Radar Waveform Pulse Analysis Measurement System for High-Power GaN Amplifiers

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***Abstract*—This work presents a measurement system to characterize the pulsed response of high-power GaN amplifiers for use in space-based SAR platforms that require very strict amplitude and phase stability. The measurement system is able to record and analyze data on three different time scales: fast, slow, and long, which allows for greater detail of the mechanisms that impact amplitude and phase stability. The system is fully automated through MATLAB, which offers both instrument control capability and in-situ data processing. To validate this system, a high-power GaN HEMT amplifier operated in saturation was characterized. The fast time results show that variations to the amplitude and phase are correlated to *DC* supply transients, while long time characteristics are correlated to temperature changes.**

I. Introduction

A key Earth science mission as outlined in the decadal survey [1] is the development of a high-precision remote sensing system that can provide detailed quantitative observations of the Earth to predict and analyze seismic events, ice dynamics, and ecosystem structure. The proposed DESDynI SAR Instrument (DSI) accomplishes these requirements through an L-band InSAR imaging system utilizing the SweepSAR concept [2]. The science goals for this mission require mm-scale resolution, which places strict constraints on the amplitude and phase stability of the radar system [3], [4].

Signal distortion arises from correlated and un-correlated sources within the radar system. Noise, atmospheric effects, interference and other non-systematic changes can be removed through averaging, pulse compression and advanced data processing techniques. However, other systematic effects due to the digital or RF hardware will reduce the signal quality. Calibration routines can correct for these distortions, however, frequent calibration will reduce the receive data collection window. The SweepSAR concept employed by the DSI utilizes a long transmit pulse to allow sufficient energy for the reflected signal and a receive duty cycle of close to 100 precent to track the received energy over the swath distance. Therefore any receiver dead-time due to pulsed RF transients or calibration can causes swath gaps and reduces science data quality.

A critical piece of the radar electronics is the RF front-end, specifically, the transmit/receive module (TRM). The TRM is typically comprised of a high-power transmitter, receiver, amplifiers, phase shifters, attenuators, and other passive elements. The final stage high-power amplifier (HPA) is typically driven into 3 to 4 dB gain compression in order to achieve high efficiencies and stable power output. However, saturated output power operation can significantly distort the transmit waveform due to device non-linearities, therefore characterization of the pulsed waveform behavior aids in understanding the amplitude and phase stability of the TRM.

Existing phase and amplitude measurement systems are limited by sampling rate, memory depth, bandwidth, and complexity [5], [6]. For the operation frequency and bandwidths of the DSI, no commercial solution existed that provided accurate phase and amplitude characterization across the time-scales of interest. In addition, the measurement setup outlined in this work also measures the instantaneous *DC* current and voltage waveforms as well as temperature, which aids in understanding the amplitude and phase variations and other transient phenomena due to the high-power RF pulsing.

This work outlines a novel measurement setup that can characterize the amplitude and phase stability of complex wide-band radar waveforms. Section II outlines the details of the amplitude and phase measurement setup, highlighting the various time scale domains that the system is able to measure. Section III presents the measured amplitude and phase history of a high-power GaN amplifier and concludes with a summary of the proposed measurement system in section IV.

II. Measurement Description

In order to characterize the distortion caused by the RF components in the TRM, an understanding of the different types of phase and amplitude variations is necessary. There are three major time scales to measure the stability of the signal. “Fast-time” characterizes how the amplitude and phase change within a single RF pulse event (μs time scale). The fast-time scale divides the pulse into “bins” as highlighted by the colored bands annotated in Fig. 1 (1). “Slow-time”, Fig. 1 (2), measures the change in the amplitude and phase from sequential pulses (pulse repetition interval time scale). The “long-time,” Fig. 1 (3) measures changes between pulse events from different data acquisitions separated by many seconds. Within each time-scale, the variation of the amplitude and phase will be due to different sources. For instance, in the fast-time scale, variations can be produced by reactance charging and discharging during the RF pulse, while, for long-time scales, the source of the variations could be thermal drifts. Therefore, in order to correlate these variations, the characterization requires not only measurement of the RF signals, but also the *DC* waveforms and temperature to understand the dynamics of the RF waveform.

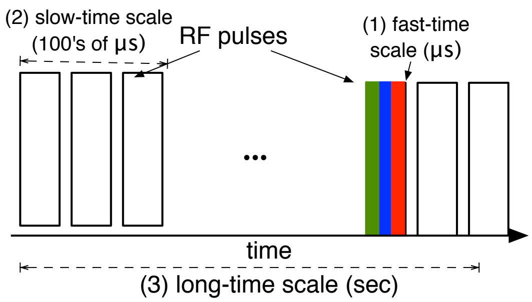

Fig. 1. Representation of time scales for data analysis. Fast time (1) within the pulse, slow time (2) a series of consecutive pulses, and long time (3) between different data acquisitions spaced many seconds apart.

