High-Efficiency, Digitally Calibrated TR Modules Enabling Lightweight SweepSAR Architectures for DESDynI-Class Radar Instruments

ESTO Forum

October 2014

Jim Hoffman, PhD
Radar Science & Engineering
Jet Propulsion Laboratory

Background

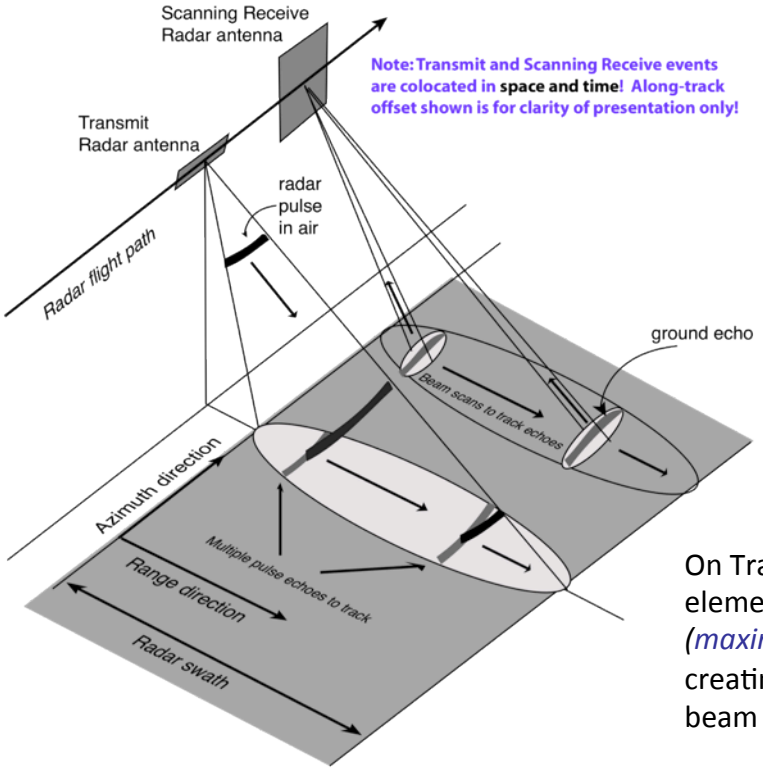
- Development of a real-time DBF (Digital Beamforming) and associated digital calibration—technologies enabling SweepSAR
- SweepSAR would enable broad ground coverage, allowing shorter repeat-pass time—significantly improving science return—while dramatically reducing resources, including cost, as compared to a standard phased array system—(50% cost reduction, 70% mass reduction)

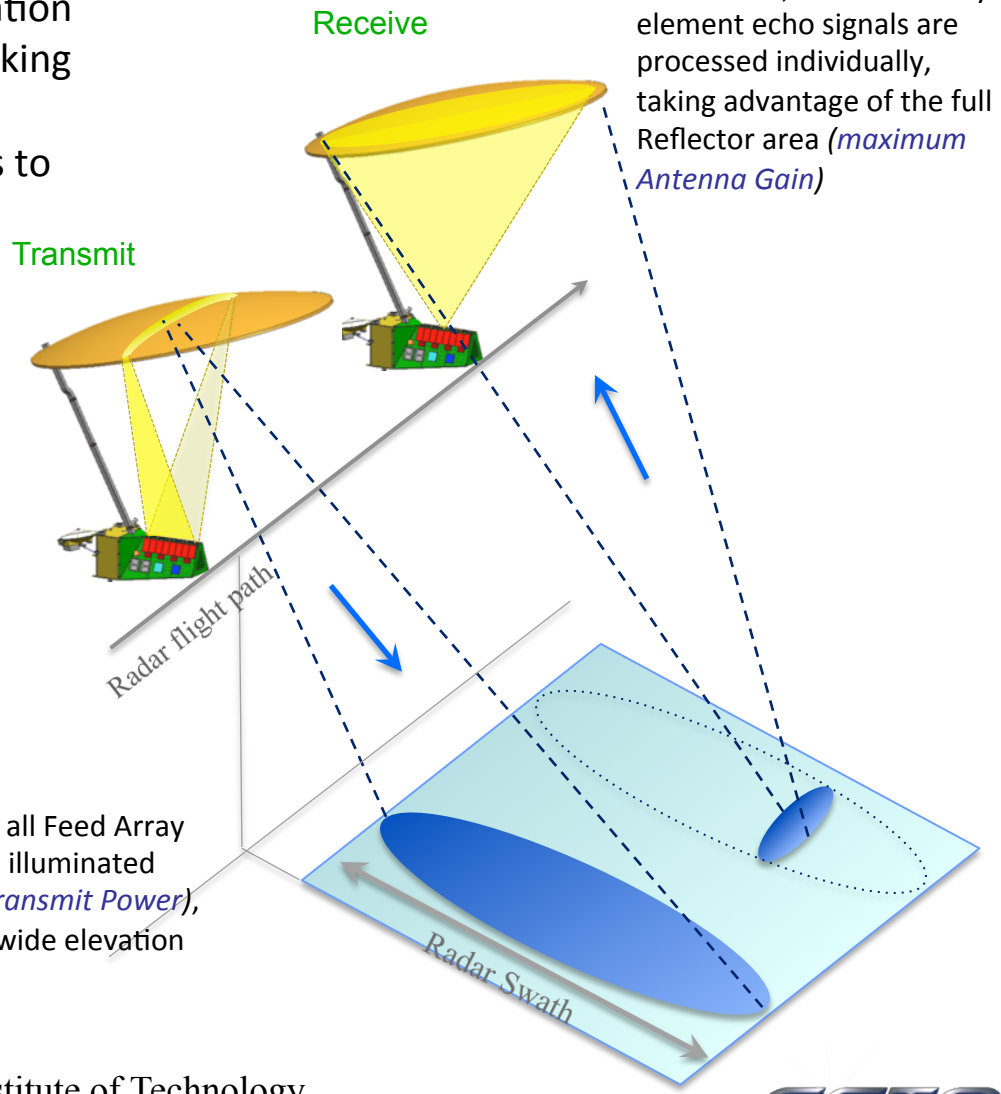
Just Cargo

SweepSAR Technique

What is SweepSAR?

- Transmits a pulse over wide beam in elevation
- Receives the echo over narrow beam, tracking echo with scanning receive beam
- Uses multiple *simultaneous* receive beams to track multiple echoes



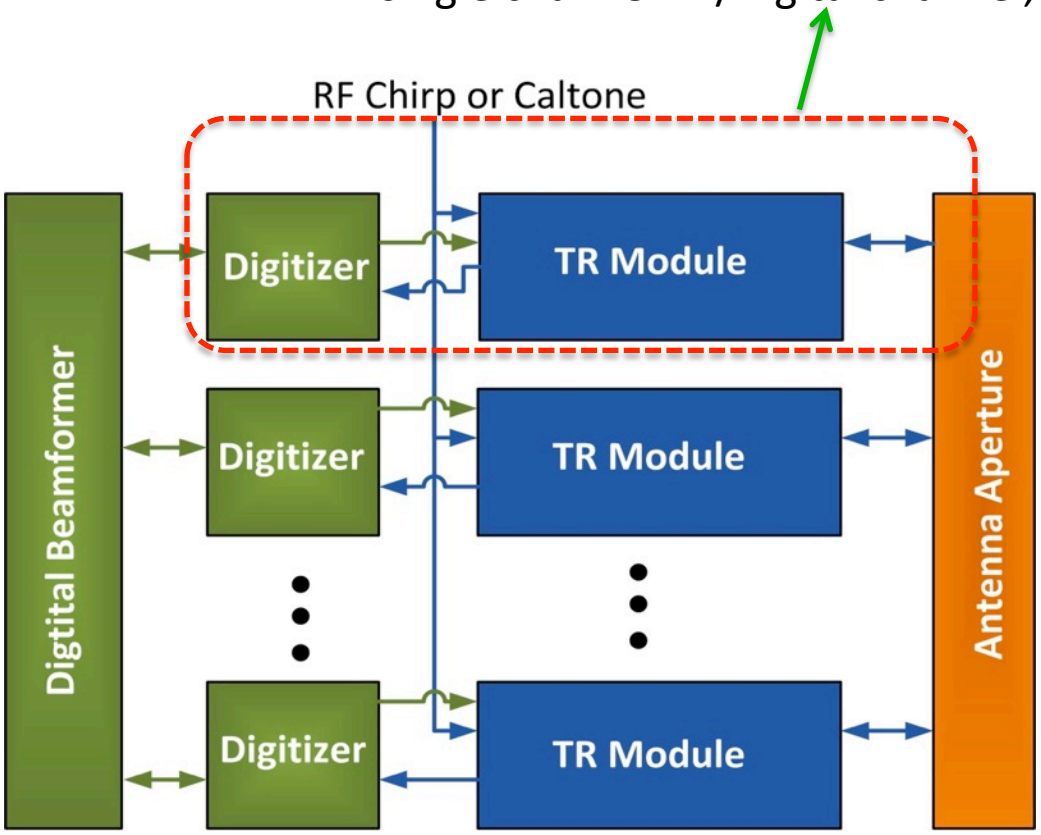


On Transmit, all Feed Array elements are illuminated (*maximum Transmit Power*), creating the wide elevation beam

ESTO Earth Science Technology Office

High-level Block Diagram of Beamformer/Calibration System

A single channel RF/Digital channel, effectively a single functional block



The "Digitizer", called a First Stage Processor for the proposed DESDynI SAR Instrument, both receives the RF signal from the TRM, and controls each TRM's Attenuator and Phase Shifter

The "Digitizer" also contains the algorithms to estimate Amplitude and Phase of the Calibration Signal from the TRM, once digitized

For Transmit: The TRM receives an RF Chirp, which is both Transmitted and coupled to the "Digitizer", where its Amplitude and Phase are estimated

For Receive: The TRM receives a Caltone simultaneously with the radar return. The Caltone is stripped off in the "Digitizer", and its Amplitude and Phase are estimated.

For Bypass Calibration: An RF Chirp or Caltone is routed directly to the "Digitizer" where its Amplitude and Phase are estimated

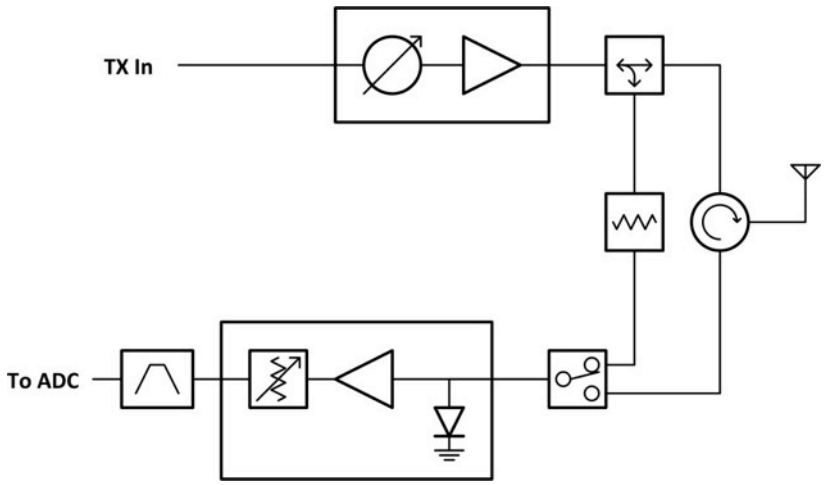
SweepSAR Calibration Modes

- Three calibration modes run in the background while collecting science data
  - Receive Calibration using cal tone (Rx-Cal)
  - Transmit Calibration using chirp (Tx-Chirp)
  - Receive-Only Noise (RON)
    - Noise will be measured at a frequencies out of the transmitted chirp band
- One type will be exercised periodically
  - Bypass Calibration using chirp
- Other types, used for diagnostics, will be exercised on ground command only
  - Receive calibration using chirp (Rx-Chirp)
  - On ground command, data from Tx-Chirp, Rx-Chirp and T/R Bypass will be downlinked for all modules.
    - The ADC sampling time in each FSP can be adjusted by using digital sampling control (either by commanding it from the ground or from the instrument computer).
    - An offset can be applied to the Rx-Cal data if the relative phase between cal tone and chirp drifts (either by commanding it from the ground or from the instrument computer).

