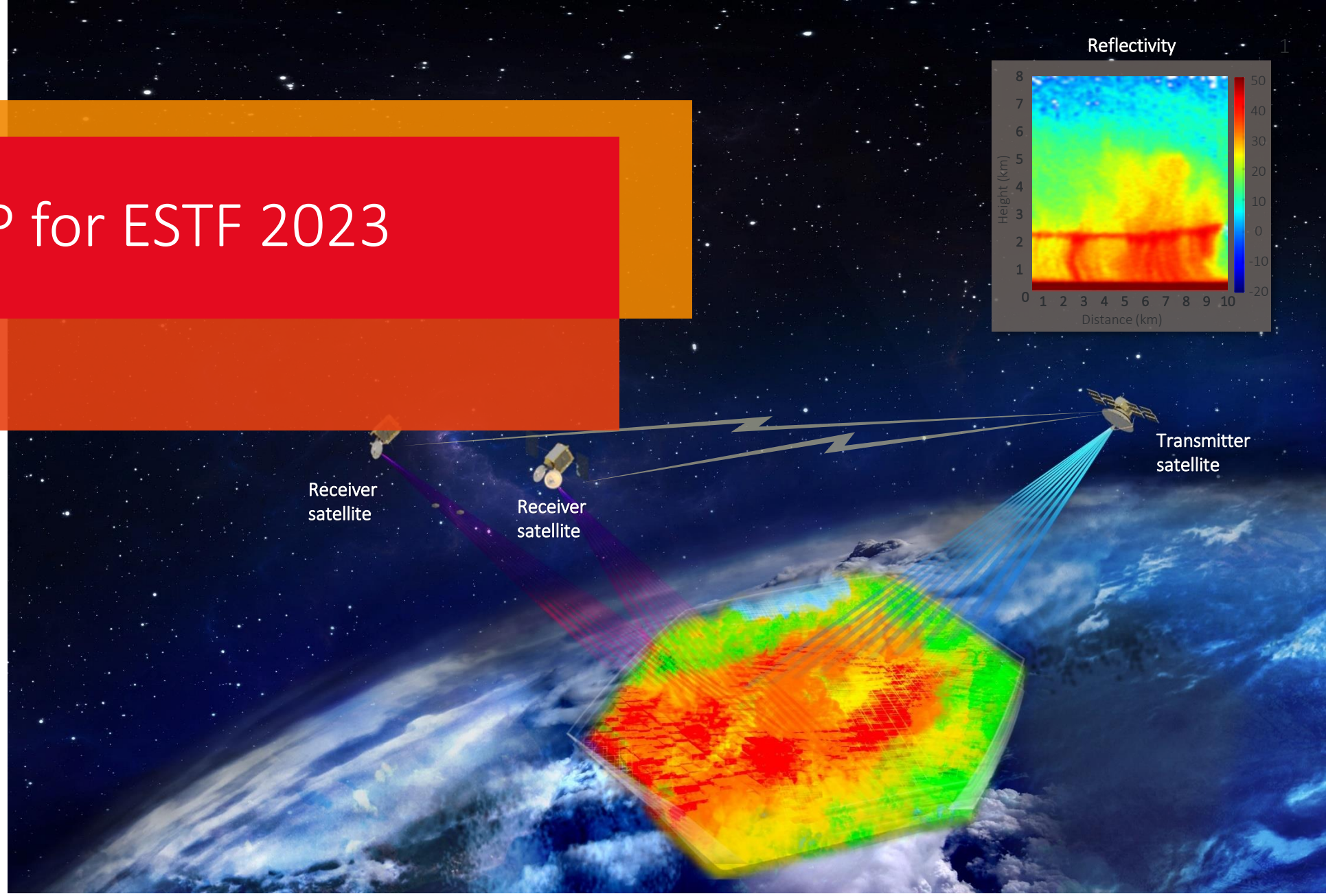
SToRM SAR IIP for ESTF 2023

22 June 2023



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SToRM SAR (Instrument Incubator)

