A Spaceborne Design and Airborne Demonstration of Digitally-Beamformed Antennas for SweepSAR Imaging

Gregory Sadowy, Neil Chamberlain, Scott Hensley, Ernie Chuang, Hirad Ghaemi, Brandon Heavey, Eric Liao, Sean Lin, Timothy Miller, Dragana Perkovic, Momin Quddus, Mauricio Sanchez- Barbetty, Scott Shaffer, Jordan Tanabe, Tushar Thrivikraman & Louise Veilleux

Jet Propulsion Laboratory, California Institute of Technology

4800 Oak Grove Drive, Pasadena, CA 91109

IDGA 8th Military Antennas Conference

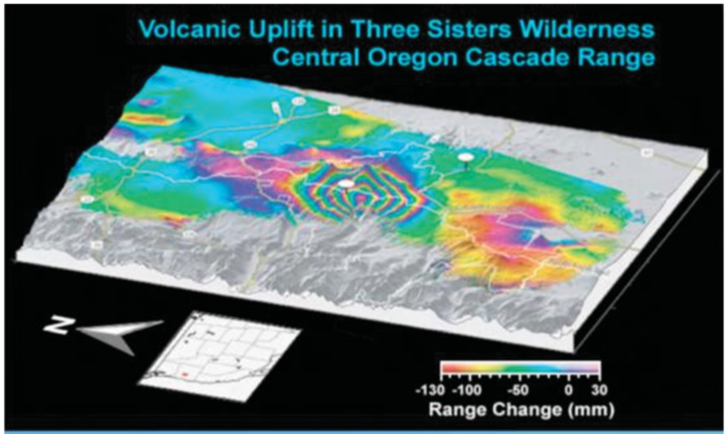
Sept 13th 2011, Washington, DC

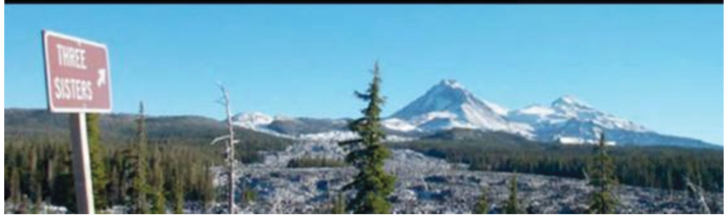
Outline

- Overview
  - NASA Science Applications – Proposed DESDynI Mission Overview
  - SweepSAR Overview
- Proposed DESDynI Array-fed Reflector Design and Performance
  - Reflector and Feed Configuration
  - Modeling
  - Patterns and gain
  - Pointing and blockage
- Airborne Demonstration
  - Hardware Overview
  - Test Flight Results
- Conclusions

Proposed DESDynI Mission Overview

DESDynI: Deformation Ecosystem Structure Dynamics of Ice



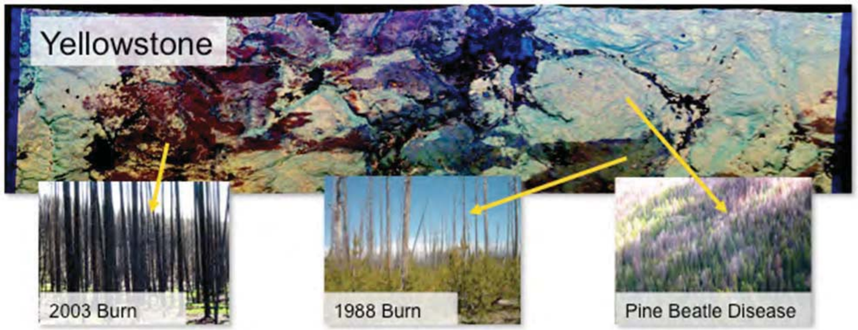


Mission Objectives:

- Determine the likelihood of earthquakes, volcanic eruptions, and landslides.
- Predict the response of ice sheets to climate change and impact on sea level.
- Characterize the effects of changing climate and land use on species habitats and carbon budget.
- Understand the behavior of subsurface reservoirs.

Status:

- Successful Mission Concept Review in Jan. 2011
- Phase-A start delayed due to NASA budget issues



http://desdyni.jpl.nasa.gov/

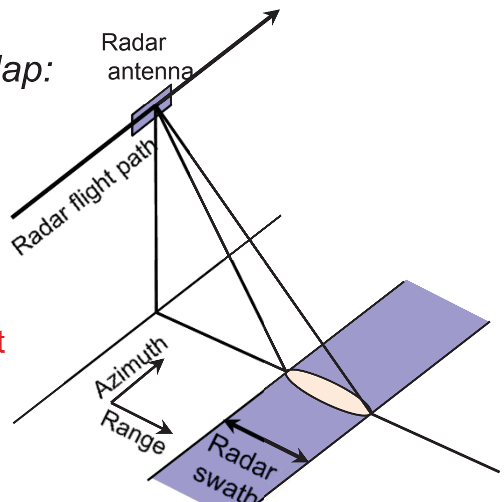
Radar Design to Meet Critical Requirements

- Repeat Period requirement for Deformation science drives the Radar Swath
  - 13-day Repeat Period => 218km Swath Width
- Sensitivity requirement for Biomass (cross-pol) measurement drives Antenna Size and Radar Power
- Accuracy requirements for Deformation and Biomass drive Electronics & Mechanical Stability and Calibration

- A new SweepSAR technique was adopted as a means to achieve much wider swath than conventional SAR strip-mapping, without the performance sacrifices associated with the traditional ScanSAR technique

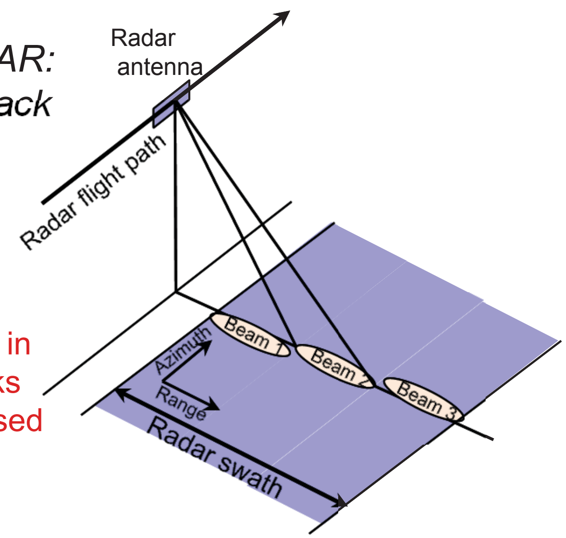
Conventional StripMap:
<~70km Swath

Resulting ~40 day repeat does *NOT* meet proposed deformation and ice science requirements



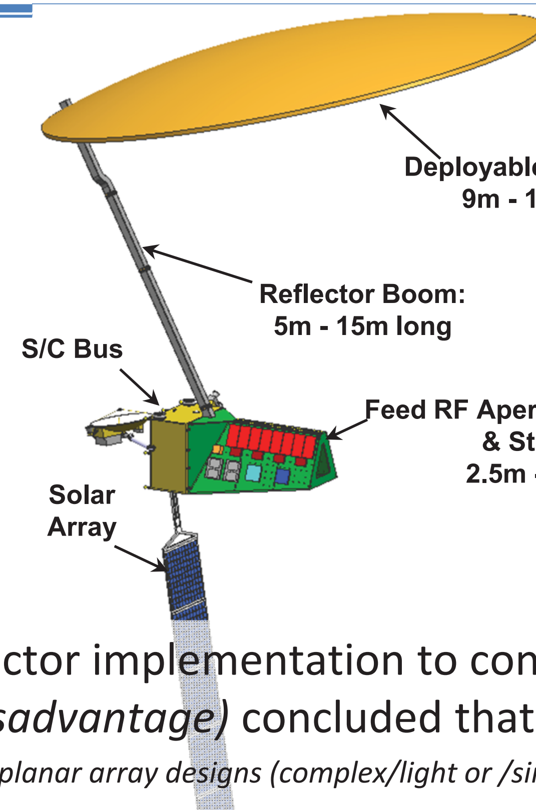
Conventional ScanSAR: non-uniform along-track sampling

Resulting degradation in effective azimuth looks does *NOT* meet proposed ecosystem science requirements



SweepSAR with Array-Fed Reflector

- Our selected implementation for the SweepSAR technique would provide a completely new capability
  – Solves the traditional unwieldy, complex antenna problem with a large passive mesh reflector, and compact feed electronics
  – Breaks the standard SAR performance limits by separating transmit and receive apertures using digital beamforming techniques on receive
- ***SweepSAR with Array-Fed Reflector turns out to be the only option that meets proposed DESDynI science requirements, given the cost constraints***



- Aerospace Corp study* comparing the Array-Fed Reflector implementation to conventional Planar Phased Array *(with its ScanSAR performance disadvantage)* concluded that
  - *"The array-fed reflector design is predicted to be lower cost than either of the planar array designs (complex/light or /simple/heavy structure), primarily due to two factors:*
    - The larger antenna area for the array-fed reflector concept, together with the SweepSAR technique would allow a great reduction in transmit power compared to the planar array concepts
    - The mesh reflector for the array-fed reflector is lighter than either of the planar arrays and nearly "off-the-shelf"

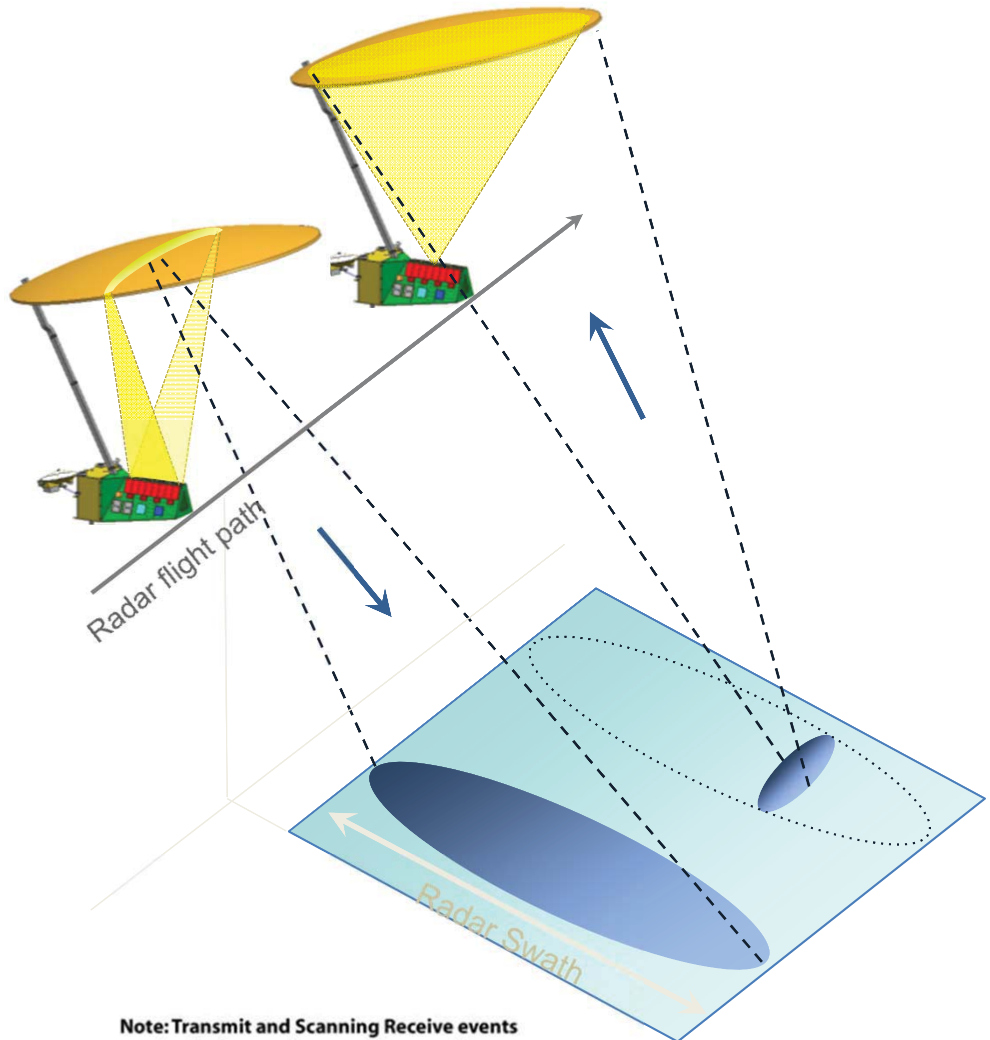
Cost (normalized)	Array-Fed Reflector	Planar Array c/l	Planar Array s/h
Radar	1	2.4	1.7
Bus	1	1.0	1.1
Space Segment Total	**1**	**1.7**	**1.4**
Mass (normalized)			
Radar	1	1.7	2.7
Bus	1	1.3	1.5
Total Launch Mass	**1**	**1.4**	**2.0**
Power (normalized)			
Space Segment Total	**1**	**1.5**	**1.5**

[* Frank Kantrowitz, Dave Ksienski, Mark Barrera, Walter Bloss, Vince Canales, Peter Carian, Adam Chandler, David Chien, Keven MacGowan, Samuel Osofsky, Dec 17, 2010]

SweepSAR Introduction

Advantages

- On Transmit, all Feed Array elements are illuminated *(maximum Transmit Power)*, creating the wide elevation beam
- On Receive, the Feed Array element echo signals are processed individually, taking advantage of the full Reflector area *(maximum Antenna Gain)*
- Uses digital beamforming to provide wide measurement swath
  - DBF allows multiple simultaneous echoes in the swath to be resolved by angle of arrival
- Uses large reflector to provide high aperture gain
  - Full-size azimuth aperture for both transmit and receive
  - Full-sized elevation aperture on receive
  - Aperture size effectively reduced on transmit to provide full-swath illumination
- Only need to store and process data from feed array elements being illuminated by an echoes
  - This can be predicted with *a priori* knowledge of measurement geometry (orbit, pulse timing and topography)

