NASA/TM—2009-215663

Concept for a Low-Cost, High-Efficiency Precipitation Radar System Based on Ferroelectric Reflectarray Antenna

Robert Romanofsky
Glenn Research Center, Cleveland, Ohio

Carl Mueller
Qinetiq North America, Cleveland, Ohio

Chandra V. Chandrasekar
Colorado State University, Fort Collins, Colorado

October 2009

NASA STI Program . . . in Profile

Since its founding, NASA has been dedicated to the advancement of aeronautics and space science. The NASA Scientific and Technical Information (STI) program plays a key part in helping NASA maintain this important role.

The NASA STI Program operates under the auspices of the Agency Chief Information Officer. It collects, organizes, provides for archiving, and disseminates NASA's STI. The NASA STI program provides access to the NASA Aeronautics and Space Database and its public interface, the NASA Technical Reports Server, thus providing one of the largest collections of aeronautical and space science STI in the world. Results are published in both non-NASA channels and by NASA in the NASA STI Report Series, which includes the following report types:

- TECHNICAL PUBLICATION. Reports of completed research or a major significant phase of research that present the results of NASA programs and include extensive data or theoretical analysis. Includes compilations of significant scientific and technical data and information deemed to be of continuing reference value. NASA counterpart of peer-reviewed formal professional papers but has less stringent limitations on manuscript length and extent of graphic presentations.

- TECHNICAL MEMORANDUM. Scientific and technical findings that are preliminary or of specialized interest, e.g., quick release reports, working papers, and bibliographies that contain minimal annotation. Does not contain extensive analysis.

- CONTRACTOR REPORT. Scientific and technical findings by NASA-sponsored contractors and grantees.

- CONFERENCE PUBLICATION. Collected papers from scientific and technical conferences, symposia, seminars, or other meetings sponsored or cosponsored by NASA.

- SPECIAL PUBLICATION. Scientific, technical, or historical information from NASA programs, projects, and missions, often concerned with subjects having substantial public interest.

- TECHNICAL TRANSLATION. English-language translations of foreign scientific and technical material pertinent to NASA's mission.

Specialized services also include creating custom thesauri, building customized databases, organizing and publishing research results.

For more information about the NASA STI program, see the following:

- Access the NASA STI program home page at *http://www.sti.nasa.gov*

- E-mail your question via the Internet to *help@sti.nasa.gov*

- Fax your question to the NASA STI Help Desk at 443–757–5803

- Telephone the NASA STI Help Desk at 443–757–5802

- Write to:
  NASA Center for AeroSpace Information (CASI)
  7115 Standard Drive
  Hanover, MD 21076–1320

NASA/TM—2009-215663

Concept for a Low-Cost, High-Efficiency Precipitation Radar System Based on Ferroelectric Reflectarray Antenna

Robert Romanofsky
Glenn Research Center, Cleveland, Ohio

Carl Mueller
Qinetiq North America, Cleveland, Ohio

Chandra V. Chandrasekar
Colorado State University, Fort Collins, Colorado

Prepared for the
2009 Radar Conference
sponsored by the Institute of Electrical and Electronics Engineers (IEEE)
Pasadena, California, May 4–8, 2009

National Aeronautics and
Space Administration

Glenn Research Center
Cleveland, Ohio 44135

October 2009

Level of Review: This material has been technically reviewed by technical management.

Available from

NASA Center for Aerospace Information
7115 Standard Drive
Hanover, MD 21076–1320

National Technical Information Service
5285 Port Royal Road
Springfield, VA 22161

Available electronically at http://gltrs.grc.nasa.gov

Concept for a Low-Cost, High-Efficiency Precipitation Radar System Based on Ferroelectric Reflectarray Antenna

Robert Romanofsky
National Aeronautics and Space Administration
Glenn Research Center
Cleveland, Ohio 44135

Carl Mueller
Qinetiq North America
Cleveland, Ohio 44135

Chandra V. Chandrasekar
Colorado State University
Fort Collins, Colorado 80523

Abstract

This work proposes a concept on a novel scanning phased array, based on thin film ferroelectric phase shifters, for an X-band precipitation monostatic radar.

