The role of cloud and precipitation radars in convoys and constellations

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ABSTRACT

We provide an overview of which benefits a radar, and only a radar, can provide to any constellation of satellites monitoring Earth's atmosphere; which aspects instead are most useful to complement a radar instrument to provide accurate and complete description of the state of the troposphere; and finally which goals can be given a lower priority assuming that other types of sensors will be flying in formation with a radar.

1. INTRODUCTION

The CloudSat Cloud Profiling Radar (CS-CPR, [1]) and Tropical Rainfall Measuring Mission (TRMM) Precipitation Radar (PR, [2]) have demonstrated the capability of these instruments to characterize the vertical profiles of clouds and precipitation from space. The immediate impact they had on cloud and precipitation science has been obvious. However, besides the obvious advantages brought by these range-resolving instruments, they have delivered even more significant findings when deployed in coordination with other sensors (such as microwave radiometers on TRMM and AQUA, the lidar on CALIPSO, infrared imagers, etc.). In fact, one of the fundamental paradigms of the soon to be launched Global Precipitation Measurement (GPM) mission is that the Dual frequency Precipitation Radar (DPR, [3]) will 'train' the passive sensors where they provide collocated measurements, so that they can in turn provide higher quality retrievals on the portions of their many and wide swaths where the DPR is not available at the same time. Also, the ESA/JAXA EarthCARE mission will follow and augment the A-Train synergies between radar, lidar, and other sensors by deploying the first spaceborne Doppler Cloud Profiling Radar (EC-CPR, [4]) together with an HyperSpectral Resolution Lidar (Atmospheric Lidar, ATLID), a multi-angle Broad Band Radiometer (BBR) and the Multi Spectral Imager (MSI). While the mission is not going to launch before 2016, significant efforts to define and test multi-instrument algorithms have already achieved a significant level of maturity.

The Aerosol/Cloud/Ecosystems (ACE, [5,6]) Mission was recommended for a NASA launch in the next decade. 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 [6] specifically calls for *"a cloud radar with 94 and possibly 35 GHz channels for cloud droplet size, glaciation height, and cloud height measurements"*. Doppler capability and cross-track scanning are also indicated in the same document as highly desirable to achieve the scientific goals. While the full complement of instruments considered for the ACE mission is not finalized yet, the baseline configuration includes, besides the radar, a lidar, a polarimeter and an ocean color instrument.

Other notable initiatives including cloud and precipitation radars in the last decade include, among others, missions focused on the monitoring of the cloud precipitation processes (both over the entire globe, or focused to specific latitude ranges), on the observation of the dynamics of storms at cloud-scale resolution, on 3-D direct observation of wind fields inside storms (either from geostationary orbit to provide sub-hourly observations, or from LEO to provide high resolution observations) (see e.g., [7,8]).

The definition of specific radar configuration has become more and more tied not only to the specific scientific goals of a mission and to the desired set of instruments planned for a particular platform, but also to the overall availability of certain types of measurements from other platforms either in tight or loose formation, or even in no particular coordinated flying. In general, one can expect that future missions focusing on the atmosphere are likely to include of large number of observables that have already been pioneered in the last two decades, with the addition of focused improvements or niche measurements targeting specific observational gaps made necessary by the progressive advancement of understanding and experience both in earth sciences, remote sensing science, and modeling capabilities.

Significant radar technological advancements have emerged in the past few years, and many are being currently integrated in the definition and design of new instruments. They break some of the barriers that had imposed significant limitations in the design of the existing radars. In fact, cloud and precipitation radars that operate at multiple frequencies (e.g., Ku-, Ka- and W-band simultaneously), and provide scanning, polarimetric and Doppler capabilities at all frequencies are now being defined and developed. These new instrument concepts hinge upon the feedback from the TRMM and CloudSat science community, and the new requirements target specifically the observational gaps that have been identified as the most important for the advancement of weather and climate models: measurements of precipitation closer to the surface, Doppler measurements, improved resolution and sensitivity, and three dimensional information. However, the capability of achieving outstanding performances and capabilities does not cancel the resource requirements that often drive the cost of a mission (e.g., power and size). The new generation of radars, conceived to operate in well-defined synergies with passive and other active instruments, must be designed leveraging on the detailed lessons learned from the A-Train experience and others. The use of resources must be optimized to deliver first and foremost the measurements most needed to close the gaps that cannot be closed by other types of sensors.

2. CLOUD AND PRECIPITATION RADAR TECHNOLOGY ADVANCEMENTS

Radar technology in general has advanced significantly in the last decade mainly in parallel to advances in digital technology and signal processing. Use of more advanced signal generation schemes and real-time processing, digitally reconfigurable subsystems and digital receivers have significantly expanded the range of application and enable significant steps in mass and volume reduction.

Cloud and precipitation radars in particular, have traditionally occupied the upper part of the spectrum of radar frequencies (from Ku- to W-band), mainly driven by the needs to detect targets as faint as clouds and raindrops from orbit and to resolve spatially with real aperture techniques. As such they have been affected by higher system losses, lower power conversion efficiencies and reduced availability (and higher costs) compared to the more popular and widespread lower frequency bands adopted in telecommunications and large networks of ground based radars. In the last decade, however, telecommunications and military applications have steadily expanded upwards in the RF spectrum. This has resulted in significant progress in the area of power amplification and deployable antennas at sub-cm wavelengths.

