

# A Dual-Polarized mm-wave Active Array Feed for the Second Generation Rain Radar

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**Abstract** — The Second Generation Precipitation Radar (PR-2) is a dual frequency (14 and 35 GHz), dual polarization radar system concept with substantially increased capabilities compared to today's instruments (TRMM). Dual frequency and polarization capability enhance rain retrieval accuracy and adaptive wide-swath scanning greatly increases areal coverage.

The system concept is built upon a novel 5-m inflatable cylindrical reflector fed by an electronically-scanned phased array feed. A prototype subarray of the full 368-element feed array is being developed under the NASA ESTO ATI program. This 35 GHz subarray combines eight 1 watt transmitter channels and 16 receiver channels into a module that is 4.2 cm wide. Compact orthomode transducers and square waveguide apertures are used to feed a pair of flared, corrugated plates. This technique along with state-of-the-art mm-wave MMICs and innovative packaging yields a robust, high-performance and relatively low-cost subarray.

## I. INTRODUCTION

The Precipitation Radar (PR) aboard the Tropical Rainfall Measuring Mission (TRMM) satellite has successfully demonstrated the feasibility of measuring rainfall using spaceborne radar [1]. However, it is desirable for future rainfall measuring missions, such as NASA's planned Global Precipitation Mission (GPM) to both enhance the performance of the precipitation radar and reduce its mass. To these ends, a system concept using a dual-frequency radar with a deployable 5.3-meter electronically-scanned membrane antenna and real-time digital signal processing has been developed. This new system, the Second Generation Precipitation Radar (PR-2), will offer greatly enhanced capability with a fraction of the mass of the current TRMM PR [2].

The antenna concept is illustrated in Fig. 1. A metalized Kapton<sup>®</sup> membrane is stretched between two parabolically curved inflatable tubes, forming a parabolic cylinder with the flat dimension oriented across the track of the spacecraft. An innovative adaptive cross-track scanning

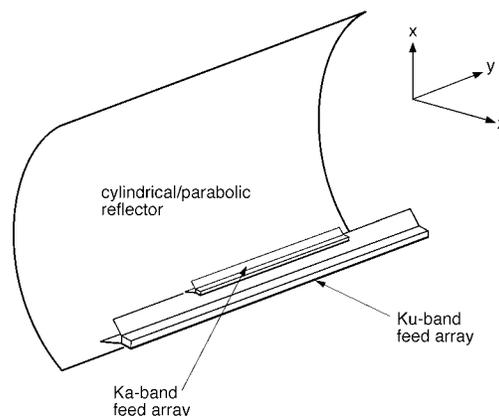


Fig. 1 PR2-Antenna Configuration

algorithm is used to maximize the fraction of sampling time devoted to measuring rain-filled pixels, thereby effectively increasing the swath width. The requirement for highly agile cross-track scanning using the parabolic cylindrical reflector dictates the use of a phased-array line feed. This line feed consists of two active dual-polarized phased arrays. We are currently developing a subarray prototype of the Ka-band active array. This array incorporates miniaturized, active transmit receive (T/R) modules, each capable of delivering 1W of output power and receiving two orthogonal linear polarizations. Dual polarization operation is achieved by using a compact orthomode transducer (OMT) with a width of less than 5mm, as is required to suppress antenna grating lobes over the desired scan range.

Table 1. Feed Array Requirements

Frequency	13.6 GHz	35.6 GHz
Number of elements	368	368
Transmitted power	1 W / el	1 W / el
Transmit polarization	H	H
Receiver noise figure	3 dB	4 dB
Receive polarization	H,V	H,V
Phase Shifter bits	5	5
Sidelobe level	-30 dB	-30 dB
Crosspol leakage	-25 dB	-25 dB
Maximum scan angle	37°	37°
Element spacing	5.4 mm	14.3 mm
Array Length	2.0 m	5.2 m