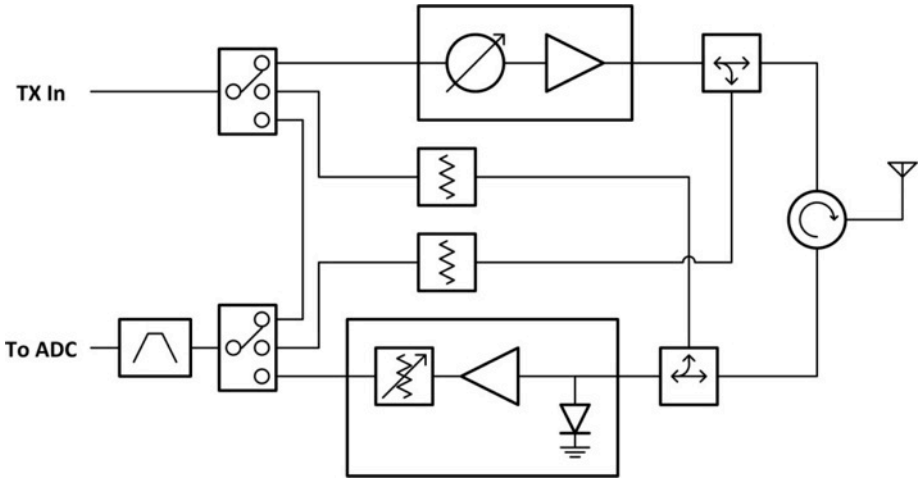
*Modes highlighted in red are the technology drivers

Calibration Concept

Traditional Loopback Calibration



SweepSAR Digital Calibration



- **Relaxes the isolation requirement between TX and RX**
- **Calibration can be done during actual receive events**
- **Differentiates between TX and RX changes (important for SweepSAR)**
- **Compensates for all changes not just temperature**

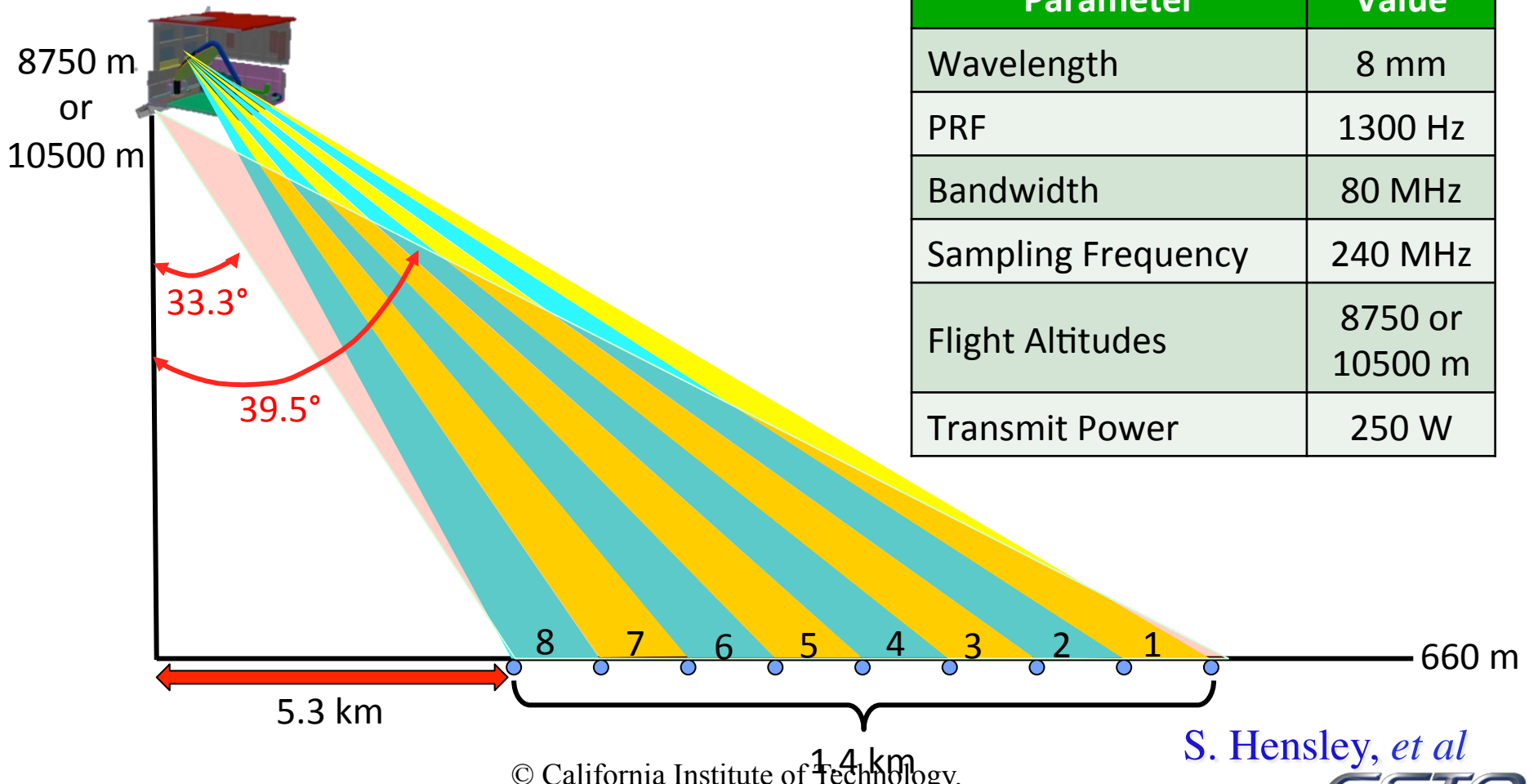
ESTO Earth Science Technology Office

Reasons for this calibration approach

- The unique architecture of SweepSAR requires separate characterization of Transmit and Receive
- Each of the N-channels (currently 24 for DSI) requires independent characterization (Tx and Rx)
- Once beamforming is performed (on-board), characterization and correction of each channel becomes impossible, and therefore must be performed on-board, and in near real-time due to limitations of on-board storage and downlink capacity
- An example of a beamforming system was demonstrated by the DSI team
  - Demo used a scaled Ka-band airborne system (an antenna/reflector is required for SweepSAR, and an airborne system at L-band is implausible)
  - Processing was all done at L-band
  - The following are actual flight data (pre, and post processed)

Radar Parameters and Mapping Geometry

- **Eight beams map a swath extending from 33.3°-39.5° that gives a swath width of 1.4 km.**



Radar Parameters

Parameter	Value
Wavelength	8 mm
PRF	1300 Hz
Bandwidth	80 MHz
Sampling Frequency	240 MHz
Flight Altitudes	8750 or 10500 m
Transmit Power	250 W

