Microstrip Patch Antenna Panel for Large Aperture L-band Phased Array

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Abstract

This paper describes the design and development of a large, lightweight antenna panel for an active phased array operating at L-band. The panel was developed under a JPL program of technology development for space based radar. It utilizes dual-stacked patch elements that are interconnected with corporate feed manifold of striplines. This paper focuses on the electromagnetic design and performance of the radiating elements, with emphasis on scan performance, and also addresses mechanical and thermal aspects of the panel. The element in the array environment has a bandwidth of more than 80MHz centered at 1260MHz and is fed so that it can radiate orthogonal linear polarizations. The envisioned phased array, with a nominal aperture of 50m x 2m, is designed to scan ±45 degrees in azimuth and ±20 degrees in elevation. The panel of radiating elements has a mass density of 3.9 kg/m^2, which represents approximately 50% of the target 8kg/m^2 total panel mass density that includes T/R modules and feed manifolds.

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1. INTRODUCTION

JPL is involved in a collaborative program the Air Force Research Laboratory (AFRL) to develop technology for large aperture space based radar (SBR) at L-band [5]. The project is known as *L-band Lightweight Space Based Radar* (LLSBR). This radar technology is envisioned as dual use – primarily with science and military end-users – and is designed to operate in a variety of synthetic aperture radar (SAR) and moving target indicator (MTI) modes. As such, the system requirements call for a high-performance, active phased array that is both mass-efficient and is amenable to large-scale production at low-cost. This paper describes the design and development of the radiating elements for an active antenna array that will meet these requirements. A companion paper describes the RF electronics of the phased array [1].

Background

JPL has been involved in a number of synthetic aperture radar missions over the last three decades. These range in scope from the pioneering Earth Science missions of SeaSat and SRTM (1978 and 2000 respectively) to the Planetary Science missions of Magellan and Cassini (1990 and 2004 respectively). A representative summary of JPL and other Earth Science SAR missions is given in Table 1, along with the anticipated parameters for an LLSBR-class mission.

Table 1. Representative Earth Science SAR Missions with Antenna Size and Mass.

SAR	Agency Year	Altitude (km)	Band (GHz)	Pk Pwr (kW)	Area (m x m)	Mass (kg)
SeaSat	NASA 1978	805	1.27	1	2 x 11	220
SRTM	NASA 2000	233	5.17 9.68	1.7 1.4	0.7 x 12 0.4 x 12	13600
RadarSat1	CSA	800	5.3	5	1.5 x 15	1540
Envisat (ASAR)	ESA	800	5.3	3.2	1.3 x 10	850
LLSBR	*NASA*	*508*	*1.26*	*25*	*2 x 50*	*1800*

The 50m length aperture of LLSBR facilitates an ultrawide swath and revisit rates for interferometic SAR on the order of a few days [4]. As such, LLSBR calls for

a significant reduction in the areal mass density of the radar aperture over comparable phased array technologies. It should be noted that SeaSat used a passive array, not an active array as is the baseline for LLSBR. The stated mass of 1800 kg for a 100 m^2 aperture equates to an areal mass density of 18 kg/m^2. This number includes the mass of the antenna panels, deployment mechanism, power supplies, and various radar-subsystems that are distributed at the panel-level. The mass goal for the RF front-end of the aperture, which includes antenna panels (radiating elements and support structures), T/R modules, corporate manifolds, and harnessing is 8 kg/m^2. This breaks down as shown in Table 2.

Table 2. Mass Density Goals of LLSBR Active Phased Array Antenna Panel.

Item	Mass Density (kg/m^2)
Radiating Elements / Panel Structure	3.5
Printed Circuit Board for RF, Power, & Digital Feed Manifolds	2.5
Harnessing & Power Dividers	0.5
T/R Modules	1.5

To meet this goal, the panel of radiating elements (measuring 2m by 1.5625m) must weigh approximately 11kg.

