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Science and Experiment Plan
Spring 1999 Flight Series

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ARM
CLIMATE RESEARCH FACILITY

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ARM – UAV

Atmospheric Radiation Measurement – Unmanned Aerospace Vehicle

Science and Experiment Plan

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Introduction

Objectives

The ARM-UAV (Atmospheric Radiation Measurement - Unmanned Aerospace Vehicle) Program is a multi-agency, multi-laboratory program funded by the Department of Energy. The program uses a variant of a UAV originally developed for defense surveillance as a remotely piloted platform for making important climate measurements. Using a UAV to make these measurements offers the significant advantage of high-altitude and long-endurance operations, two features that are very important when studying evolving cloud fields and their effect on the solar and thermal radiation balance in the atmosphere, a major goal of the ARM-UAV program. Additionally, the program is seeking to exploit the high altitude flight capability of UAVs to provide measurements to calibrate satellite radiance products and validate their associated flux retrieval algorithms.

A corollary to these scientific goals is the technical objective of using improved measurement techniques and instruments for radiative fluxes, cloud properties, and *in situ* water vapor that were developed earlier in this program. The demonstration of this objective was begun in the five previous flight campaigns flown in the spring of 1994, fall of 1995, spring of 1996, fall of 1996, and fall of 1997 and will be continued in the fall 1998 campaign discussed herein.

The primary focus for this campaign is to improve understanding of tropical cirrus clouds. This is important for at least two principal reasons. First, tropical cirrus has a direct effect, through their optical properties, on both thermal and solar radiative transfer (this broad affect is referred to as cloud-climate forcing). Second, they are a stage in the circulation of water from high cumulus towers into the upper troposphere. The feedback between the density of water vapor in the upper troposphere and other changes in the physical climate is a crucial issue.

Science Questions

As with the ARM program the primary scientific focus of the ARM-UAV program is on radiation-cloud interactions. Uncertainties in how clouds interact with the earth's solar and thermal radiation account for almost the entire factor of three variation in the predicted temperature rise for a doubling of atmospheric CO_2. While some of these uncertainties can be addressed by the ground-based measurements being made in the ARM program, others require measurements from within the atmosphere. For example, the measurement of atmospheric heating in a slab requires the measurement of the net fluxes at the top and bottom of the slab as well as the relevant cloud properties and water vapor profiles. Satellite based measurements are a natural way of extending these process measurements to larger scales but would benefit from the additional calibration and validation that carefully controlled high altitude aircraft measurements can provide.

This science plan outlines an experiment using an Unmanned Aerospace Vehicle (UAV) as a platform for collecting measurements that will shed some insight on these broad issues. It will further the basic long-term goal of improving our understanding of the effect of cirrus clouds on the radiative and water budgets of the upper troposphere. Specifically, this experiment seeks to contribute toward answering the following critical science questions.

What are the distributions and amounts of ice mass and total water in the upper tropical troposphere? Information leading to answers to this question is fundamental both toward understanding the cloud feedback related to cirrus clouds and toward predicting the properties of these clouds in current climate models. Clearly methods (both in situ and remote) are needed to measure both the ice mass of clouds and upper troposphere water vapor.

What are the radiative properties of upper troposphere cirrus clouds? Measurements of the essential optical properties of cirrus clouds and the relation between these properties to information about the microphysical properties of these clouds are sorely needed. Measurements available from this campaign will provide important information to begin to address this question. Measurements of these radiative properties will also provide valuable information that can be used to check model simulations of the climate forcing of cirrus clouds.

To what extent do the radiative properties of these clouds depend on environmental conditions including the extent of the surrounding deep convection? It is important to study cirrus cloud under a variety of different environmental conditions as it is expected that their optical properties depend on these conditions. This question is also fundamental to understanding and testing our knowledge of how and why these clouds form and their life cycle characteristics. Again, this knowledge serves as the building block on which prognostic schemes in global models will be based.

Previous experiments, most notably the ARM-UAV fall 1995 campaign known as ARESE, have suggested that cloudy skies absorb more shortwave radiation than predicted by current models. Unfortunately, instrumentation, flight opportunities, and meteorological conditions did not permit the acquisition of an unchallengeable data set in this regard on previous campaigns. Therefore, shortwave absorption questions continue to dominate the science issues for this fall 1998 campaign.

Approach

As noted above, the approach is to use UAVs because of their promise for sustained endurance at altitudes up to 20 km. This will be the first ARM-UAV campaign to use an Altus UAV that has two stages of turbocharging, and whose ceiling is thereby expanded to the full 20 km. A second, manned aircraft will be used to provide supporting measurements at considerably lower altitude operations.

An ARM-UAV Science Team has provided guidance for the preparation of this science plan, and its members are responsible for the usage and analysis of data from all UAV instrumentation. Team members are identified in the descriptions of the various experiments.

Campaign History and Resources

During the initial phases of the ARM-UAV program, spanning the four-year period between late calendar 1993 and late 1997 four aircraft types were flown in five separate campaigns with payloads comprised of a subset of nineteen different instruments. The aircraft and their planned payload complements are discussed below. All five campaigns were flown at the Southern Great Plains (SGP) Cloud and Radiation Testbed (CART) Site in north central Oklahoma in the spring of 1994, fall of 1995, spring of 1996, fall of 1996, and fall of 1997. This campaign will be flown from the Pacific Missile Test Range on the island of Kauai, Hawaii.

The first campaign used the General Atomics Gnat 750, a midsize UAV capable of carrying a 100-kg payload to a maximum altitude of 7 km. The Gnat was first operated in a checkout flight at Edwards Air Force Base with a basic radiometric payload in November, 1993, and again at the SGP CART site in April, 1994, for a seven flight science mission, called UDF. The operable payload contained four broadband radiometers plus a downwelling TDDR developed by Francisco Valero — the radiometers were the four combinations of upwelling and downwelling, solar and thermal. Valero, Gore, and Giver, 1982; Valero, Ackerman, and Gore, 1989; and Valero and Pilewskie, 1992 describe these instruments. Additionally the payload included an *in situ* package with total temperature, pressure, and dew point sensors. There are no plans to fly this UAV in conjunction with the experiments discussed in this science plan.

The General Atomics Altus, capable of carrying a 150-kg payload to a 10-km altitude, was utilized in the fall 1996 and fall 1997 campaigns. Its payload included the Gnat 750 instruments (with a frost point hygrometer instead of the dew point sensor) plus a SSP, CDL, and MPIR. These latter instruments are described below. In this campaign, the Altus will additionally mount a SSFR. Only two of the following three instruments can be flown simultaneously – CDL, MPIR, and SSFR.

A DHC-6 Twin Otter manned aircraft was flown during all previous campaigns as a chase plane for the various UAVS and as a low level instrumented platform in all but UDF. Its instrument suite includes four Valero radiometers covering various broad spectral bands for both upwelling and downwelling fluxes, two TDDRS for upwelling and downwelling spectral fluxes, and an *in situ* package with total temperature, total pressure, differential pressure, and dew point sensors. In the two 1996 campaigns and the fall 1997 one the Otter also carried a microwave radiometer to determine total cloud water and columnar water vapor. That instrument will not be flown in this campaign, but a SSP, MMCR, and SSFR will be added.

A Grob Egrett manned aircraft, capable of carrying a 200-kg payload to greater than 16-km altitude, was flown in the fall 1995 and spring 1996 campaigns. Its instrument suite is the same as that mentioned for the Altus UAV without the SSFR. The Egrett will not be flown in this campaign.

New Instrument Developments

Seven new UAV compatible instruments have been developed by or for the ARM-UAV program. Since these are not well documented in open literature they will be discussed briefly here, except for the *in situ* frost point hygrometer, which is a natural extension of the well known dew point hygrometers. This new hygrometer was first flown on the third campaign.

The Cloud Detection LIDAR, or CDL, was developed by LLNL based on technology from the Clementine moon mapping mission for the profiling of aerosols, profiling of optically thin clouds, and determining cloud top or base height of optically thick clouds. It features a fully eyesafe 100 μJ/pulse 5 kHz laser with a divergence of 53 μrad and a wavelength of 1.05 μm. The receiver telescope has a 20 cm aperture. The entire system can be rotated in flight for either nadir or zenith viewing, and has a coaxial CCD camera to image the cloud fields. The CDL was first flown on the second campaign. When mounted in the Altus, the CDL is only nadir viewing.

The UAV Atmospheric Emitted Radiance Interferometer (UAV AERI) is being developed at the University of Wisconsin as a derivative of the ground-based AERI based at the SGP cart site. It has approximately 0.5 cm^{-1} spectral resolution across 3-25 μm spectral coverage band. Its viewing mirror can be rotated in flight to study either upwelling or downwelling radiation with a spatial resolution of 1-10 km. This instrument has an on board calibration source. The UAV AERI will not be flown before 1999.

The Hemispherical Optimized Net Radiometer, or HONER, detects the net difference between upwelling and downwelling fluxes to about 3% accuracy. It has greater than 170° FOV upward and downward and covers the 0.3 to 4 μm shortwave and 4 to 50 μm longwave bands. The HONER will not be flown before 1999.

