiometer. And finally, Chapter 4 briefly summarizes some of the lidar analysis underlying our conclusion that a robust, highly versatile, lidar is currently attainable. Each of these chapters is written as a self-contained report, can stand alone, and may be read without reference to the other chapters.

2. Unmanned Aerospace Vehicles (UAV): a unique tool for meeting DOE climate needs.

As noted in the Introduction, DOE is a major participant in the United States Global Change Research Program (USGCRP) and has focused much of its attention on understanding how sunlight and thermal energy interact with clouds to heat the atmosphere. Uncertainties in this radiation-cloud interaction are the dominant uncertainty in existing climate models, accounting for almost the entire factor of three uncertainty in the predicted temperature rise for a doubling of CO₂. It is for this reason that radiation-cloud interactions is rated as the top scientific priority by the USGCRP and has become the focus of the DOE's Atmospheric Radiation Measurement (ARM) program. While ARM, with its ground-based measurements was addressing some of the key measurement needs, other key needs—most notably for measuring radiative fluxes *in the atmosphere*, for measuring upper tropospheric water vapor, and for measuring cloud top properties—were going unmet because of the need to make these measurements to high altitudes and for long durations. This section describes a technical approach for using an emerging generation of UAVs to fulfill these unmet measurement needs. First, the role for UAVs is established based on measurement needs and the capabilities of manned and unmanned airborne platforms. Second, candidate instruments are considered that provide the needed observations and that are compatible with the general characteristics of airborne platforms. Third, the measurement needs and the platform and instrument characteristics are combined to determine overall performance goals for a UAV system capable of meeting DOE climate measurement needs.

The resulting plan emphasizes the development and operation of small (~150-kg payload), high altitude (≥ 20 kilometers), long endurance (48 to 72 hours) UAVs capable of taking measurements for multiple diurnal cycles above the tropopause in the tropical Pacific Ocean. While this new generation of UAV is under development, the program will gain operational experience and useful scientific data by using existing mid-altitude capable UAVs at the DOE climate site in north central Oklahoma.

2.1 Airborne Measurement Needs

The ARM Airborne Measurements Working Group (AAMWG) have identified four major areas of measurement needs:

- radiation fields (both broad and narrow band)
- cloud properties
- trace gases (especially water vapor) and aerosols
- surface characteristics

In addition, airborne measurements play an important role in calibrating and validating remote sensing techniques. All of these areas, with the exception of surface measurements, are well suited to high-altitude UAVs and are discussed below. The following discussion draws heavily on the ideas and words of a draft report of the AAMWG (Daum, 92).

Radiation Fields

Ground-based and satellite-based measurements can measure the shortwave and longwave radiation fields at the bottom and top of the Earth-atmosphere system, respectively. While these boundary measurements provide an important measurement of the integrated effect of the entire atmosphere on the radiation field, they are not sufficient to test our understanding of specific atmospheric features (e.g., water-vapor and cloud distributions) on the radiation field. Clouds, radiatively active trace

gases, and aerosols absorb portions of the solar and thermal radiation giving rise to radiative heating within the atmosphere. It is this vertical distribution of interactions that constrains the heating profile in the troposphere and drives both our weather and climate systems. Therefore it is critical to measure the radiation field at selected altitudes in the troposphere, and at a minimum, at the tropopause. Such measurements can only be made directly at altitude and hence require in-situ airborne measurements, including:

Short-wave, long-wave and net fluxes at the tropopause: A first order issue in quantifying the greenhouse effect is to understand and predict radiative fluxes at the tropopause. Therefore the measurement of these flux components at the tropopause constitutes a critical test for general circulation models (GCMs), indicating whether a model has parameterized properties and processes to the necessary accuracy to begin to predict climate change. Tropopause fluxes are also fundamental measurements needed to estimate climate forcing. It is also useful to relate measured tropopause fluxes to top of the atmosphere fluxes, as estimated by satellites, as a means of evaluating the ability of satellites to provide such measurements.

Flux divergence: Flux divergence measurements, in which one measures the difference in net flux at two selected altitudes, are essential for evaluating the performance of climate and data assimilation models, since these models depend sensitively on the atmospheric heating rate. For example, measurement of the divergence of IR and solar radiation from about 10 to 20 km would allow us to understand the role of diabatic forcing in moisture and cloud transport in the tropics. Similarly, one of the fundamental uncertainties in the parameterization of cloud feedback in GCMs is accounting for the vertical distribution of cloud radiative forcing and latent heating. GCMs currently rely on convection models, and various empirical schemes to simulate these fields that are the fundamental forcing terms of general circulation. To test the various schemes that have or will be developed to predict these key quantities, it will be necessary to conduct *in situ* measurements since there is no known way to make direct measurements of flux divergences by remote sensing methods.

Reflectance and absorption of clouds: These measurements are necessary for understanding cloud radiative properties. Reflectance can be inferred from satellite measurements, but not under all circumstances. Furthermore, the accuracy of computational methods used in converting satellite based reflectance measurements at one angle to a reflectance integrated over all angles is unknown. Airborne measurements can provide a better measure of this bidirectional reflectance distribution function, and hence enhance the value of satellite data. Similarly, the contribution of the absorption of IR radiation in the window region by optically thin cirrus to the heat budget of the upper troposphere and tropopause region is an important issue that cannot be addressed by remote sensing methods. Airborne measurements can also provide enhanced spectral resolution and the ability to sample between clouds.

Spectral long wave radiances: One of the major remaining uncertainties in clear-air radiative models relates to how the different models treat the pressure broadening of various absorption lines as a function of altitude. Measurements as a function of altitude would provide key data that simply is not available through ground or satellite-based measurements.

Radiative properties of intermediate cloud layers: Such layers will influence the long wave radiative flux to space. It is not possible to characterize properties of intervening layers from the surface or from satellites.

Cloud Properties

Uncertainties in our knowledge of the radiation-cloud interaction are the major source of uncertainty in current GCMs, accounting for a factor of 2 to 3 uncertainty in the predicted rise in global average temperatures associated with a doubling of CO₂. Improved understanding of these interactions will require improved knowledge of both the macrophysical (size, shape and reflectivity) and microphysical properties (total water/ice content, particle size, ...) of clouds. While some of these properties can be measured remotely, many cannot and require *in situ* measurements. Even where some properties can be inferred from remote sensing, *in situ* measurements are needed to validate and refine the retrieval algorithms. Key *in situ* measurements include:

Cloud microphysics: Number concentration, size distribution, particle morphology, and liquid and ice water content are important parameters for use as either input or diagnostic variables for cloud radiative modeling. None of these properties of clouds (with the exception of cloud liquid water path) are measured with current remote sensing methods with sufficient accuracy and precision to be of use in DOE radiation-cloud studies. Furthermore, there is also a need for airborne measurements of cloud microphysical properties to evaluate satellite-derived parameters. Measurements in cirrus clouds are especially important. Cirrus cloud bulk radiative properties are determined by ice-water path, crystal shape, and similar microphysical parameters. DOE currently has no means to remotely sense cirrus ice water content or to sample ice crystal properties. Without such information it will not be possible to fully explore ways to parameterize cirrus optical properties for use in GCMs.

Altitude and thickness of cloud layers: These measurements are needed to supplement and evaluate information obtained from surface launched soundings and remote sensing.

Cloud morphology including three dimensional structure: This is a key feature of clouds that determines radiative properties. Satellites can give information on the two dimensional distribution of the top-most layer. Surface measurements with whole sky imaging systems can give information on cloud morphology under broken cloud conditions, but do not give useful information under completely overcast conditions. Cloud radars also have the potential of giving useful information on cloud morphology, but are not well tested. Airborne measurements can provide needed confidence in algorithms to derive this information from ground based observations.

Mean and spatial variability of cloud coverage: This is a critical property that determines atmospheric radiation budget. It can be estimated from satellite and surface measurements, but can be subject to large uncertainty when multiple cloud layers exist. Measurements from aloft are highly desirable.

Water-Vapor and Aerosol Characteristics

To properly model the radiation fields it will also be necessary to specify the vertical distributions of various radiatively important trace species, especially water-vapor and aerosols. Although not normally considered a trace gas, measurement of water vapor will be very important since the water vapor distribution from the surface up to about 20 km in altitude is a fundamental climate variable. Particularly important are very accurate measurements of the vertical and horizontal distribution of water vapor in the tropical tropopause because of the importance of water vapor in atmospheric heating. Even though water vapor concentrations will be measured routinely using a variety of sounding systems, measurements at high altitudes where water vapor concentrations are quite low are especially difficult, and cannot currently be done with sufficient accuracy for current purposes with remote sensing techniques.

Aerosol particles are important from two perspectives, the direct effect that they have on the radiation fields, and the indirect effect that they have on the properties of clouds, since their number density (and to a lesser extent their composition) will influence the microphysical properties of clouds, which in turn will influence the optical properties of clouds. However, there are currently no satisfactory remote-sensing techniques for obtaining such key aerosol parameters as number density and composition, therefore in-situ measurements will be required.

Calibration and validation of remote sensing techniques

Airborne measurements can play a major role in the calibration and validation of remote sensing techniques and hence enhance the utility of such measurements. Two specific examples are the indirect calibration of satellite sensors and the validation of "derived" quantities such as cloud properties. All presently operating satellites lack adequate on-board calibration for climate studies. One way of addressing this limitation is through so-called indirect calibration in which a calibrated radiometer is flown on a high-altitude aircraft at the time of the satellite overpass and in the same viewing geometry. The calibration is then transferred from the aircraft to the satellite with minimal need for atmospheric corrections since the aircraft was at high altitudes. In addition to such "radiance calibrations," the airborne measurements are key to validating and refining such derived data products as cloud microphysical properties (droplet size, ice-water phase, top height and temperature) and upper tropospheric water-vapor profiles.

2.2 Comparison of Capabilities of Manned and Unmanned Aircraft

In this section potential airborne measurement platforms are evaluated in the context of DOE high altitude measurement needs. The principal factors that enter into this analysis are operating characteristics, such as service ceiling, sampling speed, payload, and endurance. However, in specific instances availability of the aircraft and/or the presence of significant measurement capabilities that are of use to DOE may override one or more of the preceding.

Conventional Aircraft

Conventional aircraft have been the mainstay of airborne atmospheric measurements to date. The conventional aircraft listed in Table 2.1 have very different characteristics that may cause them to be favored or excluded from certain measurement tasks. Of these aircraft, only the ER-2 and the WB-57 can reach the tropical tropopause, while the remaining aircraft can reach the tropopause most of the time, at all locales except the Tropical Western Pacific Ocean (TWPO). Thus, if measurements at the tropical tropopause are essential, only these two aircraft need be considered. Of the two, the ER-2 has been used extensively for measurements that are similar to those contemplated for DOE radiation-cloud studies and may be favored because of the existence of a wide array of instrumentation that has been designed specifically for use in this aircraft. Such an advantage is contingent upon agreement with various NASA Principal Investigators (PI) since much of the instrumentation is PI controlled, and is not normally supplied with the aircraft.

Many of these aircraft could be made available to DOE programs for limited periods of time at costs that typically range from \$3,000-\$6,000 per flight hour depending on the nature of the deployment (i.e., location, number of flight hours, equipment provided, need for data processing, and similar factors). Use of these aircraft for extended periods of time (e.g., for a 5% duty cycle), however, may involve scheduling conflicts as well as increased costs. In this regard the aircraft listed in Table 2.1 are currently being used, to a greater or lesser extent, in other projects, and

it is unlikely that DOE would be able to arrange for use of these aircraft for extended periods of time.

While conventional aircraft have demonstrated competence to provide high-altitude measurements, they also have significant constraints that may compromise the quality of some of the radiation-cloud measurements required by DOE. One of the most significant of these, is the limitation of time on station due to aircraft fuel capacity and pilot endurance.

Table 2.1. Specifications of airborne measurement platforms, existing and proposed conventional research aircraft.

Platform	Ceiling (km)	Range (km)	Endurance (hrs)	Payload (kg)
McDonald-Douglas DC-8 (NASA)	12	9,600	12.0	13,700
Cessna Citation (NOAA, UND)	14	3,000	3.5-4.5	900
Gulfstream G-IV ¹	16+	7,400	10.0	9,500
General Dynamics WB-57	21	4,000	7.0	1,800
Lockheed ER-2 (NASA)	23	5,100	7.0	1,200

¹Aircraft exists but not currently equipped for atmospheric research.

In a sense, conventional high altitude aircraft will give “snapshots” of upper atmospheric properties, and this will impose a significant limitation on the ability of many DOE investigators to make rapid progress in a number of areas.

Unmanned Aerospace Vehicles

Although still under development, the emerging generation of high-altitude long-endurance UAV offers the greatest potential for meeting the endurance, cost and availability requirements of the DOE’s radiation-cloud measurements program. Table 2.2 summarizes the characteristics of representative high-altitude UAVs that either exist, are under development, or are proposed.

Table 2.2. Specifications of airborne platforms, unmanned aerospace vehicles.

Name	Status	Ceiling (km)	Range (km)	Endurance (hours)	Payload (kg)
Condor (Boeing)	Exists	23	29,000	30	900
Egrett II (E systems)	Exists	15	—	TBD	900
GNAT 750-93L (Gen. Atomics)	Proposed	20	—	75-85	150-550
HILINE (Aero-Vironment)	Under development	13	—	18 hrs	45
PERSEUS-B (Aurora)	Proposed	20	14,000-24,000	24 - 100	45-150

Not limited by pilot endurance and pilot safety considerations, several of these platforms (such as Perseus and Amber/Gnat follow-ons) are of greatest interest, since their small size should result in both relatively low initial acquisition costs (~\$1-2 M/RPV) and operational costs (~\$1000/ft-hr). Other attractive features include long range (as much as 15,000 km or greater) and the potential to operate in high risk environments.

Small, high-altitude, long endurance UAVs such as Perseus-B are only now being developed and so their final performance and costs are yet to be determined. Perhaps the greatest uncertainty in estimating costs is UAV lifetime, i.e., the number of flight hours between catastrophic losses, and hence the amortization costs associated with the platform.

Other pending issues in the use of UAVs include potential problems in obtaining FAA (or similar foreign agency) approval for operation at ARM sites because of safety considerations such as location of airways and population centers.

Because the FAA is a safety conscious organization, it may require extensive review of the design, operational plan, and safety considerations prior to giving approval for regular flights. Approval for operation in remote areas or in military operation areas may be considerably easier to obtain. UAVs that are affordable in the context of ARM funding can only carry a payload of limited size. Finally, high performance UAVs currently proposed cannot fly in icing conditions, and, therefore, must avoid clouds and other conditions that have the potential for icing.

