Efficiency Improvement of the Three-Meter Ka-Band Inflatable Reflectarray Antenna

J. Huang[1]

The inflatable 32-GHz (Ka-band) 3-m reflectarray is being developed to achieve low mass and small launch-vehicle stowage volume for future deep-space telecommunication spacecraft antenna application. A technology demonstration model was developed previously with excellent radiation characteristics but poor antenna efficiency. This article documents the development of a second model that has improved the efficiency from the previous 10 percent to 30 percent. This improvement is achieved primarily by a new element design with significantly improved impedance matching. A step-by-step development process and the areas for future improvement are also presented in this article.

I. Introduction

The first unit of the 3-m 32-GHz (Ka-band) inflatable reflectarray developed by JPL/International Latex Corporation (ILC) Dover, Inc. was tested in April 1999 at the compact range of Composite Optics Inc. (COI).[2] Excellent radiation patterns, as shown in Fig. 1, were measured with the expected beamwidth (0.22 deg) in the broadside direction, a very low side-lobe level (below -30 dB within ± 15 deg; below -50 dB outside ± 15 deg), and a very low cross-polarization (cross-pol) radiation (below -40 dB within ± 40 deg; below -50 dB outside ± 40 deg). These excellent results indicated that the antenna has achieved the required surface flatness (0.5 mm rms required; 0.1 mm rms achieved) and that the 3-m inflatable reflectarray antenna is mechanically feasible at the Ka-band frequency.

However, the measured antenna efficiency for this first unit (50-dB gain) was only 10 percent, which is far from the expected 40 percent (56-dB gain). This antenna inefficiency was traced to an RF design flaw. All the patch elements on the reflectarray surface had very poor impedance matches to their phase-delay lines, as shown in Figs. 2 and 3. Each patch had an edge impedance of 300 ohms, while the phase-delay lines had impedances of only 100 ohms. At the time, this was the only way to get the antenna fabricated since a 100-ohm line (0.076-mm line width) reached the limit of etching tolerance. In other words, line impedances higher than 100 ohms (lines thinner than 0.076 mm) cannot be etched accurately. Consequently, a 300-ohm patch connecting to a 100-ohm line resulted in at least a 2.5-dB mismatch loss. With two phase-delay lines attached to a single patch element to generate circular polarization, at least a 5.0-dB loss is accounted for.

[1] Spacecraft Telecommunications Equipment Section.

[2] J. Huang, "RF Test Results of the Inflatable 3m Ka-Band Reflectarray Antenna," JPL Interoffice Memorandum (internal document), Jet Propulsion Laboratory, Pasadena, California, April 26, 1999.

The research described in this publication was carried out by the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

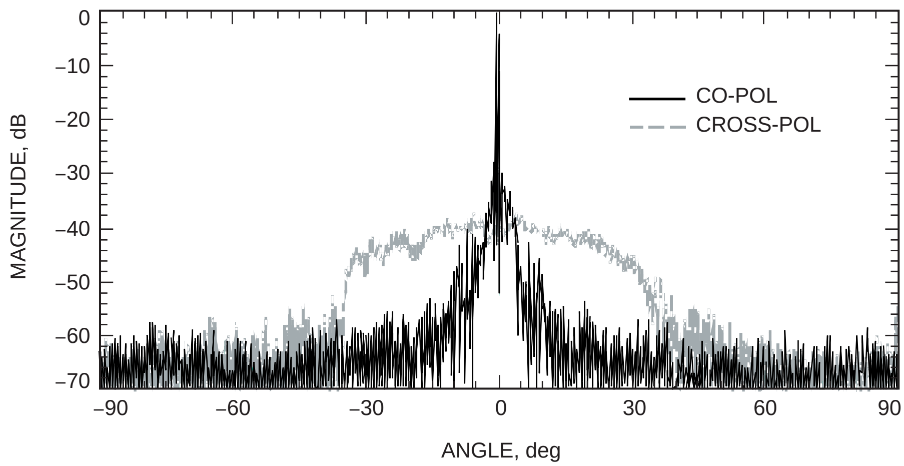

Fig. 1. The measured radiation pattern of the first unit; the peak gain is 50 dB.