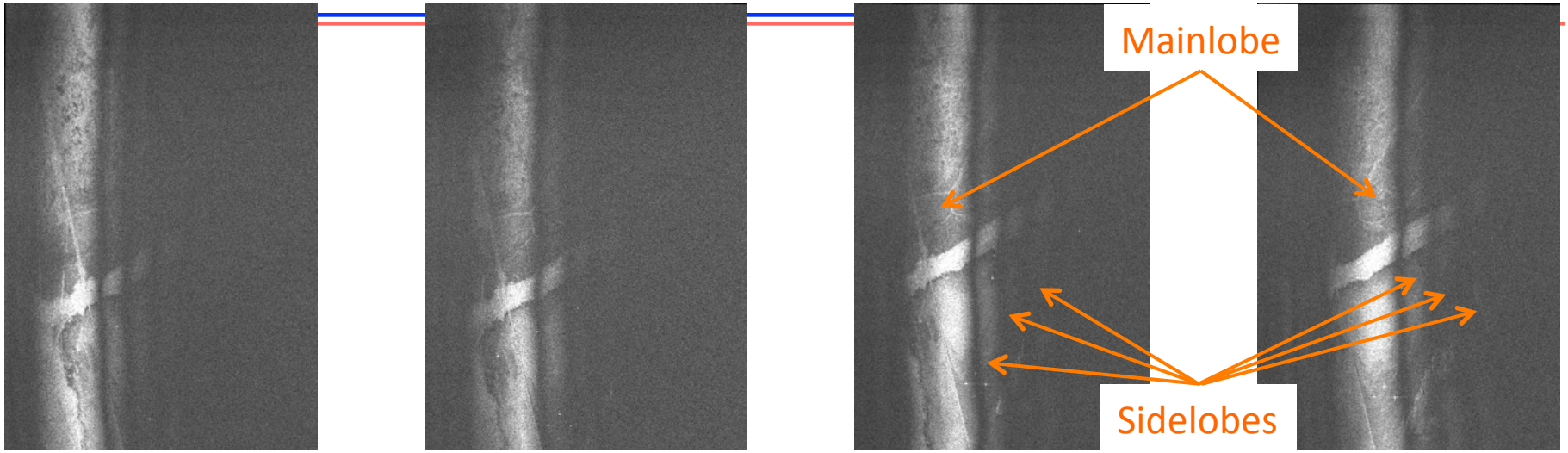
Not drawn to scale

S. Hensley, *et al*

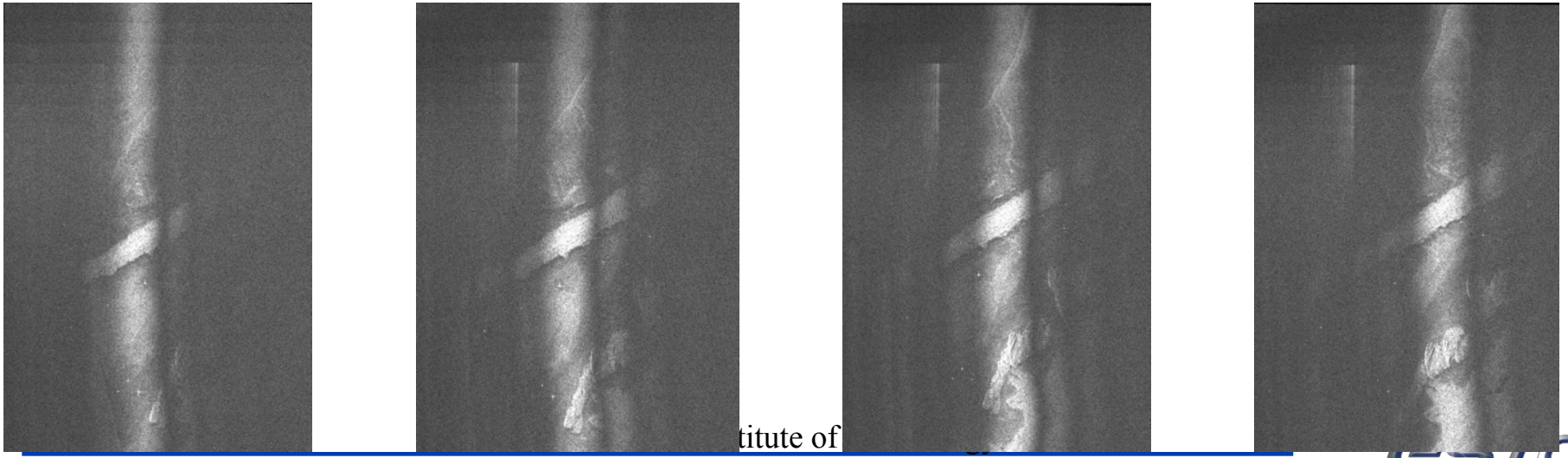
ESTO Earth Science Technology Office

Individual Beam Imagery

S. Hensley, *et al*



Beam 8 Beam 7 Beam 6 Beam 5

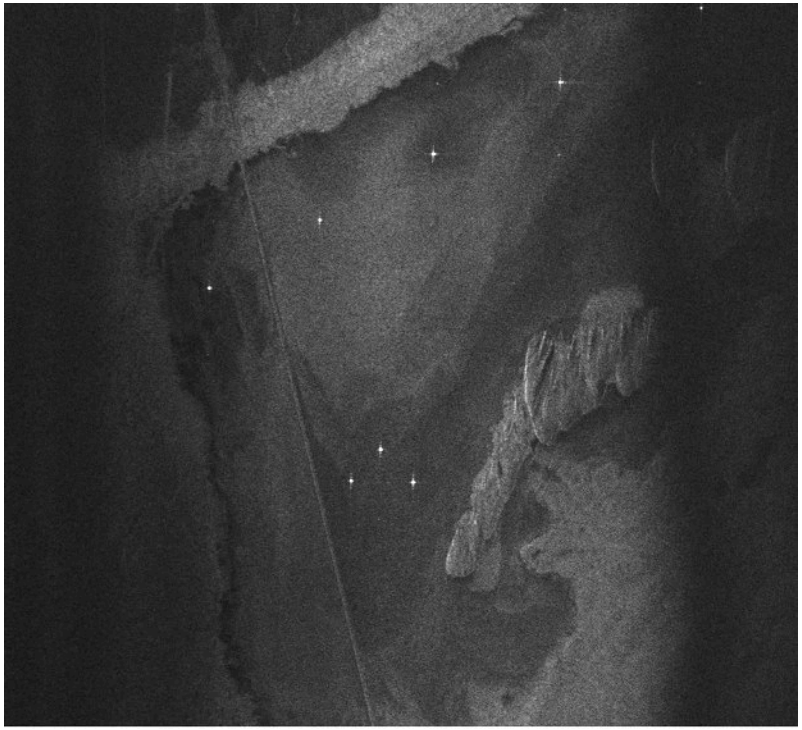


Beam 4 Beam 3 Beam 2 Beam 1

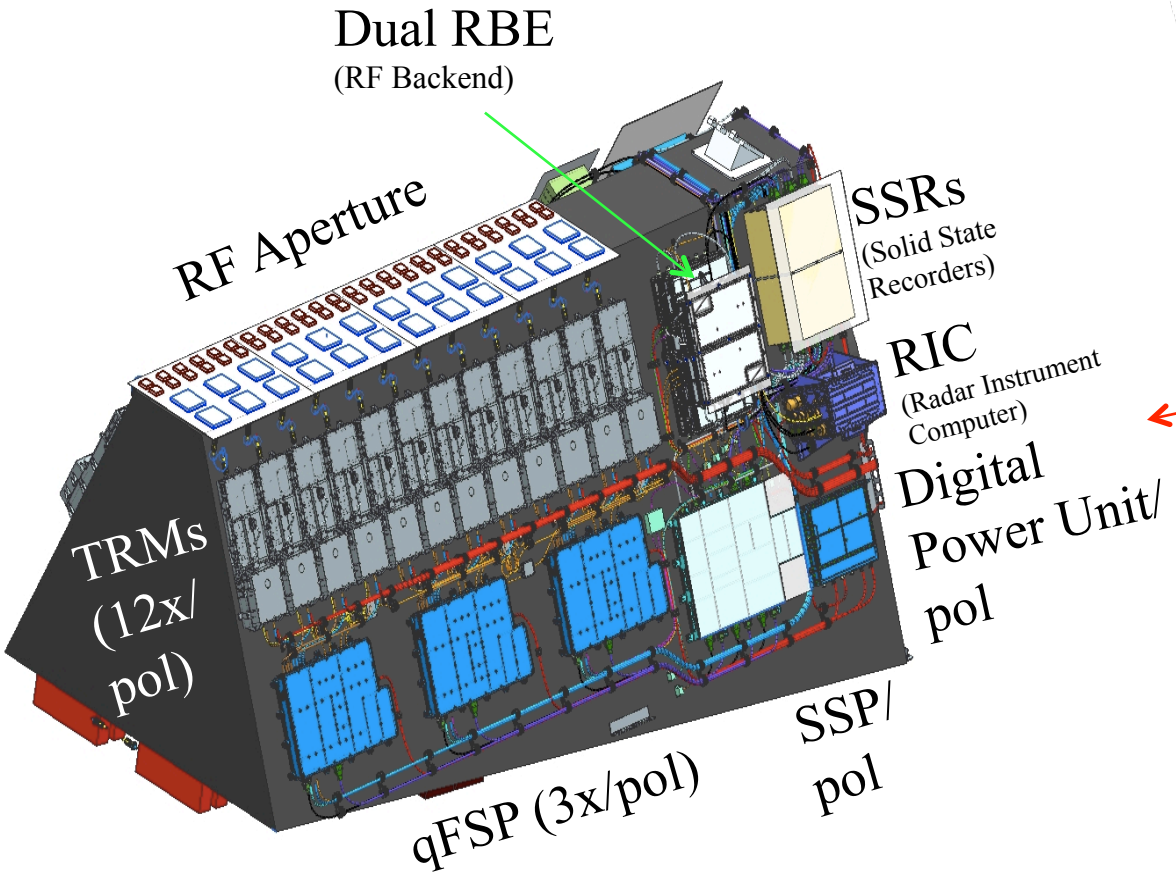
titute of
Government sponsorship acknowledged

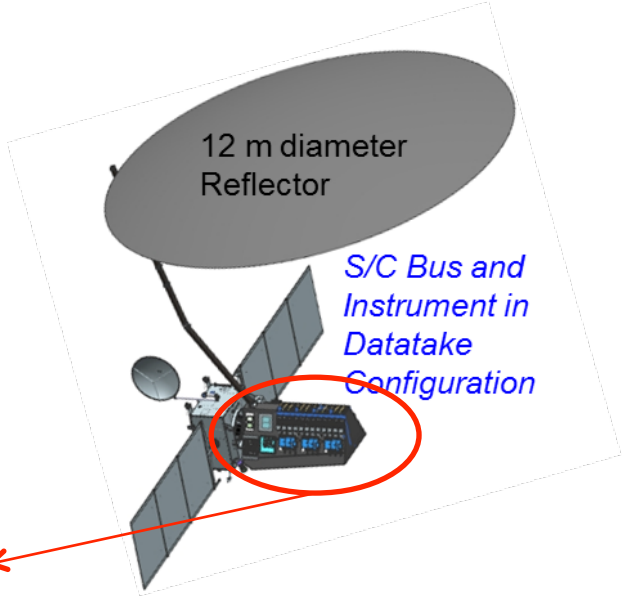
Calibrated-Beamformed Image

The left image is the beamformed image from the prior slide. The right image is after calibration. Both operations were done with extensive human-in-loop. For a spaceborne radar, this must be done autonomously, in space since we cannot support the downlink volume required to send pre-beamformed image for ground processing



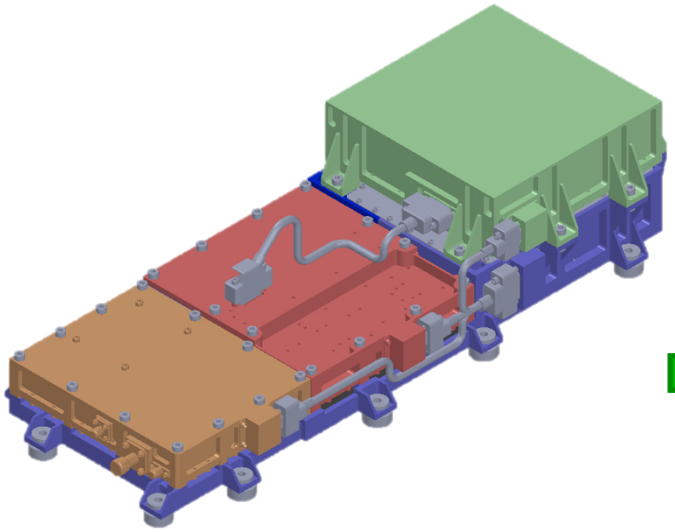
Instrument Concept
DSI (Deformation SAR Instrument) for NISAR

