A Cloud and Precipitation Radar System Concept for the ACE Mission

S. L. Durden, S. Tanelli, L. Epp, V. Jamnejad, R. Perez, A. Prata[1], L. Samoska,
E. Long, H. Fang, D. Esteban-Fernandez, C. Lee

Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109

Abstract —**One of the instruments recommended for deployment on the Aerosol/Cloud/Ecosystems (ACE) mission is a new advanced cloud profiling radar. In this paper, we describe such a radar design, called ACERAD, which has 35- and 94-GHz channels, each having Doppler and dual-polarization capabilities. ACERAD will scan at Ka-band and will be nadir-looking at W-band. To get a swath of 25-30 km, considered the minimum useful for Ka-band, ACERAD needs to scan at least 2 degrees off nadir; this is at least 20 beamwidths, which is quite large for a typical parabolic reflector. This problem is being solved with a Dragonian design; a scaled prototype of the antenna is being fabricated and will be tested on an antenna range. ACERAD also uses a quasi-optical transmission line at W-band to connect the transmitter to the antenna and antenna to the receiver. A design for this has been completed and is being laboratory tested. This paper describes the current ACERAD design and status.**

I. INTRODUCTION

The CloudSat Mission [1] is a satellite mission jointly developed by the National Aeronautics and Space Administration (NASA), the Jet Propulsion Laboratory (JPL), the Canadian Space Agency, Colorado State University, and the US Air Force to acquire a global data set of vertical cloud structure and its variability. The Cloud Sat mission successfully demonstrated [2] a) the reliability of the technology necessary to operate a high sensitivity W-band radar in space, b) the radar performance in providing cloud reflectivity measurements at the sensitivity (-30 dBZ) and spatial resolution (500m vertical and 1.4 x 1.7 km horizontal) required by CloudSat's Science Team, and c) the capability of providing collocated measurements of cloud and aerosol backscattering together with the CALIOP lidar on board the twin mission CALIPSO which flies in close formation with Cloud Sat within the A-Train [1]. Such a data set is providing crucial input to the studies of cloud physics, radiation budget, water distribution in the atmosphere, and to numerical weather prediction models.

A second mission, EarthCARE, continuing the heritage of active instruments for cloud and aerosol profiling, is scheduled for launch in early 2013 by the European Space Agency (ESA) and the Japanese Aerospace Exploration Agency (JAXA). The radar onboard EarthCARE is also a W-band radar (EC-CPR) [3] which shares some technological choices with CloudSat, while introducing some new features; the most notable being Doppler capability, improved sensitivity (mainly as result of a lower orbit and larger antenna than CloudSat), and improved horizontal resolution.

In 2007, the Aerosol/Cloud/Ecosystem (ACE) mission was recommended for a NASA launch in the next decade by the NRC "Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond", hereinafter, "Decadal Survey" [4]. One of the primary goals of ACE is to reduce the uncertainty in the impact of clouds and aerosols on climate modeling. This objective requires that cloud-aerosol interaction be better constrained by simultaneous measurement of clouds and aerosols by radar, lidar, polarimeter, and multi-wavelength imager/spectrometer. The Decadal Survey specifically calls for a cloud radar with 94- and possibly 35-GHz channels for cloud droplet size, glaciation height, and cloud height. Doppler capability and cross-track scanning are also indicated in the same document as highly desirable to achieve the scientific goals. In general, the Decadal Survey requires that "ACE is to provide significantly more data of a much higher quality than its predecessors"; its predecessors are the A-Train and EarthCARE. The absolute necessity of a radar working in synergy with lidar and passive sensors is demonstrated by the role that CS-CPR data is already playing [5-6], and is reflected in the choices made by ESA and JAXA for EarthCARE. At the same time, the experience with cross-track scanning precipitation radars (e.g., the spaceborne Ku-band PR on NASA/JAXA TRMM mission in orbit since 1997 [7], the Ku-/Ka-band DPR under development for the NASA/JAXA GPM mission [8], or NASA/JPL's airborne Doppler polarimetric Ku-/Ka-band APR-2 on board NASA DC-8 [9]) highlights the benefits of a cross-track scanning instrument, especially in terms of improved characterization of atmospheric events and increased global statistics.

