Self-Calibrating High-Efficiency L-band T/R Modules for Phase-Stable Array Antennas

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***Abstract* – L-band repeat-pass Interferometric Synthetic Aperture Radar (InSAR) techniques have been shown to provide very accurate and systematic measurements of surface deformation and surface strain accumulation due to seismic and volcanic activity, as well as assessing natural or man-made deformation caused by subsidence, flooding or landslides. Numerous studies and reports have concluded that an L-band phased-array InSAR instrument would be best suited to meeting the solid-Earth science needs. While existing repeat-pass InSAR instruments (e.g., SIR-C, ERS-1/2, Radarsat-1) have been able to provide sufficient accuracy over small scales or in select areas, future systematic measurements will be required over very large areas (300 km) for a variety of surface conditions and over long time intervals. Given that many areas around the globe will exhibit low temporal correlation over time due to vegetation, it is important that future InSAR systems employ temporally stable systems (i.e., phase stability over time) operating at longer wavelengths (i.e., L-band). This paper describes a novel transmit/receive (T/R) module technology to enable such phase-stable systems.**

I. MEASUREMENT CONCEPT & MOTIVATION

Existing synthetic aperture radar (SAR) instruments have provided a glimpse of the exciting science InSAR data can enable. Repeat-pass InSAR observations of surface displacements associated with earthquakes have become ubiquitous in the solid-Earth science community [1], and the speed with which InSAR techniques have gained widespread popularity is indicative of their power.

The Manyi earthquake shown in Fig. 1, measured by repeat-pass interferometry using the European ERS-2 satellite, covers such a wide spatial extent that three individual interferograms acquired at different times from adjacent orbit tracks had to be stitched together into a mosaic. Moreover, while the area depicted in this particular scene is in general characterized by good temporal coherence, areas where phase data were not recoverable are still evident. Given that many other areas around the globe will exhibit much lower temporal correlation (particularly heavily vegetated areas), it is important that future systems employ temporally stable systems (i.e., phase stability over time) operating at longer wavelengths (i.e., L-band).

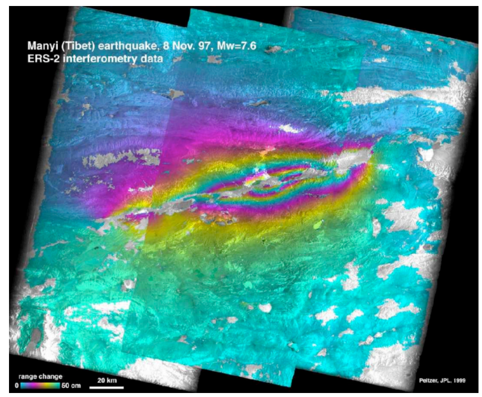


Fig. 1. Signature of an earthquake from space, measured by repeat pass interferometry. The color indicates relative line-of-sight displacement of the Earth's surface of well over 1 meter from before to after the Manyi magnitude 7.6 earthquake. The earthquake covered such a great extent that it was necessary to mosaic three adjacent tracks of repeat-pass interferometric data from the ERS-2 radar satellite [2].

An L-band InSAR instrument is well suited to meeting the science needs described above. The L-band wavelength (24 cm), because it responds to larger, more-stable surface scatterers, will offer significantly higher temporal coherence and will enable useful InSAR measurements to be made for the greatest number of fault zones, over the widest possible extent at each site. The use of an electronically steerable radar antenna, together with recent advances in real-time GPS positioning of the spacecraft, will allow the instrument to operate in an interferometric ScanSAR mode with a swath width over 300 km. Such a mode will allow sites such as the one shown in Fig. 1 to be observed with only a single pair of spacecraft passes.

For repeat-pass interferometric SAR systems, variations in the insertion phase of the antenna over a data acquisition interval will manifest themselves as along-track undulations in the interferometric phase data. These undulations, which cannot be removed through spatial averaging, would be indistinguishable from large-scale surface displacements and would therefore corrupt the InSAR observations. To achieve the required temporal stability using a phased-array radar system, highly stable and efficient transmit/receive (T/R) modules are required. In order to achieve 1 cm displacement accuracy, artifacts from variations in T/R-module insertion phase should be kept well below this level. If variability of the T/R-module insertion phase is allocated 1 mm in the surface-displacement error budget, an absolute phase stability of 1-deg is required. To reduce the frequency of on-orbit calibration, it is desirable that this stability requirement be maintained over long intervals (days to weeks to months).

