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Authors

Sadowy, Gregory
Heavey, Brandon
Moller, Delwyn
et al.

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Technology Demonstration of Ka-band Digitally-Beamformed Radar for Ice Topography Mapping

Gregory Sadowy, Brandon Heavey, Delwyn Moller, Eric Rignot, Mark Zawadzki
Jet Propulsion Laboratory
4800 Oak Grove Drve
Pasadena, CA 91109-8099
sadowy@jpl.nasa.gov

Sembiam Rengarajan
California State University, Northridge

Abstract—GLISTIN (Glacier and Land Ice Surface Topography Interferometer) is a spaceborne interferometric synthetic aperture radar for topographic mapping of ice sheets and glaciers. GLISTIN will collect ice topography measurements over a wide swath with sub-seasonal repeat intervals using a Ka-Band digitally-beamformed antenna. This paper will give an overview of the system design and key technology demonstrations including a 1m x 1m digitally-beamformed Ka-band waveguide slot antenna with integrated digital receivers. We will also detail the experimental scenario that we will use to demonstrate both the beamforming and interferometric performance of this system. [1] [2]

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1. INTRODUCTION

This paper describes technology being developed to support a novel Ka-band (35 GHz) radar for mapping the surface topography of glaciers and ice sheets. During our three year program (funded by NASA ESTO Instrument Incubator Program), we are developing instrument and mission designs and are demonstrating a 1m x 1m Ka-band digitally beamformed (DBF) slotted-waveguide array antenna. This DBF array is composed of slotted-waveguide receiving elements, 16 Ka-band down-converters and digital receivers. The use of digital beamforming in the elevation (cross-track) direction yields a wide-swath with a sufficient number of looks but does not require nearly as much power as a wide-beam antenna would.

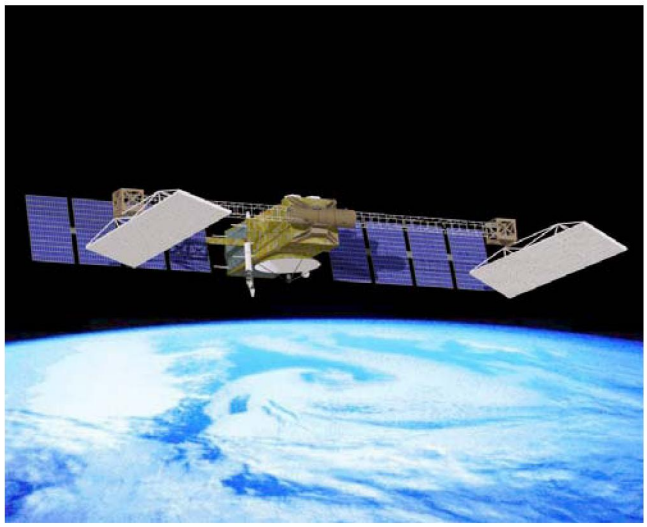

Figure 1 - GLISTEN Interferometer Configuration

2. GLISTIN INSTRUMENT DESIGN

The proposed instrument, the "Glacier and Land Ice Surface Topography Interferometer" (GLISTIN) and depicted in Figure 1, will map the surface topography of glaciers and ice sheets at high spatial resolution, high vertical accuracy, independent of cloud cover, with a swath-width of 70 km. The system is a single-pass, single platform interferometric synthetic aperture radar (InSAR) with an 8.6 mm wavelength, which minimizes snow penetration yet remains relatively impervious to atmospheric attenuation. In contrast to lidars, the instrument will be insensitive to clouds, provide significant swath-widths, cover the poles sub-monthly, and provide inherently variable spatial resolution: high spatial resolution for meter-scale vertical precision on glaciers and coastal regions and coarse spatial resolution for decimeter accuracy on featureless ice sheet interiors. Previous attempts at using millimeter-wave InSAR faced fundamental problems, including limited swath widths and high transmitted power requirements.

Our approach overcomes those two major limitations by applying digital beamforming techniques to standard InSAR. Both Ka-band antennas and digital beam forming

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[1] 1-4244-0525-4/07/$20.00 ©2007 IEEE

[2] IEEEAC paper #1499, Version 6.6, Updated Nov 21, 2006

have been used in various ground-based and airborne applications, however, no antenna systems exist that are substantially similar to the proposed system. To date, no civilian spaceborne imaging InSAR system has utilized Ka-band. There has also never been, to our knowledge, any digital beam forming radar flown in space. This technology has no alternatives when high resolution and swath is required other than the use of extremely high power transmitters that are impractical from both a technological and power consumption standpoint The use of DBF achieves greater than an order of magnitude savings in power (1 kW as compared to 14 kW). Our system also results in a substantial mass savings when compared with a lower frequency system. For example, for equivalent accuracy at 13 GHz (proposed Wide Swath Ocean Altimeter frequency and the highest interferometric radar frequency to date) a boom of nearly 24m would be required as opposed to the 8m of our design.

