UAVSAR Active Electronically-Scanned Array

Gregory Sadowy, Kyle Brown, Neil Chamberlain, Harry Figueroa, Charlie Fisher, Maurio Grando, Gary Hamilton, Vatche Vorperian, Mark Zawadzki

Jet Propulsion Laboratory, California Institute of Technology
4800 Oak Grove Dr., Pasadena, CA 91009

Abstract— *The Uninhabited Airborne Vehicle Synthetic Aperture Radar (UAVSAR) L-band (1.2-1.3 GHz) repeat pass, interferometric synthetic aperture radar (InSAR) used for Earth science applications. Using complex radar images collected during separate passes on time scales of hours to years, changes in surface topography can be measured. The repeat-pass InSAR technique requires that the radar look angle be approximately the same on successive passes. Due to variations in aircraft attitude between passes, antenna beam steering is required to replicate the radar look angle. This paper describes an active, electronically steered array (AESA) that provides beam steering capability in the antenna azimuth plane. The array contains 24 transmit/receive modules generating 2800 W of radiated power and is capable of pulse-to-pulse beam steering and polarization agility. Designed for high reliability as well as serviceability, all array electronics are contained in single 178cm x 62cm x 12 cm air-cooled panel suitable for operation up 60,000 ft altitude.*

1. INTRODUCTION

The Uninhabited Airborne Vehicle Synthetic Aperture Radar (UAVSAR) is a pod-based L-band repeat pass, interferometric synthetic aperture radar (InSAR) used for Earth science applications. Using complex radar images collected during separate passes on time scales of hours to years, changes in surface topography can be measured. Further description of the UAVSAR system and initial results can be found in [1]. The UAVSAR System currently operates aboard a NASA Gulfstream III aircraft (see Fig. 1), and is being ported to the Global Hawk UAV. In the Global Hawk configuration two pods can be carried, enabling either cross-track interferometry at a single frequency or simultaneous measurements at two frequencies. Currently UAVSAR is operated with the L-band AESA (described here) or a Ka-band cross-track interferometer configurations [4].

The repeat-pass InSAR measurement requires that the look angle between the radar and target area be approximately the same on both passes. For spaceborne repeat-pass InSAR this can be achieved by spacecraft attitude control systems. However, in airborne systems the platform attitude is strongly influenced by the winds aloft. Variation in high-altitude winds from pass-to-pass can cause variations in aircraft yaw angle of +/- 20º. For small antennas, compensation can be accomplished by a mechanical gimbal system. However, the UAVSAR system design required an antenna aperture length of 1.5 m, making it impractical to steer the antenna mechanically.

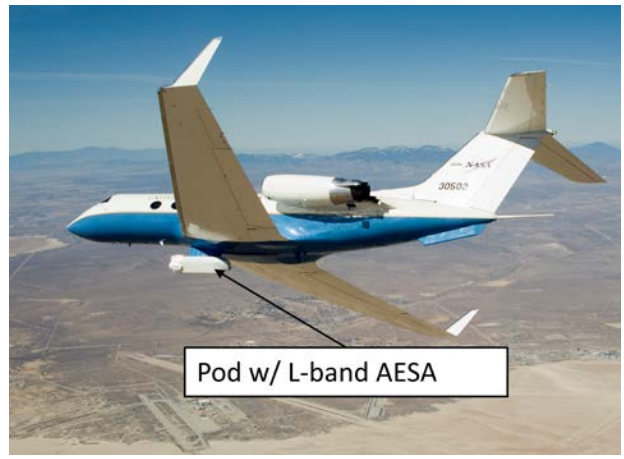

Figure 1 — NASA Gulfstream 3 w/ UAVSAR Pod

To compensate for the varying yaw angle, an Active Electronically Steered Array (AESA) has been developed for UAVSAR. A summary of the key performance parameters is given in Table 1. This antenna is mounted with the long dimension (azimuth) perpendicular to the nominal (zero yaw) direction of flight. The short dimension

Table 1— UAVSAR AESA Performance Parameters

Radiating Aperture Dimensions	1.5 m x 0.4 m
AESA Panel Dimensions	1.78 m x 0.62 m
Azimuth Beamwidth	8.1 degrees
Elevation Beamwidth	38 degrees
Azimuth Scan Range	+/- 25.6 degrees
Transmit Sidelobe Level (no weighting)	-11 dB
Receive Sidelobe Level (w/ weighting)	-20 dB
Array Aperture Gain	19 dB
# of Radiating Elements	48
# of TR modules	24
Peak Radiated Power	2800W
Duty Cycle	5%, max
Operating Temperature Range	-40 ºC to 40 ºC