II. T/R Module Architecture

While a self-calibrating T/R module capability has been sought for years, a practical and cost effective solution has never been demonstrated. The work described in this paper adds new capability to an L-band T/R module by adding an internal closed-loop self-calibration circuit. The integral adaptive calibrator will result in only a modest increase in module size and power, while providing a new capability not currently available in existing T/R modules. The T/R module compensates for all environmental and time related changes and provides very stable phase and amplitude characteristics. This self-correcting feature eliminates costly T/R module calibration and allows for increased tolerance of T/R module components. This approach provides an inexpensive way to implement improved phase stability where no extensive individual phase matching is required. Therefore the T/R module and phased-array antenna manufacturing and test costs will be reduced.

A. Technical Challenges

Phased arrays used for interferometric measurements require not only amplitude and phase tracking, but each module requires a constant insertion phase and amplitude (typically less than 1 deg and 0.1 dB change) over long time intervals in a space environment, where huge temperature variations can occur. If left uncompensated, phase drift in individual array elements affect both the formation of antenna beams as well as the interferometric phase measurements. Additionally, since these LEO systems have very high transmit power requirements, requiring hundreds to thousands of T/R modules, high efficiency T/R modules are critical to making these systems feasible.

B. Technical Approach

We have designed and demonstrated a T/R module with internal calibration to achieve precise and stable phase and amplitude. The 30W, 60% efficient L-band T/R module uses a high-efficiency Class-A/B GaAs power amplifier and associated low power receive and beam steering electronics [4-6]. The T/R module was implemented using discrete parts and assembled using surface mount technology. This T/R module architecture was then augmented with a closed-loop calibration circuit to achieve the 1 deg phase and 0.1 dB amplitude stability. This is achieved using a gain and phase detector, recently available as a low cost single-chip Bi-CMOS integrated circuit. We achieve this using an adaptive correction scheme which does real-time phase and amplitude calibration so that the module characteristics are continually corrected to the required values.

A block diagram of the T/R module with built-in calibration loop is shown in Fig 2. The correction circuitry consists of directional couplers at the input and output of the module, and an integrated gain and phase detector. The required gain and phase are input to the detectors as the reference signals which are then compared to the sampled RF signals. The difference is used to adjust the programmable attenuation and phase shifters and close the loop to minimize the errors. To achieve high precision, an analog phase shifter and an analog attenuator are added to the 6-bit digital circuits (within the T/R module). The loop bandwidth can be set so that a single pulse can be used to do each correction and minimize the calibration cycle time. Since the closed-loop self-calibration architecture must be bi-directional, that is, it must function in both receive and transmit modes, switches were added to route the signals alternately.

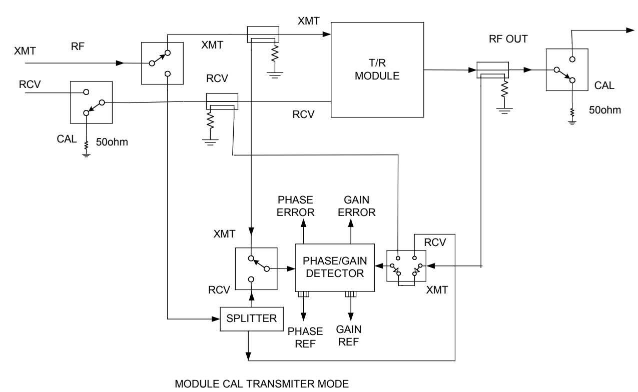


Fig. 2. Block diagram of the phase and amplitude calibration approach. The existing T/R module is augmented with the closed-loop calibration circuit (shown in transmit mode). The power detector is not depicted.

