Radar concepts for the next generation of spaceborne observations of cloud and precipitation processes

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Abstract—**Two decades of spaceborne cloud and precipitation radar data provided by the TRMM's Precipitation Radar (PR) [1], CloudSat's Cloud Profiling Radar (CPR) [2,3] and GPM's Dual-frequency Precipitation Radar (DPR) [4] have enabled unprecedented advancements in the global mapping of occurrence and vertical structure of most types of meteorological events. After the immense success of these radars, two new spaceborne atmospheric radars, the EarthCARE Cloud Profiling Radar (CPR) [5], and the Radar in a CubeSat (RainCube) [6] have been developed and will be launched in the upcoming years, and several new radar concepts have been developed and are being considered for a variety of mission concepts. For example, spaceborne precipitation and cloud radars operating at multiple frequencies (e.g., Ku-, Ka- and W-band simultaneously) with a single antenna, and that provide scanning, polarimetric and Doppler capabilities at all frequencies; extremely compact radar architectures that enable accommodation of this category of radars in spacecrafts as small as a 6U CubeSats, as well as Doppler-capable millimeter-wave weather radars for Low Earth Orbit (LEO) or Geostationary Earth Orbit (GEO) satellites, are being defined and developed. These new instrument concepts are intended to fill the current observational gaps in the advancement of weather and climate models, and leverage on the TRMM, GPM and CloudSat experiences.**

Keywords—spaceborne, cloud, precipitation, radar

I. INTRODUCTION

The most recent generation of spaceborne cloud and precipitation radar (SCPR) concepts leverages on the rapid advancement of radar and other related technologies in recent years, and promises to deliver measurements that improve the specific aspects of their predecessors identified by the science community as highest priority to further advance our understanding of the global processes that lead to the formation and evolution of atmospheric events.

In the US, the majority of new spaceborne cloud and precipitation radar concepts have been developed primarily focusing on the needs of the Aerosol Clouds and Ecosystem (ACE) mission concept [7], or on the need of frequent (i.e., at the cloud temporal scale of minutes to tens of minutes) observations of the evolution of storms (in particular in the tropics, including but not limited to tropical cyclones), or on the need of improved observations of polar clouds and precipitation.

In this paper, we provide a summary overview of the primary science drivers that have directly or indirectly guided the efforts in technology development and system architecture studies in the last decade, followed by a short description of a selection (not comprehensive) of instrument concepts that have reached several levels of maturity in preparation for the next decade. Essentially each one of these radars is envisioned to operate in coordination with other types of sensors (primarily microwave and mm-wave radiometers and sounders, IR imagers, LIDAR's, as well as other types of radars) as well as with other radars so that the largest feasible number of independent pieces of information regarding the atmospheric phenomena of interest is gathered within the available resources.

II. DESIRED IMPROVEMENTS IN THE SCIENCE PRODUCTS

TRMM, CloudSat and GPM have established themselves as the natural extension of ground based and airborne weather radars and vertical cloud profilers to all locations of the globe where ground based and airborne radar deployment is either impossible or unfeasible for any extended length of time. Furthermore, they have demonstrated themselves to be excellent and stable benchmarks for calibration of the same ground based radars. At the same time, all of their progress in algorithm development and retrievals of cloud microphysical properties has been either informed, or validated by the ground based and airborne assets. Much like the ground based and airborne radar instruments, their spaceborne counterparts have served a vast array of science areas in the atmospheric sciences as they pertain to cloud and precipitation, many of which were not even in the initial primary charter of the mission. For example, most recently, a significant body of work that exploits both CloudSat's W-band and GPM's Ku- and Ka- band data has blossomed to improve our understanding of topics such as cold-phase precipitation occurrence and processes and orographic effects. Field campaigns specifically including analyses to aid the formulation of the radar instrument for the next generation of mission among their objectives have been co-sponsored by GPM, CloudSat and ACE (e.g., LPVEx, IPHEX/RADEX'14, OLYMPEX/RADEX'15 [8]). An excellent depiction of the current array of topics of interest is provided by the ensemble of inputs to the Earth Science Decadal Survey 2017 process [10-12] (by the time of this conference their synthesis by the appointed panel is expected to have been published as part of the comprehensive report). In this paper, we provide a summary of the prevalent science drivers that in the last decade have stimulated specific technological investments by NASA's Earth Science Technology Office (ESTO) and other programs as well as internal investments at Jet Propulsion Laboratory and at Goddard Space Flight Center.

