Configurable Reflectarray for Electronic Wideband Scanning Radiometry (CREWSR)

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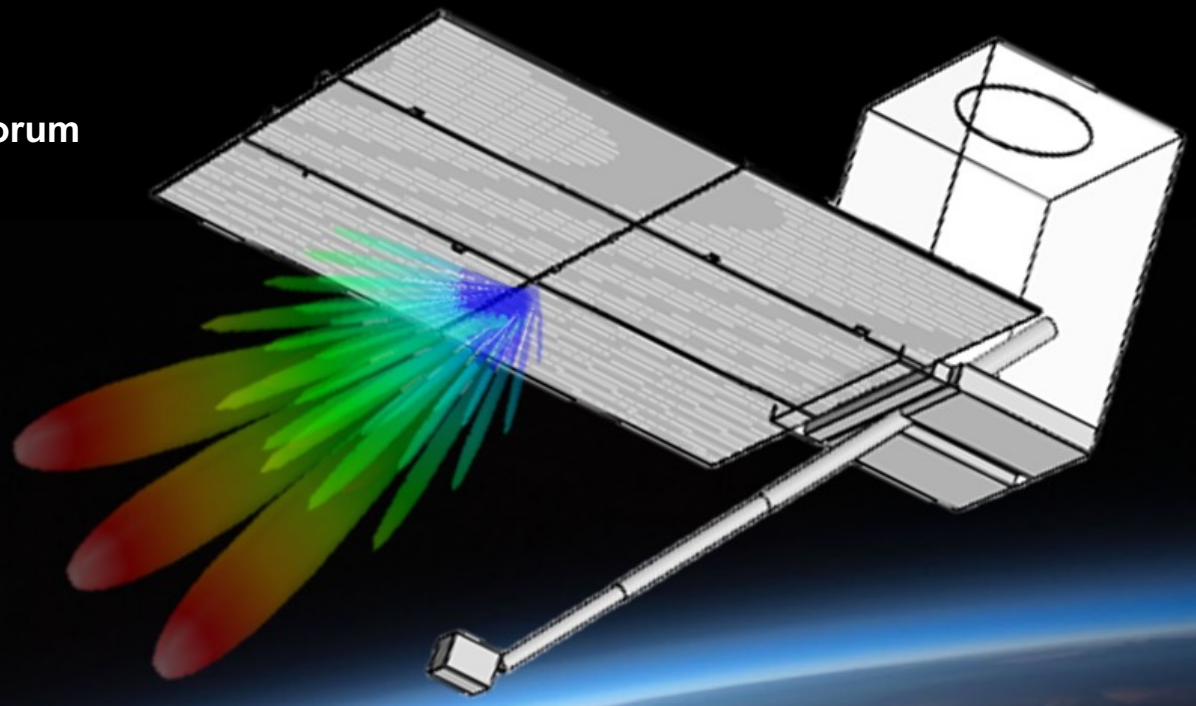

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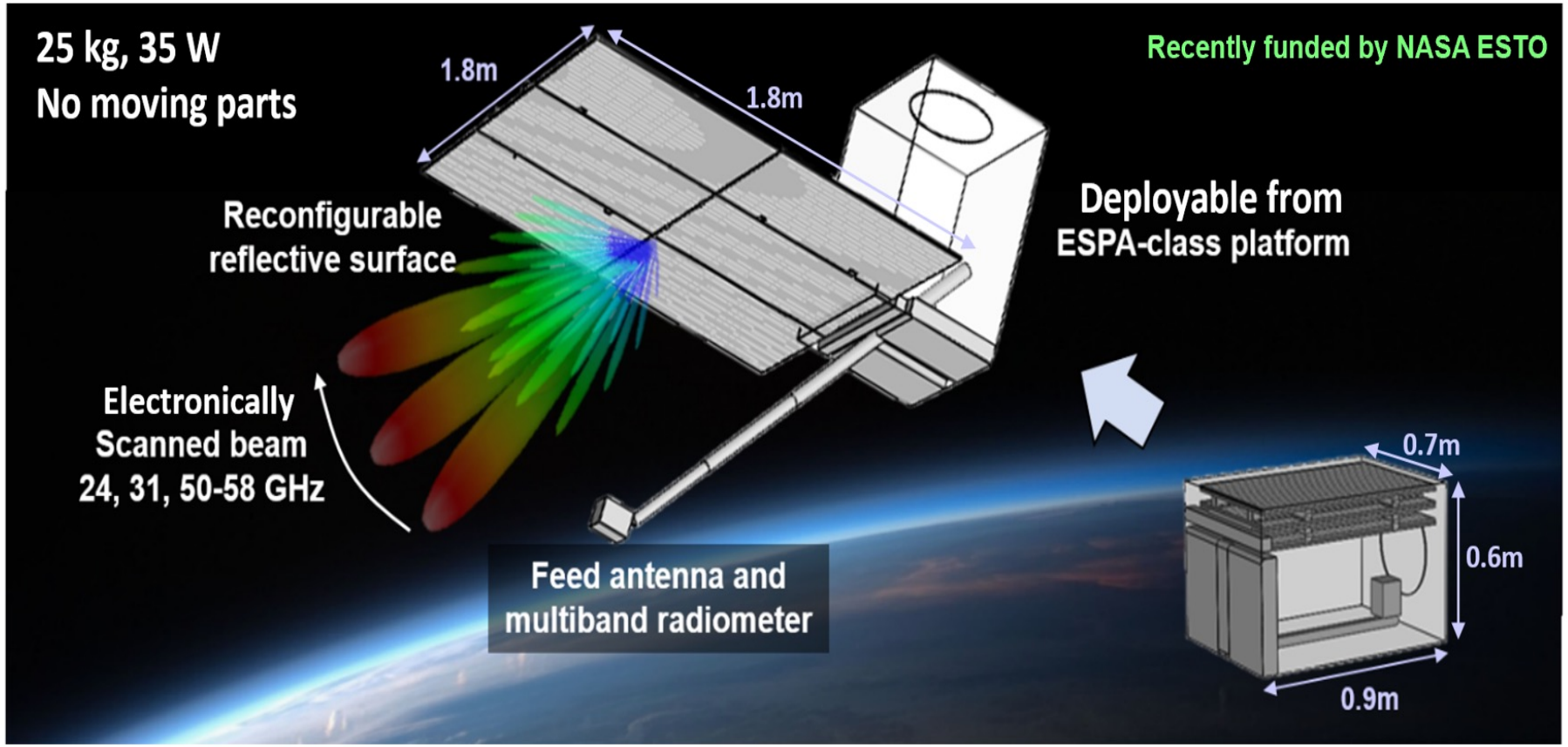
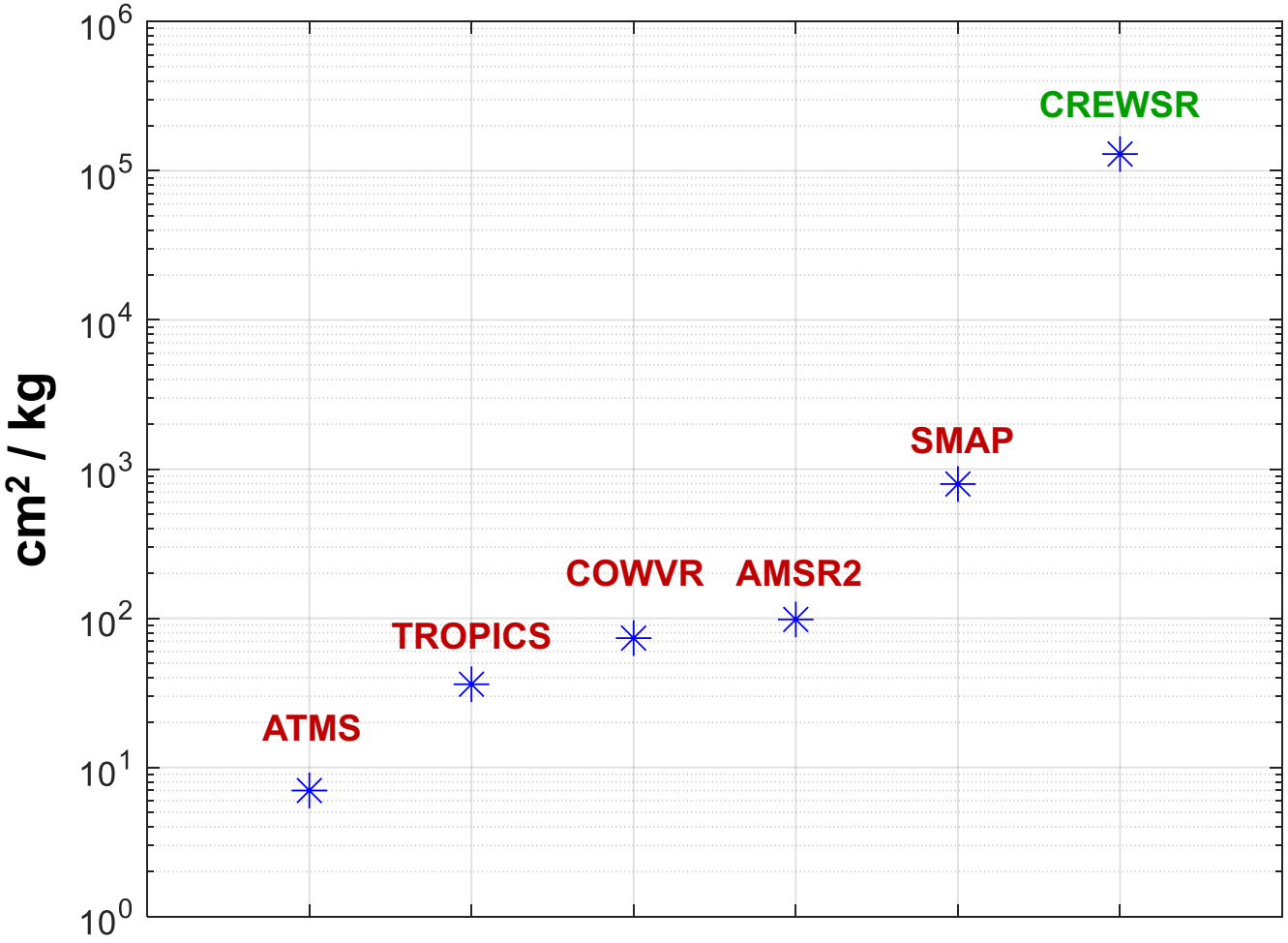


- Enables large apertures from SmallSats
- Agile beam pointing and resolution
- Software-defined spectral resolution/coverage
- Multiple spatial beams and spectral bands

ESTO IIP has funded a prototype of ONE sub-panel

Ratio of Aperture Area to Payload Mass



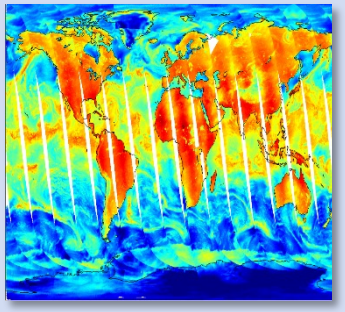
Mechanical Scanning

Electronic Scanning

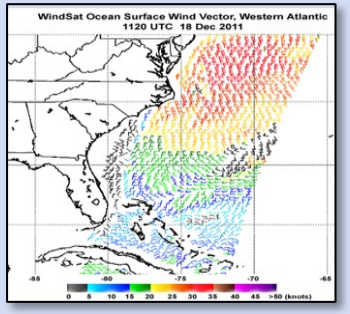
CREWSR Provides Improved Observing Capabilities Relevant to Many NASA Science Mission Areas

Earth Science

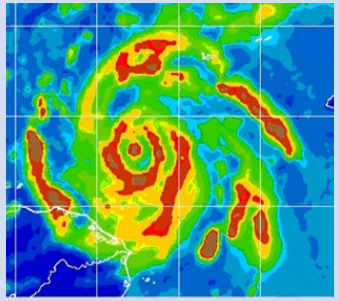
High-Resolution Atmospheric Sounding (23/31/50-58 GHz)



Wind Speed/Direction (10/18/36 GHz)

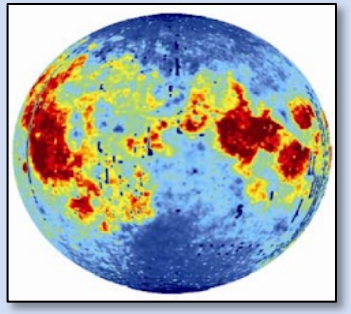


Polarimetric Imaging (37 GHz)



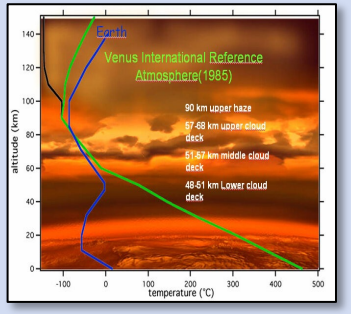
Planetary Science

Lunar surface mapping (1-5 GHz, polarimetry)