Satellite Tomography of Rain and Motion via Synthetic Aperture Radar

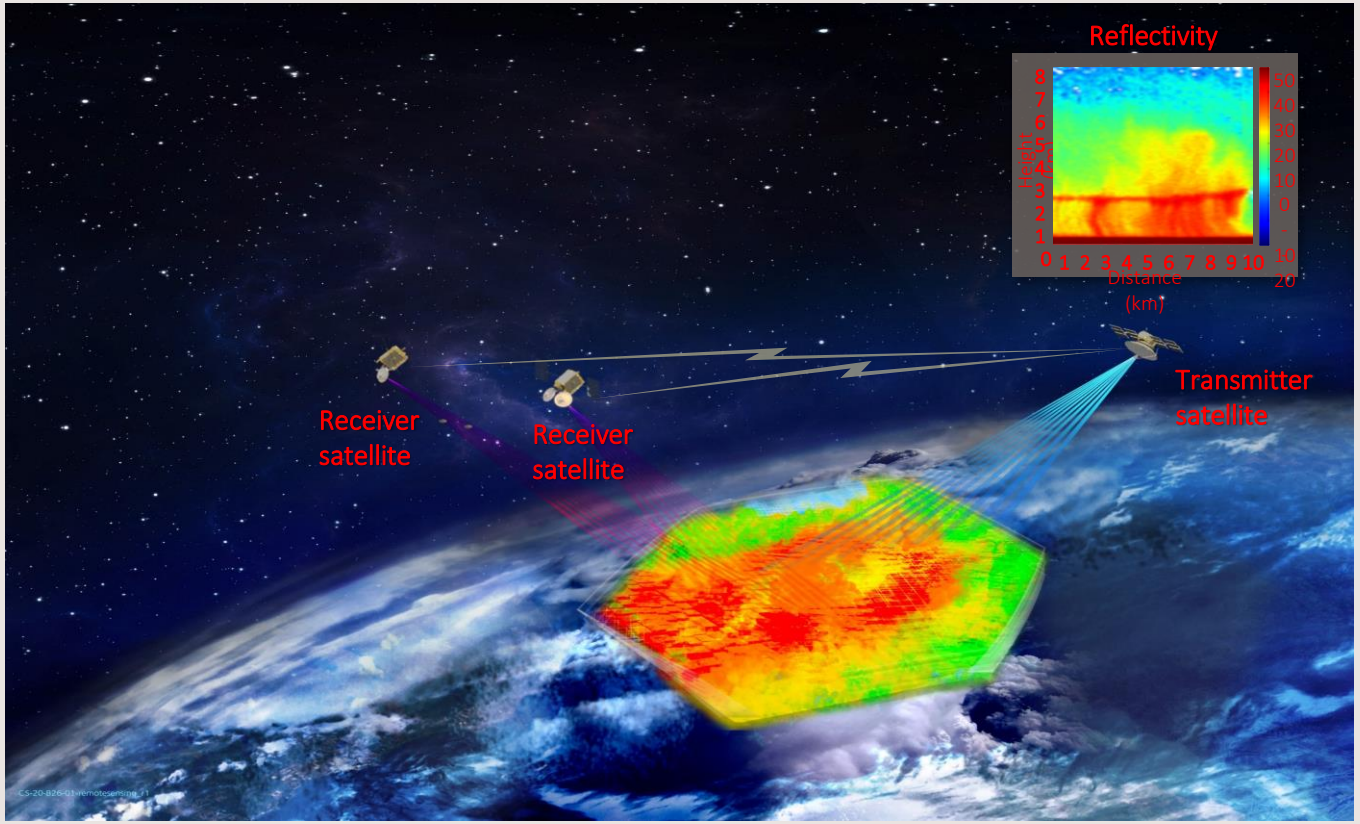
PI: Kevin Maschhoff , BAE Systems

Co-I: M. Ryba, BAE Systems

Co-I: V. Chandrasekar, Colorado State University

Concept Summary

- **Precipitation Observations from space at ~ 1 km horizontal resolution are needed to characterize severe storm processes for weather research**
- **Providing these observations via up-scaled real-aperture methods would be very costly**
- **SToRM employs a distributed architecture of microsatellites to implement a networked weather radar**



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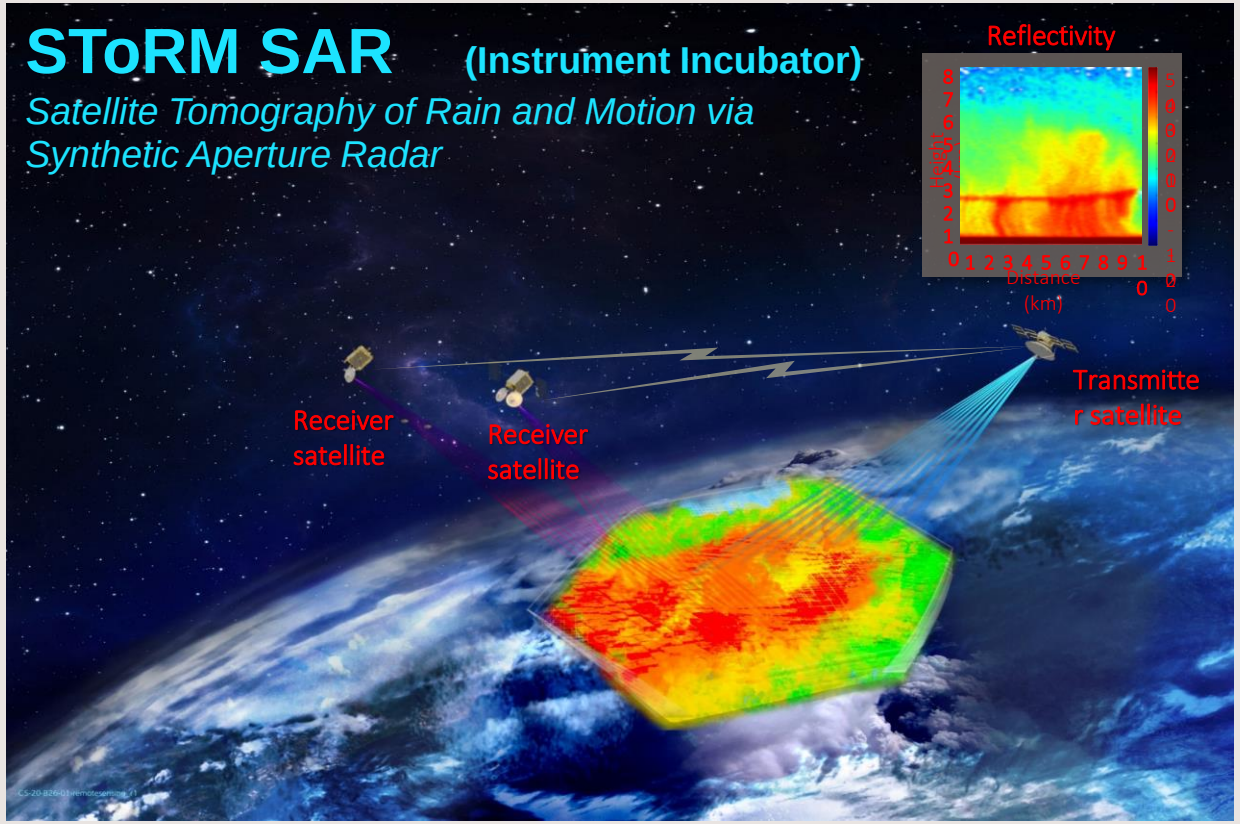
SToRM SAR Methods Address Observation Needs Other Approaches Cannot Provide

- Diffraction (λ/D issues) Strongly Limit Horizontal Resolution
  - SAR Methods Required to Provide Significant Improvements in Horizontal Resolution with Affordable Antenna Sizes
- Increasing Radar Frequency (above Ku-band/14 GHz) is Inconsistent with profiling intense storms
  - Attenuation > 100 dB/km in Ka-Band, higher in W
- Monostatic FM SAR Observing Methods (e.g. GPM/DPR, RainCube) face severe range/Doppler ambiguity limitations in Precipitation Observation
  - Bi-Static geometry with Phase-Encoded Pseudo-Random waveforms and R/D/Aggregation Tomography Methods provide observations in the presence of Doppler Spectral Spread