The Multispectral Pushbroom Imaging Radiometer, or MPIR, uses filtered linear detector arrays for nine band coverage of upwelling radiation. The arrays have 256 elements, with a total cross track FOV of $\pm$40° and in track direct nadir FOV of 6 mrad. The nine bands are 0.62-0.67, 0.86-0.90, 1.36-1.39, 1.58-1.64, 2.11-2.22, 3.55-3.93, 6.54-6.99, 8.40-8.70, and 10.30-11.30 μm. These were chosen with cloud water and water vapor studies in mind. Images from the arrays are captured twice per second, so the aircraft's velocity relative to the imaged scene determines in track image. MPIR was first flown on the third campaign. Only the five shortest wavelength bands will be available for the fall 1998 campaign.

A UAV compatible variant of the Solar Spectral Flux Radiometer, SPFR, will be flown on both the Altus and DHC-6 for the first time in the fall 1998 campaign. The SPFR covers a 300 nm - 2500 nm spectral range with 5-10 nm resolution while operating in one of two modes: irradiance (hemispheric) or radiance (narrow field of view – 1 mrad). Both modes have zenith and nadir pointing optic heads. Several parameters may be retrieved from the data taken by the SPFR, including cloud water phase, optical depth, particles size, liquid/ice water path, and liquid/ice water content.

A microwave radiometer MWR system consisting of 22 and 37 GHZ channels is flown in an upward viewing mode on the DHC-6. The 22/37 MWR system has been previously flown as part of the Airborne Multichannel Microwave Radiometer, AMMR, on the NASA DC-8 aircraft, and was flown in the ARM-UAV program on the third through fifth campaigns. A new 22/37 and 89 GHZ MWR system is being constructed specifically for the DOE ARM-UAV program DHC-6 aircraft, but will not be flown before 1999.

Finally, a 95 GHZ radar, developed at the University of Massachusetts and the NASA Jet Propulsion Laboratory Center will be flown on the DHC-6 in this fall 1998 campaign in a zenith-pointing mode.

While the technology is not unique to the ARM-UAV program, the INS/GPS system flown on all the aircraft described above is crucial to the success of experiments involving two stacked aircraft. It allows pilots, whether in the aircraft or in a UAV ground control station, to control the lateral separation of their platforms to within several hundred meters. Additionally, the attitude sensing function of this system provides critical information for the reduction of radiometric data with a direct solar component.

Document Structure

The bulk of this document describes five experiments that have been proposed for the next campaign. Since most of these require specific meteorological conditions, the experiment suite for this fall 1998 campaign will be a subset of these, with the details of the subset depending on the conditions encountered during the course of the campaign. The appendices provide contact information and a glossary of acronyms.

Experiment 1 — Tropical Cirrus Optical and Radiative Properties

Part A – Science Issues

Science Objective

The objectives are (I) to determine the radiative properties of upper troposphere cirrus clouds and (ii) to gain insight into the extent that the radiative properties of these clouds depend on environmental conditions such as the extent of surrounding deep convection.

Observing the optical properties of cirrus clouds and gaining an understanding of the relation between these properties to information about the microphysical properties of these clouds is sorely needed. Data from this campaign will provide important information to begin to address this issue and can also be used to check model simulations of the climate forcing of cirrus clouds.

It is important to study cirrus clouds under a variety of different environmental conditions as it is expected that their optical properties depend on these conditions. This objective is also fundamental to understanding and testing our knowledge of how and why these clouds form and their life cycle characteristics. Again, this knowledge serves as the building block on which prognostic schemes in global models will be based.

Advocate

Graeme Stephens champions this experiment.

Measurement Strategy

This experiment relies heavily on measurements made from the Altus UAV supported by a manned DHC-6 Twin Otter to obtain these basic measurements of the radiative properties of tropical and subtropical cirrus clouds. All data will be collected within the PMTR restricted airspace near Kauai, Hawaii, during the fall of 1998.

The Altus will be used to measure solar and longwave fluxes at cirrus cloud top and base to determine both the radiative properties (such as the spectral and broadband albedos, infrared emittances) and the radiative budget of cirrus. Additionally the optical properties of the cirrus such as profiles of extinction, optical depth, and scattering asymmetry information will be deduced from measurements of spectral reflectances, lidar backscatter, diffuse and direct fluxes. DHC-6 instrumentation will indicate the extent and density of the observed clouds.

It is expected that analysis of the measurements mentioned above can be used to assist in the development and support of new remote sensing techniques applicable to cirrus directly from the UAV aircraft data.

The experimental strategy is to optimize coordination between the Altus UAV and the DHC-6 so that the same sections of a cloud structure are observed by both nearly coincidentally (i.e., within 60 seconds). The principle Altus payload will include spectral (SSP, SSFR) and broadband radiometers (RAMS), while the DHC-6 principle payload will be the MMCR. The desire is to make measurements using the Altus measuring platform at altitude above or just below the cirrus while the DHC-6 obtains radar profiles from a position much lower in altitude.

The desired flight path is a very long (on the order of 150 km) straight leg oriented into the wind at the level of the cirrus clouds. The aircraft are to fly straight and level until the Altus, which has the higher ground speed, is observing a cloud patch that will not be observed by the DHC-6 in less than 60 seconds. At that time the Altus will execute a 360° repositioning maneuver back onto its own (and the DHC-6's) track behind the DHC-6 and then will resume straight and level flight and data acquisition. Under the direction of the mission scientist, the Altus will fly either atop of just under the cirrus, while the DHC-6 will fly at a constant altitude between 3000' and 5000' MSL.

Desired meteorological conditions are single layer extensive cirrus cloud decks at any upper troposphere altitude. The Altus can either fly at its service ceiling or at altitudes just above or below the deck. Measurements should be made when the SZA is less than 70°.

Required and Supporting Measurements

UAV

The UAV will measure upwelling and downwelling solar fluxes in the upper troposphere with a RAMS, and upwelling spectrally resolved broadband fluxes and radiances directly below the UAV with a nadir SSP. The SSFR will also measure upwelling and downwelling solar spectrally resolved fluxes and radiances. The CDL will be used to determine distance to and variability of the cloud top altitude, as well as assess cloud reflectivity at its laser's wavelength of 1.53 μm.

DHC-6

The DHC-6 will use its MMCR to profile the extent and density of the cirrus deck. Additionally, the zenith pointing radiometers (SSP, SSFR, and RAMS) will measure downwelling solar and thermal radiances and fluxes

Satellite

Supporting satellite instrumentation will measure the extent and uniformity of the observed cirrus. As available considering orbital position, data from the imager on GOES-9 or GOES-10, the AVHRR on NOAA-12, NOAA-14, or NOAA-15, and the VIRS on TRMM will be used.

Data Analysis Strategy

Analysis will attempt to relate observed microphysical properties, with their dependency on cloud origin, to the radiances and fluxes observed. Details of this strategy have yet to be defined.

Relation to Other Experiments

This experiment is related to experiment 9, "Cirrus Cloud Optical Properties," of the ARM–UAV Science and Experiment Plan, 1996 Flight Series, Revision 4, March 2, 1996

Part B – Experiment Details

Flight Strategy

In general, both aircraft will acquire data while flying a long linear pattern oriented into the wind that exists at the cirrus deck altitude. It is desired that the path be on the order of 150 km long; however, it is constrained to be within the airspace of the assigned PMTR warning area. Figure 1 is a map of PMTR airspace.

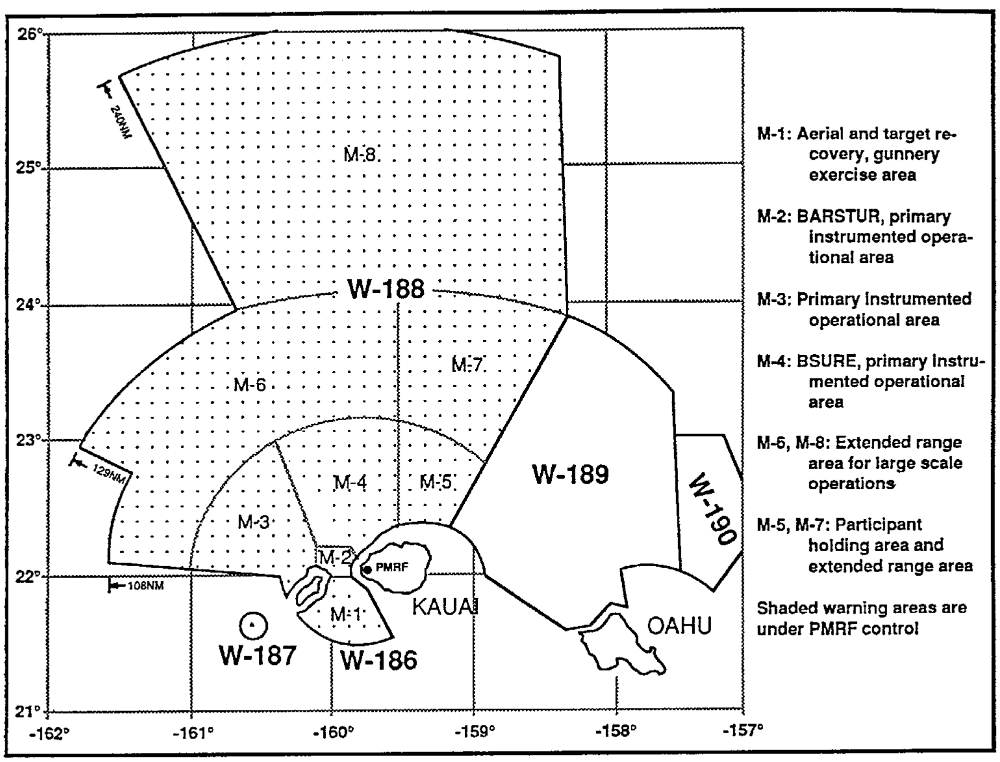

Figure 1. Pacific Missile Test Range area definition.

