The CloudSat Mission

G. L. Stephens
Colorado State University
Department of Atmospheric Science
1371 Campus Delivery
Fort Collins, CO 80523-1371
D. G. Vane
California Institute of Technology
Jet Propulsion Laboratory
4800 Oak Grove Drive
Pasadena, CA 91109

I. INTRODUCTION

The CloudSat mission deploys the first spaceborne 94 GHz cloud profiling radar in space. The mission was selected under the NASA Earth System Science Pathfinder Program (ESSP http://essp.gsfc.nasa.gov) with a scheduled launch for the alter part of 2004. The unique feature of the CloudSat radar lies in its ability to observe jointly most of the clouds and precipitation within its nadir field of view. The CloudSat satellite also flies as part of a constellation of satellites that includes EOS Aqua and EOS Aura at each end of the constellation. CloudSat, a second ESSP mission that flies an aerosol lidar (CALIPSO) and another small satellite, PARASOL, carrying the POLDER polarimeter (see Ref. [2]) inserted in the formation between the larger EOS spacecraft (Fig. 1). This constellation is referred to as the A-train.

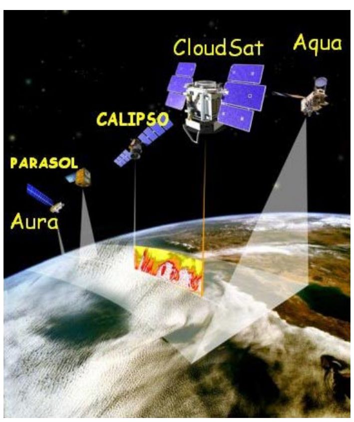

Fig. 1 The A-Train constellation and its members.

II. THE SCIENCE

An overview of the CloudSat mission, its science goals, science products and validation are summarized in Reference [3]. CloudSat seeks to solve a number of outstanding cloud-climate problems that are described in Reference [3] and thereby spur improvements in both weather forecasting and climate prediction. It aims to evaluate quantitatively the representation of clouds and cloud processes in global atmospheric circulation models, and the relationship between the vertical profiles of cloud liquid water and ice content and cloud radiative properties, including the radiative heating by clouds. In so doing, CloudSat seeks to provide the first direct global survey of the vertical structure of cloud systems. It will also measure the profiles of cloud liquid water and ice water content and match these profiles of the bulk cloud microphysical properties to cloud optical properties. Optical properties contrasted against cloud liquid water and ice contents are a critical test of key parameterizations that enable calculation of flux profiles and radiative heating rates throughout the atmospheric column. To date this type of evaluation can only be carried out using data collected in field programs and from surface measurements limited to a few locations worldwide.

These primary objectives are also augmented by other science objectives. CloudSat data provides a rich source of information for evaluating cloud properties derived from other satellite data including those produced from Aqua as well as cloud information derived from operational sensors. CloudSat information will also improve when data from other sensors are combined with the radar. CloudSat and the A-train also offer an unprecedented resource for understanding the potential of aerosol for changing cloud properties and thus the radiative budget of clouds. The aerosol context provided by other constellation measurements include MODIS on Aqua, the lidar on CALIPSO, the polarimeter on PARASOL and aerosol chemistry from Aura measurements. This information can be combined with the cloud water, ice and precipitation information of CloudSat and AMSR to a lesser degree, cloud optical property information of MODIS and PARASOL, and the CERES radiative fluxes to explore aerosol-chemistry-cloud interactions.

III. MISSION OVERVIEW

The CloudSat is formed via a number of partnerships. The Jet Propulsion Laboratory (JPL) of the California Institute of

Research sponsored by NASA contract s NAS5-99237 and NAS7-1407. The research described in this paper was performed by the Jet Propulsion Laboratory, California Institute of Technology, and by Colorado State University, under contract with the National Aeronautics and Space Administration, Goddard Space Flight Center.

