A CROSS-TRACK CLOUD-SCANNING DUAL-FREQUENCY DOPPLER (C2D2) RADAR FOR THE PROPOSED ACE MISSION AND BEYOND

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1. INTRODUCTION

The National Resource Council's Earth Science Decadal Survey" (NRCDS) [1] has identified the Aerosol/Climate/Ecosystems (ACE) Mission as a priority mission for NASA Earth science. The NRC recommended the inclusion of "a cross-track scanning cloud radar with channels at 94 GHz and possibly 34 GHz for measurement of cloud droplet size, glaciation height, and cloud height". Several radar concepts have been proposed that meet some of the requirements of the proposed ACE mission but none have provided scanning capability at both 34 and 94 GHz due to the challenge of constructing scanning antennas at 94 GHz. In this paper, we will describe a radar design that leverages new developments in microwave monolithic integrated circuits (MMICs) and micro-machining to enable an electronically-scanned radar with both Ka-band (35 GHz) and W-band (94-GHz) channels. This system uses a dual-frequency linear active electronically-steered array (AESA) combined with a parabolic cylindrical reflector. This configuration provides a large aperture (3m x 5m) with electronic-steering but is much simpler than a two-dimension AESA of similar size. Still, the W-band frequency requires element spacing of approximately 2.5 mm, presenting significant challenges for signal routing and incorporation of MMICs. By combining (Gallium Nitride) GaN MMIC technology with micro-machined radiators and interconnects and silicon-germanium (SiGe) beamforming MMICs, we are able to meet all the performance and packaging requirements of the linear array feed and enable simultaneous scanning of Ka-band and W-band radars over swath of up to 100 km.

2. RADAR SYSTEM DESIGN

A major objective of the proposed ACE mission 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 NRCDS specifically calls for a cross-track scanning, Doppler, W/Ka-band cloud radar for cloud droplet size, glaciation height, and cloud height. The NRCDS also requires that "ACE is to provide significantly more data of a much higher quality than its predecessors" the A-Train and EarthCARE [2]. The necessity of a profiling Doppler radar working in synergy with other instruments is demonstrated by the role that CloudSat's data is already playing within the A-Train ([3], and ~200 publications to date), and is reflected in the choices made by ESA and JAXA for EC's CPR radar [4]. The C2D2 concept enables simultaneous use of four radar features (multi-frequency algorithms, Doppler, scanning and polarimetry) that greatly enhance the overall radar capability and of the suite of proposed ACE instruments as a system.

Table 1 shows the main radar requirements as well as the prioritized goals defined by the ACE Science Working Group [5]. The requirements necessary to achieve *minimum* scientific objectives, were found to be achievable by technology at mature TRL in 2010, enabling relatively low risk implementation according to a tentative timeline leading to a pre-2020 launch [6]. Additional capabilities were proposed by Racette, *et al.,* for instrument that would implement electronic scanning at Ka-band but provide only a nadir beam at W-band[7]. However, the goals (prioritized according to their capacity to enable new scientific objectives) are more indicative of the instrument performance needed to fulfill the complete set of science objectives. The goals' priority levels were set in 2008 based upon projected advancement of the required technologies in the upcoming years. New technologies available since 2008 have made scanning at W-band a realistic option.

Furthermore, the SWG's Cloud Studies Team (CST) provided "dual requirements" to capture the challenges associated with the design and implementation of such instrument: one set for a nadir-view (i.e., the CloudSat's style "curtain plot") and one for off-nadir view. The nadir-view requirements and goals reflect the measurements needed to update the global statistics of cloud properties according to the same approach used by CloudSat, EarthCARE. The off-nadir goals are designed to use 3-D volumetric measurements to complement and improve upon the nadir measurements without comprising nadir performance.

Table 1. ACE radar requirements and goals (number in parenthesis indicates priority level for each frequency, Tanelli et al. 2010), ACERAD performance, C2D2 performance for the 4 swaths. Requirement met, goal met.