1.0 Introduction

NASA Glenn Research Center (GRC) and Colorado State University are investigating an innovative X-band ferroelectric reflectarray antenna (FRA) system for cloud and precipitation radar applications, especially for spaceborne applications. The FRA can be used as a dual-polarization antenna, thus providing capability to perform the full covariance matrix measurements of the precipitation medium for remote sensing applications from ground, air and space. These measurement capabilities will enhance our ability to discern between different precipitation types and sizes, and improve measurement resolution. The FRA provides viable electronic beam steering over at least a ±45° swath, which will offer substantial performance and reliability benefits over existing precipitation radar antennas, as well as mechanically steered antennas or other electronic scan systems. Most importantly, the FRA promises a tenfold cost advantage over conventional phased arrays, a 5 times efficiency improvement, and elimination of existing thermal management problems associated with conventional phased arrays.

Unlike conventional directly-radiating phased arrays, the FRA aperture is inherently reciprocal, thus ideally suited for radar. The FRA promises to be substantially less expensive than current state-of-the-art phased array antennas. It uses ferroelectric phase shifters to enable beam steering, and vertical and horizontal polarization will be accomplished using switching circuitry at the feed. The high power-handling capabilities of the ferroelectric phase shifters (relative to semiconductors) accentuate the applicability of this technology for radar applications. Moreover, because of the quasi-optical feed, the aperture can be large compared to directly-radiating arrays to provide high spatial resolution. This is particularly important for enhancing the success for cloud and precipitation measurements that are affected by spatial gradients. The algorithm development teams conducting spaceborne precipitation observations have determined that spatial non uniformity within the beams are an important source of error (Ref. 1).

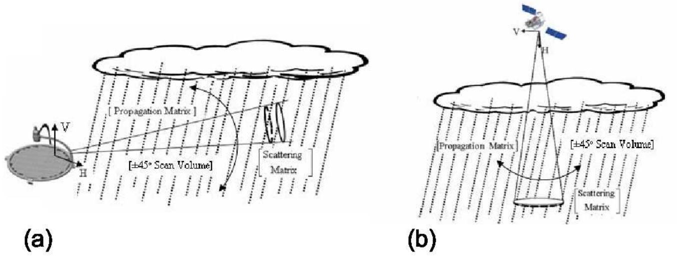
2.0 Rationale

Spaceborne microwave radar has proven to be an outstanding instrument for precipitation and wind velocity measurements, but these instruments are expensive to build, launch and operate. Due mainly to the high value of the data returned, and partly to the high cost of follow-on missions, the Tropical Rainfall Measurement Mission (TRMM) and QuikSAT missions have been extended well past their intended completion dates. A recently published report by the National Academy of Sciences recommends that NASA implement a 12-yr program that would deploy 15 missions dedicated to studying various aspects of the Earth's environment, with a goal of building a comprehensive model of the Earth's climate, where the Earth's ecology is treated as a unified system (Ref. 2). Several of these missions require microwave radar measurements at frequencies from L-band (1 to 2 GHz) up to Ka-band (26.5 to 40 GHz). Given the limited budget and high cost of missions that utilize microwave radar instruments, it will be challenging to comply with the National Academy of Science's recommendations even if the requested funding becomes available. The FRA is an electronically steerable microwave radar antenna promising better functionality than current state-of-the-art beam-steerable phased array antennas, yet is considerably less costly to design, fabricate, and operate. Mass is expected to be about the same as a comparable directly-radiating phased array.

2.1 Dual Polarization Precipitation Radar Using Ferroelectric Reflectarray Antenna

Dual-polarization precipitation radars provide information about the precipitation particle microphysics. The use of electronic scan in the application for spaceborne radars has been well established. Similarly rapid scan can be used for ground based radars (Ref. 3). The FRA can be designed to reflect either the same sense or opposite sense polarization of the feed. Figure 1(a) shows schematically the ground-based polarimetric radar measuring the backscatter covariance matrix of precipitation volume noting that the propagation or forward scatter properties also influence the measurements. There are well established theories that can use the differential propagation phase for quantitative precipitation estimation. Once the radar system is demonstrated on the ground, it is the obvious next step to demonstrate the same for spaceborne and airborne applications. Figure 1(b) shows the spaceborne implementation of the same system.