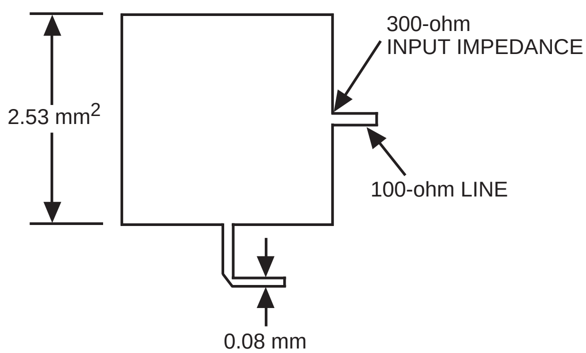

Fig. 2. The reflectarray patch element of the first unit.

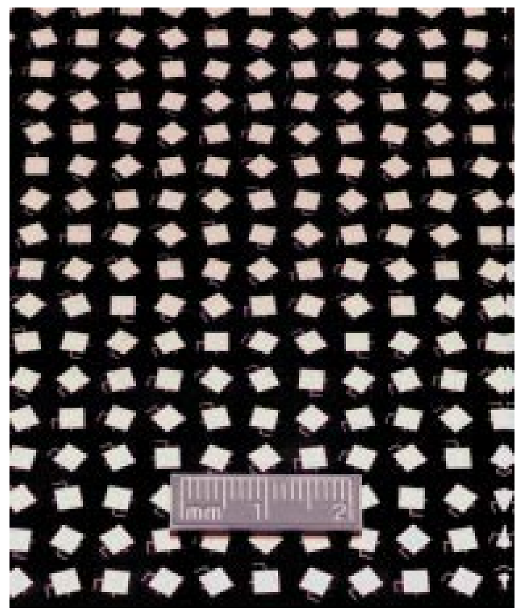

Fig. 3. Photo of the reflectarray patch elements for the first unit.

A second-iteration effort was initiated at the end of FY'99 to correct the above design flaw. The detail of the new design for this second iteration is presented in the following section. The new design has improved the efficiency from 10 percent to 30 percent (a 4.4-dB gain improvement). Although this has not reached the goal of 40 percent, it is a significant improvement. Several possible areas for further improvement have been identified and are discussed in a later section.

II. New Element Design

The unique new patch element design that allowed patch impedance to be matched to the attached transmission line is shown in Fig. 4, with a photograph provided in Fig. 5. The patch element has a nearly square shape with a corner-fed phase-delay line. The corner feed generates the required two orthogonal polarization components in the patch element, while the slightly rectangular shape (two unequal patch dimensions) provides the needed 90-deg phase differential for circular polarization. The input impedance at the corner of the patch, for this case, is about 150 ohms, which still is not quite matched to the 100-ohm phase-delay line. This is why the two additional stub tuners are used toward the end of the phase-delay line to enhance the impedance matching. These two stub tuners, together with the phase-delay line, form a fork-like shape. The calculated impedance match (or return loss) versus frequency is given in Fig. 6, where it shows a −15 dB return loss with a −10 dB bandwidth of 550 MHz.

III. Second-Iteration Development Process

The detailed step-by-step development process, starting from the new element design to the final antenna testing, is described in the following subsections.

A. Element Design

The new element design was primarily carried out by the computer analysis tool Ensemble, developed by Ansoft Corp. The slightly rectangular patch element first was analyzed as a radiating element with

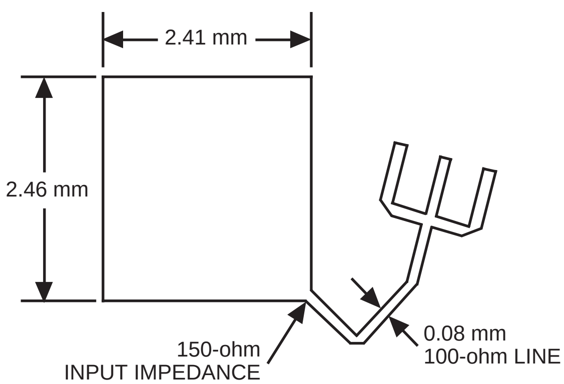

Fig. 4. The new patch element with matched impedance.