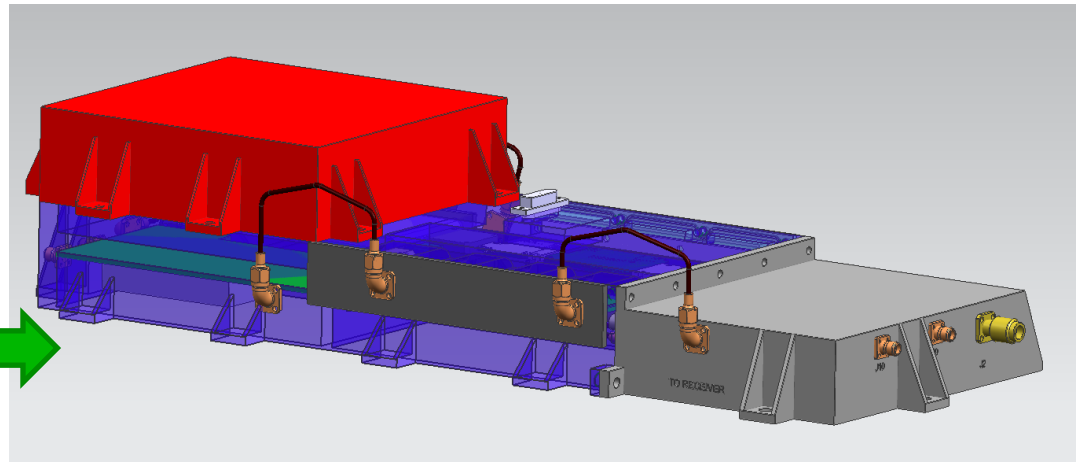


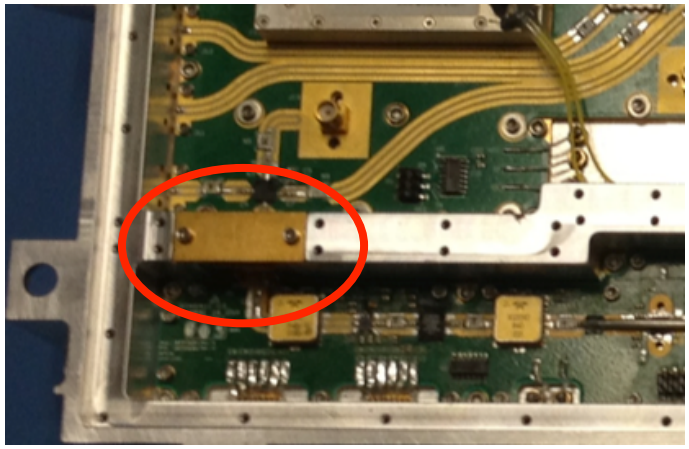


ESTO
Earth Science Technology Office

Updated packaging concept



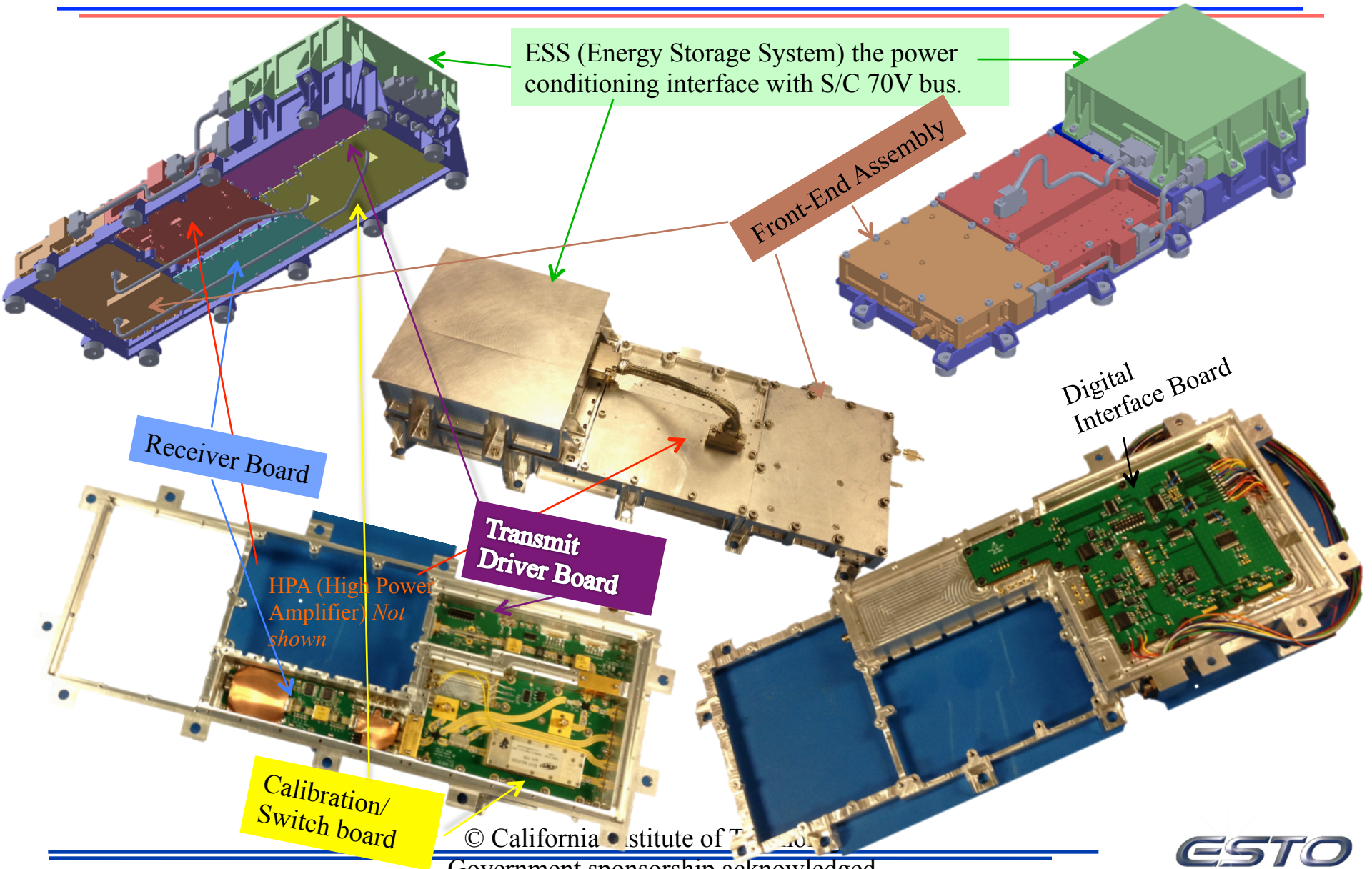




Drop-in walls caused poor matching

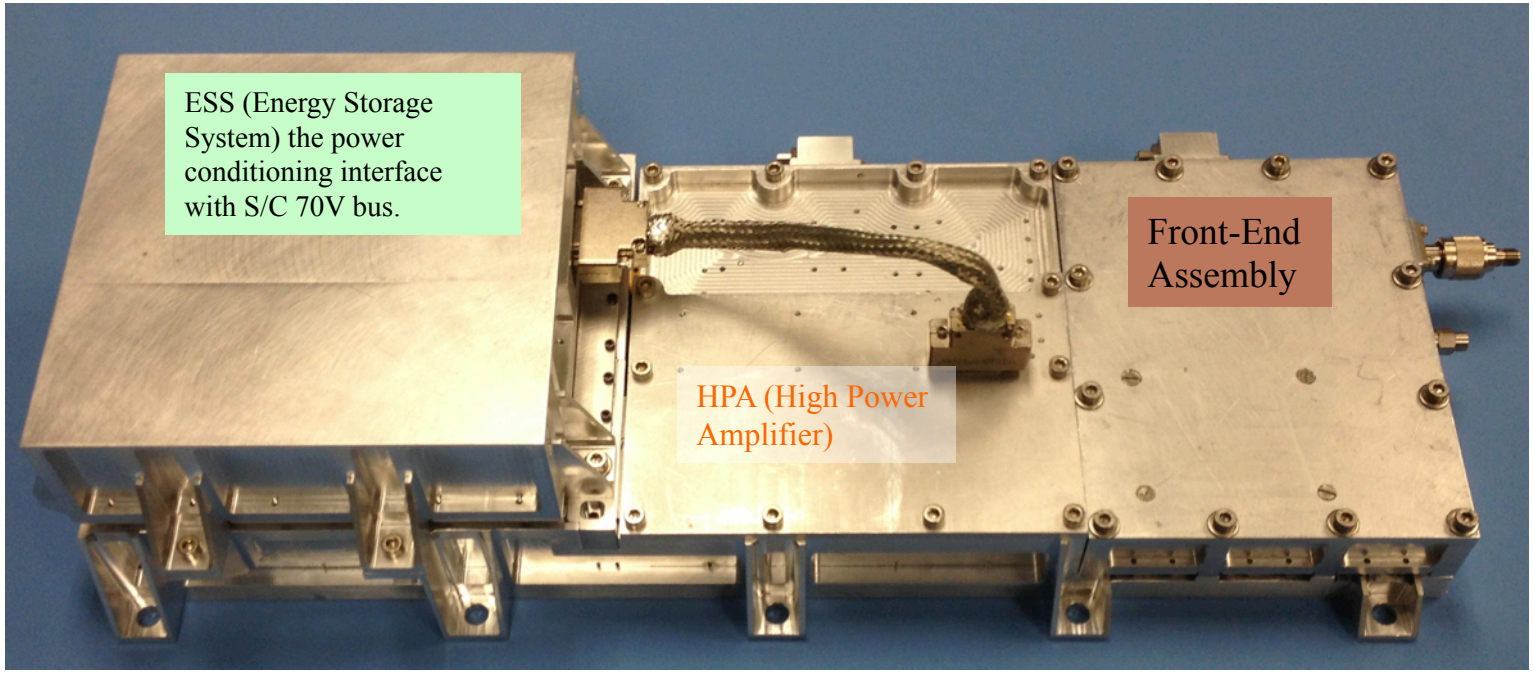
Receiver ripple (shown earlier in performance plots) is largely due to poor match at the drop-in walls. These were used to reduce recurring machining costs. Going forward, the connections will be made using external patch cables, thus improving match (reducing ripple) significantly, improving testability, and maintaining a low recurring cost machining (ie, no EDM)

Revised TR Module (Rev1 EM)