The two microwave radar instruments with demonstrated precipitation measurements are the Precipitation Radar–1 (PR–1) (Ref. 4) and the SeaWinds radars (Refs. 5 and 6). The FRA draws its legacy from these two antennas. Although PR–1 and SeaWinds operate at similar frequencies (13.6 and 13.4 GHz, respectively), they are used for different purposes. PR–1 is one of two primary instruments on the TRMM mission (the other instrument is the TRMM Microwave Imager (TMI), and data from the two complement each other). PR–1 is used to measure the amount and type of precipitation (water and/or ice) in selected three-dimensional columns from the earth's surface up to a height of about 20 km. This data is crucial for climate modeling and weather forecasting. TRMM was launched in 1997 with a planned lifetime of 3 years, and remained operational for 8 years. The total mission cost was approximately $750 million (Ref. 7). The fact that its lifetime was extended several times is a testament to the value of the data that was generated, and the cost highlights the expensive nature of spaceborne microwave radar systems. The Global Precipitation Measurement Mission (GPM), scheduled for launch in the 2010 to 2013 time frame, carries on the TRMM legacy. The GPM mission expands the use of radar precipitation measurements by including both 35.5 and 13.6 GHz phased array precipitation radars (Refs. 8 and 9). These two antennas are collectively named PR–2. The fact that the international program is placing such a high emphasis on a mission for which microwave radar is a primary instrument illustrates the value of these measurements. The second major use of microwave radar for Earth Observation is the SeaWinds radar antenna, which is the only instrument on NOAA's high-profile QuikScat mission. SeaWinds is used to measure wind speed and direction near the sea surface, and thus is valuable for hurricane tracking.



(a) (b)

Figure 1.—Polarimetric electronic-scan radar measuring the backscatter covariance matrix of precipitation volume. (a) Initial application. (b) Ultimate application.

NASA and NOAA's ambitions for Earth Science Observation missions go far beyond simply replacing instruments that are operating past their anticipated lifetimes. However, budget constraints mitigate these ambitions, and new technologies are needed so as to provide the needed measurement capabilities. NASA, together with partners from other United States as well as international agencies, has a strong need for novel instrumentation that expands our understanding of how various forcing factors and feedback mechanisms affect the global climate. Understanding the amount and distribution of water across the globe is essential to understanding the factors that shape the Earth's climate, and the coupling between these factors. Questions that the FRA can help answer include: how is precipitation distributed and re-distributed over time, how are sea surface temperature and sea currents affected by sea winds, how much water is in the form of ice, and how quantitatively do we understand the extent to which ice in the polar regions melts and re-freezes.

The realities of budget constraints place added emphasis on the need to develop instruments and missions that generate the needed data in a cost-efficient manner. The National Academy of Sciences Decadal report (Ref. 2) recommends that NASA implement a "minimal yet robust observational component of an Earth information system that is capable of addressing a broad range of societal needs." The report suggests a number of missions that should be carried out over the next 15 years, the instruments needed for these missions, and ranks the missions in their order of importance.

3.0 Technology

The reflectarray is a cost-effective, high-efficiency alternative to directly-radiating phased array antennas. A key advantage of reflectarray antennas over conventional phased arrays is elimination of the complex beam-forming manifold and costly transmit/receive modules. The reflectarray is also reciprocal—the same aperture can be used for transmit and receive functions. But a viable technique for including variable phase shift with the printed radiators to permit beam scanning has proven elusive. The ferroelectric reflectarray holds promise to dramatically reduce manufacturing costs of phased arrays and alleviate thermal management problems associated with microwave integrated circuit transmit arrays. Successful technological and economic operation depends on the realization of very low loss, very low cost phase shifters—which we have demonstrated.

3.1 Antenna

A scanning reflectarray consists of a *flat* surface with diameter D, containing $M\times N$[1] integrated phase shifters and $M\times N$ patch radiators with inter-element separation d, that is illuminated by a single feed at a virtual focus located a distance F from the surface such that $F/D \approx 1$ (Fig. 2). This value of F/D is a reasonable compromise between feed gain (and blockage) for proper illumination and modulo 2π effects.