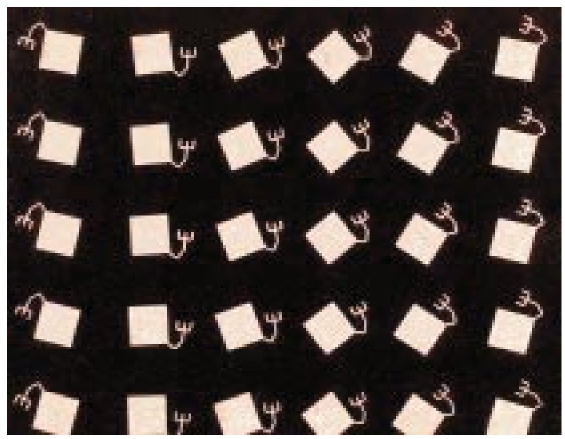

Fig. 5. Photo of the new reflectarray elements.

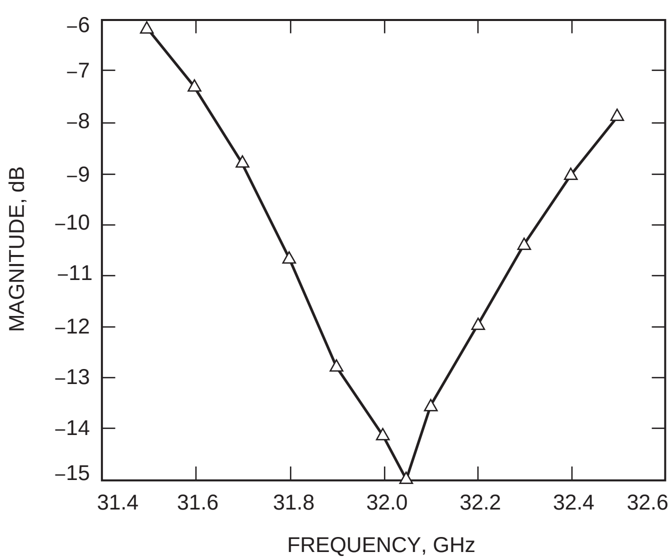

Fig. 6. The calculated input impedance match (return loss) of the new reflectarray element shown in Fig. 4.

a strip excitation source. This strip source was attached to the end of the fork phase-delay line. This calculation was to ensure that the patch element's resonant frequency occurs at the design frequency of 32.0 GHz. The result is shown in Fig. 6. The second step was to analyze the patch as a reflectarray element by calculating its radar cross section (RCS). The element configuration is the same as that in Fig. 4, and the calculated RCS is given in Fig. 7. Since Version 5.1 of the Ensemble software, used at the time of the design, can calculate only a linearly polarized RCS, Fig. 7 shows RCS results for only horizontal TMTM (transmit transverse magnetic and receive transverse magnetic) and vertical TETE (transmit transverse electric and receive transverse electric) linear polarizations. The intersection point of the two curves gives the best resonant frequency for the circularly polarized reflectarray element. The phase curves of the two linear polarizations also were calculated (for brevity, not shown here), where the 90-deg phase differential was achieved at the same resonant frequency. To give additional assurance, this element design also was analyzed and confirmed by using a different software tool: High Frequency Structure Simulator (HFSS). It employed an infinite array approach and included mutual coupling effects between neighboring elements. The result was positive and indicated the correct resonant frequency for the element.

B. Reflectarray Design

The complete reflectarray using the above element was designed using the reflectarray analysis tool developed by the author of this article. The reflectarray configuration is identical to the first unit developed in FY'99. It has a focal length-to-diameter ratio (f/D) of 0.75, a diameter of 3 m, a corrugated feed horn with edge taper of -9 dB, and approximately 200,000 elements with variable rotation angles. The variable element rotation angles [1], shown in Fig. 5, are used to compensate for the different phase delays from the elements to the feed horn. The design then was given to the JPL Electro-Mechanical Design Engineering Group (and designed by John Cardone), where a complete computer-aided design (CAD) drawing and a complete set of geometry data of the reflectarray elements were created.

