Dual-Band Shared Aperture Reflector/Reflectarray Antenna Designs, Technologies and Demonstrations for NASA’s ACE Radar

Thomas Hand, Michael Cooley, Gary Kempic, David Sall, Peter Stenger, Sarah Woodworth, Richard Park
Northrop Grumman Electronic Systems (NGES)
Baltimore, MD USA
thomas.hand@ngc.com

Paul E. Racette, Gerald Heymsfield, Lihua Li
NASA Goddard Space Flight Center (GSFC)
Greenbelt, MD USA

Abstract—NASA’s planned Aerosol, Cloud and Ecosystems (ACE) mission will provide RF measurements for studying the role of aerosols on cloud development. The space-borne radar requires a fixed-beam at W-band and a wide-swath (>100 km) scanning beam at Ka-band.

The full scale antenna is comprised of a parabolic cylinder reflector/reflectarray with a fixed W-band feed and a Ka-band Active Electronic Scanning Array (AESA) feed. Cassegrain folded optics is employed to reduce the required mass, volume, mechanical complexity and cost. An innovative reflectarray design provides a focused low-loss pencil beam at W-band, and is RF transparent at Ka-band. The AESA transmit/receive (T/R) modules provide high RF output power and low noise figure.

Several planar reflector/reflectarray prototypes were designed and fabricated to validate the novel reflectarray element/surface technology and design methodology. The measured W/Ka band reflector/reflectarray gains and patterns agree very well with predictions thereby confirming the viability of the full scale design.

Keywords—Reflectarrays, Reflectors, Millimeter Wave, NASA Earth Science, Phased Arrays, AESA

I. DUAL-BAND ANTENNA ARCHITECTURE

The proposed ACE dual-band reflector/reflectarray antenna system design, first described in [1-5], is shown in Figure 1. For Ka-band (35 GHz) operation, the parabolic cylinder reflector is fed by an AESA line feed located at the virtual focal line of the parabolic cylinder (Cassegrain optics) and ±10 degree azimuth beam steering is provided by electronically scanning the feed in one dimension (azimuth). Array fed offset reflector trades were performed using the COTS GRASP™ code, and a T/R module design was developed in parallel to meet radar performance requirements such as sensitivity and side lobes. System trades were used to develop a module design (shown in Figure 2) to meet critical requirements, while also addressing mechanical and thermal concerns. Four elements are needed in the elevation (vertical) plane to provide proper secondary reflector illumination taper and meet stressing sidelobe requirements.

For W-band (94 GHz) operation, a horn feed source is located at a virtual focal point (Cassegrain optics with beam waveguide) as shown. A very thin single layer printed circuit reflectarray surface [6] (transparent at Ka-band) provides azimuth and elevation focusing of the W-band energy to/from the main parabolic cylinder [7-16]. The W-band reflectarray surface also provides a slight elevation displacement of the virtual focus that enables separation of the sub-reflectors and the feeds. This design retains co-alignment of the Ka and W-band beams.

II. DUAL-BAND REFLECTOR/REFLECTARRAY DESIGN

A. Reflectarray Design

Reflectarrays combine the features of reflector and array antennas and typical designs employ a periodic lattice of printed circuit elements etched on one or more dielectric layers [7-16]. These designs can be fully passive (fixed beam) or active with tunable devices to provide phase shifting (scanned beam) [7,17]. Most reflectarrays are designed with array lattice spacings of ~λ/2 and crossed dipoles, microstrip patches and loops/rings are commonly employed as elements [7,11-12,17]. For passive fixed beam reflectarrays, the required surface phasing is typically achieved by using printed circuit board (PCB) elements of differing size (operating above, below and at resonance). There are several important factors to consider in reflectarray design: 1) phase swing (range of achievable reflection phase), 2) absorption loss (dissipative losses in the metal and dielectric substrate), and 3) phase slope/sensitivity (derivative of the reflection phase with respect to element size). All of these factors have a significant impact on gain, pattern fidelity, bandwidth and manufacturability.

Figure 1: Full-Scale shared aperture Ka/W-band Cassegrain reflector/reflectarray architecture.