Technology is developing the payload and managing the project. The Canadian Space Agency (CSA) is contributing key components and subsystems of the radar. Ball Aerospace provides the spacecraft bus, which is the fifth in the RS2000 line of spacecraft used both for QuikScat and ICESat. Ball Aerospace is also responsible for spacecraft integration and testing. The U. S. Air Force Space Test Program is providing ground operations and is managing communications with the spacecraft. The data will be down-linked several times per day through S-band links as part of the US Air Force SIGLS network of receiving stations. Validation activities take advantage of ground-based observational sites such as the DOE Cloud and Radiation Test bed (CART) sites as part of the ARM program ([Ref. 4]), NASA and ARM airborne science campaigns, and various national and international university and government research facilities reflected in the science team membership. The Cooperative Institute for Research in the Atmosphere (CIRA), also located at CSU, will process all CloudSat level 0 data and higher-level products (i.e. Levels 1 - 3). The data processing center (DPC) system design is based on the current CIRA satellite earth-station model, which has been operational since 1994.

CloudSat is to be launched on a Delta-II rocket co-manifested with the CALIPSO mission. The mission is designed for a two-year lifetime to observe more than one seasonal cycle. There is no anticipated technical reason, however, why the mission could not last longer as the radar is expected to operate beyond 3 years with an approximate 99% probability.

IV KEY MISSION ELEMENTS

There are two key elements of this mission that make it unique. The first is the cloud radar and the second is the precise formation flying of the Cloudsat spacecraft creating a virtual observatory with Aqua and CALIPSO in particular.

A. The Cloud Radar

Clouds are weak scatterers of microwave radiation especially in contrast to the reflection of the underlying Earth's surface. The overriding requirement on the radar is to achieve the maximum possible sensitivity to maximize cloud detection. Sensitivity is primarily determined by radar received power and noise level and optimizing this sensitivity involves a careful tradeoff among competing and conflicting factors, including the cloud backscattering properties, the vertical resolution, atmospheric attenuation, available power delivered to the system, the orbit altitude and radar technology. The received power can be increased by increasing the antenna size and increasing transmitter output power. The CloudSat antenna diameter of 1.85m is limited by launch constraints. The transmitter power is also limited by both the transmitter technology and the power supply capability of the spacecraft. Sensitivity considerations also dictated the operating frequency of 94 GHz as an optimum providing an increase of 33dB over the 14 GHz TRMM radar. An international frequency allocation at 94 GHz was subsequently established for spaceborne radar use.

Sensitivity is also related to the pulse length. The radar uses 3.3 μs pulses providing cloud and precipitation information with a 500-m vertical range resolution between the surface and 30 km. The radar measurements along track are averaged in 0.32 sec time intervals, corresponding to an effective along track averaging of 3.5 km. To enhance the capabilities of the system, the radar measurements are also sampled at 250m in range and 0.16 sec along the nadir track.

Three of the more noteworthy components of the radar hardware are highlighted in Fig.2. The antenna subsystem consists of the collimating antenna and the quasi-optical transmission line (QOTL). The antenna, constructed of composite graphite material, meets the challenge of low surface roughness (less than an rms of 5 μm over the entire surface) and delivers a highly directional beam of half width <0.12°. The antenna also has far side lobe levels 50 dB below that of the main lobe as required to remove aliasing of these side lobes into the profiles of the following pulses. The QOTL minimizes loss through the system. This will be the first time QOTL technology has flown in space at the wavelength of the radar. Another important challenge in the radar design is the high power amplifier (HPA) subsystem. The HPA has complete redundancy and consists of two extended interaction klystrons (EIK) and two high voltage power supplies. One key development was the re-design of the commercial EIK unit to one qualified to operate in space (Fig. 2).

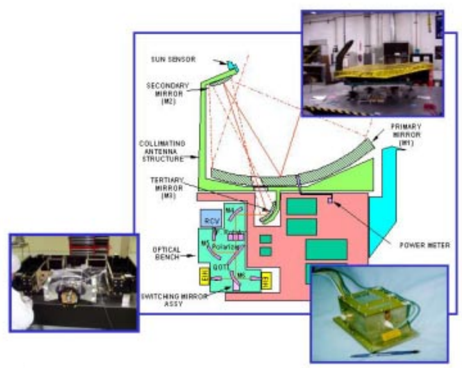

Fig. 2: The radar is composed of the following subsystems: the radio frequency electronics subsystem (RFES), the high power amplifier (HPA), the antenna subsystem and the digital subsystem. Shown is a schematic of the antenna and HPA subsystems. The inset figures are actual photographs of flight hardware. The antenna subsystem consists of the antenna (inset) and quasi-optical transmission line built on an optical bench (inset). A key component of the HPA is the EIK (inset) which is required to amplify the transmitted pulse to 1.7kW. The approximate 2kW output of the flight-model EIK exceeds this requirement.