C. Membrane Etching

The membrane material (110 m by 61 cm), made of 5-mil-thick UPLEX polyimide dielectric substrate and 5-μm copper, was procured from Gould Electronics, Inc. This procurement took about 2.5 months because the raw material had to be ordered from Japan. The membrane material along with the reflect-

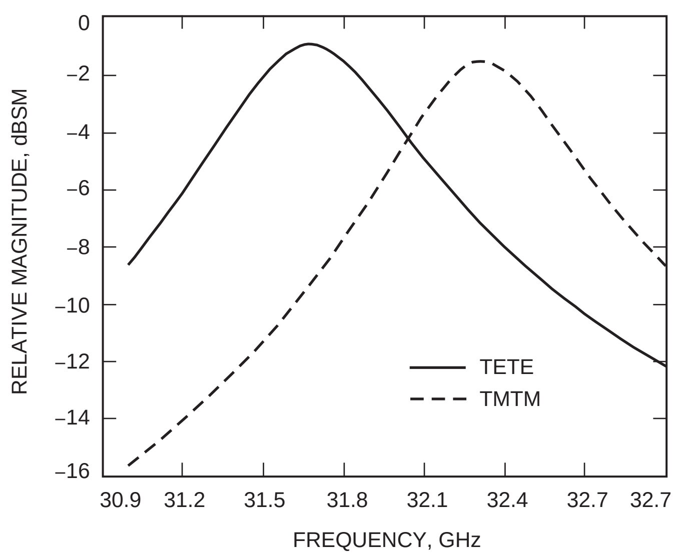

Fig. 7. A radar cross-section calculation of the new element shown in Fig. 4. Two linear polarizations are used (TETE and TMTM).

array CAD design data were furnished to the etching company, FlexLink, where the etching masks were manufactured. Subsequently, two sets of reflectarray membranes were etched. Each set, which makes up a single 3-m-diameter aperture, consists of seven strips of 45.7-cm-wide etched membranes. The extra set of membranes was intended to serve as spares. The above etched products (including the etching masks) required about 6 weeks of effort. The two sets of etched membranes then were taken back to JPL, where thin layers of acrylic solution coatings were sprayed onto all membranes to protect the copper from oxidation. This spraying was performed by human and not by automated machine, which most likely caused nonuniformity in coating thickness and lowered the antenna efficiency slightly. Nonuniform coating will cause the elements to resonate at slightly different frequencies.

D. Membrane Assembly

The two sets of membranes (each set consisting of seven rectangular strips) were shipped to ILC Dover, Inc., where the seven strips were assembled into a 3-m-circular aperture. The seven strips first were precision cut to the correct sizes and taped together to form the required 3-m aperture. ILC Dover did an excellent job of ensuring there is minimal membrane wrinkling due to handling. Along the perimeter of the circular aperture, 16 catenary connecting points with tension cords also were assembled. These catenary points are to be used to connect the circular membrane to the inflatable frame structure that previously was developed by ILC Dover. The above membrane-assembly task was a 4-week effort.

E. Membrane Installation

The circular-aperture membrane assembled by ILC Dover was shipped back to JPL for installation onto the inflatable structure. JPL mechanical engineers, Dr. Alfonso Feria and Mr. Eric Gama of the Communications Ground Systems Section, carried out the installation. The inflatable tube first was deflated, and the old membrane was carefully replaced by the new one. The inflatable tube then was inflated. The new circular membrane was tensioned, and the complete inflatable antenna was installed onto an aluminum/steel supporting fixture. After installation, the flatness of the membrane was measured by using the trammel arm/caliper system (see Fig. 8) developed by ILC Dover. Catenary points were adjusted until the membrane's proper tension and flatness were achieved.

