Advances in Digital Calibration Techniques Enabling Real-time Beamforming SweepSAR Architectures

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Abstract— **Real-time digital beamforming, combined with lightweight, large aperture reflectors, enable SweepSAR architectures, which promise significant increases in instrument capability for solid earth and biomass remote sensing. These new instrument concepts require new methods for calibrating the multiple channels, which are combined on-board, in real-time. The benefit of this effort is that it enables a new class of lightweight radar architecture, Digital Beamforming with SweepSAR, providing significantly larger swath coverage than conventional SAR architectures for reduced mass and cost.**

This paper will review the on-going development of the digital calibration architecture for digital beamforming radar instrument, such as the proposed Earth Radar Mission's DESDynI (Deformation, Ecosystem Structure, and Dynamics of Ice) instrument. This proposed instrument's baseline design employs SweepSAR digital beamforming and requires digital calibration.

We will review the overall concepts and status of the system architecture, algorithm development, and the digital calibration testbed currently being developed. We will present results from a preliminary hardware demonstration. We will also discuss the challenges and opportunities specific to this novel architecture.

TABLE OF CONTENTS

1. INTRODUCTION

SweepSAR promises to be a powerful new tool for Earth and planetary observations by radar [1], while both requiring and enabling advances in instrument calibration. The proposed DSI (DESDynI SAR Instrument) baseline includes SweepSAR techniques, and the associated digital calibration, which is required to make SweepSAR viable, which is in the baseline architecture for this mission recommended in the Earth Science Decadal Plan [2].

SweepSAR requires real-time digital beamforming, combined with lightweight, large aperture reflectors, but promises a significant increase in instrument capabilities for solid earth and biomass remote sensing. This instrument concept requires new methods for calibrating the multiple channels, each of which includes a TR module and a dedicated digitizer/processer, creating N-channels of unique data. Even a standard SAR instrument generates enormous volumes of data that must be downlinked, so downlinking these N-channels of data is impractical. These N-channels must be combined on-board, in real-time, in a process called Digital Beam-forming (using a DBF, or Digital Beam-Former). Therefore, the calibration of these channels must also be performed on-board and in real-time, prior to digitally combining signals, since one the signals are combined, much of the required calibration becomes impossible.

The calibration of current state-of-the-art Electronically Steered Arrays typically involves pre-flight TR (Transmit/Receive) module characterization over temperature, and in-flight correction based on temperature, which ignores the effects of element aging and drifts unrelated to temperature. This digital calibration of the DBF array is able to reduce development time, risk and cost of precision calibrated TR modules, by accurately tracking modules' characteristics. This is accomplished through closed-loop Digital Calibration that tracks systematic changes regardless of the cause.

SweepSAR requires a series of N-beams that act in unison on transmit; concentrating the energy on the large reflector, see Figure 1, but N-beams that act independently on receive, using the full aperture provided by the large reflector, yielding N independent sub-swaths. This is done to provide wide coverage, while reducing range sidelobes [1].

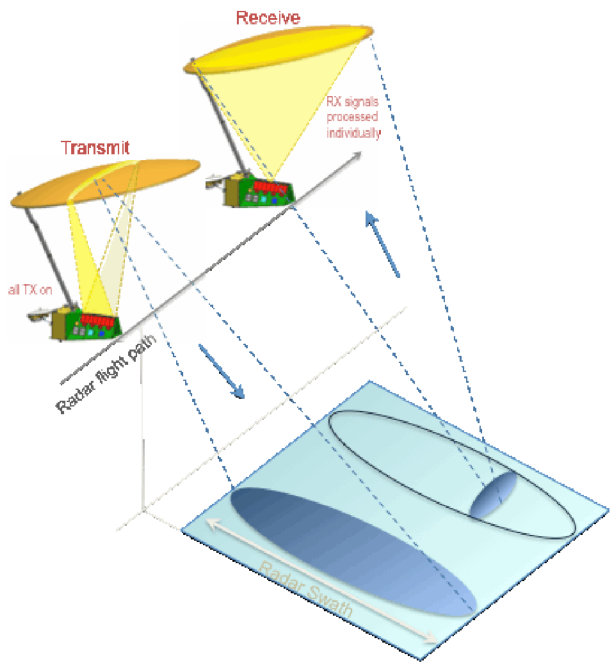

Figure 1 SweepSAR Instrument: Large reflector is sub-illuminated in Tx yielding a large swath, and fully illuminated for each Rx beam, yielding N smaller sub-swaths.