## II. FEED ARRAY DESIGN

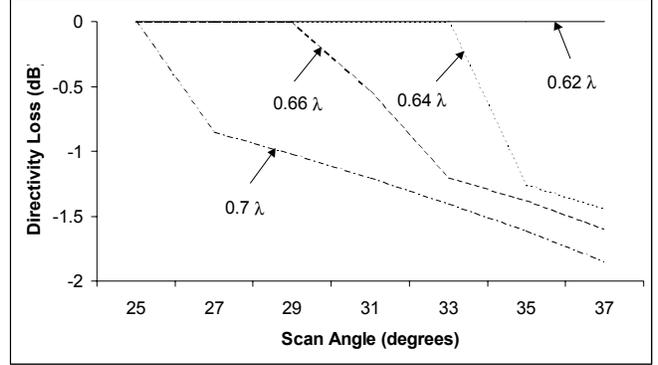
The requirements for the dual-polarized active array feed are listed in Table 1. Because it is desirable to match the beamwidths between the two frequencies, both the Ku-band and Ka-band arrays have similar number of elements, although the Ku-band array is 2.6 times longer than the Ka-band array. The Ka-band array, which is the focus of this research, will be 2 m long. This will be composed of 368 elements spaced at a pitch of 5.4 mm ( $0.64 \lambda$ ). The 368 elements will be packaged in groups of eight. Each of these 8-packs will contain eight 1 W transmitter channels and 16 receiver channels. These are coupled to the eight radiating element using circulators and the compact OMTs. The output of each OMT is a square aperture, which supports both polarizations, opening onto a flared, corrugated, plate waveguide. The corrugated flared plates provide the necessary gain and sidelobe suppression for proper illumination of the reflector surface.

### A. Array Size and Spacing Considerations

Complete elimination of grating lobes over the scan region of  $37^\circ$  from broadside requires an array spacing of  $0.62 \lambda$ , where  $\lambda$  is the free space wavelength. However, this would necessitate the use of a greater number of array elements and increase the difficulty of packaging the module electronics. Simulations were conducted to find a spacing that is as large as possible without degrading performance unnecessarily. For a spacing of  $0.64 \lambda$ , a maximum loss of about 1.4 dB at the extreme scan angles is encountered due to the presence of a grating lobe. Fig. 2 shows a plot of scan loss introduced by the onset of grating lobes for different values of array element spacing and scan angles. The scan loss due to beam broadening effect has not been accounted for, since such an effect is common to all values of element spacing.

### B. Design of Orthomode Transducer

An orthomode transducer (OMT) multiplexes the two linear polarization channels into the square waveguide feed. A compact OMT was designed to accommodate the



5.3 mm array spacing. The design of OMT was facilitated by a full wave electromagnetic analysis by the finite element method and subsequent optimizations. By a proper choice of spacing between the inline and the orthogonal ports and matching iris (inductive and capacitive, respectively) we were able to match both ports and achieve the required polarization isolation. Subsequently, we analyzed the structure for dimensional tolerance and found that a tolerance of  $40 \mu\text{m}$  is adequate.

A prototype of the OMT design was fabricated using the electroforming process. During this process, copper is electroplated upon a mandrel. After sufficiently thick metalization is built up, the mandrel is removed. This process creates very accurate interior surfaces with an excellent finish.

Since the OMT uses non-standard reduced-height waveguides to achieve its compact dimensions, adapters to standard WR-28 waveguide were also fabricated. These adapters were used to connect the OMT to a vector network analyzer in order to measure the s-parameters. A conical load was inserted into the antenna port of the OMT. The results of the testing of the OMT prototype are shown in Fig. 3. The OMT shows a peak return loss of over 30 dB at both the H and V ports with a return loss of better 26 dB at the design frequency. Port-to-port isolation is 35 dB and is very broad in frequency. The results agree well with simulation and are better than required for our application.

### C. Analysis and Design of Square Waveguides Feeding Flared Corrugated Plates

Our previous study of the PR-2 antenna showed that a  $\cos^{20}\theta$  radiation pattern in the vertical plane is required for the Ka-band feed array illuminating the reflector. The vertical plane pattern of a vertically polarized (E-plane) wave of the flared horn without corrugations would exhibit high sidelobes, as shown in Fig. 5. It is possible to design optimum values of flare angle and the aperture size so that the two patterns coincide in the main beam region. However, without the use of corrugations it is not possible

