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T/R Module Development for Large Aperture L-band Phased Array

Neil Chamberlain, Constantine Andricos, Kendra Kumley*, Andrew Berkun, Richard Hodges, Suzanne Spitz
Flight Communications Systems, Jet Propulsion Laboratory, California Institute of Technology
4800 Oak Grove Drive, Pasadena, CA 91109
* Electrical and Computer Engineering Department, South Dakota School of Mines and Technology
501 E. St. Joseph St, Rapid City, SD 57701

Neil.F.Chamberlain@jpl.nasa.gov, Constantine.Andricos@jpl.nasa.gov, klkumley@ieee.org,
Andrew.C.Berkun@jpl.nasa.gov, Richard.E.Hodges@jpl.nasa.gov, Suzanne.J.Spitz@jpl.nasa.gov

Abstract

This paper describes a transmit / receive (T/R) module for a large L-band space based radar active phased array being developed at JPL. Electrical performance and construction techniques are described, with emphasis on the former. The T/R modules have a bandwidth of more than 80 MHz centered at 1260MHz and support dual, switched polarizations. Phase and amplitude are controlled by a 6-bit phase shifter and a 6-bit attenuator, respectively. The transmitter power amplifier generates 2.4 W into a nominal 50 ohm load with 36% overall efficiency. The receiver noise figure is 4.4 dB including all front-end losses. The module weighs 32 g and has a footprint of 8 cm x 4.5 cm. Fourteen of these T/R modules were fabricated at the JPL Pick-and-Place Facility and were tested using a computer-controlled measurement facility developed at JPL. Calibrated performance of this set of T/R modules is presented and shows good agreement with design predictions.

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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. 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 electronics for an active antenna array that will meet these requirements. A companion paper describes the radiating elements and panel design [ ].

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*

LLSBR calls for a significant reduction in the areal mass density of the radar aperture over comparable phased array technologies. 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. Target mass density breakdown 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, a T/R module must weight approximately 33 g.

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. The LLSBR panel is defined as the sub-array of elements that is down-converted to IF and then digitized. These digitized signals are communicated through optical fibers to an on-board process where digital beam forming is done.

Based on beam-steering and sidelobe requirements, the LLSBR panel is designed as an array of 12 x 12 patch antenna elements, each fed by a dedicated T/R module. The interconnect concept for a half-panel (measuring 6 elements in elevation by 12 elements in azimuth is shown in Fig. xxx.)

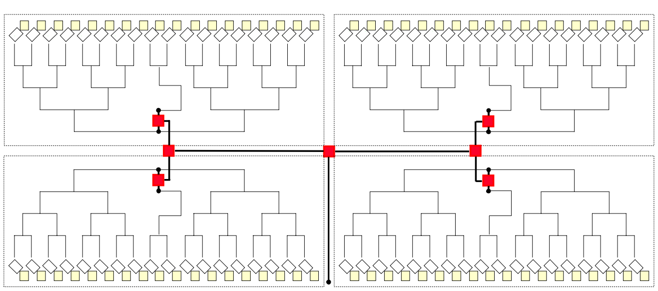


Fig xxx. Half-panel Interconnect Architecture Showing Four Panels of 18 Elements (Arranged as 3x6) and One RF Manifold.

Each of the small squares represents a patch antenna element and each of the diagonal rectangles represents a T/R module. (The modules are actually mounted in this manner as a consequence of accommodation constraints.) Each of the four dotted rectangles represents a multi-layer printed circuit board that contains RF corporate stripline feeds, power planes, and control lines for digitally controlling the T/R modules. Only one of the two RF feed networks is shown in Fig xxx. The four manifold boards are interconnected by means of power splitters and coaxial cables (shown), and also by DB25 connectors and wire harnesses for power and digital control (not shown). An overarching goal in the system-level design of this hardware is to obtain a high degree of modularity, to significantly reduce the amount of touch-labor associated with installing cables and wire harnessing, and to reduce the overall time and cost of panel-level integration and test.

System Requirements

The following requirements were formulated as a guideline for the joint-mission phased array development.

Table 3. Key System Requirements

Polarization	Switched H & V
Transmit center frequency	1.26 GHz
Bandwidth	> 80.0 MHz
Gain flatness over 80 MHz	< 0.5 dB
Input & output return loss	> 14dB
Pulse duration	5 - 07 µs
Pulse repetition frequency	350 - 4000 Hz
Duty cycle	0.3% - 8.7%
Transmit peak power	7.3 W
Transmit gain (max)	30 dB
Transmit efficiency	> 36%
Transmit harmonics	< -20 dBc
Transmit spurious signals	< -60 dBc
Receiver gain (max)	20 dB
Receiver 3rd order o/p intercept	> - 20 dBm
Input power 1dB compression	> -30 dBc
Noise figure (@ input to T/R)	< 2.5 dB
Phase shifter range	360 deg
Phase shifter step	< 6 deg
Attenuator range	> 30 dB
Attenuator step	0.5 dB

The required phase shifter and attenuator steps correspond to 6-bit quantization. There are additional requirements on the combined transmit/receive amplitude linearity and phase linearity of the entire RF front end (antenna element, T/R module, and beamformer) to meet an integrated sidelobe ratio specification of 35dB. In order to accommodate project constraints of schedule and cost, an existing T/R prototype design with lower peak output power (3W) was utilized in this development. This was justified on the basis that the array will not be used in a radar system, and that realistic thermal dissipation can be emulated by increasing the transmit duty cycle. With respect to the latter, the T/R module is designed so that is can operate in continuous wave (non-pulsed) mode while transmitting.