	REQ	GOAL	ACERAD	C2D2	
W-band/nadir				**Nadir 250**	**Nadir 100**
MDS (dBZ)	-35	(3)-40	-35	-38	-30
Doppler Acc (m/s)	0.4	(2) 0.2	0.2	0.2	0.2
Vert Res (m)	250	(1) 100	250	250	100
Surf.Clut. max hgt (m)	500	(1) 250	500	500	250
Hor Res (km)	1 x 1	--	0.6 x 1	0.6 x 1	0.6 x 1
Polarimetry	NO	(5) YES	YES	NO	NO
W-band/off-nadir				**Narrow**	**Wide**
Swath width (km)	--	(4) > 1	NA	4	75
MDS (dBZ)	--	-20	NA	-32	-29
Doppler Acc (m/s)	--	1	NA	0.8	1.5
Vert Res (m)	--	250	NA	250	250
Hor Res (km)	--	1 x 1	NA	0.6 x 1	0.6 x 1
Ka-band/nadir				**Nadir 250**	**Nadir 100**
MDS (dBZ)	-10	(2) -20	-10	-24	-15
Doppler Acc (m/s)	1	(3) 0.5	0.5	0.5	0.5
Vert Res (m)	250	(4) 100	250	250	100
Surf.Clut. max hgt (m)	500	(4) 250	500	500	250
Hor Res (km)	2 x 2	1 x 1	1.5 x 1	1.5 x 1	1.5 x 1
Polarimetric	NO	(5) YES	YES	YES	YES
Ka-band/off-nadir				**Narrow**	**Wide**
Swath width (km)	--	(1) > 25	25	4	100
MDS (dBZ)	--	-10	0	-21	-15
Doppler Acc (m/s)	--	1	NA	0.7	1.5
Vert Res (m)	--	250	250	250	250
Hor Res (km)	--	2 x 2	2	1 x 1.5	1 x 1.5

The proposed C2D2 architecture is scalable over a wide range of size, power, and duty cycle. The performance parameters in Table 1 derive from a configuration selected to minimize departure from the budgeted mass, size, power, data rate and cost used for previous mission configuration studies. This configuration is not limited by the capability of the proposed technology, and enhanced performance can be achieved by scaling; nevertheless, it fulfills not only the requirements, but also 8 out of 10 of the prioritized ACE SWG radar goals.

The C2D2 antenna configuration is similar to the a Ku-band/Ka-band antenna proposed more than a decade ago for the Second Generation Precipitation Radar (PR-2)[8]: a parabolic cylinder is illuminated by a linear dual-frequency active linear array feed (ALAF) to enable electronic beam scanning in the cross-track direction (Figure 1). The array-fed parabolic cylindrical reflector has several attractive characteristics: 1) it provides a large aperture that would not be feasible using a two-dimensional active array, 2) it provides the cross-track scanning and beam agility required to maximize science return, 3) the solid-state array transmitters provide significantly lower phase noise than high-power vacuum electron devices used in CloudSat and EarthCARE.

The key enabling component is the pair of 35 and 94 GHz ALAF located along the focal line of the parabolic cylinder. The 94 GHz array is centered on the focal line while the 35 GHz array is slightly offset. JPL has already demonstrated 35 GHz ALAF technology with 5-mm element spacing intended for use in PR-2 [9]. This successful design is useable requiring only minor updates for parts obsolescence. However, the approach used at 35 GHz is not applicable at 94 GHz where the required array spacing is approximately 2.5 mm and the fabrication tolerances are almost three times tighter. Our approach to implementation of the 94 GHz ALAF utilizes technology breakthroughs in packaging, micromachined radiators and MMIC technology. These breakthroughs allow substantially enhanced radar capabilities with a feasible path to implementation and satisfy the full science goals of the proposed ACE mission.

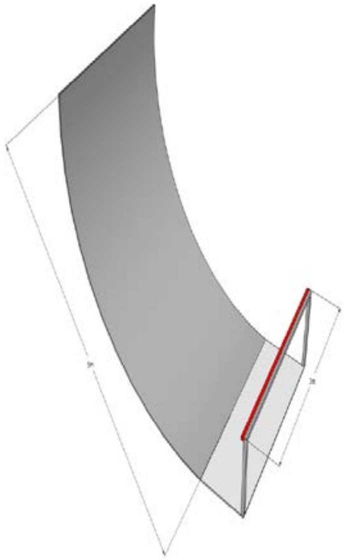

Figure 1. Ka/W band Scanning Antenna Configuration.

2.2. Antenna System Design

Antenna system preliminary design was performed using a combination of commercial and custom computer codes to perform three-dimensional electromagnetic simulation of antenna element patterns, synthesis of array patterns and calculation of array/reflector patterns using physical optics and physical theory of diffraction. The antenna system trade space was explored, trading performance vs. area, aspect ratio and focal length. We have also studied the effects of displacing the Ka-band feed array from the focal line of the parabolic cylinder while accommodating the W-band array on the focal line. For the required displacements, degradation of Ka-band antenna pattern was insignificant. Displacing the Ka-band feed causes small along-track beam shift (relative to W-band). However, it is simple to correct the registration of the Ka- and W-band data by applying a very small time shift to the data. Due to the challenging array spacing and performance constraints of the W-band feed, new technology is required. We have developed a preliminary feed design that incorporates high-power and efficiency GaN MMIC power amplifiers, GaN LNA, SiGe beamforming MMICs and micro-machined radiators and interconnects.