System Overview

The 50 meter LLSBR aperture is divided into 32 panels, each measuring 1.5625 meters in azimuth by 2 meters in elevation. It is envisioned that the array will be deployed from a z-fold stowed configuration with two of these 1.5625m panels integrated as a single hinged panel. The deployable structure will thus comprise 16 panels and 15 hinges and is shown in Fix xxx. The total mass of the 50m deployed antenna is 1800 kg, of which 1543 kg is allotted to the antenna subsystem. The mass of the deployment truss and associated mechanisms is thus 257 kg, which equates to a linear mass density of 2.6kg/m^2. Typically, deployment accuracy is specified as $\lambda/20$, approximately 1cm at L-band, and orbital stability for an L-band mission may be on the order of a few millimeters depending on the mode of the radar. This is will require the development of large, lightweight structures [1].

The LLSBR panel is defined as the sub-array of elements that is down-converted to IF and then digitized. The panel comprises 12 x 12 elements, with each element fed by a dedicated T/R module. These digitized signals are communicated through optical fibers to an on-board processor where digital beam forming is done. Panel architecture is depicted in Fig. 2.

Phase / time shifting is accomplished in three distinct ways:

- The signal at each element is shifted in phase between 0 deg and 360 deg in 5.625 deg steps using a 6-bit analog MMIC-based phase shifter that is integral to the T/R module.
- The signal at the output each 6x6 sub-array is time-shifted using a stripline time delay with 4-bit control.
- The signal at the output of each 12x12 subarray is digitized and time shifted in the FPGA-based digital beamformer.

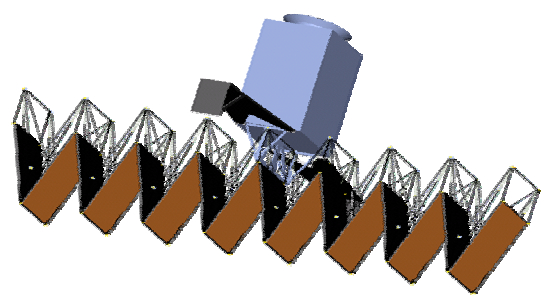

Fig. 1. Sixteen Panel LLSBR Aperture Showing Z-Fold Deployment and Truss. Graphic Courtesy of AEC-Able Inc.

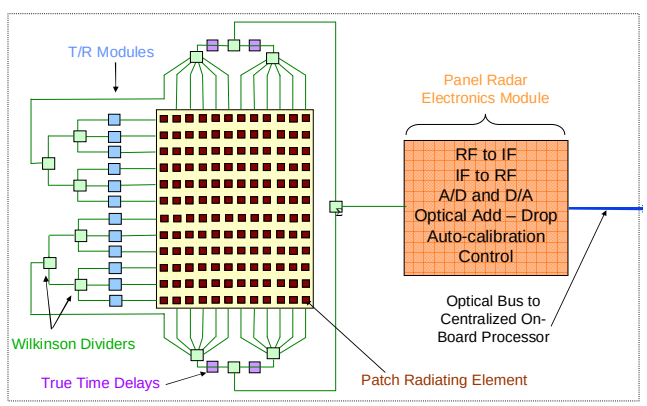

Fig. 2. Panel Architecture Showing RF to Optical Conversion

In the current development, the upper half of the panel shown in Fig. 2 was designed and is currently in the

process of being fabricated and assembled. No true-time delays are incorporated into this version of the panel.

System Requirements

The following requirements were formulated as a guideline for the joint-mission phased array development. A key and challenging requirement is that the antenna array must have a bandwidth of 80 MHz for both polarization over a scan range of ± 45 deg in azimuth and ± 20 deg in elevation.