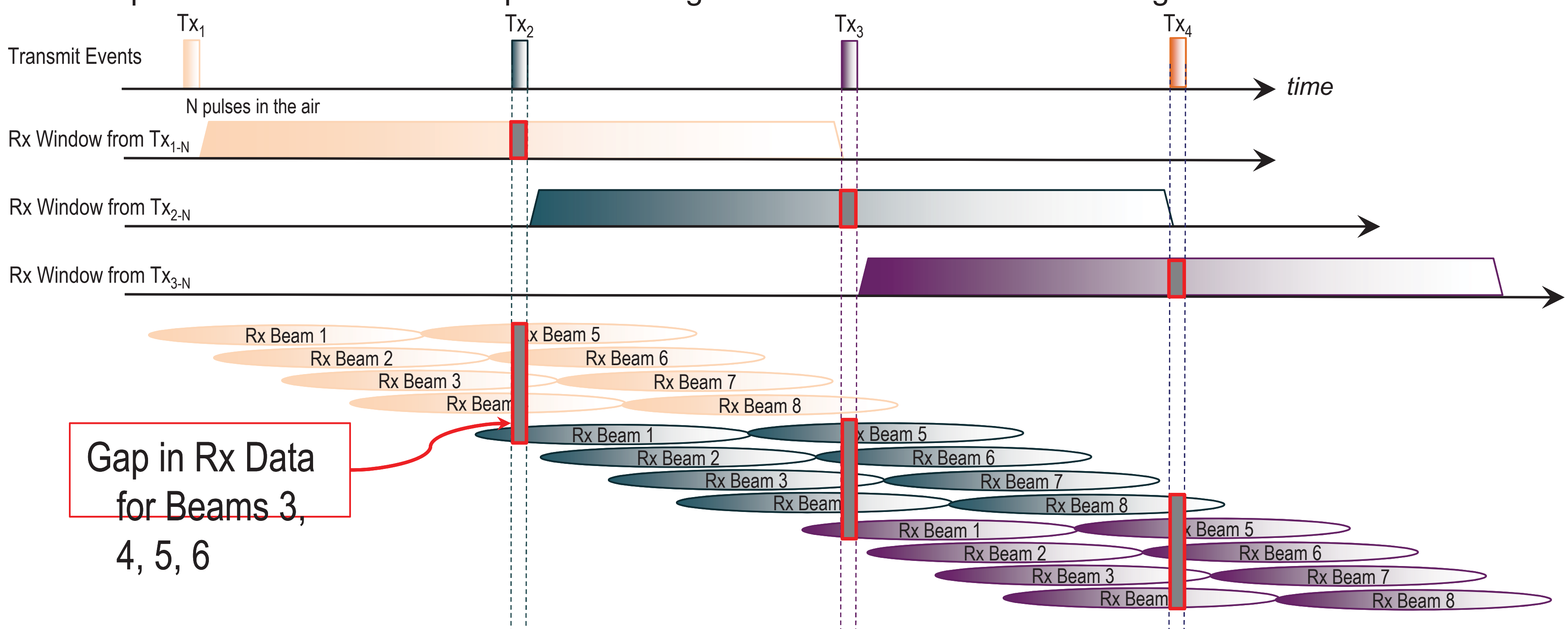


Note: Transmit and Scanning Receive events overlap in time and space. Along-track offset shown is for clarity of presentation only.

SweepSAR Pulse Timing

- Conventional Radar data acquisition timing – Receive Window is within the Inter-Pulse Period (IPP):

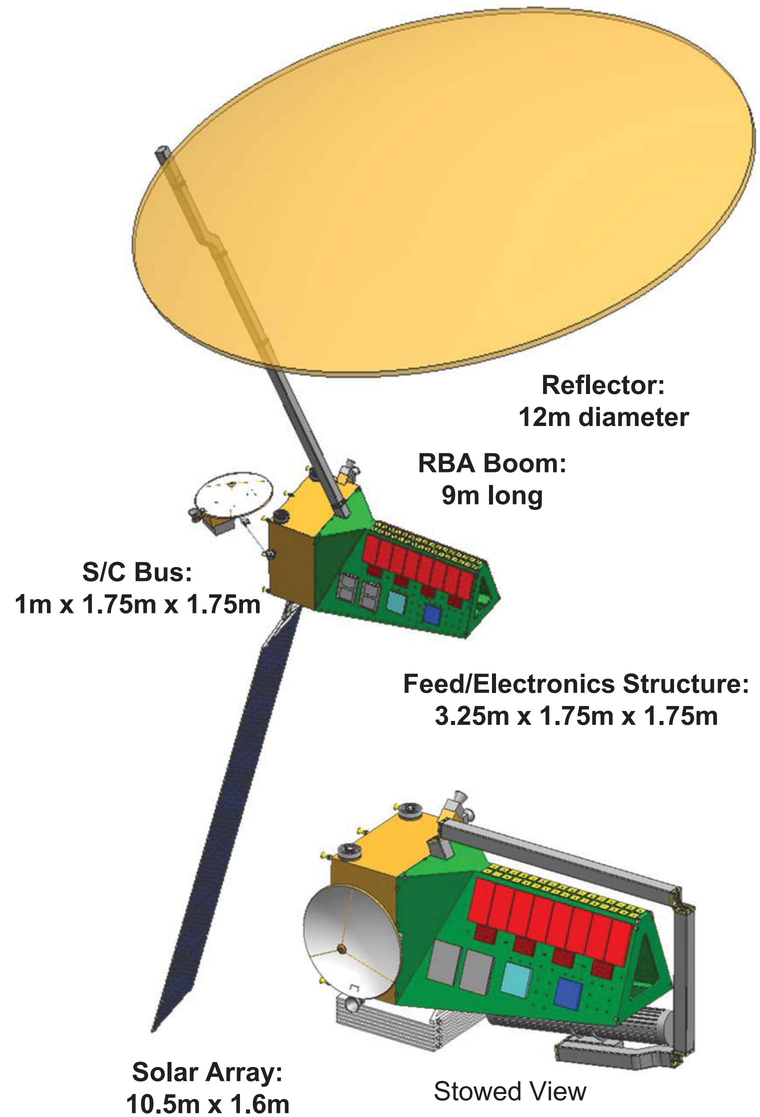
- SweepSAR wide-swath data acquisition timing – Receive Window extent is longer than an IPP:



- The Receive channels ("Rx Beams") that are active during a Transmit event are blanked for the duration of the Transmit pulse, resulting in gaps in the swath

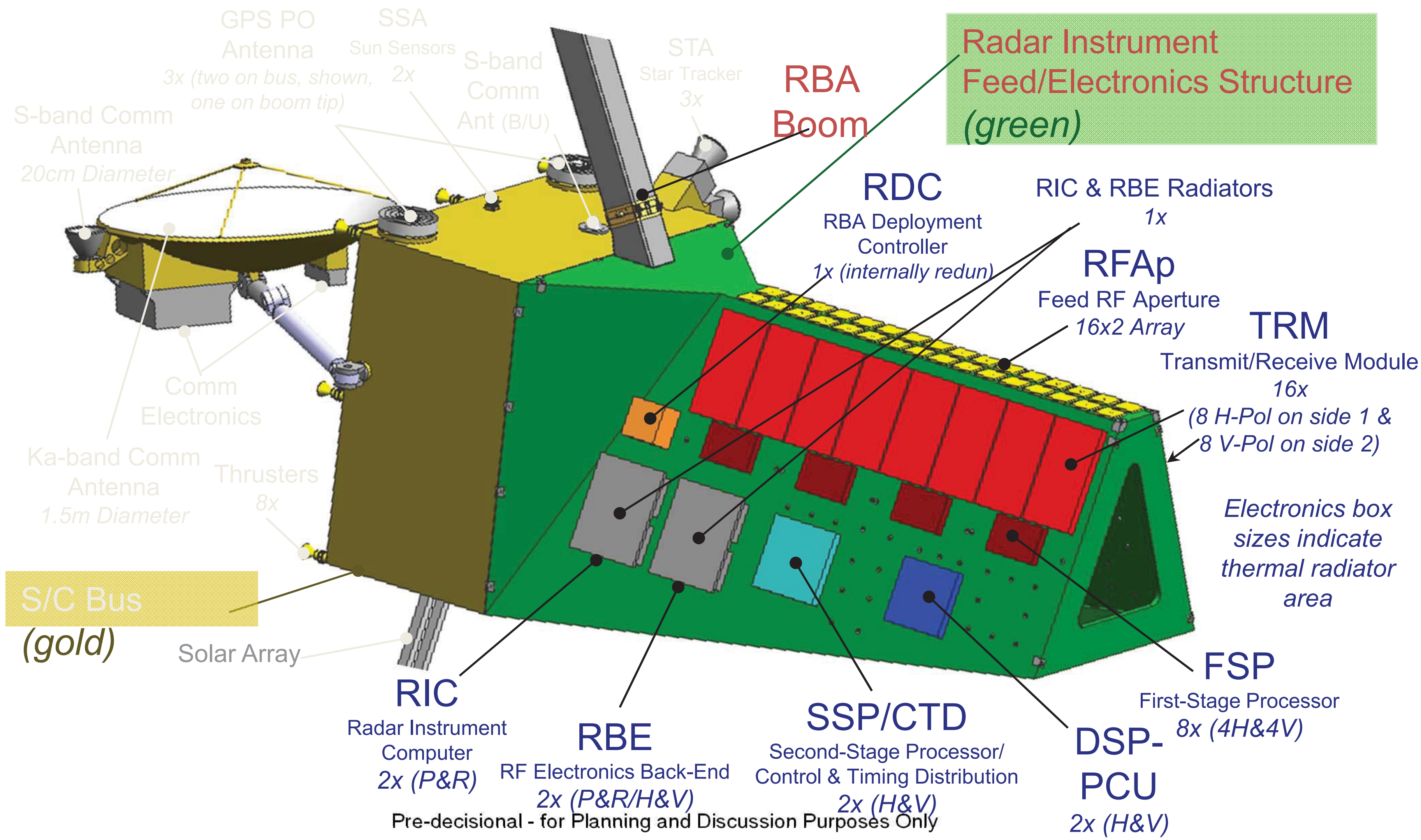
Antenna System

- Deployable mesh antenna
  - 9m to 15m projected diameter
  - Northrop AstroMesh or Harris Deployable Truss
  - High mass efficiency: 1.0 – 1.5 kg/m^2
  - High TRL with many successful deployments
- Array feed
  - 16x2 to dual-pol patch elements
  - 4x2 antenna tiles
  - Elements fed in 1x2 or 2x2 configurations
  - Separate TRMs for H-pol and V-pol
  - 3.25m length structure

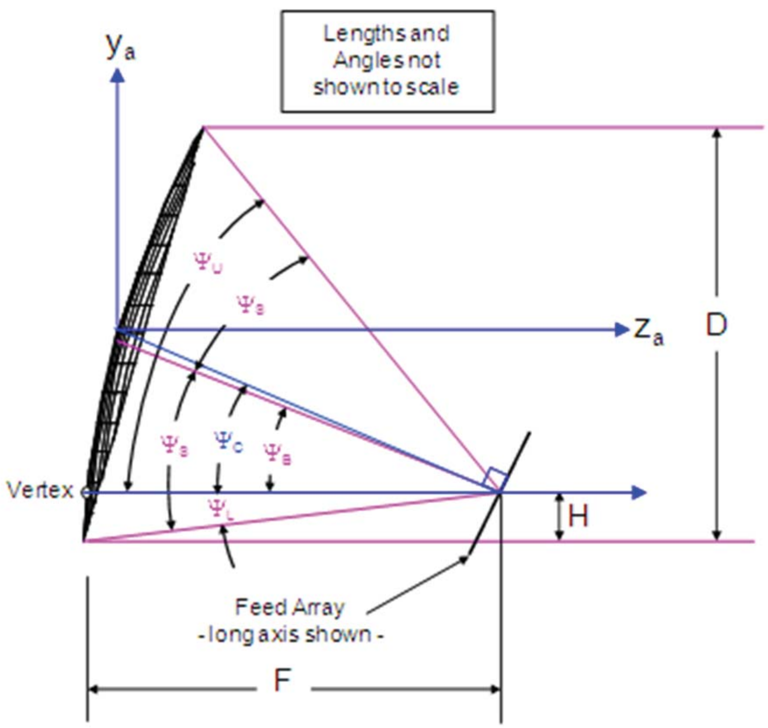


Radar Instrument Configuration

- All Radar components are mounted on the Feed/Electronics Structure to facilitate integration, test, and calibration prior to instrument delivery to ATLO



Antenna Optics and Performance



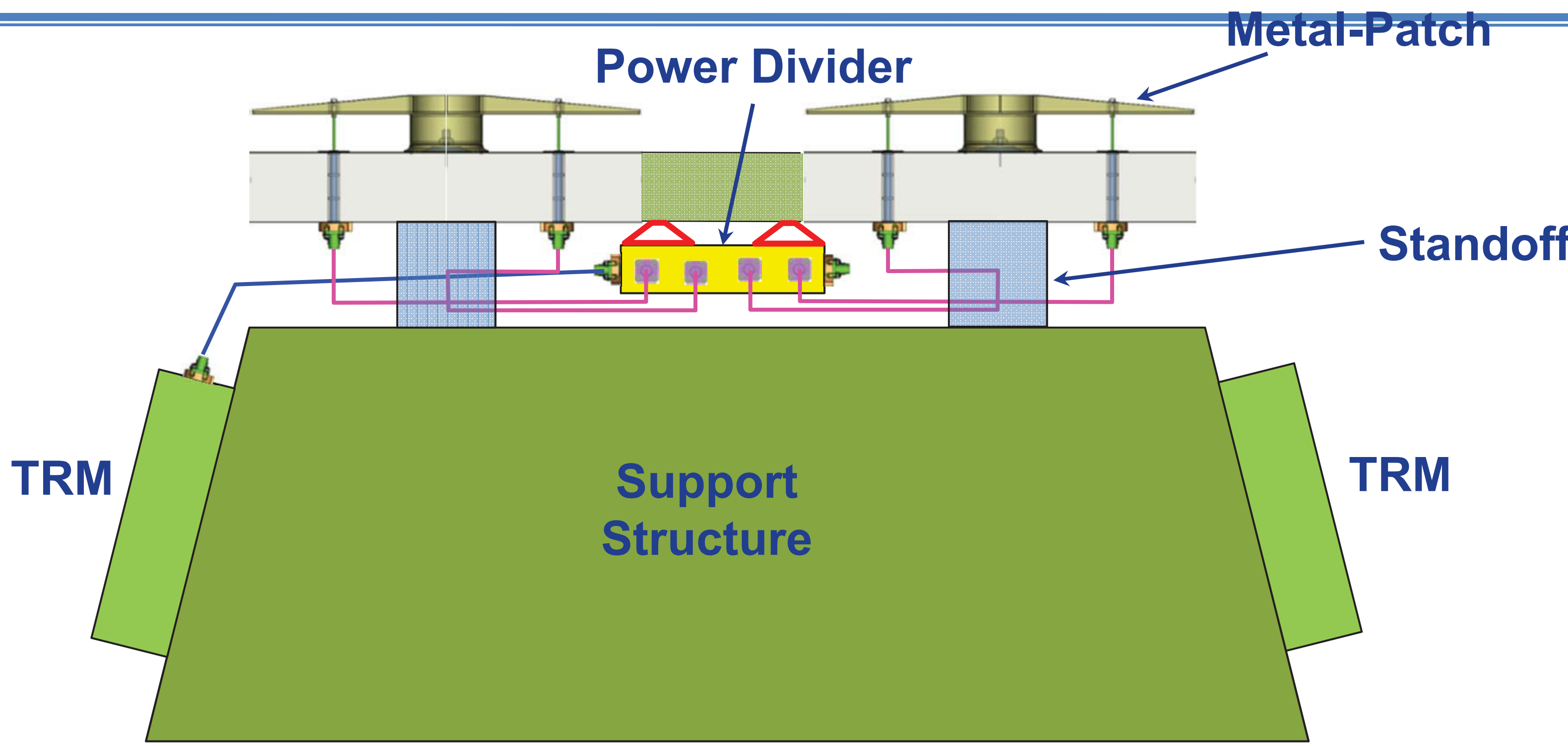
15m Diameter Prescription

Parameter	Description	Value
D	Projected aperture	15 m
F	Focal Length	15 m
H	Edge offset	-2.0
Ψ_C	Center angle	21°
$2\Psi_S$	Subtended angle	55°