Our point-design for the W-band feed is 2.56 m long with 2x1024 radiating elements. The 2048-element array is composed of separate transmit and receive arrays that are interlaced on a triangular grid. This approach eliminates the need for circulators (which are impractically large) or switches (which introduce substantial front-end losses). However, this approach requires careful design to minimize element-to-element coupling over the full range of scan angle. Additionally, the receiver, LNA MMIC must be able to tolerate significantly higher leakage power than a typical LNA. GaN LNAs are used to provide high leakage power tolerance. While the noise figure may be degraded (compared to an Indium Phosphide LNA), the degradation is less than the losses that would be incurred by using switches.

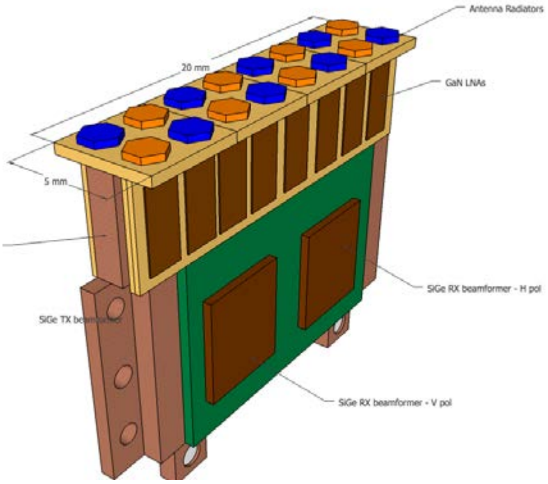

Figure 2. W-band Scanning Array Tile concept

The ALAF is composed of scanning array tiles (SAT). A conceptual drawing of an SAT is shown in Fig 2. Transmit elements are shown in orange and receive elements in blue. The elements are fabricated in a micro-machining process called PolyStrata™ (Nuvotronics, LLC)[10]. The PolyStrata™ process permits precise fabrication of dual-polarized, probe-fed patch radiators with no dielectric. The lack of dielectric improves radiation efficiency and also improves our ability to accurately model the element performance using 3D electromagnetic simulations. Figure 3 shows a photograph of a prototype 4-element unit cell fabricated in the PolyStrata™ process.

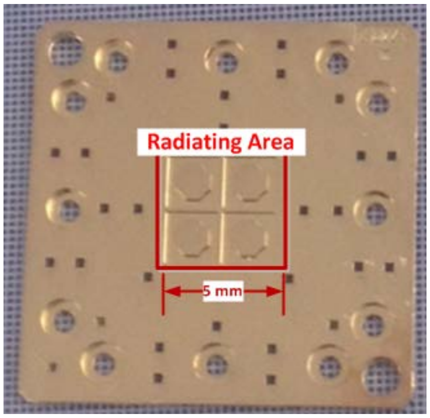

Figure 3: Prototype 94-GHz dual-polarized radiator unit cell implemented in Nuvotronics' PolyStrata™

The PolyStrata™ radiator assembly routes the transmit and receive elements to carriers that contain GaN PA and LNA MMIC. A single-sided carrier on one side of a central heat-spreader holds eight PA MMIC each with a transmit peak power of greater than 1 W. On the opposite side of the heat spreader is double-sided carrier with sixteen LNA MMICs (eight per receive polarization). Behind each GaN MMIC carrier is a SiGe integrated beamformer assembly. SiGe bipolar technology enables the integration of many phase-shifter channels along with digital control circuitry on to a single die only a few millimeters on a side. With integrated seriacontrol circuitry, the SiGe beamformer eliminates thousands of interconnects compared to standard phase shifter ICs with parallel control

3. CONCLUSION

The proposed instrument concept uses a combination of new technologies that have matured over the last five years to provide dual-frequency (35, 94 GHz) scanning radar capabilities for the proposed ACE decadal survey mission. This approach will substantially improve the science benefits of the mission by providing three-dimensional data at both radar frequencies (as specified in the NRCDS). The current state-of-the-art and ongoing technology development supports an early 2020's launch date for the C2D2 radar as part of the proposed ACE mission or other mission.

4. REFERENCES

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Acknowledgement - This work was performed at the Jet Propulsion Laboratory / California Institute of Technology under contract with the National Aeronautics and Space Administration.