The control algorithm is nearly identical to that of a conventional phased array, the exception being an a priori setting of all phase shifters to compensate for the spherical wave-front from the feed. That is, in order for the reflectarray to emulate a parabolic surface, the phase shifters are adjusted to compensate for the increasing path length from the aperture center towards the perimeter. If the phase shifters are to be integrated onto the radiating surface they must be very small (i.e., $<\lambda_o/2$). The modulated signal from the feed passes through the reflect-mode phase shifters and is re-radiated as a focused beam in essentially any preferred direction in the hemisphere in front of the antenna, as in a conventional phased array. Of course the physics in sofar as inter-element spacing, mutual coupling, scan loss, etc. is concerned is the same as for a conventional array that uses a transmission line manifold to distribute the signal among the $M\times N$ elements. The most troublesome issue with implementing a scanning reflectarray arises from the fact that the phase shifters are necessarily between the feed and the patch radiating elements. Hence, they introduce line loss in front of the first stage low noise amplifier (LNA) and can cause system noise temperature to escalate in the case of a receive array. Analogously, in the case of a transmit array, the phase shifters largely determine system efficiency. However, most of the Effective Isotropic Radiated Power (EIRP) can be generated by the aperture instead of the amplifier, so there is an inherent spacecraft prime power advantage over a conventional directly radiating array. Figure 3 shows calculated EIRP and power consumption for a reflectarray and a Monolithic Microwave Integrated Circuit (MMIC) array.[2] The MMIC array used a microstrip corporate feed network, which results in an additional inefficiency because of significant dissipation in the manifold.

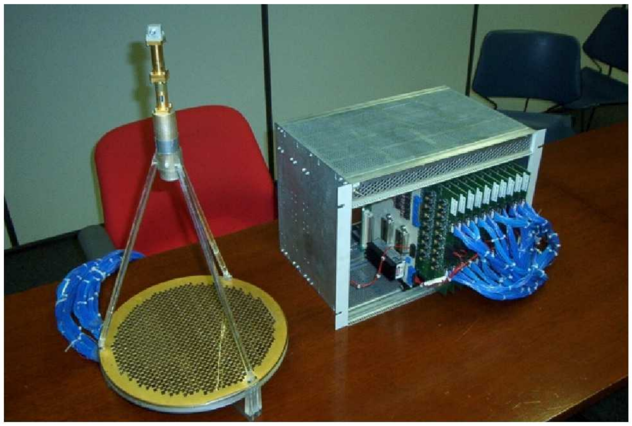


Figure 2.—Prototype 615 element ferroelectric reflectarray and low power controller. Diameter is 30 cm.

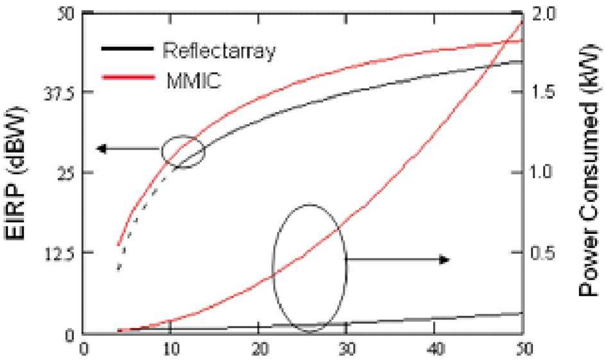


Figure 3.—Square root of the number of elements.

3.2 Ferroelectric Phase Shifters

We have already devised relatively low loss phase shifters based on thin ferroelectric films (Refs. 10 to 12). A novel hybrid phase shifter combining an analog ferroelectric section and a “digital” switch was devised. A photograph of the hybrid ferroelectric/semiconductor phase shifter is shown in Figure 4. Four coupled microstrip sections are attached to a virtual short circuit (radial stub) via a GaAs beam lead diode. When the diode is forward biased, a short circuit terminates the analog phase shifters and provides an additional approximately 180º of phase shift. When the diode is off, the termination is essentially an open circuit with a near unity amplitude reflection coefficient and approximately 0º of phase shift. Average loss was 3.5 dB. A loss of 1.2 dB is assigned to the diode since replacing it with a true open (off) and wire bond (on) reduces the loss to 2.3 dB. Maximum phase shift was ≈320º (Fig. 5).

Bandwidth and true time delay are important considerations. Figure 5 shows that the insertion phase shift is essentially proportional to frequency, and bandwidths in excess of 5 percent are achievable.

---

[1] The actual number of elements is truncated for a practical circular aperture of diameter D inscribed inside the rectangular aperture defined by $M\times N$. The FRA to be developed will have a circular aperture containing 2560 elements.

[2] Reflectarray Assumptions: 10 W, 40 percent efficient TWT feed, 4 dB loss phase shifters, 41 mW per channel controller power consumption. Direct Radiating MMIC Array Assumptions: 100 mW, 15 percent efficient MMIC amplifiers, 85 percent efficient power supply.