The entire array comprises 384x12 elements, so the power at the input to each element (including 1.3dB dissipative losses) is 7.3W peak,

Table 3. Key Antenna Requirements for 50mx2m Antenna Array

Polarization	H & V
Transmit center frequency	1.26 GHz
Bandwidth	> 80.0 MHz
Azimuth scan	± 45 deg
Elevation scan	± 20 deg
Pointing accuracy	± 0.15 deg
Peak gain (at broadside)	> 42.1 dB
Gain flatness over 80 MHz	< 0.5 dB
Cross-pol (over scan)	< -20dB
Peak sidelobe (transmit)	< -13 dB
RMS sidelobe (receive)	< -50dB
Return loss	> 10 dB
Insertion Loss	< 0.9 dB
Efficiency (uniform taper)	> 90% (0.4dB)
Peak radiated transmit power	25 kW
Mass	< 1535 kg
Flatness	<1.2 cm

Element Design

The radiating element, illustrated in Fig. 3, is fabricated on a low-moss substrate of relative permittivity 1.1 in order to minimize panel weight. A dual stacked patch design is used to obtain the required bandwidth over scan. The approximate spacing between the two patches is 1cm, and the spacing of the driven patch above the groundplane is also approximately 1cm. The element is fed with dual probe feeds. These suppress modes that can cause scan blindnesses and also produce patterns with better symmetry and cross-polarization performance. The principal disadvantage of a dual feed is the doubling of the number of element interconnects, and there are issues with the probe interconnect fabrication that we address later. The probes are terminated in matching capacitors of approximately 2pF to resonate with the approximately 7nH of probe inductance at 1.26GHz.

Coaxial sub-miniature connectors and short coaxial jumper cables are used to connect the element to a transmit / receive (T/R) module that is mounted on a manifold board that attaches to the back of the groundplane. The T/R modules have a pair of integrated 180° stripline-based hybrids that provide the anti-phase signals for the dual feed. Fabricating the hybrid in the T/R module (Rogers-based) substrate proved easier than fabricating it in the microstrip layer above the groundplane, or in stripline layers below the groundplane. In the former case, there was concern that placing two large (quarter wavelength) microstrip circuits beneath the driven patch might result in isolation problems. In the latter case, the groundplane layer increases from 2 to 3 layers, and the probe attachment becomes more complicated.