Figure 2 depicts another way to understand the SweepSAR technique. What is important to this work is that the transmit and receive events are dependent on the channels being calibrated to have the desired amplitude and phase distribution (here we are assuming uniform illumination), which is also true for standard systems. However, while the transmitter is basically identical to that of a standard system, the receive-beamformer is made up of N independently digitized channels, rather than a single analog beamformer. These channels must digitally filter the signal, both to minimize noise bandwidth and to separate any calibration signals from the valid science, prior to beamforming. Once filtered, the science signal must be stitched together (beamformed) to form the final products. Once this stitching is complete, the opportunities for calibration become severely limited.

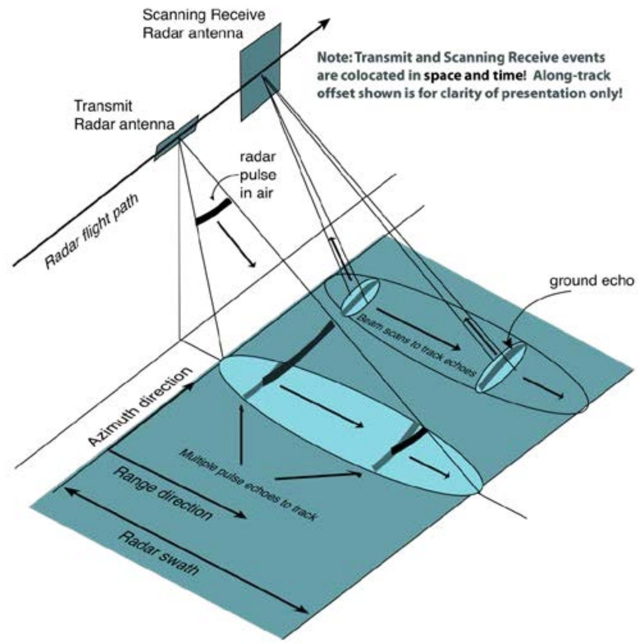

Figure 2 Effective aperture and relative incident beamwidths of SweepSAR.

Since the transmit event, where all of the energy is directed at the large reflector, is inherently an analog phenomenon, all control of the transmit signals characteristics must be achieved in analog. Within reason, as long as the analog receiver channels have a good enough noise figure and linearity, all of the actual control for aligning the channels can be done digitally by altering the weightings on the digital beamforming algorithm.

2. CALIBRATION REQUIREMENTS

The significant advantages of the SweepSAR architecture can only be realized if the N-channels can be matched appropriately for gain and phase. High-level science requirements (e.g., displacement and biomass error) can be flowed down to lower level requirements on the allowable degradation on MNR (multiplicative noise ratio), impulse response, SNR and phase uncertainty due to calibration errors.

If the transmit modules are not matched in gain and phase, then there will be degradation of the RASR (range ambiguity to signal ratio), AASR (azimuth ambiguity to signal ratio) and phase uncertainty. These distortions lead to degradation on ISLR (integrated side lobe ratio), PSLR (peak side lobe ratio) and impulse response width. Requirements on the maximum RASR, AASR, gain and impulse response degradation impose requirements on phase and amplitude stability or control, whereas the phase uncertainty imposes tight requirements on phase and amplitude knowledge.

The DBF (Digital BeamForming) hardware architecture independently digitizes and processes each receiver channel. This architecture is also employed in performing digital calibration. Among its advantages over traditional analog combining, DBF allows modification (weighting) of each channel's amplitude and phase. For DBF, each receive channel is a digitally weighted combination comprised of the N-nearest neighboring channels analog (digitized) channels, so each final channel benefits from the signals received by its nearest neighbors. Since the weighting may be altered in near real-time to compensate for changes in system response, calibration on receive can be implemented through the beamforming coefficients. This allows an unprecedented level of control that will improve calibration compared to current capabilities. This enables the precision required for employing SweepSAR for geophysical remote sensing. By taking advantage of the beamforming architecture's independent processor on each channel, digital calibration may be performed with precision that exceeds standard analog techniques by an order of magnitude or more.