Ideally, both aircraft should over- or under-fly the same patch of cirrus deck at the same moment. Since the ground speed of the aircraft will in general be different with the Altus being the faster, it will not be possible to maintain their stacking above and below the patch. To accommodate this differential, the Altus will need to commence a 360° reposition maneuver each time it has advanced beyond the DHC-6 so far that the cirrus patch it is over will not be above the DHC-6 within 60 seconds. The reposition will take the Altus to a position on the mission flight path behind the DHC-6 from which it will begin overtaking again the slower DHC-6, and data taking will resume when the cloud patch under the Altus was sampled no more than 60 seconds earlier by the DHC-6.

Thorough the course of the flight, the Altus will be assigned a variety of data altitudes, including 1000′ below the base of the cirrus deck, 1000′ above the deck top, or any altitude from there to its service ceiling of 65000′. The exact altitudes flown above will be chosen during the pre-flight planning meeting prior to the flight day based on projected winds and science requirements. Winds are a consideration in trying to minimize ground speed differential between the aircraft, and thereby the frequency of repositioning maneuvers.

The DHC-6 will fly between 3000′ and 5000′, with the exact altitude chosen to minimize turbulence and, as for the Altus, speed differential.

Constraints

All flight operations are to be conducted within restricted or warning airspace as assigned by PMTR controllers.

Special Needs

This experiment has no special needs.

Instrument and Data List

UAV

Instrument 1: SSFR — zenith and nadir spectral radiance in $wm^{-2}sr^{-1}nm^{-1}$, 0.3 to 2.5 μm; upwelling and downwelling spectral irradiance in $wm^{-2}nm^{-1}$, 0.3 to 2.5 μm; 5-10 nm resolution; 30 second data averaging

Instrument 2: nadir SSP2 — reflected spectral radiance in $wm^{-2}sr^{-1}nm^{-1}$, 0.4 to 4.0 μm; reflected spectral flux in $wm^{-2}nm^{-1}$, 0.4 to 2.5 μm; 2 channels linearly polarized (||, $\perp$) reflected spectral radiance in $wm^{-2}sr^{-1}nm^{-1}$, 0.4 to 2.5 μm; reflected broadband radiance in $wm^{-2}sr^{-1}$, 0.4 to 4.0 μm; reflected broadband flux in wm^{-2}, 0.4 to 2.5 μm

Instrument 3: zenith TDDR — downwelling hemispherical flux data; seven channels each 10 nm wide; channel center wavelengths are 0.5, 0.86, 1.0, 1.25, 1.5, 1.65, and 1.75 μm; shadow rings move across the FOV periodically blocking direct solar radiation thus enabling determination of the diffuse : direct ratio

Instrument 4: nadir TDDR — upwelling hemispherical flux data; seven channels each 10 nm wide; channel center wavelengths are 0.5, 0.86, 1.0, 1.25, 1.5, 1.65, and 1.75 μm

Instrument 5: zenith IRBBR — broadband radiometer with hemispherical FOV; measures downwelling flux from 4 to 30 μm

Instrument 6: nadir IRBBR — broadband radiometer with hemispherical FOV; measures upwelling flux from 4 to 30 μm

Instrument 7: zenith SBBR — broadband radiometer with hemispherical FOV; measures downwelling flux from 0.3 to 4 μm

Instrument 8: nadir SBBR — broadband radiometer with hemispherical FOV; measures upwelling flux from 0.3 to 4 μm

Instrument 9: CDL — 200 range bins with intensity of reflected laser light plus one background bin; range bins provide information on the location and density of aerosols and clouds; background bin for data correction

Instrument 10: *in situ* met package — frost point, temperature, pressure at the aircraft's location

DHC-6

Instrument 1: zenith SSP1 — reflected spectral radiance in $wm^{-2}sr^{-1}nm^{-1}$, 0.4 to 4.0 μm; reflected spectral flux in $wm^{-2}nm^{-1}$, 0.4 to 2.5 μm; 2 channels linearly polarized (||, $\perp$) reflected spectral radiance in $wm^{-2}sr^{-1}nm^{-1}$, 0.4 to 2.5 μm

Instrument 2: MMCR— 95 GHZ radar sensitive to cirrus ice particles

Instrument 3: SSFR — zenith and nadir spectral radiance in $wm^{-2}sr^{-1}nm^{-1}$, 0.3 to 2.5 μm; upwelling and downwelling spectral irradiance in $wm^{-2}nm^{-1}$, 0.3 to 2.5 μm; 5-10 nm resolution; 30 second data averaging

Instrument 4: zenith TDDR — downwelling hemispherical flux data; seven channels each 10 nm wide; channel center wavelengths are 0.5, 0.86, 1.0, 1.25, 1.5, 1.65, and 1.75 μm; shadow rings move across the FOV periodically blocking direct solar radiation thus enabling determination of the diffuse : direct ratio

Instrument 5: zenith IRBBR — broadband radiometer with hemispherical FOV; measures downwelling flux from 4 to 30 μm

Instrument 6: zenith SBBR — broadband radiometer with hemispherical FOV; measures downwelling flux from 0.3 to 4 μm

Satellite — GOES-9 or GOES-10

Instrument 1: imager — multi-channel instrument designed to sense radiant and solar-reflected energy from sampled areas of the Earth; produces full-Earth disc images

Satellite — NOAA-12, NOAA-14, or NOAA-15

Instrument 1: AVHRR — cross-track scanning system with five spectral channels; the spectral band widths are 0.58-0.68, 0.725-1.10, 3.55-3.93, 10.3-11.3, and 11.5-12.5 μm; IFOV of each channel is approximately 1.4 mrad leading to a resolution at the satellite sub-point of 1.1 km for a nominal altitude of 833 km; IR channels are calibrated in-flight; no in-flight visible channel calibration is performed

Satellite — TRMM

Instrument 1: VIRS — (description to be supplied)

Experiment Group 2 — Geometric Dependencies of Flux Measurements

Part A – Science Issues

Science Objective

The objective is to characterize the measured radiative properties of clouds as a function of measurement geometry. The radiative heating of the atmosphere induced by clouds is an important component of the energy budget of the atmosphere. The relationship between this heating and the properties of clouds is not well developed for several reasons. Accurate measurements of the column heating have been elusive in the past, and have been affected by 3D structure of clouds and biases introduced by inadequate sampling and limitations of experimental design. Unfortunately, characterizing the full 3D properties of clouds has also proved elusive at best, especially in the case of aircraft-based field programs.

This ARM-UAV experiment proposes to overcome some of these problems by maintaining the UAV over a surface with known properties, i.e., the ocean, and also keeping it in close lateral coordination with the other aircraft platform, the DHC-6. The cloud profiling sensor onboard the DHC-6, i.e. the MMCR is important for characterizing the cloud and its structure. The sensors on the UAV, i.e. the CDL, SSP, and MPIR as well as the SSFR and SSP on the DHC-6 will provide the best possible estimate of the cloud or aerosol optical properties. These in turn can be compared to similar properties derived from satellite radiances.

This experiment addressed the particularly bothersome problem of the interpretation of the altitude dependence of radiative measurements over clouds. Data gathered simultaneous at two levels above a cloud deck could be used to estimate the spectral smoothing scale of the cloud. This result will provide an empirical measure of the amount of spatial smoothing required to infer broadband absorption from collocated flights above and below a cloud.

Advocate

Individuals expecting to analyze the data include Francisco Valero, Catherine Gautier, Robert Ellingson, and Bob Cahalan.

Measurement Strategy

The experimental strategy, as stated above, is to optimize coordination between the Altus UAV and the DHC-6. The principal Altus payload will include spectral (SSP, MPIR) and broadband radiometers (RAMS) and the CDL. The principal DHC-6 payload will include spectral (SSP, SSFR) and broadband radiometers (RAMS) and the MMCR. The desire is to make continuous measurements using the Altus and DHC-6 as a dual, coordinated measuring platform. The strategy is to: (i) measure the broadband fluxes and spectral radiances at two altitudes , and (ii) obtain cloud structure information from remote sensors such as the MMCR, MPIR, and CDL.