Mars wind sensing (100 GHz)

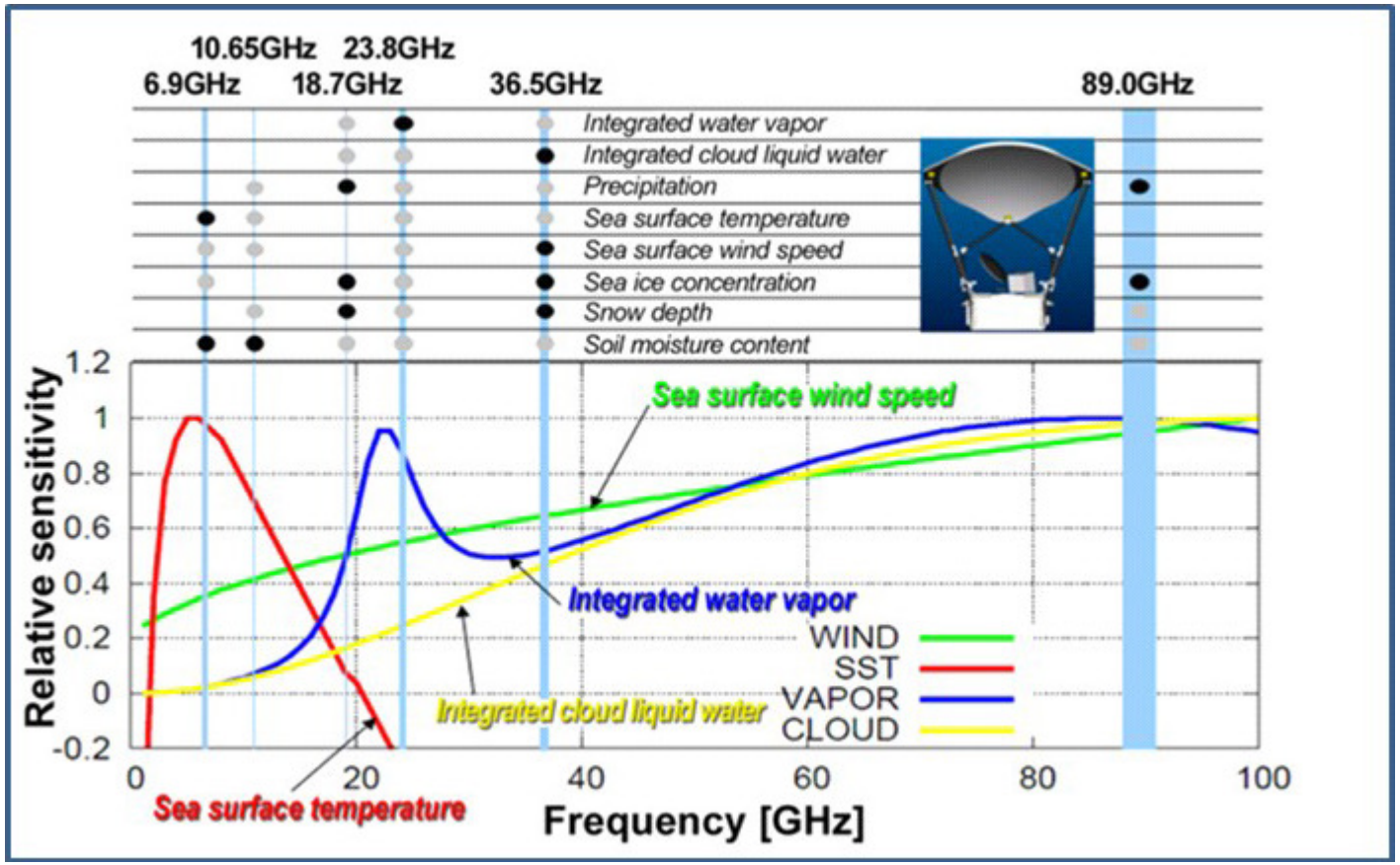
Thermal profiling
Venus: 20-60 GHz
Titan: 115 GHz



Heliophysics

Lower thermospheric winds (118 GHz)

CREWSR Band Selection:
23.8 and 31.4 GHz (water vapor) & 50-58 GHz (temperature)



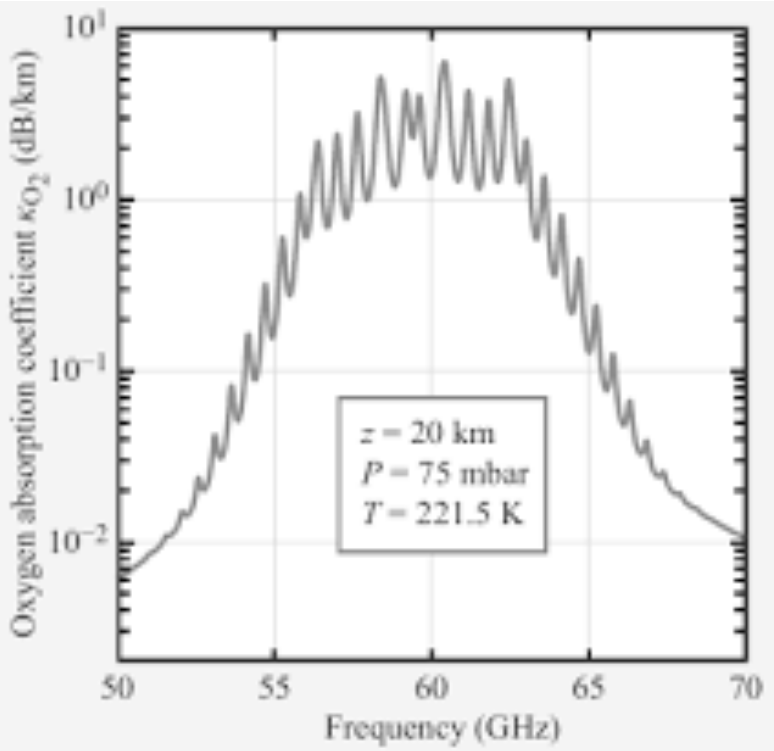
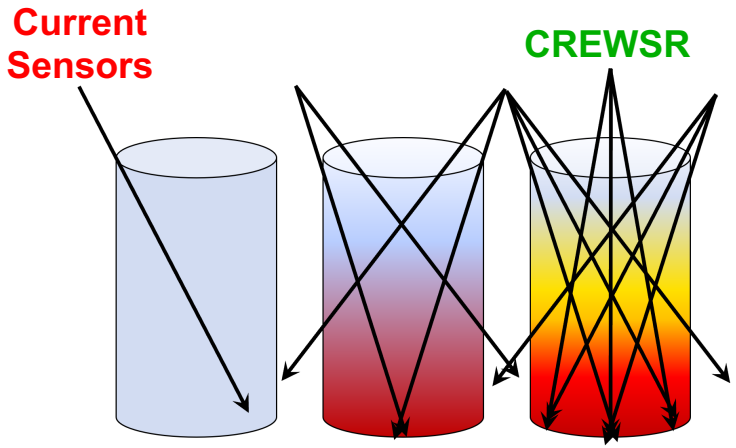
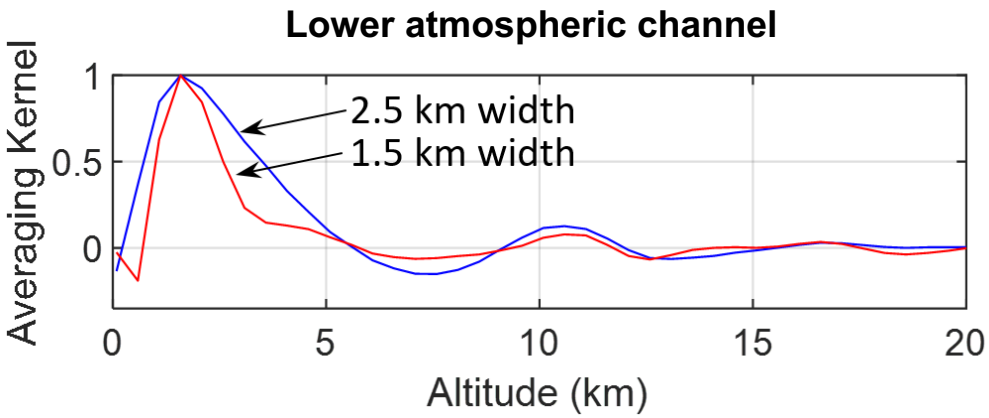


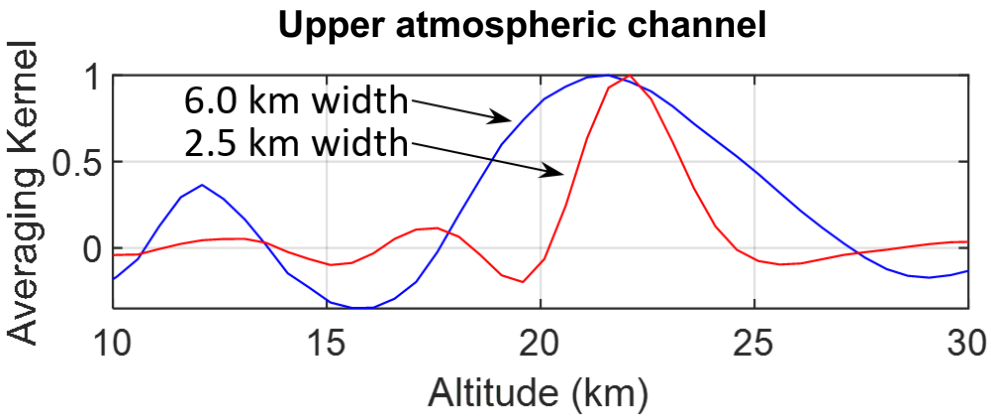
Figure 8-6: Absorption spectrum of the 60 GHz oxygen complex at an altitude of 20 km.

CREWSR supports (in principle) polarimetric sensing and RADAR

Agile Beam Pointing Enables Improved Vertical Sampling (Tomography) of the Atmosphere





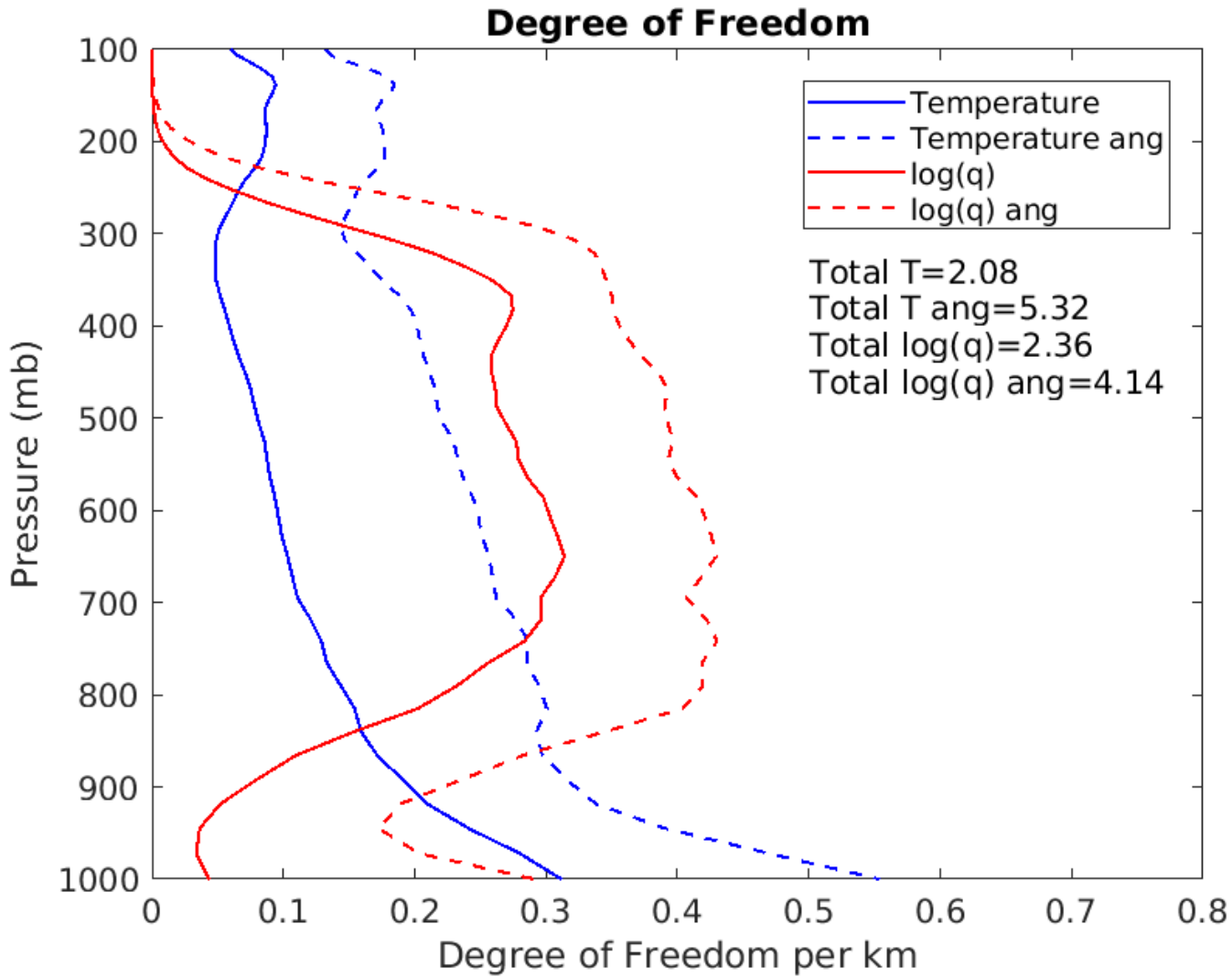


Traditional Sounder — Multi-Angle Sounder (PT-CREWSR)