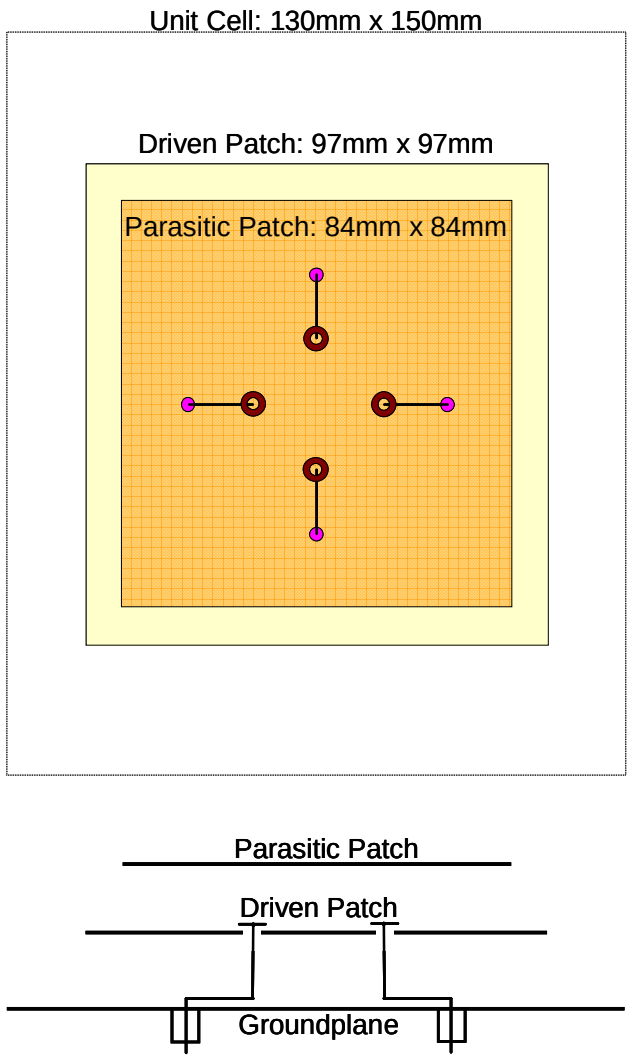

Fig. 3. Unit Cell, Patch Dimensions and Interconnect Scheme

Short microstrip lines connect between the probes and the sub-miniature coaxial connectors. Ideally, the connector would be placed directly beneath the probe, but a displacement of the connector was required in this case to accommodate the T/R module. This arrangement of coaxial interconnects is for development purposes only. It is useful to be able to make impedance measurements at each element port, and to be able to phase the array without using T/R modules. Homogeneity facilitates electromagnetic analysis by the Method of Moments (whereas an inhomogeneous dielectric would require more computationally expensive CEM analysis such as the Finite Element Method). A large dielectric panel can be designed to be self-supporting, without the need for additional structural elements (such as a rigid frame) that support and otherwise interface the sub-arrays. This reduces antenna mass and simplifies antenna integration. Fig. 4 Illustrates the panel; stackup and interconnect design.

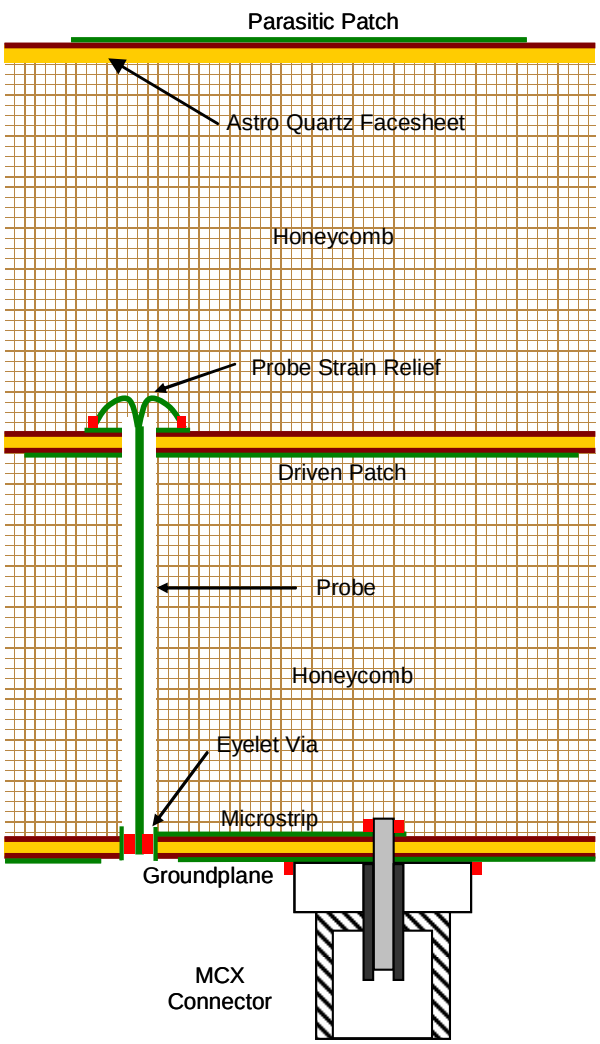

Fig. 4. Panel Construction.

2. Performance

Mechanical and Thermal Performance

The LLSBR antenna panel is designed for electromagnetic performance and ease of construction. However, it must also meet stringent structural requirements to survive the acoustic environment of launch and it must also meet strict thermal requirements to survive the large temperature gradients that are encountered in low Earth orbit. Unfortunately, as one tries to make the panel lighter, thermal management and structural rigidity become more difficult to obtain. These requirements ultimately limit the mass reduction that is possible for an antenna with this type of construction and performance. Planar arrays with areal mass densities substantially below 4 kg/m^2 will require the development of new techniques, such as membrane and inflatable structures [2].