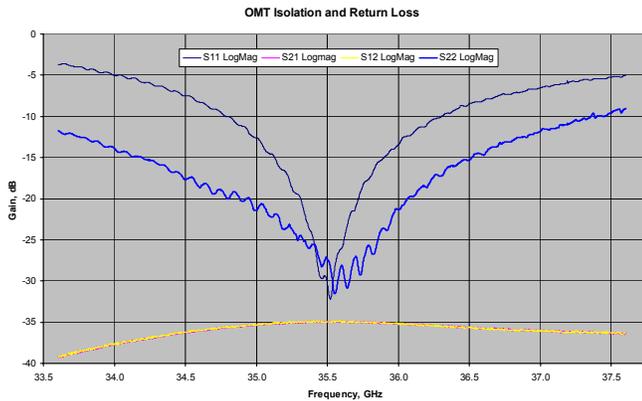
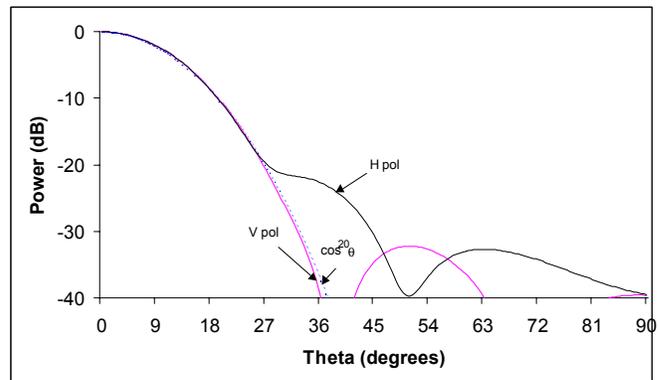
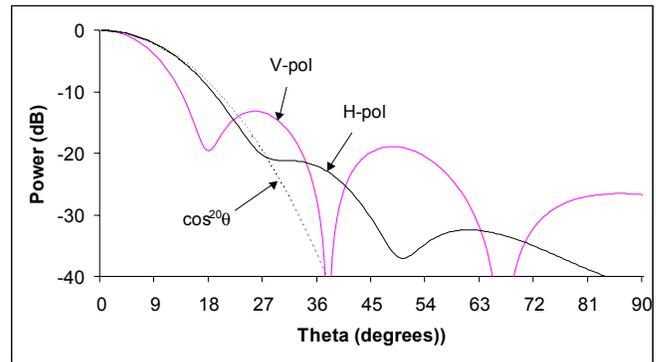


Fig 4. Corrugated, flared plate feed

to reduce the level of these sidelobes. Since the cylindrical reflector of the PR-2 antenna is under-illuminated at Ka-band, radiation from the high sidelobes mentioned above will be scattered by the reflector and produce undesirable effects in the main beam of the reflector.

Properly designed corrugated walls reduce the sidelobes in the vertical plane for the vertically polarized wave as shown in Fig. 6. It is also noted that the patterns for both polarizations are very close to that of the  $\cos^{20}\theta$  pattern desired. The results in Fig. 7 were obtained by the well-known mode matching technique. Instead of using an array of flared horns, we propose to use a pair of flared corrugated walls fed by an array of square waveguides. This simplifies the manufacturing process considerably since the corrugated plates may be easily milled or extruded. Fig. 4. illustrates the structure of corrugated flared plates excited by an array of square waveguides.

In order to determine the input reflection coefficient of each waveguide port, initially we studied the problem of an infinite array of square waveguides feeding a parallel plate waveguide system. This problem is easier to model analytically by a full wave electromagnetic code. Again, the finite element analysis yielded the value of reflection



coefficient as a function of scan angle. The reflection coefficient is generally small for the vertical polarization ( $TE_{10}$  mode excitation) and for smaller values of scan angles in the case of horizontal polarization ( $TE_{01}$  mode excitation). Our studies on wide-angle impedance matching with a single dielectric sheet did not produce significant improvements to the input reflection coefficients for both polarizations. Note that over a wide range of scan angles the reflection coefficient is either small or constant. Therefore, a tuning arrangement at the input port of each polarization separately would be adequate for matching, except for large values of scan angles for the horizontal polarization. Since the PR-2 radar uses the horizontal polarization only for reception, we may tolerate a higher value of mismatch, especially for large values of scan angles.

We also studied the reflection coefficient at an input port of an infinite array of square waveguides with flared corrugated plates. These results were found to be similar to the parallel plate results. This shows that the reflection occurs primarily at the junction of the square waveguides and the flared plates. In the experimental model of a small finite array we plan to use some dummy elements at each end of the array.