2017 Decadal Survey calls out 1-km vertical resolution in PBL as a threshold requirement

ATMS: Slide provided by Zhenglong Li (UW)

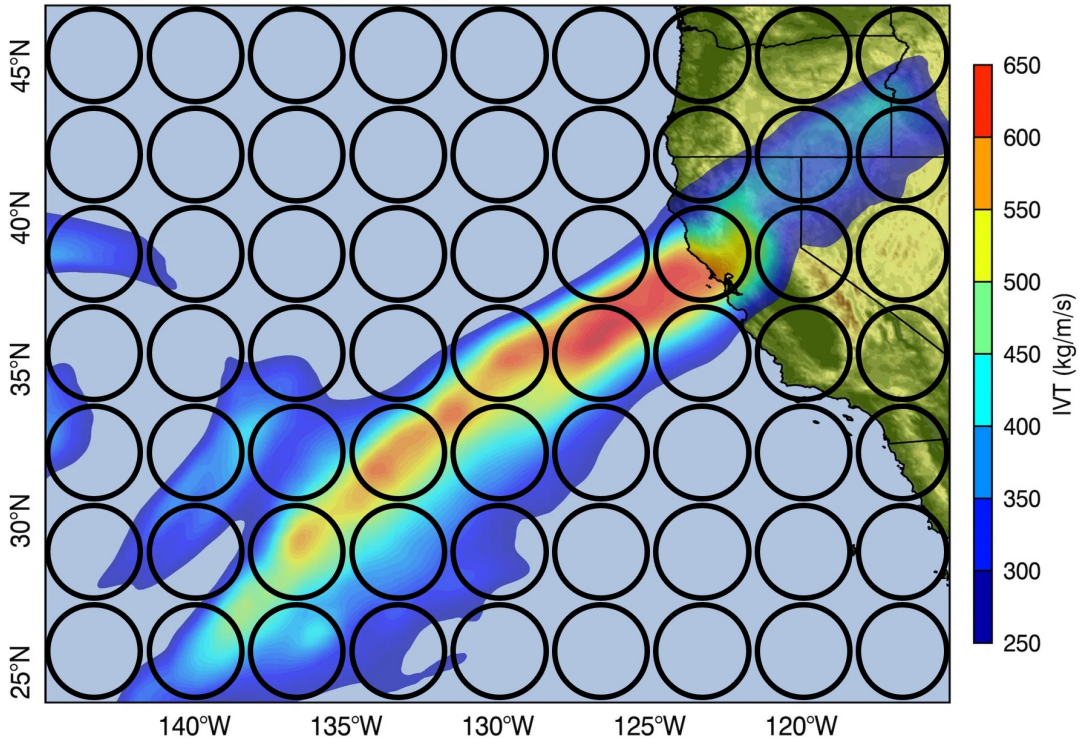
1976 US Standard Atmosphere



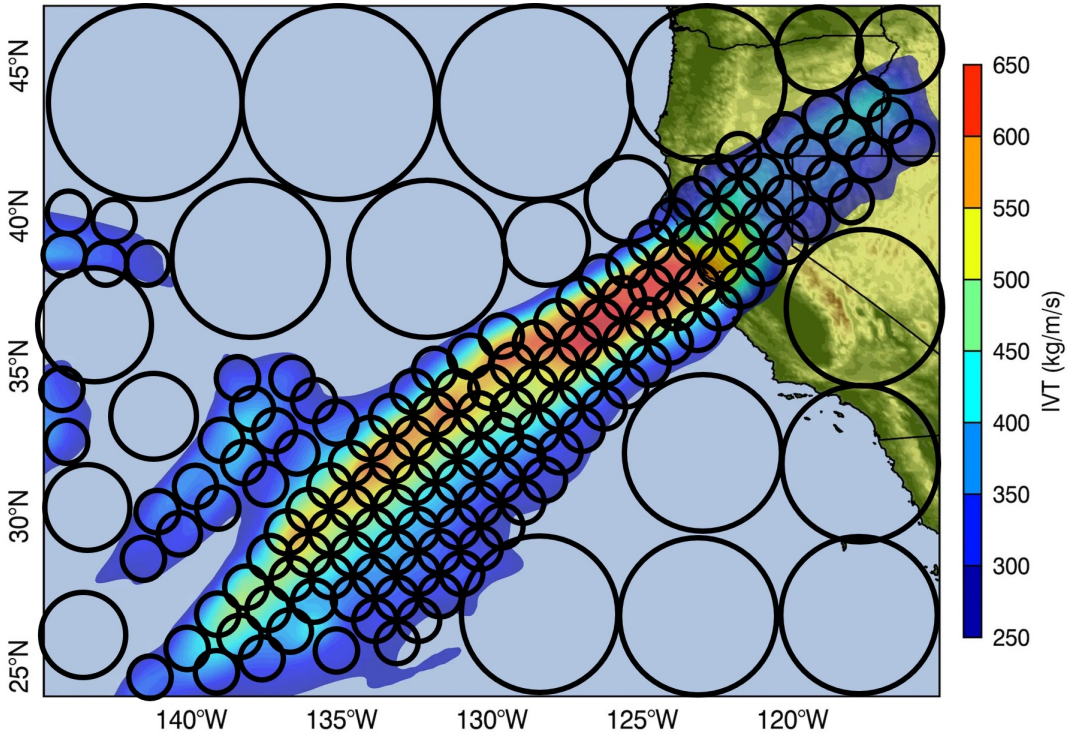
Solid lines: single angle (nadir);
Dash lines: multiple angles (11);

Agile Beam Resolution Enables Improved Horizontal Sampling of the Atmosphere

Current Sensors



CREWSR

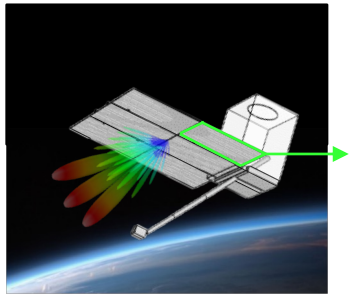


Observing System Simulation Experiment now in progress to assess and optimize CREWSR configurability benefits