Structural modeling was performed with the assumption that the antenna panel has an areal mass density of 4 kg/m^2 and an additional 4.5 kg/m^2 of non-structural mass (feed manifold boards, T/R modules, harnessing) is attached to the electro-structure. The panel (measuring 3.125m by 2m in this model) is assumed to be pinned at its four corners. The first mode bending frequency of the antenna panel alone (without the non-structural mass) is approximately 35 Hz. The first mode bending frequency of the antenna panel plus non-structural mass is approximately 25 Hz. The maximum deflection of the panel in this latter case is 2.9cm, representing a z-axis deformation of 1.5% over 2m. Calculations show that this second frequency can be increased to 39 Hz by the placement of a snubber in the middle of the panel.

Panel stresses were analyzed by simulating a 30g load normal to the plane of the panel. With a factor of safety of 2.0, positive margins of safety are observed on all structural components of the panel. The stress on the probe was not modeled. The relatively small degree of local bending and the strain relief in the probe are assumed to be adequate to prevent the probe from detaching.

A number of orbital thermal environments were examined to determine panel deflection and stress. A z-axis thermal gradient of 90 degrees Celsius (front to back of the antenna panel) results in a panel deflection of 2.8cm and positive stress margins (within a safety factor of 2) on all structural elements. This environment is consistent with antenna panels (painted white) in a LEO orbit of beta angle -60 degrees. On the other hand, if the antenna panels are painted black and are in a LEO orbit of beta angle -90 degrees, a z-axis temperature gradient in excess of 110 degrees Celsius results and causes a

negative shear stress margin on the honeycomb. This suggests the use of denser honeycomb, thicker honeycomb, thermal blanketing, or thermal painting to reduce temperature gradients.

High lateral thermal gradients may also be possible due to shadowing from solar panels, the spacecraft bus, and possibly from the antenna truss. These are much less problematic in terms of antenna deformation than z-axis gradients.

Electromagnetic Modeling

Electromagnetic performance is first evaluated using Ansoft Designer™ before fabrication and testing is done. Designer™ is used in this instance to do Moment Method-based analysis of the antenna element and interconnect. The design process starts by first taking a single element with a simplified interconnect and stackup, and then 'tuning' the element (adjusting size and probe position) to obtain a reasonable numerical estimate of return loss over bandwidth.

The element is then simulated in the infinite array environment by imposing appropriate periodic boundary conditions along the E-plane and H-plane boundaries of the unit cell. The element is tuned to have a return loss of 15dB or better over bandwidth and scan angle. Automatic optimization and tuning are not practical in infinite array simulation because run times tend to be lengthy (on the order of a day), particularly for detailed models. Tuning over scan was therefore accomplished by obtaining a good match at 25 degrees scan in azimuth, and then noting return loss at other scan azimuth angles. The element is modified until the return loss is acceptable over the desired range of scan angles and frequencies. Scanning in elevation tends to be less problematic because the maximum scan angle is smaller.

Additionally, it is possible to inspect the scan element pattern (also known as the active element pattern) with this type of boundary condition, in order to ascertain pattern symmetry, cross-polarization performance, and to detect scan blindnesses.

Next, the element is placed in a finite array, typically smaller in terms of number of elements than the actual array that is being designed. We have found that 12 elements (plus interconnects) having a 16-layer stackup can be modeled with reasonable fidelity and speed using a moderately capable, modern desktop PC. The finite array simulations thus used arrays of 1x12 for determining azimuth scan performance and 12x1 for elevation scan performance. Return loss as a function of frequency and scan angle is recorded, along with the antenna patterns for co-polarized and cross-polarized radiation. It should be noted that the return loss calculations include the mutual coupling effects of the other 11 elements [3].