III. RESULTS

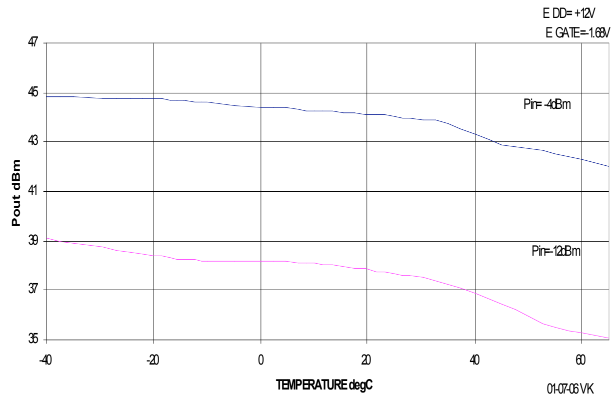
The module architecture allows for the calibration circuit to be incorporated externally into any existing L-band T/R module (or with minor modifications to frequencies up to 2 GHz) and is compatible with a range of gain and output power requirements (3-200W) such that the T/R module can be adapted to different array antenna designs. To validate our architecture and design, we have modified an existing 30-watt L-band T/R module with the built-in calibrator for stabilized output power (on transmit) and gain and phase stability (on receive). This was done by first developing the amplitude and phase detector circuit. We then integrated this into a closed-loop calibration circuit within the L-band T/R module and then characterized performance over temperature to demonstrate the ability to self-correct for variations in insertion phase or amplitude.

A. Stability of the Uncompensated T/R Module

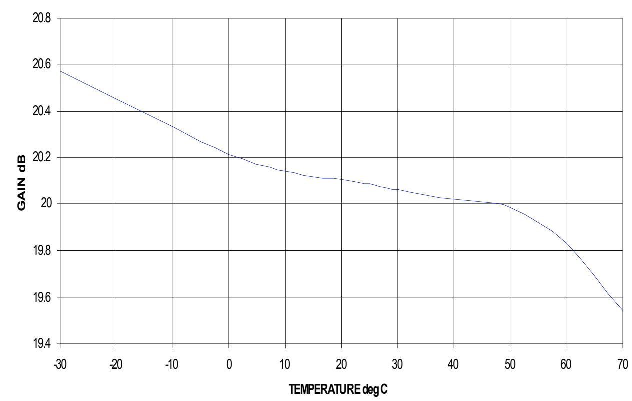
The uncompensated T/R module was first tested for transmit power, receive gain and phase stability over temperature, prior to implementing the calibrator (Fig. 3). The transmit power, while well behaved over temperature, varied over 4 dB. The receiver gain varied 1 dB and the phase varied roughly 5.5 degrees over temperature. Additional testing of the module over a variety of attenuator and phase shifter settings introduced additional variations on the order of 2.5 deg phase and 2 dB gain variation. The self-calibrating T/R module should maintain the transmit power, receive gain and absolute phase stability to within 0.1 dB and 1 degree over all phase and attenuation settings, power supply variations over a temperature range of -40 deg-C to +70 deg-C. This would be an order of magnitude improvement over the current state-of-the-art where no amplitude or phase compensation is used.

B. Phase Detector

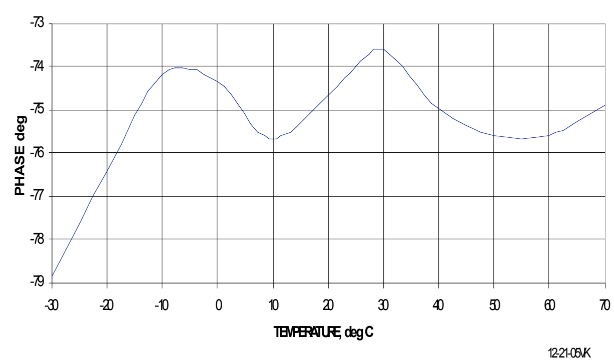
The novelty of the phase-stable T/R module design is in the use of a simple, stable and high-accuracy gain and phase detector circuit in the closed-loop calibration circuitry. The gain and phase detector is available as a single-chip integrated circuit (IC) which can operate up to 2.7 GHz. The detector is used to force the gain and phase of an input signal toward predetermined set points. The IC consists of a closely matched pair of demodulating logarithmic amplifiers, each having a 60 dB dynamic range. By taking the difference of their outputs, a measurement of the magnitude ratio or gain between the two input signals is available. The phase detector also has precise phase balance, and thus, the phase accuracy measurement is independent of signal level over a wide input range. Temperature testing of the gain/phase detector shows very stable amplitude and phase stability (Fig. 4 and 5), demonstrating the suitability of this device for our application to achieve 0.1 dB and 1 deg stability over the full temperature range.



