Atmospheric Radiation and Hydrology (ARHM) Mission

Response to the RFI on Post 2002 era mission concepts. Submitted by

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1.0 Scientific Rationale

Earth's climate is continually changing. The major scientific challenge before us is to understand and predict these climate changes (e.g., IPCC, 1995; ESE, 1998). Meeting this challenge requires a quantitative understanding of the sensitivity of climate to factors such as changing concentrations of greenhouse gases or natural climate variability. The most significant obstacle that impedes progress towards determining this sensitivity is our lack of understanding of the climate feedback processes. Feedbacks of most importance are those determined by processes that connect radiation, the hydrological cycle and the large-scale atmospheric circulation.

Progress on this important topic requires new observing approaches that will allow us to:

> *link changes in water vapor, clouds and the hydrological cycle to the circulation of the atmosphere.*

This response describes a concept mission, Atmospheric Radiation and Hydrology Mission (ARHM), that will allow us to quantify these links. The mission is an atmospheric thermodynamic process study mission of a scope that integrates the interests and expertise of scientists in three main NASA Centers as well as the international Earth Science community and the respective space agencies supporting these communities. It is an experiment that could be conceived as two satellites flying in formation.

ARHM is specifically designed to study critical hydrological-related climate feedbacks by way of the addressing the following science questions:

> **Given the large-scale circulation patterns of the atmosphere, what are the associated distributions of water vapor, cloud water (liquid and ice) and precipitation?** This question, in principle is straightforward to address. However, it has not been possible to make significant progress even on this question owing to a lack of relevant observations. Our most accurate depiction of the large-scale circulation, both now and in the foreseeable future, derives from Numerical Weather Prediction (NWP) models. The assimilation of current observations as well as the day-to-day verification of forecasts produces highly validated and accurate sources of information about atmospheric circulation. The accuracy of water vapor, clouds and precipitation predicted by these models is uncertain despite the sophistication information about clouds that are predicted by the models. This uncertainty largely stems from a critical lack of observations. The first goal of ARHM is to**:**

> *provide the first complete view of the atmospheric branch of the hydrological cycle involving coincident measurements of water vapor, cloud water and ice, precipitation and aerosol.*

Through this goal, ARHM will provide information that can provide direct and immediate answer to this basic question.

> **Given the distribution of the three phases of water in the atmosphere, what is the effect of this distribution on the circulation of the atmosphere?** This is a more difficult question to address. The critical mechanism that determines the effect of water on atmospheric circulation is the heating of the atmosphere. This heating takes place through absorption and emission of radiation by water vapor and clouds, latent heating associated with condensation and precipitation formation, and the heating associated with direct contact with the surface. The combined heating is referred to as diabatic heating. An important factor that affects the heating of the surface and atmosphere, and that also needs to be observed, are aerosols. Aerosols heat the atmosphere and cool the surface via direct effects on radiation or indirect effects on cloud physics. The effect of aerosol on cloud formation and evolution is potentially more important than is the effect of aerosol on radiation. The second goal of ARHM is to~~;~~

> *provide the first combined radiative and latent heating profiles of the atmosphere*.

Global-scale and <u>coincident</u> information on the vertical distribution of water vapor, precipitation, cloud liquid water and cloud ice, and aerosols are required to close the atmospheric circulation →hydrology→atmospheric circulation feedback loop. The simultaneous acquisition of this information cannot be obtained from existing observing systems.

2.0 Measurement Approach and Objectives

The science objective of ARHM as identified above is to develop an understanding of how complex interactions of aerosol, water vapor, clouds and precipitation link to the circulation of the atmosphere. The objective is to determine the synoptic variations of the diabatic forcing for the general (ie, large scale) circulation of the atmosphere. This requires a mission lifetime to allow aggregation of the synoptic variations to seasonal and "climate" (.ie, annual) scales. The idea is to quantify how the synoptic variations, where the feedback processes actually operate, aggregate up to the "climate-scale" where feedback occurs.

ARHM measurement goals are to:

(i) Measure 3D -distributions of amounts of water vapor, clouds, precipitation & aerosols;~~,~~
(ii) Retrieve the relevant optical properties of cloud and aerosol particles;
(iii) Apply this information to determine atmospheric diabatic heating
(iv) Correlate space-time derivatives of cloud and heating to large scale circulation properties as diagnosed by operational NWP models.~~,~~

The measurement philosophy of ARHM relies on the demonstrated synergy of active and spectroscopic measurements to obtain coincident observations of profiles of amounts of water vapor, cloud water and ice contents, precipitation, and aerosol and to link this information to measured optical properties. These measurements do not have to be part of a single payload and could be achieved via formation flying of two or more satellites.