After performance has been verified for the model with simplified layup and interconnect, the Designer™ model is elaborated to more accurately reflect the actual construction. This includes, for example, modeling the adhesive that is used to bond the honeycomb to the Astro Quartz facesheets and accurately modeling the microstrip via and matching capacitor. This model comprised 11 dielectric layers and 5 metallic layers. In all simulations, an infinite groundplane was used to help speed up the computation.

Results of Electromagnetic Modeling

Fig. 5 shows the return loss bandwidth of a single stacked-patch element with dual probe feed. The bandwidth is 165MHz at 15 dB return loss. In this case, the match has not been optimized to obtain the classic double-notch reflection coefficient response of a dual stack patch, because there really is no point in fine-tuning the element without the proper array environment boundary condition.

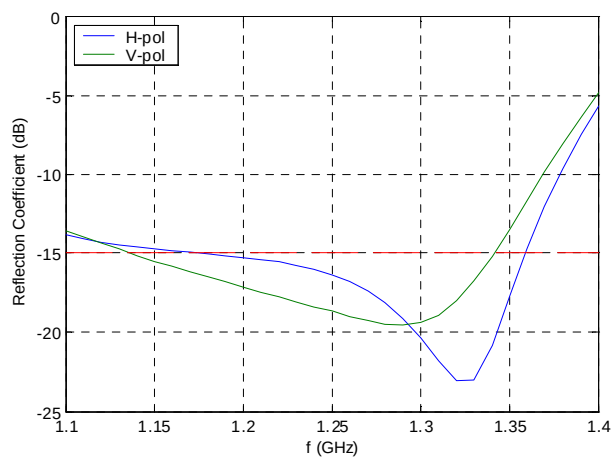

Fig. 5. Simulated Input Match of Isolated Dual-Stack Patch Element

Table 4 shows the return loss at different scan angles and for frequencies at the edge and center of the band. Generally speaking, performance is good for all angles of scan in the elevation plane, and for angles up to about 30 degrees in the azimuth plane. An E-plane scan angle of 45 degrees in azimuth produces a return loss of approximately 7dB, which corresponds to a 1dB matching loss. It is interesting to note that an H-plane scan of 45 degrees (for V-pol) is much less degraded.

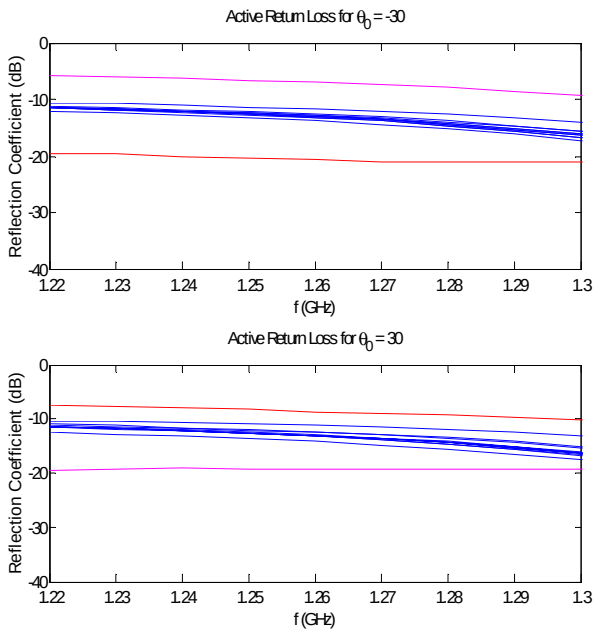

Fig. 6. Simulated Input Match of 12-element Array for Scan Angles of ±30 degrees in Azimuth (H-Pol).

Table 4. Infinite Array Return Loss Performance as a Function of Scan Angle and Polarization.