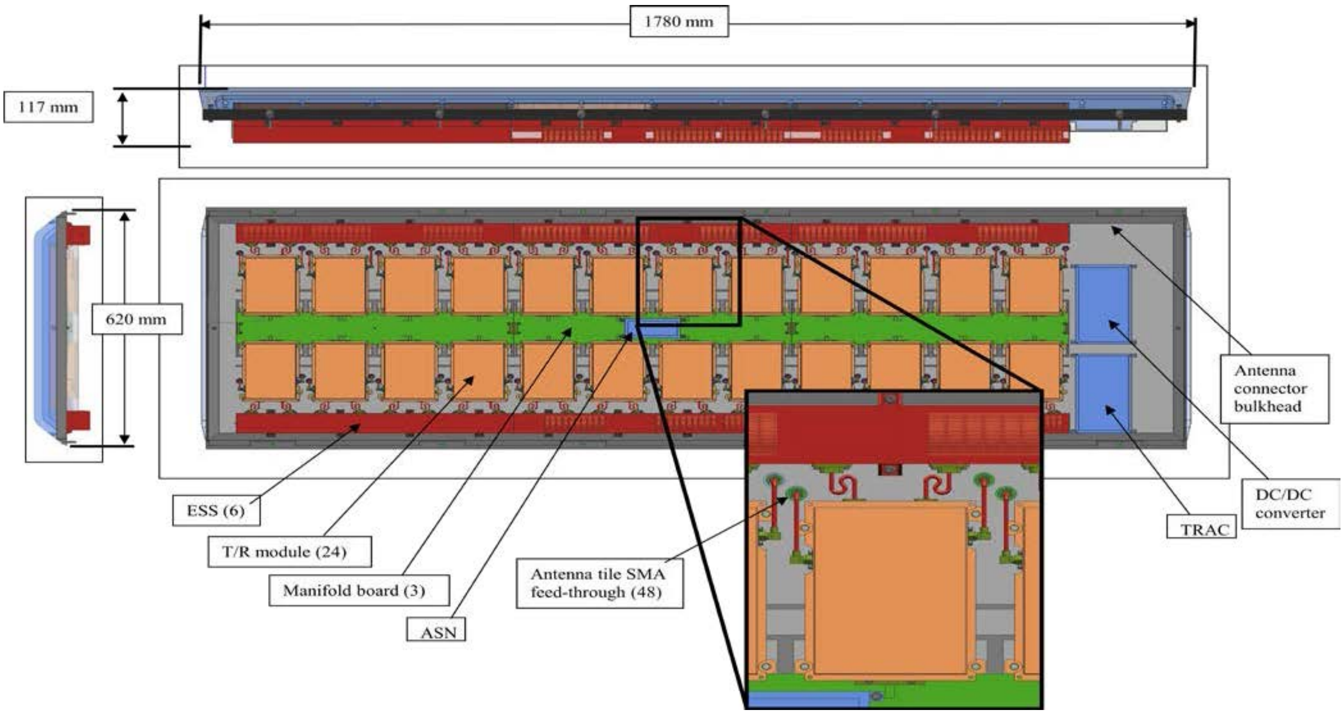

Figure 2 – UAVSAR AESA Configuration

(elevation) is mounted such that electrical boresight is at 45º relative to the Nadir direction.

Since UAVSAR was designed to operate autonomously aboard a UAV, it incorporates an Automatic Radar Controller (ARC). The ARC, using data from GPS and inertial navigation systems (INS) automatically controls every aspect of data collection including beam steering. Based upon measured three-axis aircraft attitude data, the ARC calculates the optimal steering angle for the L-band AESA. The AESA may be updated on every single pulse, however, changes in yaw (the main component of pointing error) typically occur on a longer timescale so update rates of approximately once per second are sufficient.

2. Array Overview

The UAVSAR AESA Panel configuration is shown in Figures 2 and 3. The radiating aperture comprises 48 patch antenna elements arranged as an array of 4 elements in elevation by 12 elements in azimuth. The spacing of the elements is 10 cm in elevation and 12.5 cm in azimuth. The aperture is fabricated as an array of 6 antenna tiles, each of which has 4 elements in elevation by 2 elements in azimuth. Each antenna tile is bonded to an aluminum honeycomb panel using conductive epoxy. The aluminum honeycomb panel forms the mechanical backbone of the antenna, with radiating elements on one side and antenna electronics on the other side. The antenna tiles are covered by a protective radome, which is fabricated from fiberglass face sheets and a fiberglass honeycomb core. All electronics are mounted in a single layer to facilitate cooling as well as servicing of the electronics. A design requirement of this AESA is that any active component is replaceable within hours to minimize aircraft downtime (which can be costly when deployed to remote locations). However to date, it has operated for over 600 hours of data collection with no failures.

3. Radiating Aperture

The radiating aperture is constructed of six tiles with each tile being composed of a radiator circuit board, a honeycomb spacer and feed stripline board. Figure 3 illustrates the tile construction.