The proposed instruments includes:

- A differential absorption/backscattering lidar to obtain profiles of water vapor above and around clouds and aerosol and with backscattering capabilities to profile cloud and aerosol backscatter. This lidar will operate in nadir mode only.
- A dual frequency (14 GHz/95 GHz radar) to measure precipitation, cloud water and ice contents. Scanning capabilities of this radar system are desired and the combined instrument mission implications of this requirement needs to be assessed.~~,~~
- A multiple frequency microwave/sub-millimeter spectrometer to support in the retrieval of the critical hydrological parameters (vapor, liquid water ice and precipitation).~~,~~
- A visible near infrared spectrometer to retrieve relevant optical properties.~~,~~
- An IR spectrometer for temperature, moisture profiles and optical properties.~~,~~
- Top-of Atmosphere radiation fluxes to constrain radiative heating estimates.

Matching of the Fields-of-View (FOVs) of the sensors and the different capabilities of vertical resolution will have to be studied. The idea is to use active and the passive measurements to view the same atmospheric column, and together provide high vertical resolution and accurate properties of the region in common view (in the case of lidar this matched view will be along the satellite track). In the case of radar, this will be a 3D volume of atmosphere similar to the TRMM data set. The passive instruments also provide a wider cross-track scan and thus record a large region of the atmospheric and surface properties. In this way, the information retrieved across track can be continuously validated and enhanced using the high resolution profile observations obtained from active sensors. The vertical resolution of the active instruments will be vary according to the parameter derived. The nominal vertical resolution of the radar is 250 m. The nominal vertical and horizontal resolution for lidar varies according to the application. For clouds and aerosol, the vertical resolution is 50 m - 100 m; and 1 km for water vapor. The horizontal resolution will be 1-4 km for radar less than 1 km for lidar observations of clouds, 20 km for aerosol and 100 km for water vapor. The design goal is to insure easy matching in ground processing, including integer-multiple relationships of dimensions, similar centers of samples. Where technically feasible, some instruments (eg, vis-ir imager) will over-sample the FOV of other instruments to provide information about scene inhomogeneities at smaller scales.

3.0 Mission Type

An important issue for observing clouds, and to a lesser extent aerosol, is the diurnal or day/night variability. The preferred orbit would be a non-sun synchronous low altitude orbit to precess through the diurnal cycle. The altitude of the orbit should be maintained at 400-500 km to optimize sensitivity of the active sensors. Selecting the inclination of the orbit will involve some trade-off considerations. Lower inclination provides a more rapid sample through the diurnal cycle. However, the amount and distribution of polar clouds is also of critical importance to the topic of climate change. These clouds are difficult to detect and current retrieval methods are inaccurate. Active measurements are an important tool for studying these clouds and a polar or near polar orbit is also justified.

In view of the relatively short time-scales associated with atmospheric water processes and related heating processes, an adequate sample of different latitude and surface conditions, as well as seasonal and interannual variations, we can address the objectives of ARHM with a single research mission of a 5 year duration. Relevant to the objectives of the mission are the overlapping observations from weather satellites that will provide smaller-space-time scale context of ARHM measurements. Three years is a minimum (descope) duration but this is less likely to catch a typical ENSO climate anomaly. In 5 years ARHM will sample roughly 800,000 cloud systems which is a sufficiently large ensemble statistics of a wide range of dynamical cloud types from equatorial convective systems to polar cloud systems. The combination of sensors required to meet the goals of ARHM can be configured on a single platform or be accomplished through formation flying and/or coincident measurements with two (or more) satellite platforms.

For meaningful time-mean statistics it would be preferable to design the mission with two or more satellites to adequately sample the diurnal cycle. A two--satellite mission of comparable payload may be possible within the framework of international collaboration. Collaborations on missions similar to ARHM have been discussed with NASDA and ESA since the early 1990's. For instance, ESA is currently studying an Earth Radiation Mission (ERM) which proposes a payload that has some similarity to the payload of this mission (backscattering lidar, cloud radar and radiative flux measurements but without precipitation radar). NASDA is also considering two missions, Atmos-A and Atmos-B, that have combined payloads similar to ARHM. The Atmos A is the TRMM follow-on mission and Atmos-B is a mission similar to ERM and the proposed CloudSat (ESSP).