Nominal Performance Prediction

		Tx	Rx
Scan range	deg	N/A	± 8
Directivity	dBi	33.3	42.3
Loss	dB	1.7	1.7
Gain	dBi	31.6	40.6
HPBW az	deg	1.0	1.0
HPBW el	deg	15.9	1.0
Cross Pol	dB	-25	-25
EIRP	dBW	65.4	N/A

Feed Concepts

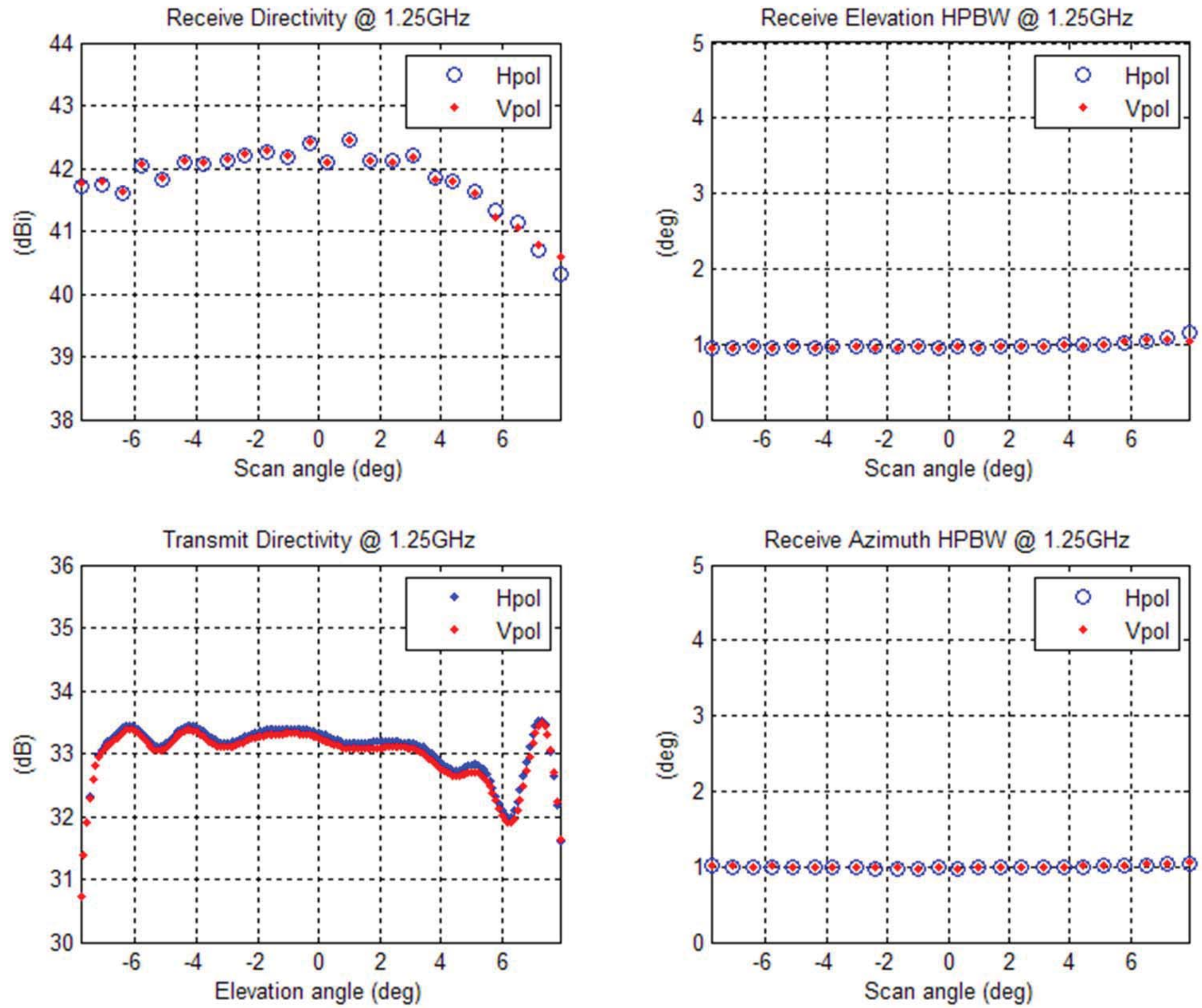


- Various antenna feed concepts are being evaluated for cost and performance
  - Integrated composite antenna tiles (adapted from UAVSAR and Deep Impact)
  - Metal-patch arrays (adapted from Juno Microwave Radiometer design)

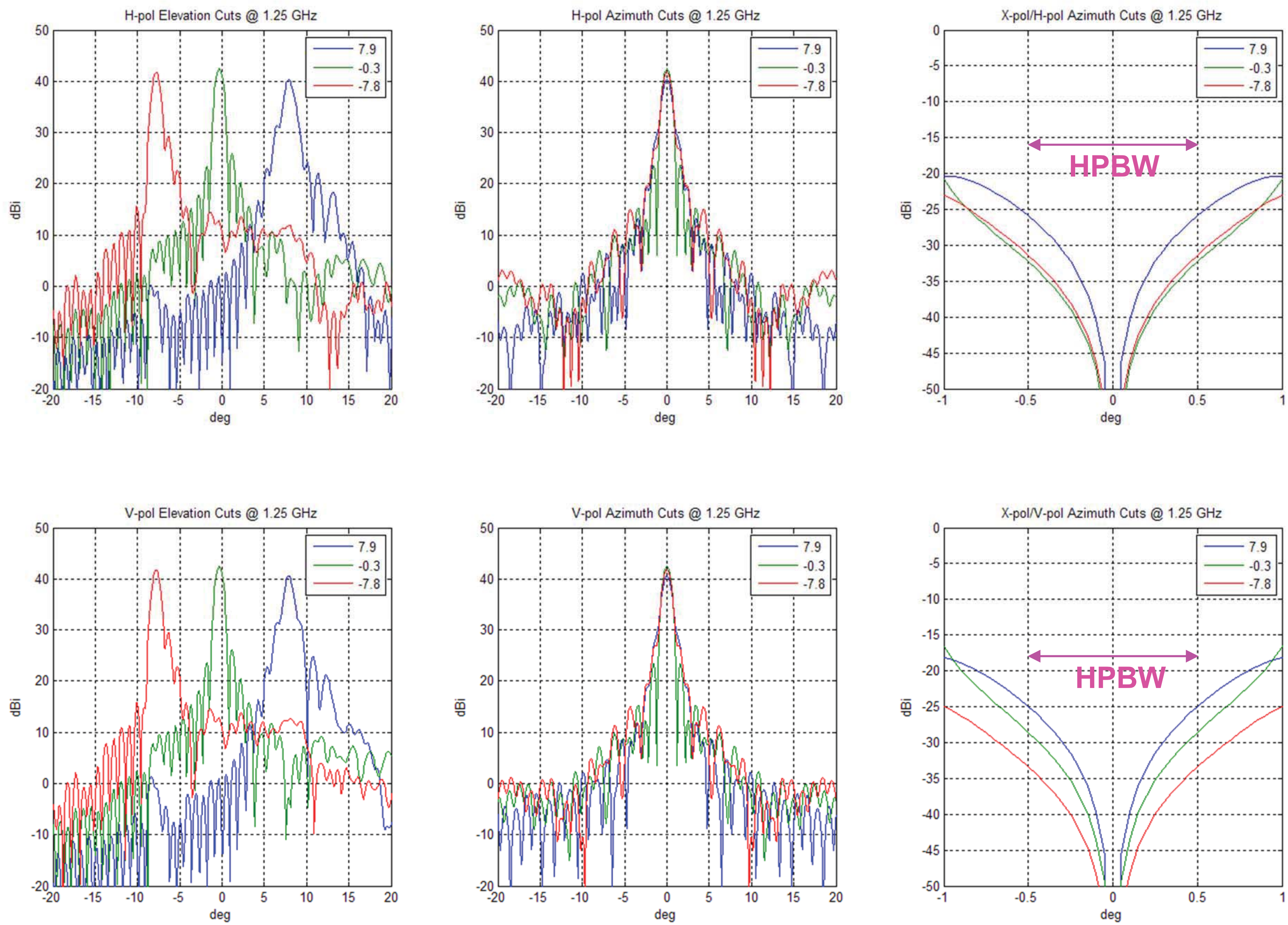
Antenna Modeling

- Two key steps:
  - 1) Generate 1x2 feed patterns calculated in HFSS
  - 2) Analysis using Ticra Grasp
    - Import HFSS fields as tabulated feed to array object
    - Perform spherical wave expansion of feed fields
    - Perform PO and PTD synthesis
      - Feed and boom blockage modeled suing method of moments
      - Feed-reflector interaction (P3) included
      - Conductive loss not modeled (accounted in gain budget)

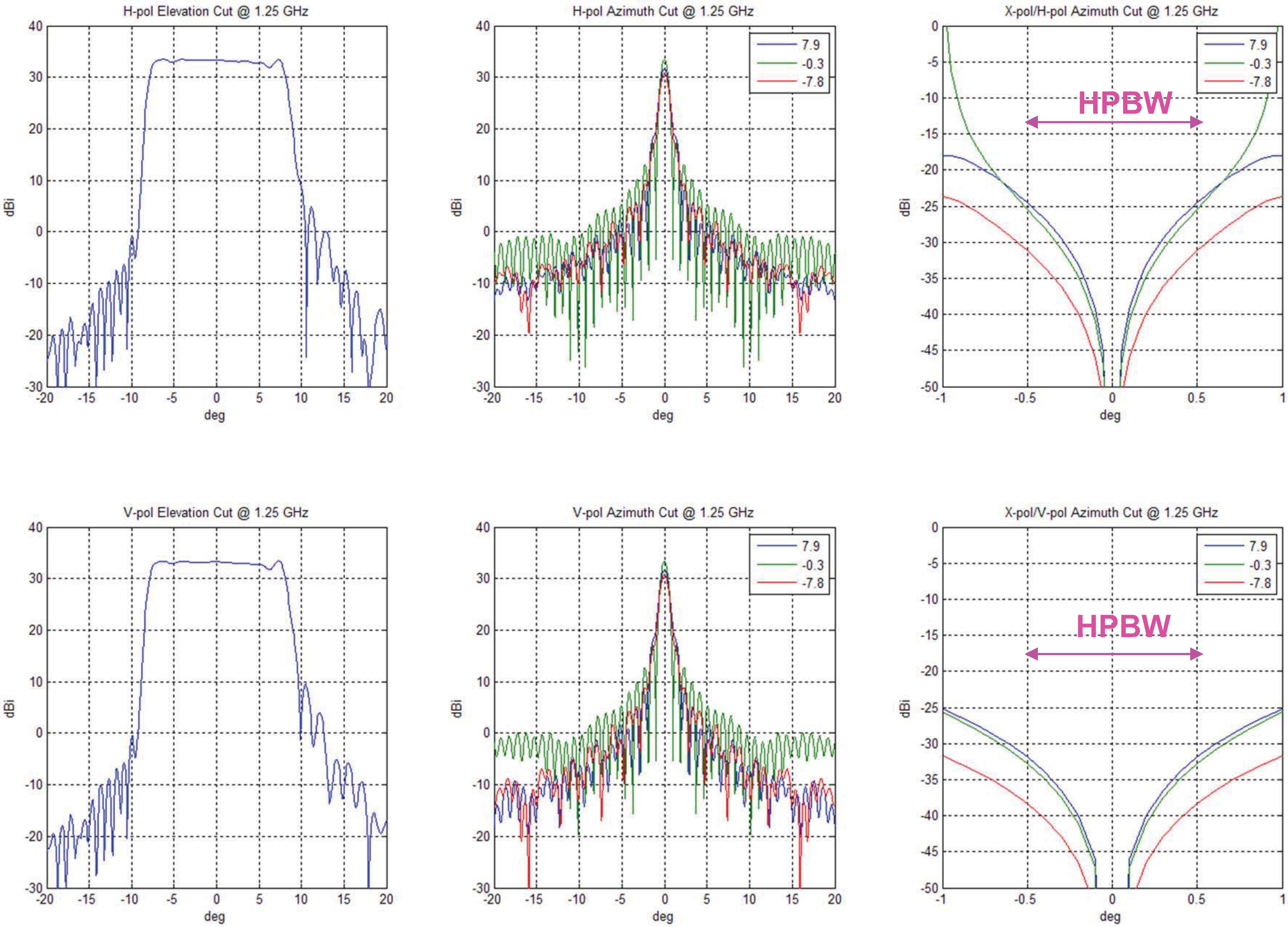
Antenna Performance Summary



Receive Pattern Predictions



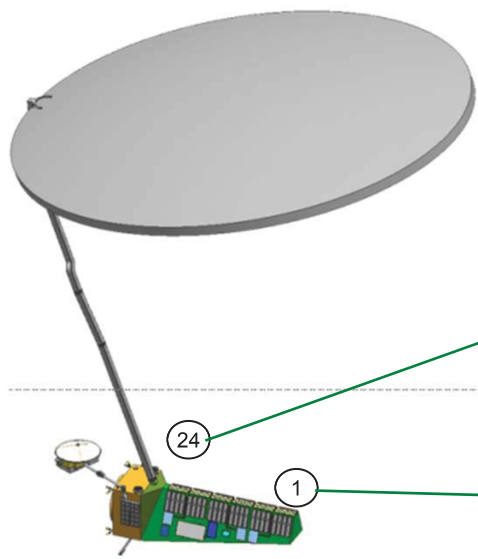
Transmit Pattern Predictions

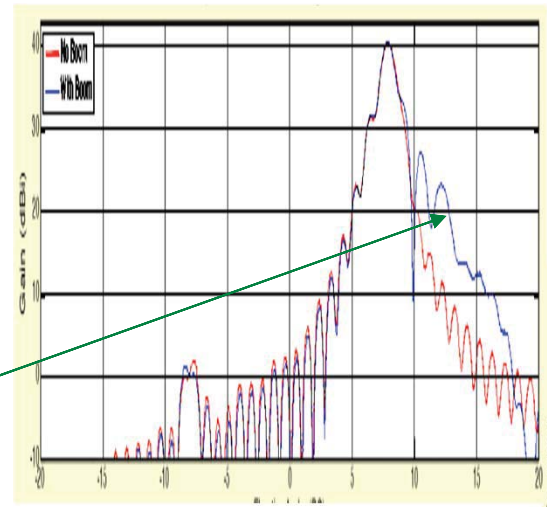


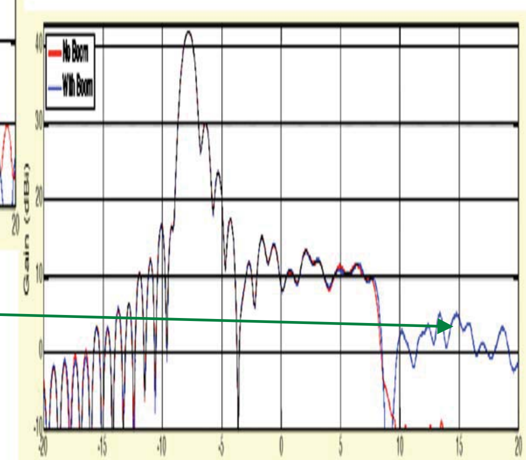
Pre-decisional - for Planning and Discussion Purposes Only