II. ACERAD REQUIREMENTS

Use of W-band (94 GHz) radar for cloud profiling has been proven to be an optimal choice in terms of maximum sensitivity and system compactness for ground-based, airborne and spaceborne radar systems. Key W-band subsystems successfully demonstrated in space by CloudSat [2] and planned for use in EarthCare are high-gain amplifiers (Extended Interaction Klystrons, or EIKs, produced by CPI Canada and generate a 1.8 kW output RF signal); quasi-optical transmission lines (to avoid the about 3dB/m waveguide losses

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[*] also affiliated with the University of Southern California

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at W-band, and the use of ferrite switches); and low noise amplifiers. However, W-band is affected by substantial atmospheric attenuation, and CloudSat data include evident multiple-scattering contributions in convective cores [5]. Such effects limit the usefulness of W-band radar to light precipitation and only the upper portions of convective cores. The Decadal Survey confirms W-band as the primary choice for ACERAD. Use of a second frequency is also recommended, namely, Ka-band (35 GHz). Attenuation and multiple scattering substantially less affect Ka-band than W-band. ACERAD's Ka-band channel should allow measurement into moderate precipitation and profiling over a wider range of convective cells. Ka-band will also be used on the dual-frequency radar on the Global Precipitation Measurement (GPM) mission for moderate rain, in combination with the lower frequency channel of 13.4 GHz [6]. Dual-frequency algorithms could also be applied to the ACERAD Ka-/W-band pair in similar fashion to obtain more accurate retrievals of microphysical parameters such as mean particle size [10], [11]. Such dual-frequency retrievals would be possible over a fairly broad range of clouds and precipitation. It would be limited at the low end by clouds too thin to be detected by Ka-band and at the high end by precipitation that is strong enough to completely attenuate the W-band signal.

Two requirements competing against the improved sensitivity are evaluated in the definition of requirements of ACERAD: improved range resolution and cross-track scanning capability. The baseline requirement for range resolution defined for ACERAD at this stage is 250 m, sufficient to reduce the ground clutter contamination problem to below the height of cloud-base of low level clouds (although not sufficient for fog formations) and to resolve some of the most important features of cloud systems. Although finer resolution is possible, the increased bandwidth would make it more difficult to achieve the needed sensitivity. Both CloudSat and EarthCare radars are nadir looking instruments. This choice allows achievement of the required sensitivity by allowing relatively long integration times (and therefore large number of integrated pulses to reduce signal variability). Lack of scanning in the cross-track, however, represents a weakness for cloud monitoring systems. As a compromise, ACERAD will scan at Ka-band and will be nadir-looking at W-band.

The inclusion of Doppler on ACERAD allows measurement of particle motions in clouds, providing better classification of cloud type, direct measure of vertical mass transport and of convective intensity, and it allows estimation of particle size, of air motion, and of latent heat release with higher accuracy than non-Doppler estimates. Fig. 1 shows an example of Doppler and latent heat retrieval from a simulation of ACERAD measurement of a convective system.

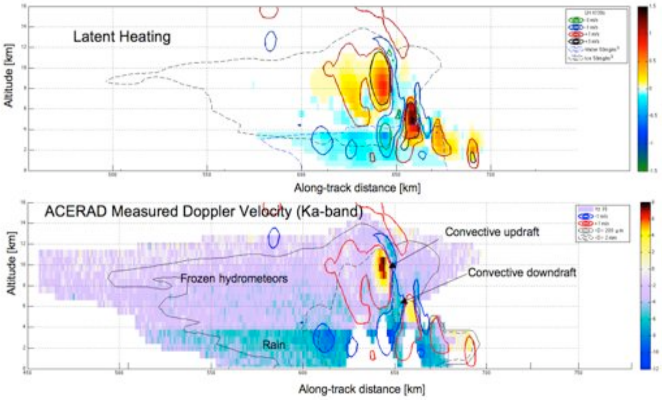

Figure 1. a) Vertical structure of Latent heating (LH) diagnosed by a cloud resolving model, b) simulated ACERAD mean Doppler velocity at Ka-band (V_{Ka}). Classification of precipitating regimes (i.e., convective vs stratiform), and hydrometeor phase states is immediate with V_{Ka}. LH structure can be estimated directly rather than by inference from databases.