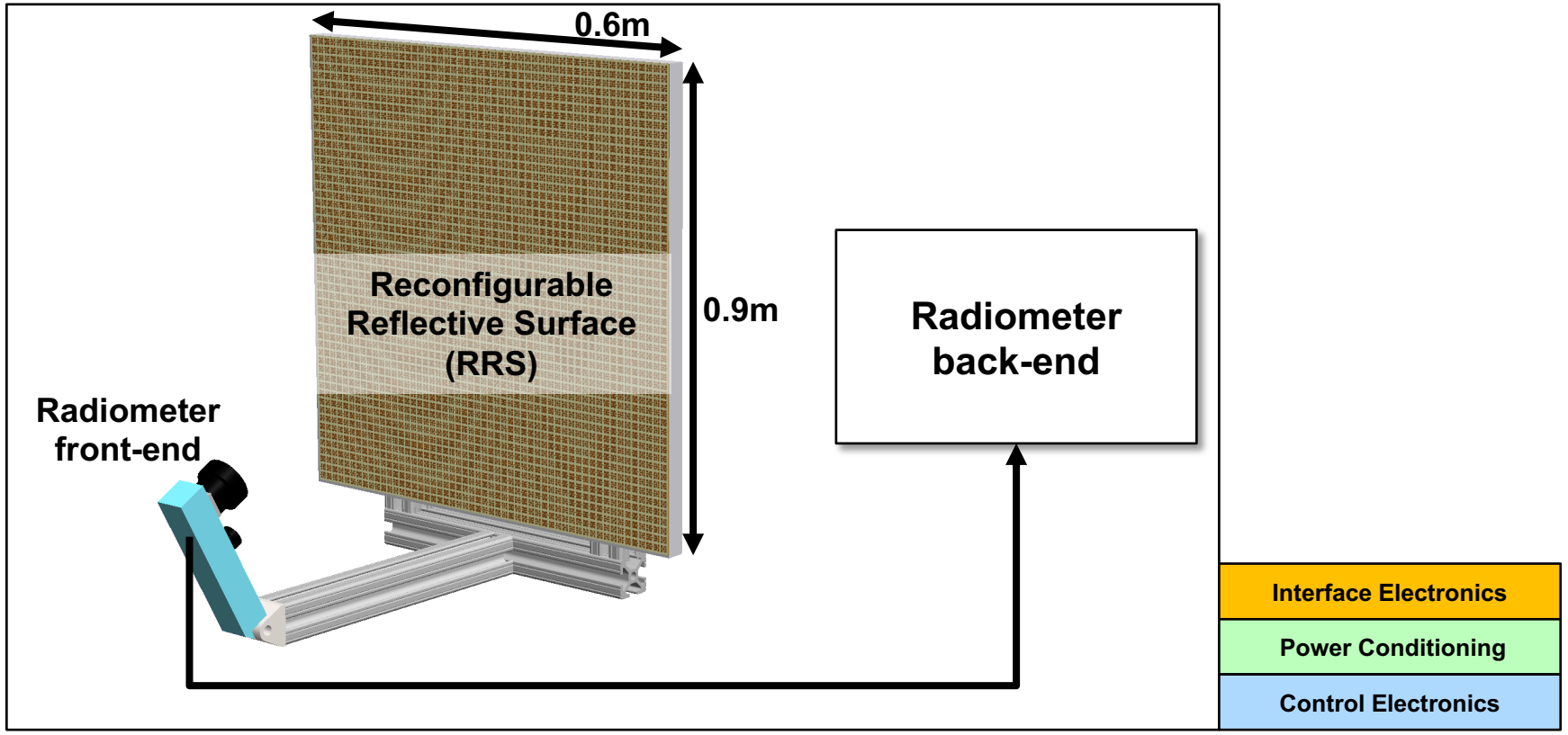
Prototype Instrument: PT-CREWSR

Program Objective: Realization and assessment of PT-CREWSR instrument

CREWSR

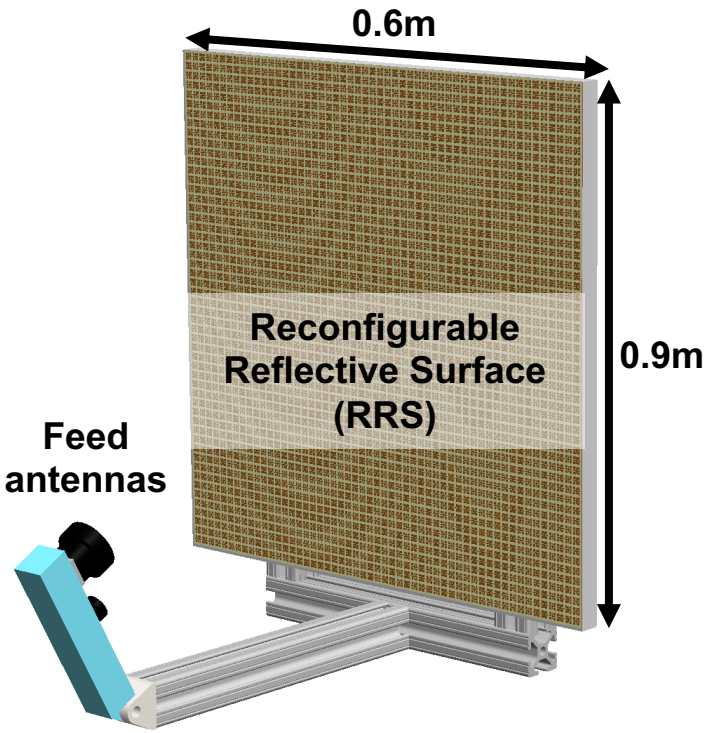


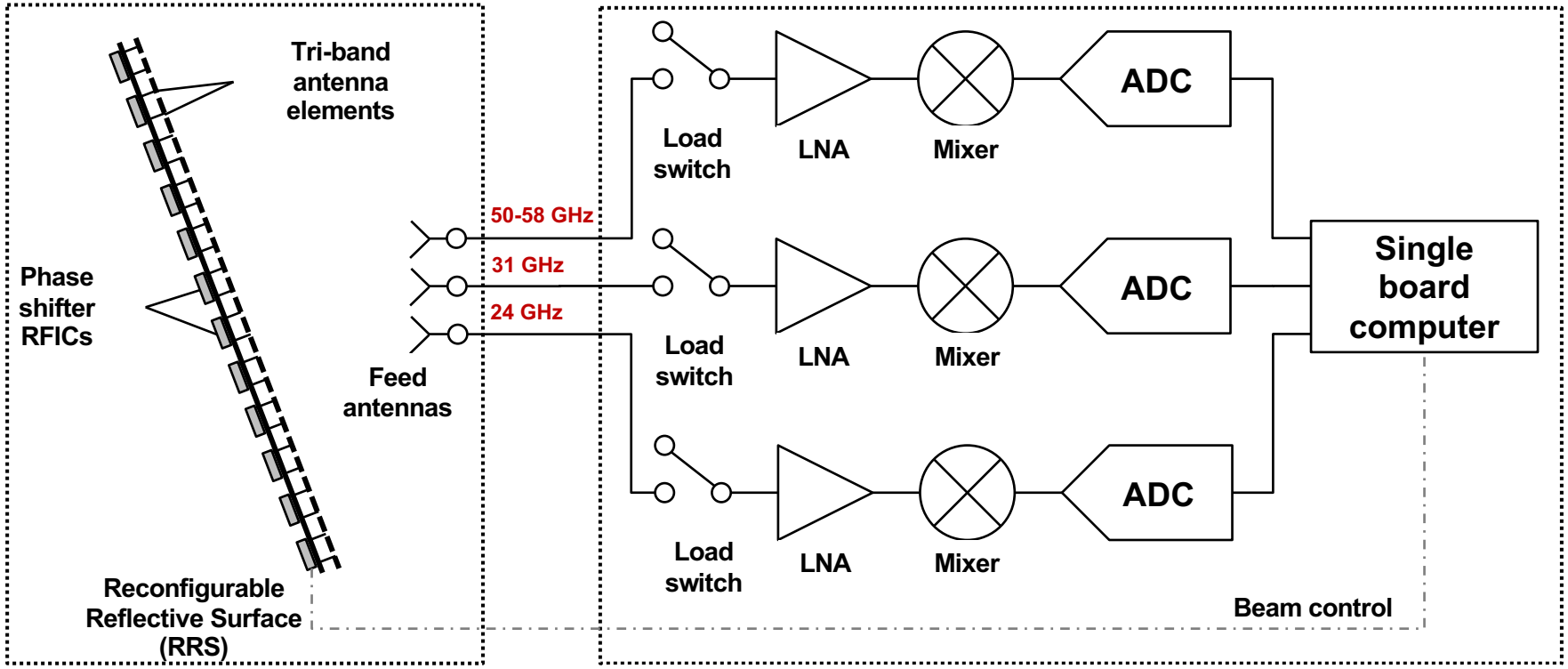
PT-CREWSR



Prototype Unit: PT-CREWSR Instrument

PT-CREWSR: 0.6m x 0.9m scanning reflectarray, brassboard radiometer, control, power supply, and interface electronics



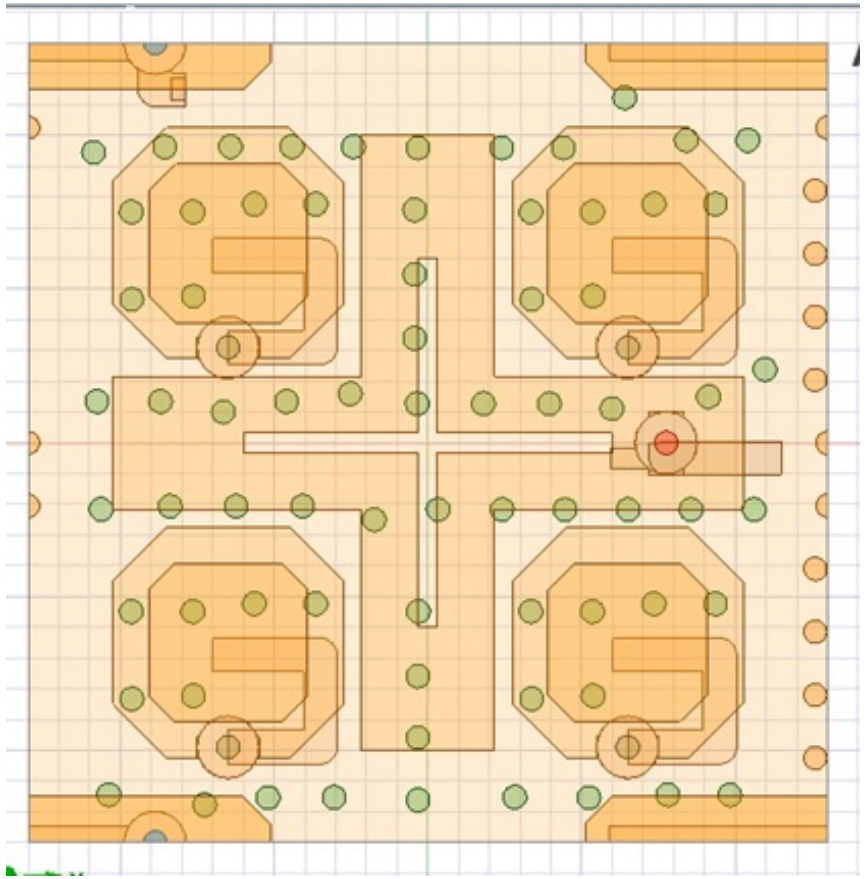


Scanning Reflectarray

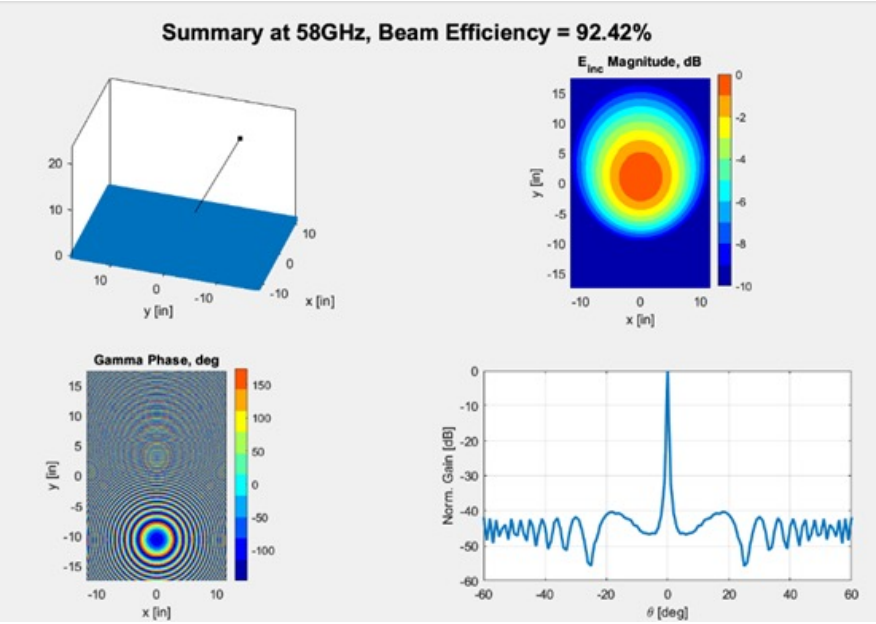
Electronically-calibrated radiometer

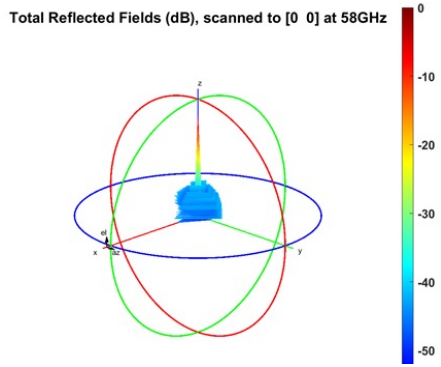
Antenna “Unit Cell”

Unit Cell Design



Unit Cell Reflection Performance



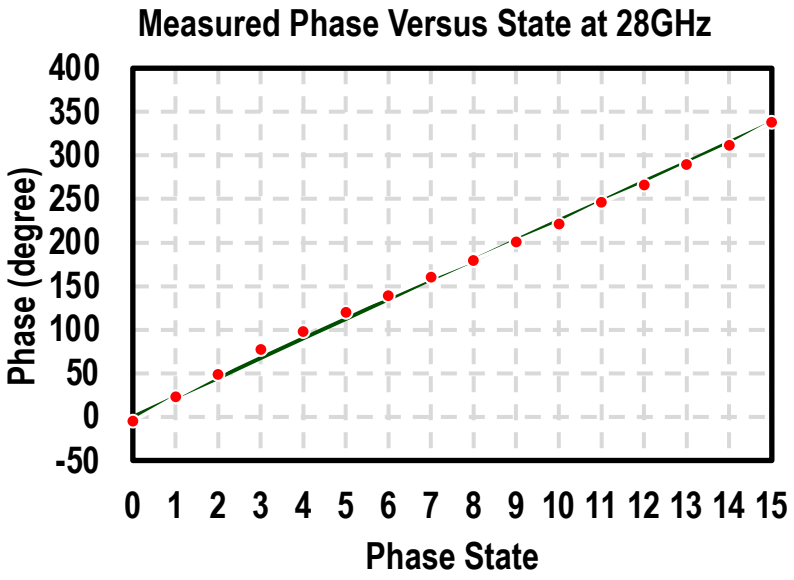


RFIC Measurements

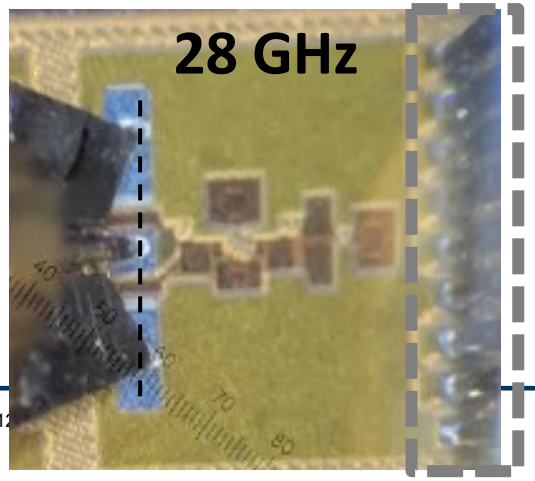
Developed by Univ. California, San Diego

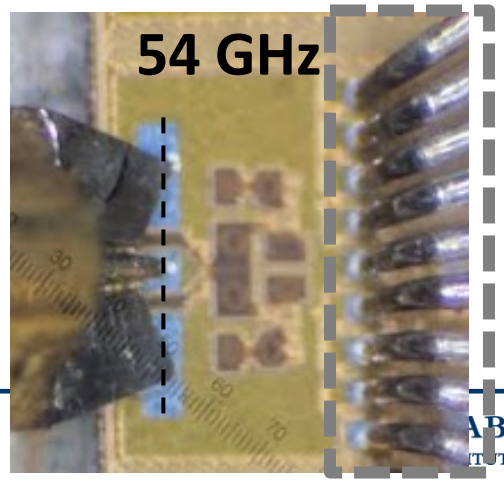
PNA-X (N5247A): 100MHz-67 GHz

Pout=-10 dBm



DC probing





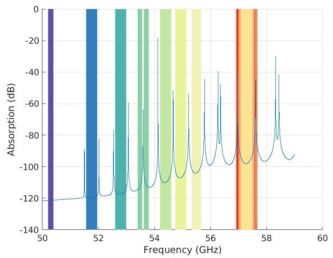
Summary of Progress (After Year 1 of 3): Key Performance Parameters

	Threshold	Objective	Current Status
Frequency bands	50-58 GHz	Low: 22-26GHz Mid: 31-35GHz High: 50-58GHz	23.6-24GHz 31.3-31.6GHz 50-58GHz
Beam Efficiency (co-polarized power within 2.5*HPBW)	90%	95%	Low: 83% Mid: 92% High: 90% (mean)
Aperture Size	0.3m x 0.3m	0.6m x 0.9m	Planned fabrication: 0.6m x 0.9m
DC power consumption per 6-channel RFIC	1.2mW	0.2mW	Mean: 1.2mW *
Phase shifter losses	4dB	3dB	RMS: 4-5dB *
Beam update rate	1 kHz	55 Hz	5 Hz (for system power estimates)

* Measured on first MPW (RF only)

CREWSR vs. State-of-the-Art (SOA)

- **CREWSR Advantages:**
  - **Temporal efficiency (τ)**
    - **25% "time on earth" = 6 dB / 2 = 3 dB**
  - **Spectral efficiency (B)**
    - **3.188 / 8 = 4 dB / 2 = 2 dB**



- **CREWSR Disadvantages:**
  - **RFIC loss (T_{RCVR})**
    - **4.0 dB**
  - **Antenna element loss (T_{RCVR})**
    - **0.7 dB**
  - **Radiometer RF switch loss (T_{RCVR})**
    - **0.7 dB**