Unlike other amplitude and phase characterization systems, such as advanced network analyzers [7] or analog amplitude and phase detectors [8], our proposed system processes the signals in real-time, which adds flexibility in processing and analyzing the results. In addition, the system can operate over wide-bandwidths and with modulated waveforms. The system is comprised of an Agilent pulse generator that triggers the RF pulse, data acquisition, and controls the timing of the waveforms and capture. All instruments are synchronized through the 10 MHz reference clock to ensure accurate timing between signals. The RF pulses are generated from an Agilent PSG signal generator and amplified by a mini-circuits broadband amplifier to achieve the appropriate input power. The input and output signals are sampled through couplers into a Agilent high-speed digital oscilloscope (DSO) that can capture data at 20 Gs/s with memory length of 100 MSamples. A block diagram of the measurement setup is shown in Fig. 2. The relative amplitude and phase of the amplifier is determined by comparing the output signal to the input signal, which is used as a reference to remove distortions effects of the input waveform.

In addition to the RF input and output pulses, the *DC* voltage and currents are also captured for each pulse. The voltage waveform is measured from a 10x high impedance probe and the current is measured using a current probe and amplifier to capture high-speed signal transients. To ensure accurate timing acquisitions of the RF signals, the input and output signals must be captured on either even or odd channels (1 & 3 or 2 & 4). This is due to the acquisition clock timing within the DSO, which is captured on both rising and falling edges for subsequent channels, therefore, in order to ensure continuity in the sample clocking, alternating input channels provides the most phase matched result. The acquisition mode can either be real-time, which captures continuously, or segmented mode that captures just RF pulses maximizing oscilloscope on-board

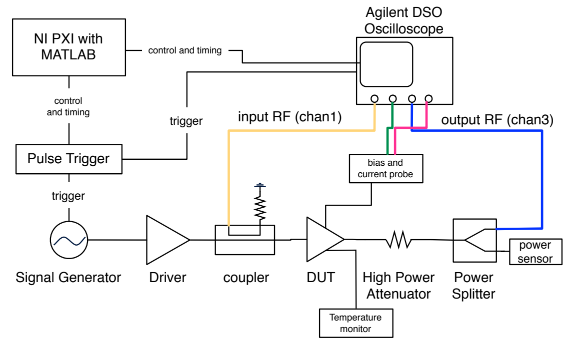

Fig. 2. High-power pulsed RF waveform characterization measurement setup. System captures and records RF input, output, *DC* voltage and current of the amplifier during each RF pulse.

memory utilization. In either capture mode, the data processing and results are identical.

All of the instruments are controlled from a National Instruments PXI running Matlab with the instrument control toolbox. This system configures the instruments; acquires and stores the data from the instruments; and analyzes, plots, and saves the results. The timing and triggering information configured by the instrument into the pulse generator is used throughout the software to ensure that the data start times and processing are synchronous. Matlab provides both automated measurement capability and complex data processing, yielding more rapid results and reporting of the behavior of the DUT. Traditional measurement scenarios where the data acquisition and processing are done in separate steps requires more measurement time and user intervention to perform the processing and do not provide real-time feedback of the measured device.

The measurement is executed through a script that fully automates the data capture, storage, and processing. The script loops for a set number of cycles, capturing a user-defined amount of data given by the number of samples per channel and sampling rate. The software extracts the pulses from the data, performs FFTs over each of the given time scales and computes the amplitude and phase of the signal as compared with the input reference signal. Due to the latency within the PC for transferring, storing, and processing the data, each loop on the long-time scale may not be equally spaced in time. However, they are still time coherent, since all of the measurement equipment is triggered from the pulse generator that is continuously running.