Science Motivation

The Greenland and Antarctic ice sheets together hold enough ice to raise global sea level by 80 m. The annual exchange of mass on the ice sheets is equivalent to 8mm/yr of sea level, so that any fluctuation in that level of exchange is significant on a global scale. Recent airborne laser altimetry campaigns, satellite radar altimetry, and ICESat altimetry in Greenland and Antarctica have revealed glacier thinning rates ranging from a few cm/yr in the interior to meters or tens of meters per year at the coast, along channels occupied by outlet glaciers. Most interior changes are explained in terms of fluctuations in snowfall, whereas large coastal changes are caused by glacier ice dynamics. While coastal changes dominate in Greenland and West Antarctica, changes in interior accumulation have a significant impact on total mass balance in East Antarctica; it is therefore important to monitor both interior and coastal regions. In order to obtain meaningful results on ice sheets based on existing observations and interpretation of the results, we estimate that surface elevation needs to be measured with a sub-10 cm accuracy on a 1 km scale in the interior, and a few tens of cm at a spatial resolution of 100m at the coast, where the kilometer-scale dimensions of glaciers demand finer resolution. If these measurement objectives are achieved – specifically, better than 1m at 100 m resolution on glacier ice along the coast, less than 10 cm at 1 km resolution in the interior – one will be able to improve current estimates of ice sheet mass balance obtained from other altimetry techniques significantly. Compared with satellite radar altimetry, this instrumentation will be able to resolve coastal changes more accurately (errors could be larger than 100% at present).

Spaceborne Instrument design

A Ka-band single-pass InSAR is ideally suited to meet the requirements for glacier and ice sheets. Single-pass imaging radar interferometry has unique capabilities in providing fine resolution, topographic mapping over a wide swath independent of solar illumination. A Ka-band (35GHz) center frequency maximizes the single-pass interferometric accuracy (proportional to the wavelength), reduces snow penetration (when compared with lower frequencies), and remains relatively impervious to atmospheric attenuation.

Figure 1 illustrates the measurement configuration whereby two antennas – displaced in the cross-track direction - view the same region on the ground. The interferometric combination of data received on the two antennas allows one to resolve the path-length difference from the illuminated area to the antennas to a fraction of a wavelength. From the interferometric phase the height of the target area can be estimated. Therefore, an InSAR system is capable of providing not only the position of each image point in along-track and slant range as with a traditional SAR, but also the height of that point through interferometry. The height precision is a function of the baseline length, the system frequency and the radar signal to noise ratio [1]. While the millimeter-wave center frequency maximizes the interferometric accuracy from a given baseline length, the high frequency also creates a fundamental problem of swath coverage versus signal-to-noise ratio. While the length of SAR antennas is typically fixed by mass and stowage or deployment constraints, the width is constrained by the desired illuminated swath width. As the across-track beamwidth – which sets the swath size – is proportional to the wavelength, a fixed swath size equates to a smaller antenna as the frequency is increased. This loss of antenna size reduces the two-way antenna gain to the second power, drastically reducing the signal-to-noise ratio of the SAR system. To overcome this fundamental constraint of high frequency SAR systems, we will use digital beamforming (DBF) techniques to synthesize multiple simultaneous receive beams in elevation while maintaining a broad transmit illumination. Through this technique we will preserve a high antenna gain on receive, reduce the required transmit power, and thus enable high frequency SARs, and high precision InSAR from a single spacecraft.

As previously noted, a digitally beamformed receive array was selected in order to achieve the required swath and looks while minimizing the required transmitter power. There are several possible approaches achieving a wide measurement swath. The pro and cons can be summarized as follows:

1. Wide Beam:

   - A wide beam (covering the full swath) is used on both transmit and receive.

   Pros: Simplicity

   Cons: Reduced antenna gain requires substantially higher transmitter power to produce adequate SNR

2. Narrow Beam ScanSAR:

   - A narrow beam is used on both transmit and receive and is electronically scanned over swath.

   Pros: High 2-way gain

   Cons: Time multiplexing reduces number of looks, degrading measurement resolution, Increased complexity

3. Digital Beamforming:

   - A wide illumination beam is used for transmitting. An array of wide-beam subarrays is used for receiving. Data is collected separately on all subarrays and used to form simultaneous subswaths in post-processing .

   Pros: Combines best features of 1 and 2. Reduced transmit power as compared to 1. Same number of looks as 2. Separate transmit and receive antennas minimize losses

   Cons: Increased complexity, high data rate

Of the above configurations, only digital beamforming provides the required measurement performance and swath using feasible transmit power levels.