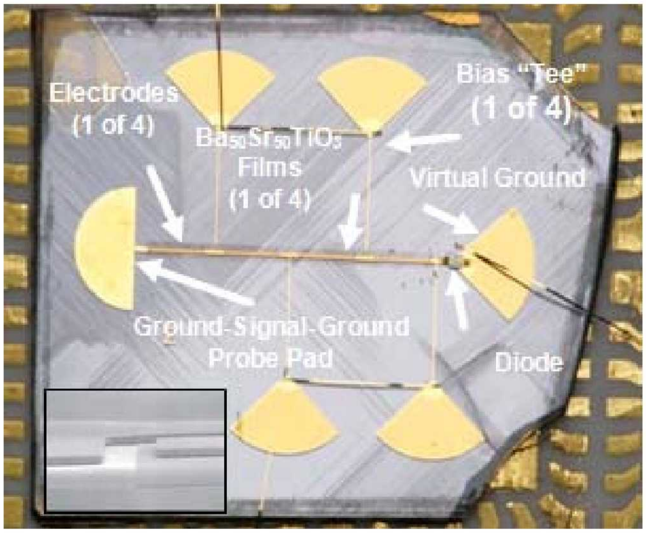


Figure 4.—Hybrid X-band ferroelectric/semiconductor phase shifter on 0.5-mm-thick lanthanum aluminate. The device is 10 by 9 mm. The 1.2-mm-long G–S–G pad is sacrificed (sawed) after characterization, so final size is approximately 9 by 9 mm^2. Each $\lambda_g/4$ electrode produces ≈40° of phase shift. Inset shows SEM of partial electrode.

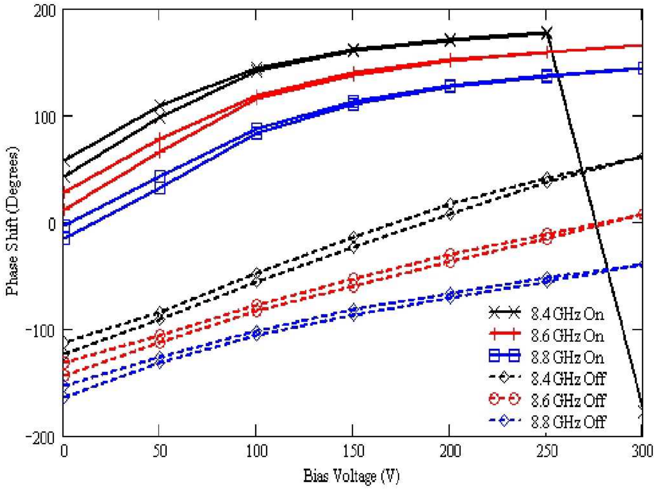


Figure 5.—Measured insertion phase of hybrid ferroelectric/ semiconductor phase shifter as a function of bias voltage on the ferroelectric section and switch state.

3.3 Phased Array Radar

Three specific NASA Earth Science applications illustrate the potential benefits of power-efficient, beam-steerable phased array X-band antennas (Table I). Precipitation radar is used to measure the amount and type of precipitation (water and/or ice) in selected three-dimensional columns from the earth's surface up to a height of about 20 km. This data is crucial for climate modeling and weather forecasting. The 13.8 GHz PR–2 electronically steerable phased array antenna (Ref. 9), scheduled for upcoming Global Precipitation Mission, illustrates the key attributes of this antenna class. The TerraSAR–X is used to take high resolution images of the Earth (Ref. 13). The FRA could be engineered to perform similar functions at considerably developmental costs and power requirements.

TABLE I.—SUMMARY OF ANTENNA PARAMETERS FOR SPACE-BASED PHASED ARRAY ANTENNAS

Parameter	Precipitation Radar–2 (Global Precipitation Mission)	TerraSAR–X (spotlight mode)	Specifications for SAR Antenna (Snow and Cold Land Processes)
Frequency	13.6 GHz	9.65 GHz	X-band
Orbit	400 km	514 km	510 km
Dimensions	2.4 by 2.4 m (58 dBi)	4.8 by 0.7 m	Not specified
Beam-steering	±17°	±20° (±0.75° in spotlight mode)	N/A
Swath width	245 km	50 km	40 km
Horizontal resolution, m	5 km	1.5 m (azimuth resolution)	50 to 100 m
Range resolution	250 m	1 m	2 cm accuracy
Pulse width	1.67 µsec		Not specified
Pulse repetition factor	4000 Hz		Not specified
Transmit bandwidth		300 MHz	Not specified
Peak power	>700 W	2 kW (peak)	100 W (peak)
Mass	375 kg	400 kg	
Power consumption	350 W	4500 W	