Current requirements on the TR module's Transmitter and Receiver chains phase and amplitude, knowledge and control, are derived from the desire to have the TR's contribution to errors in the height change estimate of the interferometric product to be no more than 0.2mm. In other words, the contribution to height change uncertainty from the TR hardware must be less than 0.2mm. The requirements, as currently derived from the proposed science goals are shown in Table 1. A derivation of these requirements can be found in [3].

3. CALIBRATION ARCHITECTURE

The calibration architecture must support three main calibration modes that must be completed during science data takes, as well as several housekeeping calibration modes, which may occur before and/or after a science data take. All of the housekeeping calibrations are derived from the three main calibration modes, and since these will only be performed when the instrument is not taking science data, the full resources of the system are available. Therefore, these modes are less challenging to perform than the main calibration modes that must be completed while the instrument is taking science data. These three modes are the main topics of discussion for the calibration architecture.

The three main calibration modes are 1) Transmit Calibration 2) Receiver Calibration 3) Bypass Calibration. The latter mode, Bypass-Cal, is required to remove all of the common contributions to the channels' transfer functions, as well as to line-up the timing of the N-digitizers that are part of the N-channels. The units and RF network that generate the RF chirps and calibration tones (caltone), as shown Figure 3, are common to all channels, up until the power splitter that splits and feeds the RF signal to each TR module.