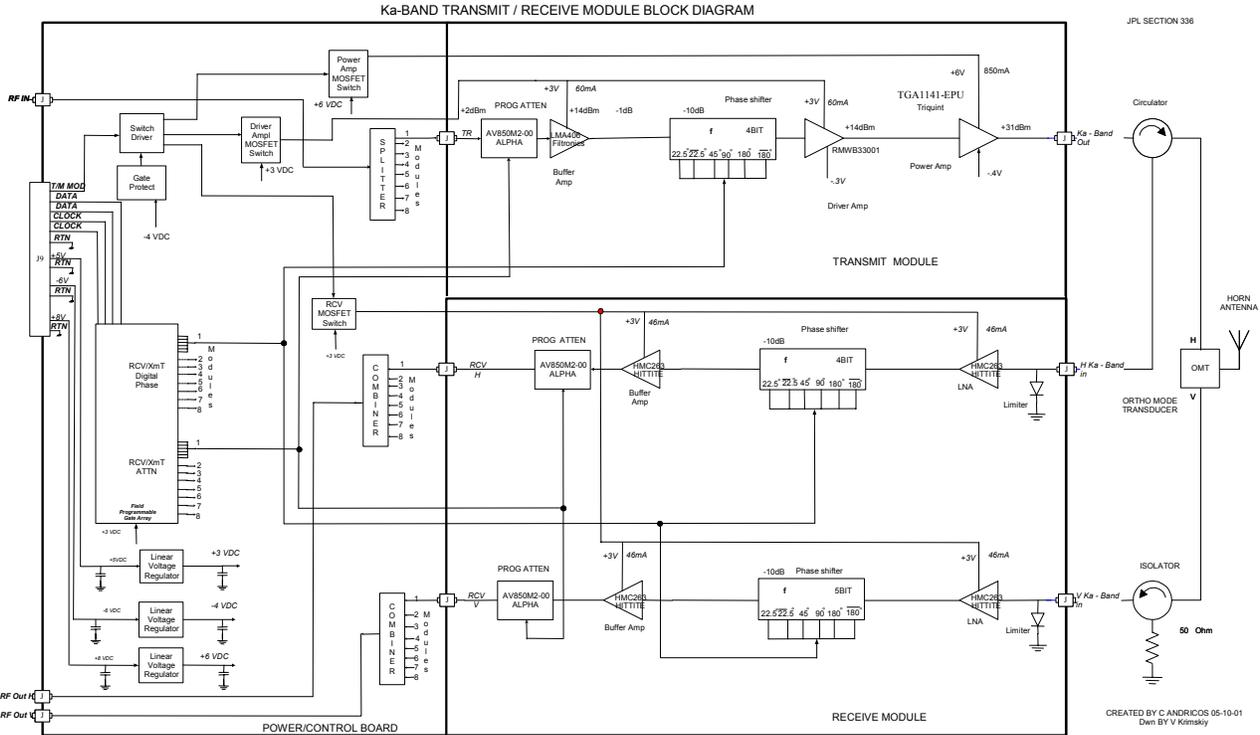


Fig. 7. Block Diagram (one receive and one transmit channel shown)

### III. T/R MODULE DESIGN

The overall system requirements and the results of antenna configuration studies determined the requirements for the T/R modules, which were summarized in Table 1. The specifications that present the greatest challenge are the transmitter output power (1 W) and the element spacing (5.3 mm). The required transmitter power is very near the limit of what can be obtained from a single MMIC and the required element spacing makes combining power from several MMICs difficult. The elements spacing also presents challenges for the receiver design, since two receiver channels (one for each polarization) must fit in the space allotted to one array element.

In order to achieve the required element density, the electronics are fabricated as eight element subarrays, each containing 8 transmitter channels and 16 receiver channels, power dividers and combiners, control and DC bias circuitry that is shared amongst the channels. The block diagram for this T/R 8-pack is shown in Fig. 7.

The transmit signal is received from a 46-way divider network that will feed all the 8-packs in the full size array. It is then distributed to the transmitter channels using an 8-way corporate microstrip divider. After buffering, signal is fed to a programmable attenuator and phase shifter. Amplitude and phase is programmable individually for

each channel. This signal is then fed to a driver amplifier and the power amplifier (PA) that produces 1 W output power. The final amplifier operates at its 1 dB compression point providing nearly linear amplitude control. This permits the use of pulse shaping which is required to achieve the very low range sidelobes required for a nadir-look rain radar. In order to reduce power consumption the PA is biased off during the receive intervals. This is achieved using a low on-resistance FET that feeds all the power amplifier channels.

On the receive side, the signals pass from both ports of the OMT, through circulators to the low-noise amplifier (LNA). A diode limiter is used on the LNA input in order to protect the LNA from leakage during the transmit interval. The signal from the output of the LNA is fed to a phase shifter, another amplifier and then a programmable attenuator. Amplitude and phase of the receiver channels are adjustable in pairs.