The purpose of Snow and Cold Land Processes Mission (SCLP) is to measure the quantity and distribution of water stored in the form of snow, on land and on ice sheets (Ref. 14). An objective of this mission is to correlate terrain variations with microclimate-related snow processes, and understand how these interactions impact macroclimate conditions. Hence high spatial resolution is important to the success of this mission, and a goal of 50 to 100 m resolution has been set. Since the space craft orbit is nominally 510 km, this resolution can only be achieved using synthetic aperture radar (SAR). Prior measurements have shown that the optimal frequency range to measure volumetric snowpack properties is 8 to 18 GHz. The key instrument for the SCLP mission will be X-band (8 to 12 GHz) and Ku-band (12 to 18 GHz) SAR. SCLP seeks to relate changes in snow levels and distributions with weather events; hence time resolution on the order of 3 to 6 days will be needed. Benefits from the SCLP mission include better understanding of the water cycle and improved water resource management, and enhanced ability to predict natural and human-induced disasters and alleviate their negative impacts. Better understanding of snow accumulation and water storage cycles is also critical to refining models for climate change hypotheses.

Electronic beam steering in the active SAR antennas can substantially improve the quality of data generated by SLCP. The baseline X– and Ku–band synthetic aperture radars for the SLCP mission specify that both antennas will be non-scanning, and will share the same aperture. The aperture will have a 30° incidence angle. The X–band antenna will have 100 W peak transmit power, with a resolution of 100 m and swath width of 40 km. Although the simplicity and economy of this approach is appealing, the major shortcoming is that approaches such as conical scanning are needed in order to achieve temporal measurement resolutions of 3 to 6 days. This necessitates a gimbaled design, where the antenna feed is mechanically rotated so as to increase the swath area. However, the mechanical vibrations decrease resolution. Even for non-gimbaled, non-steerable antennas, satellite motion and the rotating motion of the Earth causes displacement of the targets along the range axis during illumination (Ref. 15). To maintain the antenna phase center relative to points on the ground, either the satellite must be constantly steered in the yaw direction, which consumes fuel and shortens mission lifetime, or the antenna must be electronically steerable in the azimuth plane. Electronic beam steering would enable the antenna to lock onto ground features and auto-correct for spacecraft motion. To illustrate, space-based beam-steerable X–band SAR antennas such as Radarsat–2 and TerraSAR–X achieve 1 m resolution when operated in high-resolution modes.

Figure 6 illustrates potential performance characteristics for an FMCW system. The horizontal distance between transmitted and returned signal τ is related to range R as $R = c\tau/2$ and the maximum unambiguous range R_{max} is cT/2 where T is the waveform repetition period. In a pulse modulated system, $Rmax = c/(2f_{pr})$ where f_{pr} is the pulse repetition frequency. Given a bandwidth $B = f_{max} - f_{min}$, from similar triangles $R = cf_R T/(2B)$ where f_R is the beat note frequency. The corresponding range resolution is c/(2B) which is below 1 meter for an X-band FRA.

In order to provide a meaningful demonstration of a prototype, a preliminary design for an X-band Reflectarray Precipitation Radar System would use a target beamwidth of about 2°. This specification represents a compromise between the resolution offered by state-of-the-art instrumentation such as that aboard the Tropical Rainfall Measuring Mission and proposed for the Global Precipitation Measurement System and realistic costs. This beamwidth corresponds to a 2560 element, ≈1 m diameter FRA, an achievable goal. A schematic of the radar digital signal processing is shown in Figure 7.