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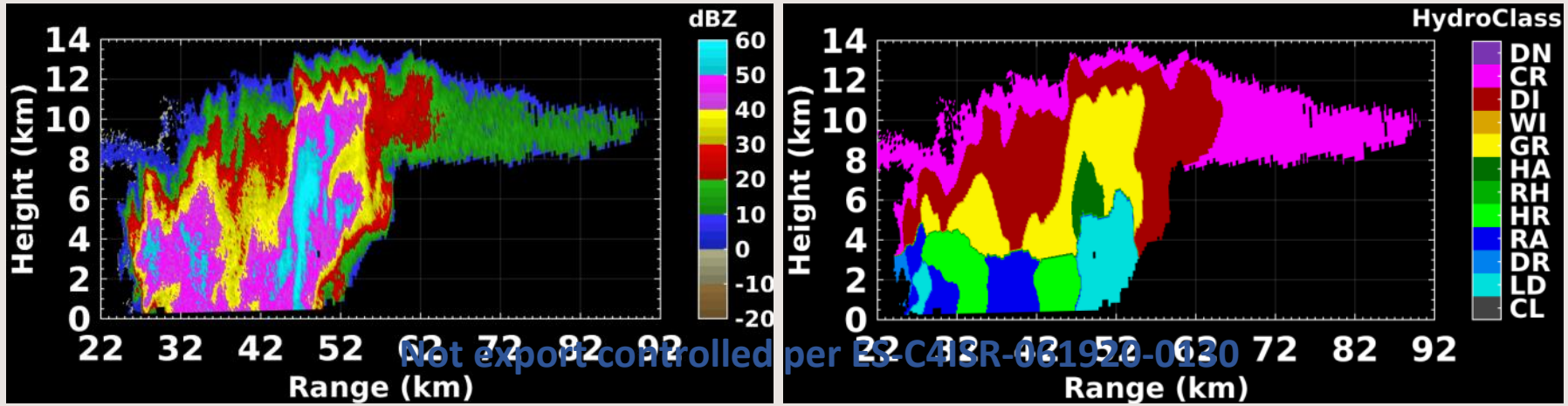
What Spatial Resolving Power Is Needed to Observe Intense Mid-Latitude Storms From Space?



Radar Reflectivity Cross Section and Hydrometeor (classified) Cross-Section for a Precipitation Event Observed at 23:43UTC, May 29, 2013 by NPOL during the IFLOOD Field Campaign (HydroClass: CL: Clear Air, LD: large drops, DR: drizzle, RA: rain, HR: heavy rain, RH: rain plus hail, HA: hail, GR: graupel, WI: wet ice, DI: dry ice, CR: crystals)

Ground-Based Radar Observations Illustrate that ~ 1 km Horizontal Resolution Needed to Characterize Intense Storms

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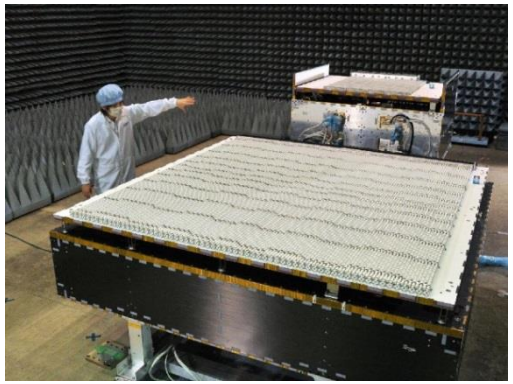
Problem to Solve-Providing 1 km Horizontal Resolution Precipitation Observations from Space

NASA/JAXA's Premier Space-Based Precipitation Radar:

- ~$1B Mission, a Decade in Development
- Its 5 km Spatial Resolution at Ku-Band is 5x Coarser than Needed For Many Intense Storms



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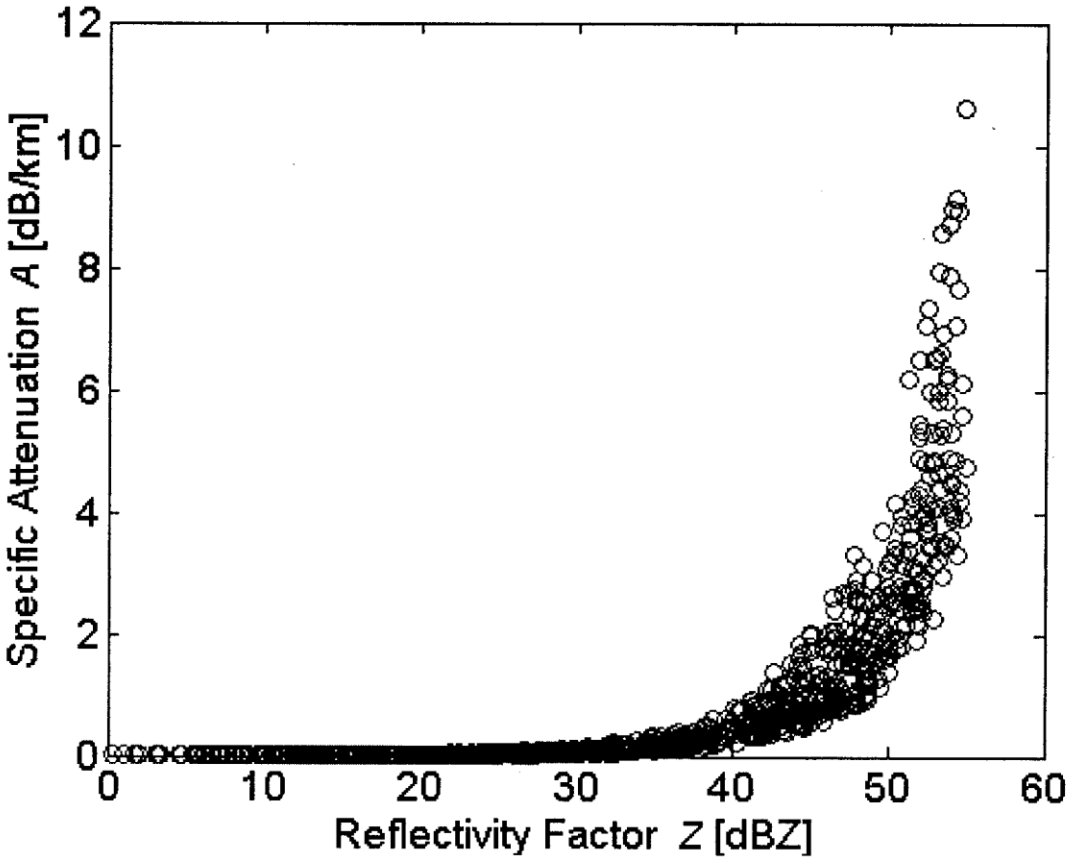
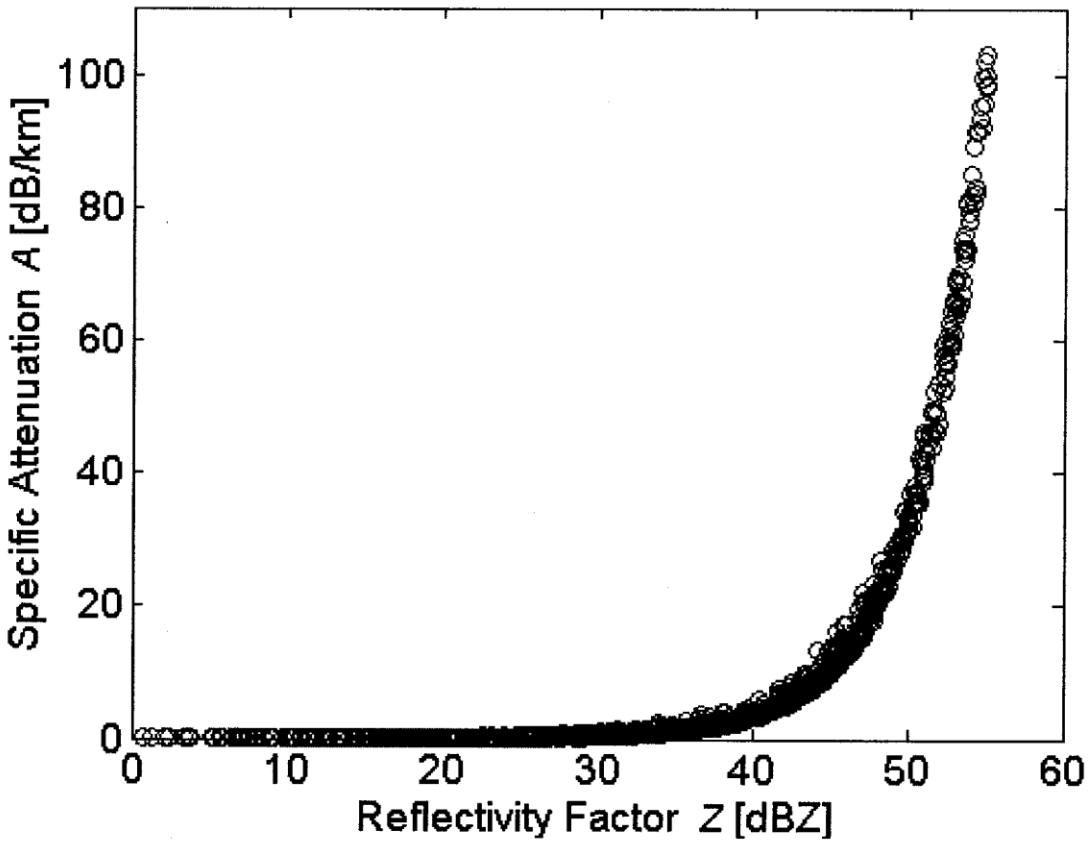
Specific Attenuation at Ka and Higher Frequencies Limits Vertical Profiling of Intense Convective Storms





