# Next-generation spaceborne Cloud Profiling Radars

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***Abstract* —One of the instruments recommended for deployment on the Aerosol/Cloud/Echosystems (ACE) mission is a new advanced Cloud Profiling Radar (ACE-CPR). The atmospheric sciences community has initiated the effort to define the scientific requirements for this instrument. Initial studies focusing on system configuration, performance and feasibility start from the successful experience of the Cloud Profiling Radar on CloudSat Mission (CS-CPR), the first 94-GHz nadir-looking spaceborne radarwhich has been acquiring global time series of vertical cloud structure since June 2, 2006. In this paper we address the significance of CloudSat's accomplishments in regards to the design and development of radars for future cloud profiling missions such as EarthCARE and ACE.**

***Keywords - cloud radar ; CloudSat; EarthCARE ; ACE***

## 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 reduced horizontal resolution. The main parameters of CS-CPR and EC-CPR are shown in Table 1.

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. While each one of the stated features is within reach of our current capabilities, the integration of all of them into one radar system presents interesting challenges and trade-offs that are best addressed at these early stages by refining the scientific requirements for the ACE mission.

ACE Science Working Group, and mission study teams at GSFC and JPL studied mission design and cost estimation. Efforts are ongoing to a) consolidate the scientific requirements, b) promote the level of technological readiness required to achieve the baseline scientific requirements already set by the Decadal Survey. In this presentation, we report on the progress made towards the ACE Cloud Profiling Radar (ACE-CPR).

## II. RADAR SCIENTIFIC REQUIREMENTS & SYSTEM DESIGN

### A. *Operating frequency*

Use of W-band (94.05 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

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and spaceborne radar systems. Key W-band subsystems successfully demonstrated in space by CS-CPR and planned for use in EC-CPR are high-gain amplifiers (Extended Interaction Klystrons produced by CPI Canada generate a 1.8 kW output RF signal); quasi-optical transmission lines (to avoid the about 3dB/m waveguide losses at W-band, and the use of ferrite switches); and low noise amplifiers. However, W-band is affected by substantial attenuation, and CS-CPR data include evident multiple-scattering contributions in convective cores. 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 ACE-CPR. Use of a second frequency is also recommended: Ka-band (35 GHz). The Ka-band channel is substantially less affected by attenuation, turbulence and multiple scattering than at W-band. ACE-CPR'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. ACE-CPR will apply dual-frequency algorithms to the Ka-/W-band pair in similar fashion to obtain more accurate retrievals of microphysical parameters such as mean particle size. In Figure 1 the region of applicability of W/Ka-band dual-frequency radar algorithms is located between the black and the yellow contour lines.

Besides the two primary bands discussed above, the potential use of higher (e.g, EHF band around 240 GHz) or lower (e.g., Ku-band at 13.4 GHz) frequencies is being investigated. For example, the scattering at EHF is non-Rayleigh for cloud droplets larger than 200 μm, allowing retrieval of cloud droplet size [10-12], more accurate retrieval of cloud water content, and better insight in the aerosol-cloud formation and interaction processes. At the same time, lower frequencies would allow coincident observation all the way to the surface in stronger precipitation and convective cores (similar to TRMM/PR).

Table 1: CPR instrument and performance parameters for CloudSat (CS) and EarthCARE (EC). CS parameters are approximate in-orbit actuals, EC are approximate design requirements.

| | CS | EC |
|---|---|---|
| Frequency (GHz) | 94.05 | 94.05 |
| Altitude (km) | 705 | 400 |
| Range res. (m) | 500 | 500 |
| Cross-track res. (m) | 1.4 | 0.8 |
| Along-track res. (m) | 1.7 | 0.9 |
| Pulse width (μs) | 3.3 | 3.3 |
| Peak power (nom. kW) | 1.8 | 1.8 |
| PRF (kHz) | 3.7-4.3 | 6.1-7.5 |
| Antenna diam. (m) | 1.85 | 2.5 |
| Ant. gain (dBi) | 63.1 | 65.2 |
| Ant. Sidelobes (dB) | -50 @> 7° | |
| Integration Dist. (km) | 1 | 0.5/10 |
| Data window (km) | 30 | 12-20 |
| Scanning | NO | NO |
| Min. det. Refl. (dBZ) | -30 | -35 |
| Doppler Accuracy (m/s) | N/A | 1 @ 10km/ -19dBZ |

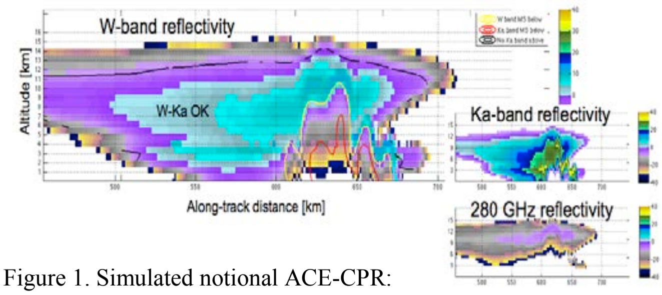

Figure 1. Simulated notional ACE-CPR: Vertical section of reflectivity across a mid-latitude frontal system. Regions of applicability of dual-frequency algorithms are identified by contour lines: above the black one, only the pair W-EHF can measure particle sizes by exploiting the differential Mie scattering; below the yellow one, W-band is affected by multiple scattering.