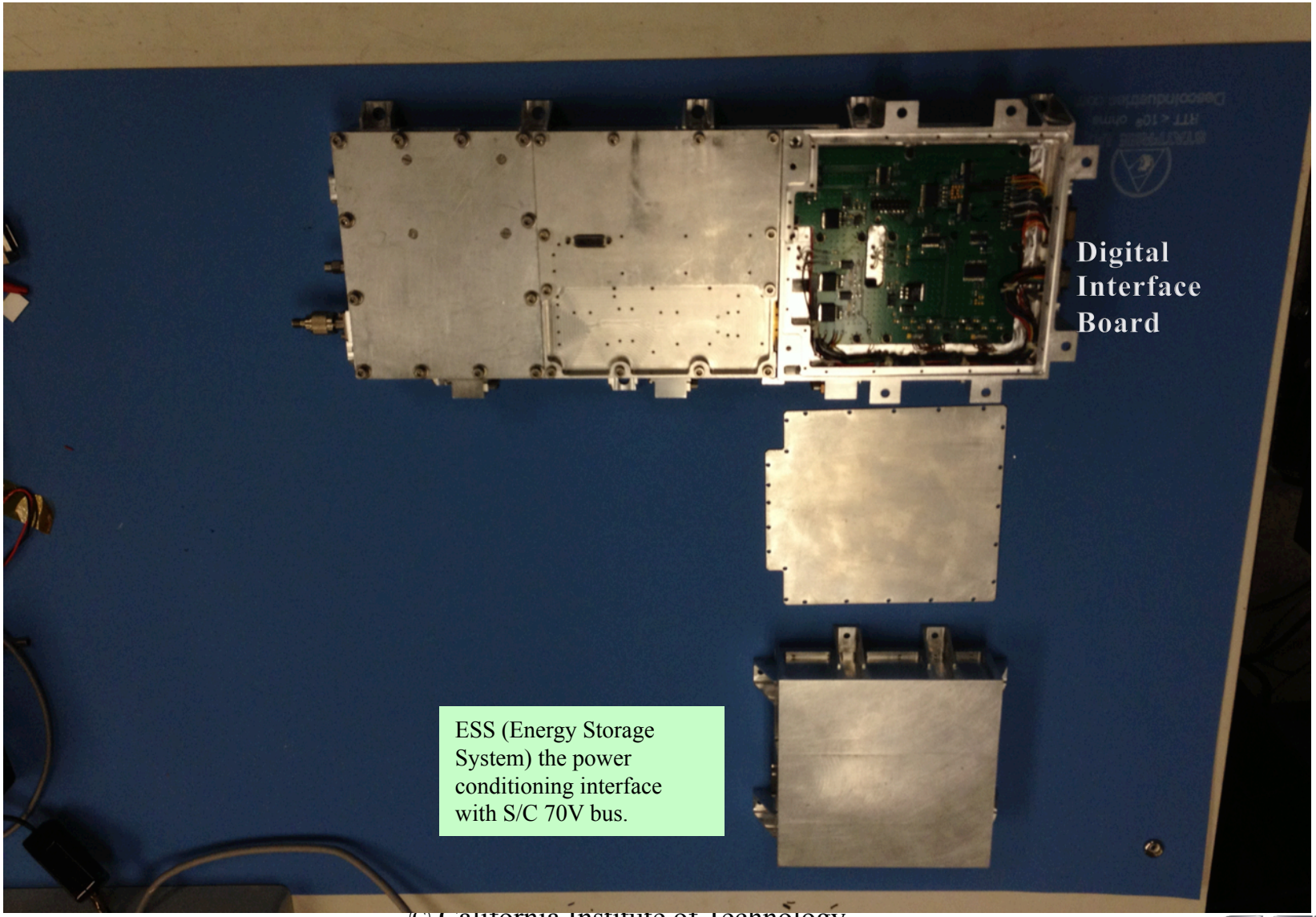


ESTO Earth Science Technology Office

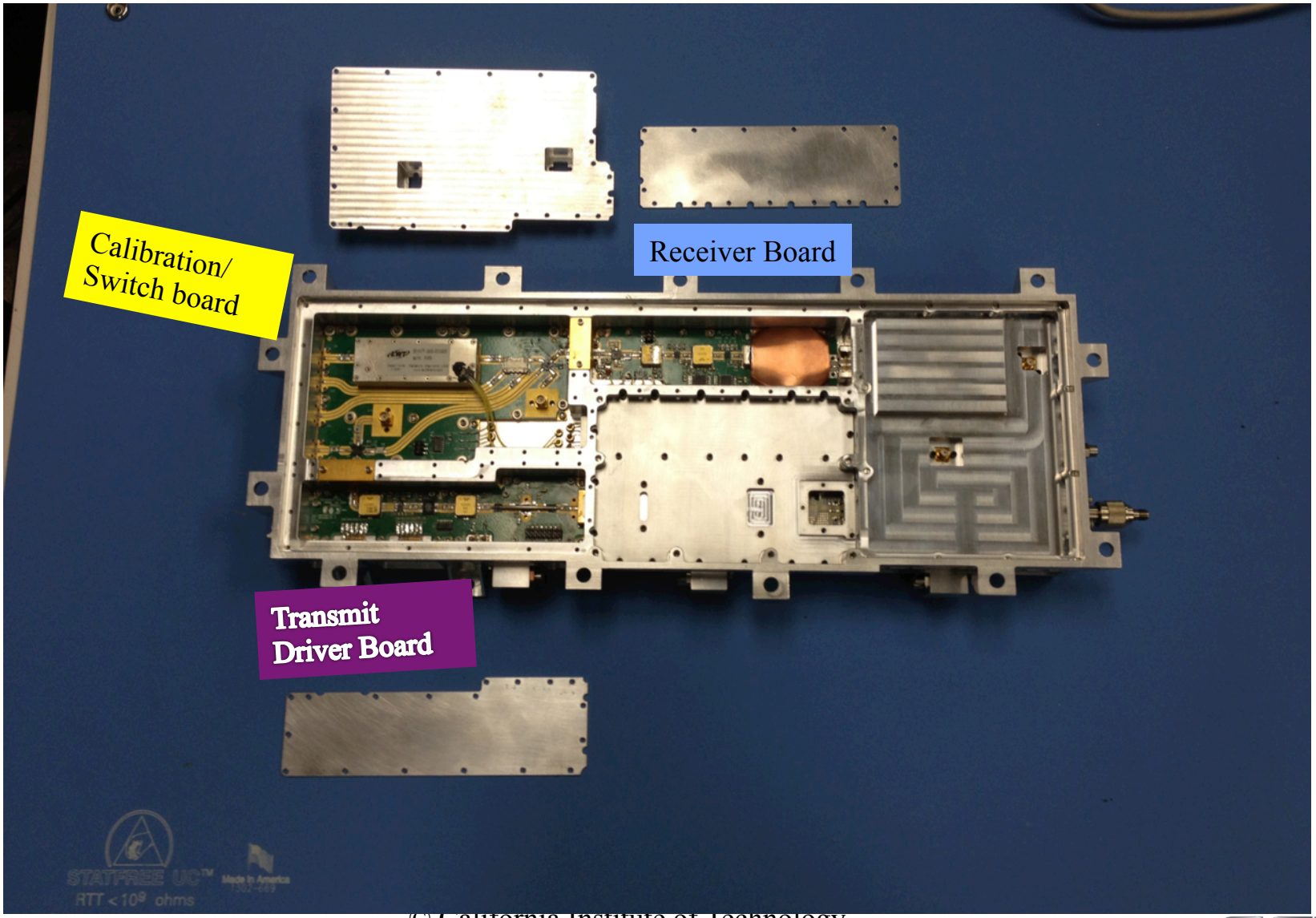
Final Assembly of Rev1



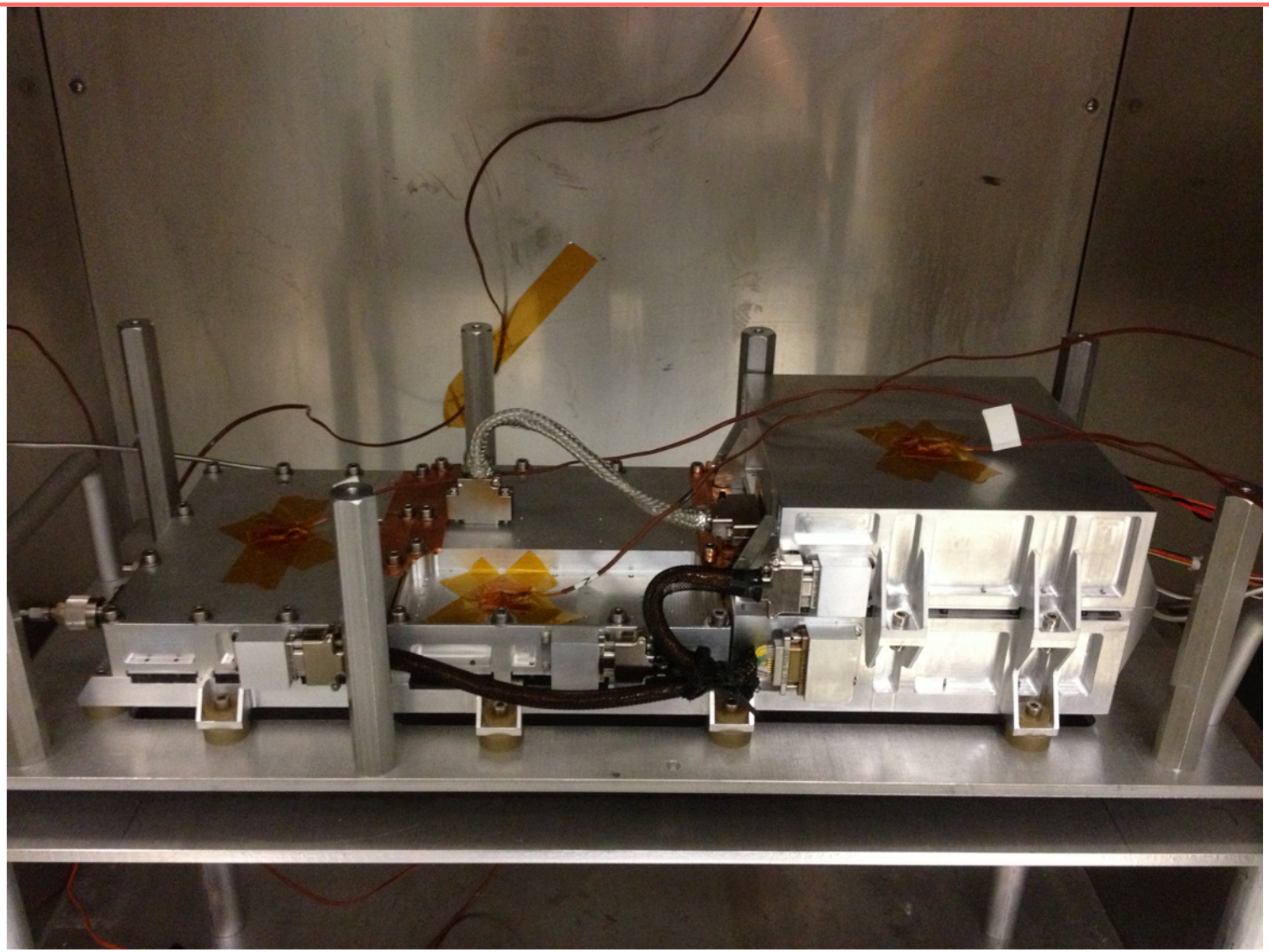
Rev1 with S/C Power Supply/Conditioning



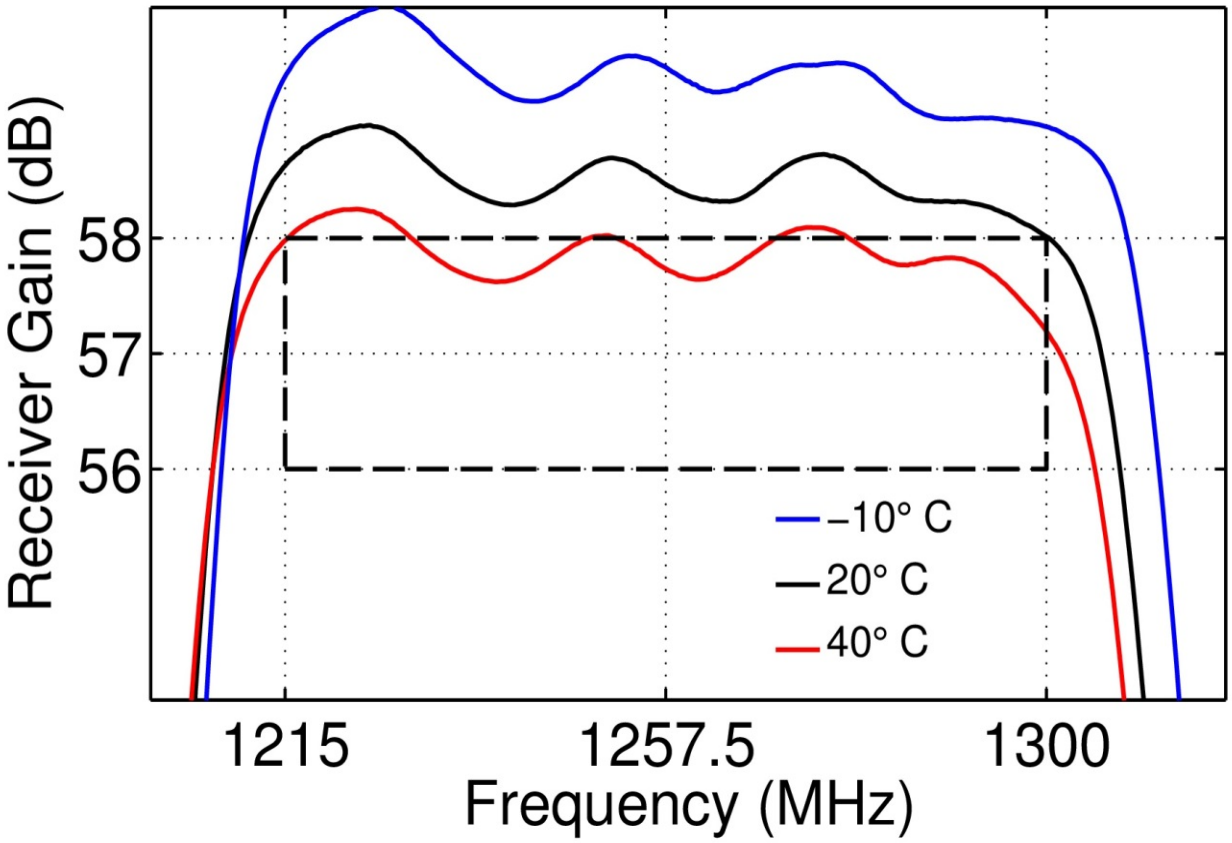
Rev1 Backside with Receiver exposed



Rev1 in thermal chamber

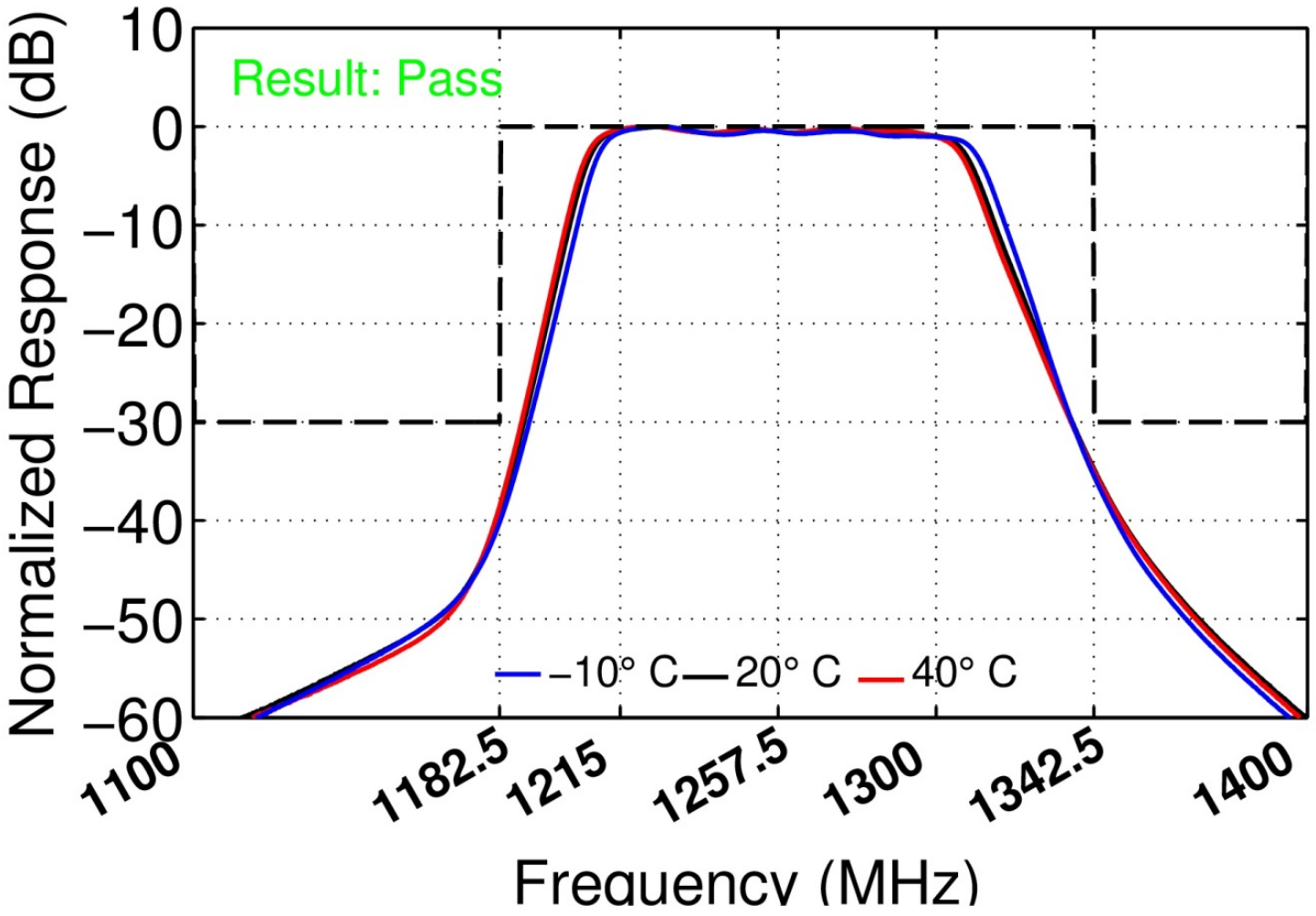


RX Gain

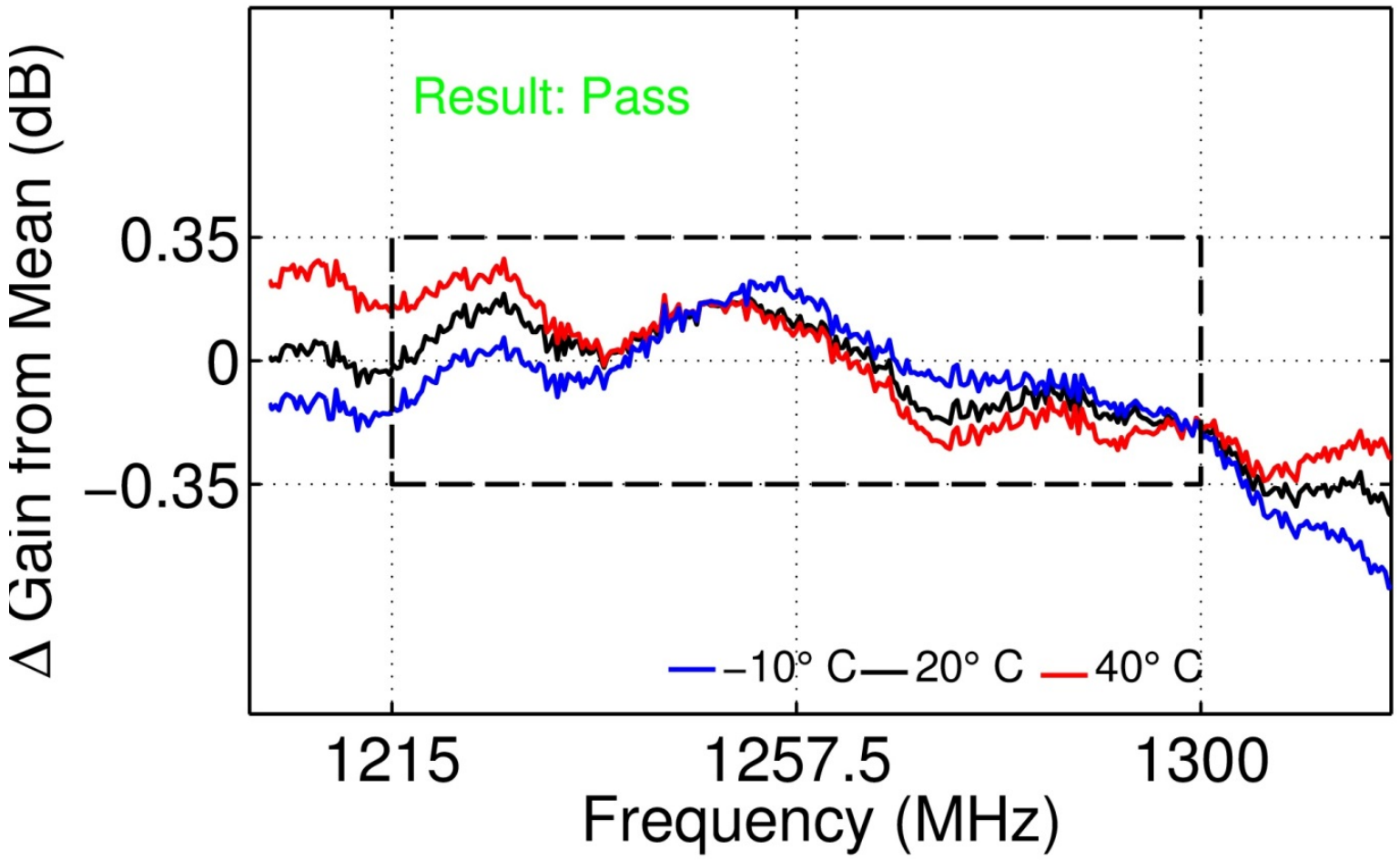


Ripple is due in large part to poor matching at connector interfaces—being addressed in next revision (out of scope for this ACT).
ACT can accommodate within scope with 1) near perfect "antenna" match, since we are using test equipment and not an actual antenna 2) adding input attenuation and increasing power