Global Mapping of Attenuation at Ku- and Ka-Band

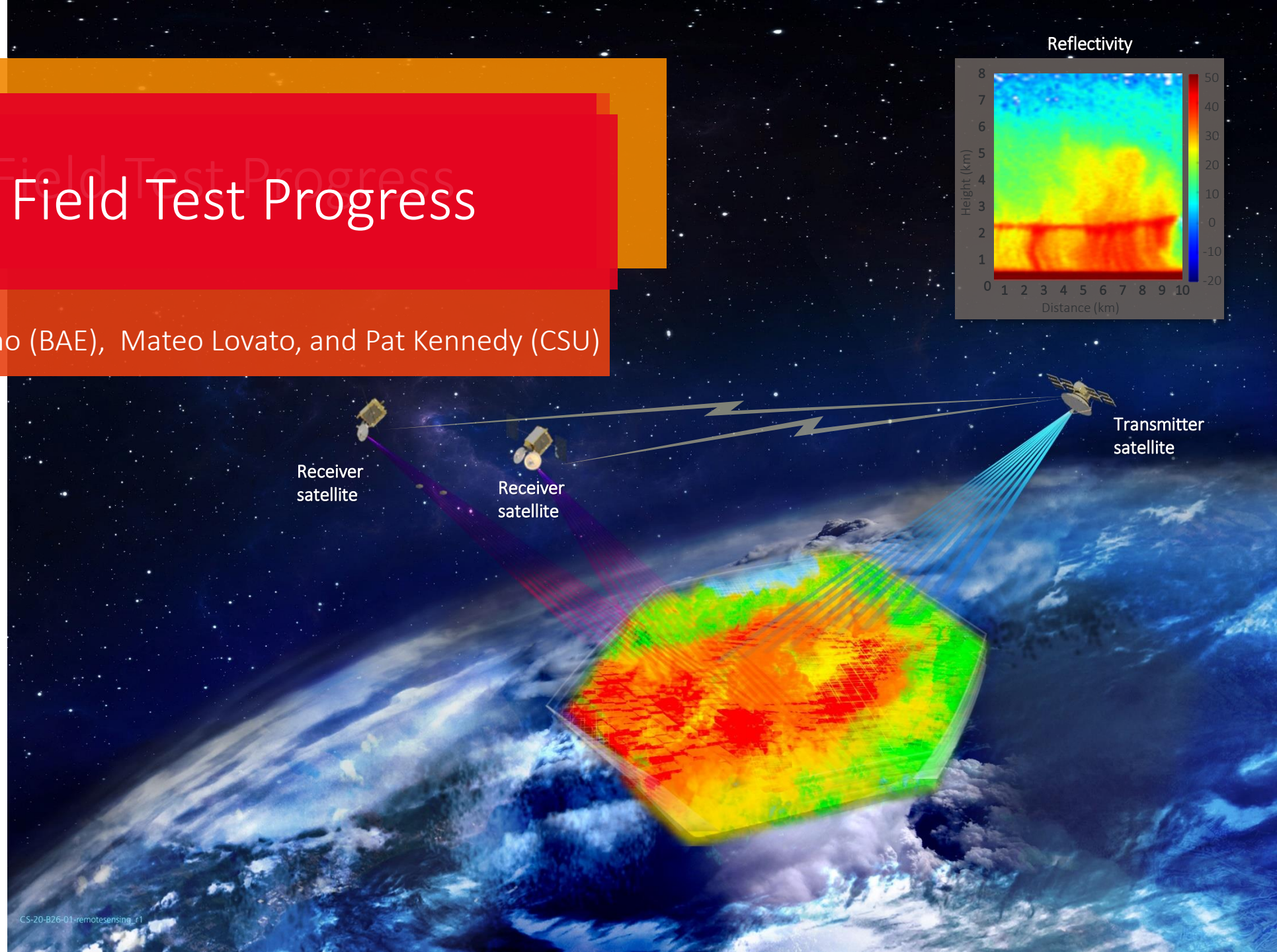
V. Chandrasekar, Hiroki Fukatsu, and K. Mubarak

While Real-Aperture Diffraction-limited Footprints (and Antennas) are Smaller at Ka, Path Attenuation is Much Larger