(a) (b)

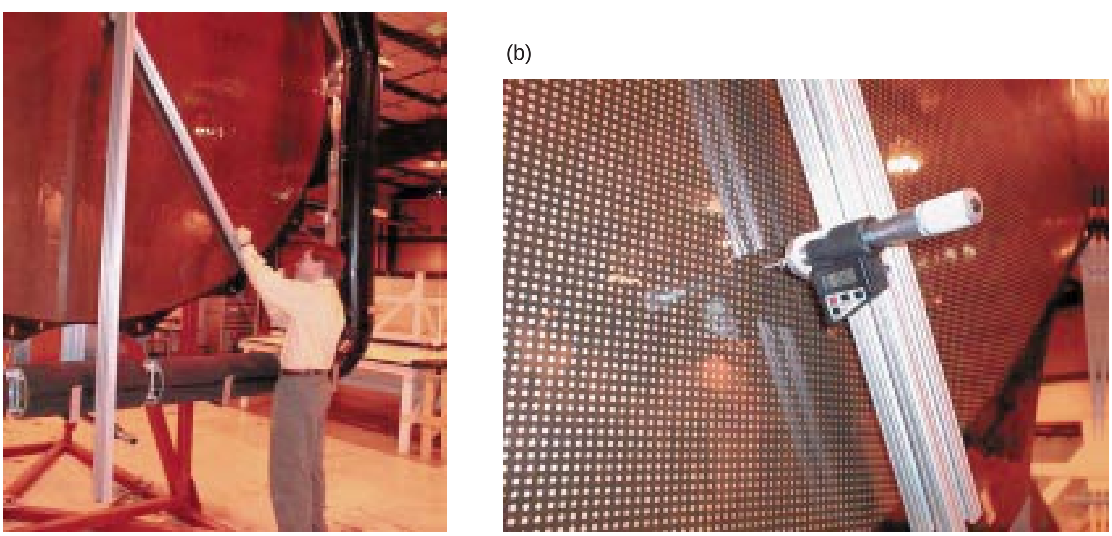

Fig. 8. The trammel arm/caliper system used to measure the flatness of the reflectarray membrane: (a) trammel arm and (b) caliper with digital readout.

F. RF Test

The inflatable antenna was deflated and its supporting structure disassembled, and both were packed and shipped to Composite Optics, Inc. (COI) at San Diego, California, where the antenna RF characteristics were measured. COI has a huge indoor compact range where antenna sizes up to 10 m can be tested. Prior to the RF test, the antenna was unpacked, inflated, and installed onto its supporting fixture. The membrane tension and flatness were adjusted again at the catenary points by using the trammel arm/caliper system. Feria and Gama performed an elaborate flatness measurement. By using a total of 48 points on the reflectarray surface, the measured rms flatness deviation value is 0.2 mm with a peak deviation of 0.5 mm. This is quite good since the required rms value is 0.5 mm, which is about 1/20th of the free-space wavelength at 32 GHz.

The inflatable antenna and a portion of its supporting structure were mounted onto COI's antenna-range mounting fixture. This is shown in Fig. 9. The following measurement steps were carried out:

(1) It was established that the antenna was left-hand circularly polarized.

(2) The peak of the main beam was located.

(3) The feed location was adjusted to achieve the best gain.

(4) The gain-versus-frequency curve was plotted, and 32.2 GHz was established to be the best-gain frequency.

(5) Patterns (co-polariaztion (co-pol) and cross-pol) were taken at various frequencies and at four different roll angles: 0, 45, 90, and 180 deg.