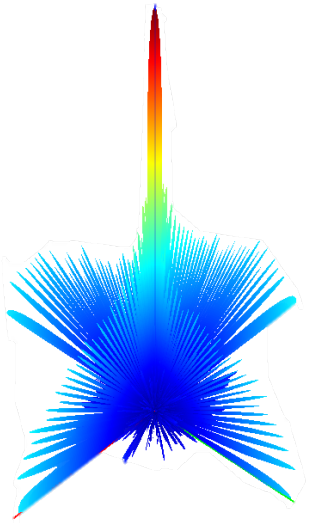
These "efficiency" and "loss" terms effectively cancel: CREWSR will offer noise performance at least as good as SOA, but with much LARGER APERTURE and ELECTRICALLY STEERED BEAM

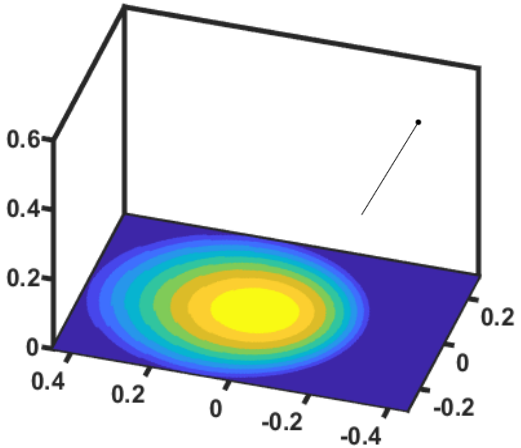
$$\text{NEDT} = \frac{T_A + T_{RCVR}}{\sqrt{B\tau}}$$

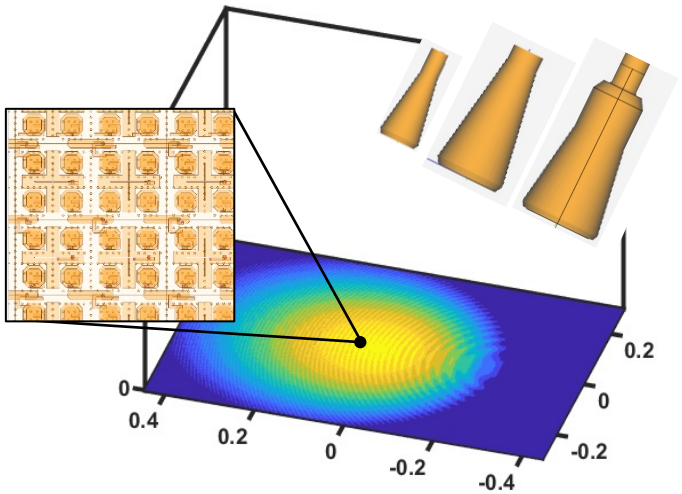
Summary of Array Simulation Results

Frequency Band	Directivity	HPBW	Beam Efficiency, Idealized	Beam Efficiency, Antenna Fields Modeled
Low (24GHz)	44 dBi	1.1˚	95%	83%
Mid (31GHz)	47 dBi	0.8˚	94%	92%
High (mean over 50-58GHz)	51 dBi	0.5˚	95%	90%

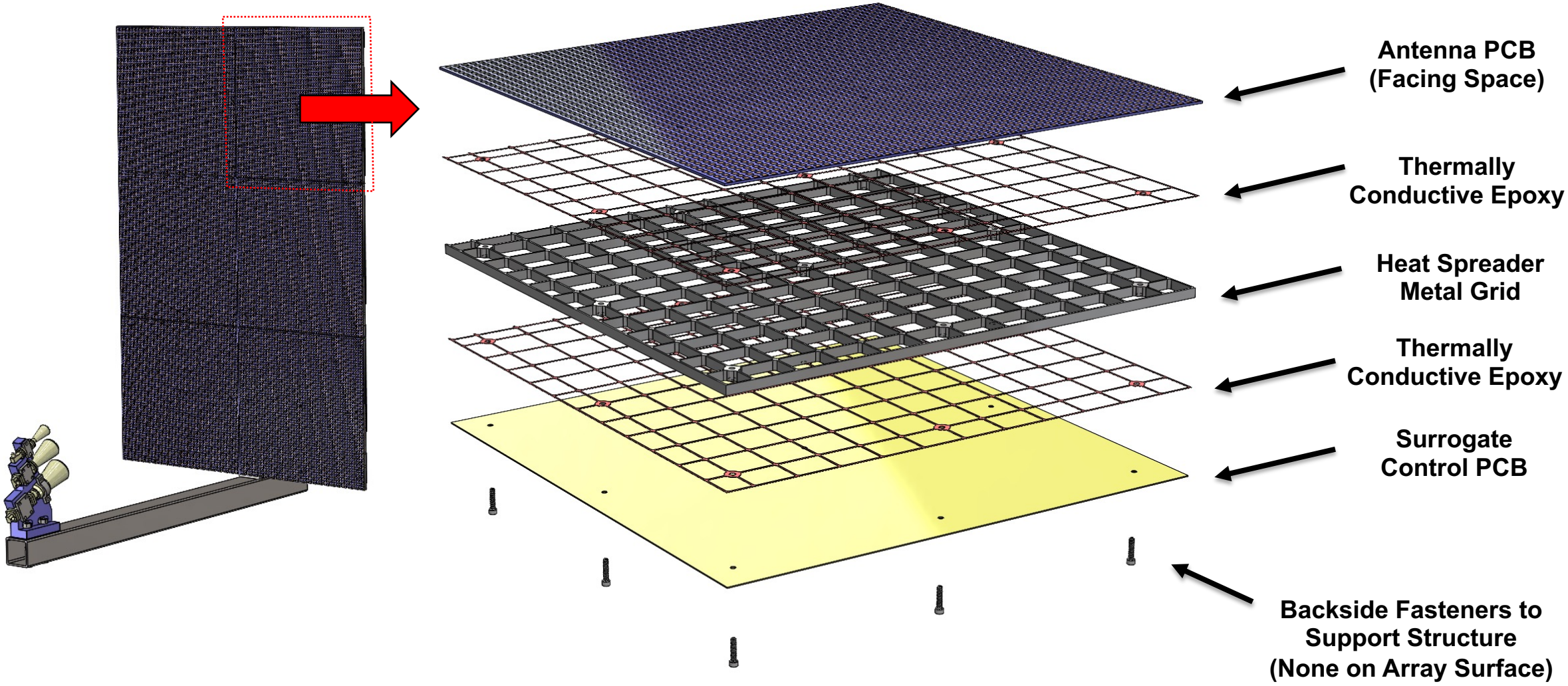
- Idealized model: point sources for array, $\cos^{15}$ taper for feed horns
- Model with antenna fields: includes simulated fields for feed horns, phase and amplitude response for "infinite" array





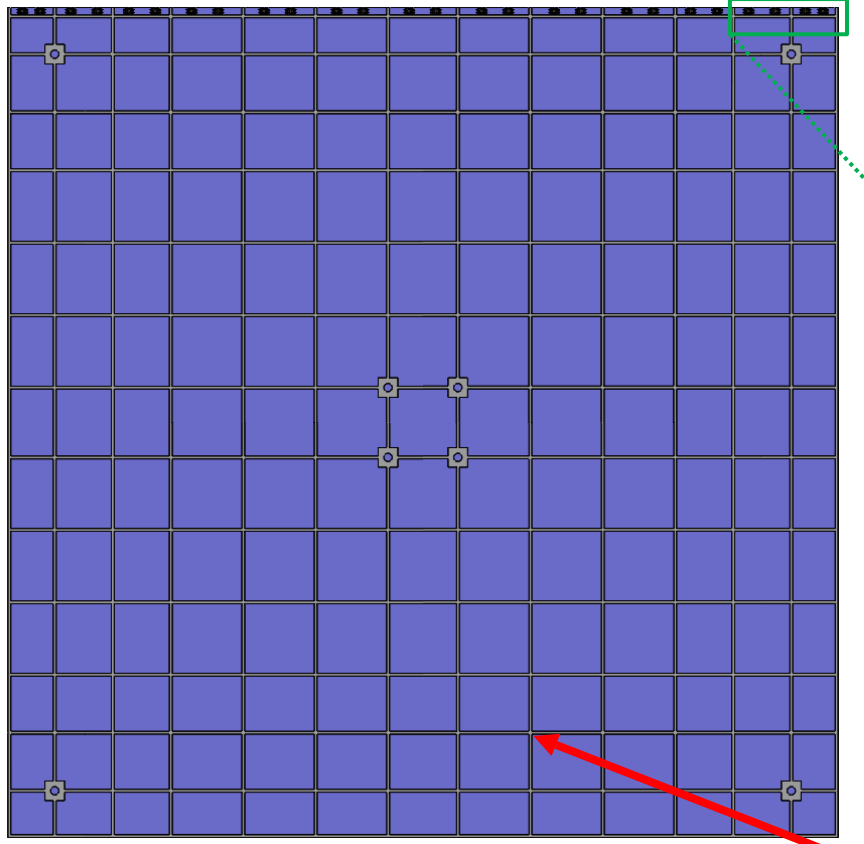


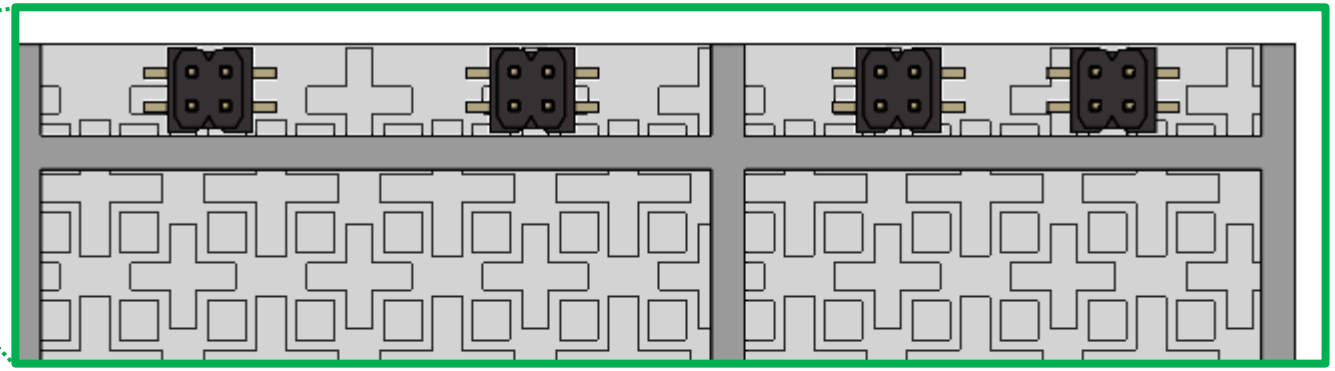
Exploded View of Fixed Beam CREWSR Subpanel



Structural-Thermal Grid Design

Antenna PCB Non-Radiating Side





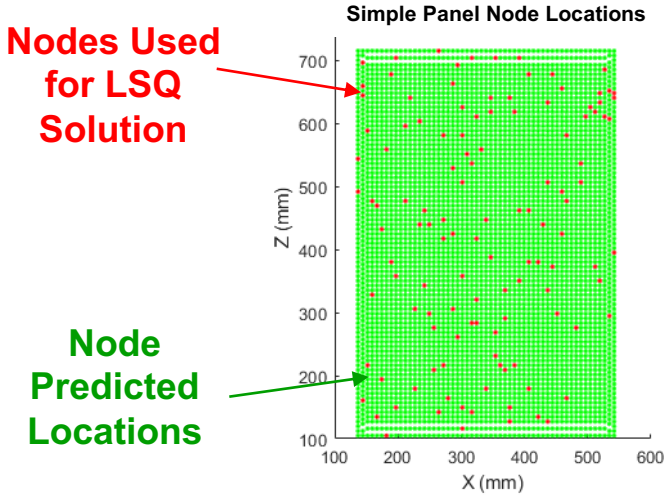
Antenna PCB
Metal Grid
Control PCB

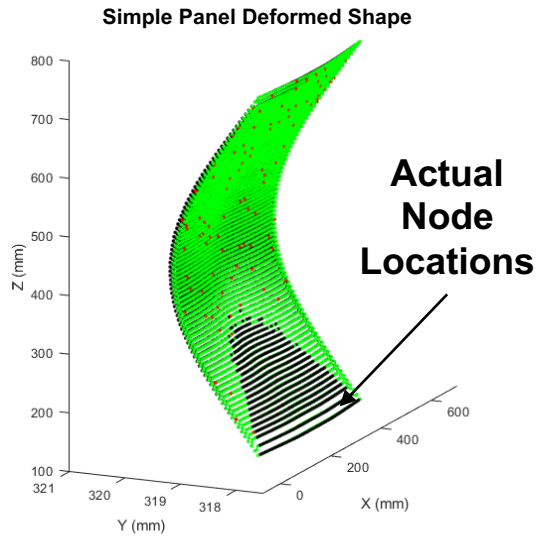
Heat Conductive
1mm Wide Metal Grid
Bonded to Antenna PCB