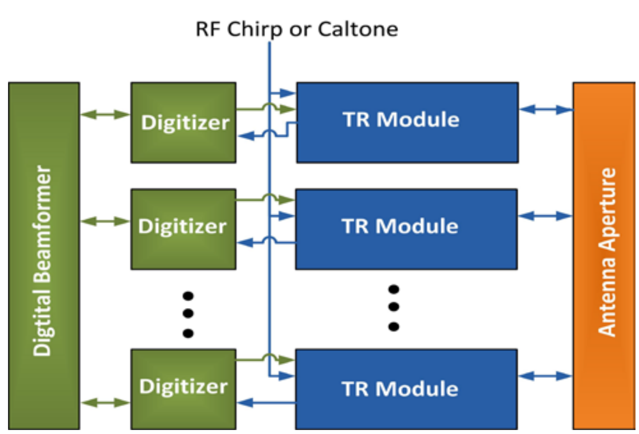

Figure 3 Digital Beamforming Architecture

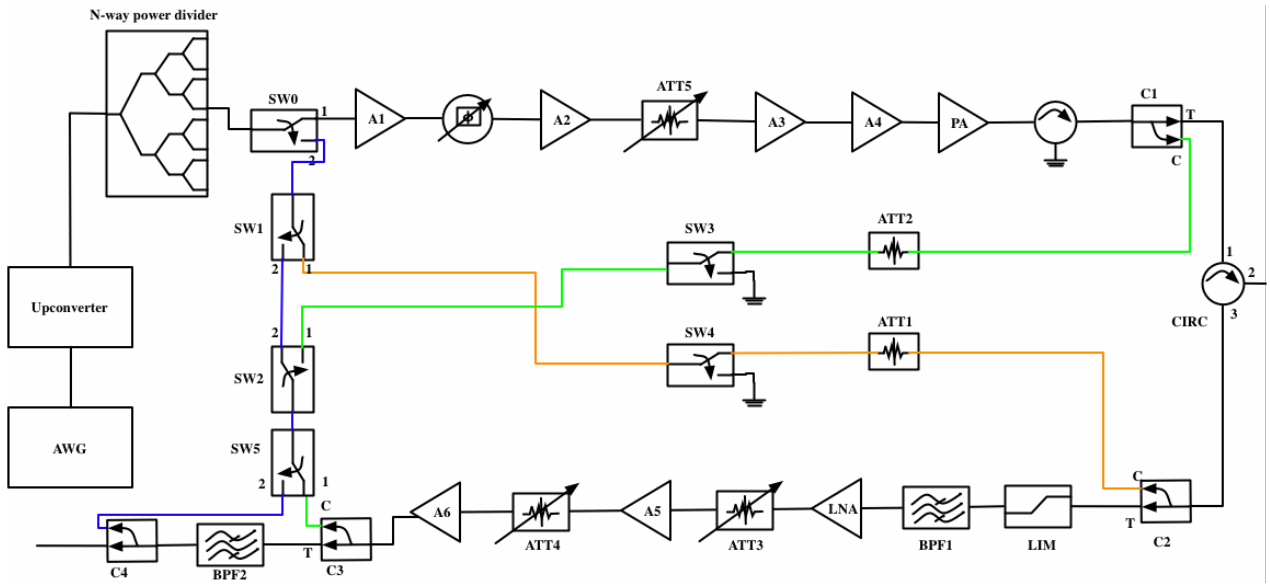

Figure 4 TR Calibration Architecture. Orange line is the receiver-cal path, green is transmitter-cal path, and blue is the bypass-cal.

Transmitter Calibration Architecture

The purpose of the Transmit-Cal is two-fold. Primarily, this calibration is to ensure that the N-transmit beams align on the reflector, as shown in Figure 1. The transmit-cal path is shown in Figure 4, as the green path. A small portion of each transmitted waveform is coupled off and sampled by the digitizer. The channel's processor then estimates the amplitude and phase of the signal.

Once the phase error is estimated, a phase shifter may be used in the Transmitter to correct the phase to within 5 degrees. A secondary purpose of the Transmitter calibration is to determine the residual phase errors of the channels, to aide in the ground processing. The same algorithm is used to estimate the residual phase of each transmit channel, which is then recorded in telemetry. The algorithms to determine the estimates will be discussed in a later section.

Receiver Calibration Architecture

The Receive Architecture is quite similar to the Transmit Architecture, however, the receiver does not contain a phase shifter, and rather than sampling the transmitted waveform, a known signal is intentionally injected into the receiver.

A phase shifter is not required in the receiver since each channel is independently processed, and any phase or amplitude corrections may be done in the digital domain. Once the combined signal, which is comprised of radar returns plus calibration signal, is digitized, a digital filter separates the radar returns from the calibration signal, which is intentionally placed just out of band.

Bypass Calibration Architecture

The Bypass Calibration, shown as the blue path in Figure 4, is used primarily to ensure the N-channels' digitizers are lined-up in time and phase. The signal is directed, via switch, from the input of the TR to the output, so that the TR does not significantly affect the Bypass signal.

4. Calibration Algorithms

The calibration algorithms actually include two distinct types: estimation and correction. Once the signal's amplitude and phase have been estimated, something must be done with that information to effect closed-loop calibration and this corrective action is often non-trivial. A list of the algorithms currently under development is shown in Table 2.

The three-tap correlator is used to estimate the amplitude and phase of the chirp waveform. This is in place of performing an FFT on the chirp waveform and looking at the resulting peak to determine the "location" of the chirp in time/phase. While conceptually easier to understand, the FFT is much more resource intensive when implemented in firmware. The three-tap correlator effectively calculates the amplitude and phase of the waveform at three points on the FFT.

An example of the correlation is shown in Figure 5, however, 21 taps are shown for clarity. The on-board algorithm would only calculate the center three correlation lags due to the limited resources available to the on-board processor. The red line depicts an ideal cross-correlation, offset by 1 lag, while the blue shows the non-ideal chirp, which has passed through analog filtering. In both cases, the center lag is the correct estimate, and the lags to the "left" and "right" are equal. Had those two lags been unequal, the result of the center lag is known to be incorrect, and the algorithm must shift fractionally, up or down in delay, depending on the slope between the "left" and "right" lags.

Currently, these algorithms are being tested in software, using modeled results from measured hardware, such as analog filters. An extensive characterization campaign is underway, which is discussed in the following section. A full ground-based demonstration of the combined analog/digital system will be performed using the digital calibration testbed, discussed next.

The Receiver characterization is a fairly straightforward single-bin FFT of a CW Caltone (continuous wave calibration tone). This tone is placed out-of-band, spectrally close enough to accurately represent the channel's transfer function, but far enough away in frequency that the downstream digital filter can separate the caltone from the desired science. What passes for "close enough" and "far enough" is an on-going iterative process that is due in large part to the different requirements to be imposed on the different mode—all of which have different bandwidths.