Pointing and Blockage

Element nearest to boom affects sidelobe the most



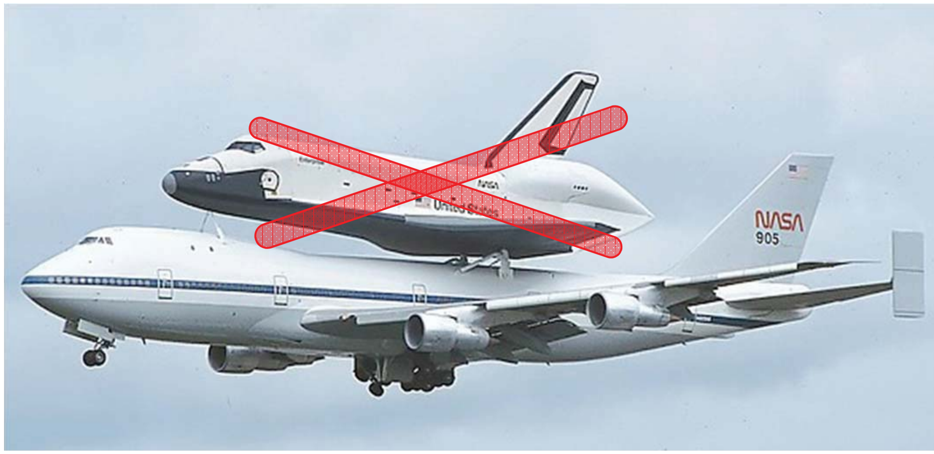




- **Thermally-induced misalignment:**
  - Pointing error: 2x mechanical rotation (~1/100 degree)
  - Gain drop: ~0.01 dB
- **Amplitude error (0.5 dB rms) and phase error (10 deg rms) in TRMs and feed network:**
  - Pointing error: ~0.1 deg rms
  - Gain drop: ~0.08 dB

SweepSAR Airborne Demo

- Now that the shuttle has finished flying…



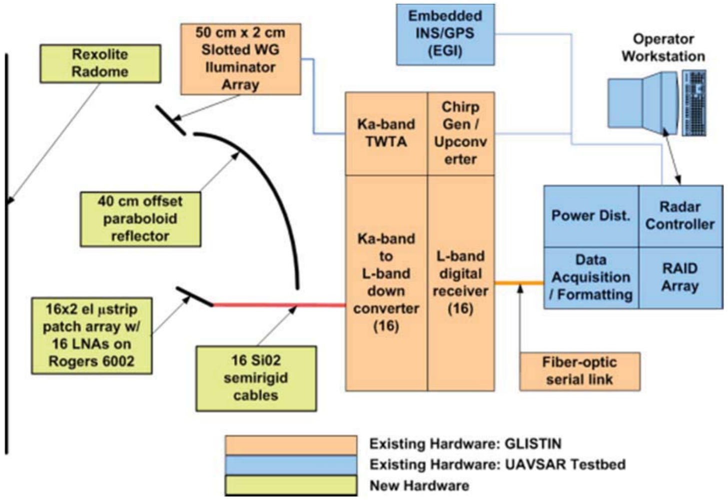
Surprisingly, this concept was rejected.

SweepSAR Airborne Demo Overview

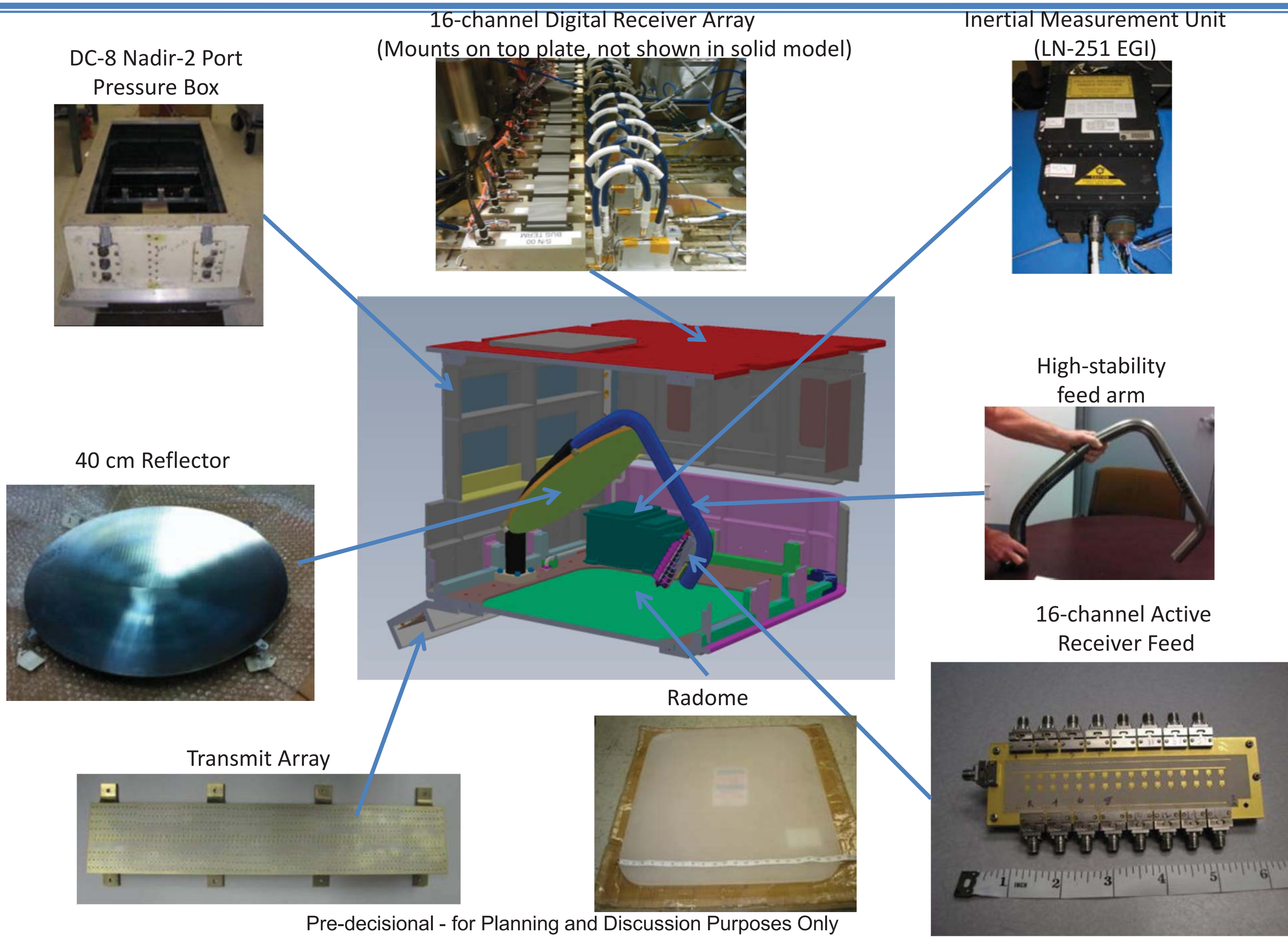
- Ka-band (35.6 GHz) airborne SweepSAR using array-fed reflector and digital beamforming
  - 8 simultaneous receive beams generated by 40-cm offset-fed reflector an 8-element active array feed
  - 8 digital receiver channels, all raw data recorded
  - Receive antenna system is approximately 1/28th scale of proposed DESDynI antenna
- Supports radar instrument development and risk mitigation for proposed DESDynI mission:
  - Demonstrates first-of-it's-kind, real-world performance of SweepSAR with array-fed reflector
  - Reduces risk by shaking out engineering issues that are not predicted by simulation
  - Demonstrates performance of critical beamforming and calibration techniques
    - Identify, quantify and mitigate error sources
    - Trade algorithm performance vs. computational resource consumption
  - By manipulating the data can also
    - Demonstrates suppression of range ambiguities
    - Demonstrates "transmit-gap" mitigation

NASA DC-8

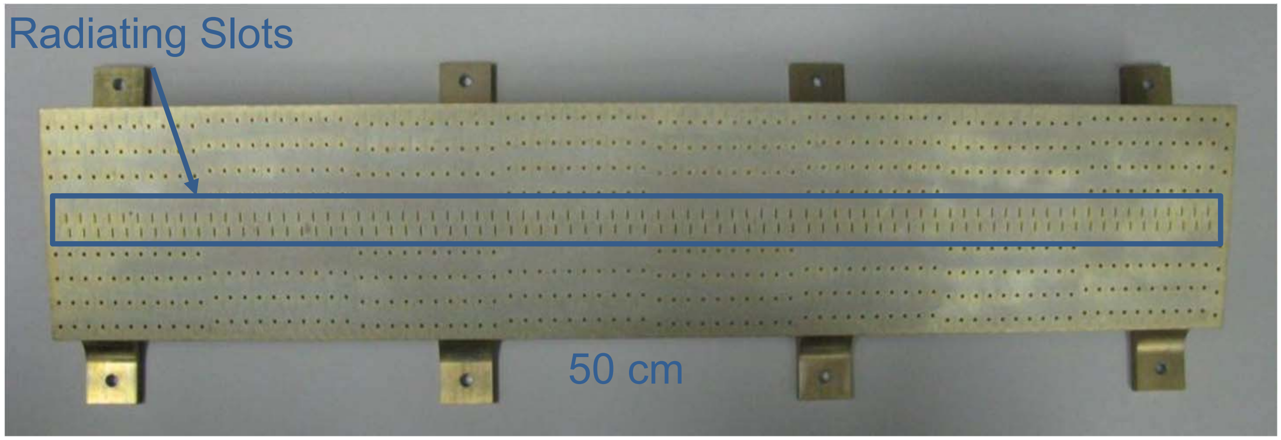
SweepSAR Demo Block Diagram



SweepSAR Airborne Demo Hardware



Transmit Antenna



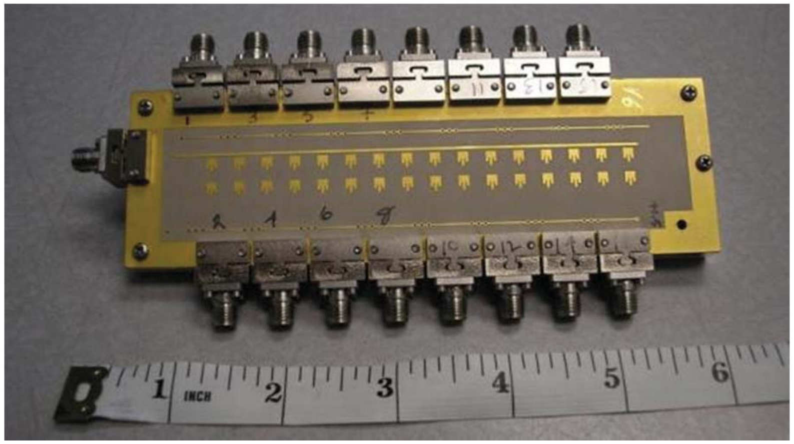
~2 cm
(active region)

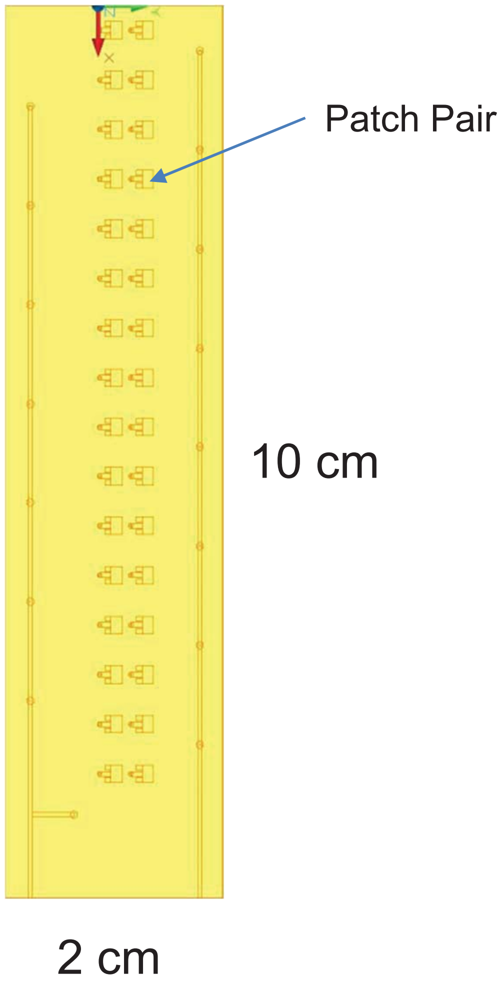
- Approximate dimensions: 50 cm (azimuth) x 2 cm (elevation)
- Beamwidth: 1 degree (azimuth) x 20 degrees (elevation)
- Successful design from GLISTIN Airborne Interferometer

Ka-band Receive Feed Array

- 32 microstrip patch radiators arranged in 16 pairs
- One low-noise amplifier (LNA) for every pair
- Low-loss temperature stable substrate
- Embedded calibration signal injection path
  - Calibration data collected continuous during flight
- 16 connectors on back connect to DBF array using phase stable coaxial cables