The top layer is a double-sided circuit board fabricated from Rogers Duroid 6002 substrate. This material was chosen for all substrates based upon its temperature stability and suitability for multi-layer fabrication. The patch layer contains microstrip patch radiators on the inner side (facing the honeycomb). On the outer side are small capacitive patches that are fed by pins through a clearance hole in the radiating patch. The patch capacitance is designed to resonate with the inductance of the feed pins.

Below the honeycomb is a stripline circuit board that contains the feed network for the elements. The feed network (illustrated in Fig. 4) contains two 10 dB couplers and four 180º "rat-race" hybrids whose shapes have been distorted to fit in the available space.

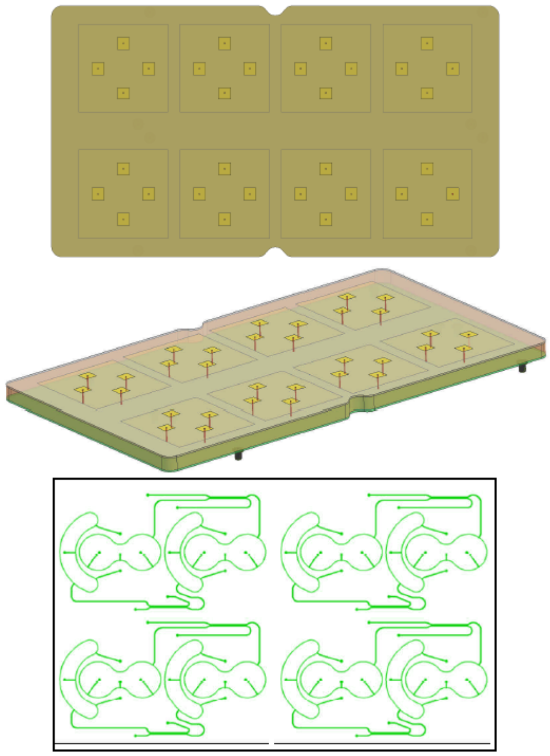

Figure 3 — Tile Construction. Top: Patch Layer, Middle: Projected view showing honeycomb spacer layer and feed pins, Bottom: Stripline feed circuits

Each of the two linear polarizations is fed by a separate port on the TR module. This signal passes through a 10 dB coupler that routes the majority of the signal to the inner two rows of the array. This fixed elevation amplitude weighting is used to achieve the desired beamwidth while suppressing sidelobes in the direction of the aircraft wing. A further consideration was the requirement to spilt the array for independent reception on the upper and lower halves; this required an even number of elements in elevation.

After the coupler, each signal is divided evenly by the 180º hybrids in order to provide balanced excitation to the patch element. The balanced feed arrangement, while adding complexity, provides superior polarization purity for the scanned array.

Each tile is bonded onto the aluminum honeycomb structural panel by conductive adhesive. During development, the radiating tiles underwent extensive environmental testing including: thermal cycling, vibration and high-power breakdown up to 70,000 ft. Careful choice of material properties (especially CTE) and fabrication processes yielded a product that is robust and reliable over the wide range of conditions seen by the UAVSAR AESA. More detail on the design of the radiating aperture can be found in [3]

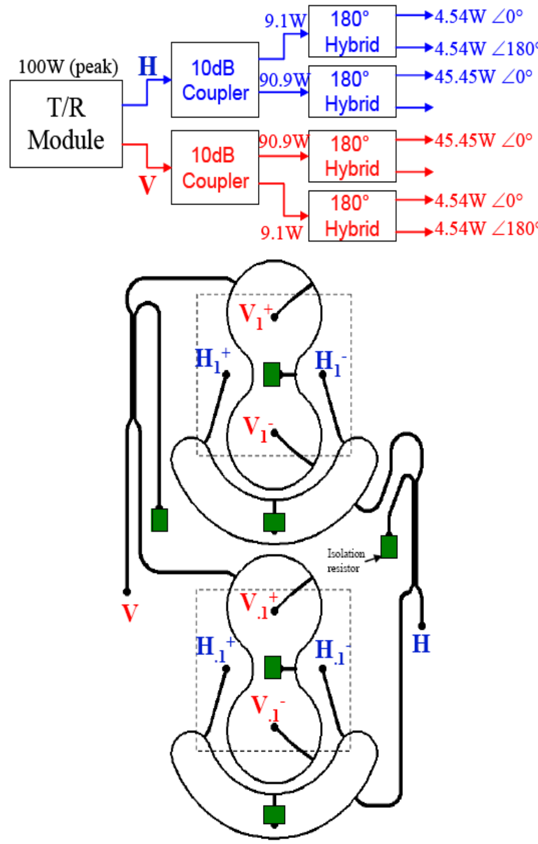

Figure 4 — Interconnect network for element pair. Top: Block diagram showing no-loss power levels with a nominal 100W input level. Bottom: Stripline layout showing edge couplers and ring hybrids. There are four such networks in each antenna tile.