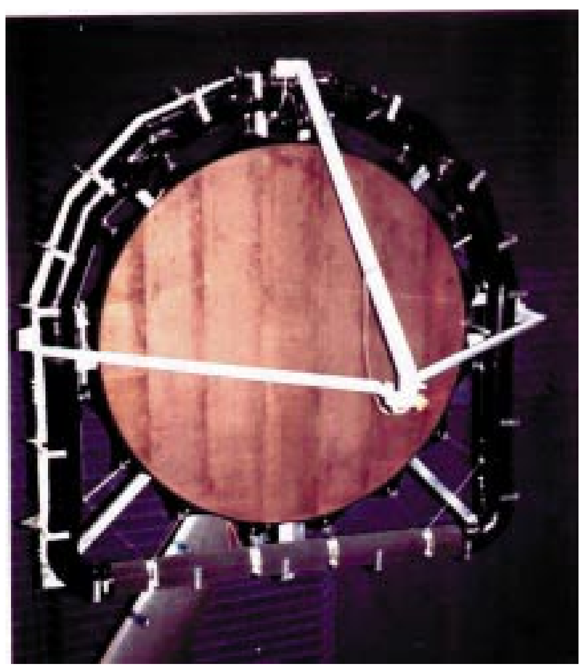

Fig. 9. Photo of the antenna mounted in COI's compact in-door chamber, showing the rigid feed-support struts and the support fixture for the complete inflatable antenna.

The antenna gain-versus-frequency curve is shown in Fig. 10, where it indicates a −3 dB gain bandwidth of 470 MHz (the requirement is 500 MHz). A typical antenna pattern across the angular range of ±90 deg is given in Fig. 11. To see a better resolution over the main beam region, the same pattern data were plotted over a smaller angular range of ±10 deg and are shown in Fig. 12. These patterns show a single high side lobe/coma lobe at the level of −18 dB from the main beam peak. This indicates that the antenna is not well focused. Within ±10 deg, all the other side lobes are below −23 dB. Beyond ±10 deg, all side lobes are below −50 dB. The cross-pol level, within the main beam region, is about −28 dB. Outside the main beam region, the average cross-pol level is below −50 dB, which is about 10 dB below that shown in Fig. 1 for the first unit. This extremely low cross-pol level indicates that very little mismatched energy is reflected from the membrane surface. Instead, most of the energy is reradiated according to the design by the well-matched elements.

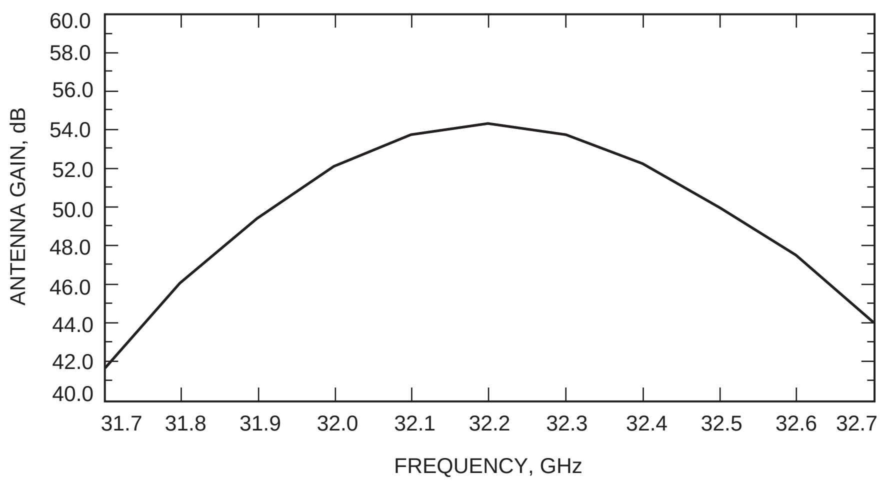

Fig. 10. The measured antenna gain-versus-frequency curve for the new inflatable antenna.