16-channel Active Receiver Feed



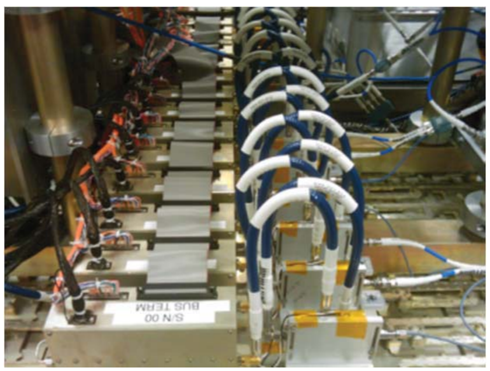


Digital Beamforming Architecture

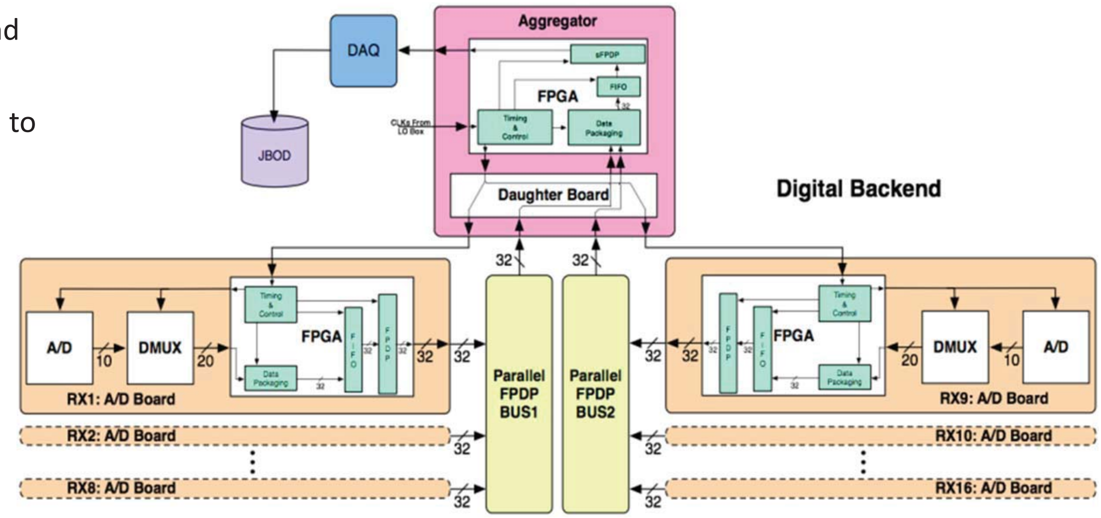
Beamforming Data System

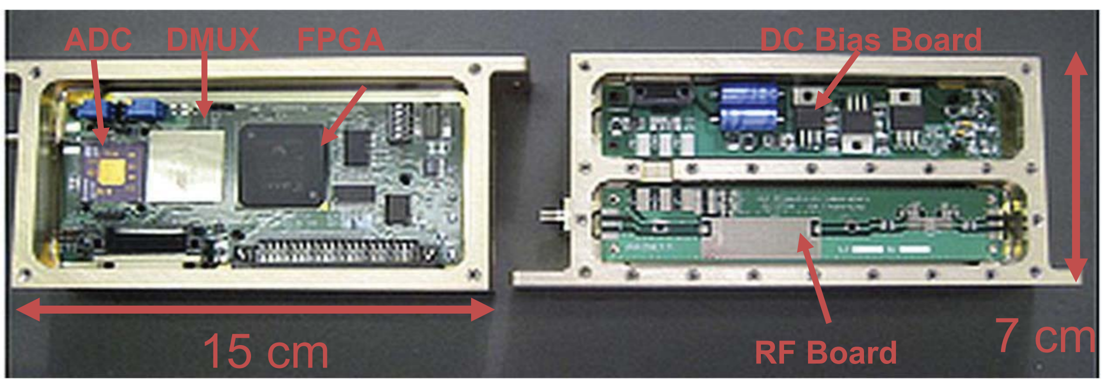
- 16 L-band Digital Receivers
  - 16 Ka-band signals are converted to L-band
- Two parallel FPDP data busses (8 receivers each)
- Aggregator board multiplexes all data streams on to as single serial FPDP connection
- All data is written to a high speed disk array (JBOD – "just a bunch of disks")

16-channel Digital Receiver Array



DBF System Block Diagram

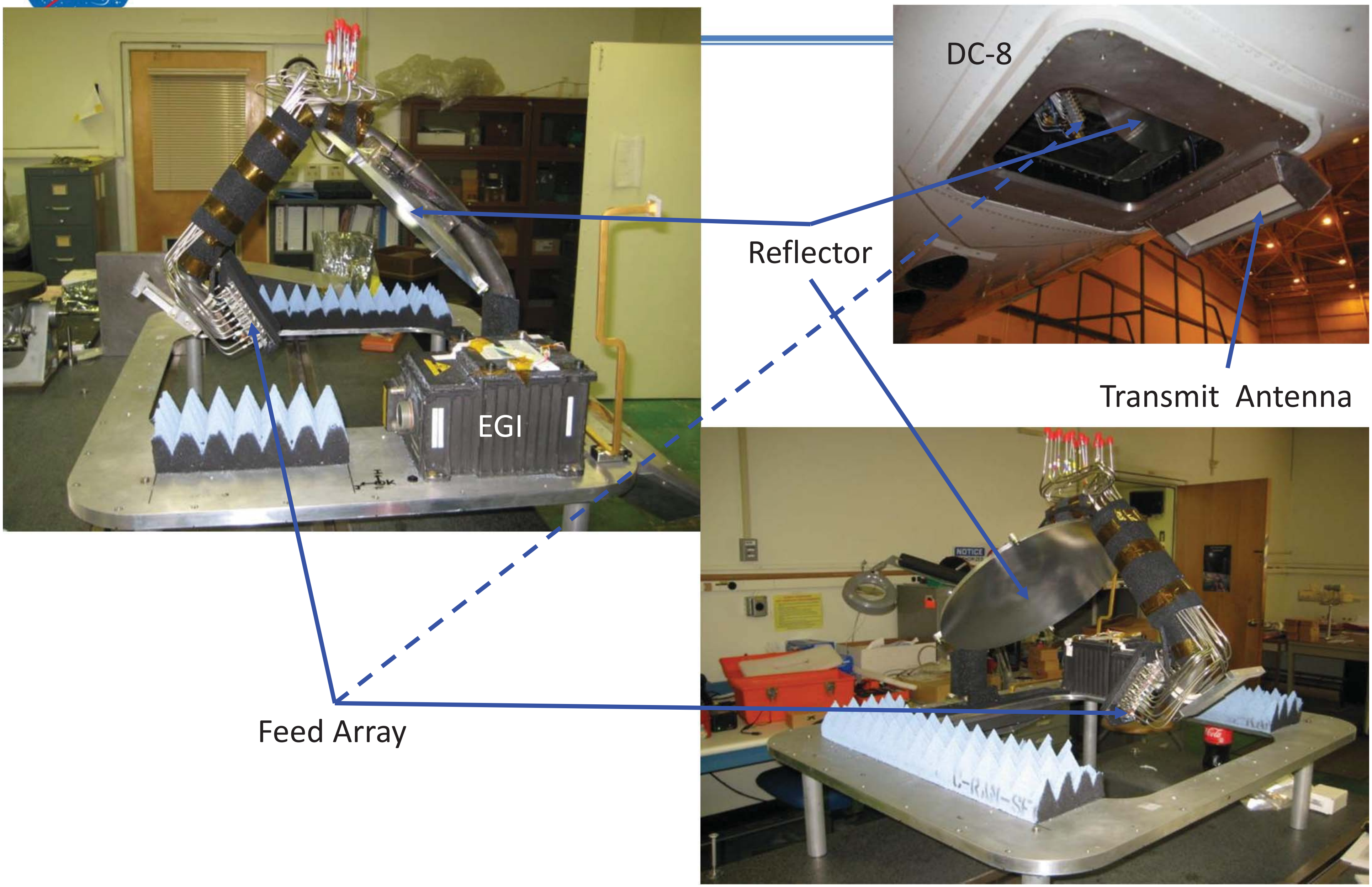




L-band Digital Receiver

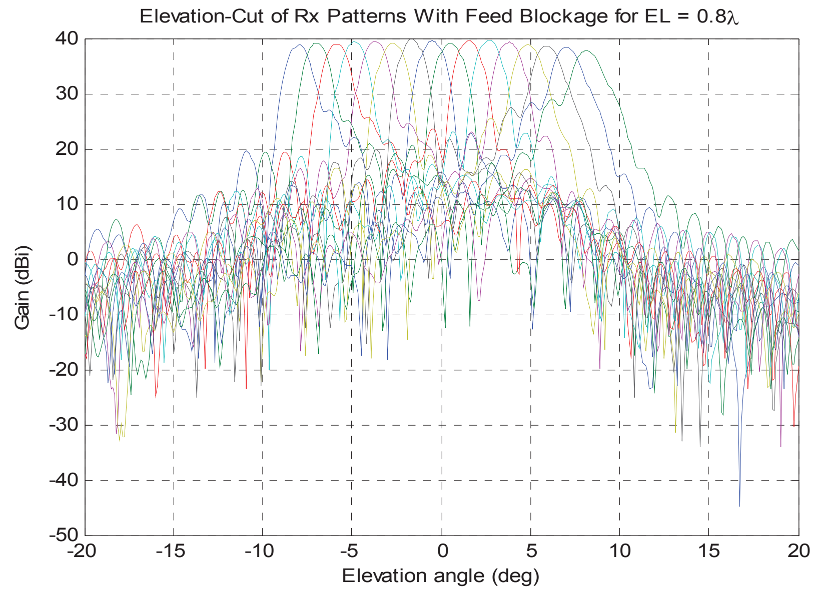
- Input 1215-1300 MHz
- Input analog bandwidth: 3.3 GHz
- Sample rate 240 Ms/s @ 10 bits resolution
- Digital demodulation and filtering using Xilinx Virtex 5 FPGA
- Output bandwidth: 80 MHz
- Data output over front-panel data port (FPDP)

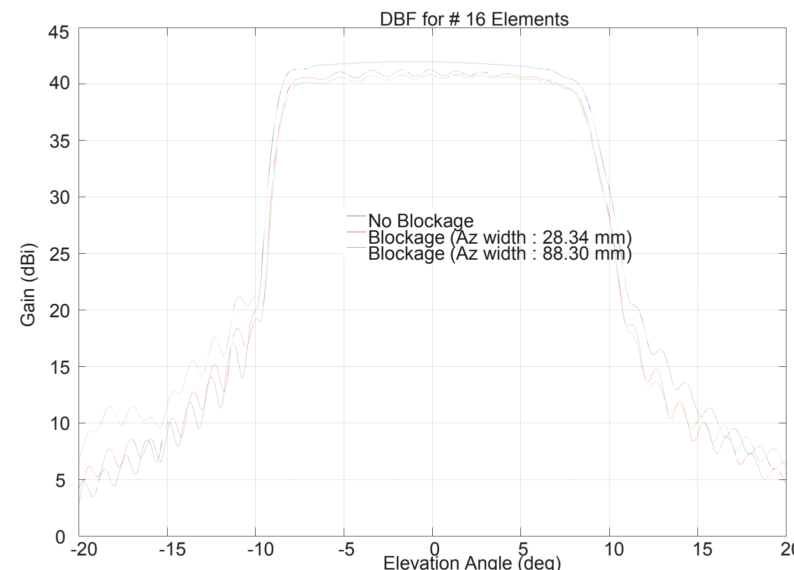
Hardware Photos



Predicted Beamforming Performance

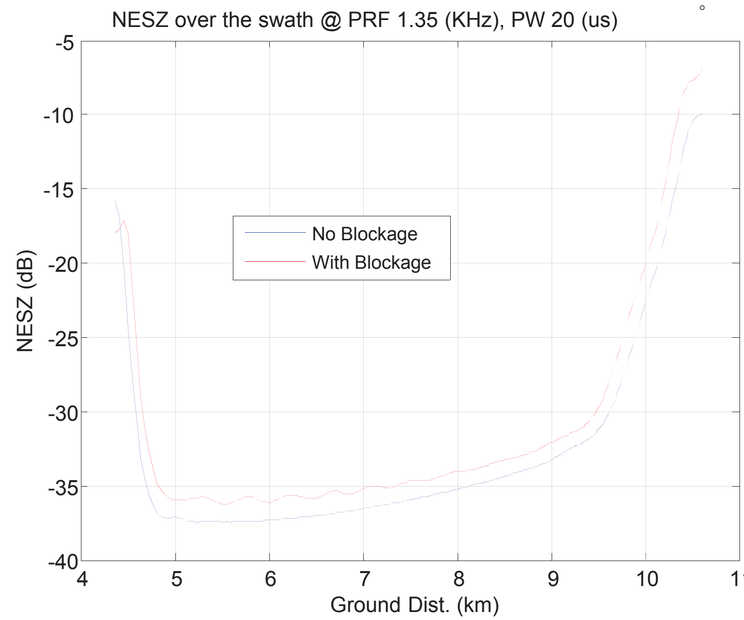
- Studied beamforming performance
  - HFSS used to generate feed patterns
  - Ticra GRASP used to model reflector/feed system
- Modeling include feed blockage and obstructions at edge of beam due to antenna mounting in aircraft
- Feed blockage causes small reduction in gain as well as gain ripples across the swath
- Similar to proposed DESDynI antenna models