Following from the science requirements for accuracy, and spatial and temporal sampling we have derived the measurement system parameters. The system parameters are summarized in Table 1. We have chosen a 0.063 m x 4.0 m transmit antenna to illuminate 7 degrees in elevation. At a boresight incidence angle of 22 degrees, this results in a ground swath of 70 km. On receive, the full swath is synthesized as 16 simultaneous subswaths in elevation using DBF over the full receive antenna (1 x 4 m comprised of an array of sixteen 0.063 m x 4 m antenna "sticks" in elevation). One fundamental consideration of using an elevation array is the trade between the size, or number of "sticks" and the ability to steer the array due to the presence of grating lobes. In order to avoid grating lobes the array must be critically sampled spatially ($\lambda/2$). In the case of GLISTIN, the inter-stick spacing is $\sim 7.4\lambda$ resulting in grating lobes at +/- 7 degrees. When off-boresight beams are formed, the grating-lobe levels become significant, as they are no longer rejected sufficiently by the element pattern of the sticks. However, because beam formation occurs only in elevation, we are easily able to range-gate out the ambiguous returns. By simple geometry, the local slope of the surface could cause the grating-lobe to occur at the same range as the desired viewing angle. However, in this scenario the scene would not only need to have a slope of ~18 degrees (quite possible for glaciers) but also to extend for 42km for a total height of 14km, a geometry which does not exist on Earth.

Table 1. Fundamental system parameters for GLISTIN spaceborne interferometer

Parameter	Units	Quantity
Peak transmit power	kW	1.5
Frequency	GHz	35
Bandwidth	MHz	80
Antenna length	m	4
"stick" height	m	0.063
Number of sticks	#	16
Total array height	m	1.01
Pulse width	us	25
Pulse repetition frequency	kHz	4
Interferometric baseline	m	8
Polarization		Horizontal
Swath width	km	70
Incidence angle range	degrees	18.6-25.2

The peak transmit power is 1.5 kW, which is within the realm of currently available technology. The pulse repetition frequency is 4 kHz to satisfy critical sampling requirements. The bandwidth is kept relatively low (40MHz) to minimize data-rates yet satisfy glacial resolution goals. Despite this, the data-rate still presents a substantial challenge.

3. GROUND-BASED DEMONSTRATION

The overall objective of this program is to develop and demonstrate the key technology of the GLISTIN concept including the end-to-end measurement technique and associated processing. A block diagram of the key development, the digital antenna array, is shown in Figure 2. The antenna will be integrated into a simple radar system, mounted on a positioner at a site overlooking the JPL facility, and used to collect an interferometric image. The demonstrated antenna will be a 1m long (1/4 of the spaceborne length) full-height array (1m, 16 "sticks"). Dedicated digital receivers will be integrated with each antenna stick and a 0.5m interferometric baseline will be synthesized by interfering the beamformed returns from the upper and lower halves of the array. An interferometric image will be produced through a combination of digital beamforming for the fine-scale coupled with elevation scanning on a coarse scale using the positioner. Azimuth scanning will be achieved by rotating the positioner in that axis.

The two key sub-elements of the demonstration are the antenna aperture and the integrated digital receiver. These efforts are described in subsequent sections. Additional hardware such as data acquisition computer are included in the demonstration but are not considered a focus of this technology risk reduction program.