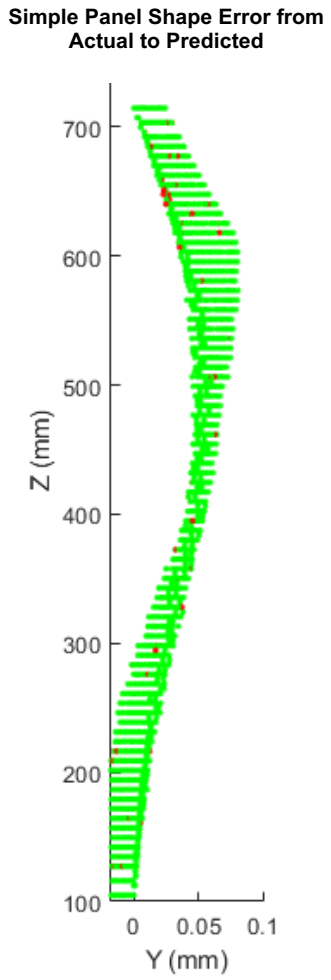
- Antenna PCB and Control PCB connected across grid via pin headers
  - Using 2x2 SMT headers with 1mm spacing
- Headers located on one tile edge
  - Accessible after assembly for rework
  - Minimal impact on structural symmetry
  - Located to minimize line length impacts from antenna control electronics

Deformation Monitoring for Calibration

- **Fiber Bragg Grating (FBG) strain sensors:**
  - **Past work shows promising results**
  - **Limited by 1 micro-strain minimum resolution**
    - **Borderline to detect 0.25mm RMS deformations**
    - **Shape prediction accuracy degradation**
  - **Temperature dependence**
    - **Investigating athermal mounting fixture**
  - **May require dozens to hundreds of sensors to achieve desired accuracy**
- **Can we use temperature instead?**
  - **Shape deformations on orbit are thermally driven.**
  - **Full field measurements possible with cameras**
  - **CTE deformation is linear**
    - **Superposition applies -> Valid for LSQ approach**
- **Other approaches to investigate**
  - **Combination of first two bullets**
  - **Regression techniques**







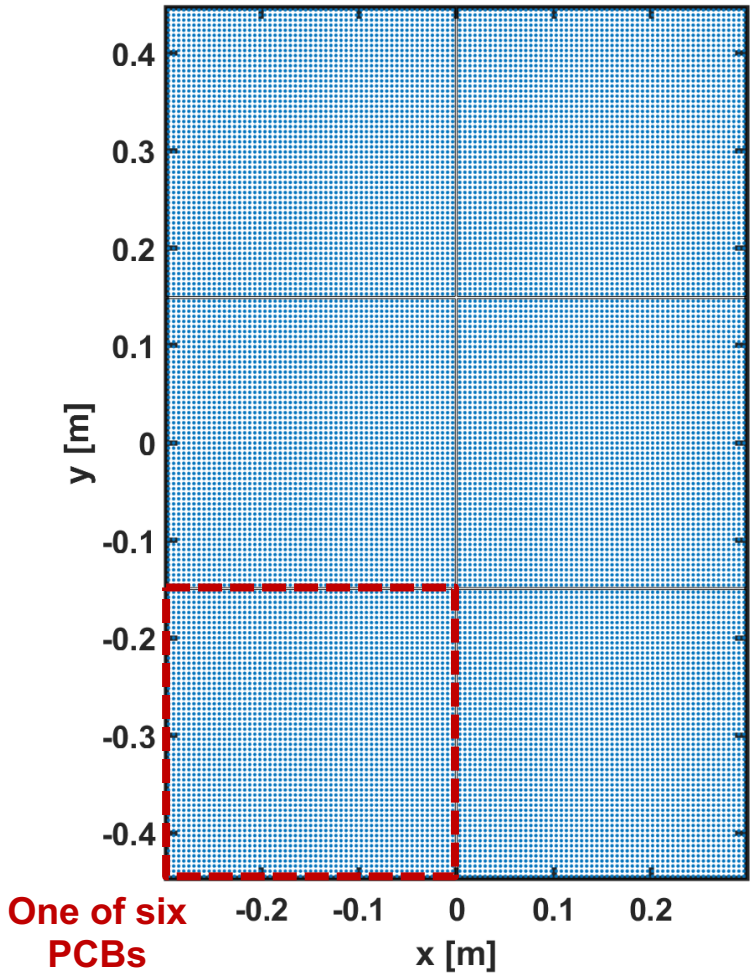
Fixed Beam Array Antenna Development

Current Status

- Updated stackup to reduce complexity and cost
- Preliminary PCB layout complete
  - 6 boards + backups
  - Risk reduction: fabricate a single board and test on frame to verify expected pattern
- Simulated performance using Ansys HFSS + Circuit
- Evaluation of expected levels of beam efficiency using antenna model

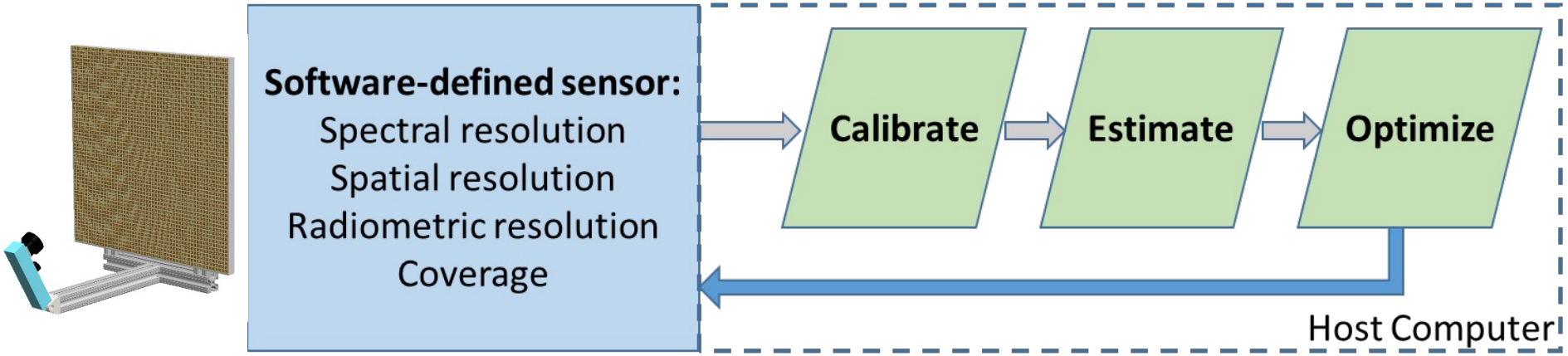
Next Steps

- Design review of antenna to move forward with fabrication
- Finalize layout/oversee fabrication
- Update test plan



Sensor-in-the-Loop Testbed to Enable Versatile, Intelligent, & Dynamic Earth Observation (VIDEO)

NASA AIST 2021 Project



Sensor-in-the-Loop Testbed to Enable Versatile, Intelligent, & Dynamic Earth Observation (VIDEO)

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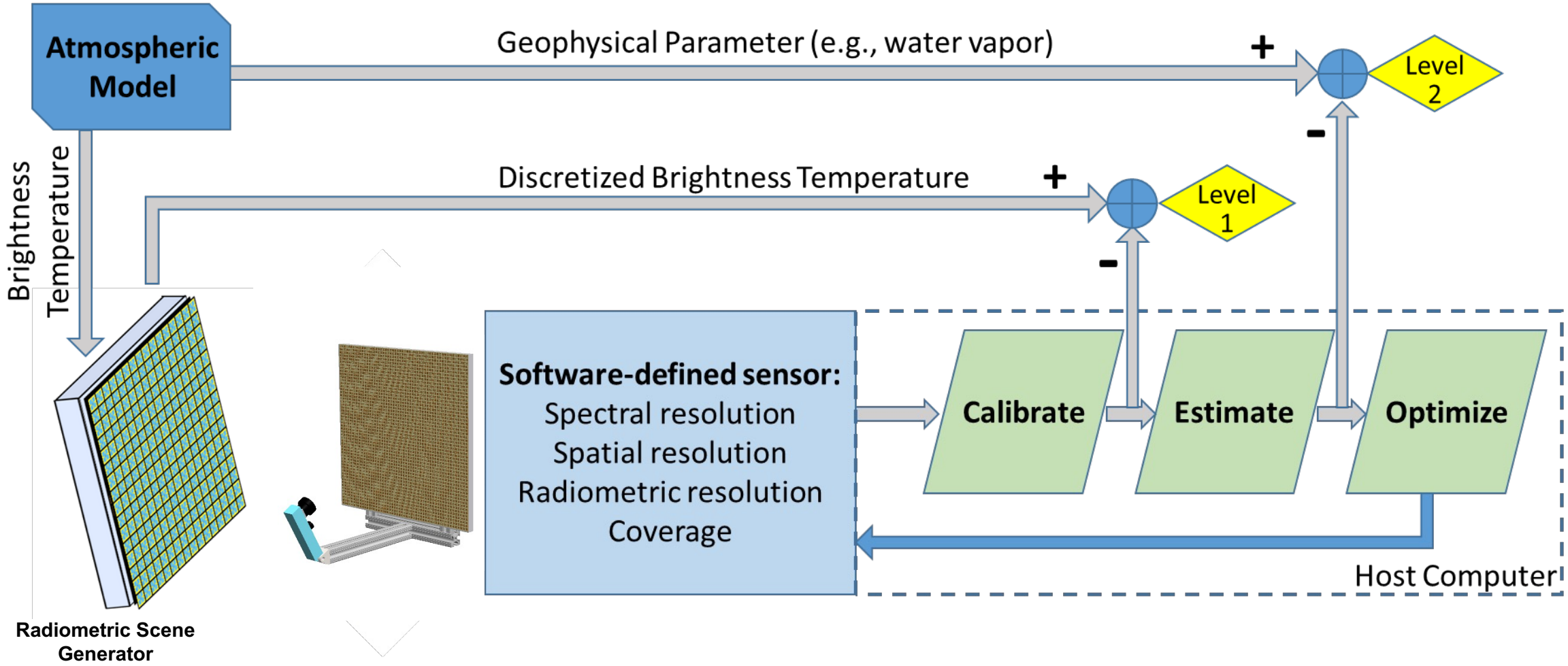


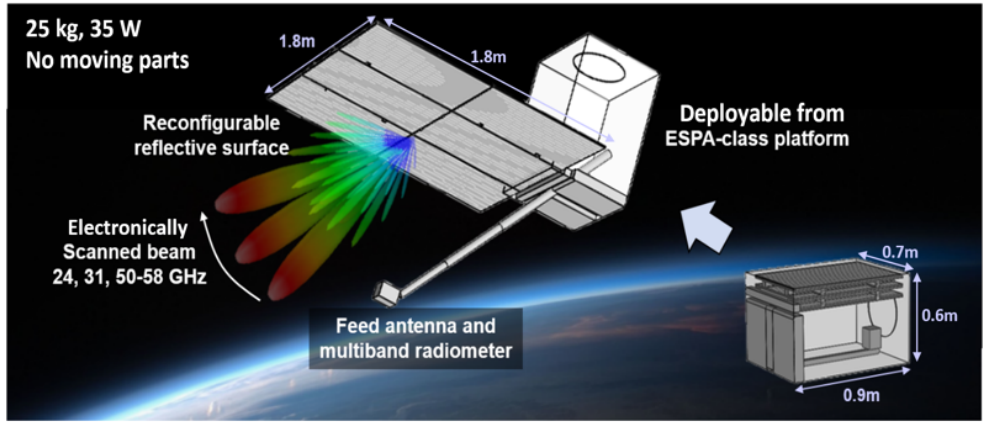
New laboratory testbed system would permit full closed-loop testing of a reconfigurable sensor

Configurable Reflectarray for Electronic Wideband Scanning Radiometer (CREWSR)

PI: William Blackwell, MIT Lincoln Laboratory

Objectives

- Develop and test the PT-CREWSR instrument to enable very large, lightweight, deployable apertures from a small satellite in low-earth or geostationary orbit (relevant to many missions)
  - 24, 31, 50-58 GHz operation; single 0.6x0.9m panel (one of six needed for the full CREWSR instrument)
  - High-resolution, lightweight, low-power, multiband scanning radiometry instrument based on deployable scanning reflectarray
- Performance goals: > 95% beam efficiency, < 3 dB phase shifter loss, 10 W/m2 DC power consumption.
- Technologies include: low-loss, low-power reflective phase shifter RFIC in 45RFSOI process; multiband reflectarray antenna element, multiband radiometry receiver/feed module.



The full CREWSR concept is depicted above. The prototype (PT) PT-CREWSR instrument proposed here will include one (of six) panels shown above and the tri-band feed. A MIT LL internal R&D program has already proven the mechanical viability of the six-panel scheme.