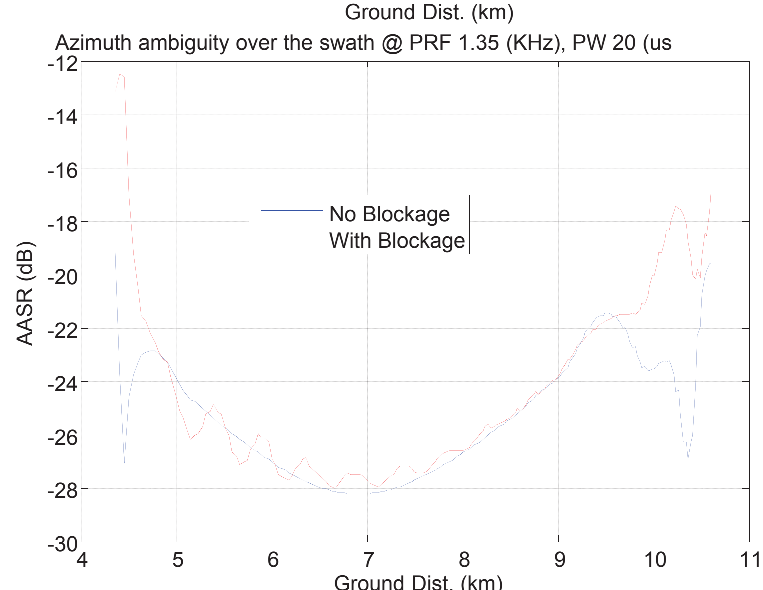




Predicted SNR and Azimuth Ambiguity Performance

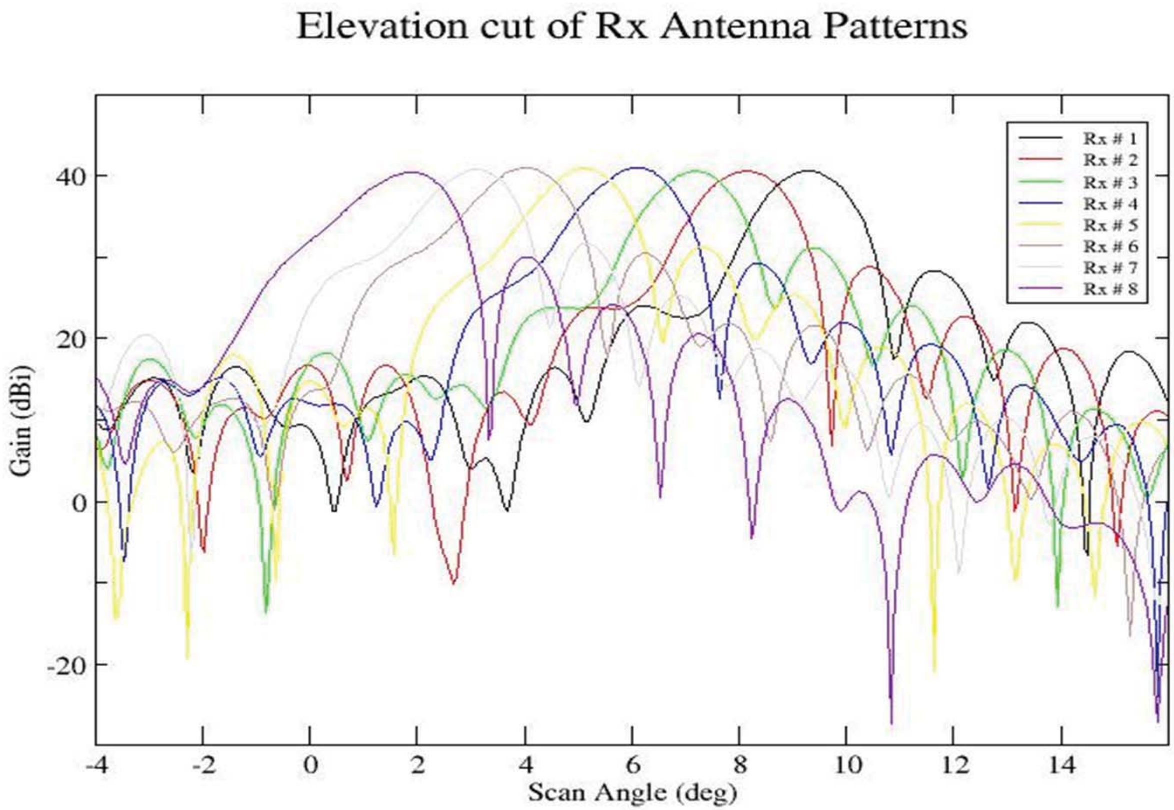
- Excellent sensitivity (-35 dB NESZ) using 20 us pulse
- Enough SNR margin to still have good sensitivity for short-pulse experiment modes (2us)
- Azimuth ambiguities < -20 dB (1350 Hz PRF)
- No significant range ambiguities using normal PRF
  - Can deliberately introduce range ambiguities and data collection gaps using staggered PRF scheme to place multiple pulses in swath
  - Simulation of proposed DESDynI radar pulsing, data acquisition and processing provides demonstration of SweepSAR technique under “real-world” condition



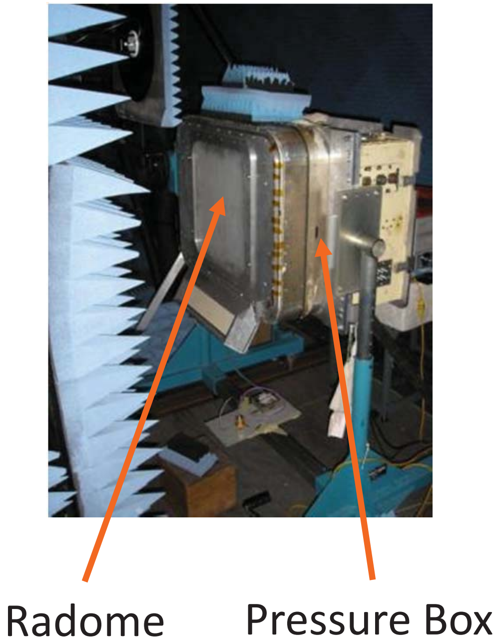


Measured Receive Antenna Patterns

- Complex antenna patterns (amplitude and phase) measured for the 8 receive beams.
- Beamwidth is approximately 1° and the peak sidelobe level is around -10 dB.

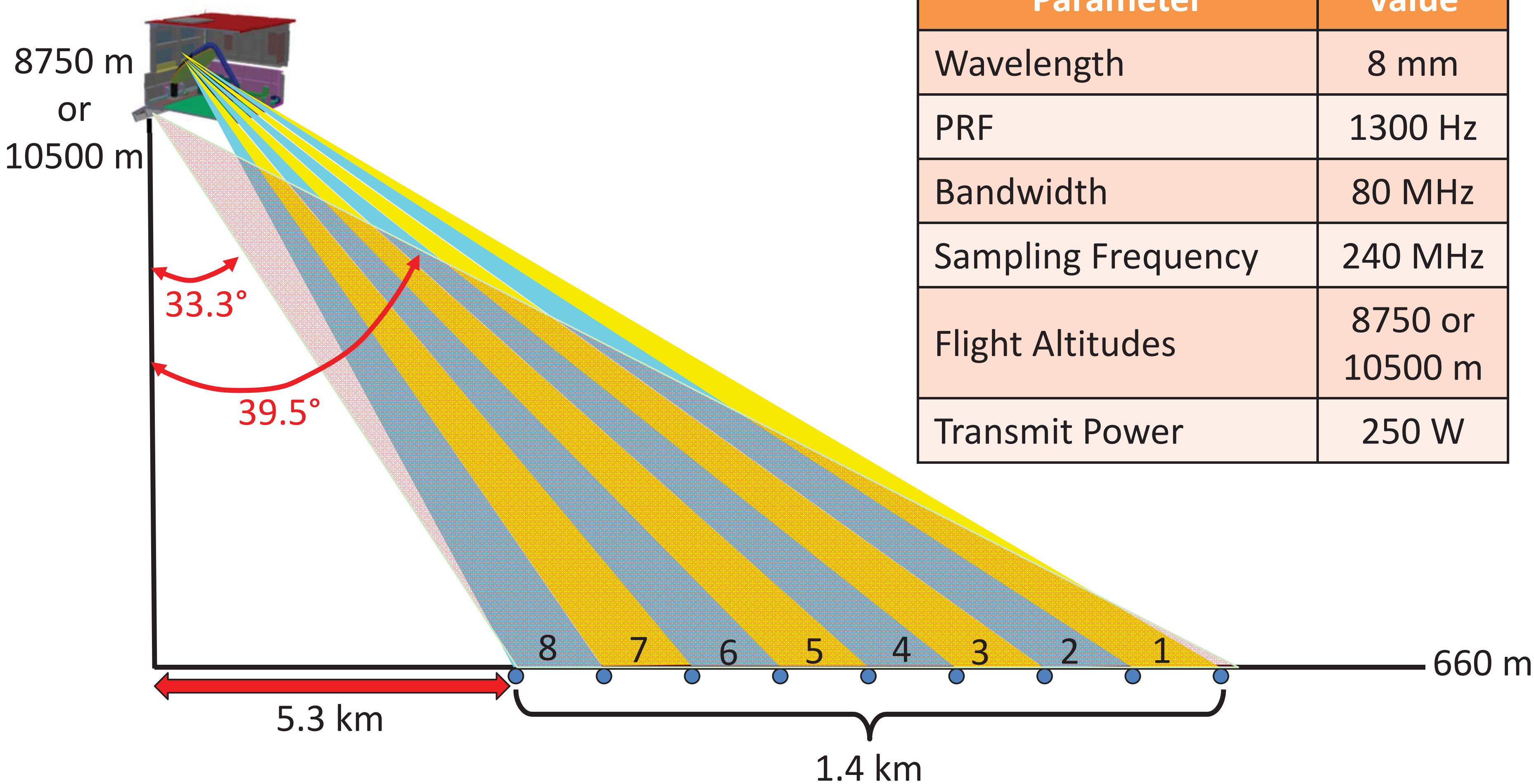


SweepSAR Antenna System on near-field scanner



Radar Parameters and Mapping Geometry

- The 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

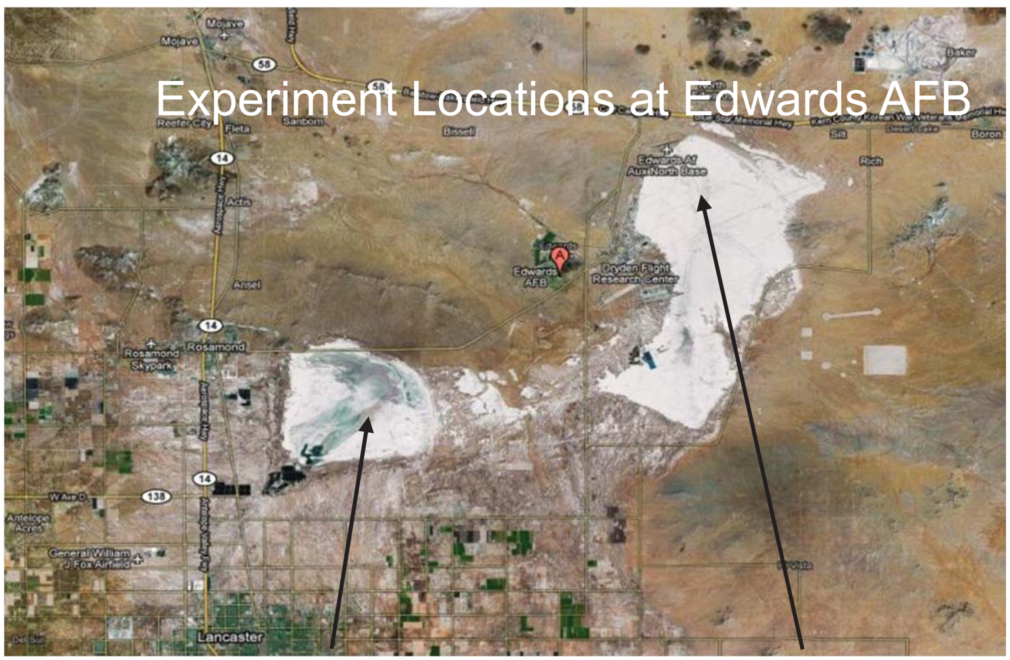
Not drawn to scale

SweepSAR Test Site

- Data Collection Flights
  - Data collected using corner reflectors deployed in radar dark areas at Edwards AFB
  - Two sites identified:
    - Rosamond Lake – UAVSAR calibration array with large 2.4 m reflectors
    - Rogers Lake – Smaller 1 m reflectors deployed
    - Reflector spacing designed to effectively measure beamformed pattern performance