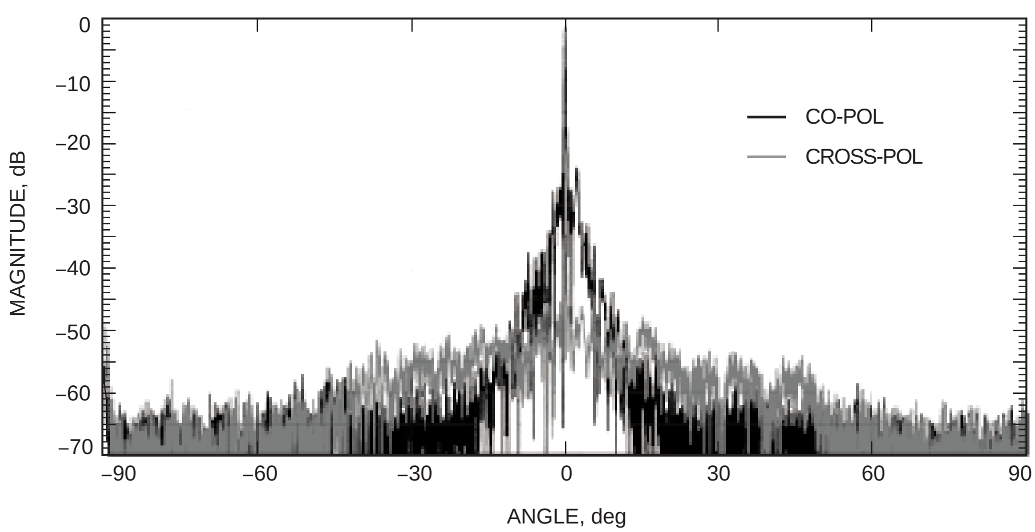

Fig. 11. The measured antenna pattern of the new inflatable inflectarray.

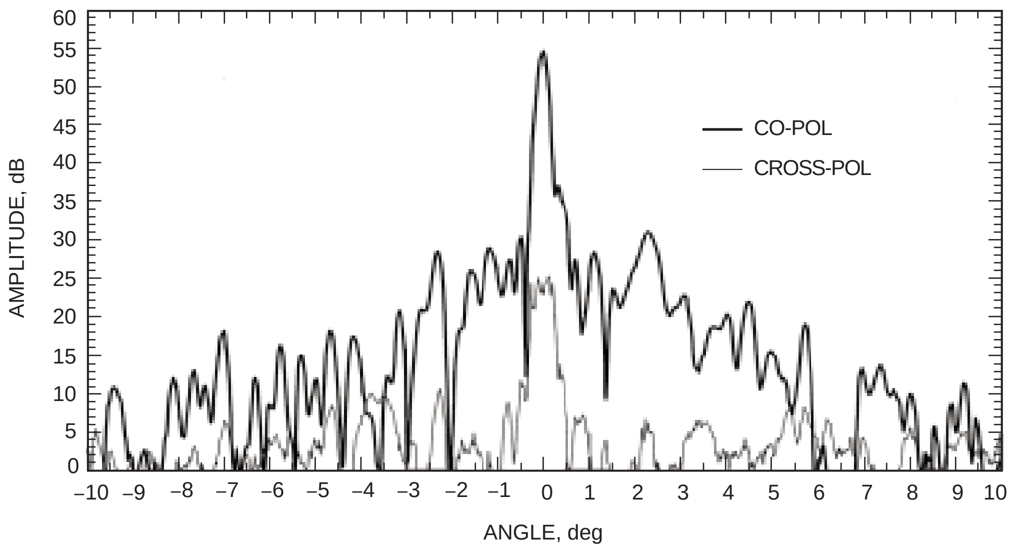

Fig. 12. The measured antenna pattern of the new inflatable inflectarray over the angular range of ±10 deg.

IV. Areas for Future Improvement

The measured antenna peak gain is 54.4 dB. With the directivity of the aperture calculated to be 59.7 dB, the antenna achieved an efficiency of 30 percent. Although this is a significant improvement from the previous unit with an efficiency of 10 percent, it is still short of the expected value of 40 percent. Several possible contributors have been identified during the development and measurement processes. These are discussed separately below.

A. Feed Defocusing

The feed horn is believed to be defocused due to two observations: (1) there is always a single high side lobe (-18 dB) at a particular side of the reflectarray, which is generally an indication of feed defocusing, and (2) the feed-support structure and the feed-location adjustment system were crudely done. It was observed that, as the antenna was rolled around its axis, the feed moved significantly to affect the main beam position. Thus, the thinking is that the feed was not set correctly on the focal point. In the future, we need to construct a strong and stable feed-support system as well as a precision feed-locating and read-out system.