4. TRANSMIT / RECEIVE MODULES

Some of the most critical components of any AESA are the Transmit/Receive Modules (TRM). The UAVSAR AESA uses 24 TRMs, each producing more than 100W of RF power. The TRM basic requirements are shown in Table 2.

Figure 5 shows the block diagram of the TRM. It contains two receiver channels for simultaneous reception of H and V polarizations and a single transmitter channel which can be switched to either polarization. Each of three channels contains a 6-bit programmable phase shifter. Both receive channels have a 5-bit programmable attenuation. Since the transmitter is heavily saturated, it does not require a programmable attenuator.

In addition to transmitter and receiver channels, there is a passive calibration network that can either be used to sample transmitted pulses or to inject signals into the receiver channels. Transmit and receive calibration data collection is interlaced with normal SAR data collection at programmable intervals. These calibration measurements are used for diagnostic purposes and for calibration of phase and amplitude drifts in the TRM.

Table 1 - TR Module Requirements.

Electrical	
Operating frequency range	1.215-1.3 GHz
Duty cycle	0-5%
Pulse repetition frequency	0-4000 Hz
Transmit output power (50 ohm load)	≥ 48+NF dBm
Transmitter output power flatness	≤ ±0.5 dB
Transmitter output power variability	≤ 0.5 dB rms
Transmit pulse output power droop	≤ 1dB
Non-transmit polarization suppression	≥ 40 dB
Receiver gain	25-30 dB
Receiver gain flatness	≤ ± 0.5 dB
Receiver input 1 dB compression	≥ -30 dBm
Attenuation range	0 to ≥ 14 dB
Phase shifter resolution	≥ 6 bits
Phase linearity	≤ ± 10º
RF port return loss	≥ 14dB
Mid-band gain variation (nominal)	≤ 0.05 dB/ºC
Mid-band phase variation (nominal)	≤ 0.5 deg/ºC
Phase stability (30 s) at constant temp.	2^{o} rms
Settling time (Tx to Rx and Rx to Tx)	≤ 5 µs
Environmental	
Operating temperature range.	± 40ºC
Non-operating temperature.	-60ºC to +70ºC
Operating altitude	0 to 60,000’
Operating humidity range	0-100%
Mean time between failures	≥ 50,000 hrs

The TRM dimensions are 16 cm x 12 cm x 3 cm and the measured mass is 567 g. Each module is packaged in a double-sided laser-sealed hermetic aluminum housing. Within the hermetic housing is a mix of chip-and-wire hybrid and soldered assemblies. After sealing, each module is subjected to extensive environmental testing including hermiticity tests, burn-in, vibration, and temperature cycling. After this testing is completed, the phase and amplitude transfer characteristics are recorded at 10ºC intervals over the -40ºC to 40ºC operating range. This data is used in the overall antenna calibration procedure. More detail on the UAVSAR TRM design, calibration and performance can be found in [4].

5. ENERGY STORAGE SUBSYSTEM

The UAVSAR AESA is designed to operate from input voltages in the 22-36VDC range. Internally, it requires several voltages which are generated using commercially available, high-reliability DC-DC converters. However, the power amplifiers in the TRMs together require over 250 A of peak current at 31VDC. Because of the extreme peak load, typical DC-DC converters (which are primarily designed for near-constant load operation) are not suitable.

The Energy Storage Subsystem (ESS) provides a stable 31VDC supply to the TRMs over the 22-36 VDC input range while protecting the SAR electronics and aircraft power bus from input current ripple. This is achieved using a simple two-switch forward converter which provides tight