Free Balloons

Free balloons have a long history of use in atmospheric research. They have demonstrated capability to carry large payloads to high altitudes. Free balloons routinely reach altitudes in excess of 29 km with payloads of up to ~3,500 kg and float for days. However, they drift with the wind and hence will not stay over an ARM site unless some form of station-keeping technology is developed. Unfortunately, there is little experience with station-keeping for such platforms and it is unlikely that it will be developed without a substantial investment from ARM. Thus, the extent of coordination of measurements with those at the surface is dependent on the prevailing wind. For this reason, the application of free balloons for high altitude ARM measurements appears to be quite limited.

2.3 Focus of UAV Program

Previous sections have established the need for airborne measurements in the atmospheric column to the top of the troposphere to complement the ground-based measurements made at ARM CART sites. These measurements include: Radiation field measurements, cloud properties, trace gases and aerosols. Existing manned aircraft have a role in short term measurement programs and in-cloud operations such as particle sampling. Current mid-altitude UAVs will be used to gain operational experience with intensive UAV operations. The ARM-UAV Program will focus on developing high-altitude, long-endurance UAVs and compatible instruments for measurements requiring airborne observations in or at the top of the troposphere and covering multiple diurnal cycles with endurance up to 72 hours.

2.4 Instrument Requirements and Characteristics

The airborne atmospheric measurement needs discussed in previous sections impact which instrument observations need to be taken. Specific measurements might be derived from many different instruments and/or observations. This section describes classes of instruments that would be useful for high-altitude observations. This particular set of

instruments are meant to be representative but not exhaustive. The final UAV instrument suite may contain instruments not discussed here. The classes of instrumentation are (1) radiometers (broad and narrow band), (2) video imaging systems, (3) *in situ* instruments, and (4) lidars.

Radiometers are used to make the observations critical to understanding the earth's radiation budget. Broad band radiometers will be used to measure the downwelling and upwelling flux over the broad solar and thermal bands. These observations are critical to understanding the radiation forcing function. Narrow band radiometers and spectrometers provide greater spectral detail about radiation forcing in areas where ground based observations are impossible, e.g., the spectral reflectance of the cloud tops. With the proper selection of channels, these measurements can also provide inferential information on cloud properties by using the relationship among reflected and emitted radiation in different channels. Those instruments that provide angularly resolved as well as spectral data will lend insight into the clouds bidirectional reflectance.

Under *in situ* measuring instruments, we include standard packages that measure temperature, pressure, and relative humidity. They can be used to characterize the tropopause as well as provide a vertical profile of the atmosphere during ascent and descent. Video imagery provides detailed information on spatial variability of the cloud cover, type of clouds being viewed by the other instruments, and photo-documentation of the flight. Finally, lidars can be used to detect and profile optically thin clouds, including sub-visible cirrus clouds.

Radiometers

Narrow band and broad band radiometers primarily address two DOE measurement needs. The first need is to provide measurements of short- and long-wave radiances and fluxes at the tropopause. Both broadband and spectrally resolved measurements are desired. The broadband measurements provide a highly accurate measure of the total radiation balance and hence are important for quantitative studies of radiative forcing and validation of GCMs. The spectrally resolved measurements provide additional insight into the forcing mechanisms allowing us to see whether these are properly treated in GCMs. Under cloudy conditions, these observations should concentrate on upwelling and downwelling radiation in the visible and near IR, providing a direct observation of the cloud top albedo in this critical area of the spectrum. Under clear sky conditions, the observations should measure upwelling and downwelling radiation in the IR (4-50 microns) with spectral resolution of 1 cm^{-1} . The opacity of the atmosphere in the longer wavelengths makes this observation impossible from the ground. The second need is an indirect observation of cloud properties such as water phase and particle size, cloud height, and temperature. These properties can be inferred from the relationship in the reflected and emitted radiation in several selected IR bands. The following instruments can make these observations and be designed to fit within UAV constraints.

Broad-Band Radiometers

This section discusses four wide band radiometers that might be used in a UAV instrument package. The first is a commercial instrument while the second and third have been used by NASA Ames. The fourth is an instrument proposed by Los Alamos National Laboratory.

Circular Variable Filter (CVF) Spectroradiometer: The CVF spectroradiometer is an instrument manufactured by CI Systems of Hawthorne, NY. The instrument contains all the necessary optics, electronics, a chopper, and an internal blackbody. Filter wheels are available which carry up to 12 filters, and filters can be specified for the

wavelength bands of interest. This instrument can be used as a broad-band or narrow-band spectroradiometer. For a UAV application, two filters would be used concerning the visible and IR bands. Cryogenic and thermoelectrically cooled detectors along with uncooled pyroelectric detectors that cover the wavelengths from 0.2 to 25 microns have been developed. The field of view is variable from 0.3 mrad to 6 mrad. An external mirror system is required to give cross track scanning. The instrument accuracy is in the 1% range. The weight and power requirements are estimated at 25 kg and 50 watts.

Broadband Hemispherical Field of View, multiple spectral channels, infrared flux Radiometer (HFOVR): This radiometer uses an electrically calibrated pyroelectric detector, optical chopping, and null balanced operation. Optical chopping is made possible by the fast response of the lithium tantalate pyroelectric detector and is effective in eliminating drift. A gold-black coating on the detector gives it a spectral range from the ultra-violet to the far infrared. Null balanced operation, in turn, renders the resultant measurement insensitive to detector responsivity and amplifier gain and hence to ambient temperature. This instrument incorporates a long-pass interference filter and uses the field of view inversion method. This is achieved by reversing the field of view of the radiometer to determine upwelling and downwelling fluxes. To obtain the net flux, one is subtracted from the other thereby eliminating the systematic error introduced by the temperature dependent IR emission from the optical components.

Total Direct Diffuse Multiple Spectral Channels Radiometer (TDDR): This radiometer measures total, direct, and scattered solar radiation fields in several spectral channels. A unique optical radiation collecting system is used to collimate and spectrally separate hemispherical radiation. It has been successfully used for research in the Arctic from high altitude aircraft (Valero et al. 1989).

By using an optical system that is capable of separating the contribution of the direct (parallel) solar beam from the total hemispheric radiative flux, the requirement for sun tracking for separation is eliminated. This has been achieved by incorporating an oscillating shadow ring in front of the optical aperture of the hemispherical field of view radiometer. At some point during the oscillation cycle the ring will project a shadow that will exclude the direct solar beam from the field of view of the radiometer so only the scattered, or diffuse, component of the total radiation field will reach the aperture of the optical system. On the other hand, when the oscillating ring is out of the field of view, the total hemispherical radiation field is detected. From these two values, the direct solar beam is obtained. An important consequence of the TDDR method of operation is that the oscillating shadow arm provides a semi-independent set of measurements comprised of flux values determined when different sectors of the hemispherical diffuse radiation field are shadowed. These measurements can be inverted to derive the angular dependence of the scattered field.

Los Alamos Radiometric Instrument (LARI): LARI is a flying-spot, cross-track scanner using uncooled pyroelectric detectors for broad-band coverage. This instrument has not been developed but has been proposed for development by Los Alamos National Laboratory. The instrument covers a spectral range from 0.3 to 50 microns and provides total broadband radiance along with the short-wave component of radiation from 0.3 to 4 microns. While these two bands allow a separation of solar and thermal radiation, spectral resolution is required to identify the causes of changes in these integrals. Coarse band spectral resolution is provided by dispersing part of the radiation by prisms and then using linear arrays for detectors. The spectral region is divided into 9 wavelength bands. On-board calibration sources are provided such that a complete calibration is performed every scan. The accuracy goal is 1% for the total

and integrated short-wave channels. The weight and power requirements are estimated to be 20 kg and 50 watts.

Narrow-Band Radiometers

This section discusses four narrow band radiometers/spectrometers that might be used on a UAV mission. Two of these instruments, CPRAD and Modis-N Airborne Simulator (MAS), are existing instruments which have been successfully used on airborne platforms. The third (MPIR) is a design proposed by Sandia National Laboratories. The fourth is a description of an instrument that might be designed to address clear sky longwave IR observations.

CPRAD: CPRAD was built by Graeme Stephens at Colorado State University. The instrument was originally developed to measure the spectral reflectance of clouds. It is a non-scanning spectrometer that measures downwelling flux and upwelling radiance.

CPRAD contains two circular variable filter spectrometers. One measures radiation from 0.4 to 1.2 μm with a resolution varying from 0.01 to 0.03 μm , and the other measures from 1.2 to 2.5 μm with a resolution between 0.023 to 0.04 μm . Each spectrometer contains two detectors, one measuring downwelling flux through a 2 pi hemisphere diffuser, and the other measuring upwelling radiance through a lens so that its field of view is 7 mrad. The instrument produces a complete spectral scan at a rate of approximately 8 Hz. It occupies the volume of a 60 cm long by 15 cm diameter cylinder and weighs approximately 15 kg. The total power required is less than 50 W. To date, accuracy has been limited by the calibration source, exceeding it by 2%, e.g. if the source is good to 5%, then the overall CPRAD calibration accuracy is 7%.

The modifications necessary for this instrument to be used in a UAV mission include 1) re-engineering to fit efficiently in the final UAV form factor, 2) extension to longer wavelengths, and 3) the addition of on-station calibration capability. In addition, a scanning capability to produce spatially resolved images would be desirable.

MAS: Developed by Daedalus Enterprises for the Goddard Space Flight Center, the Modis-N Airborne Simulator (MAS) is designed to fly in the instrument bay of an ER-2 to provide early data of the type expected from the Modis-N instrument to be carried on the EOS satellite. It is a grating spectrometer with a cross-track scanner.

MAS contains four grating spectrometers. The measurement range for each spectrometer is 1) 8 bands from 0.55 to 0.94 μm , 2) 16 bands from 1.63 to 2.38 μm , 3) 16 bands from 3.00 to 5.25 μm , and 4) 9 bands from 8.55 to 14.3 μm . A scanning mirror is used in the cross-track¹ direction to produce 716 pixels, with a resolution of 2.5 mrad per pixel, at a rate of six scans per second. The UAV's forward motion then produces a two-dimensional image of the scene flown over in each of the 49 bands. The current design contains two black body sources for in flight calibration. Currently, the MAS instrument² weighs approximately 50 kg, occupies a volume measuring approximately 45x45x75 cm, and consumes 200-300 watts. The electronics were not designed for limited power consumption. Redesigned electronics would significantly reduce power consumption. Calibrated accuracy for MAS is 2%.

The modifications needed for a UAV mission include 1) re-designing the electronics to consume less power, 2) re-designing the instrument to fit more efficiently in a UAV form factor and to measure downwelling as well as upwelling radiance, and 3) possibly changing the wavelengths addressed by each of the spectrometers.

¹Crosstrack with respect to the vehicles motion.

²Including scanner, optics, detectors and digitizers.

MPIR: MPIR is a highly accurate, UAV-compatible, cloud radiometer proposed by Sandia. It measures upwelling radiance in nine narrow spectral channels between 0.6 and 11.5 microns. The center wavelengths and spectral bandpasses of these channels have been selected to allow retrieval of key cloud properties such as reflectivity, ice/water phase, and droplet size, as well as to provide highly accurate calibration for existing satellite based measurements. Incoming radiation is imaged through optical filters onto 256 or 512 element linear arrays to provide a cross-track resolution of approximately 6 mrad in each band. The UAV's forward motion produces a two-dimensional image of the scene overflown by the UAV. Black body sources and a lamp are included to allow in flight calibration. The current design weighs 25 kg, measures 20x20x36 cm and consumes 50 watts.

Mini-ITS: None of the previous three instruments address the need to provide moderate to high resolution spectral radiance measurements in the IR. Mini-ITS is an FTIR spectrometer which may be able to address this region of the spectrum as well as provide high resolution spectral measurements in other parts of the spectrum. It draws heavily on the design of the Bomem Michelson MB100 interferometer, a design which is rugged and well suited to airborne conditions. The MB100 has been used successfully on the Shuttle and shipboard applications. Interferometer optics provide a field of view of 14 mrad. A scanning mirror allows for off-nadir measurements. Mini-ITS includes an on-board black body source for in-flight calibration. The current design measures thermal emission from 3.7 to 16 microns with a resolving power of 1000. However, future designs are planned to incorporate pyroelectric detectors for measurements into the far infrared. Mini-ITS is projected to weigh 25 kg and consume 25 W. The radiometric accuracy is expected to be < 1%.

Video Imaging Systems

Macroscopic cloud property measurements of certain types are best made using a video imaging system. Although cloud activity is primarily concentrated in the mid- and low-altitude regimes, the Tropical Western Pacific Ocean has activity at high-altitudes. Since the primary mission of the proposed UAV is long endurance high altitude flights, it is an appropriate platform for down looking observations of high-altitude cloud activity. It also provides an excellent platform for down looking observations of the top of mid- and low-altitude cloud decks.

Determination of the mean two-dimensional (2D) cloud coverage (specified as a percentage of the total area, assuming a uniform distribution) requires relatively coarse spatial resolution. Spatial variability of 2D cloud coverage and cloud morphology (including three-dimensional structure) require higher spatial resolution (and possibly higher temporal resolution) than imaging systems designed only for bulk area properties like mean cloud coverage. Additionally, higher resolution images (10 to 50 m resolution) are desirable in cloudy regions and over the central site (10 to 20 km radius), while lower resolution images (100 to 500 m resolution) would be acceptable over clear sky regions and the entire CART site (200 by 200 km area). Finally, a movable camera could scan a larger area using finer resolution optics, or could keep a particular region of the sky in its field of view (FOV) as the UAV flies past. The resulting cloud images from multiple viewing angles will allow inference of the clouds' three-dimensional structure.

Commercial imaging systems exist for both daylight video and for IR imaging systems. An imaging system mounted on a stabilized platform can provide high resolution images with a minimal amount of jitter. Many commercial stabilized platforms have features that allow for area scanning and for "staring" at regions of interest while the platform is moving. Typical IR sensors and typical daylight black and white (B/W) video sensors have an individual pixel field of view (IFOV) of 100 μ rad to 1 mrad

depending on the optics. The typical weights and power requirements of these components are: stabilized platform (20 kg, 60 W quiescent), IR system including cooler (10 kg, 100 W cooldown, 70 W sensor), and daylight system (3 kg, 15 W). The total volume required for this entire package is 0.6 m³. Any re-engineering efforts toward these instruments should focus on reducing the power and volume requirements.

In Situ Instruments

Meteorological Instruments: Typical radiosonde observations, such as pressure (P), temperature (T), and relative humidity (RH), might be easily obtained using a UAV, and its ascent and descent flight characteristics could allow for vertical profiling of these observations. Table 2.3 specifies typical requested observation ranges for ARM measurements and the observation range of typical commercially available sensor packages.

Table 2.3. Comparison of requested and available observation values.