IEEE TRANSACTIONS ON GEOSCIENCE AND REMOTE SENSING, VOL. 41,

Precipitation Field Test Progress

Marty Ryba, Carissa Agostino (BAE), Mateo Lovato, and Pat Kennedy (CSU)



Ground-Based Field Tests Progress and Status

- Data collected from April-August in updated configuration (tents later added for shade)
- Several storm events measured, some hardware issues fixed; CONOPS improved with practice; trained CSU operators; August data best
- System now packed for winter, can be used this coming season to support airborne tests or other collection needs

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Receiver Location

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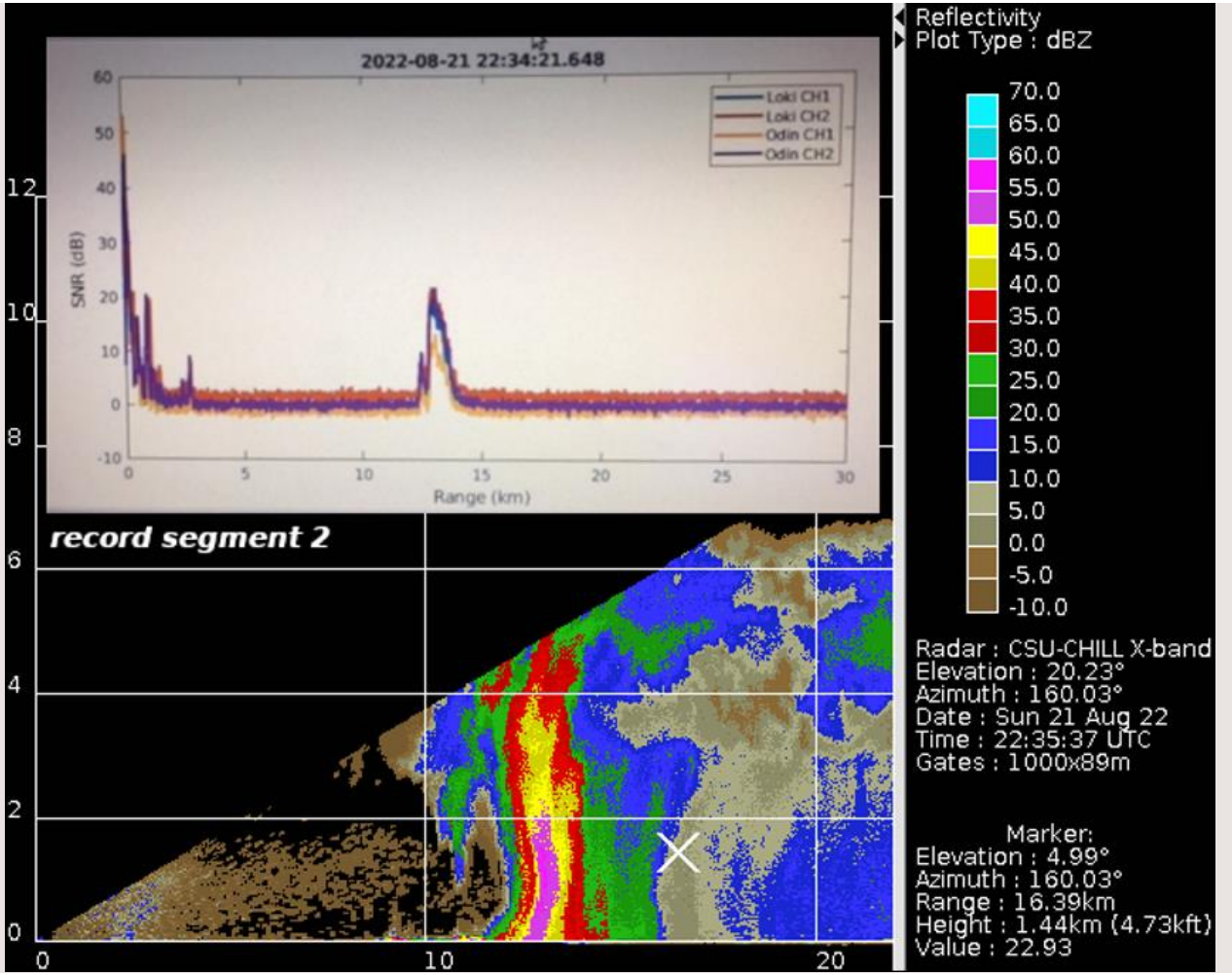
Example Data Results

- From August 21, 2022 collection, storm started strong and then weakened some as it approached CHILL but several good collections
- Example quick-look results shows CHILL RHI image, with example real-time range profile feedback from BAE receivers



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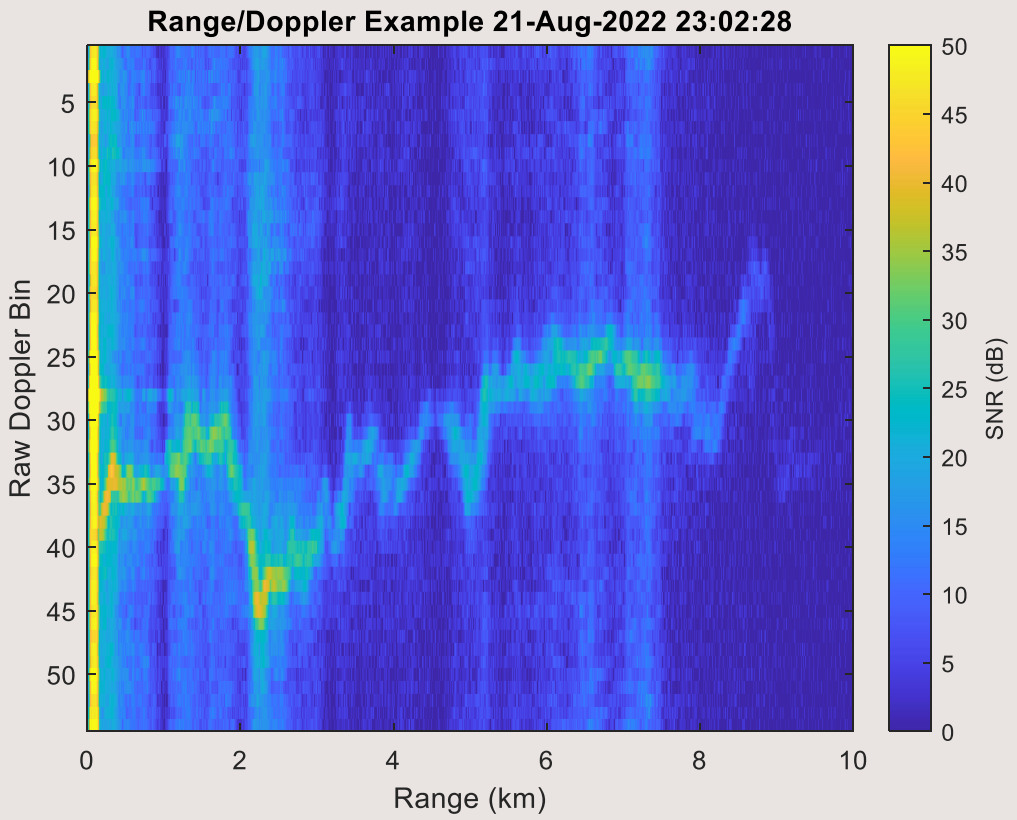
Coherent Processing Results