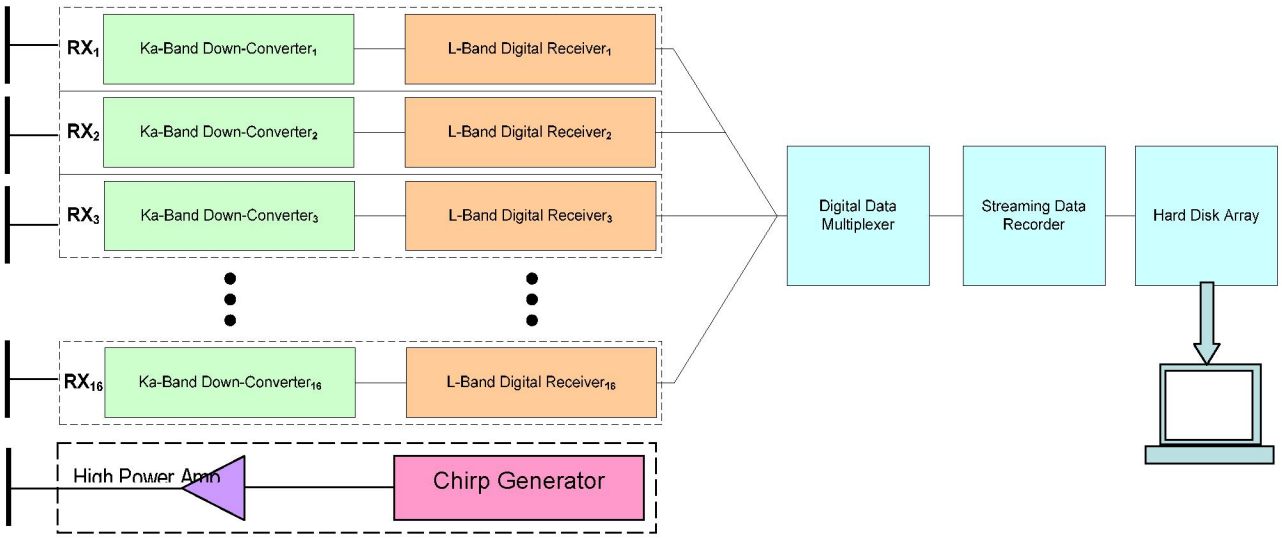

Figure 2 – Block diagram of ground-based demonstration

4. WAVEGUIDE SLOT ARRAY DEVELOPMENT

The development of a 1m x 4m aperture at Ka-band is a challenging task. The first step is to decide which antenna technology will be used. This decision is largely influenced by mass, loss, profile – all of which must be very low – and compatibility with the system's digital beamforming network. A waveguide slot array was selected as the best candidate to meet these requirements.

It is envisioned that the GLISTIN 1m x 4m spaceborne aperture will be subdivided into four 1m x 1m waveguide slot array panels for deployment, with each panel consisting of 160 slots by 160 slots. Existing technologies, however, do not permit fabrication of a complete 1m x 1m array panel in a single step. So, each panel must be comprised of several smaller subarrays that are mounted on an external support frame. The full 1m x 4m aperture would then be connected through separate power divider networks attached to the back of the array.

Given the complexities involved in fabricating the full 1m x 4m aperture, the development path must be selected carefully in order to identify potential problems early in the project. In order to test the digital beamforming radar on Earth, a 1m x 1m array panel was chosen for the demonstration aperture. This section discusses and presents the preliminary stages in development of the 1m x 1m waveguide slot array panel for the ground-based demonstration.

Theory

The GLISTIN demonstration antenna is a large slot array with 160 x 160 elements (1m x 1m). Yee has shown that the design and analysis of large slot arrays may employ an infinite array model with excellent accuracy [2]. In such a model, the external mutual coupling between radiating elements is modeled by considering each slot to be embedded in an infinite array. Thus the external mutual coupling is computed in terms of Floquet wave summation [3] instead of element by element mutual coupling integral as is done in conventional slot arrays [4]. The accuracy of the infinite array model becomes better as the array size becomes bigger and its validity has been established even for a small 7x7 array [2]. Based on Scharstein's work, [5] we believe that the use of the infinite array model for external mutual coupling employed in the GLISTIN antenna may introduce errors in slot voltages only in the outermost two rows and two columns with minimal error in the input reflection coefficient. Several computer programs were developed to solve the pertinent coupled integral equations for the slot aperture electric field by the method of moments. For the infinite array mutual coupling problem, our computer program was validated by comparing our results with those of Ansoft High Frequency Structure Simulator (HFSS).

In the design of the slot array we use half-height radiating waveguides to minimize the higher order mode coupling effects in the junction regions. Full height guides are used for feed and input waveguides. The slot conductances in the radiating waveguide and the normalized resistances in the feed waveguides have been chosen to maximize the return loss bandwidth as much as possible, even though the infinite array slot admittance has an extremely narrow band response. All of the moment method computations assumed square ended slots. Since the manufacturing process introduces round ended slots a correction is made for slot lengths assuming 'equal area' criterion. The smallest subarray unit in the 160x160 element array is a 10x10 slot array. Moment method and HFSS simulations of a full 10x10 subarray in an infinite array coupling environment are shown in Figure 3. Both these simulations include all intermediate coupling slots and waveguides (i.e. the

reflection coefficient shown is at the input waveguide to one 10x10 subarray). As can be seen, there is good agreement between the two methods. There is even better agreement when only one mode is included in the MoM analysis, which is what the HFSS simulation included. The slight shift lower in resonant frequency for the MoM calculation is due to the inclusion of higher order modes.

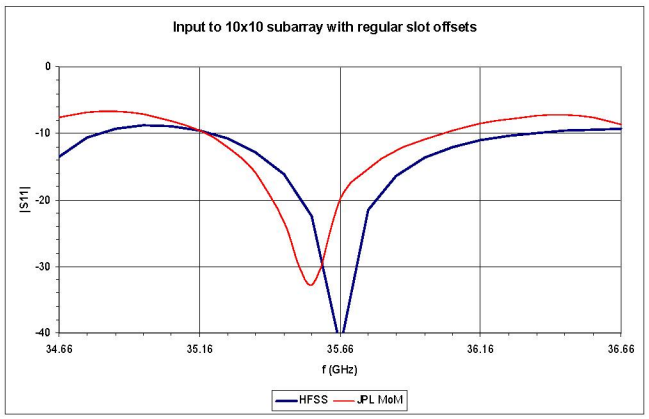

Figure 3 - Simulations of reflection coefficient at input of 10x10 subarray. Red – MoM; Blue – HFSS.