Observation	Typical requested range of observation values		Typical range of existing sensor packages	
	Range	Accuracy	Range	Accuracy
Pressure (P)	0 Pa to 105 kPa	± 100 Pa	500 Pa to 105 kPa	± 100 Pa
Temperature (T)	180 K to 330 K	± 0.5 K	183 K to 323 K	± 0.5 K
Relative Humidity (RH)	0% to 100%	± 5%	5% to 100%	± 3%

Existing commercial instruments satisfy most of the observation requirements, but may need to be re-engineered to fit into a UAV. Also, some of these existing instruments are not sufficiently accurate near the low end of their observation range. This is especially true for relative humidity sensors at very low values of relative humidity. New instruments may need to be designed to obtain sufficient accuracies. Because of their importance, water vapor measurements are separated for further discussion below.

Water Vapor Measurements: Very accurate measurements of water vapor concentrations will be required to examine the effects of water vapor concentrations on atmospheric heating. Conventional cooled mirror hygrometers are inadequate because of slow response times, hysteresis, and sensitivity limitations. These limitations are particularly significant for upper tropospheric measurements where water vapor concentrations tend to be low (< 0.1 mbar). One promising approach for high altitude measurements appears to be a Lyman α hygrometer. In this method, a 121.6-nm light source dissociates a fraction of the water vapor molecules forming excited hydroxy radicals. The excited hydroxy radicals return to the ground state by emitting a photon at 309 nm. The light intensity at 309 nm is measured with a photomultiplier tube and is proportional to the water vapor concentration. Detection limits on the order of 0.1 ppm, and response times on the order of 1 second have been reported for instruments of this type. The instruments have been used in high altitude aircraft and balloon studies in the past. Some engineering will be required to adapt the instrument to accommodate the weight and size limitations that will be imposed by use on a UAV.

Lidar: Two important observations which cannot be made easily with any of the instruments described so far are detection of sub-visible cirrus clouds and vertical profiling of water vapor content at high altitudes. The low concentration of water vapor at high altitudes makes accurate measurement problematical. Lidar can meet the first need and possibly the second. Conventional lidar measures the laser radiation backscattered by clouds below the UAV and hence provides information on cloud altitude and, for semi-transparent clouds, cloud thickness and profiles. The lidar's

sensitivity can be made sufficient to detect and profile sub-visible cirrus clouds. A mini-lidar has been proposed that will fit on a UAV. The design uses a 1.06 microns, 120 mJ/pulse laser with a 20 cm aperture telescope. The design is eye safe at 18 km even when observing the beam with an 8" telescope. The design is expected to weigh 9 kg, occupy a 20x30x40 cm space and consume 29W.

Differential Absorption Lidar (DIAL) adds a second frequency in a water absorption band to a conventional lidar. The return strength of the non-absorbing frequency is used to calibrate the signal received in the absorbing band to profile the total water content. Current DIAL designs require significantly more weight and volume than could be carried on a UAV. Research is currently underway to produce a lightweight DIAL. If this research is successful, DIAL will be considered as a possible addition for some UAV missions.

This section has described several instruments which can be re-designed to fit on a UAV platform and make useful observations at the tropopause. The instruments that will make up the final suite have not been selected and might well include others not discussed in this section. However, it is possible to specify the broad categories of instruments to be carried on the UAV and, from the discussion in the last section, to specify the UAV capabilities needed.

One instrument suite the UAV might carry is:

- A two channel broad band radiometer which will provide total upwelling and downwelling flux in the solar and IR bands. This observation is sufficiently important that it should be taken by an instrument designed specifically for this purpose.
- A narrow band radiometer or spectrometer to provide spectrally resolved upwelling radiances and downwelling fluxes. This instrument may also have imaging capabilities for the upwelling observations.
- A meteorological measurement package to measure local temperature, pressure, and relative humidity.
- A high resolution visible camera to provide detailed information on cloud cover, cloud type, and photo-documentation for the other radiation instruments.

Another possibility would be to replace the video imagery with a mini-lidar to study sub-visible cirrus.

Table 2.4 shows representative weight, volume, and power requirements for five categories of instruments. Based on this table, an instrument payload consisting of a broad band radiometer, a narrow band radiometer, a meteorological package, and either a video imager or a lidar would require the UAV to have a capacity of 80 kg and 0.4 m³ and supply 150-200 W of conditioned power for the instruments. The required volume is larger than the sum of all the instruments to allow for packing inefficiency.

Table 2.4. Representative weight volume and power requirements for the primary instrument categories.

Instrument category	Weight	Volume	Power (conditioned)
BB Radiometer	20 kg	0.05 m ³	30 W
NB Radiometer	20-30 kg	0.02-0.05 m ³	30-50 W
Met Package	< 1 kg	< 0.01 m ³	< 10 W
Video Imager	20 kg	0.06 m ³	75 W
Lidar	10 kg	0.03 m ³	29 W

One aspect of the UAVs operation that will be considered carefully is the amount of data produced. Practical considerations require the average data rate to be kept at an acceptable level. There are many ways of limiting the amount of data generated by the UAV. Not all instruments are likely to operate continuously, e.g., the high spectral resolution radiometers might be of use only directly over the central site where their observations can be assimilated with like instruments on the ground directly below them. Also, one might think of a conditional response, i.e. under specified conditions collect at the full rate, otherwise at a more modest rate. The decision on how the UAV data rate will be managed will be made in close consultation with the Science Team based on the scientific utility of the data. To be prudent, the telemetry set and ground station will be sized to handle the full data rate of the instrument suite to allow for short periods of intensive observations.

2.5 Platform Requirements and Characteristics

As established in earlier sections, there is an important role for airborne measurements in the DOE's radiation-cloud program. Existing airborne platforms provide a significant capability, particularly at medium altitudes, but do not fully meet the requirements of the program, particularly endurance and altitude. These unmet needs suggest a role for unmanned aerospace vehicles. This section reviews the platform requirements based on desired measurements (and the characteristics of the instruments required to make those measurements) and presents potential platform options.

Requirements

The desired platform attributes are derived from measurements needed to support the ARM program. Specific requirements for the platform are based on the payload of representative instruments and likely operational mission profiles. As with any aircraft, the UAV design is a closely coupled combination of payload and performance requirements, available propulsion and materials technology, and construction and operational experience. To a certain extent, the UAV requirements are tempered by capabilities that potential UAV suppliers believe to be achievable.

The tropopause is considered a key boundary in the ARM measurement cell. Up to this altitude, upper clouds and water vapor can have significant effects on the overall radiation budget. To be of maximum use, measurements need to be performed one to two kilometers above the local tropopause, to be above the highest clouds and their associated water vapor. Because the height of the tropopause varies from about 8 km for the North Slope of Alaska to about 18 km for the Tropical Western Pacific, the minimum altitude goal of 20 km was selected (Daum, 1992).

The UAV endurance at altitude is driven by the need to make high altitude measurements over an extended period of time, covering multiple diurnal cycles (Langford, 1990). Therefore, the goal for endurance at altitude is 48 to 72 hours.

The required UAV range is explicit in traversing missions and ferry requirements to transit from support locations to operational areas and is implicit in endurance and flight speed. The Tropical Western Pacific locale will probably have the most stressing range requirements for traversing missions and transit. Although the specific location and configuration for this site have not yet been chosen, it is reasonable to assume that a range in the thousands of kilometers will be required because the area of interest spans much of the equatorial Pacific Ocean (Daum, 1992). Consideration of the endurance goal and likely speed at altitude suggests that the UAV will inherently have adequate range for likely TWPO missions. Taking advantage of this range for long traversing and transit flights may require multiple

receiving and relay ground stations to maintain line-of-sight communication and control.

The UAV payload weight and volume must accommodate a useful suite of baseline instruments. From the discussion in the earlier section on instrument requirements and characteristics, it appears that a set of baseline instruments that will provide meaningful measurements can be flown in a volume of 0.5 m³ and a weight of 150 kg. Therefore, these values have been selected as the weight and volume goals for the UAV.

The most desirable UAV configuration is one with the instruments located on the flight vehicle with unobstructed views above and below the flight vehicle and in relatively undisturbed air at the nose of the aircraft. In addition, *in situ* sampling techniques would require a nose location for instruments. Two existing UAV designs have adopted a suitable configuration with the power plant and pusher propeller located at the aft end of the aircraft and the instruments located in a pod at the nose. Therefore, the configuration requirement should not pose a problem for UAV development. This configuration is shown in Figure 2.1.

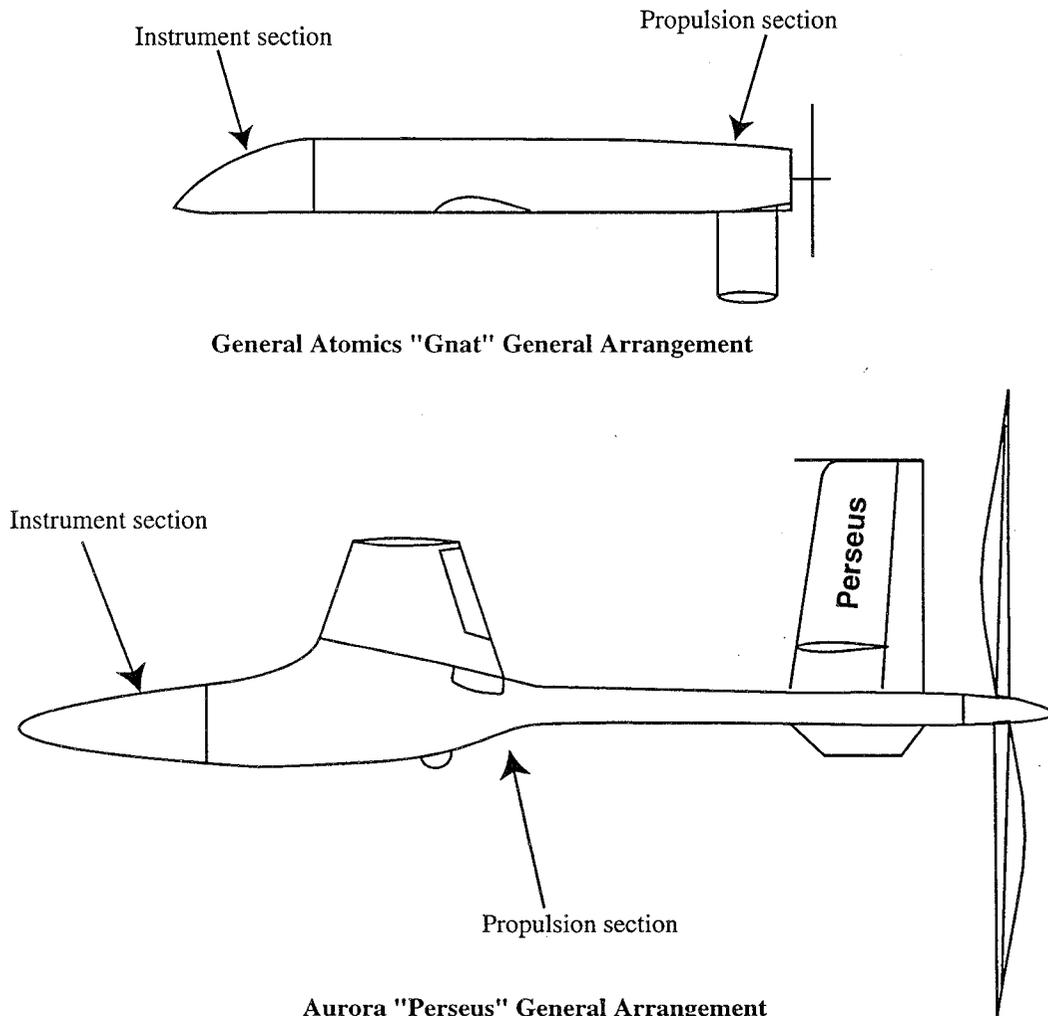


Figure 2.1 Examples of configurations suitable for ARM-UAV.

Table 2.5 summarizes the performance goals selected for the UAV.

Table 2.5. Performance goals for the ARM-UAV.

Altitude	20 km
Endurance above 20 km	48 - 72 hours
Payload volume	0.5 m ³
Payload weight	150 kg

Current Status of High Altitude UAV Technology

The use of UAVs to provide high-altitude, long-endurance ARM measurements will require integration of several key technologies in the airframe, avionics and control, and propulsion. Of these, the area presenting perhaps the greatest challenges is propulsion.

Internal combustion engines are highly developed for use in flight vehicles, are relatively low in cost, and offer good specific fuel consumption (important for long endurance). For these reasons, internal combustion engines are the basis of power plants for current UAV candidates suitable for the ARM mission. The two primary challenges in engine development are providing sufficient power at extreme altitude through forced induction and heat rejection for engine cooling. Two-stage turbocharging of internal combustion engines was demonstrated at 20 km altitude by the Boeing "Condor." Aurora Flight Systems is currently developing the Perseus-A, with a design altitude of 25 km, that includes heat exchangers designed for high altitude use. Suitable concepts have been identified for each of the key propulsion technologies, although significant time and resources will be required to extend them to the ARM-UAV flight regime.

Internal combustion engines should be capable of meeting the ARM-UAV performance goals. However, alternate propulsion technologies (principally microwave) have the potential for extremely long endurance because the source of power is not limited to fuel carried on-board the UAV. This propulsion technology is not as mature as internal combustion engines but may be attractive for long term development for extended UAV performance.

High-altitude UAV airframe challenges include structural strength and dynamics, and aerodynamic efficiency. Advanced composite materials have a good "track record" in aerospace applications and their application to the ARM-UAV make the structural issues relatively straight forward. Obtaining the required aerodynamic performance will depend upon careful design and construction, but does not appear to lie outside the bounds of other special purpose aircraft, for example, high performance sailplanes.

Avionics and flight control techniques required for the ARM-UAV have been used extensively in aircraft and other UAVs. For example, the use of multi-axis autopilots for stabilization and coupling autopilots to external navigation aids for semi-autonomous flight are common aircraft practice. Years of UAV experience have demonstrated remote control techniques including redundant links and loss-of-link logic for improved reliability. Very relevant experience is provided by the limited test flights of the Aurora "Perseus" proof-of-concept UAV and the more extensive flight experience of the General Atomics "Amber" and "Gnat" family of UAVs.

The principal flight control issue is the technique adopted for takeoff and landing. These operations account for a large proportion of operational losses. It is assumed

that initially these phases of flight will be under direct pilot control. The choice of line-of-sight pilot control or control from on-board video displayed in a remote cockpit will depend upon the experience and operational philosophy of the UAV contractor. Future development of an auto-land capability could reduce operational losses due to operator error.

In summary, the technologies required for the ARM-UAV range from mature to requiring significant development. Since suitable concepts have been identified for all cases, achieving the ARM-UAV performance goals appears feasible, unless difficulties arise that were not anticipated in the program plan.