- Was able to establish synchronization between CHILL transmissions and BAE receivers
- Collected CHILL data provided transmitter phase behavior pulse-to-pulse along with GPS data for traceability
- Coherent processing improves BAE data signal-to-noise ratio and allows measurement of velocity
- Examined detailed correlation behavior between simultaneous receive channels but did not establish any firm feature to support high resolution delta-range processing hypothesis



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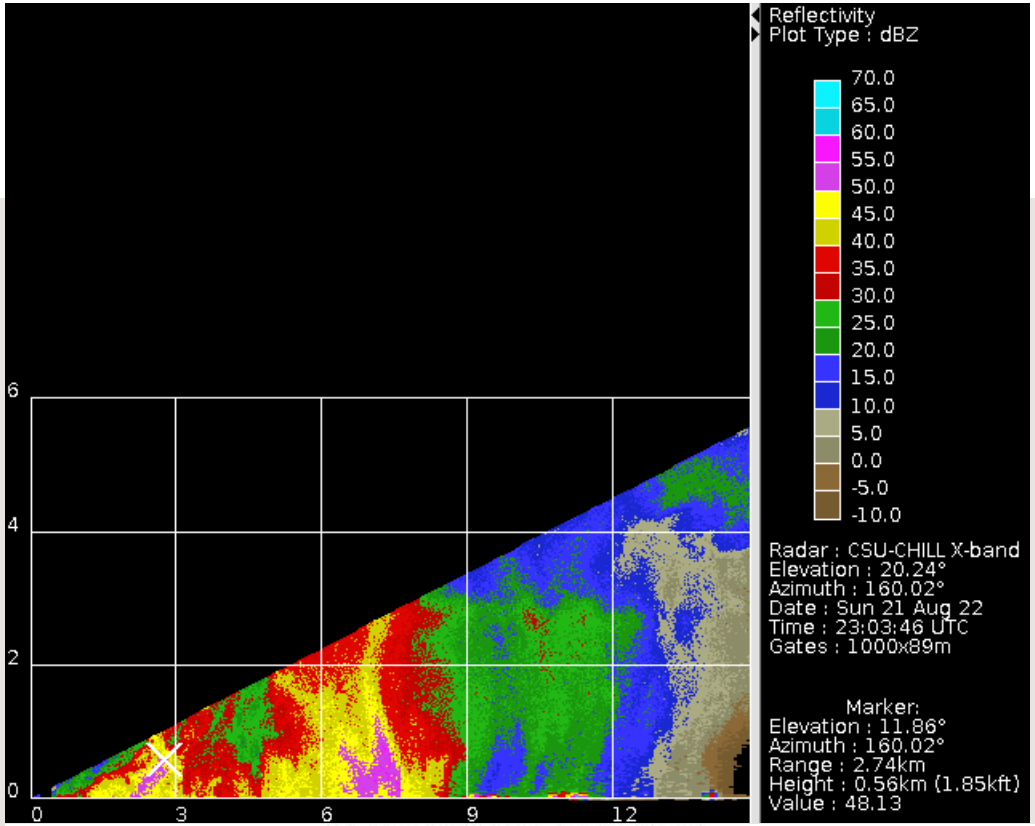
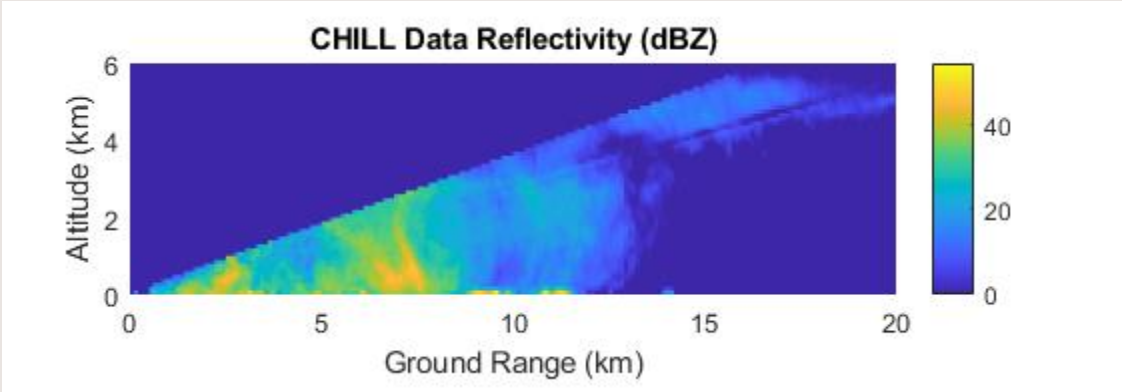
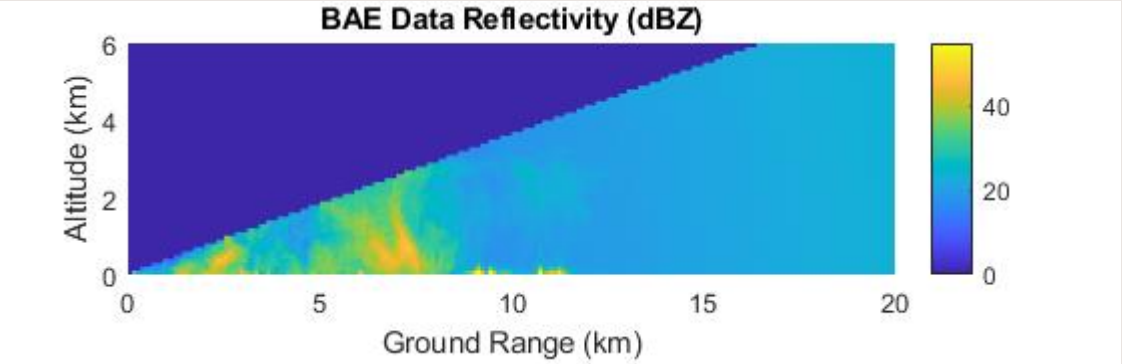
Data Comparison: Reflectivity