The requirements on Doppler accuracy for ACERAD are significantly tighter than the ones currently applied for EarthCare. There are two straightforward ways to improve Doppler quality: increase the antenna size or increase the PRF. The latter has already been pushed to the minimum set by the need to avoid second-trip range ambiguities. The only approaches that would allow use of higher PRF are those based on polarization diversity [12] or frequency diversity. Diversity techniques are used in radar to mitigate the constraint imposed by the second-trip ambiguity [10], but they increase system complexity and cost. The ACERAD concept has an along-track antenna dimension of 5 m, sufficient to reduce the Doppler bandwidth due to platform motion (i.e., to maintain coherence between pulses) and to provide high-quality Doppler information at convection-scale in realistic scenarios as demonstrated in [13]. Of more concern is the relatively small maximum unambiguous velocity at W-band. Our solution is to require ACERAD to be fully polarimetric to allow an effectively higher PRF, doubling the maximum unambiguous velocity. Furthermore, this has the added scientific benefit of measurement of depolarization in ice and melting hydrometeors, potentially enhancing classification of particle shapes.

III. ACERAD SYSTEM CONCEPT

ACERAD will take advantage of technology tested in CloudSat wherever possible. While solid-state power amplifiers could potentially be used at Ka-band, their power level at W-band band is still limited. To allow ACERAD to use a common antenna for both frequencies, a reflector antenna fed by high-power vacuum electron devices (EIKs) at both frequencies is used. Scanning at Ka-band presents a serious challenge for the antenna. For an antenna that is larger than the CloudSat antenna, the beamwidth in the scan plane will be less than 0.1 degrees. To get a swath of 25-30 km, considered the minimum useful, ACERAD needs to scan at least 2 degrees off nadir; this is at least 20 beamwidths, which is quite large for a typical parabolic reflector. The problem is that moving the feed far enough off-focus to create a large scan causes phase distortions across the aperture, in turn causing potentially serious degradation of the antenna pattern.

Several antenna concepts have been examined for ACERAD. One promising design is the Dragonian; the initial concept for this type of reflector antenna was reported in [14].

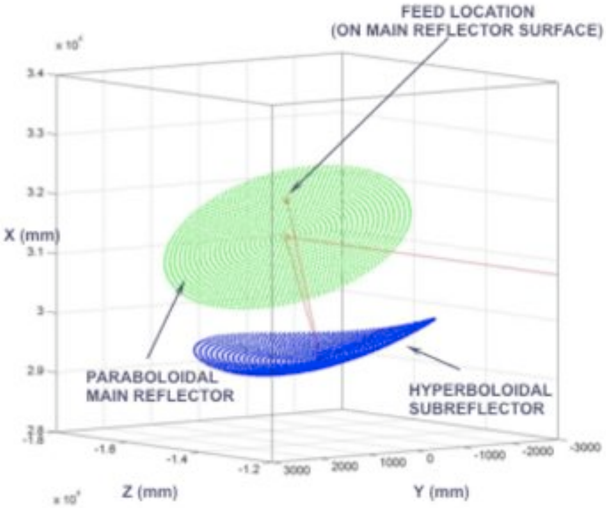

Figure 2. ACERAD Dragonian reflector antenna. This design allows scanning to 2 degrees with small pattern and gain degradation (0.6 dB), based on calculations.

As discussed there, the antenna is based on classical Cassegrain and Gregorian designs but the main reflector and subreflector have been deformed to optimize the field of view. A systematic procedure for designing Dragonian reflectors with circular aperture is reported in [15]. We are modifying this procedure to develop an elongated (in the flight direction) design for ACERAD, approximately 5 m x 2.5 m. Fig. 2 shows the ACERAD Dragonian design.