B. Feed-Strut Blockage

During RF testing, due to gravitational force, the inflatable feed-support struts were not used. Instead, three rigid struts made of fiberglass tubing material were used (see Fig. 9). Each strut used relatively wide (about 12-cm) fiberglass tubing, which contributed significant blockage and scattering effects to the radiation. All three struts contribute to about 0.4 dB of blockage loss. By using thinner, but stronger, struts in the future, the blockage can be reduced to 0.15 dB and even better, if an offset feed system were used, which would completely eliminate the 0.4 dB of blockage loss.

C. Feed Illumination Pattern

The feed was designed with a conventional cosine pattern shape, which is by no means optimized. A more "flat-top" feed pattern to give a more uniform amplitude taper across the 3-m aperture should be used. This could increase the efficiency by at least 0.5 dB. There are various techniques that have been developed to provide a flat-top feed pattern, such as a tapered feed horn, a Cassegrain shaped subreflector feed, etc. For Ka-band frequencies, additional development in this area is needed.

D. Element Impedance Match

This second-iteration effort redesigned the element to have good impedance match, which was reflected in calculated results as discussed in a previous section. This new design, however, was slightly changed during the etching process. The angle of the phase-delay line was bent (due to crowding of the elements) a little more than that designed. This resulted in a return loss of -8 dB instead of the designed -15 dB, which translates to 0.55 dB of efficiency loss. This error can be simply corrected by performing a more accurate etching job in the future.

E. Nonuniform Acrylic Spray

As discussed earlier, in order to protect the copper from oxidation, the etched membranes were manually sprayed with a thin layer of acrylic solution. Since this was done manually, nonuniform thickness of the sprayed layer was bound to occur. This, at Ka-band frequencies, causes many elements to resonate at slightly different frequencies and, subsequently, lowers the antenna efficiency by a few tenths of a dB. In the future, an automated spraying procedure should be pursued to ensure uniform coating thickness. The thickness should be less than 0.01 mm to minimize mass and should be considered in the reflectarray element design. Certainly, this would introduce additional cost to the fabrication process.

F. Surface Dents and Wrinkles

Although the rms flatness value measured for the 3-m reflectarray membrane was very good (0.2 mm was achieved, while the requirement was 0.5 mm), there are several large surface dents and wrinkles (most formed during the etching process) not included in the sampled measurement values. This is because, in order to save RF testing time at the COI range, only 48 points equally spaced across the aperture were used in the flatness measurement, and it happened that these large dents were not included. These large dents and wrinkles with surface deviation larger than 0.5 mm are formed during the manufacturing and handling processes. Together they affected about 10,000 elements out of the total 200,000 elements and contributed to about 0.3 dB of gain loss.

If all of the above losses were eliminated, the antenna efficiency could be improved from the current measured 30 percent to approximately 70 percent. However, in reality, not all these losses can be completely eliminated. For example, the surface dents and wrinkles on the very thin membrane material will be very difficult to eliminate completely. Another example is the loss due to the feed illumination taper, which, although capable of being reduced significantly, would require a very good and specially designed feed, which would require a large amount of additional funding. As a result, the expected efficiency, with a reasonable funding level, should be somewhere between 40 percent and 50 percent.

V. Summary

This second-iteration effort was carried out to improve the efficiency of the first unit. By using a redesigned reflectarray patch element with matched impedance, the second unit has significantly improved the previous 10 percent efficiency to 30 percent. Further improvement is needed to reach the expected 40 percent efficiency. Several areas have been identified for further efficiency improvement in possible future developments.

Acknowledgments

The author would like to express appreciation to Dave Cadogan and John Lin of ILC Dover, who did an excellent job in assembling the aperture membrane; to Duff Weatherington, who professionally guided the compact range RF measurement; and to Alfonso Feria and Eric Gama of JPL, who contributed diligently and effectively to the assembly of the inflatable structures.

Reference

[1] J. Huang and R. J. Pogorzelski, "A Ka-Band Microstrip Reflectarray with Elements Having Variable Rotation Angles," *IEEE Transactions on Antennas and Propag.*, vol. 46, pp. 650–656, May 1998.