- From one constant-azimuth scan 0-20 deg elevation on Aug 21 23:02:00-23:03:50
- Compare standard CHILL result (upper right) with my processing of raw CHILL data (below) and same processing of bistatic data (lower right)







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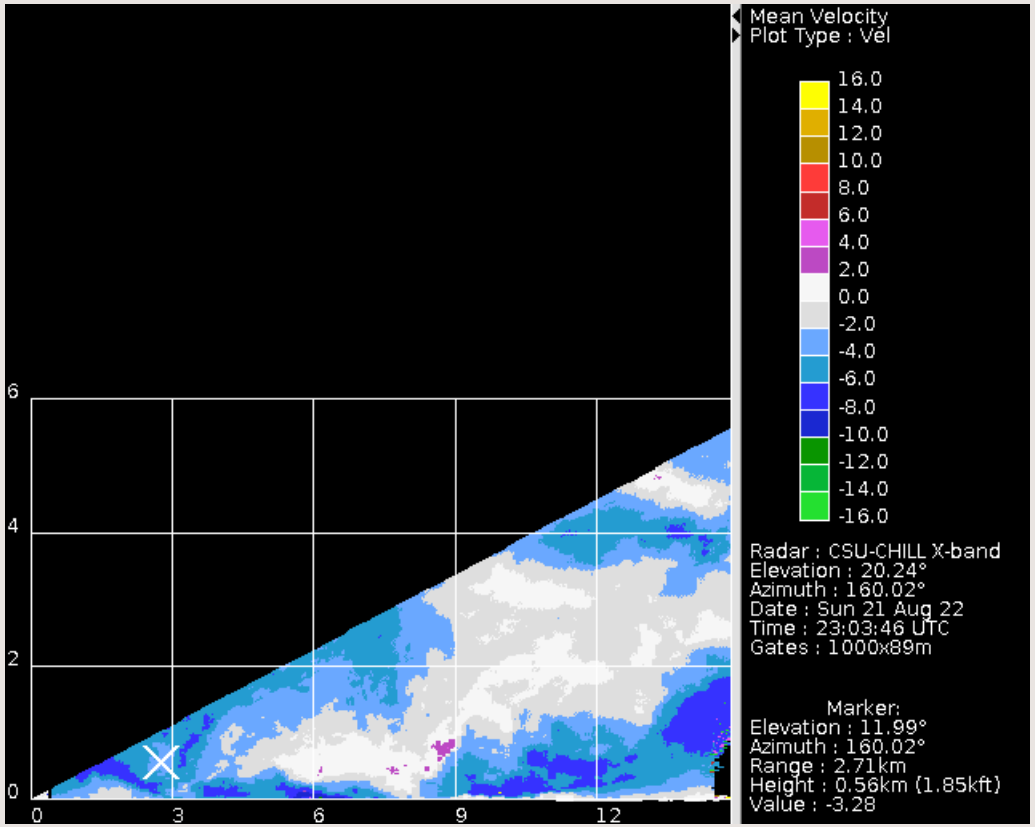
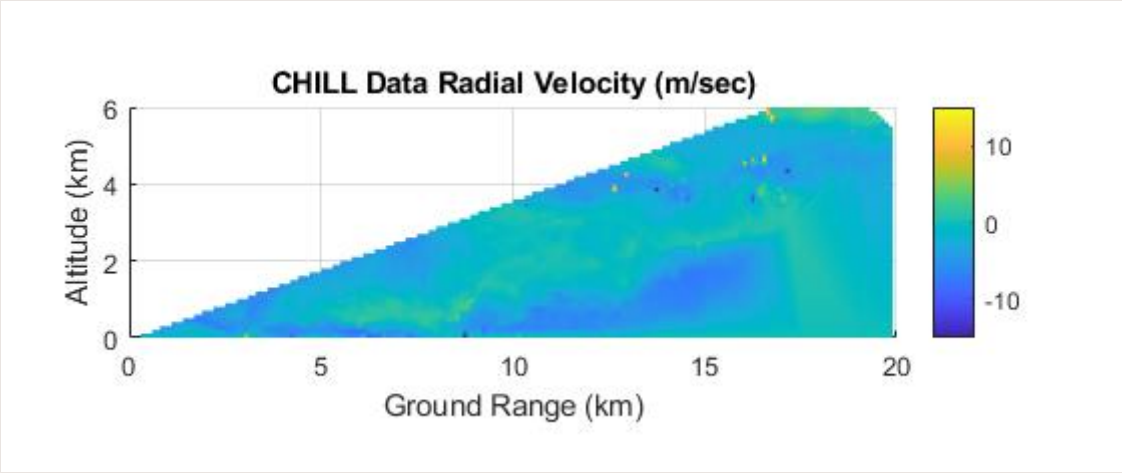
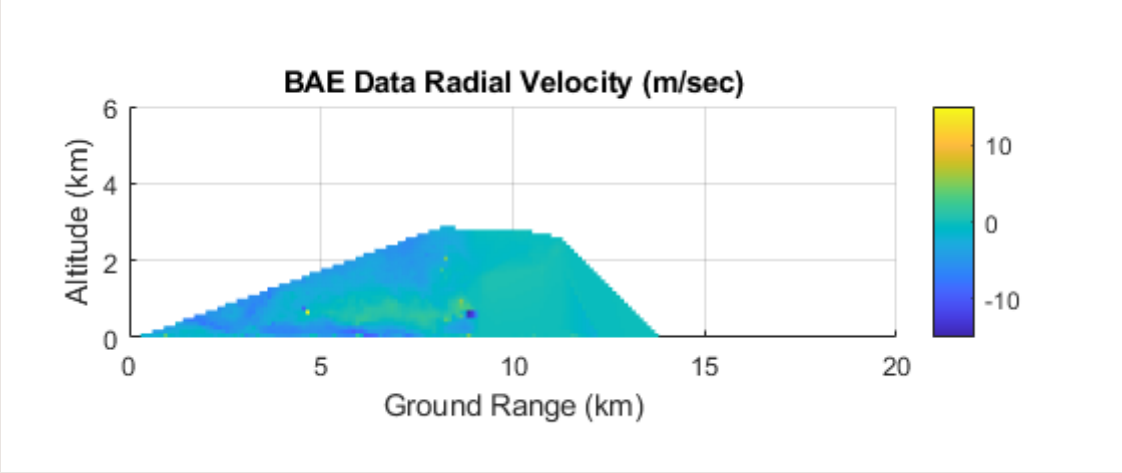
Data Comparison: Velocity