In order to compute the radiation patterns we first ran the moment method computer program for an infinite array of sub-arrays. Subsequently, we used the pattern multiplication principle to obtain the pattern of the entire array. The unit cell pattern is computed by summing the radiation from each radiating slot in the unit cell with the appropriate excitation computed by the moment method. The array factor is multiplied by the pattern of the unit cell. The moment method program was subsequently modified to account for scanning in the H-plane, as required by the system beamforming network. Thus there is a linearly progressive phase from sub-array to sub-array along the H-plane. It was interesting to note that the unit cell pattern didn't show much deviation between the scanned case and the broadside radiation. Therefore the scanned patterns can be obtained by multiplying the array factor for the particular scan direction by the pattern of the unit cell in the un-scanned case. Radiation patterns were computed over a frequency range of 35.16 to 36.06 GHz. The patterns were found to be excellent with very little degradation over this frequency range where the return loss is better than 10 dB.

Design and Fabrication

As mentioned above, the smallest subarray unit is 10x10 elements, and four of these are combined to make the next subarray level up: a 10x40 array. This subarray was selected as the prototype to validate both the model and fabrication techniques, and will be discussed in this subsection. The results of this prototype cycle will be used to scale up to a larger 40x80 subarray tile, which will then be used to fill the final 1m x 1m aperture of the demonstration antenna.

There are two main components in the design: the radiating and coupling slots (already introduced in the theory section), and a four-way equal-split corporate feed network that feeds each 10x10 subarray in the larger 10x40 prototype array. The feed network was designed using standard WR-28 waveguide dimensions to facilitate calibration and measurement. The main components of the feed network are H-plane Tee septum power dividers, H-plane bends, equal-length waveguide runs to each subarray, and an E-plane Tee at the input to the 10x40 subarray. All components in the feed network are tuned to the required operating frequency of 35.66GHz.

An additional feature introduced into the feed network was an E-plane phase "trombone", whose main function is to equalize the phase to each 10x10 subarray with shims, and required only if fabrication tolerances create phase imbalances. However, by adding mounting flanges at the trombones, it is not only possible to measure the performance of the feed network – the equality of amplitude and phase to each subarray – but also to measure the individual performance of each 10x10 subarray. A standard WR-28 waveguide calibration kit can easily be used to achieve this. An aluminum cover with two E-plane bends is used to close off the trombone for full 10x40 subarray operation.

In conjunction with the electrical design, it is necessary to make the part compatible with the fabrication process, which in this case is aluminum dip-brazing. In order for this process to go smoothly and reliably, several features must be included in the mechanical design of the components. Working closely with the vendor, these details were finalized and a 3-D solid model was created. Shown in Fig. 4, this solid model was also used to program the CNC machines.

The dip-brazing process involves first machining the various layers of the array in aluminum and then fusing them together by dipping them in a 1000°F salt bath for several seconds. After a thorough cleaning to remove excess salt from the interior, and final machining to complete mounting fixtures, the part is ready for testing. The final brazed part, shown in its feed network test configuration, is given in Figure 5.

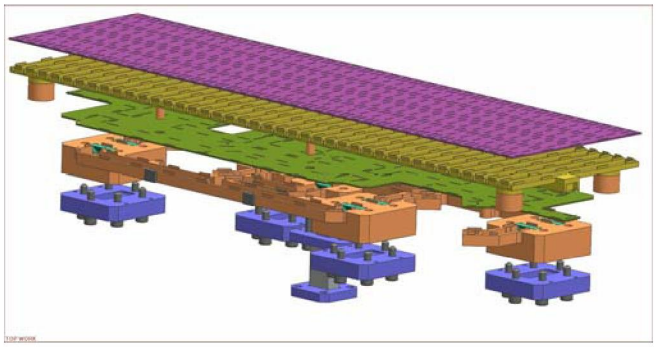

Figure 4 - Three-dimensional model of 10x40 subarray.

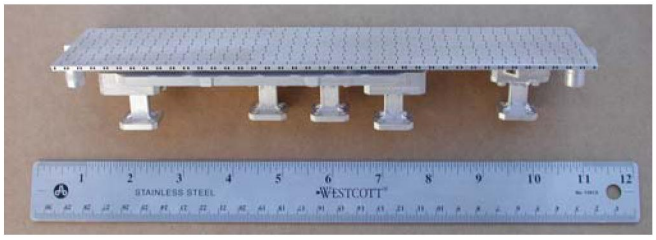

Figure 5 - Final brazed 10x40 subarray shown in feed network test configuration.

Measurements

Overall, the results were very good for a first iteration. The input match for the full 10x40 subarray, given in Figure 6, shows the resonant frequency is about 1% below the design frequency of 35.66GHz, and within simulation and fabrication tolerance errors. The power divider and individual 10x10 subarray matches are shown in Figure 7. As can be seen, the 10x10 subarrays are also tuned slightly low, but the power divider provides more than 30dB return loss at the design frequency of 35.66GHz.