To test this antenna design, a scaled prototype is being fabricated. To provide more realistic testing, a maximum test frequency near 280 GHz will be used to simulate a larger antenna at 94 GHz. Such a high frequency places significant demands on the surface shape accuracy. A workable design that should meet surface distortion requirements under test conditions and is reasonably lightweight has been developed. Once fabricated, it will be range tested to verify its scan capability. Several sources at 280 GHz have been fabricated using GaAs Schottky diodes; these are based on tripling a W-band input signal with or without power combining. The use of a diamond film for heating sinking seems to allow the highest power levels [16].

Like CloudSat, ACERAD also uses a quasi-optical transmission line at W-band to connect the transmitter to the antenna and antenna to the receiver. This is implemented with mirrors and free-space propagation, rather than waveguide, significantly reducing losses. Conventional waveguide is used at Ka-band, since losses are lower. The challenge in using quasi-optics for ACERAD is that it must accommodate dual-polarized operation. We have developed a way to accomplish this that extends the CloudSat design. The new design has been prototyped using various components (mirrors, wire grids, and Faraday rotator) on a standard laboratory optical bench, as shown in Fig. 3. Measurements indicate a similar transmit/receive isolation to CloudSat, while the isolation between different polarization ports appears better by an additional 10 or more dB.

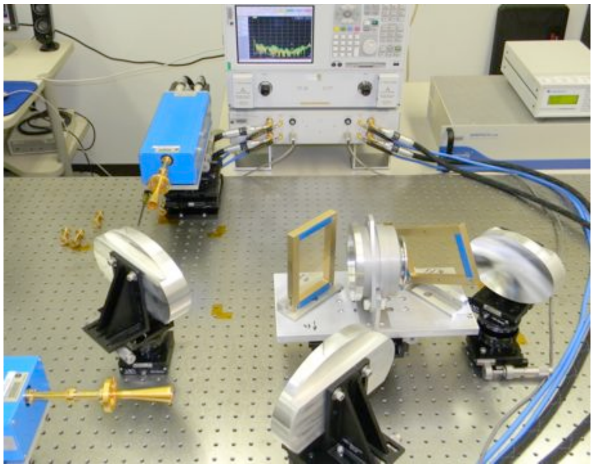

Figure 3. Laboratory testing of W-band quasi-optical front end. Isolation between transmit and receive ports is being measured.

Because waveguide is used at Ka-band, the Ka-band and W-band signals must be combined into a single beam to illuminate the antenna. This is done by a frequency selective (dichroic) surface, shown in Fig. 4. The dichroic has been tested and shown to provide low-loss at W-band while acting as a reflector at Ka-band. The dichroic has also been analyzed for multipactor problems. The calculations show no multipactor problems with well over 10 dB margin.

High-level block diagrams for the radar RF and digital processing electronics have also been created. The Ka-band and W-band channels use similar intermediate frequencies in L-band; they are separated from each other by 5 MHz, potentially allowing sampling with a single analog-to-digital converter. The L-band signals are up and down converted in a single mixing step to Ka- and W-bands. A digital processor that takes a single input (all four channels together) and digitizes at 40 Msps has been designed and simulated with Simulink. Fig. 5 shows channels 1-4 before and after filtering, while Fig. 6 shows one of the channels after downconversion and decimation in both frequency and time domain. The

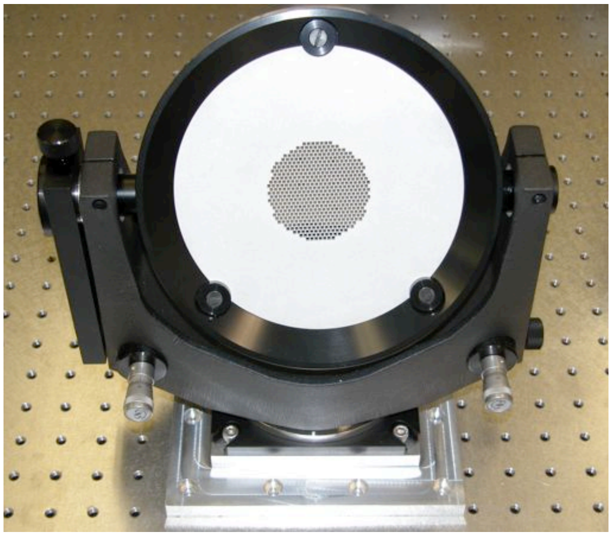

Figure 4. Dichroic portion of the quasi-optics, designed to pass W-band and reflect Ka-band.