Figure 2: Ka-band AESA and T/R Module designs provide Ka-band azimuth scanning for the ACE radar.
The reflectarray element must be rigorously analyzed and characterized to enable accurate synthesis and analysis of the reflectarray aperture patterns. The complex reflection coefficient (magnitude and phase) of the element should be calculated over all relevant incidence angles and polarizations, since the phase characteristics will vary with these parameters [7]. As the size of the element increases for a fixed frequency, the reflection coefficient phase angle typically decreases monotonically. As the element size approaches the resonance condition, the slope of the reflection phase curve will increase and then gradually decrease as the element size moves farther away from resonance [7]. Since most of the needed phase angles typically exist at or near resonance (where the phase slope is high), small changes in the element geometry can cause significant phase errors.

Achieving a reflectarray design with low loss and large phase swing on a single layer dielectric can be challenging, especially at millimeter wave frequencies (e.g. W-band). While multi-layer element designs can overcome phase swing limitations, thicker dielectric substrates can support unwanted modes or surface waves [18] which can lead to increased loss and degraded performance. Furthermore, single layer reflectarray designs are lighter, simpler and less prone to manufacturing/registration errors. The relative advantage of the ACE shared aperture design approach stems from using a dual-band reflector, as opposed to two separate reflectors, to reduce the size, weight, mechanical complexity and cost [1-4,19]. This advantage is directly linked to the achievable aperture efficiency; excessive loss in the reflectarray surface at either band would necessitate a larger aperture for a given required system sensitivity and would compromise the shared aperture approach.

B. Reflector and Reflectarray Synthesis/Analysis

The dual-band reflector/reflectarray is synthesized and analyzed using both commercial-off-the-shelf (COTS) and custom physical optics (PO) based design software tools. The W-band reflectarray design utilizes a custom MATLAB™ code that employs a PO design synthesis/analysis methodology. Our reflectarray design methodology and underlying MATLAB™ analysis code is similar to Physical Optics (PO) design tools such as those employed by the GRASP™ and OSU SATCOM codes [19,20]. However, the reflectarray surface is gridded into unit cells consistent with the printed circuit reflectarray element grid (nominally ≈0.6λ spacing) and the reflection coefficient phase from each cell is left as a variable (not 180° as for standard PO). The Ka-band reflector design and analysis utilizes the GRASP™ code and several custom MATLAB™ codes.

For synthesis of the W-band reflectarray, the complex reflection coefficient (S11) of the element is calculated parametrically by varying the element size/geometry, incidence angle, and polarization. To determine the range of incidence angles and polarizations required on the reflectarray, the feed/reflector geometry is first defined. The feed horn size (placed at the virtual focus) is chosen to provide the appropriate amplitude taper on the reflectarray surface, which determines the achievable antenna gain and side lobe performance. Our MATLAB™ synthesis/analysis code imports the feed horn pattern and reflector geometry definition file, and synthesizes a surface to collimate a beam at the desired angle. The fixed phases of the reflectarray elements are physically realized via a patterned array of printed circuit elements of various sizes on a flexible substrate that is bonded to the reflector.

The Ka-band reflector analysis is performed using the GRASP™ software. An offset AESA line feed is sized and positioned to illuminate the planar reflector with the appropriate amplitude taper, and far-field pattern cuts are then computed. The GRASP™ software has the flexibility to incorporate various feed/reflector models and/or feed/array measured patterns.

C. Reflectarray Element Design and Analysis

The reflectarray element is modeled using a COTS fullwave solver (Ansys HFSS™), where the complex reflection coefficient is computed over the appropriate range of incident angles and polarizations. Figure 3 depicts a typical unit cell; the reflectarray element is modeled in an infinite array environment. Two modes (TE and TM) are simulated at various incident angles, and the complex reflection coefficient is calculated for a parametric variation of the element geometry (i.e. dipole arm length). Figure 3 shows the unit cell HFSS™ model with plane wave illumination; the range of simulated incidence angles must be consistent with the reflector/feed geometry and architecture. The incident plane wave is decomposed into components that are parallel and perpendicular to the plane of incidence, as seen in Fig 3. Because of symmetry, the complex S11 need not be calculated over the entire forward hemisphere of the element. Only a spherical sector from θ=0°-45° degrees, and θ = 0°-θ_{max}° is needed in order to fully characterize the element over the cone of relevant incidence angles (right graphic of Figure 3). This allows for a reduced number of full-wave simulations, which reduces the computational burden of the design. The incident plane wave is then mapped onto the reflectarray surface, given in Cartesian coordinates by equation 1.
\[ E_x = E_i \cos \theta \cos \varphi + E_i \cos \varphi \\
E_y = E_i \cos \theta \sin \varphi + E_i \sin \varphi \]  
(1)