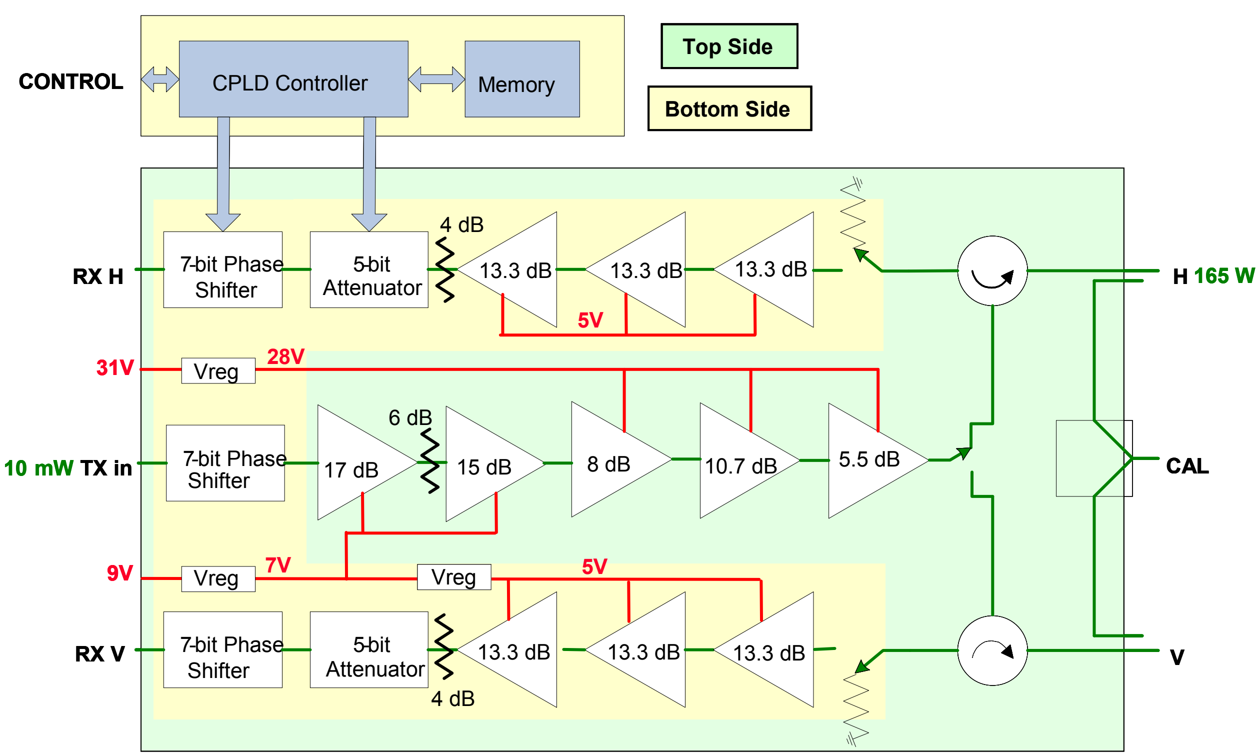

Figure 5 - UAVSAR TRM module architecture. Top side: power amplifiers. Bottom side: receivers, phase shifters, voltage regulators, and controller.

regulation, isolation and filtering of the pulsed power and by a judicious design of the input and output filters and the feedback control loop. The output droop of the ESS is less than 1V for the longest pulse width used (50 µs) and the total input current ripple for the entire AESA is 210 mA. The measured conversion efficiency is 90%.

There are six ESS units, each one powering four TRMs. The ESS's were designed with a long form factor (50 cm x 8cm x 8cm) in order provide power to the modules over short, low-inductance cable while simultaneous forming the sides of the cooling air duct.

6. Beamforming and Calibration Network

The central channel in between the two rows of TR modules is occupied by the beamforming and calibration networks. This is composed of three beamformer manifold boards and the Antenna Switch Network (ASN). Each manifold board contains eight 4-way Wilkinson corporate dividers. There are separate networks for transmit (TX), receive V-polarization (RXV), receive H-polarization (RXH) and calibration (CAL). Additionaly, there are separate networks for the upper and lower halves of the antenna. The center board also contains eight 3-way combiners, which sum the networks from all three boards to form eight 12-way networks.

Each manifold board uses eight Rogers Duroid 6002 substrates to form four stripline circuit layers (TX, RXV, RXH, CAL). Within each layer, the Wilkinson combiner geometry is highly distorted in order fit all the required networks in a space only 10 cm wide. Figure 6 illustrates a typical beamformer layer. The manifold boards are connected to the the TR modules by GPO blindmate connectors and the three manifold boards are connected together by GPPO blindmate connectors. The blindmate connectors replace 128 cables, saving valuable real estate and reducing assembly time.

The ASN resides in the center of the central manifold board. It is connected to the eight 12-way combiners using an eight-place GPPO interconnect. The ASN interfaces to the SAR RF electronics via three SSMA connectors: Transmit (TX), Receiver 1 (RX1) and Receiver 2 (RX2). A network of solid state switches within the ASN controls signal routing during transmit, receive and calibration modes. The block diagram of the ASN is shown in Figure 7.