Scan Angle	H-pol			V-pol		
ψ_{el}, ψ_{az}	1.22 GHz	1.26 GHz	1.30 GHz	1.22 GHz	1.26 GHz	1.30 GHz
0, 0	15.5	16.7	20.3	17.9	19.0	19.4
0, 25	37.1	33.8	26.8	22.2	22.6	23.5
0, 35	13.9	13.5	13.0	25.6	22.9	24.3
0, 45	7.1	6.7	6.3	16.1	14.5	14.1
20, 0	15.5	15.9	17.9	27.7	30.1	26.0

Return loss in the finite array is calculated by computing the reflection coefficient at each antenna port (all 24 ports for a 12-element array) and then combining them according. Fig. 6 shows the resulting reflection coefficients at the inputs to an ideal hybrid connected to each element. For a scan angle of 30 degrees, the return loss is 10 dB or better for the middle 10 elements, and either ~6dB or ~20dB for the end elements, depending on the direction of scan. The match seems to improve when the beam is steered towards an end element

Finite array patterns for an azimuth scan of 0 and 30 degrees from boresight are shown in Fig. 7. The computed directivity at 1.26GHz is 17.6dB. The area directivity based on a 1x12 array of unit cells is 17.2 dB. (This calculation does not account for the fact that in practice, fields extend beyond the perimeter of the unit cells, whereas in the electromagnetic model, they do.) A 0.44 dB deviation in directivity is noted at boresight, and a 0.55dB devaition in directivity is noted at 30 degrees scan in azimuth. The peak directivity is offset by approximately ±1 degree at the edges of the band.

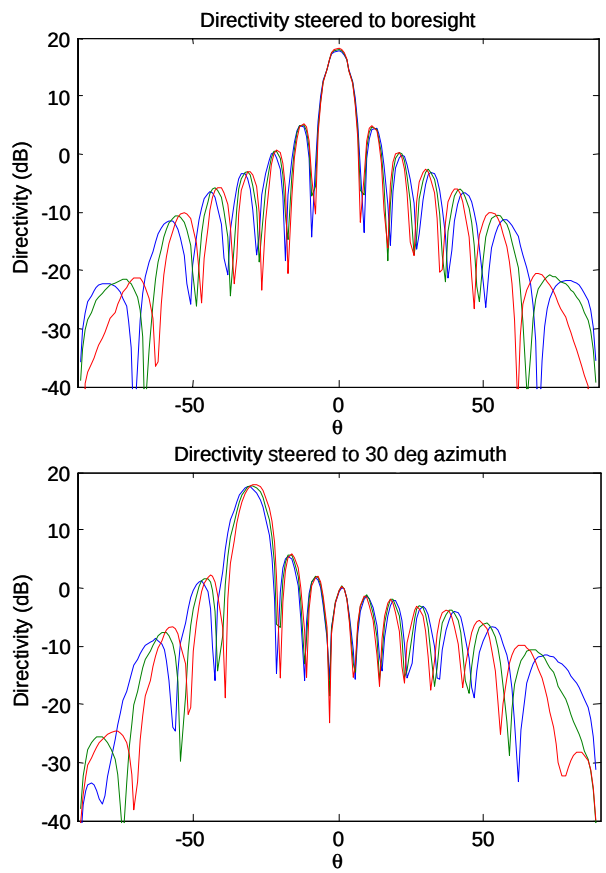

Fig. 7. Simulated Finite Array Patterns for Boresight (Upper) and 30 Degrees Scan off Boresight in Azimuth (Lower) for frequencies 1.22 GHz (Blue), 1.26 GHz (Green), and 1.30 GHz (Red).

The cross-pol component (not shown) is found to be 47dB below the co-pol component at boresight.

3. CONCLUSIONS

The design of a large lightweight phased array antenna panel for space based radar applications has been described. The panel of radiating elements and interconnects has an areal mass density of 3.9 kg/m^2. This estimate does not include the mass of the beamformer and T/R modules. The probe-fed interconnect has been designed for ease of installation, and preliminary measurements indicate good performance (return loss of 27dB or better) when the microstrip features are accurately aligned and centered.