B. Formation Flying

CloudSat is the burdened spacecraft in the A-Train maintaining a formation with both Aqua and CALIPSO to overlay radar footprints with the lidar footprints of CALIPSO at least 50% of the time as well as to make the radar footprints fall in the central portion of the Aqua MODIS swath. Because the imaging swath of MODIS is so much broader than the individual footprint of the CALIPSO lidar, CloudSat will control its formation in relation to CALIPSO more precisely than with Aqua.

The general formation flying concept is described in Reference [1]. CloudSat is to trail Aqua by less than 120 seconds (an average of 60 sec) and will maneuver to just 15-seconds ahead of CALIPSO. CloudSat will then maintain a tight formation with CALIPSO by controlling its cross track motion to within a +/-1 km of the CALIPSO ground track. This is achieved by placing CloudSat in a small circulation orbit relative to CALIPSO contained within CALIPSO's formation control box. This circulation orbit would swing roughly 2.5 seconds forward and backward of a mean position always 15-seconds in front of CALIPSO. Maneuvers to maintain this circulation orbit will be carried out approximately weekly.

V SUMMARY

Details of the CloudSat products and validation plans can be found in Reference [3]. CloudSat employs a measurement and algorithm approach that specifically combines radar information with radiance data obtained from other sensors of the constellation. CloudSat's main product however is the vertical structure of clouds and precipitation obtained directly from the first space-borne flight of a 94 GHz cloud profiling radar. Cloudsat also plans to archive data and products derived from these A-Train sensors in order to facilitate future research on clouds and precipitation with these integrated data sets. Validation requires careful coordination with other research programs and planned field activities under these programs for the period CloudSat is in orbit. There are a number of challenges and thus opportunities that confront the research community seeking to use CloudSat data. The evaluation of the sensitivity of the CloudSat radar and how cloud detection may be augmented by the other sensors of the A-Train is crucial. Differentiating precipitation from cloud condensate and mixed phase conditions also represents a challenge in interpretation of the data.

The Cloudsat mission will stimulate important new research on clouds and precipitation, and together with the A-Train, provide a unique opportunity to advance our understanding of the aerosol effects on clouds and precipitation. CloudSat also provides an important demonstration of the 94 GHz radar technology in a space-borne application.

REFERENCES

[1] Boain, R. J., 2003: The CloudSat Mission: A Virtual Platform. Proceedings of the *13th Annual AAS/AIAA Space Flight Mechanics Meeting*, Ponce, Puerto Rico, 9-13 February 2003.

[2] Deschamps, P. Y.,F. M. Breon, M. Leroy, A. Podaire, A. Bricaud, J. C. Buriez, and G. Seze, 1994: The POLDER Mission: Instrument Characteristics and Scientific Objectives. *IEEE Trans. Geosci. Remote Sensing*, **32**, 598-615.

[3] Stephens, G. L., D. G. Vane, R. J. Boain, G. G. Mace, K. Sassen, Z. Wang, A. J. Illingworth, E. J. O'Connor, W. B. Rossow, S. L. Durden, S. D. Miller, R. T. Austin, A. Benedetti, C. Mitrescu, and the CloudSat Science Team, 2002: The CloudSat Mission and the A-Train. *Bull. Am. Met. Soc.*, **83**, 1771-1790.

[4] Stokes, G. M., and S. E. Schwartz, 1994: The Atmospheric Radiation Measurement (ARM) Program: Programmatic Background and Design of the Cloud and Radiation Test Bed. *Bull. Amer. Meteor. Soc.,* **75**, 1201-1221.