The desired flight path is a very long legs above or below a cloud deck and oriented on the solar plane if possible. The aircraft are to fly straight and level on each leg. The Altus and DHC-6 are to maintain stations above and below each other with 4-km tolerance. At some time during a flight with both aircraft, they should perform an intercomparison maneuver, i.e., one complete circuit in reasonably close formation at a convenient co-altitude.

Variant A — Aircraft Atop Clouds

This variant focuses on the smoothing of the radiation field over clouds. Desired meteorological conditions are single layer (possibly scattered to broken), non-convective, single phase, extensive cloud. The DHC-6 is to fly near the cloud tops and the Altus at its maximum altitude. Alternatively, the Altus could fly at two or three equally spaced altitudes over the DHC-6. Measurements should be made at low SZA to minimize variation in solar angles during collection. The DHC-6 MMCR cannot be used in this variant since it is zenith pointing and the aircraft will likely be above the 5000' MSL maximum altitude limitation.

Variant B — Aircraft Over and Under Clouds

This variant focuses on horizontal variations in cloud properties and radiation fluxes. Desired meteorological conditions are single layer (possibly scattered to broken), non-convective, single phase, extensive cloud decks. The DHC-6 is to fly 1 to 2 km below the cloud base and the Altus a similar distance above the cloud tops. Measurements should be made at low SZA to minimize variation in solar angles during collection. The DHC-6 MMCR will be used in this variant if the aircraft is below the 5000' MSL maximum altitude limitation.

Required and Supporting Measurements

UAV

The UAV will measure upwelling and downwelling solar fluxes in the upper troposphere with a RAMS, and upwelling spectrally resolved broadband fluxes and radiances directly below the UAV with a nadir SSP The MPIR will collect cloud image data in bands centered on 0.65, 0.88, 1.37, 1.61, and 2.16 μm. The MPIR's cross track FOV will be ±40°. A supporting instrument is the CDL to determine distance to and variability of the cloud top altitude.

Instrumented Chase

The dhc-6 will measure upwelling and downwelling solar fluxes for with a rams, and downwelling spectrally resolved broadband fluxes and radiances directly above the dhc-6 with a zenith SSP. The MMCR will measure cloud structure above flight altitude as a supporting measurement for variant B if the assigned altitude is less than 5000' MSL.

Satellite

The primary instrument is the imager on GOES-8 for measurement of narrowband radiances in the visible and infrared bands. Secondarily, narrowband data will be used from the AVHRR on NOAA-12, and NOAA-14, whenever their views match the area of operations and VIRS data from the TRMM satellite.

Data Analysis Strategy

Variant A — Aircraft Atop Clouds

Because the lower aircraft cannot instantly, or fully sample, the field observed by the higher aircraft, the data analysis will tend to emphasize a statistical approach. One important statistical quantity is the spatial power spectrum (SPS) determined from the Fourier transform of the observed fluxes as a function of distance (flight time). This quantity is a powerful tool for revealing the presence (or absence) of characteristic scale lengths in the observed field. In addition, by comparing the power spectrum from various sub-samples of the data one should be able to get a measure of the adequacy of the sampling. The SPS also indicates how the variance changes with resolution.

The flights closest to the clouds will have the highest spatial resolution, and so will yield SPSs extending to the highest spatial frequency and thus give the most detailed information on characteristic scale length. These low altitude SPSs will be compared against the high altitude SPSs to verify current understanding of the effects of areal averaging on the observed fluxes. These comparisons will be done in two ways. The first will simply convolve the low altitude SPS with the field of view response function of the high altitude radiometers and compare this to the high altitude SPS. The second approach will construct models of fractal cloud fields with properties similar to the low altitude SPS and use Monte Carlo calculations to predict the observed fluxes at high altitudes.

Such analyses can be applied not only to the broadband fluxes from the SBBRS, but also to the spectrally resolved fluxes from the TDDRS — with possibly different results for conservative and non-conservative scattering channels due to the dependence of photon path length on absorptivity.

Variant B — Aircraft Over and Under Clouds

The main idea is to derive areal mean flux quantities and relate these to areal mean cloud properties as derived from profiles from active probes. For example, the along track flight data together with matched cloud profile data offer a unique data set to test 3D radiative transfer. Relation of cloud structure to satellite image data also offers the possibility to relate this transfer to the broader setting as seen by satellites.

The analysis strategy delineated below is suitable for the ideal case of a single cloud. Extensibility to multi-cloud situations will be addressed by modeling.

Since data collection legs begin and end far from the central cloud, the radiation fields observed at these extrema are not unduly influenced by the cloud. As the aircraft approach the cloud the scattered radiation, i.e., cloud reflectance and leakage, will cause increases in upwelling radiation on the nadir viewing radiometer on the UAV and similar increases in downwelling radiation on the zenith radiometer on the DHC-6 until shadowing or near-shadowing conditions exist. By using a convolution of (1) the nadir radiometer on the DHC-6 for accounting for surface reflectance and lower atmospheric absorption and scattering, (2) the zenith radiometer on the UAV for determining the atmospheric absorption and scattering above the cloud, and (3) a clear sky radiative transfer model tuned to these measurements to account for the absorption and scattering of radiation between the aircraft, it should be possible to derive the influence of clouds on the vertical heating profile as a function of the horizontal distance from the cloud.

These measurements provide a direct measure of the effects of clouds on the heating profile for cloudy atmospheric columns, which will be usable in climate modeling studies. These measurements will also provide a means for understanding the directional dependence of the radiation stream from clouds. Clouds are not isotropic scatterers and thus it is difficult to measure or model the directional component of scattered radiation. However, it is clearly a much more simple problem to model the radiation field for an isotropic scattering cloud, and thus it should be possible to compute what the aircraft measurements should be if the cloud were isotropic. By comparing the slopes of the simulated measurements for the isolated cloud and the actual data from the aircraft flights it may be possible to infer the directional component of the radiation scattered by the cloud. Clearly, radiance data provided by the MPIR for a few viewing angles will be of help in this.

Simulations using a 3d Monte Carlo radiative transfer model are possible and could be used to determine the magnitude of radiation field disturbances expected for the proposed flight legs for this experiment as a function of a few cloud types and a few solar zenith angles.

Relation to Other Experiments

Variants A and B are derivatives of variants B and C of experiment group 1 of reference 2.

Part B – Experiment Details

Flight Strategy

A very long linear flight path will be flown, ideally into the direction of the wind at the altitude of the cloud deck and simultaneously in the solar plane. If these latter two requirements are competing, than wind has precedence over solar. Pmtr range space available and the size of the cloud deck will limit the length of the leg.

Variant A — Aircraft Atop Clouds

This variant focuses on the smoothing of the radiation field over clouds. Both the Altus and the DHC-6 are required to fly over single layer (possibly scattered to broken), non-convective, single phase, extensive cloud decks. Their flight paths are to be synchronized with the faster aircraft performing a 360° repositioning maneuver back onto the flight track whenever it is more than 4 km ahead of the slower. The DHC-6 is to fly near the cloud tops and the Altus at its maximum altitude. Since the DHC-6 operation ceiling is 20 kft (~6 km), cloud tops can be no higher than ~5.5 km. Alternatively the Altus could fly at two or three equally spaced altitudes over the DHC-6. Measurements should be made near solar noon.

Variant B— Aircraft Over and Under Clouds

Except for altitude both aircraft are to fly as in variant A. Desired meteorological conditions are single layer (possibly scattered to broken), non-convective, single phase, extensive cloud decks. The DHC-6 is to fly 1 to 2 km below the cloud base and the Altus a similar distance above the cloud tops. Given aircraft performance limitations, useful cloud decks can have bases can be no higher than 8 km (DHC-6 service ceiling is ~6 km) and no lower that 2 km to allow penetration space beneath. Ideally, bases should be below 3.5 km so that the MMCR may be utilized. Measurements should be made near solar noon.

Constraints

All aircraft maneuvers are to be within PMTR warning or restricted airspace.

Special Needs

The MPIR will be in a straight nadir mount on the Altus.