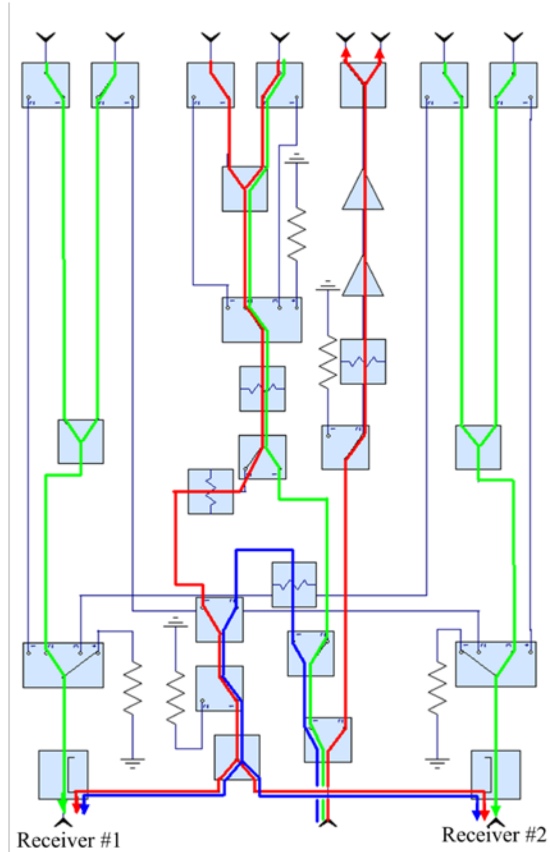

Figure 7 – Antenna Switch Network block diagrams showing calibration paths: Red – TX Calibration, Green – RX Calibration, Blue – Loopback Calibration

The ASN receives control signals from the Transmit Receive module and Antenna Controller (TRAC), which updates the switch network twice (at the start of the transmit and receive intervals) per radar pulse. The ASN also contains the transmit driver amplifier, which provides sufficient power to drive all TR modules to full output power.

The normal operating states of the ASN are:

- Transmit: Drive signal route to TRMs

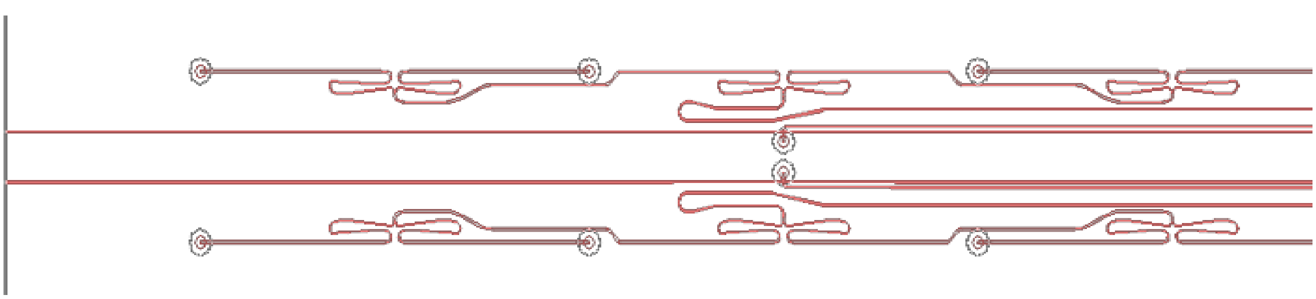

Figure 6 – Typical beamformer layout showing distorted 4-way Wilkinson combiners. Each beamformer manifold board has four of these layers.

- Dual-Pol Receive: RXH and RXV for all 24 modules are combined into two signals and fed to RX1 and RX2
- Upper/Lower H-Pol Receive: 12 channels of RXH from the upper half of the array are fed to RX1. The 12 lower RHX channels are fed to RX1
- Upper/Lower V-Pol Receive: Same as above except for V polarization
- TRM TX Cal: Signal samples from the V and H ports of the TRM by the CAL network are fed to RX1 and RX2
- TRM RX Cal: The signal on the ASN TX port is injected into the TRM receiver via the CAL network.
- Loopback Cal: The signal on the ASN TX port is attenuated and looped-back to RX1 and RX1

The ASN states listed above are invoked by configuration files stored in the Automatic Radar Controller (ARC). The sequence of states used can be tailored to specific applications, giving a high degree of operational flexibility.

7. TRM / ANTENNA CONTROLLER (TRAC)

The main control interface to the UAVSAR AESA is the TRM / Antenna Controller (TRAC). The TRAC handles all communication from the SAR Automatic Radar Controller (ARC) via the Control and Timing Unit (CTU). The CTU communicates with the TRAC using a 10 MHz 3-wire serial link. This link is used to configure the antenna for operation by downloading all the beam-steering and calibration tables prior to data collection. During data collection it is used to update the selected beam, ASN state and selected transmit polarization for each radar pulse. Additionally, the TRAC uses a similar serial link to send antenna telemetry (including 30 temperature measurements and control register states of all TR modules) to the CTU. This data is embedded within the SAR data header for diagnostic use.

The TRAC communicates with each of the TR modules using individual serial links as well as discrete signals that control the transmit polarization and transmit/receive state. The TRAC also receives a signal from each TR module indicating that each module has enabled its receiver protection circuitry in preparation for transmission. If positive indication from each module is not received, the TRAC will cause the ASN to inhibit the RF transmit pulse. This protocol provides protection against control failures that could cause receiver damage.