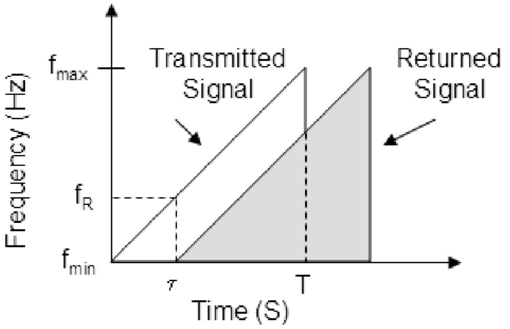
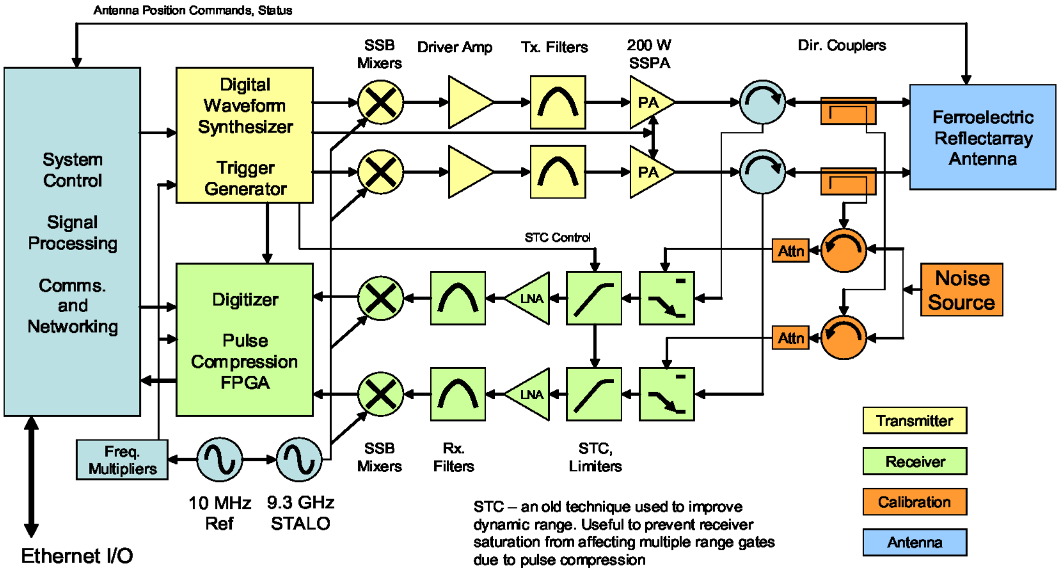


Figure 6.—Fundamental frequency modulated continuous wave radar waveform relationship.



STC – an old technique used to improve dynamic range. Useful to prevent receiver saturation from affecting multiple range gates due to pulse compression

Figure 7.—Schematic of the radar system that will operate with the FRA.

4.0 Summary

A key challenge is constructing the active array economically for radar applications—a cornerstone of this work. The ferroelectric phase shifters require only two bias lines and can be fabricated using a simple three-step (selective etch, metallization, and encapsulation) lithography process. The smallest feature size is the 8.5 μm electrode separation (inset Fig. 4) as opposed to submicron lithography that would be required for GaAs MMIC technology. The reflectarray structure requires only a multilayer DC bias distribution board, a support platen which also serves as the DC and RF ground plane, and the RF layer populated with $M \times N$ devices (patch antennas and phase shifters) that can be automatically placed and wire bonded. These qualities lead to comparatively low cost. A corrugated or dual-mode feed horn plus supporting struts, an amplifier, and a controller complete the system front end. The gradual increase in power for the reflectarray curve in Figure 3 is associated with the increase in the number of controller channels. A 616 channel controller that consumed only 25 W has been built to operate the FRA described in Section 3.0. We expect that a 1 m X–band FRA would comprise 2560 individual radiating elements and phase shifters and produce about a 2° beamwidth and offer better than 1 m range resolution.