Instrument and Data List

UAV

Instrument 1: MPIR (both variants) — five channels (0.62-0.67 μm, 0.86-0.90 μm, 1.36-1.39 μm, 1.58-1.64 μm, and 2.11-2.22 μm) each yielding data from a 256 element linear array (512 element for band 1) that is oriented to provide a curved, across track radiometric line image; the line images are spatially co-registered and temporally sampled each 0.5 second (0.25 for band 1); the instantaneous FOV for each pixel is 6 mrad (3 mrad for band 1)

Instrument 2: nadir SSP2 (both variants) — reflected spectral radiance in $wm^{-2}sr^{-1}nm^{-1}$, 0.4 to 4.0 μm; reflected spectral flux in $wm^{-2}nm^{-1}$, 0.4 to 2.5 μm; 2 channels linearly polarized ($||$, $\perp$) reflected spectral radiance in $wm^{-2}sr^{-1}nm^{-1}$, 0.4 to 2.5 μm; reflected broadband radiance in $wm^{-2}sr^{-1}$, 0.4 to 4.0 μm; reflected broadband flux in wm^{-2}, 0.4 to 2.5 μm

Instrument 3: zenith TDDR (both variants) — downwelling hemispherical flux data; seven channels each 10 nm wide; channel center wavelengths are 0.5, 0.86, 1.0, 1.25, 1.5, 1.65, and 1.75 μm; shadow rings move across the FOV periodically blocking direct solar radiation thus enabling determination of the diffuse : direct ratio

Instrument 4: nadir TDDR (both variants) — upwelling hemispherical flux data; seven channels each 10 nm wide; channel center wavelengths are 0.5, 0.86, 1.0, 1.25, 1.5, 1.65, and 1.75 μm

Instrument 5: zenith FSBBR (both variants) — broadband radiometer with hemispherical FOV; measures downwelling flux from 0.7 to 3 μm

Instrument 6: nadir FSBBR (both variants) — broadband radiometer with hemispherical FOV; measures upwelling flux from 0.7 to 3 μm

Instrument 7: zenith SBBR (both variants) — broadband radiometer with hemispherical FOV; measures downwelling flux from 0.3 to 4 μm

Instrument 8: nadir SBBR (both variants) — broadband radiometer with hemispherical FOV; measures upwelling flux from 0.3 to 4 μm

Instrument 9: CDL (both variants) — 200 range bins with intensity of reflected laser light plus one background bin; range bins provide information on the location and density of aerosols and clouds; background bin for data correction

DHC-6

Instrument 1: MMCR (variant B) — 95 GHZ cloud radar sensitive to cloud water droplets and ice particles

Instrument 2: SSP1 (both variants) — reflected spectral radiance in $wm^{-2}sr^{-1}nm^{-1}$, 0.4 to 4.0 μm; reflected spectral flux in $wm^{-2}nm^{-1}$, 0.4 to 2.5 μm; 2 channels linearly polarized ($||$, $\perp$) reflected spectral radiance in $wm^{-2}sr^{-1}nm^{-1}$, 0.4 to 2.5 μm

Instrument 3: zenith TDDR (both variants) — downwelling hemispherical flux data; seven channels each 10 nm wide; channel center wavelengths are 0.5, 0.86, 1.0, 1.25, 1.5, 1.65, and 1.75 μm; shadow rings move across the FOV periodically blocking direct solar radiation thus enabling determination of the diffuse : direct ratio

Instrument 4: nadir TDDR (both variants) — upwelling hemispherical flux data; seven channels each 10 nm wide; channel center wavelengths are 0.5, 0.86, 1.0, 1.25, 1.5, 1.65, and 1.75 μm

Instrument 5: zenith FSBBR (both variants) — broadband radiometer with hemispherical FOV; measures downwelling flux from 0.7 to 3 μm

Instrument 6: nadir FSBBR (both variants) — broadband radiometer with hemispherical FOV; measures upwelling flux from 0.7 to 3 μm

Instrument 7: zenith SBBR (both variants) — broadband radiometer with hemispherical FOV; measures downwelling flux from 0.3 to 4 μm

Instrument 8: nadir SBBR (both variants) — broadband radiometer with hemispherical FOV; measures upwelling flux from 0.3 to 4 μm

Instrument 9: SSFR — zenith and nadir spectral radiance in $wm^{-2}sr^{-1}nm^{-1}$, 0.3 to 2.5 μm; upwelling and downwelling spectral irradiance in $wm^{-2}nm^{-1}$, 0.3 to 2.5 μm; 5-10 nm resolution; 30 second data averaging

Satellite — GOES-9 or GOES-10

Instrument 1: imager — multi-channel instrument designed to sense radiant and solar-reflected energy from sampled areas of the Earth; produces full-Earth disc images

Satellite — NOAA-12, NOAA-14, or NOAA-15

Instrument 1: AVHRR — cross-track scanning system with five spectral channels; the spectral band widths are 0.58-0.68, 0.725-1.10, 3.55-3.93, 10.3-11.3, and 11.5-12.5 μm; IFOV of each channel is approximately 1.4 mrad leading to a resolution at the satellite sub-point of 1.1 km for a nominal altitude of 833 km; IR channels are calibrated in-flight; no in-flight visible channel calibration is performed

Satellite — TRMM

Instrument 1: VIRS — (description to be supplied)

Experiment Group 3 — Support for TRMM Retrieval Definition

Part A – Science Issues

Science Objective

The objective of this experiment is to provide measurements that can be used to assist in the development and support of new remote sensing techniques applicable to cirrus from satellite sensors such as from the GOES imager, the TRMM VIRS and CERES, and perhaps from MODIS on the EOS AM platform. In addition, this experiment should provide angular radiance information to assist in the development bi-directional reflection functions for use in CERES Earth Radiation Budget flux retrievals.

This experiment is especially timely since the CERES instruments will be operating on the TRMM satellite during the period of the UAV field campaign. CERES derives broadband shortwave and longwave fluxes from radiance measurements using models that depend on cloud properties in the field of view. These cloud properties: amount, height, optical depth, phase, effective particle size, and water path, are derived from the VIRS on TRMM and from a microwave radiometer on TRMM.

Advocate

Graeme Stephens is the advocate for this experiment.

Measurement Strategy

All measurements will be taken by the Altus at an altitude above 21.0 km for segments that cover half of the diurnal cycle (sunrise to noon or noon to sunset) for several days that include a variety of cloud conditions. The area for measurement must be at least 63.0 km from any feature, such as land, that would perturb the uniformity of the scene viewed by the on-board hemispheric radiometers.

Variant A — BDRF vs. Time of Day

The BDRF of a cloud field or clear sky would ideally be obtained by averaging the spectrally and angularly resolved radiation emanating upward from many points on its or the surface. Of course, such a measurement is impractical. The reverse measurement is more tractable, that is, measuring the spectrally and angularly resolved radiation converging upward to a point well above the cloud field or earth's surface. Since for clouds this measurement involves radiation from many different elements on the its surface, it only makes sense for fields that meet some uniformity criteria. Such criteria can be expressed in terms of how smoothly the derived BDRF varies and the equality of equivalent angles on either side of the solar vector.

The MPIR will be used to gather raw data for five spectral bands resolved into approximately 256 polar angle bins between 0° and 66° from nadir and 200 azimuth angle bins from 0° to 360°. This will be accomplished by turning a 360° clockwise turn with a radius of 2.5 km at 15° bank with the MPIR canted 11° to the port. The measurement will take a little over 180 seconds. Aircraft motion plus wind differential between the cloud tops or surface and the aircraft's altitude cause the measurement to be made over an area of a few kilometers rather than the desired point.

All measurements will be taken in clear skies at an altitude of 21.0 km or greater for half of the diurnal cycle (sunrise to noon or noon to sunset) for several days.

Variant B — CERES Flux Retrieval Support

Description to be supplied but assumed to be similar to the upper aircraft portion of Experiment 1.

Required and Supporting Measurements

UAV

The critical instrument on this platform for variant A is the MPIR to make spectral radiance measurements. The CDL will be used for detecting and profiling thin clouds below the UAV. The description of additional instrumentation for variant B is to be supplied.

Satellite

The supporting instruments are the CERES for radiance measurement and VIRS for visible and infrared imagery aboard the TRMM satellite.

Data Analysis Strategy

Variant A — BDRF vs. Time of Day

Data from the MPIR will be averaged into a reduced set of 36 azimuthal bins and 7° zenith angle bins for each trial after normalization to the mean solar zenith angle for the trial. High-altitude measurements will corrected to the top of the atmosphere using radiative transfer modeling and appropriate gaseous loading in the stratosphere. Radiative transfer modeling will be used to correct the near-surface BDRFS to the top of the atmosphere using surface-derived aerosol loadings.

Variant B — CERES Flux Retrieval Support

Description to be supplied.

Relation to Other Experiments

Variant A is closely associated with Experiment 10 of the ARM–UAV Science and Experiment Plan, 1996 Flight Series, Revision 4, March 2, 1996 and Experiment Group 2 of the ARM–UAV Science and Experiment Plan, 1997 Flight Series, Version 2.1, July 8, 1997.

Part B – Experiment Details

Flight Strategy

Variant A — BDRF vs. Time of Day

The Altus will be flown to a point over the ocean sufficiently far from land where subsequent maneuvering will not carry it within 63 km of land, and then will accumulate data while turning three successive 360° clockwise turns at 15° bank angle. Since this maneuver will take approximately 10 minutes, wind drift is a consideration.

All measurements will be taken in clear and cloudy skies at an altitude of 21.0 km for half of the diurnal cycle (sunrise to noon or noon to sunset) over several days, perhaps in conjunction with flights for other experiments.

Variant B — CERES Flux Retrieval Support

Description to be supplied but assumed to be similar to the upper aircraft portion of Experiment 1.

Constraints

All aircraft maneuvers are to be within PMTR warning or restricted airspace.

Special Needs

The MPIR will be canted 11° to the port side on the Altus.