Approach

- Develop, integrate, and test the PT-CREWSR instrument
- Reflective phase shifter RFICs, realized with 45RFSOI process for optimal RF and DC power performance
- Multiband reflectarray antenna, realized in low-cost, lightweight PCB proven by MIT LL internal R&D program
- Multiband radiometer feed module, realized with proven COTS components for low risk and cost
- Test reflectarray antenna patterns in anechoic chamber, radiometric performance in thermally-controlled chambers
- Emerge from program ready to scale to full CREWSR sensor

Co-Is/Partners: William Moulder, Cara Kataria, Christopher Galbraith, R. Vincent Leslie, Sungeun Jeon (MIT LL); Gabriel Rebeiz (UCSD)

Key Milestones

✓ Award start (kick-off meeting held 5/9/2022)	04/22
✓ System requirements review	09/22
✓ Successful fab/test of first RFIC chip design	03/23
• Fixed beam antenna array developed	07/23
• Array control breadboard development	07/23
• Radiometer design	04/24
• Production fabrication of RFIC (TRL3)	06/24
• Scanning array assembly	01/25
• PT-CREWSR instrument functionally tested (TRL4)	02/25
• PT-CREWSR instrument thermally tested (TRL5)	04/25

$TRL_{in} = 2$

$TRL_{current} = 2$

$TRL_{Out} = 5$

Backup Material

Power Estimation at 5 Hz Beam Update Rate

Major Contributor	Max Power Consumption (mW)
Microchip ProASIC3	129
Oscillator	24
RFIC	86
Voltage Translation (Qty 5 per RFIC Group)	5

- **Very conservative power estimation based on 1% duty cycle**
  - **Duty cycle is percent of time that IOs are toggling**
  - **A high FPGA resource utilization is assumed at 10MHz**
- **First revision of control board will be heavily analyzed for power consumption and additional refinements will be included in second board revision**
- **Example power reduction techniques in consideration**
  - **Centralized power conversion to minimize conversion loss**
  - **Centralized oscillator at lower frequency and operating voltage**
  - **Hibernation modes for FPGA as well as lower IO voltage**

Estimated Max Power (W)	
RFIC Group*	0.28
Single Panel	3.4
6-panel Array	20.2

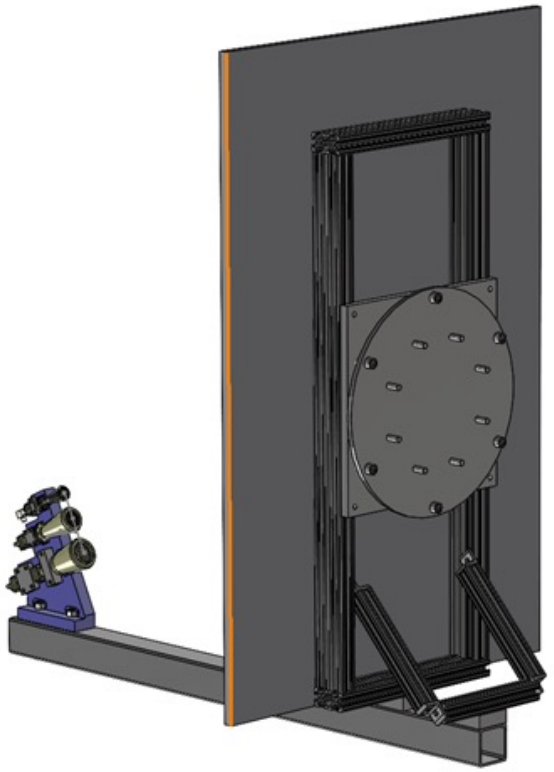
*Power supply efficiency take into account

Initial Prototypes

- **Fixed-beam array will assess**
  - Multiband antenna element
  - Feed horn antennas
  - PCB stackup
  - Mounting fixture
- **Array control breadboard will assess**
  - Control scheme/components
  - Interface S/C to bus

PT-CREWSR, without the RFICs

- **Phase shifter RFICs (MPW run, UCSD) will assess:**
  - Performance of preliminary RFIC design



Requirements and Design Challenges

Requirements

Parameter	Value	Unit
Circuit Board Area*	30 x 30	cm
Phase Shifters Per Sub-Panel*	3249	-
Number of Sub-Panels Per Array*	6	-
Beam Parameter Update Rate	5	Hz
Maximum SPI Frequency	50	MHz
Max SPI Chain Length*	16	-

Constraints

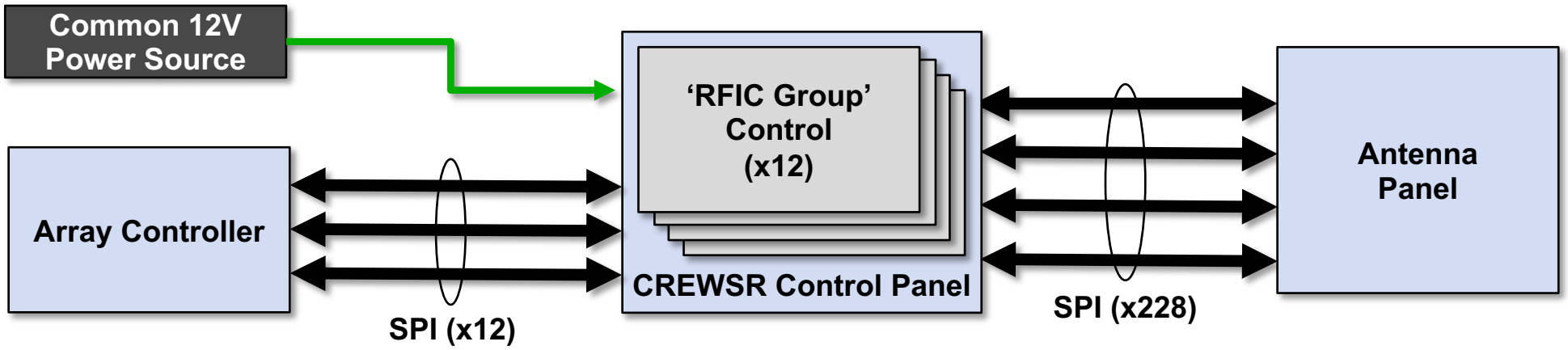
Parameter
Path for full radiation tolerance desired
Shock/Vibe Requirements restricts chip package types
Power Consumption must be minimized

Design Challenges:

- Large number of IO required for single panel control
- Industry wide high lead time for components (~52 weeks)**
- Limited radiation tolerant (RT) controller options

*Change from SRR
**Alternate, In-Stock, Parts Found

Panel Level Control Architecture

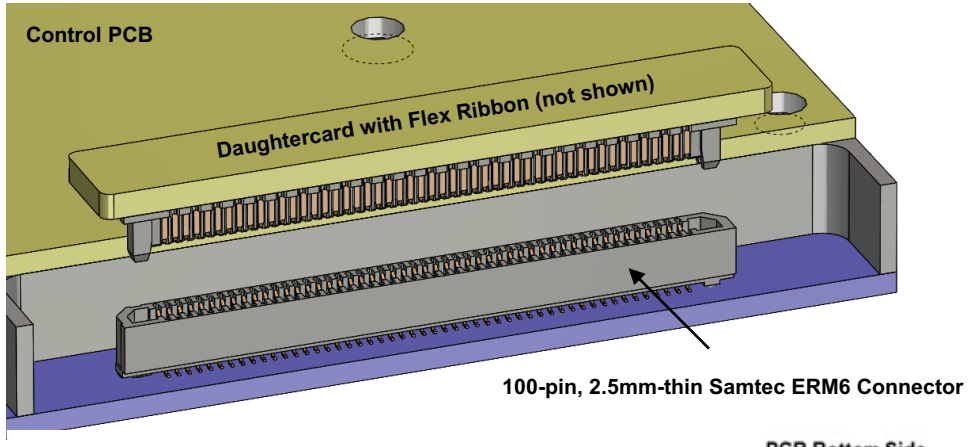


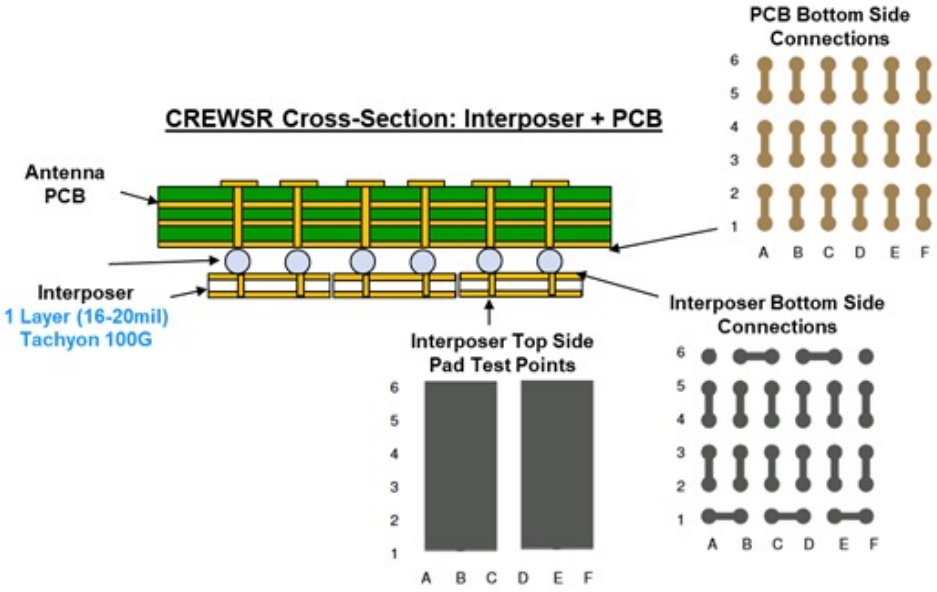
- **Single power rail**
  - Can be adjusted in 3-16V range with BOM change
- **Array Controller**
  - Sends commands over SPI to each individual 'RFIC Group'
  - Different topologies are being investigated to reduce SPI line count
- **Control 'RFIC Group'**
  - 12 on a single CREWSR panel
  - Each responsible for power and control of 19 SPI chains for RFICs (max 285 RFICs)
  - A unique panel location coordinate is set using rotary hex dip switches
  - Commands from controller interpreted using look up table
- **Antenna Panel**
  - Control in clusters of 19x14 or 19x15, limited by SPI chain maximum length
  - Power and commands received over a set of 12, high density, high pin count, low-profile board to board connectors

Surrogate PCB & Interposer Status

Current Status

- Preliminary design of interconnection between antenna & control PCB
- Component selection complete
- Updated frame and grid design to accommodate plan-of-record connectors and RFIC/interposer placement

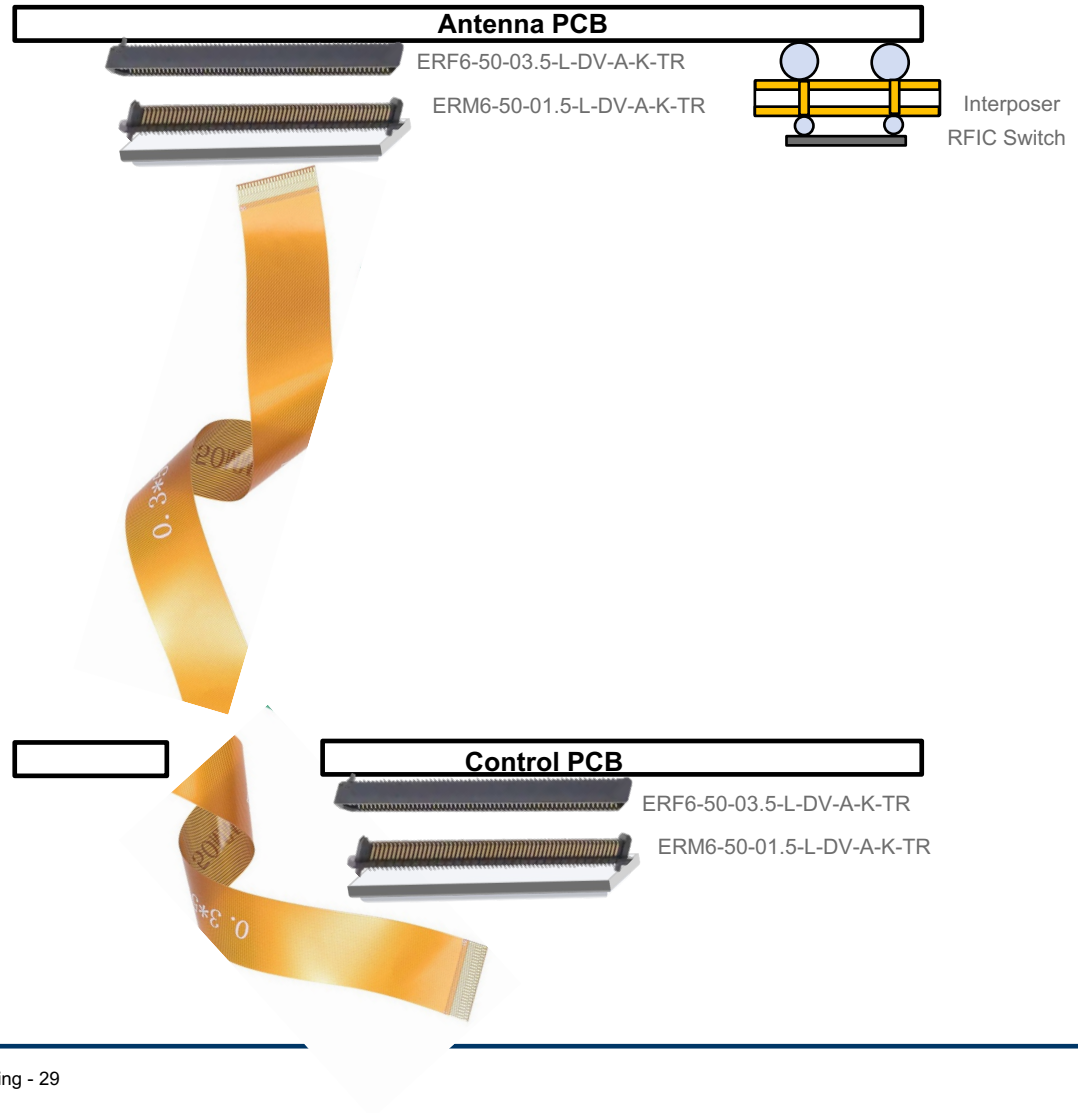




Next Steps

- Design and layout of surrogate BGA interposer
  - RFIC package footprint finalized
- Layout of Rigid-Flex PCB for connectors