T/R RF Hardware Architecture

T/R architecture is depicted in Fig. xxx. The transmit and receive chains are fed by separate RF manifolds and share a common attenuator and phase shifter. The output of the transmitter is connected to a circulator that was custom-designed for this module. The input of the receiver is switched to the circulator on receive. Poorly matched loads reflect power back into the T/R module which dissipates in a 50 ohm load that is also switched to the circulator. Dual rat race hybrids for horizontal (H) and vertical (V) polarizations are switched to the circulator depending on the transmit polarization and the receive polarization.

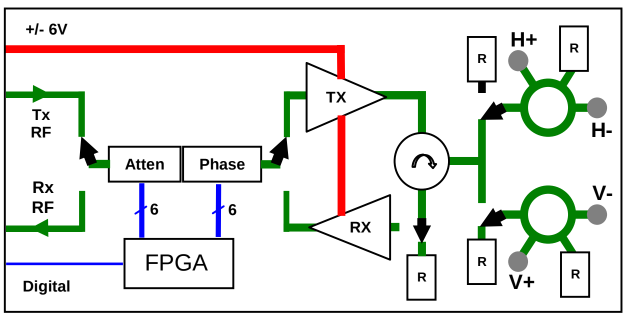


Figure xxx. T/R Module Architecture

All RF transmission lines are implemented as 50 ohm microstrips or striplines. The hybrids provide anti-phase signals for symmetrical excitation of a patch antenna element. This particular architecture does not support dual simultaneous receive polarizations but could easily be modified to do so if required. Dual RF manifolds for transmit and receive provide better isolation between these channels than a single (switched) manifold, and are used as such in this development. Alternatively, a single switched manifold for transmit and receive would free the other manifold up for BITE or calibration purposes.

T/R Power and Digital Control Architecture

The T/R module requires separate +6V and -6Vpower supplies that are provided from very low-impedance power planes in the manifold board. These voltages are regulated to +5V, -5V and +3.3V on the T/R module. The receive and transmit amplifiers and the RF switches are powered from +5V. The FPGA and other digital circuitry requires a +3.3V supply. The gate bias on the transmitter power amplifier, the phase shifter, and attenuator each require a negative voltage supply. The digital IO to the module comprises four serial lines, which include (as inputs to the module): CLOCK, DATA, and TRANSMIT/RECEIVE-ENABLE, and (as an output from the module) READBACK. READBACK allows a central controller to read the current state of the attenuator and phase shifter of an appropriately polled module, and to read the output of a temperature sensor located on the module.

The on-board FPGA is remotely programmable in situ, but is not otherwise configured with memory that can store data such as calibration offsets or a history of temperature readings. These data are ultimately communicated to and from an FPGA-based controller that controls 18 T/R modules. The outputs of these controllers are daisy chained together in a ring bus to a central panel-level beam-forming computer/controller. It is this central computer that stores the various offsets and computes the appropriate amplitude and phase states for beam forming.

T/R Physical Implementation and Fabrication.

A photograph of the LLSBR T/R module is shown in Fig. xxx.

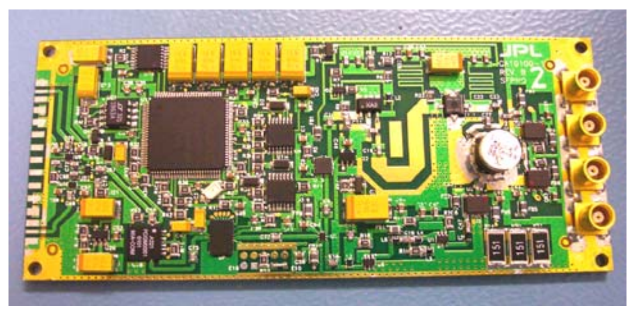


Fig. xxx. T/R Module Layout

The printed circuit board comprises 16 circuit layers fabricated on a Rogers 4003 substrate. The hybrids are implemented in stripline on two layers of the PCB. The RF components are commercial-off-the-shelf (COTS) plastic-packed microwave monolithic integrated circuits (MMICs) that use Gallium Arsenide (GaAs) technology. The large square IC to the left of the module is a Xilinx 4005 FPGA that controls the switches, the attenuator, and the phase shifter. The large circular device near at right center of the module is the circulator. The circulator weighs less than 2g and can handle 30W continuous, with 20dB of isolation and 0.7dB of loss.