Platform Options: Mid-Altitude

The focus of the ARM-UAV program is high-altitude, long-endurance missions. The primary use of the existing mid-altitude UAVs in this program would be to gain operational experience with extended UAV flight while obtaining useful science data. Such science data would include warm cloud microphysics, fluxes and heating rates as well as mid-level cloud albedo measurements. Much can be learned about radiation properties from making flux measurements near the top and bottom of high clouds. For example, extended operation of the General Atomics "GNAT" or the Aurora "Perseus" would provide valuable experience for further development of high altitude derivatives. However, FAA airspace regulation may require the use of a chase aircraft with unmanned aircraft in the continental United States (see Section 2.5).

Platform Options: High altitude

As discussed in Section 2.4 there are only two manned platforms suitable for high altitude measurements in the Tropical Western Pacific: the ER-2 and WB-57. These platforms are subject to scheduling and availability limitations, are relatively high cost, and do not meet all of the stated ARM-UAV performance goals, in particular, the goal of long endurance. An unmanned version of the ER-2 has been proposed that would meet ARM-UAV performance goals but at a substantial development and operation cost.

A class of low-payload, high-altitude UAVs has been proposed that would meet the stated ARM-UAV performance goals and offer the promise of reduced operating costs. The Aurora "Perseus/Theseus" and General Atomics "Gnat/Pursuer" aircraft are examples. Development of such an aircraft would provide a significant improvement in UAV performance and a unique upper atmospheric platform.

2.6 Operational Concept

Use of unmanned aerospace vehicles provides the ARM program an opportunity to obtain valuable information with unique characteristics. The ARM-UAV program is predicated upon development of UAVs with performance capabilities that are currently unavailable. The unique characteristics the full-performance UAV will offer are high altitude and long endurance time on station. Performance goals of the full-performance UAV will place a carefully selected set of instruments at the desired high altitude and geographical location to complement other important measurements.

Operation at CART Sites

The primary objective of the ARM-UAV program is atmospheric measurements in conjunction with one or more Cloud and Radiation Testbed (CART) sites. The CART site configuration is assumed to be a square region approximately 200 km on a side with a heavily instrumented central facility. Additional instrumentation will be distributed within this area in the form of auxiliary and extended facilities. The

auxiliary facilities are largely focused on 3-D cloud mapping and the extended facilities on measuring surface characteristics.

The preceding description is typical of the first CART site, a southern great plains location in Oklahoma. For the purposes of this program plan, it is assumed that other sites will have similar characteristics. However, ocean sites, such as the Tropical Western Pacific, may differ significantly depending upon the questions posed by the area. The UAV performance goals are selected to also meet the needs of other candidate CART locales. For example, the operational altitude goal is based on the requirements of the Tropical Western Pacific. Details of UAV operation at future CART sites can be addressed when the final locations are selected.

Extended operation at a CART site will require three UAVs: one flight-ready, one undergoing scheduled maintenance, and one undergoing unscheduled maintenance and repair. Operation of the UAV will require ground facilities within reasonable distance of the CART site. These facilities include a takeoff and landing area with clear approaches and a suitable runway at least 2500 feet in length, a ground control facility, adequate shelter for the aircraft and personnel, a telemetry ground station for receiving and preprocessing flight measurement data, and a facility for maintenance and instrument calibration.

Mission Operations

Each UAV mission will be flown with specific objectives and contingencies. A Mission Planning Working Group will develop specific mission orders and a flight plan based on standing guidance and special requests. A mission controller will supervise the mission pilot, conduct the flight in accordance with mission orders, and choose courses of action at decision points.

During the flight, the mission pilot will remain in continuous contact with air traffic control while maneuvering the aircraft to the operational altitude and area. Instruments will be prepared for operation, checked, and operated in accordance with the mission orders. Changes to the mission orders will be accepted by and transmitted to the mission pilot by the mission controller.

Following a mission, any on-board data will be retrieved and the UAV will be returned to the protective shelter for inspection, maintenance, repair, and service in preparation for its next mission.

Multiple Platform Mission

Two UAVs flying in formation to make coordinated measurements, for example, above and below cloud layers, is an attractive option (Langford, 1990). Exercising this option will require two ground control stations, multiple sets of RF links, special operational procedures, and in addition, two flight worthy UAVs.

Extended Missions

The primary use of UAVs at a CART site is in conjunction with the central facility. Additional valuable missions could be designed to obtain measurements over larger areas of the extended site. These missions would require flying an extended flight pattern for which the optimal flight path would depend upon the objectives of the particular mission and would be determined as part of the mission design as it is integrated into the overall CART observation system.

Regulatory Issues

Flight operations of the UAV will be conducted within a framework of regulations governing airspace utilization. In the United States, the Federal Aviation Agency

(FAA) is responsible for administering airspace and flight vehicles. The ARM-UAV program concept includes three elements that would require operation of a UAV in the Continental United States: (1) high altitude UAV development testing conducted within controlled airspace at a test range, (2) mid-altitude operational experience flight phase conducted at the Oklahoma CART site with an existing UAV, and (3) high altitude UAV operational development flight phase conducted at the Oklahoma CART site. Development flight testing at a controlled test range should not be a regulatory issue; however, operations in conjunction with a CART site in the United States will be.

There appears to be little guidance on civilian UAVs in the Federal Air Regulations (Langford, 1990). The FAA has formed a committee to develop regulations governing the use of UAVs in US airspace. Initial proposals appear favorable for the use of UAVs at high altitude. Final regulations should be in place in 1994 or 1995. Current guidance suggests that a chase plane or optionally-piloted UAV will be required for operation at mid-altitude over the United States. Other FAA requirements could result in additional operating restrictions, equipment requirements, and approvals. The program will coordinate closely with the appropriate regulatory agencies starting early in the project.

2.7 Data Acquisition and Management

To provide meaningful data from the airborne platform, the UAV must collect measurements from the platform instrument package and pass them to a location where they can be made suitable for relay to the ARM experiment center. The experiment center will, in turn, provide further processing and storage. The proposed structure to provide these capabilities is described below.

UAV Data Links

Data will be collected from the platform instruments by a UAV telemetry (TLM) system that will transmit these data to a ground-based receiving and pre-processing station. The TLM system will be co-located with the instrument package in the UAV payload. This system will collect, condition, format, and transmit (via RF links) the data from the selected instruments.

In addition to in-flight instrument data links, the UAV will have RF links for command, control, UAV flight data, and short range video for takeoff and landing. However, these links are at different frequencies and will not interfere with telemetry transmissions.

It is anticipated that a typical UAV instrument suite will include either a video camera (6 MHz analog output) or a lidar, a broad band radiometer, a narrow band radiometer, and a meteorological measurement package. An estimate of the output types and rates of each instrument is shown below:

<u>Instrument</u>	<u>Type of Output</u>	<u>Data Rate or Bandwidth</u>
Video camera	Analog	6 MHz
Lidar	Digital	40 kbps
Broad band radiometer	Digital	30-50 kbps
Narrow band radiometer	Digital	300-3000 kbps
Met. package	Analog	50 Hz

The telemetry system proposed for this application will require two RF links for transmission to the telemetry ground station. One link will be dedicated to the video

system, the other will relay the remainder of the instrument data streams plus the meteorological and diagnostic data.

A 2-megabit per second (2 Mbps) data rate is about the current state-of-the-art for low-error, RF transmission. The estimate above suggests that the output of anticipated flight instruments could exceed the capacity of a single RF link. To avoid the cost and weight of a second link, the data output will be managed to fit the capacity of a single link through data thinning or compression. Some instrument outputs may lend themselves to storage of the data during collection periods, with subsequent transmission of these data at a lower rate before the next collection period.

The telemetry system design will make extensive use of programmable logic devices (PLDs), an approach which permits, within limits, the system to adapt to changes in the instrument complement. Because of the restrictions on payload weight, volume, TLM data rates, and power, it is strongly recommended that the TLM system designers work closely with the instrument designers so that an efficient payload ensemble (instruments plus TLM) is realized. Key elements of the TLM system are shown in Figure 2.2.

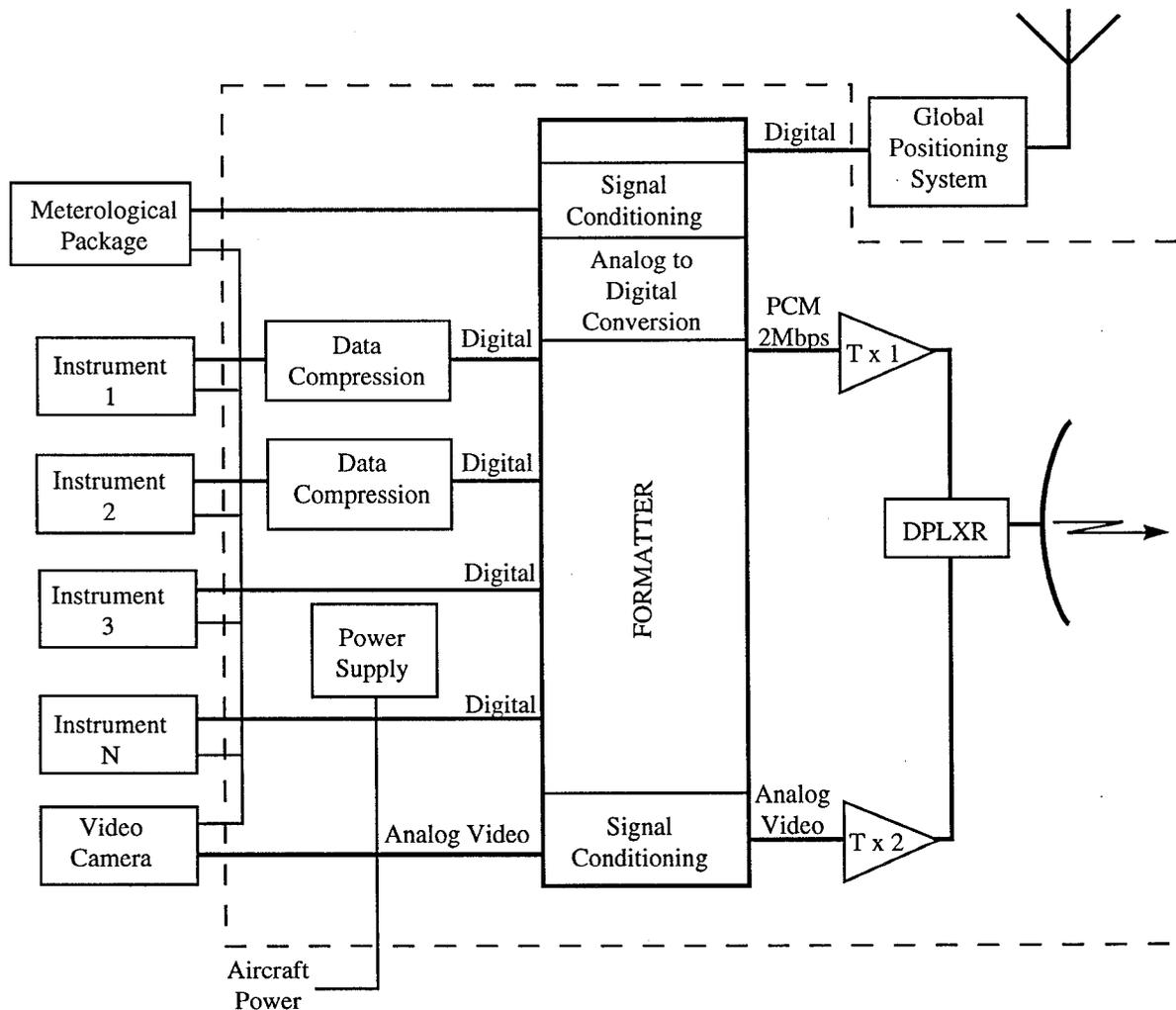


Figure 2.2. Telemetry system elements.

Listed below are some pertinent characteristics of the proposed UAV telemeter:

Number of links:	2
Transmitted power/link:	2 watts
Link 1 data rate:	≤2 Mbps, NRZL PCM
Link 2 data bandwidth:	6 MHz analog
Antenna system:	omni-directional, -6 dbi gain
TLM volume:	1350 cm ³ (864 in. ³)
Weight:	10 kg (22 lbs)
Power required:	48 watts

The estimated TLM power requirement of approximately 50 watts will require a source of cooling to maintain component temperatures to ≤80°C for the mission duration. Ground control of TLM on/off status would permit TLM powering only during periods of data taking, significantly reducing the heating problem.

The UAV telemetry ground station (TGS) must provide two primary capabilities during UAV mission support: (1) receive the RF transmissions from the UAV telemetry system and record the resultant raw serial data streams, and (2) sufficiently pre-process these raw data such that the output product can be delivered to the CART data center in a form suitable for scientific manipulation and calculation. Secondary capabilities provided by the TGS will be (a) real time displays of the meteorological data, and (b) a state-of-health monitor for the UAV instrument payload as well as the UAV TLM via display and analysis of selected diagnostic measurements. The UAV TGS proposed to provide these capabilities is shown in block form in Figure 2.3. The system is conceived as being transportable—either as a trailer, van, or other suitable container, and will not be dedicated to a particular CART site. The system will be self-contained in terms of equipment, cabling, air conditioning, etc., but will require 208 volts AC, 3 Ø power for operation. To minimize RF transmission distances, the TGS should be situated as close as possible to the geometric center of the projected measurement area.