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Table 2 Calibration Algorithms

Calibration Algorithm	Function	Typical Signal (In for est.; Out for action)	Filter Type
Receiver characterization	Estimate amplitude and phase	CW Caltone (In)	Single-bin FFT
Transmitter characterization	Estimate amplitude and phase	5-80MHz Chirp (In)	Three-tap correlation
Receiver correction	Determine and apply corrective weightings to the DBF filter taps	Complex digital words (Out)	Complex conjugate adjustment to DBF
Transmitter correction	Calculate the bit pattern to apply to the analog phase shifter, based on characterization.	Digital word (Out)	Look-up table of correction estimate vs. digital word outputs
Bypass characterization	Estimate the change in amplitude and phase due to externals	5-80 MHz Chirp (In)	Three-tap correlation
Bypass digital correction	Apply corrective weightings to the DBF filter taps	Complex digital word (Out)	Complex conjugate adjustment to DBF
Bypass analog correction	Adjust the ADC timing	Digital word (Out)	Look-up table of correction estimate vs. digital word output to ADC control

time/phase. While conceptually easier to understand, the FFT is much more resource intensive when implemented in firmware. The three-tap correlator effectively calculates the amplitude and phase of the waveform at three points on the FFT.

An example of the correlation is shown in Figure 5, however, 21 taps are shown for clarity. The on-board algorithm would only calculate the center three correlation lags due to the limited resources available to the on-board processor. The red line depicts an ideal cross-correlation, offset by 1 lag, while the blue shows the non-ideal chirp, which has passed through analog filtering. In both cases, the center lag is the correct estimate, and the lags to the "left" and "right" are equal. Had those two lags been unequal, the result of the center lag is known to be incorrect, and the algorithm must shift fractionally, up or down in delay, depending on the slope between the "left" and "right" lags.

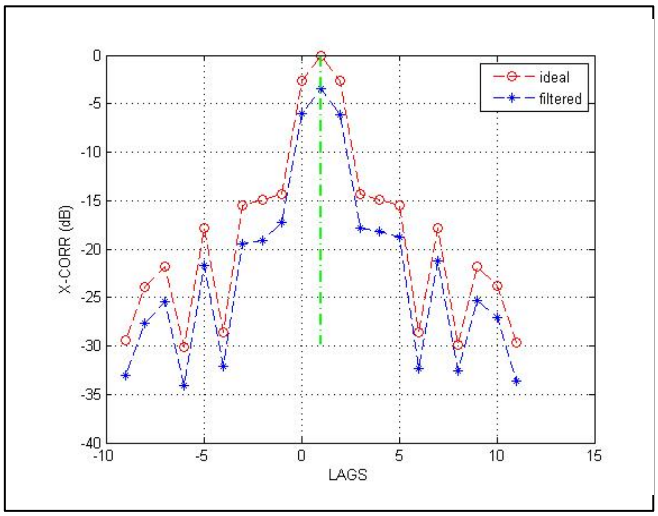

Figure 6 Multi-tap correlation results are shown for clarity, but the on-board algorithm would only perform the three-tap. A successful estimate is shown, which is the center-lag. This is determined by slope between the + and - lags, which is zero. A non-zero slope indicates that the center-lag is incorrect, and the algorithm shifts to compensate.

Currently, these algorithms are being tested in software, using modeled results from measured hardware, such as analog filters. An extensive characterization campaign is underway, which is discussed in the following section. A full ground-based demonstration of the combined analog/digital system will be performed using the digital calibration testbed, discussed next.

5. Component Characterization

All of the components to be used in the TR module are being characterized over temperature in order to create a high fidelity thermal-performance model. This model is used both to predict the impact of various architecture choices in the TR module and to provide thermal-behavioral models for testing the algorithm performance in the presence of non-ideal behavior. Figure 5, discussed earlier, also shows the impact of this modeling. The red line depicts a perfect cross-correlation, while the blue shows the impact of the actual analog filter on the signal. Prior to performing the cross-correlation, the signal was convolved with the transfer function of the filter to show the impact of the filter. This will be performed on the signal over temperature, using the temperature data acquired from thermal characterization.