The four circular ports at the far right of the module are sub-miniature coaxial connectors that connect to the patch element via short coaxial cables. The T/R module itself is bonded to a much larger printed circuit board that contains manifolds for RF, power and control. The interconnects to this board are made through a series of 15 beryllium-copper gull-wing tabs located at the far left of the T/R module. In this manner, the T/R module can be regarded as a surface mount component on a printed circuit board that is, ostensibly, amenable to automated assembly. For the purposes of this development, it is necessary that modules be readily swapped in and out of the feed manifold. Thus, the module is screwed on to a thin metallic base-plate carrier that is bonded to larger manifold board. A thin conducting lid can be placed over the module to provide additional isolation, if necessary.

The T/R module PCB is designed with a low thermal impedance from the power amplifier stage through the base-plate to the manifold board, which acts as a heat spreader. The low peak output power of this module (2.4W), the moderate efficiency of the module (35%), and the relatively low duty cycle of the radar (<10%) result in a low average dissipated power and hence leads to a relatively simple thermal design.

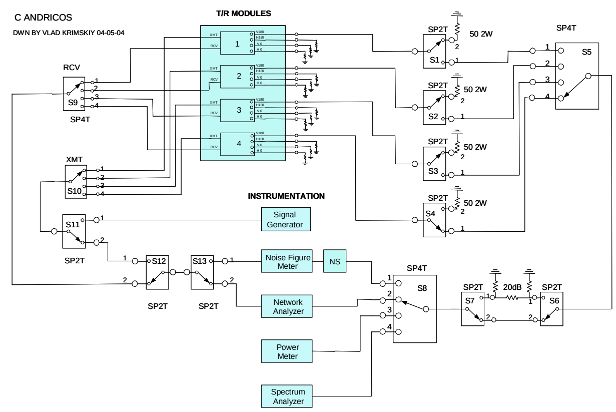
Fig xxx. T/R Module with Baseplate and Lid

The LLSBR T/R module was designed and, with the exception of the PCB, fabricated at JPL. The majority of components were placed automatically on the PCB using the JPL Pick-and-Place Facility, and then flow-soldered. Certain components, such as the circulator and coaxial connectors, are not amenable to such automated production and were soldered by hand. Utilizing large-scale production techniques helps to considerably reduce development cost and schedule time. The use of plastic MMICs, albeit unqualified for flight at this time, represents a cost-effective and time-efficient means of producing a highly functional T/R module.

The total mass of the T/R module, exclusive of the base-plate and lid, is 32g. The module measures 7.8cm by 4.5cm.

T/R Module Characterization

One of the challenges of producing a moderate size active phased array prototype is that one requires a large number (typically dozens) of T/R modules, but these quantities are not sufficient to warrant the development of the type of test-facilities that are concomitant with mass production. The approach JPL has taken is to characterize T/R modules in groups of four using an automated test station specifically designed for this project. The test station is based on a series of high-quality RF relays that switch each module to the appropriate piece of test equipment. The modules are mounted on a hot-cold plate so that they can be characterized as a function of temperature. The switching and control of the instrumentation and hot-cold plate is done using a Lab-View interface. Fig xxx summarizes the architecture of the measurement system and Fig xxx depicts the actual hardware. This equipment provides rapid measurement of output power, output power spectrum, noise figure, and S-parameters of the T/R modules. It should be noted that without this sort of automated testing, prototype development would be prohibitively costly and time consuming.



Fix xxx: Schematic of Computer Controlled Test-Station.

Fix xxx. Automated Test Station Hot-Cold Plate and RF Switching

2. Measurements And Calibration

In this Section we report on the results of preliminary S-parameter measurements of a group of 14 T/R modules, made at room temperature. The S-parameter measurements are the starting point for accurately calibrating the ensemble of modules. Natural variances in the components of each module result in differences in both the amplitude and phase of any two T/R modules.

Unless these differences are compensated, the antenna pattern formed by the phased array will suffer from increased side lobes and loss of gain. Ultimately, this calibration should be done with the T/R module in its proper environment, i.e., connected to the antenna element and to the feed manifold, mounted on a panel that may suffer from structural deformation, and subject to the orbital thermal environment. Such perturbations require the use of sophisticated real-time calibration and metrology schemes that are beyond the scope of the current development, but are the subject of ongoing research [Dalias Paper].

The measurements reported in this paper were recorded as a function of frequency from 1200 MHz to 1300 MHz in 5 MHz steps using a vector network analyzer and other RF instrumentation. Only one of the output hybrids (the one that would normally connect to the H-pol port of the antenna element) was utilized in the measurements. The attenuator and phase shifter were switched through a subset of 128 of the possible 4096 states that arise from two sets of 6 bits. This amounts to setting the attenuator to state 0 (minimum attenuation) while the phase shifter is switched through each of its 64 states, and then setting the phase shifter to state zero (nominally 0 degrees) while switching the attenuator through each of its 64 states. Small signal excitation was used for both transmit and receive S-parameter measurements. Additionally, T/R large-signal performance, noise figure, and other performance metrics were recorded and a tabulated below.