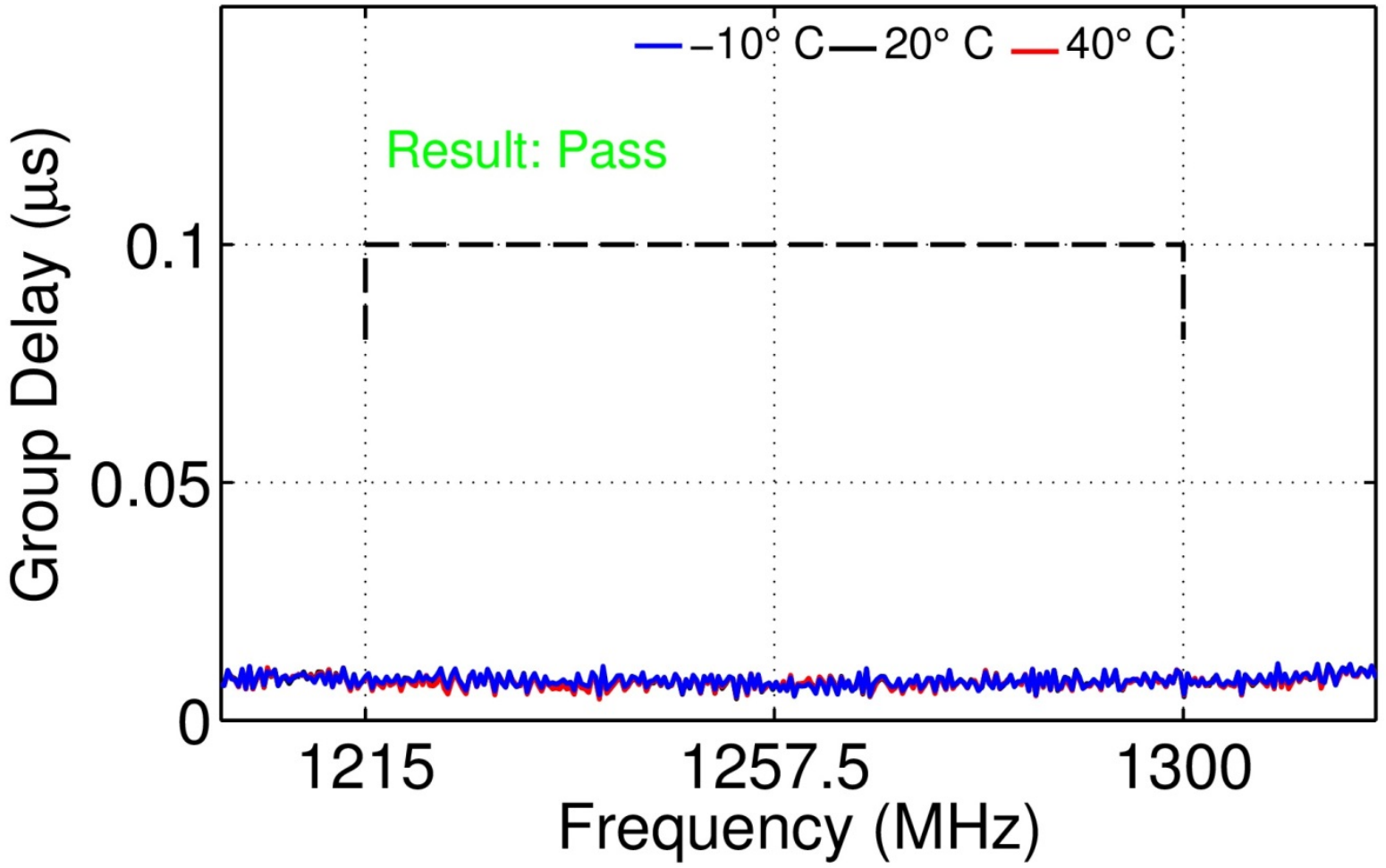
RX Spectral Mask



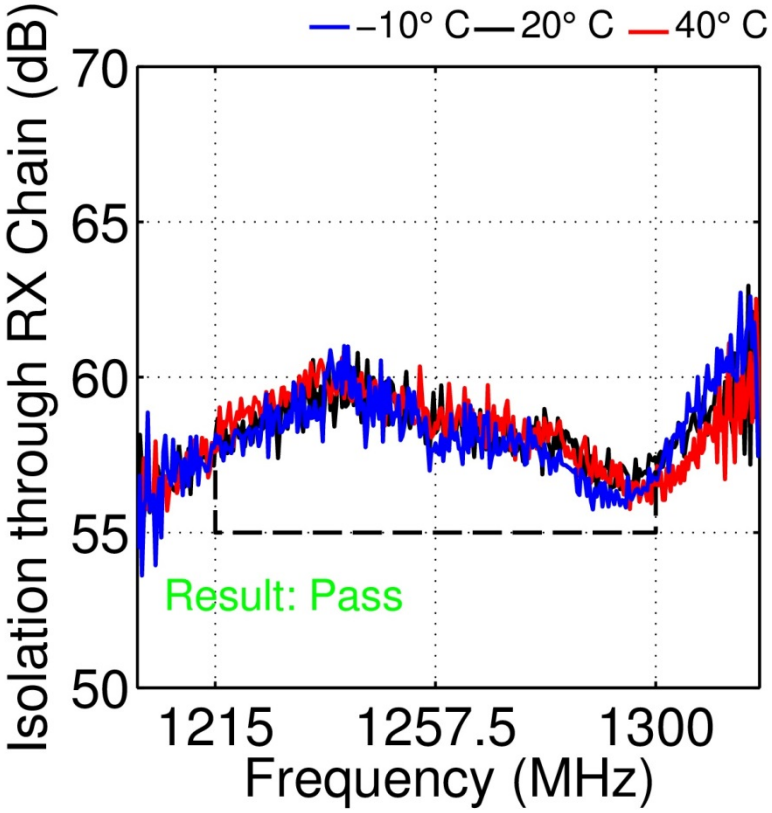
TX Gain Variation

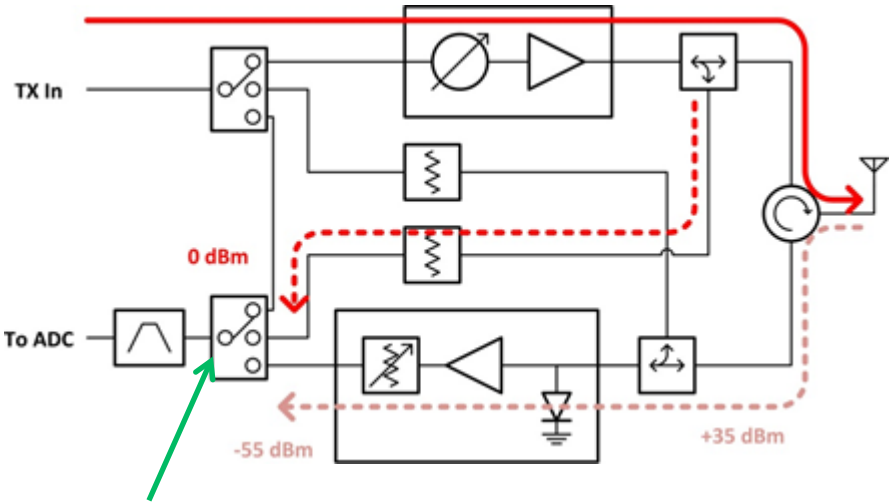


TX Group Delay



Isolation through RX in TX Mode





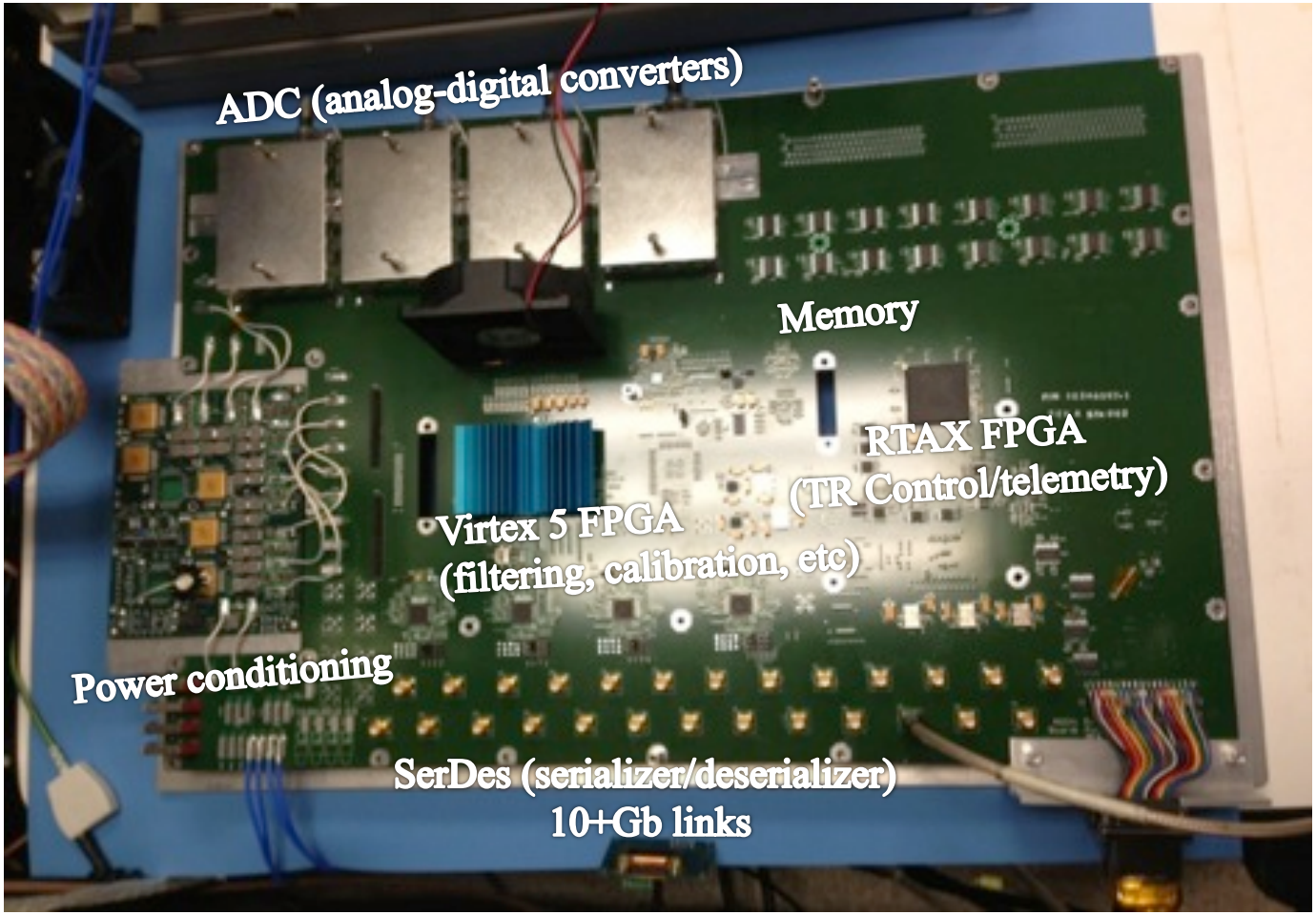
Need 55 dB isolation at combination point

Successfully isolated by:

- Combining signals with switch instead of coupler
- Switching in attenuation rather than turning off amplifiers
- Adding isolation switch (SPST) at the receiver output

ESTO Earth Science Technology Office

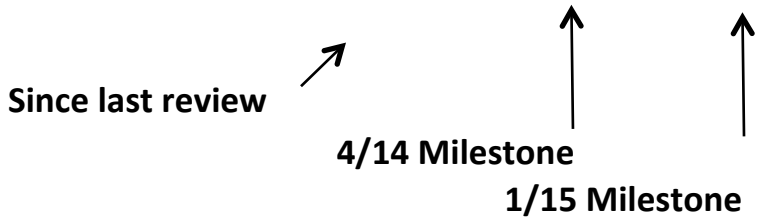
quad First Stage Processor (qFSP)



- qFSP Prototype
- Tested and meeting all functional req's
- Performance req's still be worked for timing and ENOB
- qFSP board is currently being integrated into the Digital Calibration Testbed (shown earlier).

Single channel calibration algorithms status

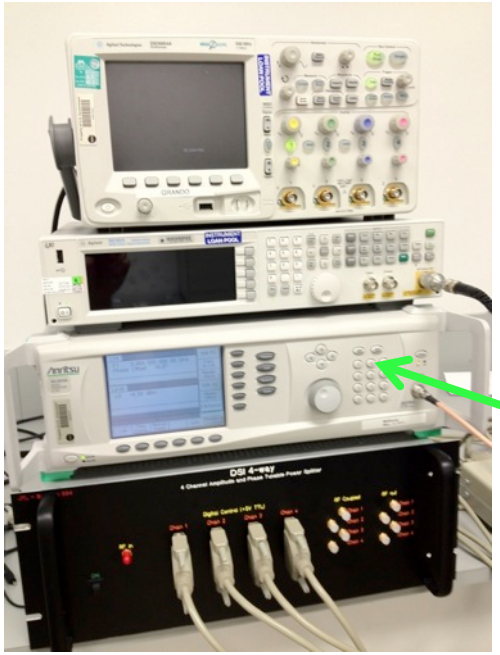
Algorithm function	Defined	Floating Point Model	Bit True Model	Verilog	Golden Model (bit true/verilog)	Firmware	HW architecture design	Tested in HW	Verified (Meets Spec)	Multi-channel Demonstrated
Receive calibration phase and amplitude estimation (cal-tone filter)	Complete	Complete	Complete	Complete	Complete	Complete	Complete	Complete	Complete	
Transmit calibration phase and amplitude estimation (80 MHz filter)	Complete	Complete	Complete	Complete	Complete	Complete	Complete	Complete	Complete	
Transmit calibration phase and amplitude estimation (chirp filter – three lag correlator)	Complete	Complete	Complete	Complete	Complete	Complete	Complete	Complete	Complete	
Transmit calibration closed-loop correction (control of Tx phase shifter)	Complete	Complete	Complete	Complete	Complete	Complete	Complete	Complete	Complete	
Bypass calibration relative delay estimation	Complete	Complete	Complete	Complete	Complete	Complete	Complete	Complete	Complete	
Bypass calibration closed loop (control of ADC clock delay)	Complete	Complete	Complete	Complete	Complete	Complete	Complete	Complete	Complete	
Receive calibration correction	Complete	Complete	Complete	Complete	Complete	Complete	Complete	Complete	Complete	