Moment Method-based electromagnetic modeling shows that the antenna is capable of scanning ±20 degrees in elevation for both horizontal and vertical polarizations and to ±45 degrees in azimuth for vertical polarization (with a 10dB or better return loss over the band). Scanning in azimuth with horizontal polarization is limited to ±30 degrees with a return loss of 10dB or better, and scanning to ±45 degrees reduces the return loss to 7dB. The patterns have good symmetry and cross-polarization performance. This is attributed primarily to the use of a dual-probe interconnect. Additionally, there is no indication of blindness or beam squinting due to scan. Breadboard measurements of a single element agree closely with the predictions obtained from the Moment Method model.

4. REFERENCES

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5. BIOGRAPHIES

Neil Chamberlain *received the B.Sc. degree with Honours in Electrical Engineering from King's College London, UK in 1981. He worked briefly for Marconi Space and Defense Systems, Ltd., Portsmouth, UK before undertaking graduate studies at The Ohio State University, where he received the M.S. and Ph.D. degrees in Electrical Engineering in 1984 and 1989. He was a professor at the South Dakota School of Mines and Technology in Rapid City, South Dakota between 1990 and 2003. His research focused on ultra-wideband phased array radar antennas and systems. He is currently a Senior Engineer with JPL's flight Spacecraft Antennas Group, where he is working on large aperture antennas and active phased arrays. Dr. Chamberlain is a member of Eta Kappa Nu and Tau Beta Pi.*

Luis Amaro *received th B.S.E.E. degree from Cal. Poly., Pomona in 1984 and the M.S.E.E. degree from Cal. State University, Northridge in 1998. Prior to coming to JPL he worked at Rockwell Intl. and TRW Inc. He has served as Chairman of the I&M Society of the IEEE, Los Angeles Chapter. Since 1991 he has been with the flight Spacecraft Antennas Group at the Jet Propulsion Laboratory, where is a Senior Engineer. While at JPL he has designed various RF, microwave, and millimeter wave components. Mr. Amaro's interests include electromagnetic simulation and the numerical analysis of antennas and micro / millimeter wave components.*

Eric Oakes *received a B.S. in Metallurgical Engineering from The University of Washington in 1999. He is currently working at the Jet Propulsion Laboratory in the Materials and Processes Group focusing on the design and fabrication of composite spacecraft parts. While at JPL he has been involved in the design and fabrication of composites for several space projects including Mars Pathfinder, Mars Exploration Rover (MER), Deep Impact, and GALEX.*

Richard Hodges *received the B.S.E.E. degree from University of Texas at Austin, the M.S.E.E. degree from California State University, Northridge, and the Ph.D. in Electrical Engineering at University of California, Los Angeles. From 1978-1984 he was with the Hughes Aircraft Company Radar Systems Group. In 1984 he joined the Adams-Russell Microwave Products Division in Chatsworth, CA (now Rantec). In 1988 he joined NASA's Jet Propulsion Laboratory where he developed*

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Suzanne Spitz *received the A.B. degree in Applied Mathematics from the University of Michigan, Ann Arbor, in 1981. She received the M.S.E.E. from the University of Virginia in 1989. She then joined the Jet Propulsion Laboratory as an antenna designer, working on various space missions and instruments including Mars Observer, Champollion, and Cassini. In 1998, she became the Supervisor of the Spacecraft Antenna Group, where she oversaw the development of antenna systems for Seawinds, Shuttle Radar Topography Mission (SRTM), Llight-weight Synthetic Aperture Radar Mission (LightSAR), Mars Exploration Rover, and CloudSat. Currently, she is Deputy Section Manager of the Flight Communications Systems Section. Ms. Spitz is a member of Eta Kappa Nu.*