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

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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

Pre-decisional - for Planning and Discussion Purposes Only
**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”

[* Frank Kantrowitz, Dave Ksienki, Mark Barrera, Walter Bloss, Vince Canales, Peter Carian, Adam Chandler, David Chien, Keven MacGowan, Samuel Osofsky, Dec 17, 2010]
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).
**SweepSAR Pulse Timing**

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

  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.

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Antenna System

- Deployable mesh antenna
  - 9m to 15m projected diameter
  - Northrop AstroMesh or Harris Deployable Truss
  - High mass efficiency: 1.0 – 1.5 kg/m²
  - 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

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Value</th>
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<tbody>
<tr>
<td>D</td>
<td>Projected aperture</td>
<td>15 m</td>
</tr>
<tr>
<td>F</td>
<td>Focal Length</td>
<td>15 m</td>
</tr>
<tr>
<td>H</td>
<td>Edge offset</td>
<td>-2.0</td>
</tr>
<tr>
<td>$\Psi_C$</td>
<td>Center angle</td>
<td>21°</td>
</tr>
<tr>
<td>$2\Psi_S$</td>
<td>Subtended angle</td>
<td>55°</td>
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### Nominal Performance Prediction

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<tr>
<th>Parameter</th>
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<th>Tx</th>
<th>Rx</th>
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<tbody>
<tr>
<td>Scan range</td>
<td>deg</td>
<td>N/A</td>
<td>± 8</td>
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<tr>
<td>Directivity</td>
<td>dBi</td>
<td>33.3</td>
<td>42.3</td>
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<tr>
<td>Loss</td>
<td>dB</td>
<td>1.7</td>
<td>1.7</td>
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<tr>
<td>Gain</td>
<td>dBi</td>
<td>31.6</td>
<td>40.6</td>
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<tr>
<td>HPBW az</td>
<td>deg</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>HPBW el</td>
<td>deg</td>
<td>15.9</td>
<td>1.0</td>
</tr>
<tr>
<td>Cross Pol</td>
<td>dB</td>
<td>-25</td>
<td>-25</td>
</tr>
<tr>
<td>EIRP</td>
<td>dBW</td>
<td>65.4</td>
<td>N/A</td>
</tr>
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</table>
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
Pointing and Blockage

- **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.

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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-its-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

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SweepSAR Airborne Demo Hardware

- DC-8 Nadir-2 Port Pressure Box
- 16-channel Digital Receiver Array (Mounts on top plate, not shown in solid model)
- Inertial Measurement Unit (LN-251 EGI)
- 40 cm Reflector
- Transmit Array
- Radome
- High-stability feed arm
- 16-channel Active Receiver Feed

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Transmit Antenna

- 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

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

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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.
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.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wavelength</td>
<td>8 mm</td>
</tr>
<tr>
<td>PRF</td>
<td>1300 Hz</td>
</tr>
<tr>
<td>Bandwidth</td>
<td>80 MHz</td>
</tr>
<tr>
<td>Sampling Frequency</td>
<td>240 MHz</td>
</tr>
<tr>
<td>Flight Altitudes</td>
<td>8750 or 10500 m</td>
</tr>
<tr>
<td>Transmit Power</td>
<td>250 W</td>
</tr>
</tbody>
</table>
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

Experiment Locations at Edwards AFB

Flight Direction 80° Heading

1.5 km

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SweepSAR Demo Successful Test Flights

- **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)**

- Terrain Echoes
- Reflector Echoes
- Antenna Beam
- Cal Tone
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

Mainlobe
Sidelobes

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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.
Palmdale, CA Beamformed Imagery

Visible image (Google Earth)  Beamformed Ka-band SweepSAR Image

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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.