### B. *Radar sensitivity*

Clouds are weak scatterers of microwave radiation especially in contrast to the reflection of the underlying Earth's surface. The detection sensitivity is primarily determined by the radar received power and the noise level. The radar received power can be written as

$$P_a(r) = \frac{P_t \lambda^2 G^2 \theta^2 \Delta \eta L}{512\pi^2 \ln 2 r^2} \qquad (1)$$

where $P_t$ is the transmitter power, $\lambda$ is the wavelength, $G$ is the antenna gain, $\theta$ is the antenna half-power beamwidth, $\Delta$ is range resolution, $r$ is the range to the atmospheric target, $\eta$ is the cloud reflectivity, and $L$ is the signal loss due to propagation through the atmosphere and to losses internal to the radar. $P_a(r)$ is the received power from the atmosphere versus range. The product $G^2 \lambda^2 \theta^2$ is proportional to the antenna effective area. Thus, the received power is increased by increasing antenna area, range resolution, transmit power, and reflectivity. The antenna size is limited by the physical launch constraints such as volume and mass. Transmitted power is limited by the technology of the transmitter itself and by the power supply capability of the spacecraft. The radar's sensitivity is calculated as the standard deviation of the received signal after the estimated noise floor contribution has been subtracted, and is inversely proportional to the square root of the number of pulses integrated to achieve each radar profile. In the field of spaceborne atmospheric radars, it is expressed in terms of the minimum detectable reflectivity factor at the top of the troposphere, expressed in dBZ.

The overriding requirement on CS-CPR was to achieve a minimum detectable cloud reflectivity (Z) of -28 dBZ. In flight performance has been verified at -30 dBZ during the first two years in orbit. By comparison, the Ku-band TRMM/PR has a sensitivity of around +17 dBZ. More than two years of global data collected by CS-CPR and CALIOP have proven that this combination of instruments is capable of capturing the wide majority of cloud and aerosol formations. However, some notable gaps remain. a) marine stratocumulus, fog, and other low-level warm cloud formations are often below CS-CPR sensitivity or within the range of about 500 m contaminated by ground clutter, but their relatively large optical thickness is sufficient to limit the usefulness of the lidar signal to a simple cloud-top detector; b) high-altitude cirri, and other optically thin cloud formations below CS-CPR sensitivity are detected by the lidar alone, hence limiting the applicability of retrieval algorithms to the lidar-only group, with the resulting increased uncertainty in the microphysical retrievals with respect to the combined radar-lidar retrieval algorithms. Consistent, with these, and other, considerations, EC-CPR has been designed to improve CS-CPR sensitivity by about 7 dB. The same requirement is considered as the minimum baseline for ACE-CPR design.

Two requirements competing against the improved sensitivity, are evaluated in the definition of requirements of ACE-CPR: improved range resolution and cross-track scanning capability.

### C. *Range resolution*

CS-CPR and EC-CPR 3.3-μs monochromatic pulses, and the resulting 500 m range resolution, do not allow to resolve geometrically thin features (e.g., the melting layer of precipitation and marine stratocumulus). On the other hand, range resolutions as small as 30 m have been successfully adopted in airborne atmospheric radars to capture such features. Such choice, however, imposes either a significant deterioration in radar sensitivity if a monochromatic pulse is adopted. The baseline requirement for range resolution defined for ACE-CPR at this stage is 250m: 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. Further studies need to be completed to assess whether finer range resolutions are needed. In this sense, the use of pulse compression (as demonstrated by APR-2) offers one solution to the sensitivity vs. high-resolution trade-off; however, the low sensitivity requirements at altitudes as low as 500m above the surface impose challenging requirements on the range sidelobes.

### D. *Scanning*

Both CS-CPR and EC-CPR are nadir looking instruments. This choice allows achievement of the required sensitivity by minimizing the system losses between the RF electronics and the collimating antenna, maximizing antenna gain and efficiency (CS-CPR collimating antenna has an overall efficiency of 82%), and by allowing relatively long integration times (and therefore large number of integrated pulses to reduce signal variability). Lack of scanning in the cross-track represents a weakness for cloud monitoring systems. First, the limited swath width (1.4 km for CS, 0.8 for EC) does not allow global coverage and limits the statistical relevance of the long-term datasets. Second, lack of the cross-track dimension does not allow reconstruction of the 3-D field of scatterers, and leaves a certain level of ambiguity in the interpretation of the observed fields where significant variability in the horizontal direction is present. Both missions compensated such weakness by integrating the radar/lidar observations with collocated 2-D imagery from passive sensors (on the A-Train for CS, and on the same bus for EC). However, given the impact that CS data are having in the fields of atmospheric modeling and retrievals, it is evident that a radar capable of providing 3-D fields of backscattering estimates is expected to provide more accurate reconstructions of the atmosphere, necessary to advance our atmospheric models and the passive instrument retrieval algorithms themselves. Since inclusion of a scanning capability reduces the radar performance in terms of minimum detectable sensitivity, accurate trade-off studies to estimate the scientific impact of the resulting measurements in various configurations are necessary.