T/R Performance

Table xxx summarizes key performance parameters of the LLSBR T/R module at room temperature. The gain flatness and return loss measurements are the worst case for the group of 14 modules, whereas the other measurements pertain to one particular T/R module.

Table xxx. Small Signal T/R Measurements

Transmit center frequency	1.26 GHz
Bandwidth	200 MHz
Gain flatness over 80 MHz Tx	0.45 dB pk,
Gain flatness over 80 MHz Rx	0.52 dB pk
Input & output VSWR, Tx	18.8 dB, 14.3 dB
Input & output VSWR, Rx	12.3 dB, 11.0 dB
Transmit peak power	2.4 W
Transmit gain (max)	39 dB
Transmit efficiency	35%
Transmit harmonics	-40 dBc
Transmit spurious signals	-60 dBc
Receiver gain (max)	24 dB
Receiver 3rd order o/p intercept	-16 dBm
Input power 1dB compression	-26 dBc
Noise figure (@ input to T/R)	< 4.4 dB

Gain flatness and phase linearity as a function of frequency on receive are depicted in Figure xxx. Similar responses are found for transmit. There is approximately a 2dB spread in gain between modules that must be compensated by calibration. It should be noted that the dynamic range of the modules, nominally 32 dB prior to calibration, is reduced by 5 dB to approximately 27 dB after calibration. The 0.52 dB peak deviation in gain from best linear fit cannot be compensated with calibration, as the calibration scheme does not equalize the frequency responses; it merely shifts their relative levels.

There is approximately a 40 degree (1/9 of a wavelength) spread in the phase paths of the modules that must also be compensated by calibration. Unlike the attenuation calibration, the cyclic nature of the phase shifter does not result in any compression of the phase range.

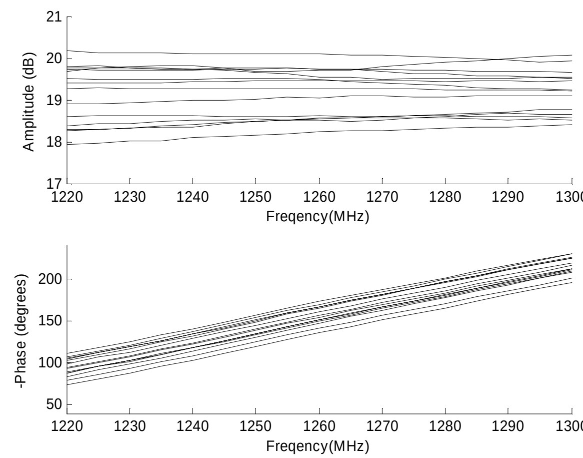


Figure xxx. Amplitude and Phase as a Function of Frequency on Receive for Each of 14 T/R Modules

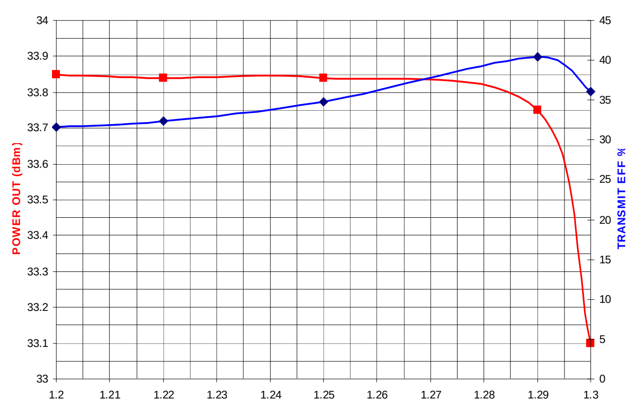


Figure xxx. Transmitter Output Power and Efficiency as a Function of Frequency

The output power for large-signal excitation of one module is shown in Fig. xxx, along with the overall T/R module efficiency. The output power is approximately 0.75 dB down at 1.3 GHz, suggesting that the output stage needs to be tuned to move this pole a little higher in frequency. Transmitter efficiency at 1.26GHz is 36%. The corresponding output and input powers are 33.84 dBm and 5 dBm respectively.