In order to ensure measurement accuracy, a thru connection was measured that ideally should measure a fixed, flat phase offset and a small amplitude offset. For this measurement, a CW pulsed signal is sampled at a rate of 10 Gs/s with 500 thousand points acquired per pulse. Fig. 3 (a) shows the intrapulse stability or fast-time response for a single RF pulse for 256 bins showing less than a 0.1 dB variation in amplitude 0.4° change in phase. The pulse-to-pulse stability or slow-time response is shown in (b) for 16 RF pulses captured during a single data acquisition. Since the number of samples for the FFT is larger, the noise is averaged down resulting in a

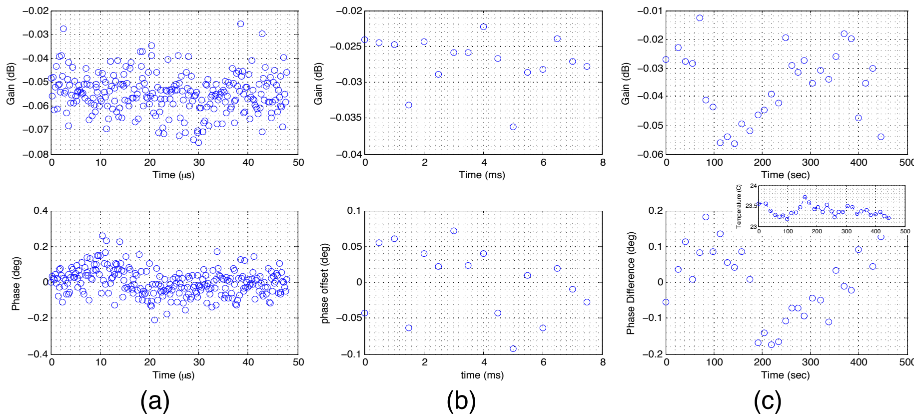

Fig. 3. Pulsed waveform analysis on a thru for (a) fast-time, (b) slow-time, and (c) long-time highlighting variations in amplitude and phase over time. In (a) the variation is likely due to thermal noise given, which is confirmed by observing (b) which is more stable due to a larger number of points used in the FFT. While in small fluctuations in lab temperature appear to cause the variations in (c).

0.02 dB variation in amplitude and 0.2° phase variation that is consistent with the analysis presented in [5] since increased samples translate into improved SNR of the measurement. Fig. 3 (c) shows the long-time response of 30 data acquisitions each spaced approximately 15 sec apart. The variation for both the amplitude and phase grew due to slight temperature variations. This thru measurement validates the system with the ability to characterize sub 0.1 dB changes in amplitude and 0.5° changes in phase.

III. Amplifier Design and Measurement

A high-power GaN amplifier for use in a TRM was characterized using the above described pulsed waveform measurement setup. The amplifier uses a GaN high electron mobility transistor (HEMT) in a packaged configuration with input and output matching networks on a Rogers 4002 substrate to drive a 50 ohm load. The supply voltage is set to 28 V with a quiescent drain voltage of 1 A. The device has approximately 15 dB of associated gain at a saturated output power of over 100 W.

The amplifier was measured at saturated output power to observe the large signal distortions that may be caused by the non-linearities in the device. The measurements were taken at 5 Gs/s sampling rate with 1 MSamples that allowed 8 pulses to be captured per data acquisition with 30 data acquisitions spaced 25 seconds intervals. The additional time between data acquisitions over the thru measurement is due to the capturing, transfer, and storage of the current and voltage waveforms. The temperature was also recorded throughout the measurement.

The fast time scale for a single pulse is shown in Fig. 4, which plots the gain (a) and the phase offset (b) over the pulse with 256 bins. The amplitude of the signal varies by less than 0.5 dB over the pulse with the signal settling to less than 0.1 dB variation within 10 μs. The phase response exhibits a similar phenomenon changing by 2.5° over the pulse. Unlike the amplitude response, the phase offset appears to have a slight slope over the entire pulse width. To understand the source of these effects, the voltage and current (Fig. 4 (c) and (d)) waveforms over the pulse can be observed to have similar responses.

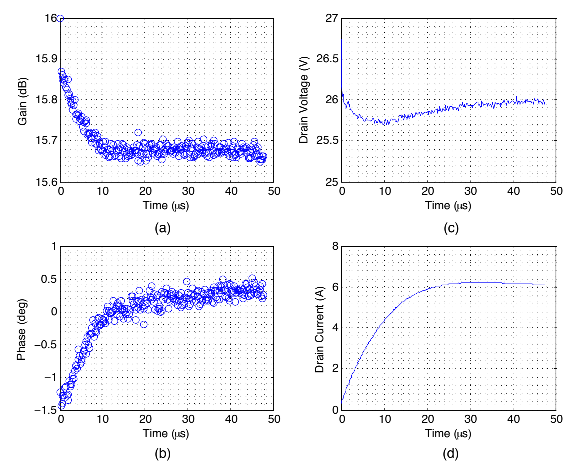

Fig. 4. Fast-time amplitude (a) and phase (b) response divided into 256 bins over the pulse for the GaN HEMT amplifier operated in saturation. The variation in amplitude and phase can be correlated to the changes in voltage (c) and current (d) waveforms.