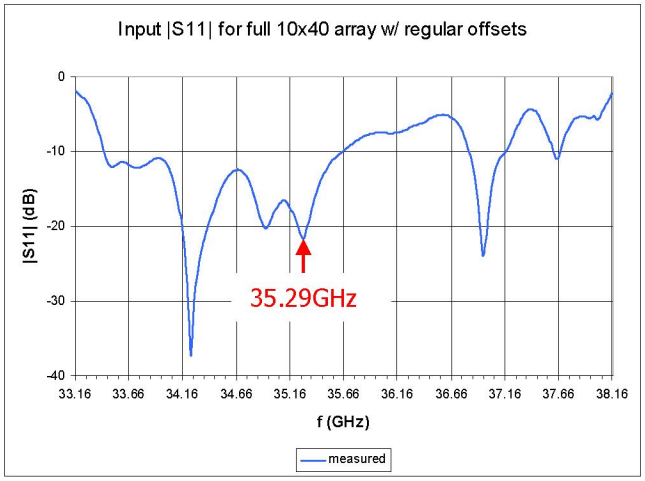

Figure 6 - Input match for full 10x40 subarray.

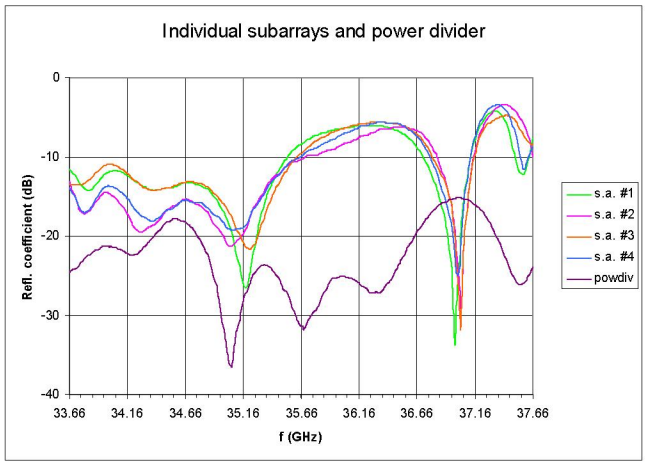

Figure 7 - Input matches for 10x10 subarrays and four-way power divider.

The E- and H-plane patterns at 35.66GHz are shown in Figures 8 and 9, respectively. Agreement with array theory is very good. The measured E-plane beamwidth of 1.73° agrees very well with the 1.70° predicted by array theory. Similary, the measured H-plane beamwidth of 6.98° agrees very well with the 6.87° predicted by array theory, and also meets the requirement for a beamwidth greater than 6.8°.

Additional measurements, not shown here, indicate that the patterns begin to degrade at frequencies below about 34.8 GHz. Note that the return loss at this frequency for the full 10x40 subarray is about 20dB, so it is clear that return loss alone is not a good indicator of performance. Patterns and return loss must be simultaneously tuned to the required operating frequency.

A key conclusion from the measurements is that any adjustments made to retune the input match must not have a negative impact on the patterns at 35.66GHz, which are already close to satisfying the requirements for the 1m x 1m demonstration antenna. Recent moment method calculations suggest that it may be possible to adjust all the slot lengths by 1% to compensate for the missed resonant frequency. While this is the simplest and most appealing of all possible solutions, it also does not take into account fabrication repeatability.

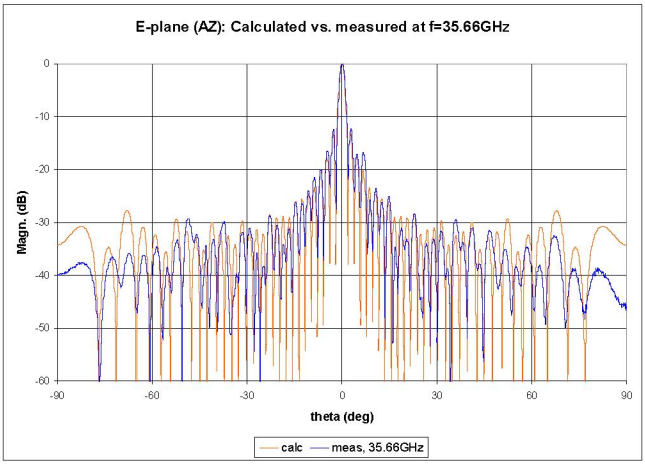

Figure 8 - E-plane patterns for 10x40 subarray.

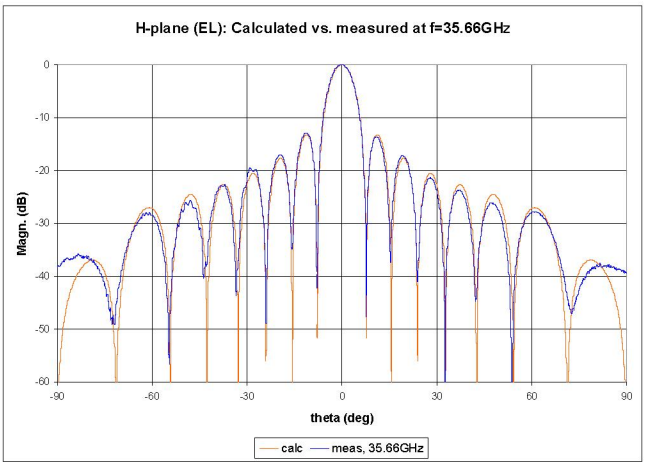

Figure 9 - H-plane patterns for 10x40 subarray.