R1

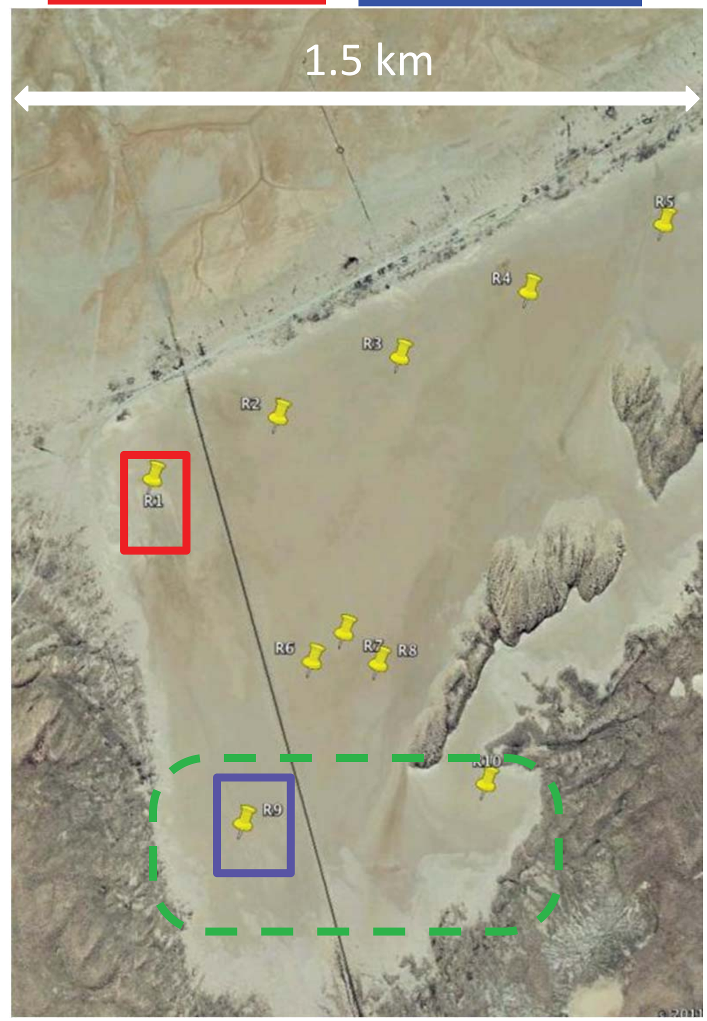
R9



Rosamond Lake

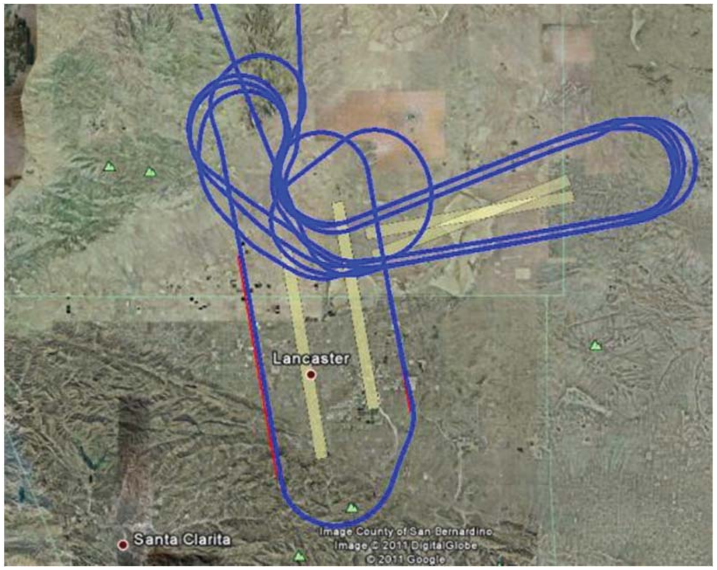
Rogers Lake

Flight Direction 80° Heading



SweepSAR Demo Successful Test Flights

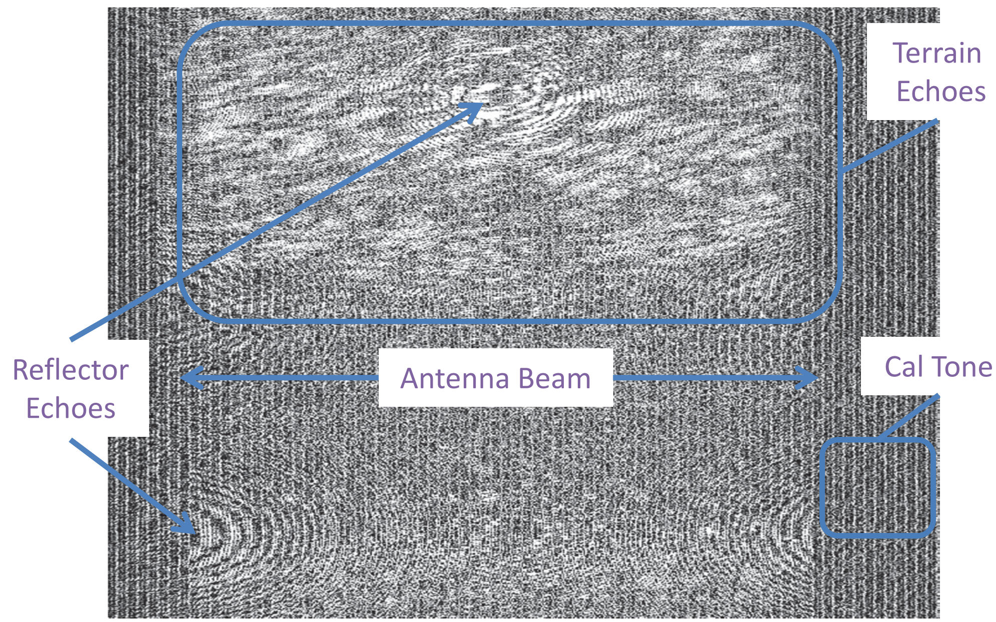
Flight Track and Swaths for Flight #2



SweepSAR Demo Flight Team

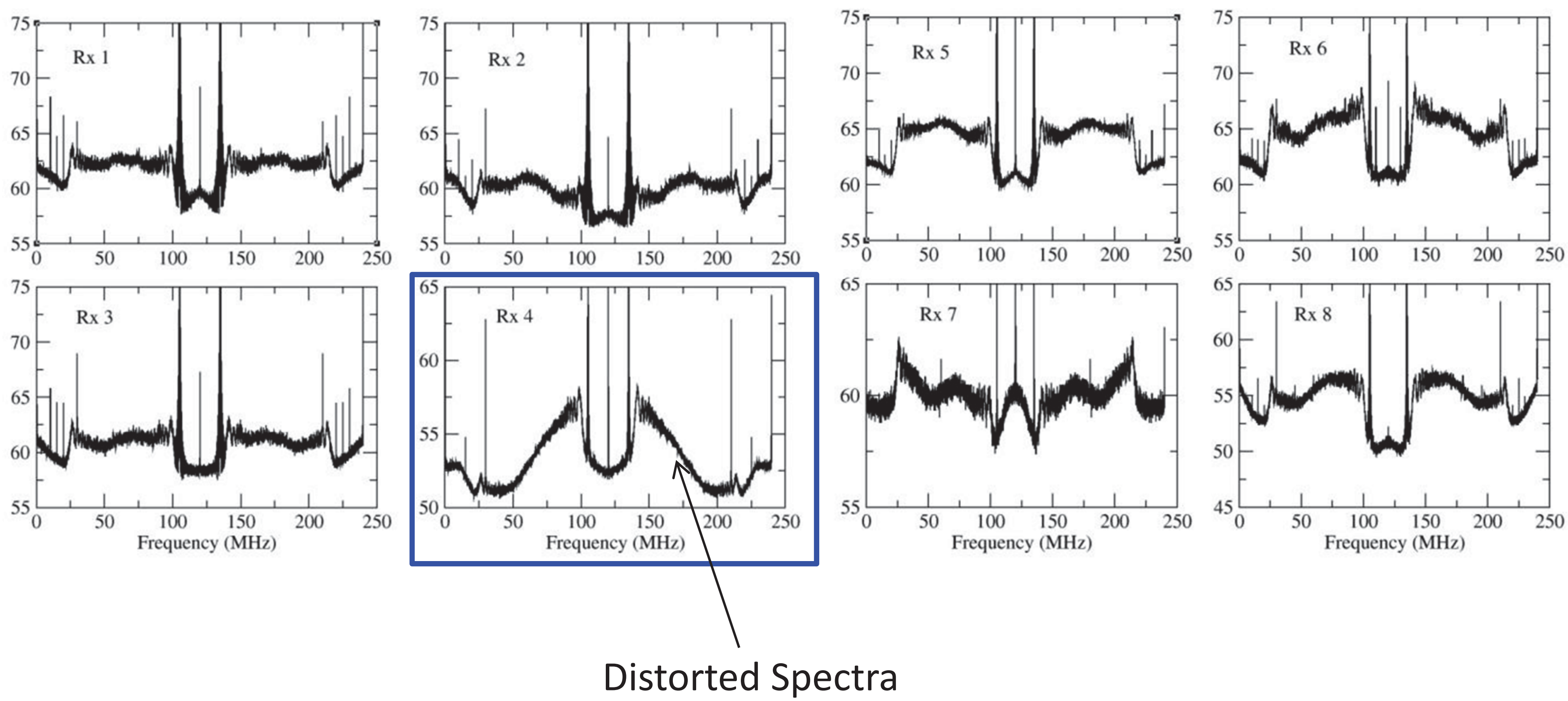
- SweepSAR Flight History
  - Two flights flown on July 7 and July 9
  - 3.5 hours per flight
  - 12 data collection lines
  - >200 GB of for flight 2
- Flight 1 used a PRF of 100 Hz so was not critically sampled in azimuth – showed had functioning radar!
- Data quality for Flight 2 is good except for gain anomaly on receiver #4 (is being investigated in lab).

Raw Radar Data (Rogers Lake, Beam #5)

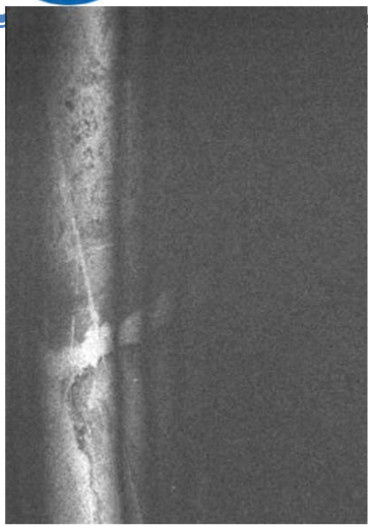


Channel Spectra

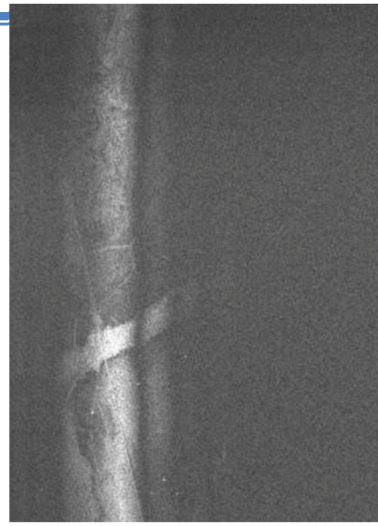
- Range spectra were generated for the 8 receive channels.
  - Power on channel 8 is low relative to the other channels by 3-5 dB.
  - Channel 4 is lower in power and shows a distorted spectrum.
  - Still able to form imagery on Channel 4, however it presents a problem to beam forming.



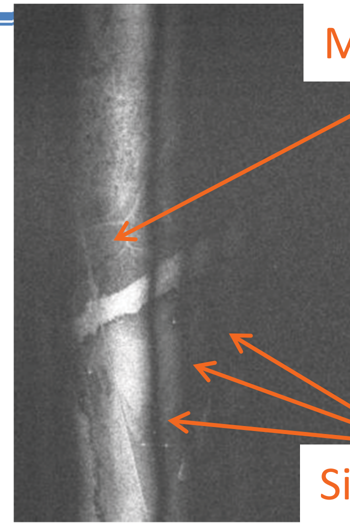
Individual Beam Imagery



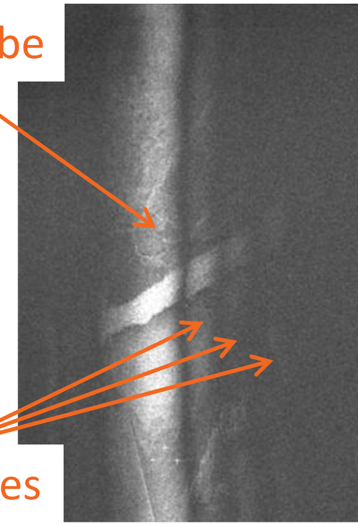
Beam 8



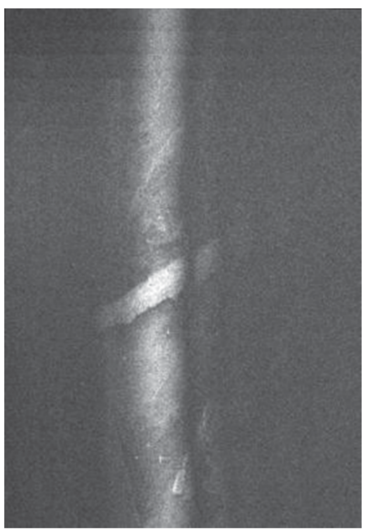
Beam 7



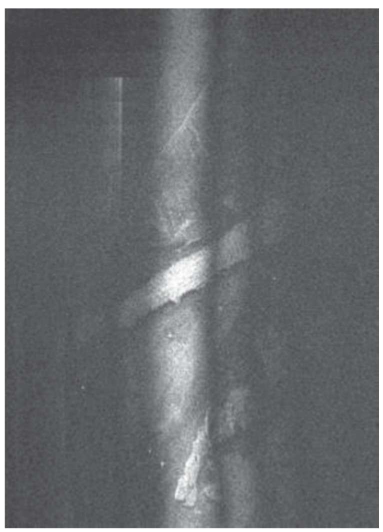
Beam 6



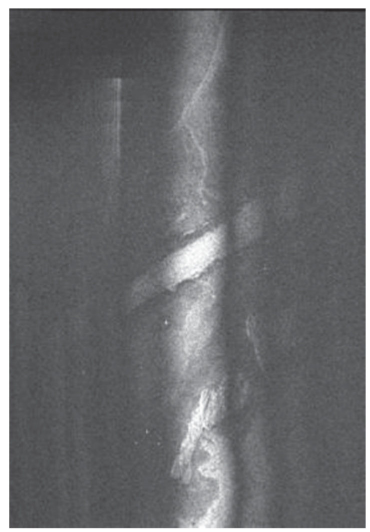
Beam 5



Beam 4



Beam 3

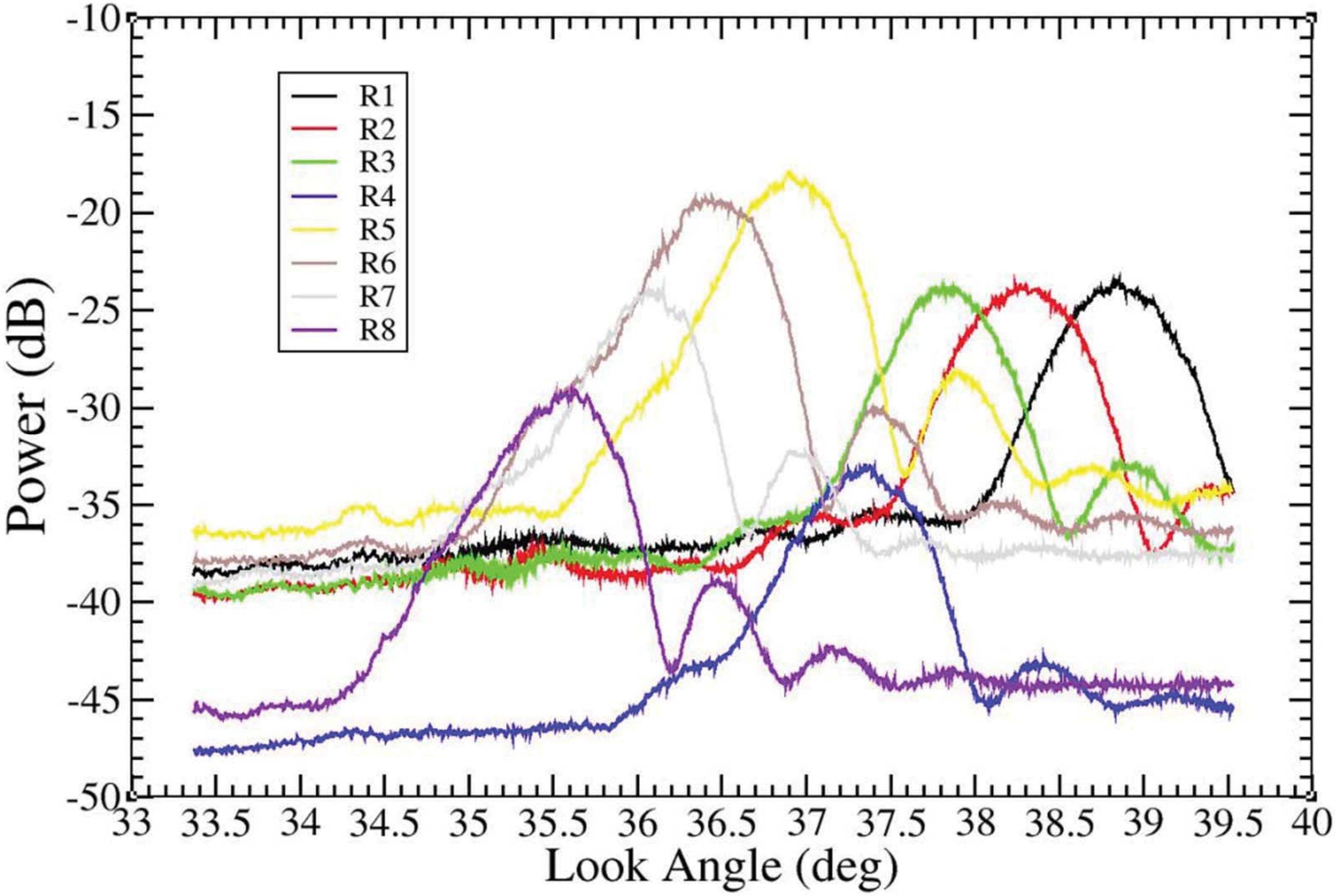


Beam 2

Beam 1

Power Profiles

- Power profiles are in reasonable agreement with measured antenna patterns.
- Note power in channel 4 and 8 are low as expected from the spectral plots.