The fields in eqn. (1) are proportional to the induced current on the reflectarray surface, and they are important in determining the element geometry (i.e. dipole arm length) at each grid point. Figure 4 shows a graphic of the reflector/feed geometry for a planar, offset-fed reflectarray. The feed horn is sized and positioned to achieve a symmetric amplitude taper on the surface, and is offset in elevation to mitigate feed horn blockage.

For the ACE full scale space-borne reflectarray, there are several stressing design requirements that drive the element design. Minimizing mass and simplifying the large aperture reflector/reflectarray manufacturing process are of primary importance and stipulating the use a single layer reflectarray element mitigates these concerns.

\[ E_y = \text{E}_m \cos \theta \sin \varphi + \text{E}_z \cos \varphi \]

\[ E_y = \text{E}_m \cos \theta \sin \varphi + \text{E}_z \cos \varphi \]

The fields in eqn. (1) are proportional to the induced current on the reflectarray surface, and they are important in determining the element geometry (i.e. dipole arm length) at each grid point. Figure 4 shows a graphic of the reflector/feed geometry for a planar, offset-fed reflectarray. The feed horn is sized and positioned to achieve a symmetric amplitude taper on the surface, and is offset in elevation to mitigate feed horn blockage.

Once the reflector/feed geometry has been defined and a feed has been specified, the required element geometry at each reflectarray grid point is calculated using the previously described MATLAB™ code. A preferred polarization must be defined in order to determine the needed phase at each grid point. For a y-oriented preferred polarization, the required return phase at each grid point is found from:

\[ E_y = \text{E}_m \cos \theta \sin \varphi + \text{E}_z \cos \varphi \]

\[ E_y = \text{E}_m \cos \theta \sin \varphi + \text{E}_z \cos \varphi \]

\[ E_y = \text{E}_m \cos \theta \sin \varphi + \text{E}_z \cos \varphi \]

D. Hybrid Loop Reflectarray Element

For the ACE full-scale space-borne reflectarray, there are several stressing design requirements that drive the element design. Minimizing mass and simplifying the large aperture reflector/reflectarray manufacturing process are of primary importance and stipulating the use a single layer reflectarray element mitigates these concerns.

Figure 4: Feed/Reflectarray configuration at W-Band. A feed horn is sized and oriented to provide a symmetric amplitude taper on the planar reflector.

The range and distribution of plane wave incidence angles onto the reflector is shown in Figure 5. The top plot of Figure 4 shows the incident \( \theta \) angle distribution, with a peak value of \(-40^\circ\). The bottom left plot of Figure 5 shows the incident \( \phi \) angle distribution, and the bottom right plot shows the incident \( \phi \) angle mapped into the \(0^\circ-45^\circ\) “octant” sector shown in Figure 3. This reduced \( \phi \) angle distribution allows for a decreased number of full-wave HFSS™ simulations.

However, typical single-layer element design approaches can suffer from high losses and limited phase swings (typically \(330^\circ-340^\circ\) or less) [7] that lead to gain loss and increased side lobe levels. Furthermore, a W-band reflection coefficient with a full \(360^\circ\) of phase swing is needed in order to meet the low side lobe requirements.

Traditional single layer reflectarray element designs such as dipoles, rings and microstrip patches have relatively high-Q resonances [7,12]. Consequently, at millimeter wave frequencies, they tend to suffer from high absorptive losses and large phase errors due to stressing fabrication tolerances. To reduce these losses and errors, a low-Q element design with a full \(360^\circ\) of phase swing is desired.

To address this challenge, we’ve developed an alternative design that utilizes two unique element designs to cover the full \(360^\circ\) range of phase swing. By operating each of these complimentary elements away from its resonant region, the element Q is reduced and the phase error losses are lowered. Figure 6 shows this two element “hybrid” element design which employs complimentary reflectarray elements, a conventional crossed dipole (left) and a crossed loop element (right). The crossed dipole is used for the “lower” phase states (less phase shift) and the crossed loop element is used for the “higher” (more phase shift) states. Each element was modeled in HFSS™, and the complex return loss was calculated over the range of

Figure 5: (Top): Incident \( \theta \) angle on the planar reflectarray surface, (Bottom Left): Incident \( \phi \) angle on the planar reflectarray, and (Bottom Right): Mapping the incident \( \phi \) angle into the \(-45^\circ\) quadrant.