(a) Transmit Power vs. Temperature



(b) Receive Gain vs. Temperature



(c) Phase vs. Temperature

Fig. 3. Measured stability of the uncompensated 30W T/R Module over temperature. (a) Transmit power, (b) Receive gain, (c) Receive phase

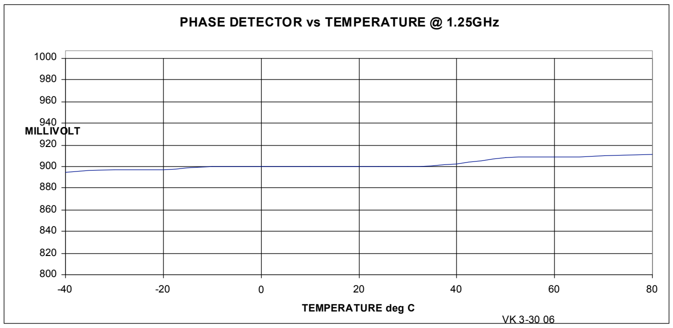


Fig. 4. Phase Detector measures 0.9 deg peak-to-peak phase variation over temperature. Scale is 10 mv/deg.

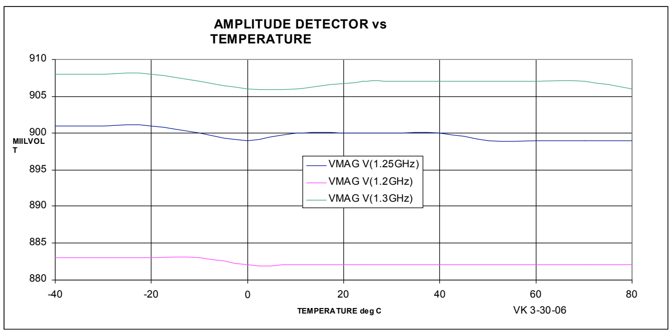


Fig. 5. Amplitude Detector measures 0.1 dB peak-to-peak amplitude variation over temperature. Scale is 30 mv/dB.

C. Closed-Loop Transmit Mode

The output power is calibrated using a power detector to dynamically adjust the drain voltage of the power amplifier. The power stabilization loop was stable to within 0.1 dB over the full range of input powers and within 0.05 dB over input power variation from -8dBm to 0 dBm, well within the dynamic range of the system (Fig. 6).

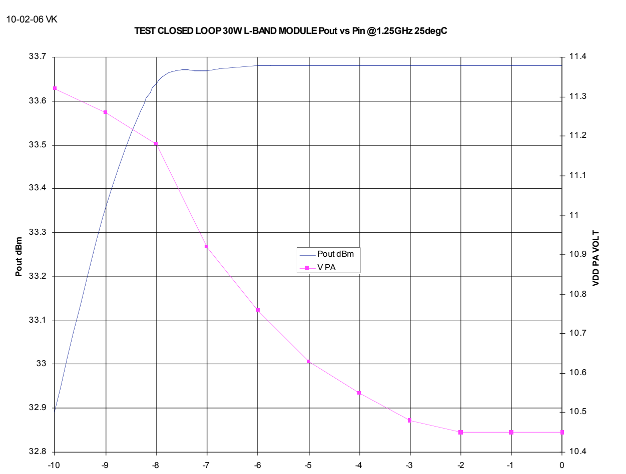


Fig 6. The closed loop output power as a function of the reference control voltage was stable to within 0.1 dB.

D. Closed-Loop Receive Gain/Phase

The receive channel gain and phase are calibrated over all 6-bit gain and 6-bit phase states using the Phase/Gain Detector for accurate and stable control. Fine corrections are made using external analog phase and gain circuits. Closed-loop gain is stable to less than 0.16 dB over all attenuation settings and bias conditions.