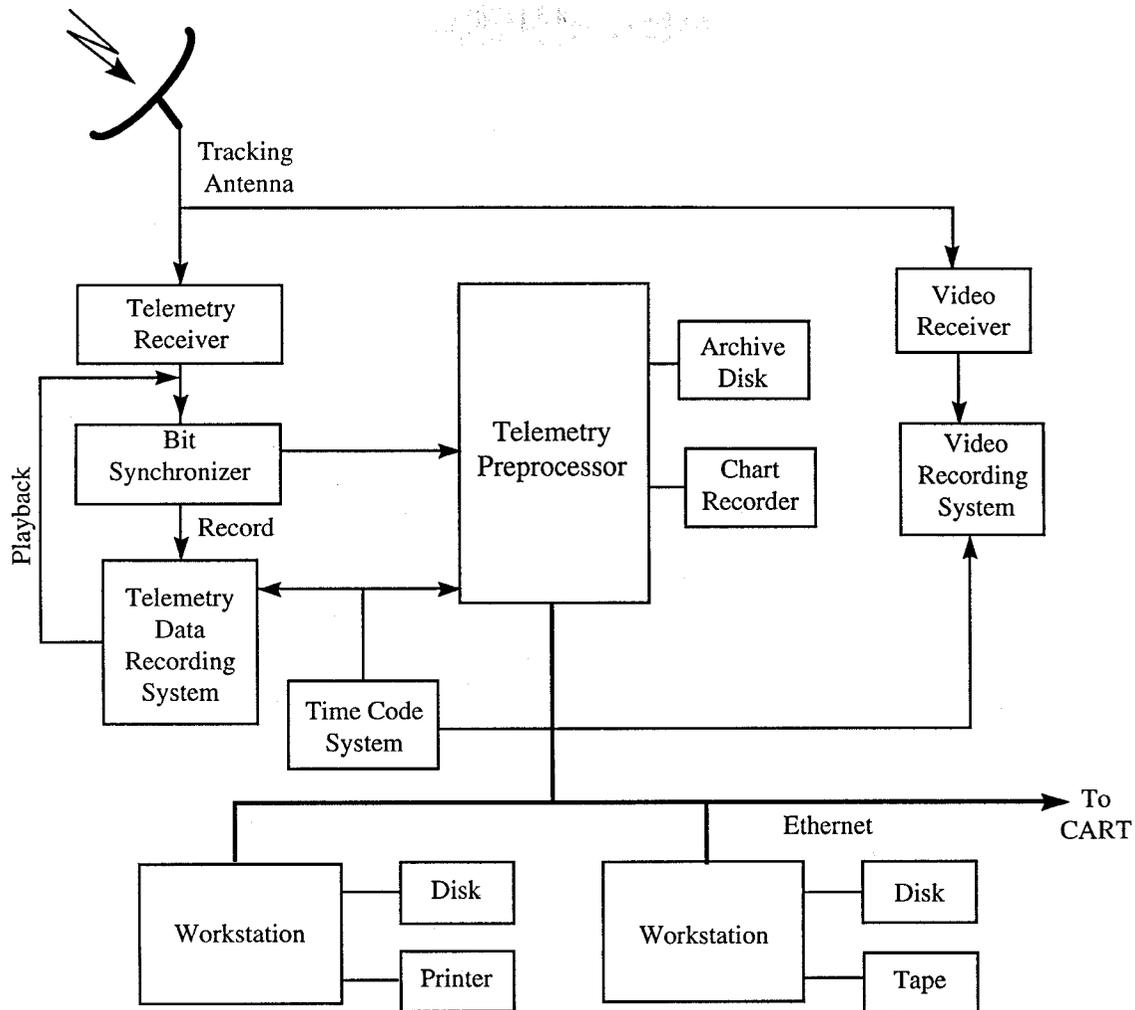


Figure 2.3. Telemetry Ground Station.

Before the scientific data collection phase of a UAV mission, the telemetry and instrumentation will be powered, permitting tracking antenna lock (tracking is controlled by received signal strength supplemented by GPS position data) and receiving of the RF data links. Once track is acquired, instrument and telemeter state-of-health can be evaluated and appropriate mission decisions made. During the scientific data collection phase, all received data will be recorded on the TGS recording system. Meteorological data will be available via Ethernet for real-time display following processing and engineering unit assignment by the telemetry preprocessor. Payload state-of-health will also be continuously displayed during the mission.

Scientific Data Management

The UAV TGS will record all incoming data streams in their analog video or serial (compressed) digital form. Following mission completion, these data will be replayed through the TGS preprocessor, which will sort the individual instrument data into separate files. These files will be passed to the CART data center and the ARM Experiment Center for further processing. The transfer will either be electronic, over existing network connections, or physical through movement of a recording media such as magnetic tapes or disks. The analog video will be recorded on tapes that will

be sent to the ARM Experiment Center for further processing. Since the TGS is not assigned to a specific CART site, any data manipulation beyond sorting (decompression, engineering unit conversion, etc.) will best be accommodated in the CART data center or the ARM experiment center, the exception being meteorological data, which will be converted to engineering units by the TGS. This approach frees the TGS for missions at other sites or to support pre-flight checkouts of upcoming missions at the same site. Any decompression algorithms and other tools required for data processing will be provided by the TLM/TGS community. Assuming the CART data center work stations are Ethernet compatible, only a hardwire link between the TGS and the data center will be required for all post-mission data transfer. The CART data center will provide any further processing for post mission analysis and also complete the data transfer to the ARM experiment center. Figure 2.4 depicts the envisioned data flow for the UAV. The experiment center or the archive center should be responsible for storing and managing the raw data tapes from the TGS for future use.

2.8 Risk Management

The proposed program for using unmanned aerospace vehicles as a measurement platform in support of the ARM Program is a significant undertaking with a variety of challenges. Any program of this size and complexity inevitably involves elements of risk. At the outset of such a program, it is important to recognize these risk elements and plan accordingly. The remainder of this section provides a preliminary identification of significant risk elements and a discussion of strategies that will be adopted to manage program risks.

Identification of Potential Program Risks

Some aspects of the ARM-UAV program use techniques and hardware that are proven and may be applied with relatively high confidence. Other aspects of the program use techniques and hardware that are new or under development and entail higher levels of uncertainty. In constructing this program plan, we have attempted to identify elements of the program that appear, on the basis of information currently available, to involve higher levels of risk than expected in proven techniques.

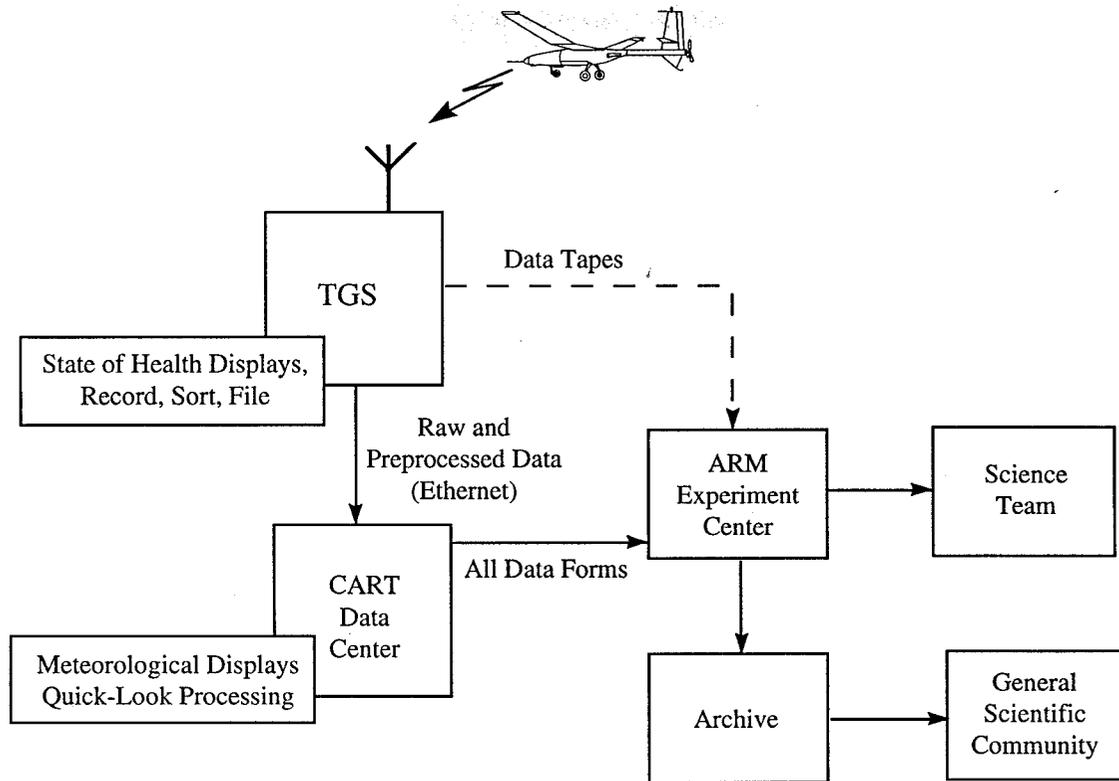


Figure 2.4. Envisioned data flow for the UAV.

UAV Development

The central feature of the ARM-UAV program is the use of unmanned aerospace vehicles as a platform for high altitude atmospheric measurements. The primary risk associated with the development of the ARM-UAV is extension of previous UAV experience to much higher altitudes. This extension involves uncertainties in the airframe and propulsion system. Of the two, propulsion development appears to offer the bigger challenges, particularly in developing adequate power at extreme altitude. A candidate propulsion system is a multi-stage turbocharged internal combustion engine as demonstrated in the Condor program at altitudes over 15 km.

An important strategy to mitigate program risk is supporting parallel development of critical elements of the UAV system, possibly including a “flyoff” between prototypes of two competing UAV designs. The risks inherent in the UAV development also can be mitigated by establishing the system requirements at the start of the development process and avoiding changes to those requirements once development is underway. The organization charged with the responsibility of developing the UAV must have access to the required depth and breadth of experienced personnel and must be provided adequate resources to pursue a successful development program.

Vehicle Operational Loss

The ARM-UAV program probably cannot afford the cost of developing a platform with reliability typical of manned aircraft. As a result, it must be expected that UAV losses will occur during the life of the program. These losses are of concern in two areas: the hazard that the loss of a UAV represents and the cost to the program for

replacement of the platform and, possibly, the instruments. The hazard aspect of UAV loss will be discussed in the next section.

Although it is difficult to estimate the expected UAV loss rate, some attempts have been made to provide such an estimate. For example, Langford, 1990, p. 50, provides a loss rate estimate for military UAVs of 0.5% to 8% on a flight hour basis. From this loss rate estimate, Langford, 1990 extrapolates a loss rate goal for civilian UAVs of one aircraft loss in 500 flight operations. Although it may be possible to improve the confidence level of these estimates with additional study, there will remain a substantial uncertainty about loss rate. This uncertainty affects estimates of operating cost for the system (including the amortized replacement cost of lost systems) and determining the number of spares that must be available to provide the required operational availability.

Factors influencing vehicle loss rate include ground or flight equipment failure, operator error, and the environment (turbulence-induced upset or overstress, icing, etc.). The risk of operational losses can be mitigated by careful selection of platform specifications, careful adherence to operating procedures, and an adequate flight test program to establish a flight envelope with adequate safety boundaries.

Ground and Air Hazards

Operation of a flight vehicle such as the ARM-UAV involves some degree of hazard to people and property. Initial testing will be conducted under carefully controlled conditions at an appropriate test site to minimize this hazard. During controlled operation, selection of flight path can substantially reduce the ground and flight hazard. However, operation of a UAV at extreme altitude results in a very large footprint of potential impact points. Loss of communication and control, active on-board equipment failure, or structural failure can result in uncontrolled descent through altitudes potentially occupied by other aircraft and ultimately ground impact.

The flight and ground hazards represented by operation of the ARM-UAV will be mitigated in several ways. The first is to perform adequate flight testing to establish a safe operating envelope. The second is the careful selection of flight areas and flight paths in order to minimize exposure to other aircraft, and to people and property on the ground. The third is adequate communication and coordination with air traffic control agencies. Finally, a "range safety officer" who monitors any flight operations with the responsibility and authority to modify or terminate a flight can be a way to control potential hazards.

2.9 References

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3. MPIR, a compact, highly accurate, cloud radiometer for UAVs

Cloud parameters are one of the greatest sources of uncertainty in present climate models. The Multi-spectral Pushbroom Imaging Radiometer (MPIR) design is for a general purpose instrument intended to gather well-calibrated optical data from the air to provide identification and characterization of clouds. Additional information such as surface reflectance, top-of-the-atmosphere radiative fluxes, aerosol concentrations, etc., may also be extracted from the data. The system could be operated from an aircraft or small satellite but is designed specifically to operate from an ARM-UAV platform (see Chapter 2). In order to supplement the ground-based data collected at the ARM CART sites, these ARM-UAVs will fly various instruments on a UAV platform at altitudes ranging from the surface to above the tropopause. The tropopause altitude varies from 8 km for the North Slope of Alaska to 18 km in the Tropical Western Pacific Ocean (TWPO). The higher altitudes at the TWPO CART site produce the maximum altitude requirement of 20 km for the ARM-UAVs. For greatest climate modeling utility, data collection is desired over multiple diurnal cycles; our design goal is to operate MPIR for a 60-hour continuous flight at 20 km altitude. During the flight, image data will be digitized, buffered, and telemetered to a nearby, line-of-sight, ground receiving station in near real-time for storage and later analysis.

The spectral bands recorded and spatial resolutions provided, will be similar to those obtainable from satellite sources such as the Advanced Very High Resolution Radiometer (AVHRR). These satellites provide data from a specific site only occasionally, while MPIR will more closely simulate a geostationary satellite parked at the tropopause above a CART site. Because of its lower altitude, MPIR, with 5 mm aperture optics, will provide spatial image resolution similar to that of available satellite remote imagers and better than would a geostationary satellite. Using a relatively inexpensive UAV to fly an MPIR instrument promises a more cost-effective method to gather the required long-duration CART-site data. There is also the advantage that between missions the UAV will land, allowing adjustment, reconfiguration, or repair of the equipment if needed or desired.

3.1 System Requirements

MPIR will form multi-spectral images by using linear detector arrays in a pushbroom imaging arrangement. The array elements each take data from spatially parallel ground tracks while the forward motion of the UAV provides the "pushbroom" motion to form a two-dimensional image as indicated by Figure 3.1. Each instantaneous reading of an array element corresponds to a single pixel of the eventual image. The ground area covered by the width of the entire array should be similar to that of the highly instrumented central area of a CART site or that of the typical footprint of a satellite imager (20-30 km). Each spectral channel will be independent, with its own optics, filter, detector array, and electronics. They will be modular and interchangeable to allow for mission requirement modifications.

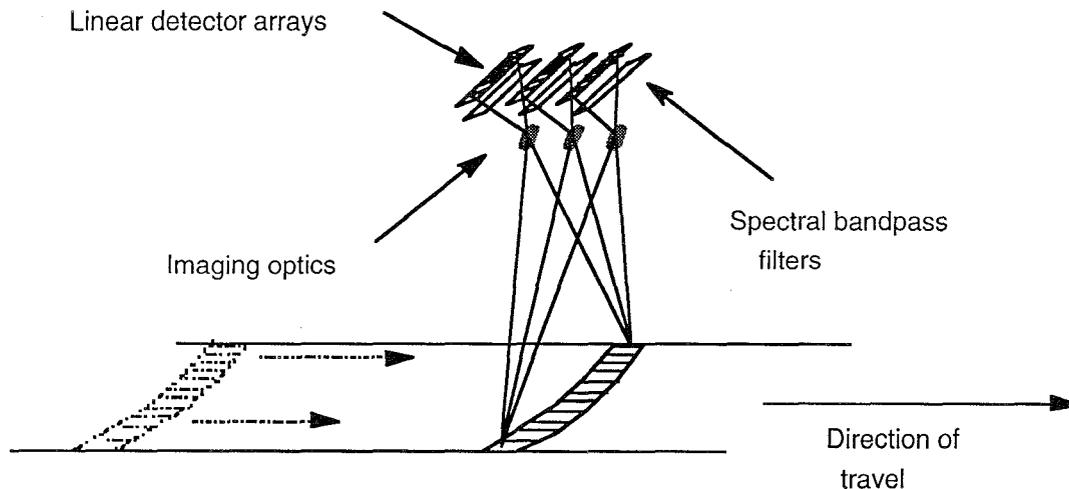


Figure 3.1. Illustration of the Pushbroom Imaging Techniques used by MPIR. (Only three parallel channels are shown for simplicity.)