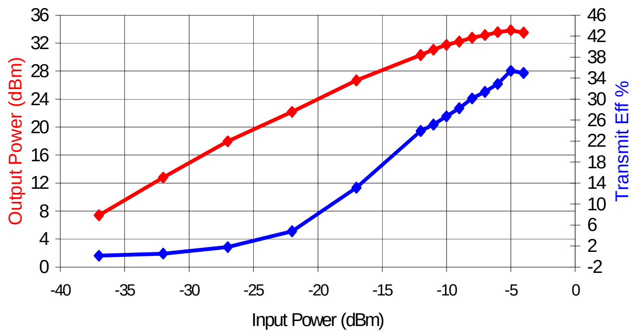


Fig xxx. Transmitter Output Power as a Function of Input Power

At low output powers the efficiency drops dramatically. For example, at 24 dBm output power (-20 dBm input power) the module efficiency is 8%. Thus even a moderate amplitude taper of 10dB on transmit would be costly in terms of overall power efficiency.

The T/R power supply is designed to operate in CW mode, as certain laboratory measurements are either difficult or impossible in pulsed mode. The DC voltage and current needed to power a single T/R module are presented in Table xxx. Power draw is computed from these measurements is also tabulated. In CW mode (a mode that is not used by the radar) the transmitter consumes 98% of the total average power. However, in the radar mode with the highest duty cycle (8.7%), the transmitter consumes 68% of the total average power, and in the mode with the lowest duty cycle (0.3%) the transmitter consumes only 7% of the total power. It is thus apparent that receiver DC power draw becomes the limiting factor in overall DC power consumption in low duty cycle modes.

Table xxx. Current and Voltage Measurements for One T/R Module at Room Temperature. T/R Output RF Power is 2.4W Peak.

Mode	**Voltage (V)**	**Current (mA)**	**Power (W)**
CW Tx	+5.5	1230	6.76
CW Rx	+5.5	25	0.14
CW Tx/Rx	-5.5	25	0.14
Total (CW)			6.90
Total (8.7%)			0.86
Total (3.5%)			0.51
Total (0.3%)			0.30

Port-to-port isolation was measured using a vector network analyzer, with the following results:

Table xxx. Port-to-Port Isolation

Horizontal to Vertical	35 dB
Transmit to Receive	40 dB
Output to Input (off state)	65 dB

S-Parameter Measurements: Raw Data

Measured S-parameter amplitude and phase data for a set of 14 T/R modules on receive at room temperature are shown in Figs xxa and xxb respectively. The measurement frequency is 1.26 GHz; the center of the radar band. A similar picture emerges for the T/R module on transmit. These data are a function of either the state of the attenuator or the state of the phase shifter, there being 64 such states in each case. In the former case, the phase state is set to state zero, whereas in the latter case, the amplitude is set to state zero. In Fig. xxa, an ideal set of amplitude versus attenuation state characteristics would comprise 14 identical linear curves with a slope of -0.5 dB/state. Likewise, an ideal set of amplitude versus phase state characteristics would comprise 14 identical linear curves with zero slope and a y-axis intercept of

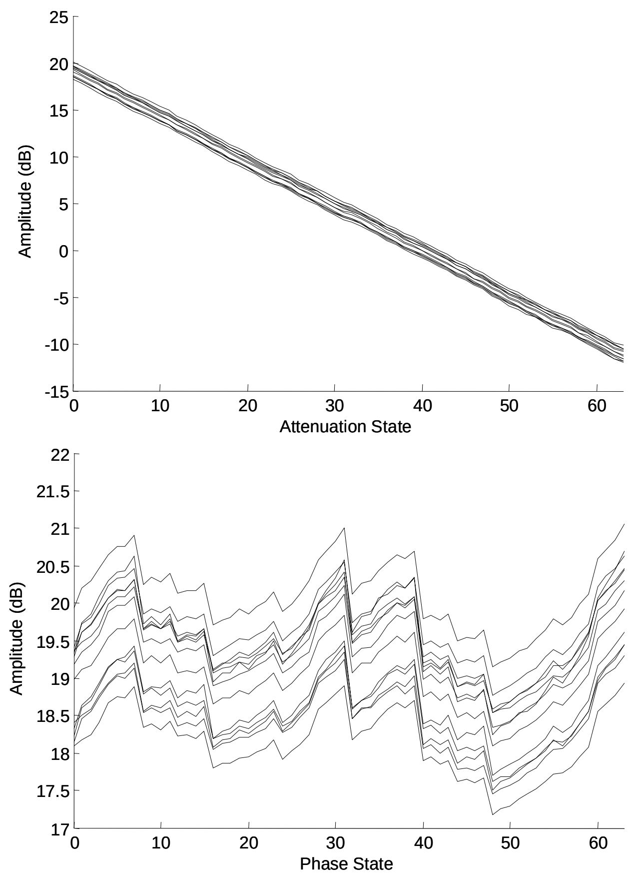


Figure xxa. Raw Amplitude Data $|S_{21}|$ for Fourteen T/R Modules on Receive at 1.26GHz.