5. DIGITAL RECEIVERS

Overview

Digital beamforming requires independent receivers and digitizers for each element in the array. We are currently developing a compact Ka-band receiver with 80 MHz bandwidth to support the 1m x 1m DBF antenna demonstration. Certain specifications were modified for the ground-based demonstration but the fundamental design decisions were made with consideration of the spaceborne implementation. Key receiver requirements for both the flight and demonstration systems are listed in the Table 2.

Table 2: Key Receiver Requirements

Parameters	Requirement	
	Flight	**Demo**
Bandwidth	40 MHz	80 MHz
Rx Window	178 usec	50 usec
PRF	4 kHz	500 Hz
Noise Figure	4.5 dB	4.5 dB
ENOB	> 7 bits	> 7 bits
ADC Jitter	< 0.01 nsec	< 0.01 nsec

This section will focus on the demonstration configuration, but will conclude with a section detailing the path to flight instrument implementation.

Receiver Architecture

Each receiver is comprised of two elements: a Ka- to L-band down-converter and an L-band digitizer. The Ka-band down-converter frequency translates the input signal from 35.06 GHz to 1.26 GHz. Down-conversion is achieved using an even-harmonic mixer, which utilizes a local oscillator (LO) frequency at ½ that of a fundamental mixer, thereby simplifying the distribution of the LO. Additionally, the down-converter filters and amplifies the input signal to provide an appropriate input to the second fundamental receive element, the L-band digitizer.

The L-band digitizer performs additional filtering and the final amplification stage to provide the analog-to-digital converter (ADC) with an appropriate signal. The 80 MHz input waveform centered at 1.26 GHz is sampled at a rate of 240 MHz. Bandpass sampling is utilized to reduce the overall data rate, which is a recurring theme in this system. The 10-bit ADC selected provides more than 7 effective bits for an input at L-band. These 10-bits are passed through a 1 to 4 demultiplexer and finally into an FPGA. Initially the FPGA will serve as a buffer and a means to communicate onto the data bus, but may eventually be used for real-time processing of data. The front panel data port (FPDP) standard was selected for transferring data from the receiver. This standard is simple in implementation, provides high-speed capabilities and provides the ability to bus together many devices.

Multi-Channel Configuration

To accomplish digital beamforming, this system requires multiple receivers working in unison. For the demonstration there will be 16 receivers all communicating data to a centralized data acquisition system. The large-scale control scheme for this system is depicted in Figure 10.

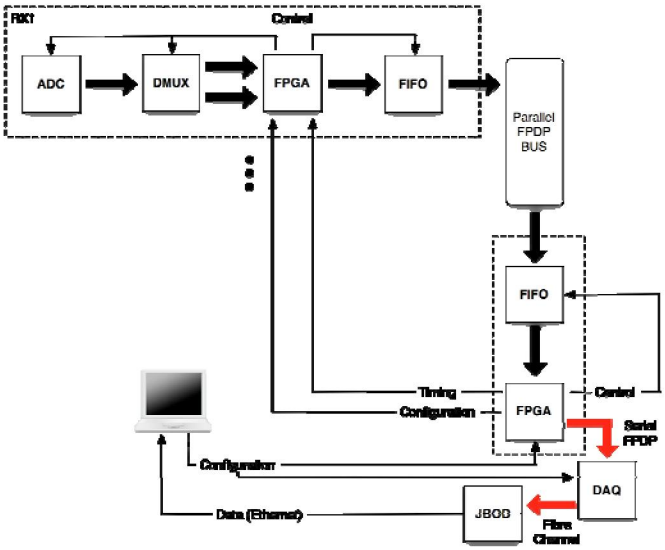

Figure 10 - Digital Backend System

A single FPGA is used to communicate timing and configuration information to each of the 16 receivers. This FPGA is also used to aggregate the data from each receiver, which communicates its data onto a parallel FPDP bus. These aggregated data are then communicated to a data acquisition (DAQ) system through a serial FPDP (sFPDP) interface. sFPDP was selected for transmission of data to the DAQ as it overcomes some distance limitations associated with parallel FPDP. The DAQ stores the data onto a hard-disk array for post-processing.