Since MPIR will operate at an altitude of 20 km or below, a wide field-of-view (FOV) imaging system is required. An additional consideration is the size of a single pixel. Spatial resolution on the order of 100-150 m is desired for parameterization of the cloud formations. An 80 degree field-of view (FOV) with a minimum of 256 elements in each array was chosen as a suitable compromise between available arrays and spatial resolution. The ground path sampled by a down-looking 80 degree FOV system from an altitude of 20 km is 33.6 km wide. Using a uniformly spaced 256-element array behind a distortion-free optical system, the ground footprint of the center pixel would be 109 m wide while that of the pixels at the edge of the array would be 186 m on a perfectly spherical earth. Perpendicular to the line-of-sight (LOS), the edge pixels subtend only 143 m at the surface. With such a system at a 20 km altitude a 125 m resolution perpendicular to the LOS would be achieved at the center of the FOV or for any clouds imaged by the edge pixels that are higher than 2.4 km. Imaging from lower altitudes will produce smaller resolution spot sizes.

The predicted ground speed of a Perseus-B UAV in still air at sea level falls in the range of 20-80 m/s. As the air becomes thinner with altitude the required ground speed increases. At a 20 km altitude a ground speed of 80-165 m/s is necessary. Any winds aloft must be added to these speeds. Prevailing wind velocities typically increase from the surface to near 9 km and gradually decrease at higher altitudes. (At 20 km a typical 50th percentile wind velocity will be 15 m/s.) When combined with the UAV still-air speed, worst-case MPIR ground speeds could approach 200 m/s at a 20 km altitude. With roughly a 100 m nadir ground resolution this dictates taking image data at a 2 Hz rate to avoid undersampling the image. To make optimum use of the increased resolution available from a 512-element array, a maximum data rate of 4 Hz per element would be required.

An MPIR stated design goal was to record data in approximately 10 spectral bands. This would allow sufficient spectral information to calculate the required cloud parameters. Although any number of channels could be designed, a compact, modular, 3-by-3 array of detector channels was judged to best be able to meet cloud data requirements while still allowing a future system replication cost of \$1,000,000 or less. The calibration scheme to be discussed below uses a shutter mechanism to alternately measure image and calibration data, effectively doubling the image data rate. The 12-bit image and calibration data for nine, 256-element detector arrays sampled at 2 Hz will be 110 kbits per second without

data compression. This may be near the data bandwidth available for transmission of MPIR signals to the ground receiving station. The potential utility of short wavelength, 512-element array data will need to be balanced against the available telemetry capacity.

Accurate determination of cloud properties requires calibration for each of the spectral detector channels. Several of the derived cloud properties rely upon data relationships between several channels. The accuracy of these quantities will be dependent upon the radiometric calibration accuracy as well as the geometric registration of multiple channels. Realizing the problems involved with both radiometric and geometric accuracy, the design goals established for MPIR are radiometric accuracies of 1% in the thermal IR bands, 3% in the visible, with geometric registration errors between channels of 10% of a pixel width. These accuracies should allow for indirect calibration of satellite sensors to make their data useful for climate studies. Achieving these accuracies will require not only pre- and post-flight ground calibrations, but continuous in-flight calibration readings as well.

The wavelength bands selected for MPIR include many of the bands frequently used in cloud remote sensing, as well as bands that have been identified as having potential for improved performance.

Proposed MPIR Wavelengths (Microns)*:

0.62 - 0.68	3.55 - 3.93
0.86 - 0.90	6.54 - 6.99
1.36 - 1.39	8.40 - 8.70
1.58 - 1.64	10.30 - 11.30
2.11 - 2.22	

*The MPIR bands have evolved slightly since the completion of the LDRD.

MPIR bands in the visible and near-IR are used in various combinations to determine cloud coverage, optical thickness, effective particle radius, phase (ice versus water), and reflectance. The longer wavelength bands provide a means of determining cloud cover at night as well as additional capabilities for determining cloud emissivity, temperature, phase, etc. The 1.139 μ m water vapor absorption band allows the determination of mass density of water vapor at the cloud top. Most of the bands are atmospheric windows with good transmission to the ground, allowing characterization of the surface conditions in the absence of cloud cover. The wide FOV of all channels will potentially allow angular reflection data to be collected.

Instruments that operate from small UAVs must themselves be small, lightweight, with moderate power requirements. Three or four instruments are anticipated on each UAV mission. Since the **total** design payload of a Perseus-B is to be only 150 kg. in 0.5 m³ the MPIR instrument should be no more than 30 kg. and 0.1 m³, less if possible. On-board generator capabilities limit MPIR to an electrical power consumption of nominally 50W.

3.2 Design Elements

Optics

Channel spatial registration needs require that each of the optical systems have similar geometric distortions. An all-reflective optical system design was chosen to provide identical geometric performance at all wavelengths. The layout of a single channel is shown in Figure 3.2. It consists of five reflecting surfaces. M1, M2, and M4 are conics with a common axis of symmetry, tilted 55 degrees from the field-of-view center. M3 is a folding flat with its normal parallel to the axis of the conics; its

periphery also acts as the aperture stop. M5 is a folding flat, providing additional mechanical clearance for the detector.

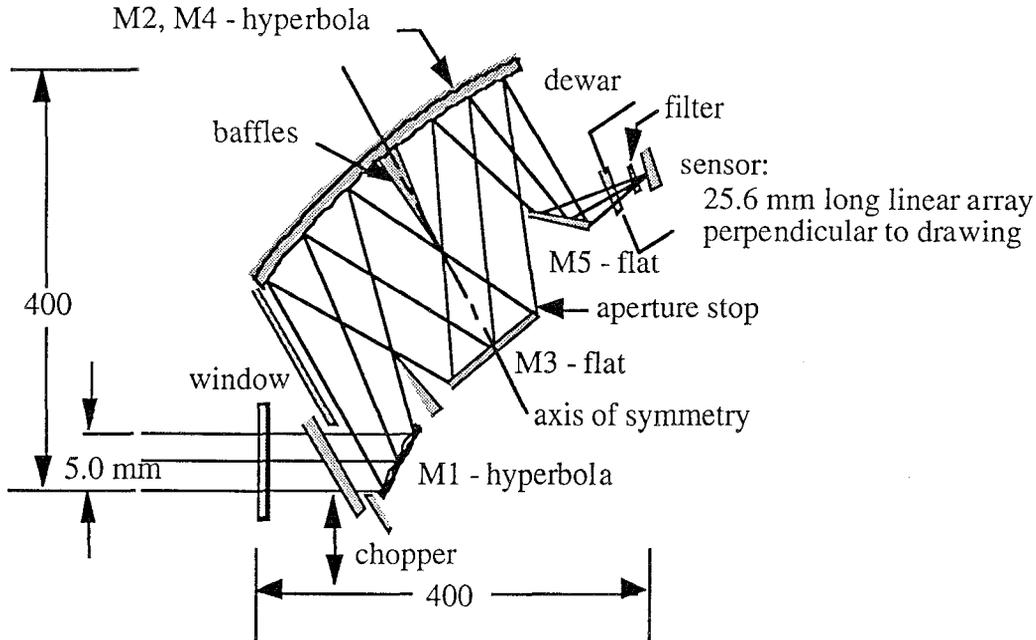


Figure 3.2. MPIR Optical System Layout

Aberrations for this type of system are corrected over an annular ring, concentric with the axis of symmetry. The width of the ring can be made large enough that it encompasses an 80 degree, one dimensional field-of-view (FOV) suitable for use with a linear detector array. The focal length of the system was adjusted to provide the 80 degree FOV over a 25.6 mm length, matching the length of a number of off-the-shelf detector arrays.

Image quality is very good over the 80 degree field. For an $f/3.5$ aperture, 85% of the geometric spot energy will be contained within a $50 \mu\text{m}$ diameter. Thus, at short wavelengths the spatial resolution would accommodate detector arrays containing 512 (or more) pixels. At long wavelengths diffraction will increase the spot diameter; at $11 \mu\text{m}$ the 85% energy spot diameter of $100 \mu\text{m}$ is suitable for 256-element use.

The system's 15% barrel distortion produces several consequences. The first is that pixels at the edge of the field are displaced inward from their positions predicted from first order optics. This is easily corrected by applying the appropriate correction equation when reconstructing the image. The second consequence is that the angular pixel subtense, and thus the ground sample width, varies with field position. For example, measuring in a direction perpendicular to the line of flight, the angular subtense of a 100 m pixel is 5.7 mrad at the FOV center and 5.0 mrad at the FOV edge. Viewing a flat earth from 20 km altitude these numbers translate to 115 m at the center and 170 m at the edge which is a smaller variation than provided by a distortion-free system. The third consequence of barrel distortion is that the projection of the linear array onto the earth's surface is curved, rather than straight, requiring a correction during image reconstruction. Fourth, the barrel distortion is actually a benefit in achieving band-to-band registration. The effective focal length varies as a function of the radial distance from the axis of symmetry. Slight differences in the length of the detector arrays can be accommodated by adjusting the radial position of each array.

Diamond turning allows aspheric surfaces to be generated as easily as spherical, dramatically reducing the fabrication time and cost. Wishing to use this advantage, the optics shapes and positions were constrained to allow easy diamond turning of the surfaces. M1 and M3 can be generated by making two cuts on a single component. M2 and M4 were constrained to have the same equation and to be coincident, allowing them to be generated by a single cut on a second component. The two components are held in position relative to each other by a cylindrical spacer. Diamond turning allows all components (including mounting features) to be fabricated to sufficient accuracy that assembly consists of simply bolting the parts together with few, if any, adjustments necessary. For the shortest wavelength channels, scattering from the diamond machined surface may limit performance. If necessary the surfaces can be post polished (i.e. hand polished after diamond turning) to reduce the scattered light. This must be done with care to avoid changing the aspheric surface figures and will obviously increase the fabrication cost. It should be done only if prototype tests show it to be necessary.

Additional features shown in Figure 3.2 include: a chopper to allow calibration using a reference temperature or a dark background, and a window to allow a more controlled interior environment on an aircraft version of the instrument. The window is curved, with a radius of curvature equal to its distance from the entrance pupil. This allows incoming rays to strike the window at near normal incidence, minimizing the polarization problem introduced by a flat window. The cost of the windows, especially for the LWIR region, will be high relative to the cost of the other optical components.

Detector types

The range of spectral bands proposed for MPIR include visible, near-infrared (NIR), medium-wave infrared (MWIR), and long-wave infrared (LWIR) channels. No single detector type is suitable for use in all of these bands. Selection of the optimum detector technology to be used for each channel is dependent on detailed performance and cost information not yet available. The following is a list of the various wavebands along with the detector materials considered.

Table 3.1: Potential Detector Technologies Suitable for MPIR use:

Waveband (microns)	Array Type	Number of elements
0.62 - 0.68	Silicon photovoltaic	512
0.86 - 0.90	Silicon photovoltaic	512
1.36 - 1.39	InGaAs photovoltaic	256 or 512
1.58 - 1.64	InGaAs photovoltaic	512
2.11 - 2.22	InSb photovoltaic	256
3.55 - 3.93	InSb photovoltaic	256
6.54 - 6.99	HgCdTe photovoltaic	256
8.40 - 8.70	HgCdTe photovoltaic	256
10.3 - 11.3	HgCdTe photovoltaic	256

In order to keep array power dissipation, and therefore cooling requirement, to a minimum, only photovoltaic HgCdTe detector arrays are considered for the LWIR channels. The bias current of a photoconductive HgCdTe array is estimated to dissipate 1 mW per element. To meet our sensitivity requirements these arrays must operate near 80 K. The electrical power, or LN_2 volume, required to cool multiple

1/4 W loads to these temperatures for a 60 hour mission was judged to be excessive for MPIR use.

The reflective optics were designed for an 80° FOV when used with a standard array length of 25.6 mm. This corresponds to a 50 μm detector pitch on arrays having 512 elements or a 100 μm detector pitch on arrays having 256 elements. An aspect ratio of about 1:1 (detector length:width) is optimal to provide for the desired 100 meter ground resolution. The 512 element detectors can provide 50 meter ground resolution in the visible and near infrared bands. Diffraction effects would limit the LWIR resolution of 512-element arrays to approximately 65 meters. Since costs dictate the use of 256-element LWIR arrays, these diffraction effects will not be a limiting factor.

Noise and sensitivity calculations presented in a later section will indicate the superiority of the silicon and HgCdTe photovoltaic detectors in the visible and LWIR bands, respectively. In the NIR region PbS and PbSe materials possess relatively long time constants (milliseconds) and pose a potential problem with 1/f noise. Otherwise they offer good performance for their cost. In the MWIR region, InSb detectors require cooling to cryogenic temperatures (80 K) whereas HgCdTe and PbSe at these wavelengths only require cooling to intermediate temperatures (193 K).

Sensitivity Requirements

A maximum data rate of 4 data samples per second using a 512-element array was determined from the ground speed of the UAV. The system will alternately take a data sample with the shutter open followed by a calibration/background sample with the shutter closed. To help prevent vehicle motion from smearing the data image, all image data will be taken during one half of the theoretically available time. Each array will use a fixed integration time for data collection, either 10 ms or 0.5 ms depending upon array type. The 1/16 second data collection time allows the system to average six readings from arrays with 10 ms integration times or 120 readings from the arrays with 0.5 ms integration times. The system shutter chops all channels at the same rate. 256-element arrays that require only two data samples per second would average data over two of the above 1/16 second data collection times. For noise calculation purposes, the effective electrical bandwidth of the 512-element data channels will be 8 Hz; 4 Hz for the 256-element arrays.

The system could be designed with a variable speed shutter controlled by the central microprocessor. The shutter could then be controlled over a speed range of 0-4 Hz to allow data to be taken at slower rates. This could be used to reduce the amount of data generated or lower the effective noise bandwidth with more data averaging. The data sampling rate could be coordinated with the ground speed of the UAV to allow data taking, transmission, and recording to take place at an optimal rate determined by image resolution.

Table 3.2 is a summary of the calculated detector requirements for several potential MPIR bands. The Noise Equivalent Irradiances shown in the table were taken from the Maximum Total Fluxes expected, as were similarly the quantizer lower limits (i.e. the 1/2 LSB of Maximum Flux). The noise equivalent powers calculated were given an improvement factor of the square root of the number of scans to average for each sample; this averaging greatly eases the NEP requirements. The effective bandwidth used for D* calculations is then 1/(2 x integration time).