Mating using Rigid Flex PCB



Pros

- Rigid daughtercard ultra thin due to 2.5mm connector thickness
- Flex cable is thin and can handle 100 I/O pins
- Flex cable can twist, and bend more easily
- 0.635mm Pitch

Con

- More expensive…but only building Qty of 12

Space Application

- Reduced weight & compact bend capabilities
- Flex circuits experience less intense vibrations and have better ability to withstand mechanical shock due to low mass
- Flex circuits can be shielded against EMI with absorbing conformal coatings
- Polymide (Kapton) film has been used on multiple space (heaters, solar cells, etc.)
- Polymide has excellent thermal stability, UV exposure resistance, and radiation exposure resistance

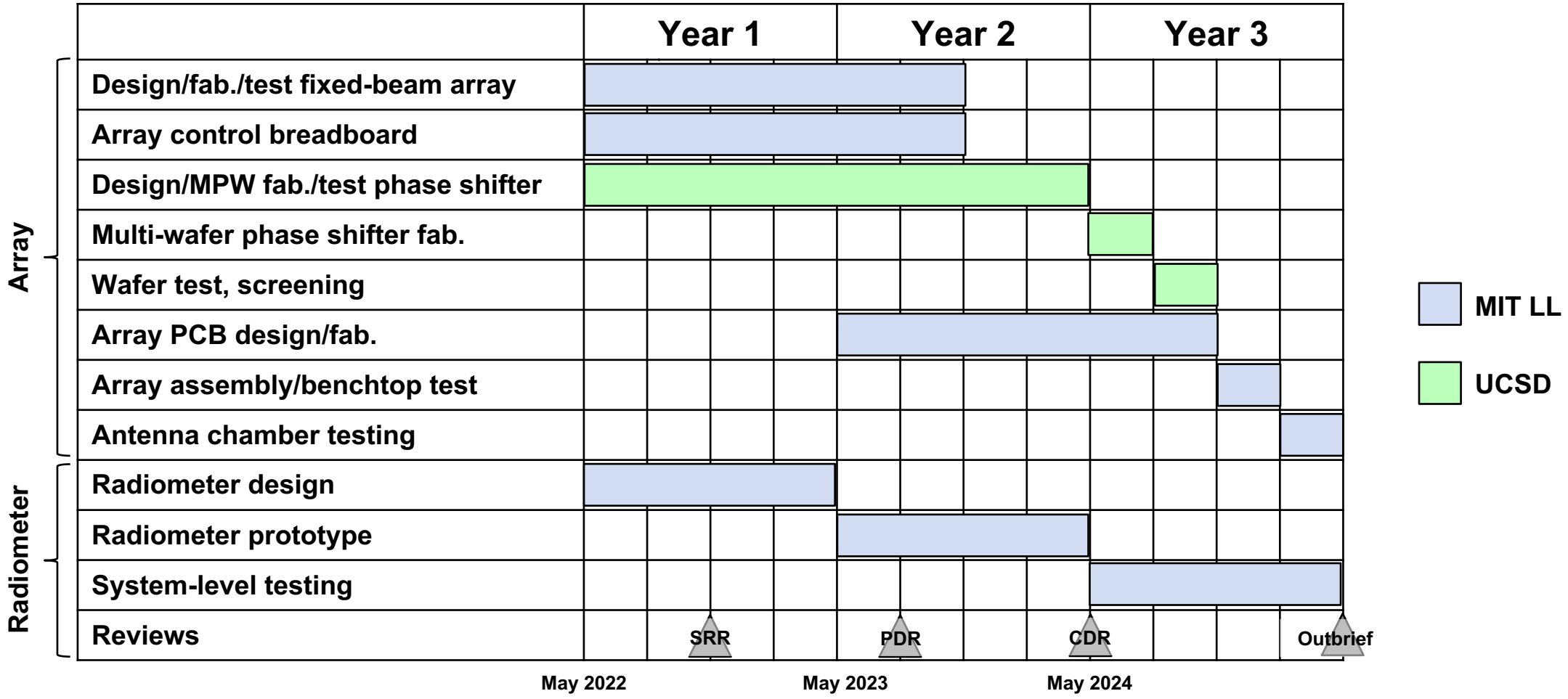
MITLL Year 2 in Detail

FBA = Fixed Beam Array

	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar
FBA PCB Layout/Fab												
Array Feed/Frame Fab												
Assembly/Test of FBA												
Electrical Design Fine Tuning												*Wafer Run
Controller PCB Layout/Fab												
Test of Controller PCB												
Surrogate PCB/Interposer Design												
Surrogate Fab												
Assembly/Test of Surrogate												
Mechanical Design Iteration												

* Global Foundries no longer supports MPWs for 45nm RF SOI: half-wafer run planned for 03/2024

Schedule



Control PCB Status

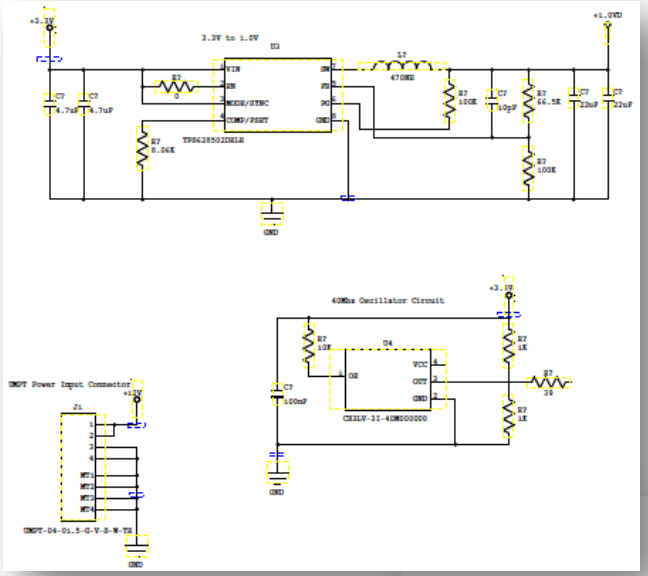
Current Status

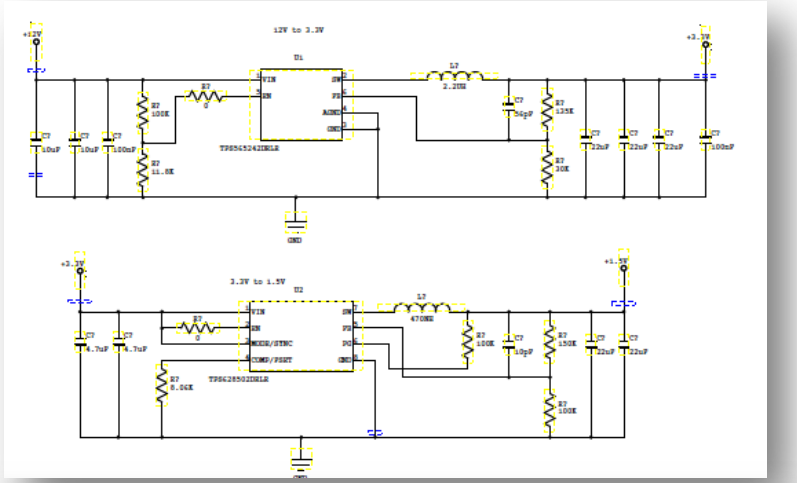
- Schematic capture underway
  - FPGA, power, clocking completed
- Final part selection nearing completion
- Board mechanical structure identified
  - Outline, keep outs, via holes

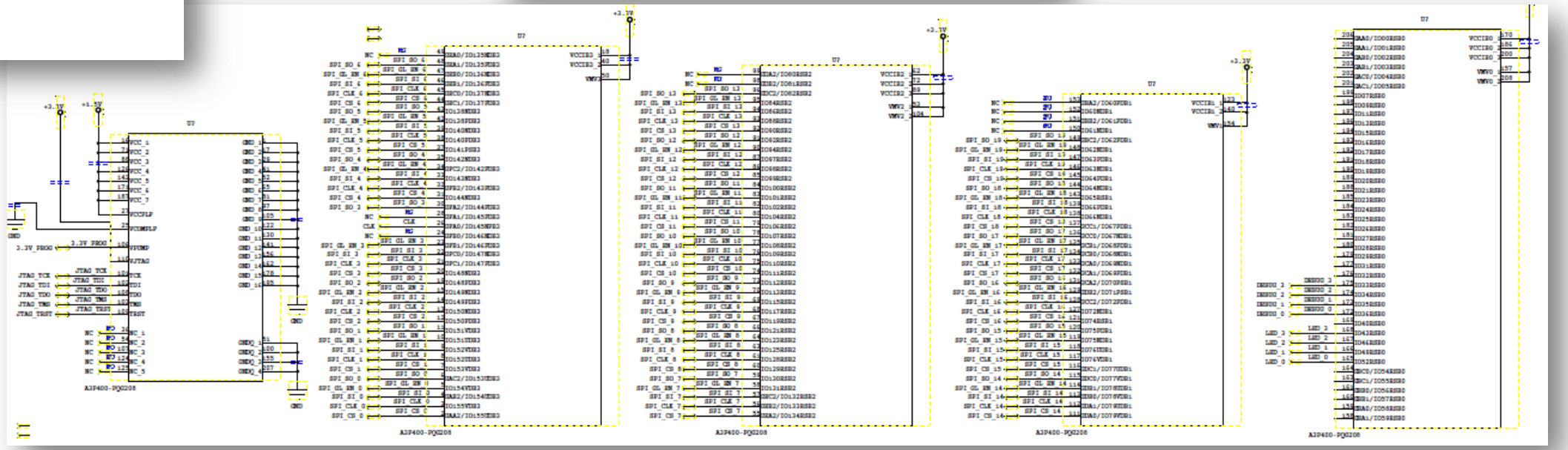
Next Steps

- Conduct formal review of schematic and layout
  - Expected end of June
- Release schematic for fabrication and assembly
- Finalize FPGA code and validate on development board

Schematic Capture, FPGA and Power Circuits

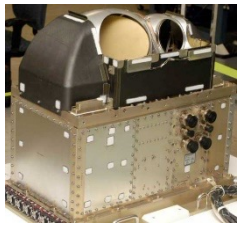
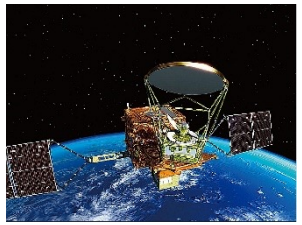
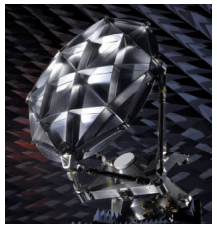
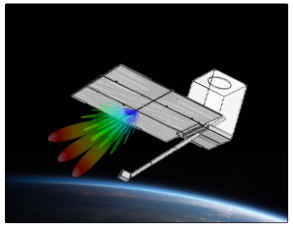






Technology Comparison

CREWSR has more flexible CONOPS and lower SWaP than competing systems

	ATMS	AMSR	COWVR	CREWSR
				
Mechanical scanning	Yes	Yes	Yes	No
Dynamic spatial/angular sensing	No	No	No	Yes
3dB beamwidth (~24 GHz)	5.3°	0.75°	0.96°-1.2° (estimated)	0.60°
Instrument mass	85 kg	324 kg	60 kg	25 kg
Power consumption	130 W	350 W	45 W	45 W