Spaceborne Implementation

The aforementioned hardware is intended to be utilized in a ground-based demonstration. However, careful consideration was given to all major design decisions and their potential impact on a spaceborne implementation. The key digital components: ADC, DMUX and FPGA were all selected due to the availability of space-qualified equivalents. A flight configuration will require the antenna to be mounted via a boom to the spacecraft. Similar to the demonstration configuration, the receive elements must be mounted directly onto this antenna, so care has been taken to minimize power consumption, size and mass of the receive elements to facilitate this configuration. A few shortcuts were taken to simplify the demonstration system, such as the use of spinning disks for data storage and the use of a slower pulse repetition frequency. These decisions were made to accommodate the large volume of high-speed data generated by the system. The flight data rate problem is further exaggerated by the larger receive window required. To address this problem, scalability and data reduction techniques have been considered. In the demonstration configuration, sFPDP is used to transfer data from the entire receive array to a centralized storage. This optical standard was selected for simplicity, but also due to the scalability of optical media. While the sFPDP protocol can transfer up to 2.5 Gbps, many other optical standards exist that are capable of operating at much higher data rates. Additionally, in year three of this program, the potential for utilizing the FPGAs onboard each receive element for real-time processing of radar data will be examined. This technique can reduce the data rate and the overall volume of data that must be stored between downlinks thereby eliminating the reliance on spinning disks. While a considerable amount of work remains to shape this system into a flight capable equivalent, a path exists. This design will continue to mature as the demonstration system is refined throughout the life of this program.

6. CONCLUSIONS

We have described the design of a novel interferometric radar system for measurement of ice topography. In order to reduce technology risks associated with this ambitious instrument we are developing a ground-based demonstration of the key technology challenge: a 1m x 1m Ka-band DBF antenna.

We have developed tools for analyzing large slotted waveguide arrays and have shown results that are in good agreement with commercially available codes (HFSS) for test cases. These tools were used to design a 10 x 40 element prototype subarray that is part of the 160 x 160 element array being developed for the demonstration. Measured results show good agreement with simulation albeit with some discrepancy in frequency of the return loss minima. Further iteration will be used to correct this issue.

Designs and breadboards have been developed for the array digital receivers. The next iteration in the digital receiver design is focused upon reducing its' size so that 16 receivers can be accommodated on the back of the 1m x 1m aperture.

In the next two years of our three year program we will assemble and test all the components of the 1m x 1m DBF array and demonstrate the performance of the array using antenna range measurements and interferometric imaging of nearby terrain and structures. In parallel with this technology demonstration we will continue to develop the system and mission designs and improve the fidelity of our design, analysis and simulation tools.

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BIOGRAPHY

Gregory Sadowy *Gregory Sadowy received a B.S.E.E from Rensselaer Polytechnic Institute in 1992 and a Ph.D in Electrical Engineering from the University of Massachusetts at Amherst in 1999. Dr. Sadowy is currently a senior engineer at the Jet Propulsion Laboratory, specializing in development of technologies for airborne and spaceborne radars with operating frequencies up to 180-GHz. He is Cognizant Engineer for the UAVSAR phased-array antenna and Principal Investigator for a task developing 180-GHz landing radar technology.*

Brandon Heavey *received a B.S. degree in computer engineering and an M.S. degree in electrical engineering from the University of Kansas is 2003 and 2005 respectively. In 2005, he joined the advanced radar technology and hardware implementation group at the Jet Propulsion Laboratory in Pasadena, CA.*

Delwyn Moller *Delwyn Moller received a Bachelor of Engineering degree (1990) and a Master of Engineering degree (1992) from the University of Auckland in New Zealand. In 1997 she then completed a Ph.D. in radar remote sensing at the University of Massachusetts. She joined the Jet Propulsion Laboratory in 1997 where she is a Senior Engineer in the Radar Science and Engineering Section Research Group.*

Sembiam Rengarajan *received the Ph.D. degree in Electrical Engineering from the University of New Brunswick, Canada in 1980. Since 1980 he has been with the department of Electrical and Computer Engineering, California State University, Northridge, CA, presently serving as a Professor. His research interests include analytical and numerical techniques in electromagnetics with applications to antennas, scattering, and passive microwave components.*

Dr. Rengarajan has authored/co-authored about 175 journal and conference papers. He is a Fellow of IEEE (1994), a member of USNC/URSI Commission B, and the Electromagnetics Academy. He served as an Associate Editor of the IEEE Transactions on Antennas and Propagation (2000-2003). He is the secretary of the Commission B of the United States National Committee of the International Union of Radio Science (2002-present) and an Adjunct Professor at the Electromagnetics Academy at Zhejiang University in China.

Eric Rignot is a research scientist for the Jet Propulsion Laboratory's Radar Science and Engineering Section. His

research interests are in geoscience applications of radar interferometry and polarimetry. He is a principal investigator on several NASA-funded projects to study the mass balance of the Greenland and Antarctic ice sheets using radar interferometry combined with other methods; the interactions of ice shelves with the ocean; and the dynamic retreat of Patagonian glaciers. He received the JPL Lew Allen Director's Award for Excellence in 1998.