The CloudSat mission proposed to ESSP is a pathfinding mission making first -of-a-kind observations of clouds from space with a 94 GHz nadir--viewing radar. The properties of clouds as a radar target at this frequency is well established theoretically. However, these properties are not as developed experimentally. The reflection properties of mid-latitude clouds is well established by surface and aircraft observations but much less data exist on the reflection properties of tropical and polar clouds. CloudSat will pathfind new knowledge about clouds providing the first global survey of their reflecting properties at 94 GHz. The next step is to produce a scanning version of this radar for ARHM. In addition to demonstrating the performance of a 94 GHz radar for cloud studies, CloudSat will demonstrate lifetime in space of 94 GHz components, and will demonstrate formation flying and coincident observations with other satellites thus opening options for implementing ARHM on multiple platforms. ICESat, flying in formation with CloudSat, will demonstrate the utility of combined lidar and cloud radar data from sensors carried on different satellites.

4.0 Remote Sensing Measurement Techniques

The suggested measurement and instrument suite for ARHM is summarized as follows

Measurement Goal	Measurement Approach	Candidate Instrument(s)	Heritage
(i) Vertical profiles of Clouds	Profiles cloud occurrence (250m resolution vertical, 1 km horizontal)	14/95 GHz radar	TRMM 14 GHz precipitation radar, 95 GHz ESSP class radar.
(ii) Ice Content	Profiles of ice content from radar scattering and sub-millimeter water scattering	Radar in combination with sub-millimeter frequencies (600 GHz, etc.) of microwave spectrometer.	Radar as above, submillimeter heritage is MLS and DC8 cloud-ice radiometer, ER2 MIR
(iii) Water content	Water contents of clouds from radar scattering and microwave emission.	Radar in combination with lower frequency of microwave spectrometer (19, 23, 37 and 85 GHz)	TMI, SSMI, AMSU A, etc
(iv) Precipitation	Precipitation amount and profiles. Radar attenuation at 95 GHz in combination with 14 GHz, microwave emission and scattering in combination with 14 and 95 GHz.	14/95 GHz Radar and microwave spectrometer.	As above as well as several aircraft radiometers
(v) Vertical profiles of (thin) clouds and aerosol	Lidar backscatter profiles	backscatter lidar	LITE, GLAS, & MDS-2, aircraft ER2 LASE

(vi) Vertical profile of water vapor	DIAL lidar for high vertical resolution (~1 km) water vapor around clouds. IR/microwave emission for coarser profiles across track.	DIAL Lidar , IR and microwave spectrometer with 19, 22 GHz, channels and others centered around 183 GHz and 54 GHz	AMSUA/B, AIRS, and ER2 instruments, eg HIS., REFDIR under phase A at ESA is also a possibility.
(vii) Profiles of Visible & IR Optical Depths	Combination of profile information from lidar and radar and visible/ near IR and IR radiances	Lidar and radar as above. Visible/near IR spectrometer, IR spectrometer	Aircraft spectrometer, ESSP proposed A-Band spectrometer, OMI, and IR spectrometer as above.
(viii) Top of atmosphere fluxes	Broad-band with limited spectral fluxes for cloud albedo and cloud emissivity.	Broad-band radiometers, possibly spectrometers	CERES, ScaRab
(ix) Profiles of Particle Sizes	Combination of active with active and active with passive.	Lidar & 94 GHz and spectrometers.	Heritage as described above.
(x) Diabatic heating	Latent heating profiles from precipitation profiles, radiative heating profiles from profiles with optical depth particle size profiles.	Requires observations of all instruments. Broadband fluxes provide check on fluxes used to derive radiative heating.	Heritage as described above.

5.0 Technical Characteristics and issues.

Although the instruments proposed have long heritage and are ready for space-borne application today, certain characteristics of the mission need to be addressed before finalizing requirements. At the mission level, the extent to which some of the measurements can be obtained from multiple satellites in orbit at the same time needs to be explored. For instance, the temperature and moisture sounding requirements might be satisfied by the operational systems. Similarly, TOA fluxes may be obtained from CERES or CERES-like sensors operating on other platforms. In addition to these considerations, issues such as FOV, pointing and overlap requirements require study.