Table 3.2: MPIR Detection Requirements Summary (5/14/94)

Waveband	Pixel Width	Number of Elements	Integrate Time per Scan	Number of Scans Avg per Sample	Maximum Total Flux	Minimum Total Flux	Noise Equivalent Irradiance at Min. Flux	1/2 LSB of Max. Flux	Noise Limit	Noise Equivalent Power	Detectivity D* (FOV)
0.62-01.68	50 (effective)	256 (averaged)	10 ms	12	2.1×10^{14}	1.0×10^{14} (day)	3.0×10^{10}	2.6×10^{10}	background	800×10^{-15}	1.8×10^{10}
0.86-0.90	50 (effective)	256 (averaged)	10 ms	12	1.4×10^{14}	7.0×10^{13} (day)	2.5×10^{10}	1.7×10^{10}	background	500×10^{-15}	2.9×10^{10}
1.36-1.39	50 (effective)	256 (averaged)	10 ms	12	7.5×10^{12}	3.0×10^{12} (day)	5.5×10^9	9.2×10^8	background	69×10^{-15}	2.1×10^{11}
1.58-1.64	50 (effective)	256 (averaged)	10 ms	12	1.2×10^{14}	6.0×10^{13} (day)	2.5×10^{10}	1.2×10^{10}	background	270×10^{-15}	5.3×10^{10}
2.11-2.22	85	256	10 ms	12	1.4×10^{14}	7.0×10^{13} (day)	2.1×10^{10}	1.8×10^{10}	background	490×10^{-15}	5.0×10^{10}
3.55-3.93	85	256	10 ms	12	2.0×10^{14}	1.0×10^{14} (day)	2.0×10^{10}	2.4×10^{10}	quantizer	320×10^{-15}	7.7×10^{10}
6.54-6.99	85	256	10 ms	12	2.6×10^{15}	1.3×10^{14} (night)	9.6×10^{10}	3.2×10^{11}	quantizer	11×10^{-12}	2.2×10^9
8.4-8.7	85	256	0.5 ms	250	3.6×10^{15}	2.8×10^{14} (night)	31.4×10^{11}	4.4×10^{11}	quantizer	12×10^{-12}	2.0×10^9
10.3-11.3	85	256	0.5 ms	250	1.4×10^{16}	1.7×10^{15} (night)	3.5×10^{11}	1.7×10^{12}	quantizer	36×10^{-12}	6.8×10^8
microns	microns		milli-seconds	Nscans	photons/cm ² sec	photons/cm ² sec	photons/cm ² sec	photons/cm ² sec		Watts x (Nscans) ^{1/2}	cm(Hz) ^{1/2} /Watt

Cooling Requirements

The sensors in the image plane arrays of MPIR use the energy of the photons which they absorb to excite electrons (called photo-electrons) into the sensor's conduction band. Hence the photon supplies the energy necessary to allow the electron to cross the bandgap from the valence to the conduction band. Once in the conduction band the electron is free to move, and it can be measured with an electrical circuit.

A photon's energy is inversely proportional to its wavelength. The long wavelength band detectors require small band-gap sensors in the image plane to detect the low energy photons. Thermal fluctuations in these small band-gap materials can generate their own thermal carriers that would swamp the desired photo-electron signal. For this reason these materials must be cooled to cryogenic temperatures to reduce the thermal noise contribution and allow optimum detection sensitivity.

For satellite use, a long-life, mechanical, Stirling-cycle refrigeration system would be appropriate for the required cryogenic cooling. For shorter duration UAV missions, a well-engineered liquid nitrogen (LN₂) system can provide the needed cooling, consume less electrical power, add no mechanical vibration problems, and cost less than Stirling refrigerators. There will also be no problem of limited cooler lifetime. The MPIR detector arrays with wavelengths beyond 6 μm will require cooling to 80K using a continuous-flow LN₂ system. The sensors in the intermediate wavelength bands (from 2 to 6 μm) can be cooled using the cold, boil-off gas from the LN₂ exhaust of the long wavelength detectors. The optimal temperature of the intermediate wavelength bands will be about 125 K depending upon which detector types are chosen. The precise response of some detector types can be optimized by adjusting the detector array's temperature. The precise operating temperature for each detector can be individually controlled by appropriate flow restrictions and pressure differentials in the LN₂ plumbing.

The necessary mass of LN₂ to support MPIR on a typical sixty hour mission will be only 1 kg. The associated dewar and plumbing will add an additional 3 kg. A flight mass of 2 kg of LN₂ will provide an adequate safety margin to ensure that cryogenic longevity will not a problem for the 60 hour mission. The relatively warm and exceptionally dry nitrogen exhaust gas could be routed to flow over the optics windows, helping to ensure that the windows remain clear throughout the mission. This might require an increased nitrogen boil-off rate and a corresponding increase the amount of LN₂ required.

Electronics

The system electronics for the MPIR package should consist of a central timing control and processing section (the host) along with individual front-end electronics for each optical channel as indicated in Figure 3.3. Each channel will have a common interface to the host processing unit. The optimal form for such interfaces between the channels and the host processor is a synchronous serial link. Such a link limits the amount of hardware and wiring to a minimum while accommodating a large data flow capability.

- Synchronous serial communications bus between all optical channels and the host processor
- Each optical channel has a common interface to the host
- Host handles all data queuing and communications

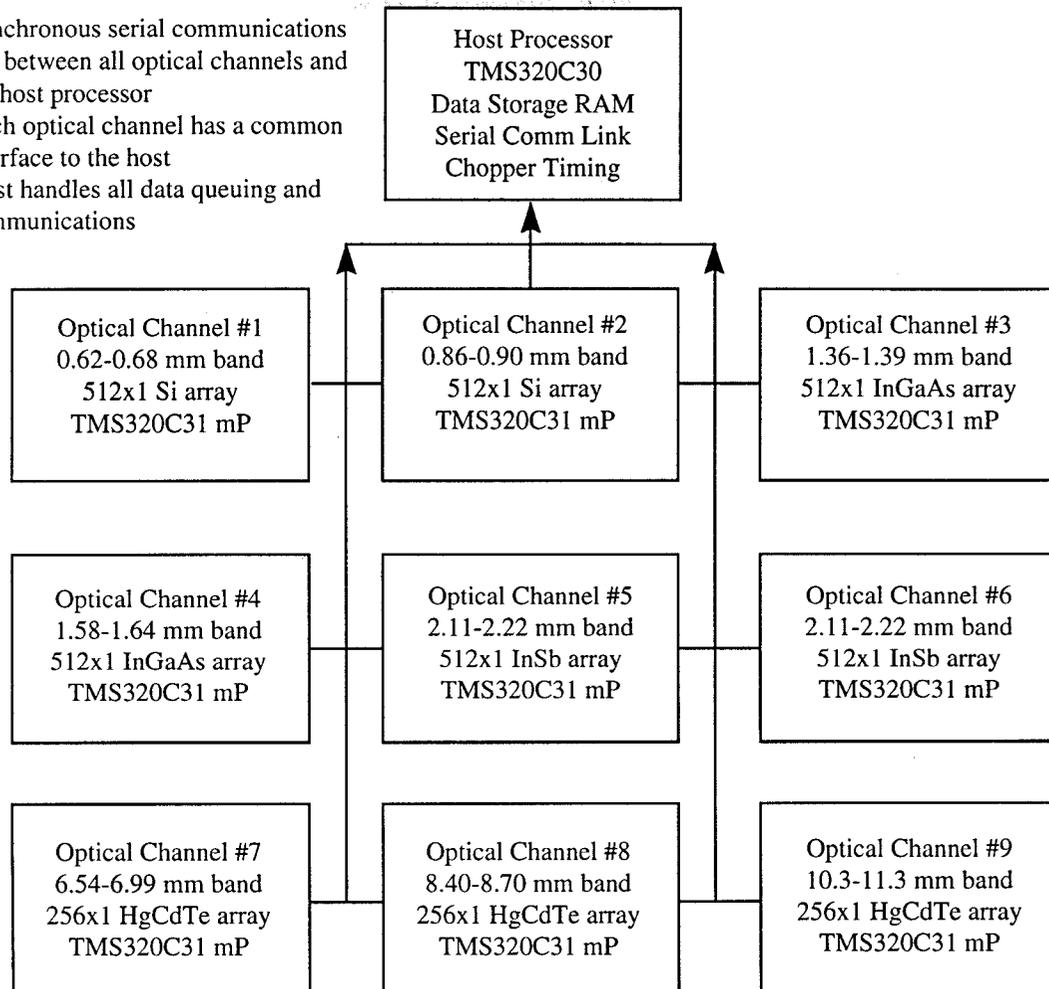


Figure 3.3. MPIR System Electronics Overview (5/14/94)

The host processing unit will perform the tasks of overall system timing synchronization, data queuing, on-board data compression (possibly necessitated by communication link limitations), error corrective data coding, and data transmission. It will require a large section of random access memory (RAM), program memory, timing synchronization logic, an external serial communication port, internal inter-channel serial communication ports, and a host processor. The optimum processor for the task defined is the Texas Instruments' TMS320C40, a floating point digital signal processor with multiple synchronous serial ports for multi-processor expandability. This processor has the computational power to handle additional on-board digital signal processing needs, should they arise.

The electronics for each optical channel (Figure 3.4) will perform the tasks which are specific to each array technology, such as voltage biasing, clock conditioning, and amplification. It will also handle the generic tasks of analog-to-digital conversion, system timing adaptation, and synchronous, serial, bus control interfacing. The circuitry which is detector-array-specific will vary from one channel to another and will reside on a separate printed circuit board in order to provide a modular system approach.

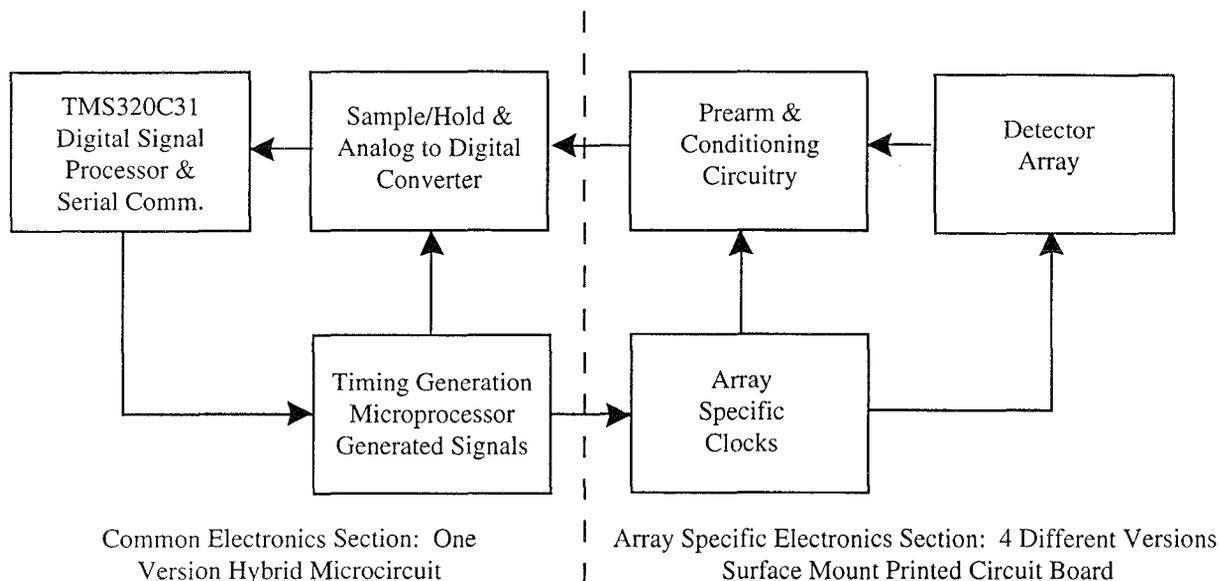


Figure 3.4. Linear Array Front End Electronics

The generic channel electronics will contain the analog-to-digital conversion electronics, system clock interface, and serial bus control interface electronics. Each optical channel will have its own generic electronics board which will be identical to that of every other optical channel. The generic channel electronics' tasks may require the use of a dedicated microprocessor of lesser capability than the host microprocessor. A candidate is the Texas Instruments' TMS320C31, which has one synchronous serial port of the same type as those proposed for the host processor.

The system will need power conditioning to convert the raw UAV power to the various levels needed throughout the system. Overall, system processing and control electronics will consume about 11 watts of unconditioned power. This permits about 1 watt for the chopper driver, 0.75 watts for each optical channel, 1 watt for the host processor. The balance of the power will be consumed by the 80% efficiency of the power converter. The total expected power consumption is comfortably below the available 50 W.

Mechanical Design

The various modular sensors are arranged in a compact, 3 x 3 matrix in a single plane as shown in Figure 3.5. Selection and/or replacement of individual sensors allows greater versatility for varying missions. It is necessary to arrange the sensors parallel to one another so that each channel will image the same ground spot. Although nine sensors are used for the current design, other rows of three could easily be added to a future design if more channels are needed. Likewise, detector positions could be left vacant if fewer channels are required.

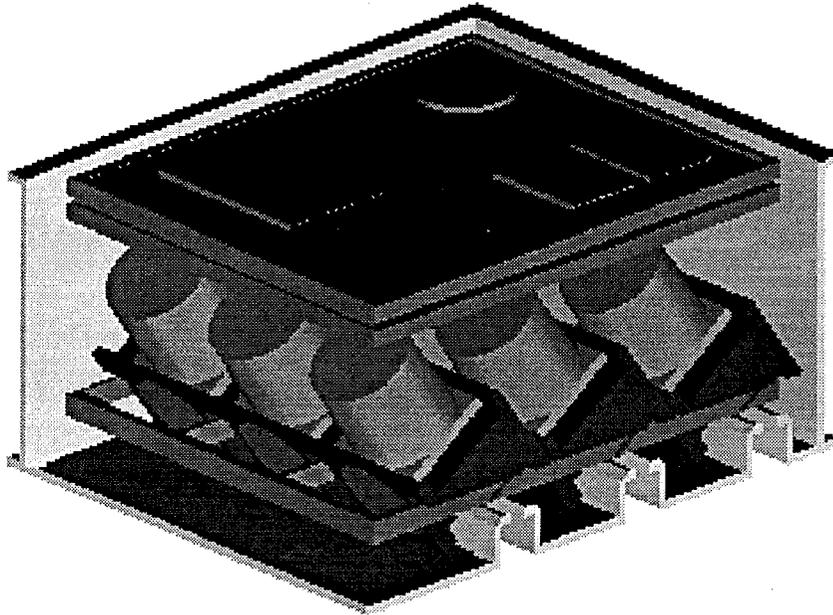


Figure 3.5: Potential arrangement for nine down-looking MPIR channels. The required system electronics are mounted on a board above the detector modules. Module and sensor-specific electronics (not shown) would be mounted with the individual sensors.