An example of the resulting temperature characterization is shown in Figure 6. These results show the performance of some key transmit chain components, tested over temperature and bandwidth. Similar results are collected for component phase over temperature and bandwidth. To estimate the robustness of the algorithms to temperature drift in analog components, the impact of real component drift can be estimated via modeling. If the potential drift in analog components, including drifts in ADC timing, is underestimated, the algorithms may fail to estimate the channels' performance correctly. This would lead to systematic corruption of the beamformed data.

The algorithm converges on a local maximum, yielding a false positive. The final demonstration will test the system with the hardware run in a thermal chamber, using the digital calibration testbed, which is under development.

6. Digital Calibration Testbed

A testbed is being constructed to demonstrate the digital calibration techniques and to validate the hardware, as well as the firmware algorithms. The final testbed will include prototype of actual flight designs to ensure that the calibration system will meet requirements for future SweepSAR systems. The system, shown in Figure 7, also includes ground-test equipment, which is required to run the testbed and to simulate spacecraft signals that are needed, but not critical to performance. The blocks in green will be flight-designs, while the blue boxes are the ground-test equipment.
Currently, the testbed has breadboard hardware, and is able to process a single channel of RF data. The prototype system is shown in Figure 8.

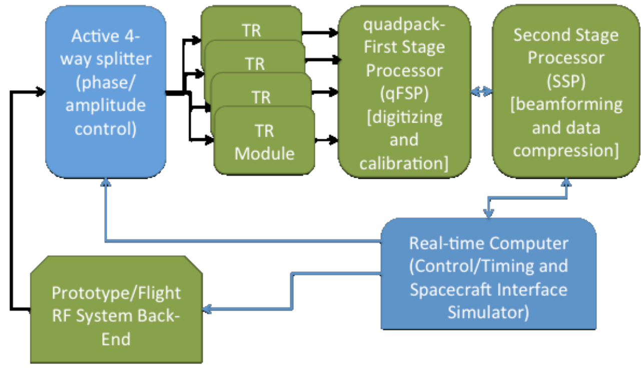

Figure 7 Block Diagram of the digital calibration testbed. Blocks in green are prototype-flight hardware; blue are ground-test equipment, black lines are RF, blue lines are digital data.

Draft algorithms can been evaluated on the prototype digital hardware, with digital or RF test signals. This enables detailed verification of the algorithms with well-behaved digital signals, while also being capable of capturing system performance to the idiosyncrasies or real world RF signals.

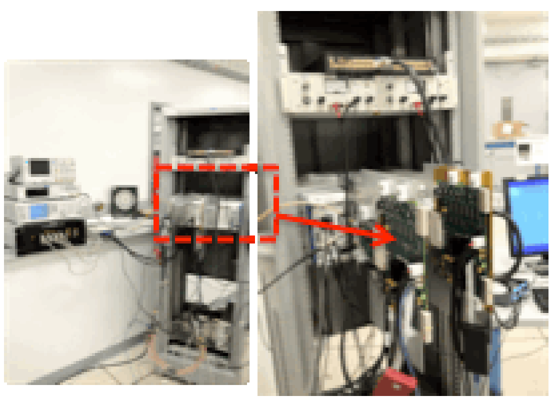

Figure 8 Prototype digital calibration testbed. The equipment shown is all ground-test equipment, except for those boxed in red, which are the prototype qFSP and SSP.

7. SUMMARY

The digital calibration techniques described in this paper, will improve TR module calibration precision and accuracy compared to state-of-the-art calibration by more than an order of magnitude in key performance parameters. Digital calibration allows for an unprecedented level of calibration parameter knowledge. When coupled with a DBF, this allows for an equally impressive level of control, reducing receiver calibration. These levels of correction and knowledge expected through digital calibration meet the baseline requirements for implementation of SweepSAR technique in the proposed DESDynI radar instrument [4]. The SweepSAR architecture is estimated to reduce cost and mass by as much as 50% and 70%, respectively, as compared to a comparable phase-array instrument [5].

The algorithm developments are supported by a comprehensive characterization and modeling of the analog components that make up the system. These components models are being used to estimate the performance of the algorithms in software, allowing for easier and less costly trades in system architectures. The final system will be demonstrated in a high fidelity testbed, which is under construction. Prototype digital calibration testbed. The equipment shown is all ground-test equipment, except for those boxed in red, which are the prototype qFSP and SSP.

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Biographies

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