A. *Choice of operating frequencies*

This aspect has been relatively straightforward: given the long data records established at Ku-band by TRMM and GPM, and at W-band by CloudSat (and likely to be soon extended by EarthCARE), these two bands are not likely to be traded off in order to preserve and extend these climatologically important series. Together they cover the vast majority of cloud and precipitation regimes. In several portions of a given profile only one of the two is viable (either because of the limited sensitivity of Ku band, or because of high attenuation and multiple scattering at W-band). In this context, Ka-band has established itself as the natural complement to either of the two, or both (as in triple-frequency measurements), for significant improvements in microphysical retrievals in the ice phase, accurate quantitative precipitation estimation of light to moderate precipitation, and observations of the upper portion of convectively active storms.

It is recognized that X-band would provide additional advantages in terms of full-column precipitation in the most extreme precipitating events, however feasibility considerations (in regards to antenna size mainly) together with record continuity needs have kept Ku-band as the primary choice. Also, there is growing attention in regards to G-band (and in general to various sub-bands from 130 to 240 GHz) which bears the potential not only of extending particles sizing capabilities down to the few 100 microns (for cloud processes and precipitation initiation), but also to obtain differential absorption measurements on the flanks of the water vapor absorption line to provide first-ever vertical profiles of water vapor in cloud.

B. *Sensitivity, resolution and scanning*

The classic set of trade-offs for pulsed weather radars (i.e., between sensitivity and range resolution), is especially challenging in spaceborne applications where available power and antenna size are particularly expensive commodities. Since most spaceborne cloud and precipitation radar concepts observe at angles close to nadir (say, within 20˚ in general) the range resolution requirement is driven by the vertical resolution. One peculiar aspect tied to the near-nadir geometry is the impact of surface clutter via the finite resolution of the receiver: the surface high cross-section (compared to the atmospheric targets) typically prevents direct measurement of precipitation or cloud directly above the surface, as it would be desired for many purposes (e.g., hydrological applications, water budget analyses, latent heating assessment etc.). In this regard, the ACE Science Working Group indicated that a 250 m range resolution was acceptable to address most science needs, but with a specific additional requirement that the ground clutter contamination be limited to the lowest 400 m above the surface [13, 14]. In order to provide more effective solutions in this specific area, pulse compression was considered for cloud and precipitation radars [15] and its use in a near-nadir geometry was first demonstrated by the Airborne Precipitation Radar 2nd Generation [16]. However, the level of the range sidelobes caused by small non-linearities in the hardware, or limitations in the digital-to-analog conversions, can cause surface clutter to spill to altitudes larger than desired. Recent specific studies address the applicability of pulse compression to SCPR [17], and one specific implementation has been demonstrated in an airborne prototype of RainCube (See Section III and [6]).

A second area of trade study of high importance in all instrument concepts discussed here is given by the need to provide high-horizontal resolution and high-precision measurements versus the need to achieve a horizontal swath. Both CloudSat CPR and EarthCARE-CPR are nadir looking instruments. This choice allows achievement of the required sensitivity by minimizing the losses between the collimating antenna and the RF electronics, and by allowing relatively long integration times (and therefore a large number of integrated pulses to reduce signal variability). The RainCube has adopted a similar strategy for the same reasons, and to implement a very compact antenna architecture.

Lack of scanning in the cross-track represents a weakness for cloud and precipitation monitoring systems. First, the limited swath width 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 level of ambiguity in the interpretation of the observed fields where significant variability in the horizontal direction is present. In this regard, until the last decade, limited scanning options were available at Ka-band, and no electronic scanning options were available at W-band, while adoption of mechanical scanning for this type of radars is not suitable (due to the fast scan rates required). It was this specific gap in technological capability (compared to the science needs explicitly stated in the Decadal Survey 2007 [7]) that spurred the efforts that have produced the C2D2, 3CPR and MASTR instrument concepts (described in section III) among others.