A primary mechanical goal was to minimize the number of parts. The optics of each channel form a reflecting telescope using only four main parts. Volumetric efficiency is achieved since two surfaces provide four bounces of the light path. The additional volume is used to provide fastening surfaces and rigidity. The folding mirror provides more space and a simpler mounting arrangement for the sensor. Accuracy is enhanced since machining and assembly operations are relegated to a single axis of concern. Because of symmetry, the rotational tolerance about this symmetry axis is of little significance. Rotation of the M1-M3 optical element also rotates the M5 turning flat. This can be used to align the detector array without adversely affecting the image quality. Both optics are installed in the holder from the same end providing good axial alignment. Mating surface tolerances in the holder are maintained since all surfaces are machined during the same setup.

The finished optical surfaces are produced by diamond turning operations using 6061 aluminum. This lightweight structural alloy is used for nearly the entire instrument reducing potential thermal expansion problems. The enclosure seals the instrument from contamination and the uncontrolled thermal environment of changing altitudes and air turbulence. Each FOV has an imaging bundle of rays that may be roughly described as an 80° pie-shaped, 5 mm thick wedge. Considerable attention must be given to tight fits and tolerances to allow installation of components where the beam is quickly converging in the telescopes. Width and height of the enclosure is dictated by the transverse separation of these FOVs so that the hardware for one will not interfere with the beam of another. Items required for each channel are a curved entrance window, chopper blade, light baffles, mirrors, filters, and (where appropriate) dewar and coldshield.

MPIR incorporates a chopper, or shutter, for in-flight radiometric calibration. To maintain parallel orientation between sensors, the use of a single rotary chopper was

not possible. Individual chopper wheels and associated drives were also rejected because of the number of parts required. A single shutter assembly with multiple blades was designed, operating common to all channels. It consists of individual blades laying crosswise on support rails forming a rectilinear grid. Each section, or blade, of the chopper is dedicated to one channel; some function as blackbodies with internally regulated and measured temperature while others are simply light shutters.

The original shutter mechanism design used flanged roller bearings to guide the chopper in a 4 Hz linearly reciprocating fashion. Twin scotch yokes with gear-driven counter-rotating masses were used to eliminate the unbalanced harmonic effects. Any difference in displacement between the yokes was compensated for at the common pivot used to drive the chopper. Although this design allows for variable speed operations, lubrication and friction are problem areas for reliability in space-based, and high-altitude, near-vacuum applications. For this reason other chopper mechanisms were investigated.

An alternate chopper design more suitable for near-vacuum operation utilizes a solid-state linear motor, having no bearings or reduction unit, similar to a voice coil actuator. Four flexures are used to form a pair of 4-bar mechanisms to support a "swinging" chopper at the couplers. Operating at resonance, the device could be driven with very little power. A difficulty arises in balancing the inertial effects of the reciprocating mass. The use of a combination of flexures reacting against an equivalent inertial mass was investigated, but the introduction of an additional spring-mass system complicates the device considerably. Between the first and second resonance frequencies a mode leading to vibro-isolation could actually stop the chopper. Other frequencies could destroy it.

A third possibility uses a rigid reversing lever, or bell crank, driven by the chopper which is used to drive an offset mass in the opposite direction. The central pivot bearing is replaced by a compliant flexural pivot, having a negligible spring constant. It is expected that virtually all vibration can be eliminated in this simple manner. The simpler mechanical design leads to a more complex control system, but one which can be implemented in software and electronics.

4. Lidars: a versatile tool for measuring atmospheric effluents

Here we focus on the development of lidar (light detection and ranging) capabilities that provide the ability to detect effluents remotely—including the presence (i.e., threshold value), spatial extent, and/or mixture composition of chemical species in the atmosphere or in associated solid or liquid phase. Lidar systems have been used successfully for ground-based atmospheric measurements for more than 20 years, and have been applied successfully to airborne platforms as well. In some ways, they correspond to a well-tested and versatile set of technologies, but for other application—especially those that require new extensions of sensitivity, new classes of chemical species, or new platform implementations—significant new research and development is required.

In particular, some of these probe systems have the potential to contribute measurement capabilities for a broad range of DOE applications which can be bundled into 3 major categories: defense, environmental and related activities, and climate.

Defense includes missions related to strategic nonproliferation activities focused on preventing the spread of weapons of mass destruction by detecting effluents characteristic of the weapons production cycle as well as tactical applications in the detection of chemical or biological releases in the battlefield. Similar technology could be applied to the prevention of illicit manufacture of drugs.

Environmental applications include remote sensing of emissions in waste site remediation efforts, environmentally-conscious manufacturing, agricultural and inland waterway assessments, oceanographic monitoring (including oil slick detection), as well as related activities such as weather monitoring. Climate is distinguished here from “environment” in being related to issues of larger scale, most prominently, global climate change studies related to the earth's radiation budget and globally-significant atmospheric chemistry issues, including ozone hole determinations.

4.1 Technique Selection

In order to address the applicability of any of the candidate laser remote sensing techniques for the applications discussed here, definition of the feasibility must be established through preliminary estimates of performance for various technique choices coupled with estimates of anticipated concentration levels in potentially important measurement situations.

Remote probing for the key emissions from processes considered here can be accomplished by use of a range of laser-based methods capable of providing chemical constituency and particulate information with excellent spatial and temporal resolution. These methods are based upon time-gated detection of signal returns from transmitted laser pulses, with the returns corresponding to either species-specific “resonant” interactions of the laser beam photons with the gaseous molecules to be probed, or the strong elastic interactions of the transmitted beam with particulate matter in its field of view. The time-gating permits the localization of the spatial region under examination, and results in the capability to resolve emissions from specific locales within a probed zone. Spatial scanning of the lidar system (composed of the laser transmitter, telescope collector, and photon detection apparatus) then permits the detection of multiple emission areas.

Here, we are primarily interested in the detection of chemical species, and particulate information is considered of secondary importance (although it may be required in order to factor out the influence of atmospheric visibility on lidar-derived species data).

The detection of chemical species can be based upon several different well-demonstrated lidar principles, of which two are considered to be excellent candidates for

the chemical composition information that we are seeking. The first of these is DIAL (differential absorption lidar), a technique that requires measurements to be made at two laser wavelengths: one at the wavelength of a specific absorption feature of the molecule being detected and the other slightly displaced from the first wavelength at a local absorption minimum. Use of this approach can provide a spatially-resolved remote absorption measurement of the gaseous material contained in the test zone determined by the time- (and thus range-) gating employed, using the backscattered elastic Rayleigh or particulate scattering produced by the transmitted laser beam just beyond the test zone as the "incident" light source. Alternatively, if the DIAL measurement is accomplished using hard-target backscatter (often, topographic backscatter) instead, then the returned signal levels are greatly enhanced, but at the expense of the spatial resolution because of the loss of time-gated data. This latter "column" data can be of strong value if the source of emissions is a localized zone, with no spectrally interfering chemical species along the optical path. Range-gated DIAL, on the other hand, is the choice if the emissions source is buried among a range of emissions sites, with localization to determine *which* part of the site (such as a large manufacturing or refinery complex) is contributing *what part* of the total returned site signature.

The second lidar technique considered as a strong candidate is based on laser fluorescence. In this technique, the incident laser beam is absorbed resonantly by the test species, causing a characteristic spectral emission that is indicative of the gas molecule. Thus, this process depends upon a complicated train of events, in which nonradiative de-excitation (quenching) of the target molecules can take place, which can lower the fluorescence yield significantly. This quenching phenomenon is dependent upon the target molecule environment (gaseous, liquid, or solid) and requires laboratory measurements additional to those performed for the cross section for the DIAL process. The power of fluorescence, however is increased when a series of excitation wavelengths (multispectral excitation) is used to excite the target molecules. In this case, one obtains an increased number of re-emitted signal spectra, which reflect the molecule's response to excitation (and internal energy transfer) correspondingly to different sets of the molecule's internal energy level structure. This increased amount of information can permit one (using multivariate analysis techniques) to determine a chemical species when it is mixed with a number of other potentially interfering compounds, and with noise sources present as well.

The sensing of particulate matter requires only the detection of the elastically-backscattered signal from a lidar of any type, and so can be achieved as a companion feature to either the DIAL or fluorescence lidars described. All of these approaches have been demonstrated in laboratories and, in some instances, in lidars, for a range of chemical species.

4.2 Sample Estimate of Lidar Detection for Solvent Vapor

Here, we pick the DIAL process as the simpler, more easily instrumented technique for providing an estimate of the sensitivity that can be achieved with only moderate requirements on the experimental apparatus. The literature shows a large number of compounds that have been determined by DIAL. [See, for example, Lidar Measurements of Tropospheric Trace Gases, E. V. Browell, Proc. Symposium on Lower Tropospheric Profiling: Needs and Technologies, Boulder, CO (AMS, NCAR, NOAA), 1988. Information is given for H₂O, O₃, SO₂, NO₂, C₂H₄, CH₄, HCl, N₂O, CO, NO, SF₆, Hg, Hydrazine compounds, NH₃, and Cl₂.] We view organic solvents (toluene is used here) for this estimate as illustrative of a class of compounds that are technologically important for a broad range of environmental studies, as well as for defense applications and some atmospheric chemistry investigations. Also of broad interest are chemicals that can present emissions problems above their normally-expected dilute concentrations distributed through industrial/urban atmospheres (SO₂ is used here).

We have run a simple lidar model for performance in the ultraviolet—a part of the spectrum for which range-resolved DIAL works particularly well because of the strength in the UV of the aerosol and Rayleigh scattering required for returning the target signals. The model tracks the flux from the laser transmitter through the atmosphere, and back to the receiver, including the effects of ozone absorption, which is strong up to about 300 nm. Tradeoffs exist among many of the characteristics of the lidar, but a clear first-order effect here is the tradeoff between the range that can be achieved for a UV spatially-range-resolved system and the deleterious effects of ozone absorption.

In Figure 4.1 we present the results of this calculation for two interesting cases: (1) **toluene**, for which *topographic reflection* was assumed (0.5 surface reflectivity) in order to increase the backscattered signal significantly (and thus also S/N ratio), and (2) **SO₂**, for which *range-resolved operation*, using aerosol and Rayleigh backscatter, was assumed. The first case corresponds to looking at a clearly defined target zone (such as a stack plume) in an atmospheric environment that is otherwise clear of this species. The second corresponds to looking at a chemical species often found in industrial atmospheres. If one used topographic reflection for the DIAL data for this species, then one would be measuring the normal atmospheric burden of this material *over the total measurement path for the lidar*, which could very easily overwhelm the target zone information.

The experimental parameters used here were chosen as reasonable values within the present state of the art, with the laser source (4.5 w tunable in the UV) at the present edge of development. An order of magnitude improvement in this laser power will likely be available in several years, following technology development already underway for existing remote sensing programs.

- Laser source: 75 mJ @ 60 Hz
- Wavelength for excitation: 267 nm for toluene
300 nm for SO₂
- Absorption cross section : 10⁻¹⁸ cm² for both molecules
- Collection mirror diam.: 0.5 m
- Atmospheric attenuation: O₃ absorption, Rayleigh scattering, aerosols
- Vertical detection configuration

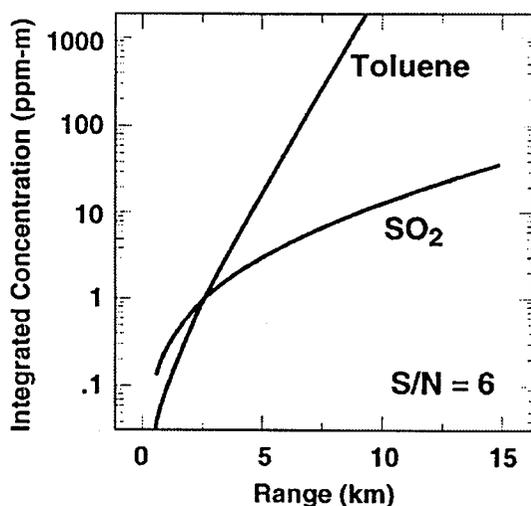


Figure 4.1. Estimates for detectable concentrations of candidate emissions compounds using DIAL laser remote sensing technology, as a function of standoff range.

As a measure of performance for detecting the gases chosen here, we list the range at which 10 ppm-m can be seen with a given S/N ratio of 6:

Detection Range for 10 ppm-m

SO ₂	9 km
Toluene	4 km

If we inspect Figure 4.1, we see that the toluene signal can be detected at a greater standoff distance than for SO₂ at low distance values, although both species have similar cross sections. This arises because of the hard background target used in the toluene calculation, which produces a stronger signal level, and therefore improves the noise problem. However, because the toluene excitation is at 267 nm (in the heart of the strongest atmospheric O₃ absorption), the toluene signal becomes increasingly weakened as the range is increased. This is not the case for the SO₂ because its chosen excitation is at 300 nm, just outside the “solar blind” O₃ spectral range.

4.3 Conclusion

The overview of laser remote sensing carried out to explore possibilities for important DOE uses, with an emphasis on environmental applications, led to the conclusion that current technology can produce equipment capable of determining important information for a variety of applications. Our benchmark calculation was based on detecting candidate widely-used pollutant materials at concentrations of several ppm over paths of several meters, at a reasonable S/N value, producing detectability standoff distances of 4 to 9 km. These numbers are very encouraging for many of the prospective applications.

APPENDIX

NASA/DOE Interactions on Space-Based Remote Sensing

An exploration of possible contributions to a NASA/DOE MOU on space-based remote sensing was performed during the time frame of this study, which involved significant technical interactions with NASA and other DOE partners on potential collaborative missions to measure winds and atmospheric species, and which provided an illuminating view of inter-agency partnering issues.

During the course of exploring potential collaborative missions to measure winds and atmospheric species, we determined that the prime overlap of strong mission interest *already present in both organizations* was in the measurement of atmospheric water vapor and aerosols. The guidelines for this study emphasized rapid (3 to 4 year) deployment, use of an "existing" platform, and less costly approaches than heretofore, and was built upon experience gained in a previous NASA proposed effort for water vapor DIAL named "Eagle." Thus, this program was termed "Quick (or Q-) Eagle."

These conditions led to the exploration of compact implementations of DIAL, which is capable of simultaneously measuring water vapor and aerosols, the essential atmospheric species of interest to both agencies. The investigation was facilitated by exploiting our capability to estimate DIAL tradeoffs from a generalized version of a Sandia lidar performance model utilized in the toluene and SO₂ calculations here, leading to rough estimates of a 300-kg instrument requiring 1 kW of power capable of profiling water vapor concentrations ($\pm 10\%$) from 0 to 10 km with 500-m vertical resolution from a 250-km orbit. Additionally, a "dual-use" laser transmitter was explored that could produce both the near IR laser pulses needed for the water vapor data (0.7-0.9 μm) as well as mid-IR pulses ($\sim 2 \mu\text{m}$) needed for the detection of winds. This concept, while attractive for efficient use of mission-oriented capabilities, is complicated by the rather different requirements of wind- and concentration-based data acquisition techniques and hardware. The wind mission possesses complexities beyond those addressable by the potential DIAL system that may present limiting issues to the program.

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