Each of the serial links includes error detection. Any malformed commands are dropped and an error counter is incremented. There is no automatic retransmission of commands, but the error counts are returned in the telemetry stream for diagnostic use. During typical operation zero errors are recorded.

8. CALIBRATION AND TEST

The UAVSAR AESA was designed to operate over the -40ºC to 40ºC temperature range. To achieve overall phase stability (important for interferometry) as well as beamforming performance over temperature, it is necessary to implement temperature dependent calibration. The total antenna calibration has two main component: 1) Position-dependent calibrations and 2) Module-dependent calibrations.

The positional calibration accounts for phase and amplitude imbalances in the beamforming manifolds and radiating tiles. Due to the materials and construction of beamforming manifolds, the temperature dependence of these components is negligible. This was verified by measurement of manifold S-parameters over a 100 ºC temperature range. Thus, the positional calibration depends only upon an element's position in the array. Because this portion of the calibration also includes the effects of reflections from the various interfaces and the effect of the radiating elements, it is difficult to make a direct, independent measurement of these calibration coefficients. Instead, it is measured as part of the total antenna calibration.

The TRMs contain high-gain active circuits whose amplitude and phase transfer functions can vary significantly over temperature. Additionally, across the set of TRMs there are amplitude and phases offsets even at uniform temperature. Thus, the TRMs also contain a temperature-dependent as well as a temperature independent part of the calibration. After environmental testing, each module is measured over the -40ºC to 40ºC operating range and the phase and amplitude of all signal paths are recorded. The phase and amplitude of each module at reference temperature is removed from this data and residual data forms the temperature-dependent part of the calibration.

In order to generate the total antenna calibration, the UAVSAR AESA is placed on a near-field scanner. The procedure is similar for transmit and receive calibrations, although the range configuration is slightly different. The scanner probe is accurately positioned at a point over each element. That particular element is then enabled (for transmit or receive depending upon the type of calibrations in progress) and the phase and amplitude are recorded. The TRM temperatures are also recorded during this procedure. The data measured in the procedure forms the positional calibration and the TRM temperature at the time of measurement is used as the reference temperature for separating time-dependent and time-independent portions of the TRM calibration.

Finally, the temperature-dependent TRM for each module calibration is interpolated to 5ºC intervals and summed with the positional calibration associated with the module location. To this calibration we add the ideal phase ramps and amplitudes tapers (on receive only) required to generate the desired beams. The results are quantized and formatted into a binary table that is unique to a particular TRM in a particular array position. The table allows for 256 arbitrarily chosen beams that can be selected with pulse-to-pulse agility.

At the start of a data collection, the SAR CTU, uses the measured antenna temperature to select and transmit the correct beam lookup tables to the TRAC via the antenna serial control bus. The TRAC transmits the table data to the 24 TRMs. Once loaded, the TRMs will retain the lookup tables as long as they remain powered. On each pulse, the TRAC receives a beam select command, which is broadcast to all of the TRMs. Each TRM then loads the correct phase and amplitude coefficients based from its own lookup table.

Figure 8 shows typical normalized azimuth patterns for transmit and receive for 0º scan and 25.6º scan. In transmit mode, the array uses uniform illumination, while on receive a Taylor-weighted amplitude taper is applied by the TRMs.
During test and calibration, automation is used to collect patterns for 256 beams ranging from -25.4º scan to 25.6º scan in a single pass of the near-field scanner. Every beam pattern is then processed and automatically checked for compliance to requirements for beamwidth, pointing accuracy and sidelobe level.

9. CONCLUSIONS

The UAVSAR L-band AESA is a 1.2-1.3 GHz electronically scanned array that has been specifically designed to enable airborne repeat-pass radar interferometry. Important design criteria included high sensitivity, calabratability and reliable performance over a wide environmental operating range.

To meet these criteria, UAVSAR AESA utilizes high-power transmit receive modules, high-density stripline beamforming networks, custom energy-storage power supplies and a serial digital interface with a simple, but powerful command protocol.

To support calibration and maintainace of the UAVSAR AESA we have developed automated methods for calibrating TRMs and the full antennas inluding automatic generation of fully calibrated beam steering tables.