Figure 6: Unit cell design for the hybrid loop. (Left): crossed dipole element, (Right): crossed loop dipole element.
appropriate incidence angles (see Figure 5). Figure 7 shows the mode 1 (TE polarization) and mode 2 (TM polarization) reflection coefficient phase and amplitude as a function of dipole arm length hp. The yellow shaded region represents states where the crossed dipole is used, and the un-shaded region (up to phase state 110) represents states where the crossed loop dipole is used. The high loss resonance region above phase state 110 is not used; phase states 0-110 provide a full 360° of phase swing.

Figure 7: S11 phase and amplitude curves for the hybrid loop design on 15 mil Rogers 6002 substrate for different incident θ angles and φ = 0°.

III. PLANAR REFLECTOR/REFLECTARRAY Prototype

We used our MATLAB™ reflectarray design tool to synthesize a prototype planar reflectarray design using the hybrid loop element design of Figure 6. The reflectarray was designed on a triangular (rotated square) grid with the unit cell shown in Figure 6. The 12" diameter circular reflectarray prototype has 23,092 elements. A mapping of the element states and types is shown in Figure 8. A total of 256 unique element states were used (analogous to an 8-bit phase shifter) to synthesize the reflectarray (the 256 states were interpolated from the 128 states of Fig. 7).

The hybrid loop element design was fabricated on a 15 mil Rogers 6002 substrate which has a measured dielectric constant of 3.24 and loss tangent of 0.0056 at 94 GHz. A second hybrid loop design was synthesized and fabricated on 12 mil Pyralux Kapton (εr = 3.49 and tanσ = 0.0044) for comparison. Two additional reflectarray designs using conventional crossed dipoles (used throughout array) were fabricated on 10 mil Pyralux Kapton and 10 mil thick Rogers 6002 substrates as a basis for a performance comparison with the new hybrid loop designs. All four reflectarray surfaces were also designed to be transparent to RF energy at Ka-band; i.e. exhibiting frequency selective surface (FSS) properties.

Figure 9 shows a top-down view of the hybrid loop design (left) and crossed dipole design (right) on Pyralux Kapton. Each reflectarray was etched using conventional photolithography and bonded to an aluminum backer plate. The reflectarrays were attached to a reflector/feed support structure using alignment pins and screws. W and Ka-band scalar/corrugated feed horns were mounted to the assembly as shown in Figure 10. Waveguide straight and 90° twist sections were interchanged to permit measurement of the reflectarray patterns for both horizontal and vertical polarizations.

Figure 8: (Left): Element state map showing the distribution of the 256 element states across the reflectarray surface, and (Right): Element type map for the planar reflectarray showing the distribution of crossed dipole and crossed loop dipole elements across the surface.

Figure 9: Planar reflectarray coupons fabricated for design verification. (Left): Hybrid loop design on 12 mil Kapton substrate. (Right): Crossed dipole design on 10 mil Kapton.

Figure 10: Dual-band planar prototype reflectarray assembly. Scalar feed horns at Ka-band (SFH-28) and W-band (SFH-10) were used to illuminate the 12” diameter planar reflectarray coupons.
For Ka-band measurements, a 2.9 mm to WR-28 adapter was used to interface an RF cable and PNA with the waveguide feed assembly. W-band measurements were made using an X-band source (PNA) which was upconverted to W-band (75-110 GHz) using a VNA extender box as shown in Figure 10. The antenna assembly was mounted on an Az/El the positioner in compact range at NASA GSFC, as shown in Figure 11.

For the compact range testing, three types of patterns were collected: raster scans (contour patterns) within a ±3.5° Az/El window around the main beam, hemispherical pattern cuts from -90° to +90° in theta, and wide band peak gain measurements. Figures 12 and 13 show the main beam raster scan results for both polarizations for the hybrid loop design on 15 mil Rogers 6002. Predicted pattern cuts from our MATLAB™ reflectarray design tool are overlaid with the measured pattern cuts. The measured patterns agree very well with predictions, and the peak gain was within 0.1 dB of the model result.