These combined advancements allow us today to realistically consider implementing spaceborne radar configurations that would have not been available one decade ago. The situation has changed in such a way that for several instrument designs pure technological feasibility has been replaced (or it is expected to be within a couple of years) by engineering challenges as the main limiting factor to instrument performance. For example since solid state power amplifiers can operate at very large duty cycles, and digital receivers can effectively process multi-frequency or wide band signals, modern radars can rely on frequency diversity approaches to significantly mitigate the performance limitations dictated by dwell time requirements. Such approach, however, can be applied only as long as the bus power availability is sufficient, which transfers the burden on the mission configuration.

It becomes therefore essential to be able to prioritize the allocation of resources based on the specific observational needs of the entire ensemble of instruments available.

3. EXAMPLES OF OBSERVATIONAL GAPS AND ROLE OF RADAR

3.1. Global Climatology of Convective Cloud and Precipitation Processes

Convection is the main mechanism by which energy is redistributed vertically in the troposphere. As source of a multitude of different cloud types (from fair weather cumuli to deep thunderstorms and thick cirrus) it is also deeply intertwined with Earth's radiation budget. We currently lack of a global database of distribution and strength of vertical velocity in convective processes. Dedicated field campaigns and local high quality observations have enabled the definition of the current algorithms aiming at resolving or parameterizing convective processes, however we do not have a comprehensive and uniform dataset to document such processes across all regions of Earth, seasons, etc.

One may consider a mission that aims at acquiring such dataset, and a collocated dataset of the other relevant geophysical quantities (e.g., aerosol distributions and speciation, water vapor content and fluxes, ect.) to validate cumulus parameterizations adopted in climate and chemical transport models and assumptions adopted in cloud resolving models. Such mission would need a radar with Doppler capability over a dynamic range wide enough to capture from non-precipitating clouds to intense precipitation in storms. In recent years it has become evident that a radar operating simultaneously at the GPM and CloudSat bands may represent the optimal choice to achieve such range.

Furthermore, given the intrinsic 3D nature of convective processes, and accounting for horizontal advection, such radar would need to provide not just nadir observations as in CloudSat, but 3D volumes as in GPM. The extent of the swath of each channel may be one of the main trade spaces in the instrument design, but more than working group has converged towards a requirement to cover at least 25 to 50 km to guarantee two essential features: coverage of the meso-gamma scale at which convection manifests itself, and coverage of one entire footprint of a low frequency radiometer to maximize the performance of combined radar-radiometer algorithms.

If deployed in convoy, such radar would provide the 'training' baseline for passive sensors better suited for the quantification of column integral quantities. In a scenario where GEO platforms or multi-angle imagers are involved, one could obtain both the cloud-scale and synoptic scale wind distribution through the complementarity of Doppler radar and atmospheric motion vector analyses.

3.2. Precipitation in Polar Regions

We currently have very little skill in detecting near-surface snowfall over the most climatologically sensitive portions of the cryosphere (i.e., polar ice sheets and mountain glaciers) [9]. As demonstrated by comparative analyses of GRACE and CloudSat measurements, variations in polar precipitation correlate significantly with ice mass changes. However the single frequency W-band measurements of CloudSat and EarthCARE are limited mainly by two factors: a) their range resolution of 500 m results in a contamination by surface clutter extending more than 500 m above the surface hence preventing detection of shallow snowfall and surface precipitation; and b) the saturation of the backscattering signal in Mie regime which affects significantly the accuracy of quantitative snowfall estimates [10]. In turn, passive sensor detection skills are challenged by the relatively shallow and poorly contrasted (with respect to the snow covered background) nature of all but the strongest snow storms. Lidars can provide good detection of cloud tops and occasionally also be able to penetrate light snowfall, but for the most part they would be unable to provide quantitative estimation with any significant level of accuracy.

Accurate quantitative measurements of snowfall are essential to interpret correctly the temporal evolution of measurements of ice thickness and the overall polar response to changing climate.

A radar operating (also) at a band lower than W-, and with range resolution such that detection is granted down to a couple hundred m above the surface would enable such measurements. The quality of quantitative estimates by such instruments is expected to be improved by collocated passive measurement in the sub-mm range. While horizontal resolutions in the order of a few km would be adequate for most events over the large expanses in the interior of Antarctica and Greenland, horizontal resolutions of 1 km or less would greatly improve detection in mountain glaciers by the resulting reduction in clutter contamination from the nearby orographic features.

3.3. Marine Stratocumulus

Vertical profiling of marine stratocumulus is another climatologically significant observational gap. We currently have no capability to profile marine stratocumulus from cloud top to base. The processes governing the formation, evolution and dissipation of marine stratocumulus are poorly represented in current models, and yet they are a radiatively important phenomenon in climate models.

Among all cloud types these clouds represent perhaps one of the most challenging ones from a profiling point of view. Because of their liquid water content they typically attenuate lidar signals within the first 100 m, in general measurements in the visible range provide extremely useful estimates of particle concentration and size but only relative to the top layers of the cloud. They are a challenge for radars because of their shallow nature they require very high resolution in range, and their close proximity to the ocean surface: these conditions require either very short pulses at very high peak power, or extremely high quality pulse compression approaches. The same factors also limit the usefulness of multi-band passive observations which cannot resolve well such shallow features.

A multi instrument approach is therefore necessary to capture the nature of these clouds, together with the aerosol and thermo-dynamical environment conditions that surround them: in principle, a high performance, multi-band and multi-frequency radar would provide profiles of the condensate as well as the water vapor content above and below. In order to relax some of the challenging requirements, such radar should be designed in the context of the partner instruments to 'delegate' some of the observations to them, where possible.

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