Instrument and Data List

UAV

Instrument 1: MPIR (variant A) — five channels (0.62-0.67 μm, 0.86-0.90 μm, 1.36-1.39 μm, and 1.58-1.64 μm, and 2.11-2.22 μm) each yielding data from a 256 element linear array (512 element for band 1) that is oriented to provide a curved, across track radiometric line image; the line images are spatially co-registered and temporally sampled each 0.5 second (0.25 for band 1); the instantaneous FOV for each pixel is 6 mrad (3 mrad for band 1)

Instrument 2: CDL (variant A) — 200 range bins with intensity of reflected laser light plus one background bin; range bins provide information on the location and density of aerosols and clouds; background bin for data correction

Other: description to be supplied for variant B

Satellite — TRMM

Instrument 1: VIRS — (description to be supplied)

Instrument 1: CERES — (description to be supplied)

Instrument 1: MWR — (description to be supplied)

Experiment 4 — ARESE Reprise

Part A – Science Issues

Science Objective

The objective is to determine if cloudy atmospheres absorb more shortwave radiation than predicted by state-of-the-art climate models.

The ARESE experiment was conducted in the fall 1995 ARM-UAV campaign, and a reprises of that experiment were proposed in the 1996 and 1997science plans[1,2]. This experiment is a follow-on to that campaign and reprise experiments. The original experiment was developed fully in a separate report[3]. This document contains only a summary description from that science plan and is adapted to a follow-on effort.

Two objectives are imbedded in this hypothesis: (1) the direct measurement of the absorption of solar radiation by clear and cloudy atmospheres and the placement of bounds on these measurements and (2) the investigation of the possible causes of absorption in excess of model predictions.

Evidence from several experimental and theoretical investigations over the past four decades has shown that the magnitude of shortwave absorption by clouds is uncertain. There has been some evidence that absorption is more than that predicted by models. F. Valero and several other investigators have concluded that the absorption by the entire atmospheric column in the presence of clouds exceeds model predictions of absorption by perhaps 35 W/m^2 (day side average) over the Pacific warm pool. The relative error this presents in current theoretical estimates of solar absorption is large, considering that average clear-sky absorption in that region is about 100 W/m^2 (dayside average). The absolute error appears to be small when compared to other terms in the energy budget, but that is misleading. Most of the solar radiation absorbed in the tropics goes toward heating the surface, the remainder, about 20%, helps drive the atmospheric circulation. Thus, what appear to be small errors in absorption by the atmosphere might have huge consequences in tropical atmospheric dynamics. Another consequence of the inadequacy of our understanding of solar absorption by clouds is the misinterpretation of remote sensing data used to infer cloud microphysical properties.

The fall 1995-ARESE experiment produced data from 12 science flights, which have been analyzed and presented in various journal and meeting papers. The results appear to strongly support the hypothesis, but have been challenged in their details. The subject of this reprise experiment is the filling of any gaps in the earlier data, if such filling is essential to the understanding of the hypothesis as indicated by preliminary analyses. If either the differing UAV instrument suite or extant meteorological conditions will not produce significantly improved data from that already taken, then this experiment will not be undertaken.

Advocate

The original ARESE experiment had its own separate science team. The chair of this team and chief scientist was Francisco Valero from Scripps Oceanographic Institute. Stephen Schwartz from Brookhaven National Laboratory and later John Vitko, Jr. from Sandia National Laboratories were the project directors. The champion for this reprise experiment is Francisco Valero. The individuals involved in data analysis are Francisco Valero, Robert Cahalan, Catherine Gautier, Kuo-Nan Liou, Patrick Minnis, Shelly Pope, Stephen Schwartz, Graeme Stephens, Warren Wiscombe, Robert Cess, Jeff Kiehl, and Ram Ramanathan.

Measurement Strategy

The experimental emphasis of ARESE and this reprise focuses on the measurement of atmospheric column absorption through the acquisition of fluxes at different altitudes in the atmosphere and at the surface. This will be achieved by using satellite and aircraft platforms. The aircraft will cover the range from the tropopause to the low troposphere. Radiances measured by both GOES and NOAA series satellites will be compared to fluxes measured by aircraft at the tropopause, and then used to retrieve TOA fluxes.

The ARESE strategy involves the acquisition of radiometric data with multiple, coordinated aircraft and from the ground. In this experiment, ground sensor however will not be deployed. The aircraft will fly tracks stacked at different altitudes. In this manner, it will be possible to obtain coeval measurements of radiative fluxes from which the absorption of radiation by the atmosphere can be estimated. Additionally, the aircraft sampling from the tropopause will be able to measure the reflectivity of the cloudy and clear atmospheres, and the lower observations will provide the radiative flux transmitted through the column. The top of the troposphere reflectivity and surface transmissivity values provide an additional indication of the magnitude of absorption by the atmospheric column.

Upper troposphere measurements will be made from a UAV and lower troposphere measurements from an ARM-UAV DHC-6 Twin Otter. Both aircraft will be equipped with identical Valero radiometers and Pilewskie spectral radiometers. The original experiment had an additional aircraft at the tropopause, the NASA ER-2 similarly equipped with Valero radiometers.

An intercomparison maneuver should be performed once each flight.

Required and Supporting Measurements

The list of measurements to be made as part of this ARESE follow-on experiment are not as extensive as for the original experiment, which were fully covered in the ARESE science plan and is modified from that of the two previous reprise experiments. Common to both aircraft is a RAMS for the characterization of shortwave and longwave upwelling and downwelling fluxes at their respective flight altitudes. The components of a RAMS are a) zenith SBBR, b) nadir SBBR, c) zenith FSBBR, d) nadir FSBBR, e) zenith TDDR (7 channels: 0.500, 0.865, 1.05, 1.25, 1.50, 1.65, and 1.75 μm), and f) nadir TDDR (7 channels: 0.500, 0.865, 1.05, 1.25, 1.50, 1.65, and 1.75 μm). Also on both aircraft are SSFRS measuring both upwelling and downwelling spectrally resolved radiances and fluxes.

UAV

The UAV will measure upwelling and downwelling solar fluxes in the upper troposphere with a RAMS and with a SSFR. Additional supporting instrumentation a nadir SSP2 for collection of spectrally resolved 0.4 to 4.0 μm radiances from features directly below the aircraft and the MPIR for clouds image data in bands centered on 0.65, 0.88, 1.37, 1.61, and 2.18 μm. The MPIR's cross track FOV will be ±40°.

DHC-6

The DHC-6 will also measure upwelling and downwelling solar fluxes, but in the lower troposphere, with a RAMS and SSFR. The additional on board supporting instrumentation is a zenith SSP1 for collection of spectrally resolved 0.4 to 1.0-μm radiances from features directly above the aircraft and a MMCR to characterize the cloud profile also directly above the aircraft.

Satellite

The primary instrument is the imager on GOES-9 or GOES-10 for measurement of narrowband radiances in the visible and infrared bands. Secondarily, narrowband data will be used from AVHRR (NOAA-12, NOAA-14, or NOAA-15) and VIRS (TRMM), whenever satellite views match the area of operations.

Data Analysis Strategy

The data taken in any reprise experiment will be used to supplement data already acquired in the Fall 1995 campaign and in the reprise experiments during 1996 and 1997campaigns. The data analysis strategy associated with the ARESE campaign will be used also for the additional data and is reviewed herein, with appropriate modifications for the reduced aircraft suite and changed instrument suites.

Three strategies will be used for evaluating cloudy sky atmospheric absorption relative to models. These can be variously adapted to use data from the three levels of this ARESE reprise: (1) 0.5 km DHC-6, (3) 20 km UAV, and (4) TOA (satellite).

A direct way of evaluating cloudy sky shortwave absorption, relative to that for clear skies, is to compare cloud radiative forcing near the surface to that at the TOA. Cloud radiative forcing is the difference between all-sky and clear sky net downward shortwave radiation. Models typically give a value near one for the ratio of cloud radiative forcing at the surface to cloud radiative forcing at the TOA although some recent measurements indicate a value near 1.5 might be more appropriate. Since model simulations of cloud radiative forcing are easily performed for the DHC-6 and Altus UAV altitudes, this approach can be used to compare measurements taken on board those platforms with model results.

During this ARESE re-reprise upwelling surface shortwave flux will not be measured. A second analysis strategy overcomes this deficiency by substituting near surface insolation for the surface net flux used in the above strategy. Models typically give a value near 1.25 for the ratio of surface cloud insolation forcing to TOA cloud radiative forcing, compared to some recent measurements indicating a value nearer 1.75 for this same ratio.

The ratio of cloud radiative forcing at the surface to that at the TOA can be shown to be mathematically equal to $-(\Delta\alpha/\Delta T)^{-1}$ where α is the TOA albedo and T is the atmospheric transmittance. This leads to a third approach that evaluates $\Delta\alpha/\Delta T$ from a linear regression of the measured quantities of albedo and transmittance. Since this approach does not require clear sky identification, it serves to remove cloud shortwave absorption from broken cloud effects.