C. *Doppler and/or Frequent observations*

A third main area of interest is associated with the general need to caputure not only static snapshots (be they 2-D or 3-D) of cloud and precipitation reflectivity, but also information in regards to the processes underlying such distrubutions. In this context there are two non-mutually exclusive approaches that have been studied: acquisition of Doppler velocity measurements, and acquisition of series of observations separated by a time window comparable to the time-scale at which the cloud and precipitation processes evolve.

Doppler allows measurement of particle motions in clouds, providing better classification of cloud type, estimates 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.

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The concept of acquiring closely-spaced observations of reflectivity has been at the basis of the “D-Train” concept and has been fist analyzed in depth in [18,19]: the short-term change in observed radar reflectivity is closely related to estimates of vertical mass transport inside convective storms, and can therefore be exploited to provide a view into the storm processes at a particular moment of the storm lifetime.

One particular instrument concept, the Nexrad-In-Space (NIS) [20] could essentially provide both by adopting a GEO orbit and a large reflector. Smaller instrument concepts deployed in LEO tend to focus on one of the two aspects because of the competing nature of their primary instrument requirements, but there are notable exceptions to this rule as discussed in Section III.

III. Instruments and Instrument Concepts

A. RainCube

RainCube (Radar in a CubeSat, [6]) is a technology demonstration mission to enable Ka-band precipitation radar technologies on a low-cost, quick-turnaround platform. A 6U cubesat includes the radar electronics (miniKaAR-C, occupying ~3U and requiring <25W of supply power), the compact lightweight deployable 0.5 m antenna (KaRPDA, occupying ~1.5 U when stowed) and the bus systems (~1.5 U). The mission is manifested for an ISS deployment on the ELaNa-23 launch, currently scheduled in 2018.

Key to the realization of the RainCube concept is a novel architecture enabled by the simplification and miniaturization of the radar subsystems. This architecture also reduces the number of components, power consumption, and mass by over one order of magnitude with respect to the existing spaceborne radars. This architecture adopts an offset IQ (in-phase and quadrature) with pulse compression as modulation technique. Previous spaceborne cloud and precipitation radars have adopted high power short monochromatic pulses to achieve the required sensitivity with low range sidelobes (to avoid contamination of the tropospheric echoes by the surface response). This requires high-power amplifiers and either high-voltage power supplies or large power-combining networks, precluding small-size/low-power platforms. Pulse compression is used to achieve the required sensitivity with a custom amplifier fabricated with off-the-shelf GaAs solid-state pHEMT chips. Optimal selection of the pulse shape, accounting for wave distortions in the process of amplification, scattering and propagation and detection, minimizes the range sidelobe to the required level of less than 60 dB.

The Ka-band Radar Parabolic Deployable Antenna (KaRPDA) adopted in the current RainCube technology demonstration is optimized for 35.75 GHz and is measured to deliver a gain of 42.6 dBi (over 50% efficiency). KaRPDA uses a Cassegrain architecture with the sub-reflector below the focal point of the antenna, allowing the antenna to stow in a tight volume. Technology development is currently ongoing for extending the same miniKaAR electronics to 1-m and 2-m antenna sizes, and concepts are being developed to combine Ka-band with other frequencies.

RainCube is the first demonstration of what could become a constellation of precipitation profiling instruments in small satellite form-factors.