### E. *Doppler measurements*

Doppler 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. Also, changes in aerosol properties due to clouds via vertical transport, scavenging, chemical processes, cloud-enhanced particle formation cannot be observed without Doppler capability. Vertical motion retrieved by Doppler can be used in conjunction with 3-D aerosol measurements to infer the impact of vertical transport. Classification of cloud type (liquid or ice or mixed) is used to better understand scavenging and chemical processes.

The following scientific requirements were originally set for the Doppler radar on EarthCARE: 0.2 m/s accuracy for ice sedimentation processes (10 km integration), and 1m/s accuracy for characterization of convection (1 km integration) and classification of hydrometeors. To achieve such accuracies from radar in low earth orbit is arduous due to the high platform velocity since Doppler broadening is proportional to the platform velocity ($v_s$) and inversely proportional to Pulse Repetition Frequency (PRF) and antenna diameter (D). EarthCARE's 2.5 m antenna and the adopted PRF of 6.1-7.2

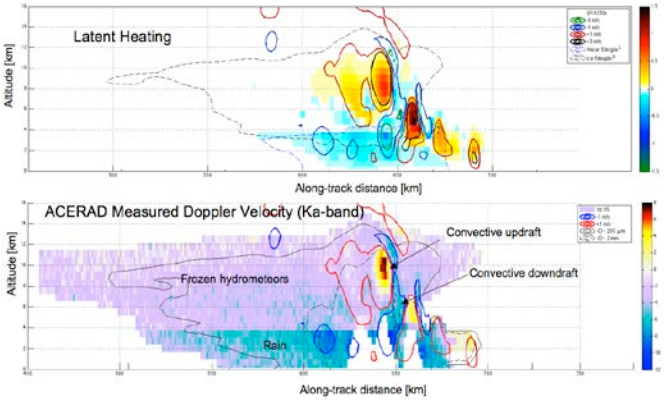

Figure 2. a) Vertical structure of Latent heating (LH) diagnosed by a cloud resolving model, b) simulated ACERAD mean Doppler velocity at Ka-band ($V_{Ka}$). Classification of precipitating regimes (i.e., convective vs stratiform), and hydrometeor phase states is immediate with $V_{Ka}$. LH structure can be estimated directly rather than by inference from databases.

kHz are expected to guarantee only the 1 m/s accuracy with a 10km integration. The EarthCARE mission will surely provide valuable information on cloud microphysics and dynamics, on an unprecedented global scale; however, gaps in velocity information are to be expected, especially in regions of strong convection, hurricanes, and regions of high horizontal variability of the cloud and precipitation fields.

There are two 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 [13-15] or frequency diversity. Diversity techniques are used in radar to mitigate the constraint imposed by the second-trip ambiguity, but they increase system complexity and cost. One of the radar concepts proposed for ACE, with Doppler capability, 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 [15-18]. Simulations of this notional configuration are shown in Figures 1 and 2.

Multi-antenna instrument configurations are also capable of providing high-accuracy Doppler measurements [19] to the expense of increased system complexity and reduced antenna efficiency.

### *F. Polarimetric measurements*

A radar design allowing polarization measurements would enable products such as the co-polar correlation coefficient ($\rho_{hv}$), necessary to estimate particle shape, and very valuable to identify mixed phase hydrometeors and multiple scattering. The use of dual-polarization will provide new information on particle shape and cloud type discrimination. By the same token, it also enables the use of polarization diversity cited in the previous section. It could result in a relaxation of antenna size requirements, and, in turn, cost savings, or improved Doppler performance, depending on cost-benefit choices that are not possible without it.

## II. SUMMARY

The Cloud Profiling Radar for the CloudSat mission is a 94-GHz, nadir-pointing, high-power pulse radar. It is the first-ever millimeter-wave and the most sensitive radar even launched into space. Its –30 dBZ detection sensitivity is enabling the first global view of the vertical structure of atmospheric clouds at 500-m resolution. The data acquired by the CloudSat radar are stimulating 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. The CloudSat mission also provides an important demonstration of 94 GHz radar technology in a spaceborne application. NICT/JAXA proceed in their implementation of the Cloud Profiling Radar for the ESA/JAXA EarthCARE mission, which will be the first-ever Doppler cloud radar in space, and will provide measurements at improved resolution and better sensitivity than CloudSat. Here we presented the result of studies initiated by NASA to define the design of the next-generation of spaceborne cloud profiling radar for the ACE mission.

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