Relation to Other Experiments

As mentioned above, this experiment is a reprise of the ARESE experiment and its reprises, which were fully developed, in the separate documents.

Part B – Experiment Details

Flight Strategy

The upper troposphere UAV will be used as an above cloud platform and the DHC-6 as a lower troposphere, below cloud platform. The mission of these aircraft is to provide measurements of net fluxes at 21 km and 0.8-km MSL, respectively, in cloudy sky conditions. The clouds should form a single nearly uniform layer. These two aircraft will fly in coordination with their horizontal distance ideally not exceeding 4 km.

The original ARESE flight plan involved two long paths (greater than 160 km) and a shorter triangular one as shown in the discussion of Experiment 3 in reference 2. The current strategy is not constrained by ground locations, since all places in the ocean area off Kauai are, generally speaking, radiometrically equivalent. For this experiment, both aircraft will fly on a track whose length is greater than 100 km and ideally greater than 150 km. The wind conditions affect the ability of the

Altus UAV and DHC-6 to maintain coordinated flight, therefore the track will be oriented to best advantage in this regard. Since the Altus is faster at its high altitude than the DHC-6 at its lower altitude, "best advantage" means to retard the Altus relative to the DHC-6. The track may be flown in both directions as time and fuel allow, however a track optimized as above for winds will be a poor choice for reverse flight, and the best strategy may be to recover to the initial point and refly in the same direction.

Anytime that the Altus proceeds more than 4 km ahead of the DHC-6 on the track, it will execute a 360° repositioning maneuver back onto the track behind the DHC-6, and then proceed to again overtake.

Either at the beginning or end of the flight both aircraft should perform an instrument intercomparison maneuver, i.e., one complete circuit of an "L" pattern oriented on the sun in reasonably close formation at a convenient co-altitude.

Constraints

All maneuvers will take place within PMTR warning or restricted airspace.

Special Needs

There are no special needs for this experiment.

Instrument and Data List

UAV

Instrument 1: SSFR — zenith and nadir spectral radiance in $wm^{-2}sr^{-1}nm^{-1}$, 0.3 to 2.5 μm; upwelling and downwelling spectral irradiance in $wm^{-2}nm^{-1}$, 0.3 to 2.5 μm; 5-10 nm resolution; 30 second data averaging

Instrument 2: zenith TDDR — downwelling hemispherical flux data; seven channels each 10 nm wide; channel center wavelengths are 0.5, 0.86, 1.0, 1.25, 1.5, 1.65, and 1.75 μm; shadow rings move across the FOV periodically blocking direct solar radiation thus enabling determination of the diffuse : direct ratio

Instrument 3: nadir TDDR — upwelling hemispherical flux data; seven channels each 10 nm wide; channel center wavelengths are 0.5, 0.86, 1.0, 1.25, 1.5, 1.65, and 1.75 μm

Instrument 4: zenith FSBBR — broadband radiometer with hemispherical FOV; measures downwelling flux from 0.7 to 3 μm

Instrument 5: nadir FSBBR — broadband radiometer with hemispherical FOV; measures upwelling flux from 0.7 to 3 μm

Instrument 6: zenith SBBR — broadband radiometer with hemispherical FOV; measures downwelling flux from 0.3 to 4 μm

Instrument 7: nadir SBBR — broadband radiometer with hemispherical FOV; measures upwelling flux from 0.3 to 4 μm

Instrument 8: nadir SSP2 — reflected spectral radiance in $wm^{-2}sr^{-1}nm^{-1}$, 0.4 to 4.0 μm; reflected spectral flux in $wm^{-2}nm^{-1}$, 0.4 to 2.5 μm; 2 channels linearly polarized ($||$, $\perp$) reflected spectral radiance in $wm^{-2}sr^{-1}nm^{-1}$, 0.4 to 2.5 μm; reflected broadband radiance in $wm^{-2}sr^{-1}$, 0.4 to 4.0 μm; reflected broadband flux in wm^{-2}, 0.4 to 2.5 μm

DHC-6

Instrument 1: zenith TDDR — downwelling hemispherical flux data; seven channels each 10 nm wide; channel center wavelengths are 0.5, 0.86, 1.0, 1.25, 1.5, 1.65, and 1.75 μm; shadow rings move across the FOV periodically blocking direct solar radiation thus enabling determination of the diffuse : direct ratio

Instrument 2: nadir TDDR — upwelling hemispherical flux data; seven channels each 10 nm wide; channel center wavelengths are 0.5, 0.86, 1.0, 1.25, 1.5, 1.65, and 1.75 μm

Instrument 3: zenith FSBBR — broadband radiometer with hemispherical FOV; measures downwelling flux from 0.7 to 3 μm

Instrument 4: nadir FSBBR — broadband radiometer with hemispherical FOV; measures upwelling flux from 0.7 to 3 μm

Instrument 5: zenith SBBR — broadband radiometer with hemispherical FOV; measures downwelling flux from 0.3 to 4 μm

Instrument 6: nadir SBBR — broadband radiometer with hemispherical FOV; measures upwelling flux from 0.3 to 4 μm

Instrument 7: zenith SSP1 — reflected spectral radiance in $wm^{-2}sr^{-1}nm^{-1}$, 0.4 to 4.0 μm; reflected spectral flux in $wm^{-2}nm^{-1}$, 0.4 to 2.5 μm; 2 channels linearly polarized ($||$, $\perp$) reflected spectral radiance in $wm^{-2}sr^{-1}nm^{-1}$, 0.4 to 2.5 μm

Instrument 8: MMCR — 95 GHZ cloud radar sensitive to cloud water droplets and ice particles

Satellite — GOES-9 or GOES-10

Instrument 1: imager — multi-channel instrument designed to sense radiant and solar-reflected energy from sampled areas of the Earth; produces full-Earth disc images

Satellite — NOAA-12, NOAA-14, or NOAA-15

Instrument 1: AVHRR — cross-track scanning system with five spectral channels; the spectral band widths are 0.58-0.68, 0.725-1.10, 3.55-3.93, 10.3-11.3, and 11.5-12.5 μm; IFOV of each channel is approximately 1.4 mrad leading to a resolution at the satellite sub-point of 1.1 km for a nominal altitude of 833 km; IR channels are calibrated in-flight; no in-flight visible channel calibration is performed

Satellite — TRMM

Instrument 1: VIRS — (description to be supplied)

Experiment 5 — Clear Sky Profiling

Part A – Science Issues

Science Objective

The objectives are (i) to characterize the radiation budget of the atmospheric column above the ocean near Kauai extending from near the surface to the UAV flight altitude on onward to the TOA in pristine and aerosol laden clear conditions and (ii) to relate these properties to measurements of broadband fluxes at the various flight altitudes.

Radiative heating is an important component of the energy budget of the atmosphere. The relationship between this heating and the (optical) properties of aerosols is not well developed for the following reasons. Accurate measurements of the column heating have been elusive in the past, and have been affected by biases introduced by inadequate sampling and limitations of experimental design.

This ARM-UAV experiment proposes to overcome this problem as much as possible by maintaining the aircraft above the ocean, whose radiative properties are generally well known, and measuring clear sky radiative properties at a variety of levels between near surface and the tropopause. Since there are two aircraft, the atmosphere can be measured simultaneously at two levels in nearly the same region. The spectrally resolved and profiling sensors on both aircraft, in particular the SSP, CDL, and SSFR will provide the best possible estimate of aerosol optical properties. These in turn can be compared to similar properties derived from satellite radiances. Deployment of in *situ* aircraft is desirable to assist in the validation of the derived cloud or aerosol properties.

Advocate

Individuals expressing an interest in this data include Robert Ellingson and Francisco Valero.

Measurement Strategy

The experimental strategy, as stated above, is to optimize coordination between the one or two aircraft over a surface whose properties are well known, i.e., the ocean. The principal Altus payload will include spectral (SSP, SSFR, and MPIR) and broadband radiometers (RAMS) and the CDL. The desire is to make measurements at a variety of altitudes between near surface and the tropopause using the Altus and DHC-6 as measuring platforms.

The desired flight path consists of data taking legs over the ocean and never closer to land than three times the altitude of the highest aircraft. This insures that greater than 90% of the upwelling flux at that altitude geometrically comes from ocean surface. The aircraft are to fly straight and level on each leg for an average of five minutes before any altitude change. Legs are to be flown in a fashion that generally places the long axes of the aircraft in a direction toward or away from the sun and that alternates direction of flight if multiple legs are flown at the same altitude. When both the Altus and DHC-6 are flying, they are to maintain stations above and below each other with 4-km tolerance if possible. At some time during a flight with both aircraft, they should perform an intercomparison maneuver, i.e., one complete circuit of an “L” pattern oriented on the sun in reasonably close formation at a convenient co-altitude.

Desired altitudes include 0.5, 1.0, 2.0, 3.5, 7.0, 14.0, and 21.0 km but in no case lower as safety considerations allow. Since platform attitude changes degrade the scientific quality of radiometric data, these altitudes may be adjusted by the mission scientist based on wind conditions at the time of the flight. Desired meteorological conditions are either aerosol laden or pristine clear. Measurements should be made with as low solar zenith angles as possible, i.e., near solar noon.