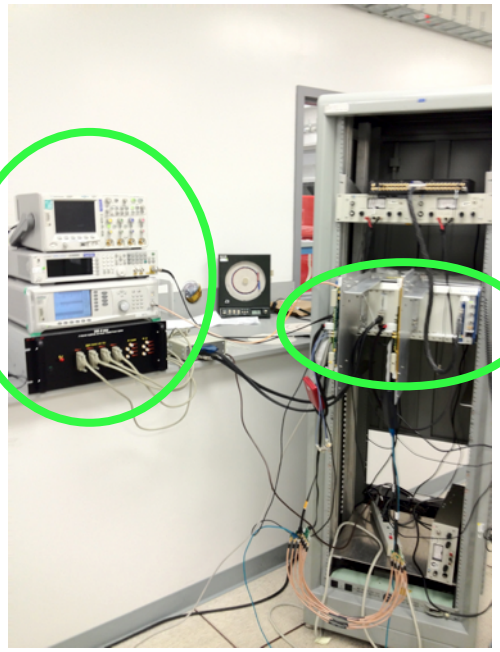
7/14 Milestone is performing these in the integrated, multi-channel “flight” hardware

1/15 Milestone is completing the characterization of the integrated system, over temperature

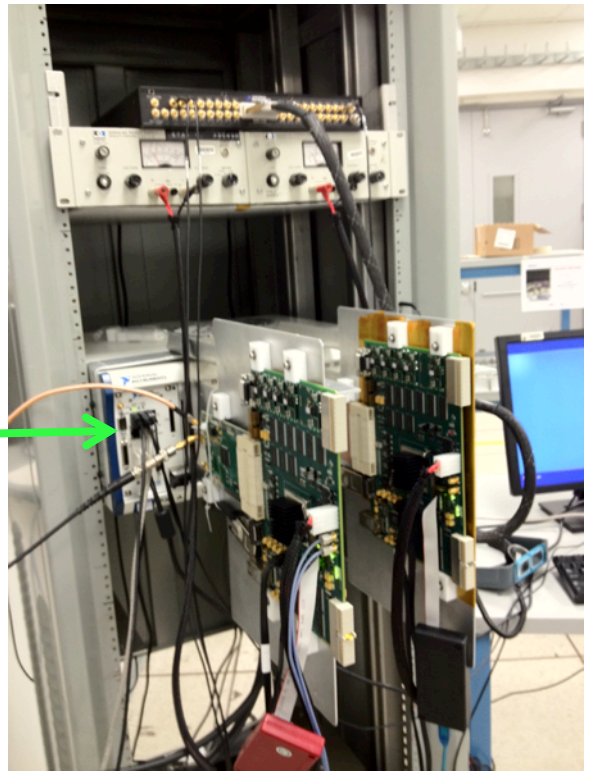
Digital Calibration Testbed



Multi-channel excitation: Single channel of CW or chirp, through an computer controlled 4-way splitter with independent control of phase and amplitude.

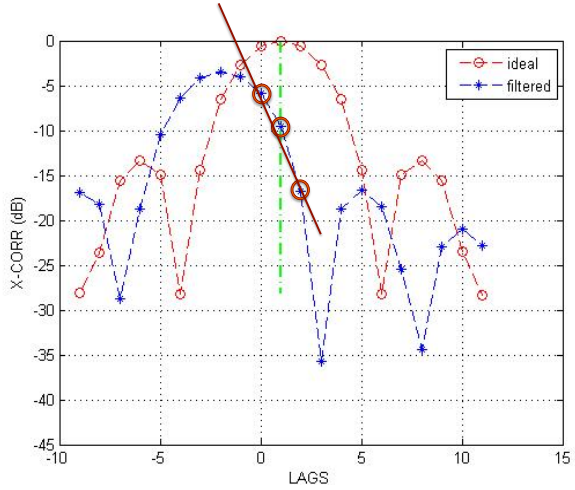


ACT: Digital Calibration Testbed

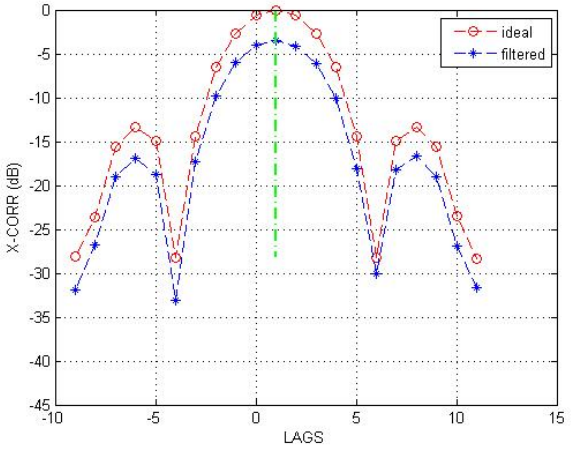


iFSP (First Stage Processor in iBoard4); iSSP (Second Stage Processor in iBoard4); and a National Instruments cPCI chassis acting as RIC (Radar Instrument Controller)

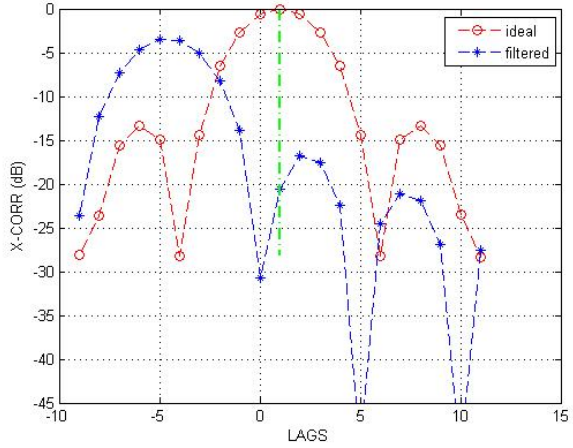
Alternate (print) view of previous slides: Synchronization Success & Failure



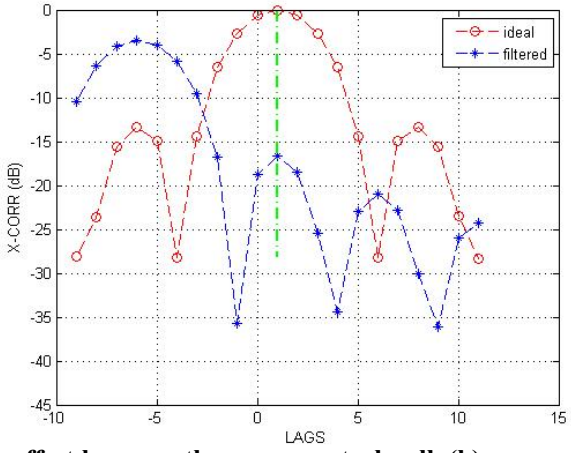
Success



(a) DFT of an ideal chirp and one shifted in phase and amplitude due to filtering (analog or digital). The three-tap correlator allows for estimating amplitude and phase with minimal processing. (b) Results of a successful calibration and correction of a chirp. This method is used for both Tx calibration and Bypass calibrations, which employ chirps.

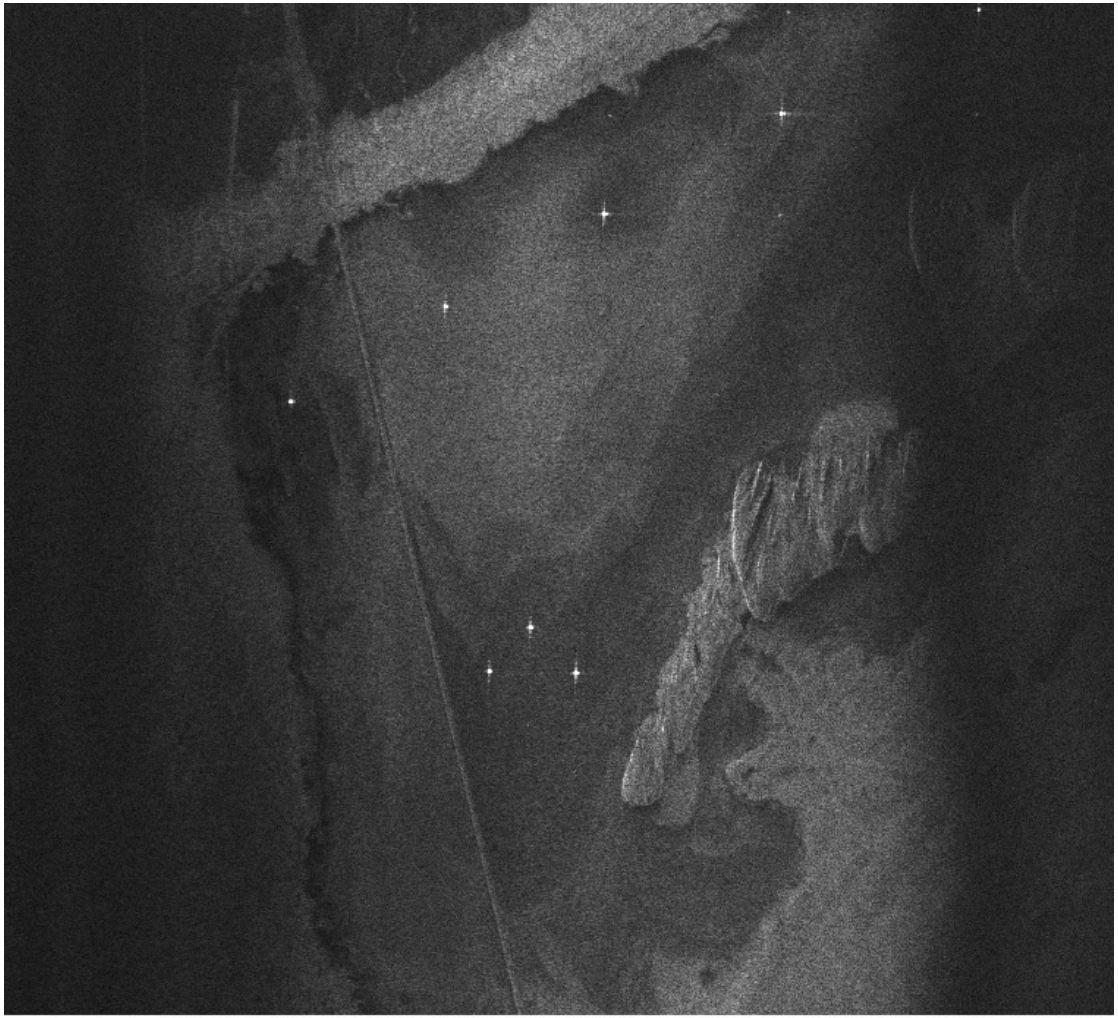


Failure



(a) Example of a three-tap correlator calibration that will fail due to being offset by more than one spectral null. (b) Successful three-tap correlation, with the incorrect solution. Maintaining system skew within the first-null of the correlation is a system constraint.

Real-time processed image of raw airborne demo data

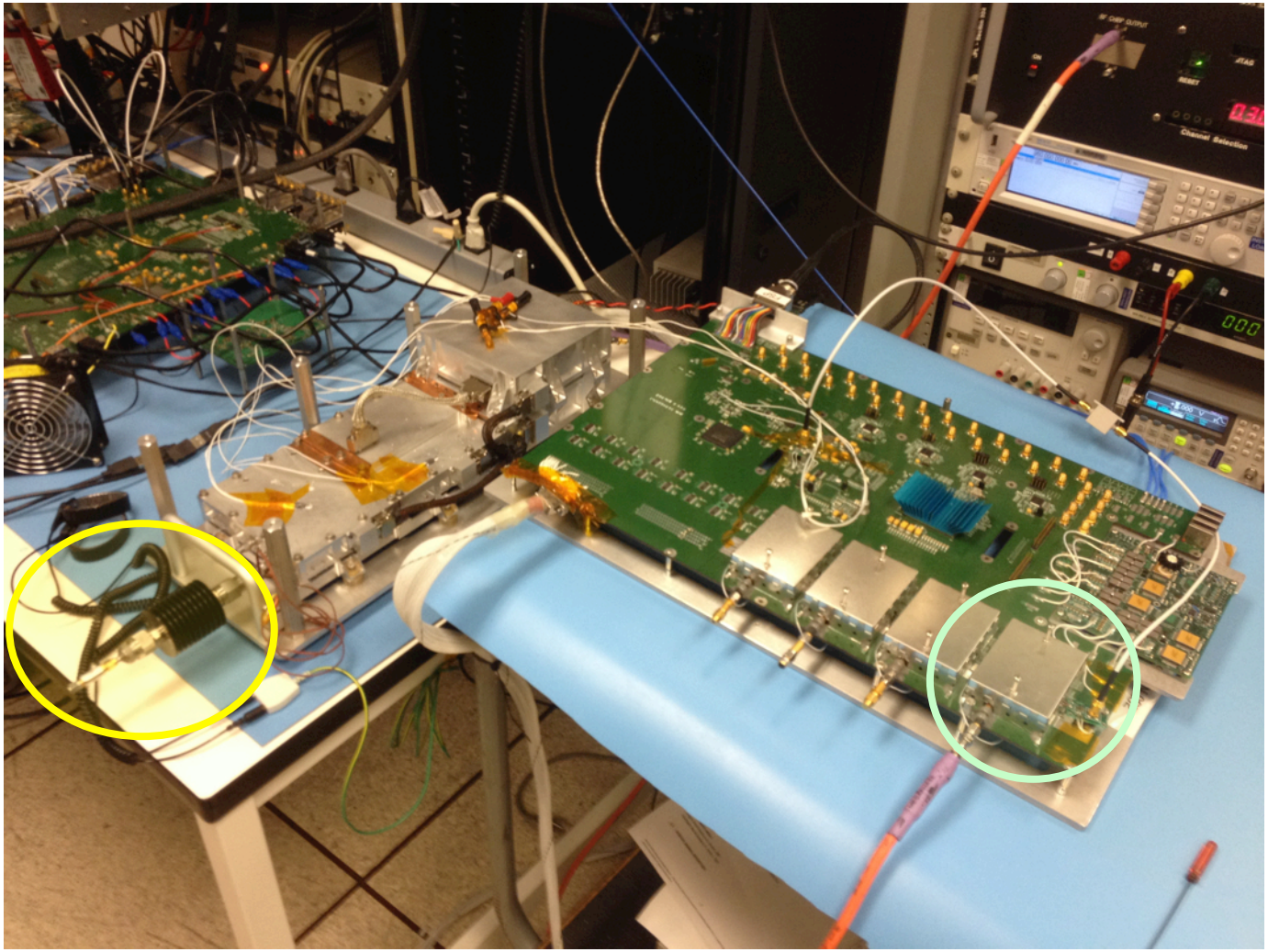


SweepSAR/Digital Cal “First Light”