In order to achieve the required packing density, the circuits are constructed using bare MMIC die on multilayer low-temperature cofired ceramic (LTCC) substrates. Fig 8. shows the 8-pack packaging configuration. A machined housing is used to carry two LTCC motherboards, one on each side. One LTCC substrate contains 8-transmit channels, the DC bias circuitry and the digital control circuitry while the other one contains 16 receiver channels. In the transmit side,

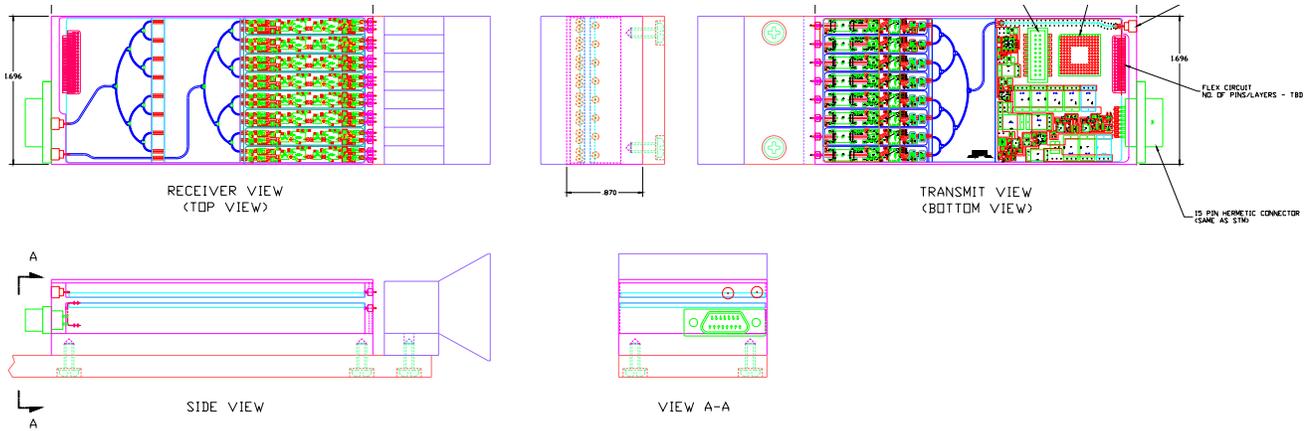


Fig. 8. T/R 8-pack configuration

each channel is separated by a metal ring frame in order to improve channel-to-channel isolation. On the receive side the channels are isolated by eight ring frames as eight pairs. Additionally, drop-in alumina power dividers and combiners are used. Alumina is used for the dividers and combiners because of its lower loss.

Prior to fabricating the LTCC 8-pack, samples of the MMIC parts were individually packaged and tested over temperature. Using the results of this testing, integrated transmit and receive chain brassboards were designed and fabricated. These integrated brassboards use the same RF circuit layouts as the LTCC version, but are fabricated on single-layer alumina substrates and omit the digital control circuitry. Because of the relatively high cost of fabricating the substrates for the LTCC 8-pack, it is prudent to use this intermediate step to validate the design and circuit layout. The performance of these brassboards should be very similar to the final LTCC version. Currently, these integrated brassboards are undergoing testing.

When brassboard testing is complete, final adjustments will be made to the LTCC circuit designs and the 8-pack will be fabricated. Initially, only one element will be populated. After initially testing, all the channels will be populated and the 8-pack will be fully characterized. Final testing will include measurements of channel-to-channel variations as well as coupling between channels.

#### IV. CONCLUSIONS

In order enable the implementation of the Second Generation Precipitation Radar, we have designed an electronically-scanned, dual-polarized 35-GHz phased array antenna feed. We have developed and analyzed an array consisting of square waveguide apertures feeding long corrugated flared plates. This arrangement has low loss, is easily manufacturable and generates the required pattern for illumination of the reflector.

To separate the polarizations of the received signal from the square waveguide, we have developed a compact OMT that uses reduced height waveguide. This OMT meets the stringent array spacing requirements and provides 35 dB of isolation between the polarizations as well as excellent return loss.

A highly integrated T/R module subarray is currently being developed. Using bare MMIC dice mounted on two LTCC substrates we have combined eight transmit channels, 16 receiver channels as well as bias and digital control circuitry for these modules into a single package with a volume of less than 90 cm<sup>3</sup>. We have successfully brassboarded the transmit and receive chains on alumina and expect to fabricate the 8-pack module later this year.

#### ACKNOWLEDGMENTS

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