Required and Supporting Measurements

UAV

The UAV will measure upwelling and downwelling solar fluxes in the upper troposphere with a RAMS. It will also measure upwelling and downwelling spectrally resolved broadband fluxes and radiances directly below and above the UAV with a SSFR, and similar upwelling fluxes below the UAV with a nadir SSP. A desired supporting instrument is the CDL for aerosol characterization and profiling.

DHC-6

The DHC-6 will measure upwelling and downwelling solar fluxes in the lower troposphere with a RAMS. It will also measure upwelling and downwelling spectrally resolved broadband fluxes and radiances directly below and above with a SSFR, and similar downwelling fluxes above with a zenith SSP.

Satellite

The primary instrument is the imager on GOES-9 or GOES-10 to estimate the extent of the clear conditions sampled.

Data Analysis Strategy

The data taken will supplement data for the ARESE reprise experiment discussed elsewhere in this experiment plan with that taken in clear and aerosol conditions. The data analysis strategy is therefore a derivative of the ARESE strategy. Those strategies will be used for evaluating aerosol laden atmospheric absorption relative to models. These can be variously adapted to use data from the various altitude levels of this experiment's measurements.

A direct way of evaluating aerosol laden atmospheric shortwave absorption, relative to that for pristine clear skies, is to compare aerosol radiative forcing near the surface to that at the TOA; that is, the difference between aerosol-sky and pristine clear sky net downward shortwave radiation. Since model simulations of radiative forcing are easily performed for the Altus UAV altitudes, this approach can be used to compare measurements taken on board this platform with model results.

Relation to Other Experiments

As mentioned above, this experiment is closely associated with the ARESE family of experiments.

Part B – Experiment Details

Flight Strategy

The basic requirement is to fly stable, five-minute data taking legs oriented generally toward and away from the sun at a sequential set of altitudes. The desired altitudes may vary, but will be approximately 0.5, 1.0, 2.0, 3.5, 7.0, 14.0, and 21.0 km. Safety considerations or the desire to avoid turbulent air that would degrade data quality may cause the variance from these. The legs may be flown either in a race track pattern or as a long linear set, at the choice of PMTR range control personnel and the mission scientist. During data runs, it is desired to maintain lateral coordination if both aircraft are flying of less than 4 km.

Either at the beginning or end of the flight both aircraft should perform an instrument intercomparison maneuver, i.e., one complete circuit of an "L" pattern oriented on the sun in reasonably close formation at a convenient co-altitude.

Constraints

All data legs are to be performed no closer to land than three times the altitude of the highest leg flown, and the same distance from any cloud field.

Special Needs

There are no special needs for this experiment.

Instrument and Data List

UAV

Instrument 1: SSFR — zenith and nadir spectral radiance in $wm^{-2}sr^{-1}nm^{-1}$, 0.3 to 2.5 μm; upwelling and downwelling spectral irradiance in $wm^{-2}nm^{-1}$, 0.3 to 2.5 μm; 5-10 nm resolution; 30 second data averaging

Instrument 2: nadir SSP2 — reflected spectral radiance in $wm^{-2}sr^{-1}nm^{-1}$, 0.4 to 4.0 μm; reflected spectral flux in $wm^{-2}nm^{-1}$, 0.4 to 2.5 μm; 2 channels linearly polarized (||, ⊥) reflected spectral radiance in $wm^{-2}sr^{-1}nm^{-1}$, 0.4 to 2.5 μm; reflected broadband radiance in $wm^{-2}sr^{-1}$, 0.4 to 4.0 μm; reflected broadband flux in wm^{-2}, 0.4 to 2.5 μm

Instrument 3: zenith TDDR — downwelling hemispherical flux data; seven channels each 10 nm wide; channel center wavelengths are 0.5, 0.86, 1.0, 1.25, 1.5, 1.65, and 1.75 μm; shadow rings move across the FOV periodically blocking direct solar radiation thus enabling determination of the diffuse : direct ratio

Instrument 4: nadir TDDR — upwelling hemispherical flux data; seven channels each 10 nm wide; channel center wavelengths are 0.5, 0.86, 1.0, 1.25, 1.5, 1.65, and 1.75 μm

Instrument 5: zenith FSBBR — broadband radiometer with hemispherical FOV; measures downwelling flux from 0.7 to 3 μm

Instrument 6: nadir FSBBR — broadband radiometer with hemispherical FOV; measures upwelling flux from 0.7 to 3 μm

Instrument 7: zenith SBBR — broadband radiometer with hemispherical FOV; measures downwelling flux from 0.3 to 4 μm

Instrument 8: nadir SBBR — broadband radiometer with hemispherical FOV; measures upwelling flux from 0.3 to 4 μm

Instrument 9: CDL — 200 range bins with intensity of reflected laser light plus one background bin; range bins provide information on the location and density of aerosols and clouds; background bin for data correction

DHC-6

Instrument 1: SSFR — zenith and nadir spectral radiance in $wm^{-2}sr^{-1}nm^{-1}$, 0.3 to 2.5 μm; upwelling and downwelling spectral irradiance in $wm^{-2}nm^{-1}$, 0.3 to 2.5 μm; 5-10 nm resolution; 30 second data averaging

Instrument 2: zenith SSP1 — reflected spectral radiance in $wm^{-2}sr^{-1}nm^{-1}$, 0.4 to 4.0 μm; reflected spectral flux in $wm^{-2}nm^{-1}$, 0.4 to 2.5 μm; 2 channels linearly polarized (||, ⊥) reflected spectral radiance in $wm^{-2}sr^{-1}nm^{-1}$, 0.4 to 2.5 μm

Instrument 3: zenith TDDR — downwelling hemispherical flux data; seven channels each 10 nm wide; channel center wavelengths are 0.5, 0.86, 1.0, 1.25, 1.5, 1.65, and 1.75 μm; shadow rings move across the FOV periodically blocking direct solar radiation thus enabling determination of the diffuse : direct ratio

Instrument 4: nadir TDDR — upwelling hemispherical flux data; seven channels each 10 nm wide; channel center wavelengths are 0.5, 0.86, 1.0, 1.25, 1.5, 1.65, and 1.75 μm

Instrument 5: zenith FSBBR — broadband radiometer with hemispherical FOV; measures downwelling flux from 0.7 to 3 μm

Instrument 6: nadir FSBBR — broadband radiometer with hemispherical FOV; measures upwelling flux from 0.7 to 3 μm

Instrument 7: zenith SBBR — broadband radiometer with hemispherical FOV; measures downwelling flux from 0.3 to 4 μm

Instrument 8: nadir SBBR — broadband radiometer with hemispherical FOV; measures upwelling flux from 0.3 to 4 μm

Satellite — GOES-9 or GOES-10:

Instrument 1: imager — multi-channel instrument designed to sense radiant and solar-reflected energy from sampled areas of the Earth; produces full-Earth disc images

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Appendix B: Acronym and Symbol List

AERI	atmospherically emitted radiation interferometer
AMMR	Airborne Multichannel Microwave Radiometer
ARESE	ARM Enhanced Shortwave Experiment
ARM	Atmospheric Radiation Measurement (program)
AVHRR	advanced very high resolution radiometer
CART	Cloud And Radiation Testbed
CDL	cloud detection lidar
CERES	cloud and earth radiant energy system
ER-2	extended range U-2 aircraft
FOV	field of view
FSBBR	fractional solar broadband radiometer
GOES	geostationary operational environmental satellite
HONER	hemispherical optimized net radiometer
IFOV	instantaneous field of view
IRBBR	infrared broadband radiometer
LIDAR	light detection and ranging
LLNL	Lawrence Livermore National Laboratory
MFRSR	multifilter rotating shadowband radiometer
MMCR	millimeter-wave cloud radar
MPIR	multispectral pushbroom imaging radiometer
MSL	mean sea level

MWR	microwave radiometer
NASA	National Aeronautics and Space Administration
NOAA	National Oceanographic and Atmospheric Administration
RAMS	radiation measurement system
RASS	radio acoustic sounding system
SBBR	solar broadband radiometer
SGP	southern great plains
SSFR	solar spectral flux radiometer
SPS	spatial power spectrum
SSP	spectrally scanning polarimeter
SZA	solar zenith angle
TDDR	total direct diffuse radiometer
TOA	top of atmosphere
TRMM	tropical rainfall measurement mission (satellite)
UAV	unmanned aerospace vehicle
VIRS	visible infrared sensor

Appendix C: References

[1] Robert Ellingson and Tim Tooman, eds., ARM–UAV Science and Experiment Plan, 1996 Flight Series, Revision 4, March 2, 1996.

[2] Robert Ellingson and Tim Tooman, eds., ARM–UAV Science and Experiment Plan, 1997 Flight Series, Version 2.1, July 8, 1997.

[3] Francisco P. J. Valero, et. al., "ARESE (ARM Enhanced Shortwave Experiment) Science Plan".