Prototype SSP (Second Stage Processor)

Qual Model TRM

Antenna Port



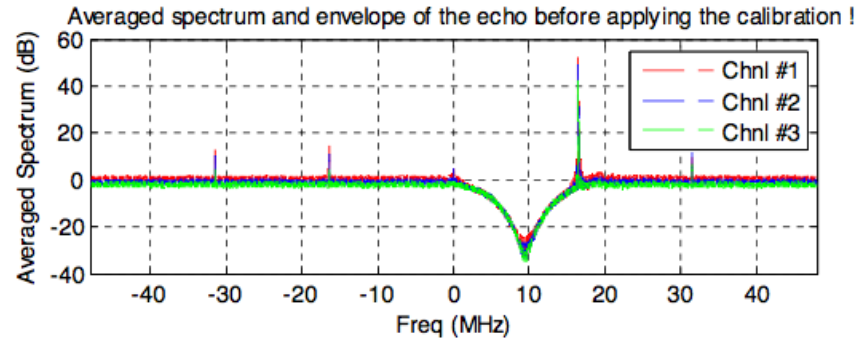
Breadboard Digital Waveform Generator & Upconverter

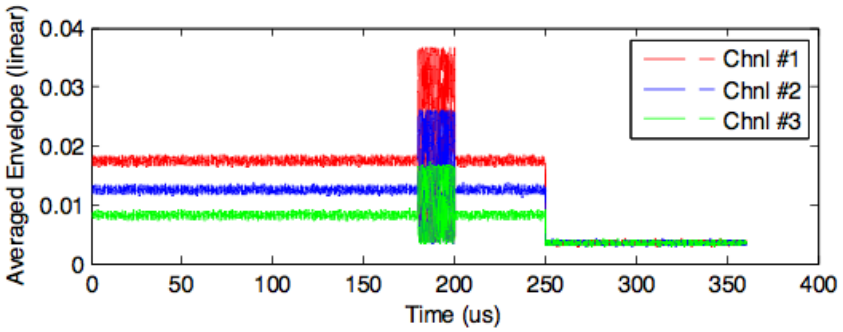
Prototype qFSP (quad-First Stage Processor)

1 of 4 ADCs

ESTO Earth Science Technology Office

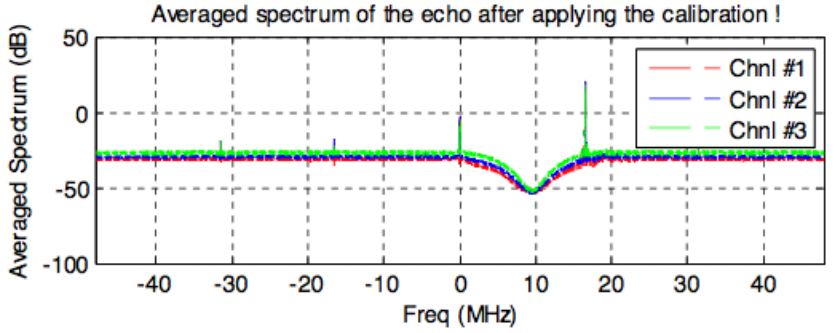
SIGNALS BEFORE AND AFTER RX CALIBRATION (POINT TARGET CASE)

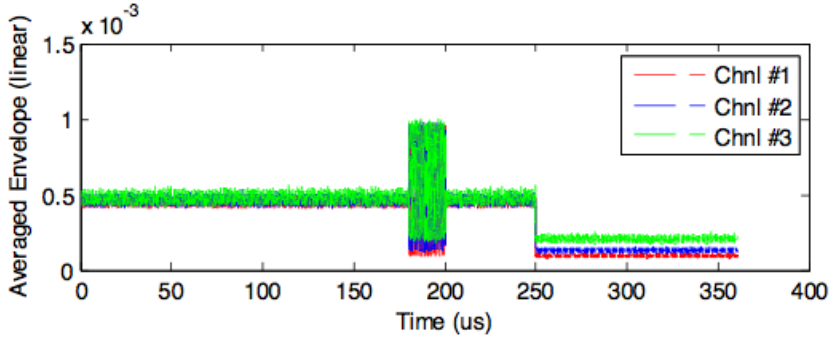




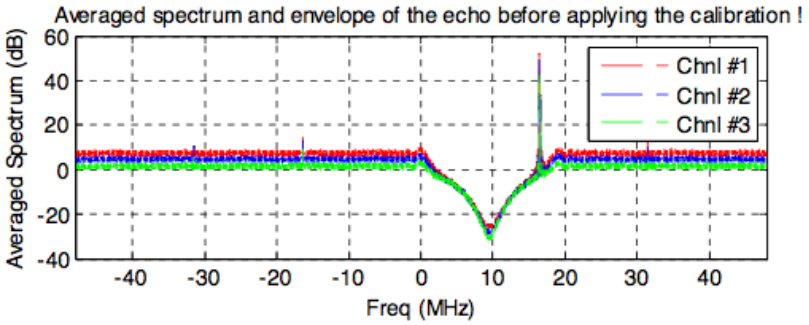
Spectrum and time-domain of digitally filtered signals **prior to** applying RX calibration for all channels!

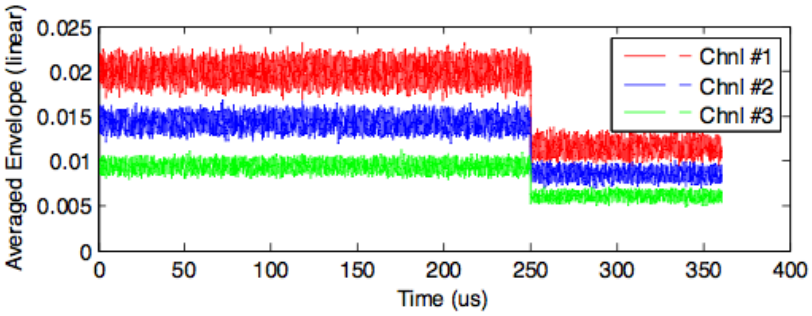
Spectrum and time-domain of digitally filtered signals **after** applying RX calibration for all channels!





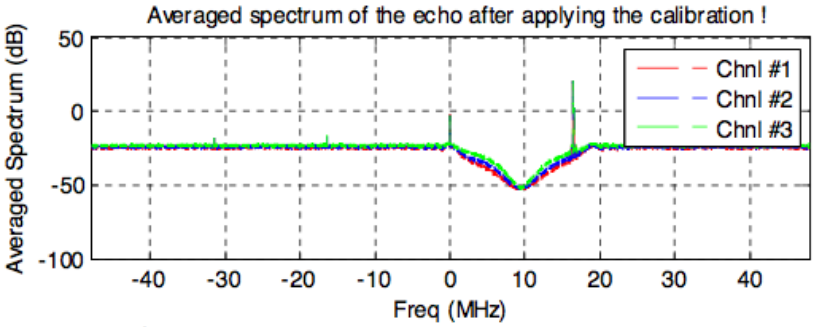
SIGNALS BEFORE AND AFTER RX CALIBRATION (DISTRIBUTED TARGET CASE)

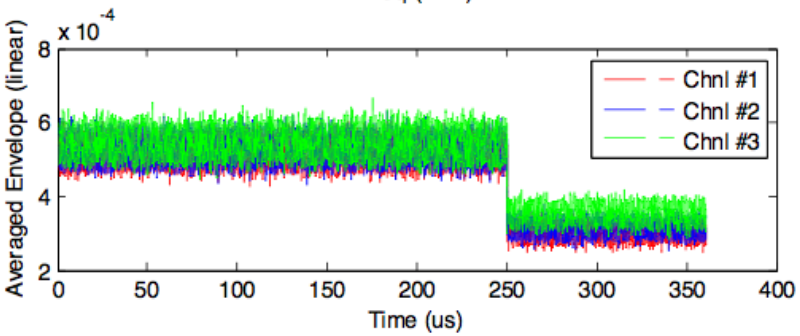




Spectrum and time-domain of digitally filtered signals **prior to** applying RX calibration for all channels!

Spectrum and time-domain of digitally filtered signals **after** applying RX calibration for all channels!

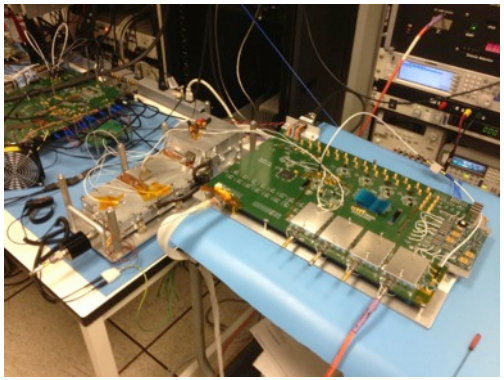




qFSP Real Time Processing

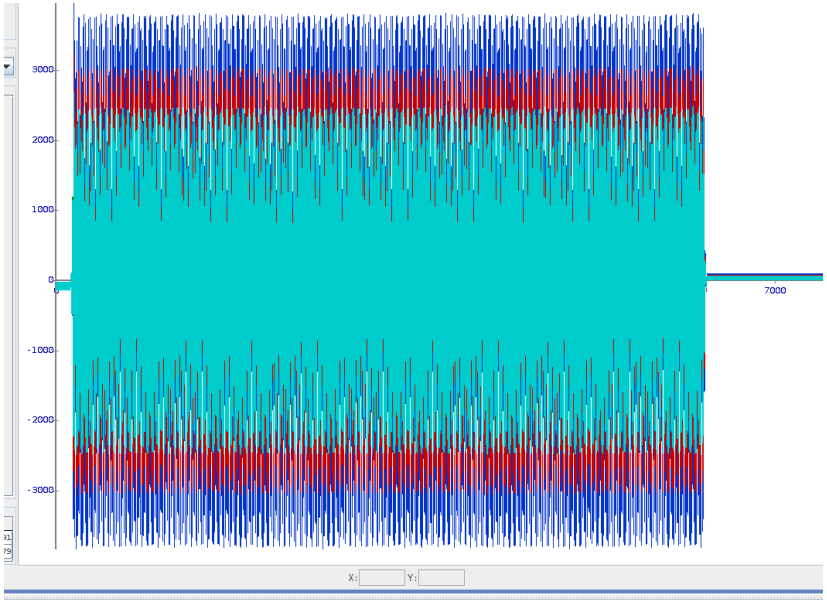
SSP

TRM

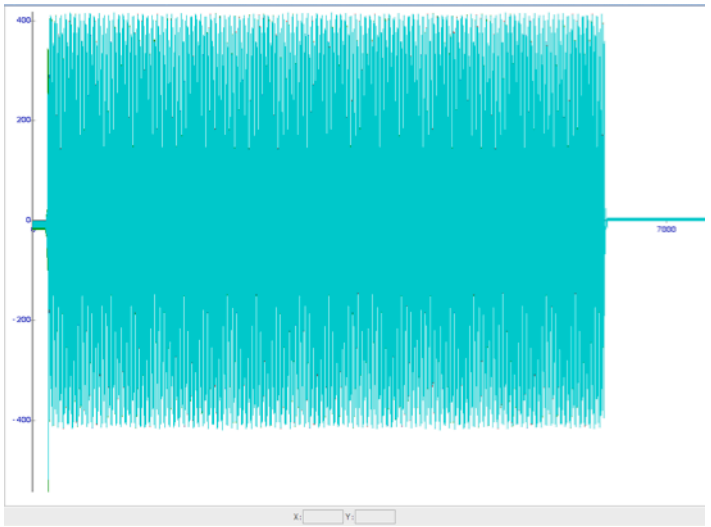


NISAR breadboard RF Backend

qFSP



Four channels in real-time (cal turned off)



Four channels calibrated in real-time