It is clear that the amplitude of the signal follows the response of the drain voltage. The measured current includes the effects of the on-board decoupling capacitors, and therefore exhibits the lagging response over the pulse. Due to a common phenomena of trapped charge in GaN devices, the drain current between RF pulses drops well below the quiescent value [9]. The phase of the signal does not fully correlate with the measured drain voltage or current, therefore, the variation might be due to internal reactances on board that were not characterized. To reduce the changes to the voltage and current, the reactance on the drain can be modified by increasing the decoupling capacitance and reducing the variation on the drain voltage, which in turn should decrease the amplitude variation over the

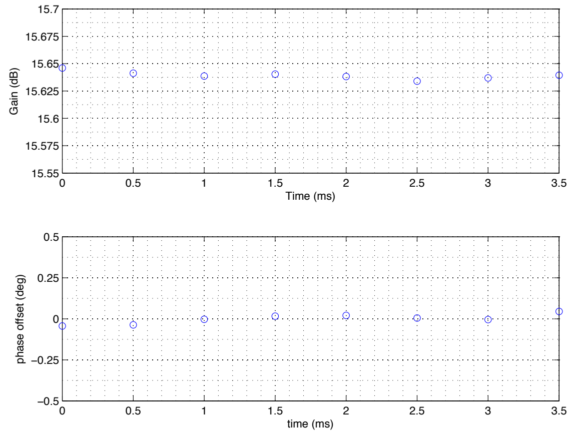

Fig. 5. Slow-time amplitude and phase response of the GaN HEMT amplifier over 8 pulses of a signal data acquisition. The aggregate amplitude and phase of each pulse is performed by performing an FFT over the entire RF pulse.

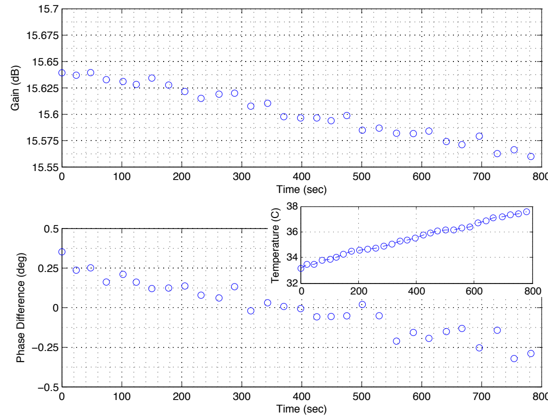

Fig. 6. Long-time amplitude and phase response of the GaN HEMT amplifier comprised of 30 data acquisitions spanning 800 seconds. The linear variation is attributed to a temperature rise in the GaN device.

RF pulse.

Even though a noticeable variation was captured within the pulse, the pulse to pulse variation exhibits much less variation as shown in Fig. 5. The figure shows that the difference in amplitude and phase of each pulse is negligible over the 8 pulses captured during a single data acquisition. Therefore, the non-linear response within the pulse can be modeled and appropriate filters can be used to remove the effects of the intra-pulse distortion since they appear to be consistent from pulse to pulse.

A very different effect is observed in Fig. 6, which plots the average amplitude and phase over all of the 8 pulses at different data acquisition times. Both the amplitude and phase appear to linearly vary with time and change by 0.1 dB in amplitude and 0.5° in phase over 800 seconds. By observing the temperature as measured on the transistor device (Fig. 6 inset), the temperature rises linearly by 4 degrees over the same time period, which is correlated to the variation in amplitude and phase between each data acquisition. This knowledge of temperature effects greatly aids in system calibration and improves radar performance.

IV. Conclusion

This work reports a novel measurement setup that is able to accurately capture amplitude and phase variations of high-power GaN amplifiers for use in pulsed radar systems. The automated system is able to characterize pulses on three different time scales (fast, slow, and long) while also recording relevant information such as the *DC* bias and temperature that help explain the sources of phase and amplitude variation.

To validate the measurement system, a high-power GaN amplifier was characterized and shown to have noticeable amplitude and phase variations (0.5 dB / 2.5 ° respectively) within the pulse due to variations in the drain voltage and current. However, these variations appear to be consistent from pulse to pulse since the slow-time response varies only a small amount. The long-time response over 30 data acquisitions also showed a linear decreasing trend that can be attributed to a 4° C temperature increase.

The data gathered from this system can be used to better understand the performance limits of using these high-power amplifiers for next-generation space-borne SAR platforms that require very strict tolerances on amplitude and phase stability. Not only can designs be optimized to improve stability, but knowledge of the specific non-linear pulse characteristics can be modeled and appropriate data processing can be performed to remove the non-ideal effects.

Acknowledgment

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