B. C2D2 & 3CPR

The Ka- and W-band Cloud Cross-Track scanning Dual Frequency Doppler radar (C2D2) and its direct evolution, the Three band Cloud and Precipitation Radar (3CPR, Ku-, Ka and W-band), are instrument concepts whose key technology development is funded as direct response to the needs of the ACE mission concept [21]. In particular, they both rely on the architecture first proposed for the PR-2 instrument concept [22], namely that of a single singly-curved parabolic reflector fed by one active line array feed for each band. The reflector is curved in the direction of flight, and the line feed array is on the orthogonal direction to enable electronic scanning in the cross-track direction. In order to simplify instrument complexity, and therefore reduce both development and testing costs, each line feed is divided in identical building blocks called Scanning Array Tiles (SAT), each comprising 8 radiative elements for the transmit function and 8 radiative elements for the receive function arranged in an interleaved pattern on a 2-row pattern. The separation of transmit and receive radiative elements provides sufficient isolation between the Solid State Power Amplifiers and the Low Noise Amplifiers, so that no Transmit/Receive switching is necessary inside the SATs. Two distinct advantages of this architecture with respect to 2-dimensional active arrays or reflectarrays are that a) the number of active devices grows linearly (instead of quadratically) with the antenna size, and b) the line feed array solution enables significantly easier solutions for the dissipation of thermal power (an aspect of particular importance for spaceborne radars).

In order to satisfy the requirements of the ACE mission concept, and accounting for launch vehicle accomodation constraints, the 3CPR instrument was originally formulated as having a 5 x 3 m antenna (with the longest dimension along the direction of flight to provide the required Doppler accuracy, and post-integration along-track resolution). However, the flexible and modular nature of this architecture for the RF fron-end has been exploited to provide also more compact solutions where the science requirements can be relaxed: these have been integrated in the MASTR instrument concept dexcribed in the next subsection.

C. MASTR

The Multi-Application SmallSatellite Tri-band Radar (MASTR) is a SmallSat instrument concept capable of electronic scanning, Doppler velocity measurement, and polarimetry at Ku/Ka/W-band frequencies. These capabilities allow MASTR to work as a cloud and precipitation radar, an altimeter (targeting sea ice height and snow depth) or as a scatterometer (in a spinning platform configuration). Consequently, MASTR has the potential to support several of NASA’s Earth science programs including Cloud and Radiation, Precipitation Measurement, Cryospheric Sciences, Climate Variability and Change, and Physical Oceanography.

MASTR can be summarized as the merger of the technologies developed for RainCube (i.e., the modulation technique and related up-/down-conversion scheme) and those developed for 3CPR (the multi-frequency line feed array for a single singly-curved parabolic reflector). Use of these methods allows to scale the size and power consumption quite freely from 0.3 m to 3 m, and from 200W to more than 1 kW. Such flexibility allows the design of a variety of possible mission concepts where one or more radars address specific science objectives. A few notional examples of projected performance of a few configurations adopting either a 1-m or a 2-m antenna are shown in [23].

D. Displaced Phase Center Antenna

Application of Displaced Phase Center Antenna (DPCA) to spaceborne observations of clouds and precipitation is introduced in [24] and demonstrated through analysis of airborne data in [25]. In this particular application, the advantage of DPCA is that of canceling (or reducing significantly) the effects of platform motion in the estimation of mean Doppler velocity.

This measurement concept can be implemented within a single radar instrument (by adopting two collimating antennas displaced along the direction of motion) or by a pair of identical radars placed in two small platforms flying in close formation. The small separation between the two platforms is such that autonomous formation flying capability is necessary to maintain safely the required baseline; however the gentle degradation associated with departures from the ideal baseline separation is such that formation flying performance as already demonstrated in space (e.g., [26]) would satisfy the instrument performance requirements. Possible implementations of a DPCA pair include use of RainCube or MASTR.

IV. CONCLUSIONS

Significant progress has been achieved in the last decade in the technologies relevant to spaceborne cloud and precipitation radars. In this survey of the state of the art we include the first ever precipitation radar capable to fit inside a cubesat, and the first technologies suitable for electronic scanning at W-band for global cloud and precipitation observations from space. Together with the arrival of several options of small platforms and the associated reduced cost to access space per unit, these brekthroughs have enabled the science community to envision feasible constellations of small radars capable of observing various aspects of the cloud and precipitation processes. In the time between the submission of this paper and the associated presentation, it is expected that the Earth Science Decadal Survey Report 2017 will be published. The selection of the next generation instruments to observe clouds and precipitation will be able to focus according to the recommendations included therein, and will not be hampered by technological limitations as much as one decade ago.

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