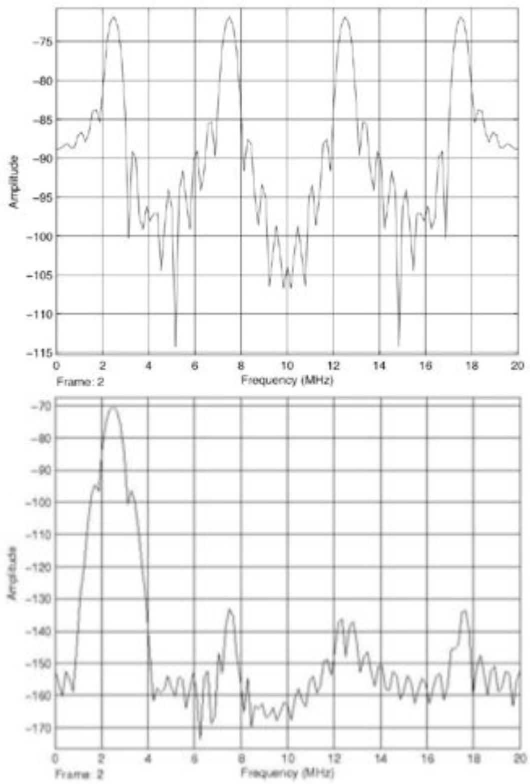

Figure 5. Upper is simulated received signals for all four channels: Ka-band HH and HV and W-band HH and HV. In the lower plot the channel 1 signal is left after filtering the other three channels.

simulation demonstrates the basic capability of the processor to separate and process the four channels. Following the processing just described, the lag-0 and lag-1 correlations are accumulated for reflectivity and Doppler estimation [17], [18]. The design would likely be implemented in a single FPGA.

IV. SUMMARY

We presented the design and status of a next-generation spaceborne cloud profiling radar for the ACE mission. A high-level design of much of the instrument has been completed, and the two newest areas, the antenna and dual-polarized quasi-optics are being demonstrated in the near future.

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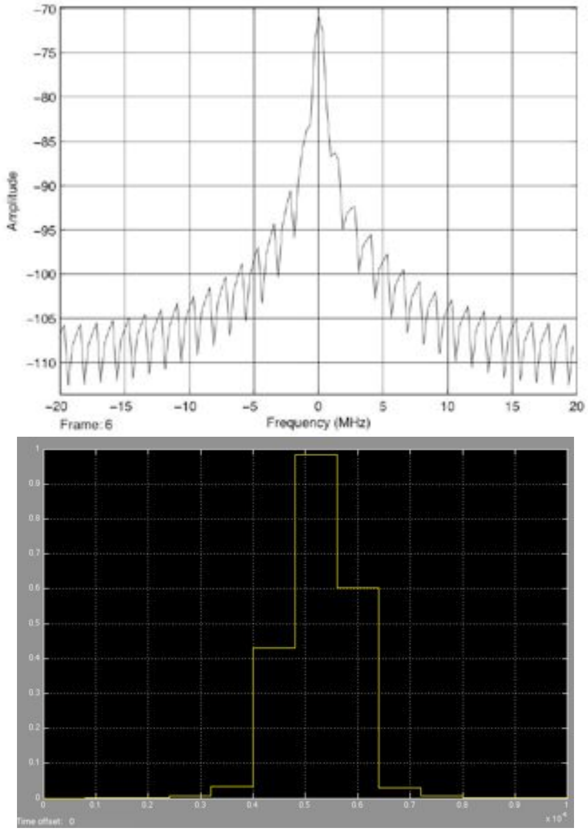

Figure 6. Upper is simulated received signal for channel 4 after removing the other three channels, downconverting, and decimating. The upper is in the frequency domain; the lower is time domain, essentially a sampled version of the nearly Gaussian shape expected from matched filtering.

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