Differential absorption/backscatter lidar: Backscatter lidar will be demonstrated by ICEsat and the MDS-2 mission of NASDA prior to ARHM. The technology for space-based water vapor DIAL is rapidly maturing with the development of high-efficiency, high energy, high spectral purity long-life lasers. The technological feasibility and capabilities of a space-borne water vapor DIAL has been addressed in a number of studies and LASE is a successfully demonstrated airborne prototype of a space-based instrument. The space-based DIAL system will operate in the 946 nm-band of water vapor, and it will have a simplified laser configuration based on a version of the Nd:YAG laser which can operate directly in this spectral region. This laser will be diode-pumped to meet efficiency and lifetime requirements for space operations. The receiver aperture will also be increased to at least 1-m diameter. A DIAL system based on this technology is proposed for demonstration under the Instrument Incubator Program (IIP), and it is expected that on an accelerated schedule this system could be ready for used in the ARHM mission as early as 2004. *Power: 300 W, Weight 250 kg.*

The 14/95 GHz radar: Measurements of precipitation using space-based 14 GHz radar have been advanced by TRMM. Cloud observations using 94 GHz radar from aircraft and the ground are also mature and space-borne measurements are expected prior to the launch of ARHM providing a level of maturity in cloud and precipitation observations at this frequency. Polarization capabilites of the radar and scanning requirements (as in TRMM) will have to be addressed. Frequency selection (e.g. 14 vs 35 GHz) needs consideration. *Power 150 W. Weight 150 kg.*

The Microwave Spectrometer: This instrument has a long heritage and represents a combination of the frequencies of the TMI, the frequencies used in humidity sounding and new higher sub-millimeter frequencies that are highly sensitive to ice content. An instrument with these higher frequencies will have flown in space before ARHM, although in limb--viewing mode~~.~~ Aircraft measurements in support of CloudSat will clearly establish the technological feasibility and confirm the capabilities of these measurements. The requirements for this instrument are largely established. Some optimization of channels is required but these are likely to be those of the TMI, the MHS and new higher frequency channels. Selection of the relevant frequencies, while largely are established, will need to be addressed before setting final requirements. An airborne prototype of the sub-millimeter component of this instrument is being proposed under the recent the Instrument Incubator Program (IIP) AO-and a smaller lightweight version of the TMI with reduced frequency capability is also being proposed under the IIP. *Nominal power 100 W, weight 100 kg.*

Visible/near infrared spectrometer: The approach of using spectrometer measurements to obtain cloud and aerosol will be firmly established prior to final ARHM design, partly through ongoing surface and aircaft measurement programs, partly through existing space-borne spectrometer measurements and partly through proposed ESSP and existing EOS instruments. For instance, OMI proposed for EOS-CHEM could serve as the basis for the proposed instrument. Spectrally--resolved measurements of oxygen absorption and water vapor/cloud particle absorption in the near-infrared are required. Additional polarization capabilities, such as demonstrated on POLDER and proposed by EOSP, as well as utility of UV measurements deserve careful consideration before finally establishing instrument specifications. Proposals to the current IIP are being developed for prototype aircraft instruments. *Power 30W, weight 30 kg.*

IR spectrometer: IR spectrometer measurements of clouds and water vapor are required to derive optical properties. The optimal spectral range and resolution for this purpose will be addressed but it is likely this spectral channels will be patterned after existing radiometer channels. Spectrometer measurements are also needed in conjunction with the microwave observations for sounding atmospheric temperature and water vapor. Sounding requirements need to be carefully identified within the context of existing operational IR sounding capabilities must be considered.

Because of the strong feedback effects of clouds on their corresponding atmospheric columns, it is necessary to retrieve the atmospheric temperature and water vapor profiles in the real environment of clouds, not just under cloudless conditions. Principally, the sounder will be the AIRS infrared spectrometer and a microwave radiometer. The two together will provide the necessary cloud clearing in order to allow for the retrieval of temperature and moisture profiles under a variety of cloud conditions in the fields of view. The combination of AIRS/AMSU will provide the necessary background information about the full atmospheric column below the clouds as well as above the clouds. AIRS has a spectral resolving power and wavelength coverage from 3.7 to 15.4 mm. The infrared measurements are complemented by two microwave instruments: AMSU-A & B. The infrared measurements provide the primary high accuracy sounding capability of 1 K/1 km for temperature and 15%/2 km for humidity in the presence of up to 80% clouds. The requirements on IR spectrometer needsto be carefully considered within the context of existing operational IR sounding capabilities and the extent to which these capabilities fulfill the needs of the mission. *Power 150 W, Mass 120 kg.*

Broadband fluxes: Utilization of CERES measurements from other platforms is preferred. Added spectral capability may be needed (e.g. visible and near-IR fluxes~~)~~ is desirable). *Power: 50W, weight 50 kg* .