In Fig. xxb, an ideal set of phase versus attenuation state characteristics would comprise 14 identical linear curves with zero slope. Likewise, an ideal set of phase versus phase state characteristics would comprise 14 identical linear curves with a slope of 5.625 deg/state. In practice, the measured data deviate from these idealizations owing to variances in the components and because of the physical implementation of the attenuator and phase shifting circuits. For example, a gradual change in phase is exhibited in the phase versus attenuation state characteristic of Fig. xxx. This arises because the circuit paths of the higher attenuation states tend to be longer (i.e., have more circuit elements) and therefore impart a larger time or phase delay. An additional subtlety that complicates the calibration process is that amplitude and phase shifter characteristics are lightly "coupled", in the sense that changing amplitude state causes a small but discernable change in phase, and vice versa.

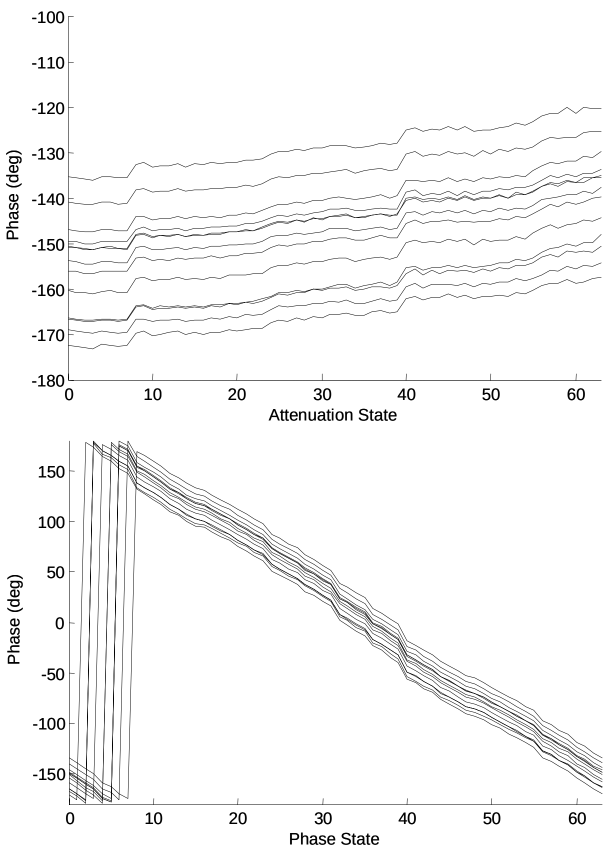


Figure xxb. Raw Phase Data $\angle S_{21}$ for Fourteen T/R Modules on Receive at 1.26GHz.

The purpose of calibration is to remove as much of these variances as possible, so that the resulting calibrated data best approximates the afore-mentioned ideal curves.

Calibration Approach

In principle, calibration can be thought of as a mapping process whereby raw attenuator and phase shifter states are mapped into calibrated attenuator and phase shifter states. So, for example, if the beamforming computer commands a block of T/R modules to all have the same minimum attenuation state (call is state 0), then state 0 is the calibrated state and some sort of translation must be performed to set the appropriate raw attenuation state on each T/R module. A look-up table is the most obvious way and, on the face of it, simple way of performing this translation. However, the table is a function of temperature and, as mentioned previously, there are interdependencies between amplitude and phase that add to the table data volume. This has lead to the development of in-situ calibration algorithms where modules are adjusted in amplitude and phase using closed loop feedback techniques [cite]. The design of these calibration circuits is itself fraught with difficulties, as one is invariably forced to use transmission lines, couplers, circuit elements, etc., that are themselves subject to component and temperature variation. Automatic calibration circuitry is not integrated into T/R module in this particular development. Rather, it is the subject of ongoing study and in the meantime we utilize look-up table techniques to do 'open-loop' calibration.

Calibration Algorithm

The calibration process is slightly different for phase adjustment than it is for amplitude adjustment. Both processes are generally done concurrently, as there is coupling between them. However, for the current measurement subset, where phase is measured independently of amplitude and vice versa, there is insufficient information to decouple the data sets and adjustment can proceed independently.

We start first by adjusting the phases of each module, essentially rotating the phase circle so that 0 degrees phase is aligned with (calibrated) state 0. This process is represented algorithmically in Fig xxx. The phase of a T/R module, $\varphi(i,j)$ is a function of the module, indexed as i, and the phase state, indexed as j. The statement

$$k_{min} = \text{argmin}\{\varphi_{raw}(i,k)-j*5.625\}$$

simply finds the state k_{min} that is the best approximation to the linear phase ramp $j*5.625°$ for j=0,1,…63. This is repeated for each calibrated state j, and for each module.

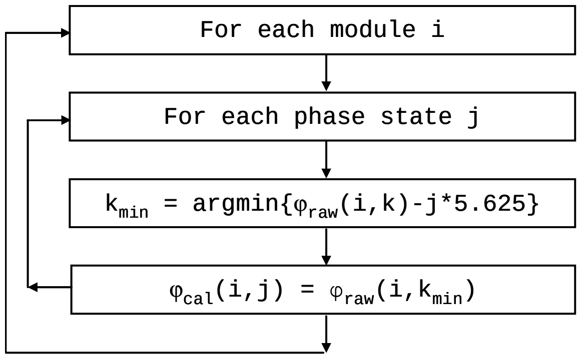


Figure xxx. Phase Calibration Algorithm.