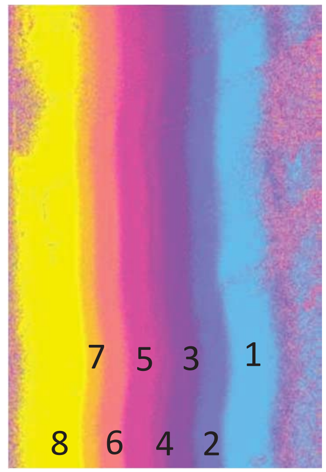


Corner Reflector Image

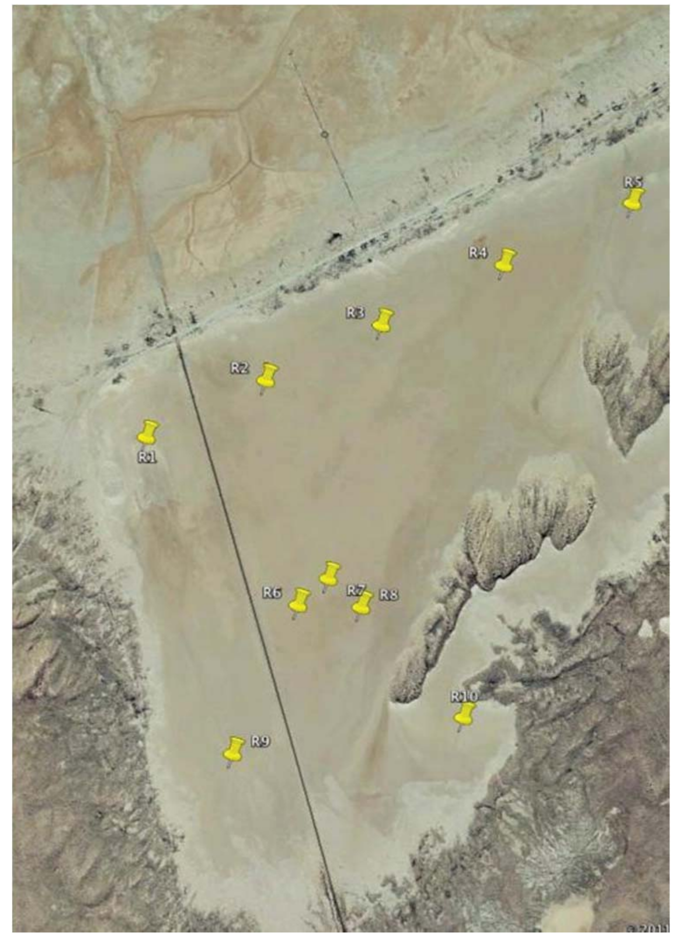
- Simple maximum power combining algorithm used to generate a simple mosaic of the individual beam images.

Beam Mosaic Image

Beam Number Image

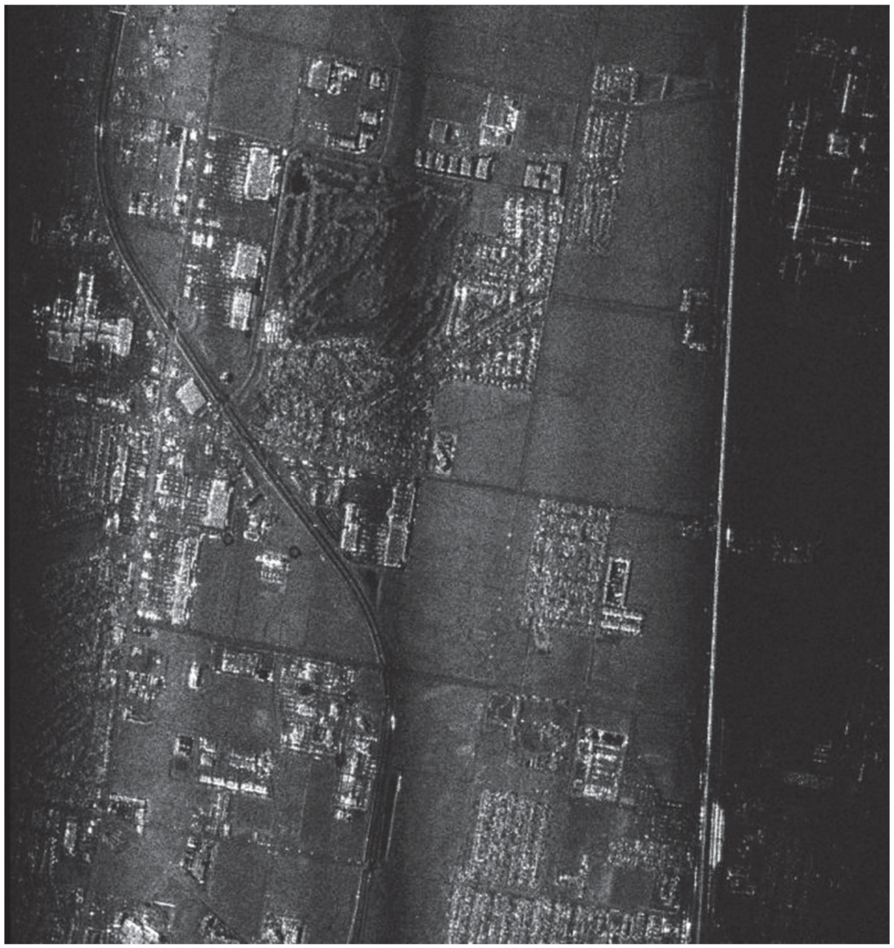


Google Earth Image



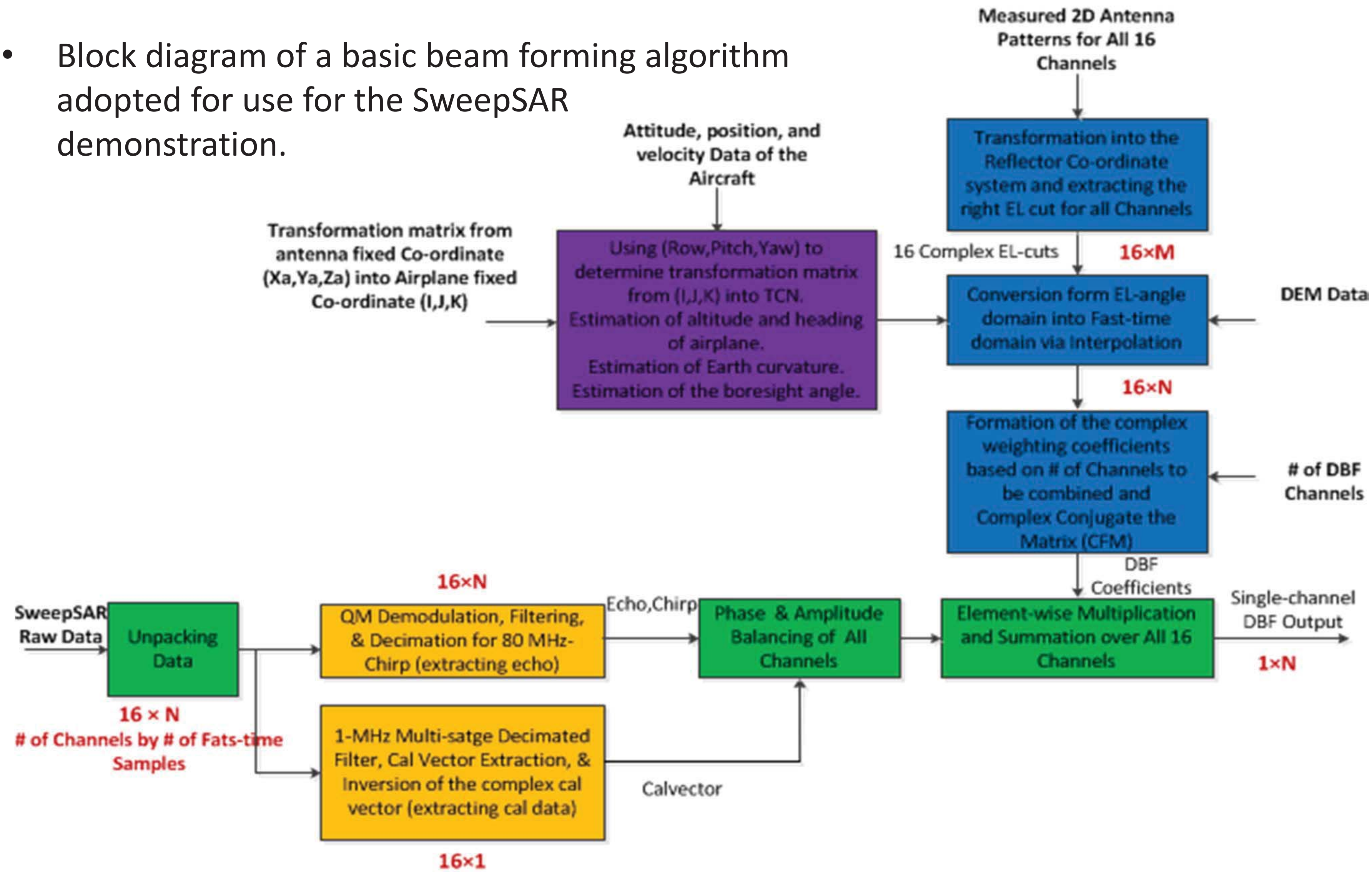
14 Freeway Imagery

- Simple maximum power beam mosaic of over section of the 14 freeway.



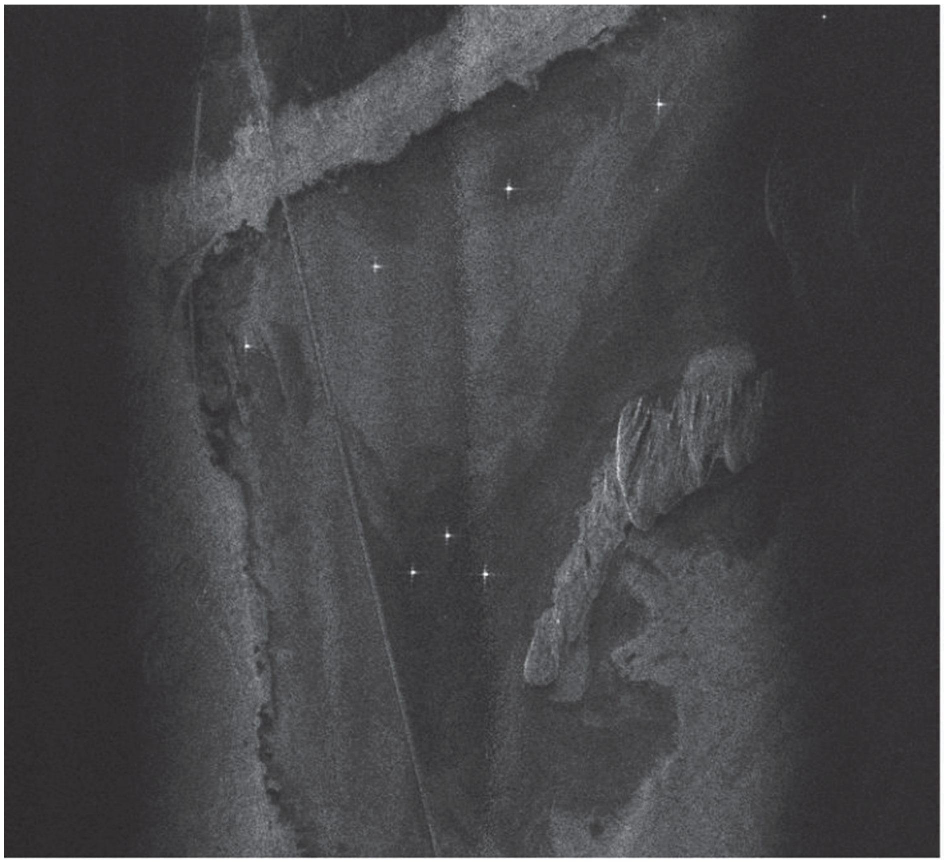
SweepSAR Digital Beam Forming Algorithm

- Block diagram of a basic beam forming algorithm adopted for use for the SweepSAR demonstration.

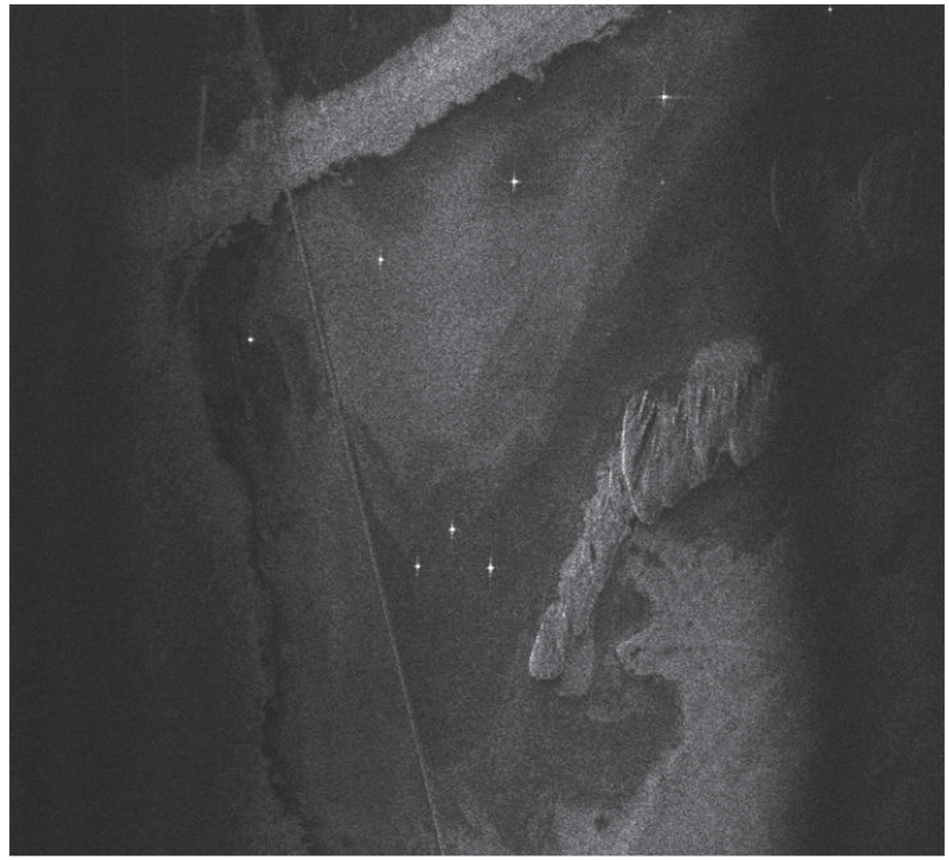


Rogers Lake Beam Formed Imagery

- Pass 11 imagery before and after beam forming.



Simple Mosaic



Beamformed Image

Palmdale, CA Beamformed Imagery

Visible image (Google Earth)

Beamformed Ka-band SweepSAR Image

Conclusions

- NASA/JPL has developed SweepSAR technique that breaks typical SAR trade space using time-dependent multi-beam DBF on receive
- Developing SweepSAR implementation using array-fed reflector for proposed DESDynI mission concept
- Performed first of a kind airborne demonstration of the SweepSAR concept at Ka-band.
- Validated calibration and antenna pattern data sufficient for beam forming in elevation.
  - Provides validation evidence that the proposed DESDynI system architecture is sound.
- Additional testing will include the injection of synthetic targets to validate the range ambiguity predictions of SweepSAR.
- Future plans include using prototype DESDynI digital flight hardware to do the beam forming in real-time onboard the aircraft.