References

1. Kozu, T. and Iguchi, T., "Nonuniform Beamfilling Correction for Spaceborne Radar Rainfall Measurement: Implications from TOGA COARE Radar Data Analysis," *Journal of Atmospheric and Oceanic Technology,* Volume 16, Issue 11 (November 1999) pp. 1722–1735.
2. Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond, Committee on Earth Science and Applications from Space: a Community Assessment and Strategy for the Future, National Research Council (National Academies Press, 2007).
3. Bringi, V.N. and Chandrasekar, V., 2001: Polarimetric Doppler Weather Radar: Principles and Applications, Cambridge University Press, p. 636.
4. Kozu, T. et al. "Development of Precipitation Radar Onboard the Tropical Rainfall Measuring Mission (TRMM) Satellite." IEEE Trans. Geoscience and Remote Sensing, vol. 39, pp. 102–116 (2001).
5. Spencer, M.W., Wu, C., and Long, D.G., "Tradeoffs in the Design of a Spaceborne Scanning Pencil Beam Scatterometer: Applications to SeaWinds." IEEE Trans. on Geoscience and Remote Sensing, vol. 35, pp. 115–126 (1997).
6. http://www.jpl.nasa.gov/news/press_kits/seawinds-adeos2.pdf
7. Assessment of the Benefits of Extending the Tropical Rainfall Measurement Precipitation Mission, Committee on the Future of the Tropical Rainfall Measuring Mission Board on Atmospheric Sciences and Climate, National Research Council (National Academies Press, 2006).
8. Im, E. Durden, S.L., and Tanelli, S., "Recent Advances in Spaceborne Precipitation Radar Measurement Techniques and Technology." IEEE Conference on Radar, pp. 15–21 (2006).
9. Senbokuya et al., "Development of Spaceborne Dual Frequency Precipitation Radar for the Global Precipitation Measurement Mission." Proceedings of the IEEE International Geoscience and Remote Sensing Symposium, vol. 5, pp. 3566–3569 (2004).
10. Van Keuls, F. et al., "YBaCuO, Au/SrTiO/LaAlO Thin Film Conductor/Ferroelectric Coupled Microstripline Phase Shifters for Phased Array Applications," Appl. Phys. Lett., vol. 71, pp. 3075–3077, 1997.
11. Romanofsky, R.R. et al., "A Statistical Analysis of Laser Ablated $Ba_{0.50}Sr_{0.50}TiO_3/LaAlO_3$ Films for Microwave Applications," Mat. Res. Soc. Proc., vol. 720, pp. 111–122, 2002.
12. Romanofsky, R., "Advances in Scanning Reflectarray Antennas Based on Ferroelectric Thin Film Phase Shifters for Deep Space Communications," Proc. IEEE, Vol. 95, No. 10, October, 2007, pp. 1968–1975.
13. Stangle, M., Werninghaus, R., and Zahn, R., "The TerraSAR–X Active Phased Array Antenna," IEEE Int. Symp. Phased Array Systems and Technology, pp. 70–75 (2003).
14. Cline, D., Davis, R.E., and Yueh, S., "Cold-Land Processes Pathfinder Mission Concept," Decadal Study, National Academy of Sciences, May 2005.
15. Lacomme, Hardange, J.-P., Marchais, J.-C., and Normant, E., Air and Spaceborne Radar Systems, (Scitech, Norwich, 2001).

REPORT DOCUMENTATION PAGE	*Form Approved* *OMB No. 0704-0188*

1. REPORT DATE *(DD-MM-YYYY)* 01-10-2009	**2. REPORT TYPE** Technical Memorandum	**3. DATES COVERED** *(From - To)*

4. TITLE AND SUBTITLE Concept for a Low-Cost, High-Efficiency Precipitation Radar System Based on Ferroelectric Reflectarray Antenna	**5a. CONTRACT NUMBER**
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S) Romanofsky, Robert; Mueller, Carl; Chandrasekar, Chandra, V.	**5d. PROJECT NUMBER**
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER WBS 439432.04.04.01
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) National Aeronautics and Space Administration John H. Glenn Research Center at Lewis Field Cleveland, Ohio 44135-3191	**8. PERFORMING ORGANIZATION REPORT NUMBER** E-17005
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) National Aeronautics and Space Administration Washington, DC 20546-0001	**10. SPONSORING/MONITOR'S ACRONYM(S)** NASA
	11. SPONSORING/MONITORING REPORT NUMBER NASA/TM-2009-215663

12. DISTRIBUTION/AVAILABILITY STATEMENT
Unclassified-Unlimited
Subject Category: 32
Available electronically at http://gltrs.grc.nasa.gov
This publication is available from the NASA Center for AeroSpace Information, 443-757-5802

13. SUPPLEMENTARY NOTES

14. ABSTRACT

This work proposes a concept on a novel scanning phased array, based on thin film ferroelectric phase shifters, for an X-band precipitation monostatic radar.

15. SUBJECT TERMS
Radar; Ferroelectric materials

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON** STI Help Desk (email:help@sti.nasa.gov)
a. REPORT U	**b. ABSTRACT** U	**c. THIS PAGE** U	UU	12	**19b. TELEPHONE NUMBER** ***(include area code)*** 443-757-5802