Next, the amplitudes are adjusted in a similar manner, with one important difference; a minimum reference attenuation level must be chosen that is smaller than or equal to the lowest gain of any T/R module in raw state zero. For the current ensemble of T/R modules in receive, this reference value was chosen as 16.5dB. The amplitude adjustment algorithm then essentially becomes one of mapping raw attenuation states to the calibrated characteristic of 16.5 – j*0.5 dB for j=0,1,…63.

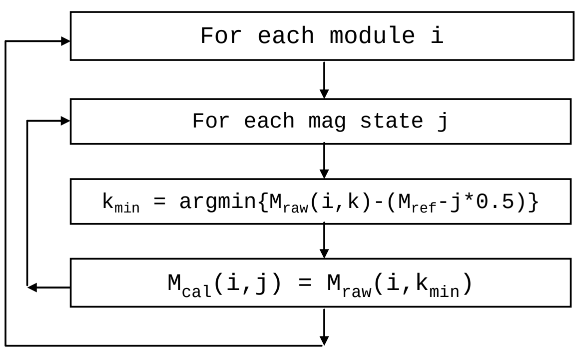


Figure xxx. Amplitude Calibration Algorithm.

These algorithms would be further iterated in the event that overlapping measurements (phase as a function of amplitude, and vice versa) were available.

In order to assess the validity of the calibration from both a graphical and statistical point of view, it is next necessary to adjust the amplitude versus phase state data and the phase versus attenuation state data. Typically, we would like these respective characteristics to be identical curves with zero slope. In reality, these characteristics are close to zero slope with a random deviation that is bounded by the quantization step.

To accomplish this goal, the amplitude versus phase state data are adjusted across all phase states by the nominal amplitude offset in attenuation state zero, and are then permuted according to the mapping of the phase calibration. Likewise, the phase versus attenuation state data are adjusted across all attenuation states by the phase offsets for phase state zero, and are then permuted according to the mapping of the amplitude calibration. These adjustments are not an additional calibration step – they are a reordering of the data for visual inspection and statistical analysis.

Results of Calibration

Calibrated T/R module characteristics are displayed in Figures xxc and xxd.

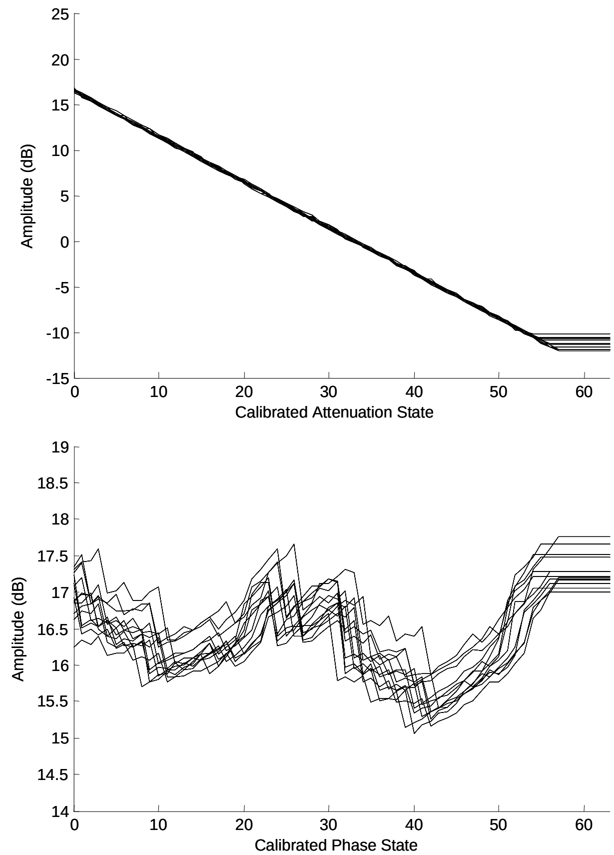


Figure xxc. Calibrated Amplitude Data $|S_{21}|$ for Fourteen T/R Modules on Receive at 1.26GHz.

A number of noteworthy features are evident. First, there is a compression in the amplitude versus attenuation state characteristic of Fig xxc owing to the fact each characteristic must be offset to a common starting gain. There is a loss of approximately 5dB in dynamic range due to this compression. This effect could be reduced by prescreening attenuator chips to have better matched characteristics. On closer inspection, the linear amplitude characteristics have a 0.5dB deviation about the mean, except in the saturated region of the curve at state 54 and above. Second, there a 2.5 dB deviation in amplitude across all modules as the phase shifters vary over 0 to 360 degrees, as exhibited in the second graph of Fig. xxc. Impressed on this ‘slow’ changing amplitude at any given phase state is a ~1dB deviation in amplitude across all modules. This suggests that additional calibration should be done in order to keep modules at the same amplitude as their phase is varied to steer the beam. This additional calibration is not possible with the given data set.