Full hemispherical cuts also were measured for both polarizations to provide a more complete assessment of the side lobe levels. These results are shown in Figure 14 for the hybrid loop on 15 mil Rogers 6002 reflectarray design. The measured gain, patterns, and side lobe levels agreed very well with the predictions. The measured cross-polarization pattern levels were slightly higher than predicted. We determined that these elevated cross-pol pattern levels were due to poorer than expected cross-pol isolation in the circular to rectangular waveguide transition (WAC) that connects the scalar horn to the WR-10 rectangular waveguide.

Figure 15 shows measured elevation patterns (copol and cross-pol) for the hybrid loop design at Ka-band. The surface was designed to be RF transparent at Ka-band and we’ve compared these results with measured patterns from a flat aluminum plate to validate the expected RF transparency. The close agreement between the reflectarray and the aluminum plate patterns demonstrate the RF transparency of the surface at Ka-band.

The measured gains of the hybrid loop and crossed dipole design are compared in Figure 16. The gain performance advantage of the hybrid loop design, as discussed earlier, is immediately evident. The hybrid loop reflectarray design has ~2-2.5 dB greater gain than the crossed dipole design. Furthermore, the 3-dB bandwidth for the hybrid loop design is approx. 10 GHz, which is greater than that of the crossed dipole design. The lower Q of the hybrid loop element enables this wider bandwidth performance. The slight upward shift in frequency response (not centered at 94 GHz), which is more noticeable for the crossed dipole design, is due to rounding of the corners of the elements during photo-etching (this was not anticipated and was not included in our initial models).
Due to this frequency shift, the peak gain of 47.1 dBi for the hybrid loop design occurred at 95.3 GHz instead of the design frequency of 94 GHz.

![Graph showing gain vs frequency for hybrid loop and crossed dipole designs.]

**Figure 14:** V-Pol (Top) and H-Pol (Bottom) full hemispherical W-band (94GHz) pattern cuts, from ±90° in theta and 0°,90° in phi.

**Figure 15:** Ka-band (35 GHz) pattern measurements of the hybrid loop design (elevation cut). Co-pol and cross-pol elevation patterns (red, magenta curves) were taken and compared with measured patterns for a flat aluminum plate (black, blue curves).

**Figure 16:** Measured gain of the hybrid loop (15 mil Rogers 6002 substrate) and crossed dipole (10 mil Kapton) reflectarray coupons from 84-104 GHz.

**IV. SUMMARY**

The novel dual-frequency (Ka/W-band) shared aperture reflector/reflectarray antenna system for NASA’s Aerosol, Cloud and Ecosystems (ACE) mission has been described. The associated ongoing hardware technology risk reduction Program has several thrusts including: (1) development of an initial planar reflector/reflectarray prototype (described herein), (2) subsequent development of a sub-scale reflector/reflectarray prototype, 3) an associated high altitude test flight, and (4) design and demonstration of a GaN T/R MMIC suitable for usage in the Ka-band AESA line feed.

This paper has focused primarily on the recent successful design, development, and testing of the planar reflector/reflectarray prototype antenna. A new reflectarray hybrid element design approach was discussed, and validations with compact range measurements of planar prototypes validate the low-loss design and the associated MATLAB™ model.

The upcoming sub-scale antenna demonstration will consist of a parabolic cylinder primary reflector fed by a passive Ka-band line array and a W-band scalar feed horn. A printed circuit reflectarray utilizing the novel hybrid loop design on Rogers 6002 will be designed to provide a bore sight W-band pencil beam (with surface transparency at Ka-band). This antenna will be installed on the NASA ER-2 aircraft for high altitude, sub-orbital flight testing and radar measurements.

**ACKNOWLEDGMENTS**

The authors would like to thank NASA’s Earth Science and Technology Office (ESTO) for their support of the ACE Mission and the IIP initiative which is enabling the development of these antenna technologies. We also thank the ACE Science Working Group (SWG) for their advocacy and support of the mission and generation of driving radar and antenna requirements.

The authors would also like to acknowledge and thank Goddard Space Flight Center (GSFC) and Northrop Grumman Electronic Systems (NGES) for providing internal funding for early ACE radar and antenna design efforts that laid the groundwork for the developments described herein.

**REFERENCES**