The UAVSAR AESA successfully completed its engineering checkout and transitioned to science data collection in February 2009. Since then, it has collected over

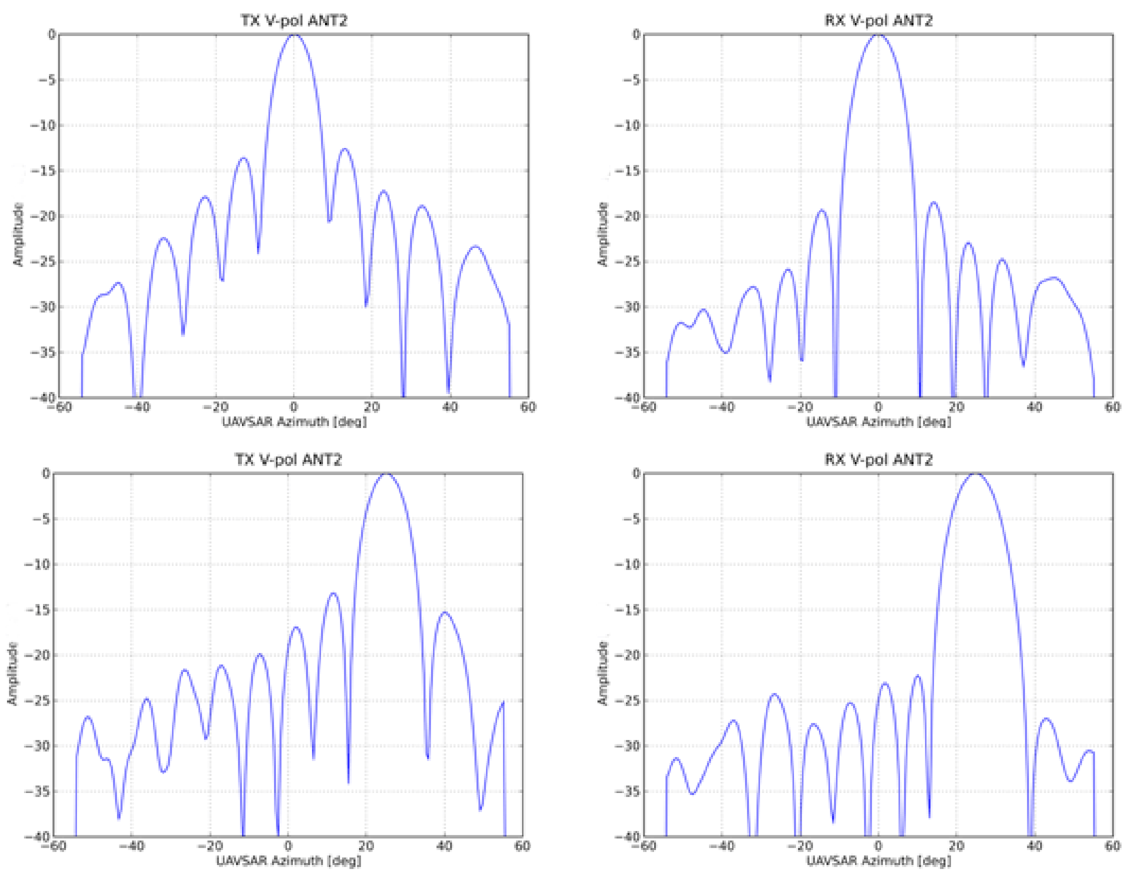

Figure 8 – Typical measured azimuth antenna pattern cuts. Upper Left: Transmit 0º scan, Lower Left: Transmit 25.6º scan, Upper Right: Receive 0º scan, Lower Right: Receive 25.6º scan

600 hours of science data in all across the Continental US, in Alaska, Greenland, Costa Rica and Haiti.

10. ACKNOWLEDGMENTS

The research described in this paper was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration. The UAVSAR TRM was designed and manufactured by REMEC Defense and Space Inc.

REFERENCES

[1] Hensley, S.; Wheeler, K.; Sadowy, G.; Jones, C.; Shaffer, S.; Zebker, H.; Miller, T.; Heavey, B.; Chuang, E.; Chao, R.; Vines, K.; Nishimoto, K.; Prater, J.; Carrico, B.; Chamberlain, N.; Shimada, J.; Simard, M.; Chapman, B.; Muellerschoen, R.; Le, C.; Michel, T.; Hamilton, G.; Robison, D.; Neumann, G.; Meyer, R.; Smith, P.; Granger, J.; Rosen, P.; Flower, D.; Smith, R., "The UAVSAR Instrument: Description and First Results, 2008 IEEE Radar Conference Proceedings, 2008

[2] Moller, D., S. Hensley, G. Sadowy, C. Fisher, T. Michel and M. Zawadzki, The Glacier and Land Ice Surface Topography Interferometer: "An airborne proof-of-concept demonstration of high-precision Ka-band single-pass elevation mapping", accepted for publication *IEEE Trans. Geoscience and Remote Sensing*, 2010

[3] Chamberlain, N.; Zawadzki, M.; Sadowy, G.; Oakes, E.; Brown, K.; Hodges, R.; , "UAVSAR Phased Array Aperture", *2006 IEEE Aerospace Applications Conference Proceedings,* 2006.

[4] Chamberlain, N.; Sadowy, G, "UAVSAR Transmit / Receive Module", *2008 IEEE Aerospace Conference Proceedings*, 2008.