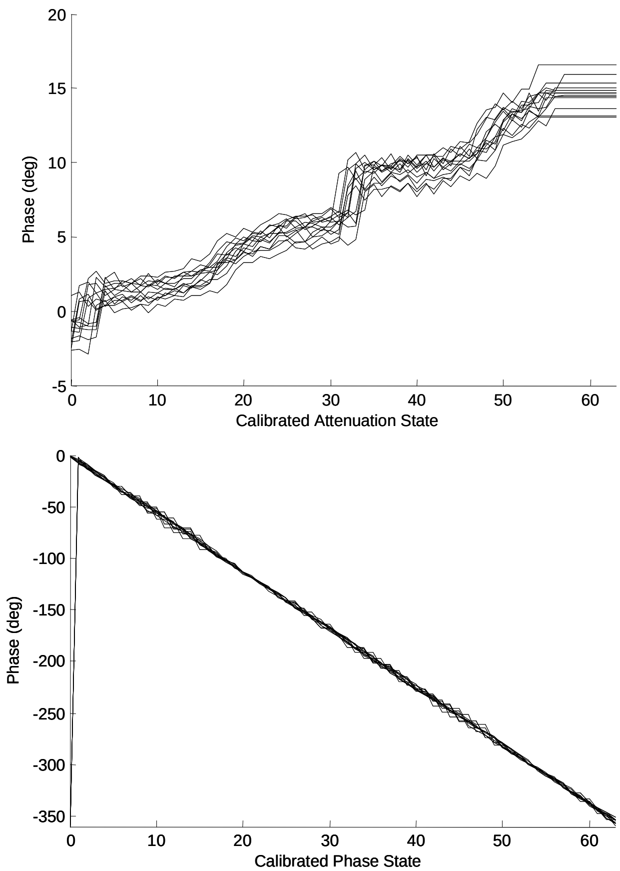


Figure xxd. Calibrated Phase Data $\angle S_{21}$ for Fourteen T/R Modules on Receive at 1.26GHz.

Third, there is a noticeable phase shift of approximately 15 degrees as the attenuator is cycled through its full range. This again suggests the need for additional calibration, otherwise tapering on receive will cause the beam to squint.

In both of the above cases, the additional calibration requires the measurement of S-parameters so that phase and magnitude in the following 3-dimensional format are available:

$\varphi(i,j,k)$, $M(i,k,j)$

where i is the module index, j is the phase state index, and k is the attenuation state index. In practice, the measurements become 4-tuples as temperature variation must also be accommodated.

A fourth feature is evident in the phase versus phase state characteristic of Fig. xxd. There is an increase in the peak deviation, typically 6 degrees, to nearly 17 degrees in some parts of the characteristic. This is attributable to anomalous behavior in the input-output characteristic of phase shifter, as illustrated for one module in Fig. xxx.

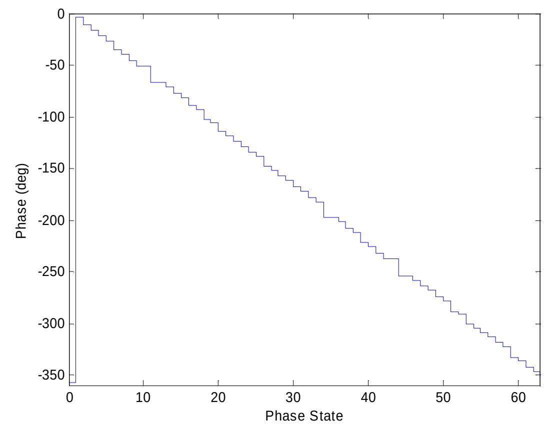


Figure xxx. Calibrated Quantization Characteristic of Phase Shifter for One T/R Module.

On closer inspection, it appears that the phase shifter is not transitioning properly in certain non-adjacent states, so an intermediate state changes by three quantization steps in order to compensate this. This feature is present in the raw data and translates directly to the calibrated data. In other words, there is no way to compensate these missing steps. This anomaly appears to be congenital to the phase shifter, as the transitions occur in different (but approximately the same) locations in the characteristic. A controller error would be much more likely to produce a systematic error.

3. CONCLUSIONS

A T/R module for space based radar at L-band is described in this paper. The T/R module is designed for low mass, and ease of manufacturability and testability. It has good electrical performance over the required band. Measurement results indicate the need for a 4-dimensional look up table that contains calibration offsets as a function of module, attenuator setting, phase-shifter setting, and temperature. Calibration results indicate performance within expected deviations.

4. REFERENCES

[1] Add refs here

[2] First_Name Last Name, Title, Journal, year 1993.

5. BIOGRAPHIES

Neil, Dino, Kendra, Andy, Richard, Suzanne