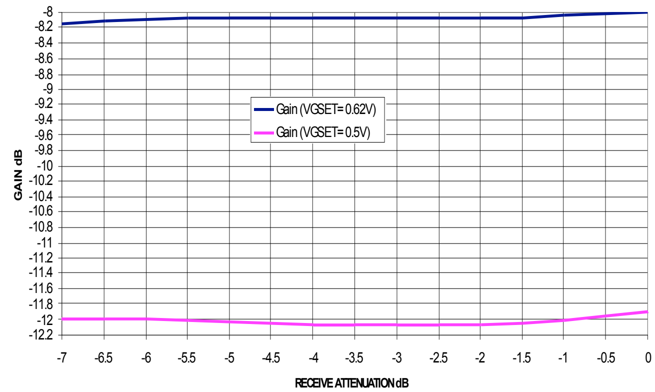


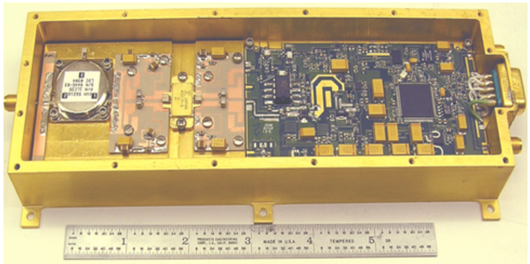
Fig. 7. Closed-loop gain vs. receiver attenuation is stable to <0.16 dB.

E. Digital Control Loop

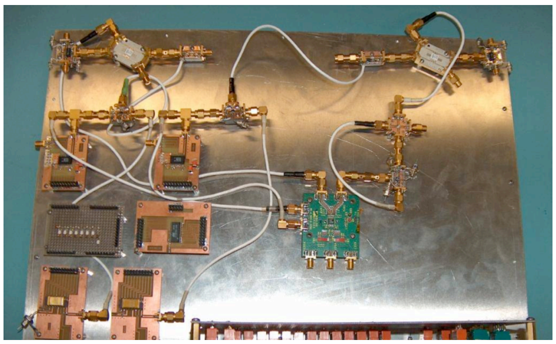
The control loop incorporates random access memory (RAM) which stores all the parameters after the module is calibrated. The calibration sequence is provided by a control FPGA, which controls the analog and RF components for the appropriate beam positions and modes. The RAM has a fast write cycle so that the complete calibration cycle can be accomplished in seconds. The control inputs to the FPGA in the T/R module are also fed to the control FPGA which acts as a slave and times the calibration sequence. In the *receive mode* the module is calibrated over all 6-bit phase and gains states. The linear phase and gain states of the transmit mode are also calibrated as well as the power output over all the phase states in the saturated power transmit state.

F. Integrated T/R module results

Photographs of the T/R module development are shown in Fig. 8 including the uncompensated high-efficiency T/R module (8a) and the breadboard of the closed-loop calibrator (8b) that was integrated with the T/R module. Preliminary test results of the phase-stable, high-efficiency L-band T/R module are summarized in Table 1. We compare the performance of the uncompensated 30W module with the breadboard results of the self-calibrating T/R module. With only a modest increase in size and small degradation in noise figure, a significant improvement in module stability is demonstrated.



(8a) The uncompensated 30W, 60% efficient L-band T/R module.



(8b) closed-loop calibration circuit breadboard.

Fig. 8. Photographs of the T/R module development.

TABLE I
T/R Module Measured Performance

Parameter	Measured (uncompensated)	Measured (self-calibrating)
Center Frequency	1.24 GHz	1.24 GHz
1dB Bandwidth	130 MHz	130 MHz
Peak transmit power	33.5 Watts	33.5 Watts
Tx Output Power Stability	4 dB	0.1 dB
Efficiency	69% PAE 60% module eff	69% PAE 60% module eff
Max duty cycle	>10%	>10%
Receive Noise Figure	2.8 dB	3.0 dB
Tx/Rx Gain	50 dB / 23 dB	50 dB / 23 dB
Phase Shifter res.	6-bit	6-bit
Phase Stability	7.5 deg	0.9 deg
Attenuation res.	6-bit	6-bit
Gain Stability	3.5 dB	0.16 dB
Operating Temp	-40 to +70 deg C	-40 to +70 deg C
T/R Module Mass	175 g	TBD
T/R Module Size	7.9" x 2.6" x 0.8"	7.9" x 3.1" x 1.4"

IV. Future Work

The next step is to physically integrate the calibrator circuit with the 30W T/R module into a compact and miniaturized package and then test this over a wide variety of environmental conditions. We also plan to adapt this design to even high-power level T/R modules.

V. Summary

This paper describes the current status of an on-going project to develop an amplitude and phase-stable high-efficiency L-band T/R module. After the first year of the 2-year project, we have assessed the performance of an uncompensated module and developed the requirements for an adaptive T/R module. We completed the design, parts selection, and component characterization over temperature. We then assembled the components into a working transmit and receive breadboard to demonstrate closed-loop performance with a 30W T/R module.

Acknowledgement

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