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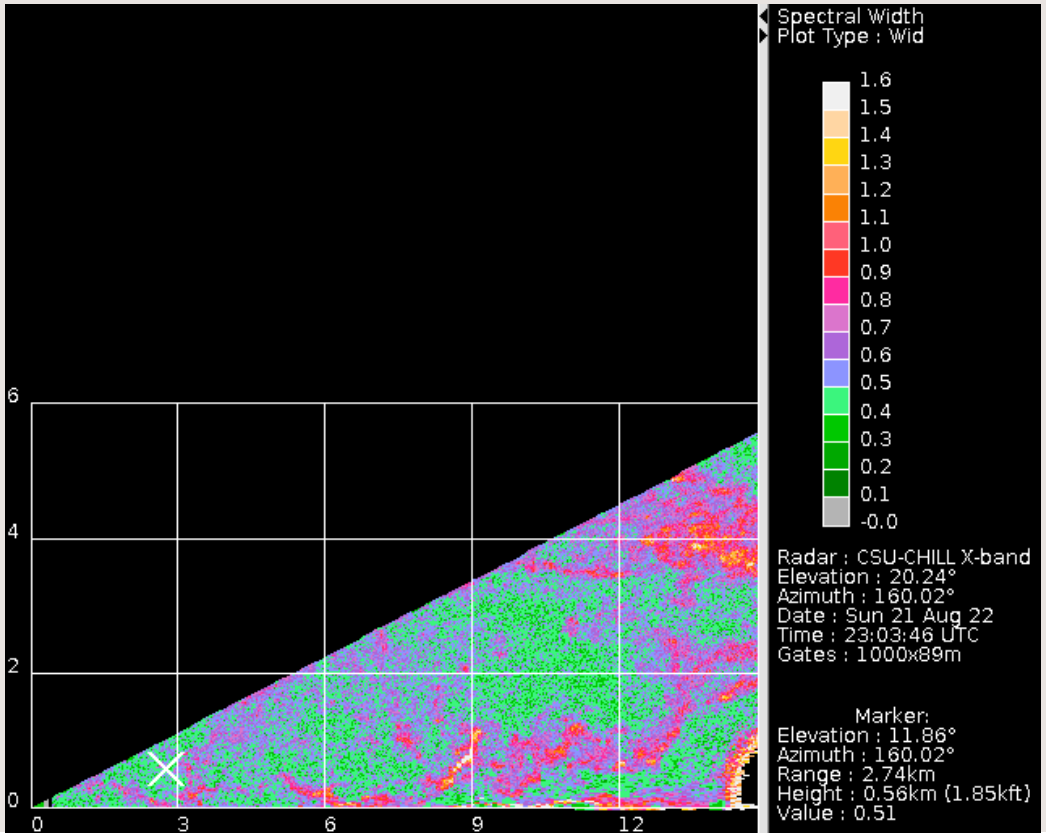
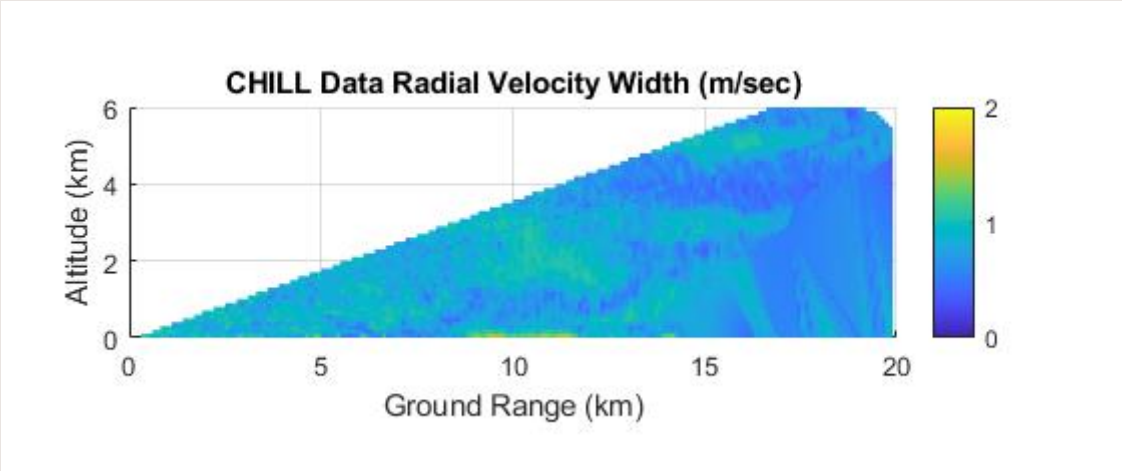
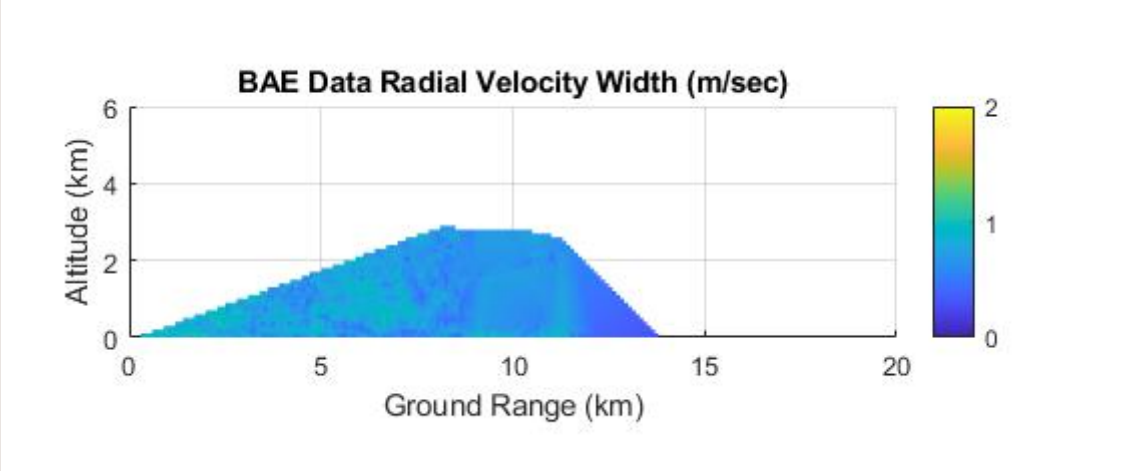
Data Comparison: Velocity Width







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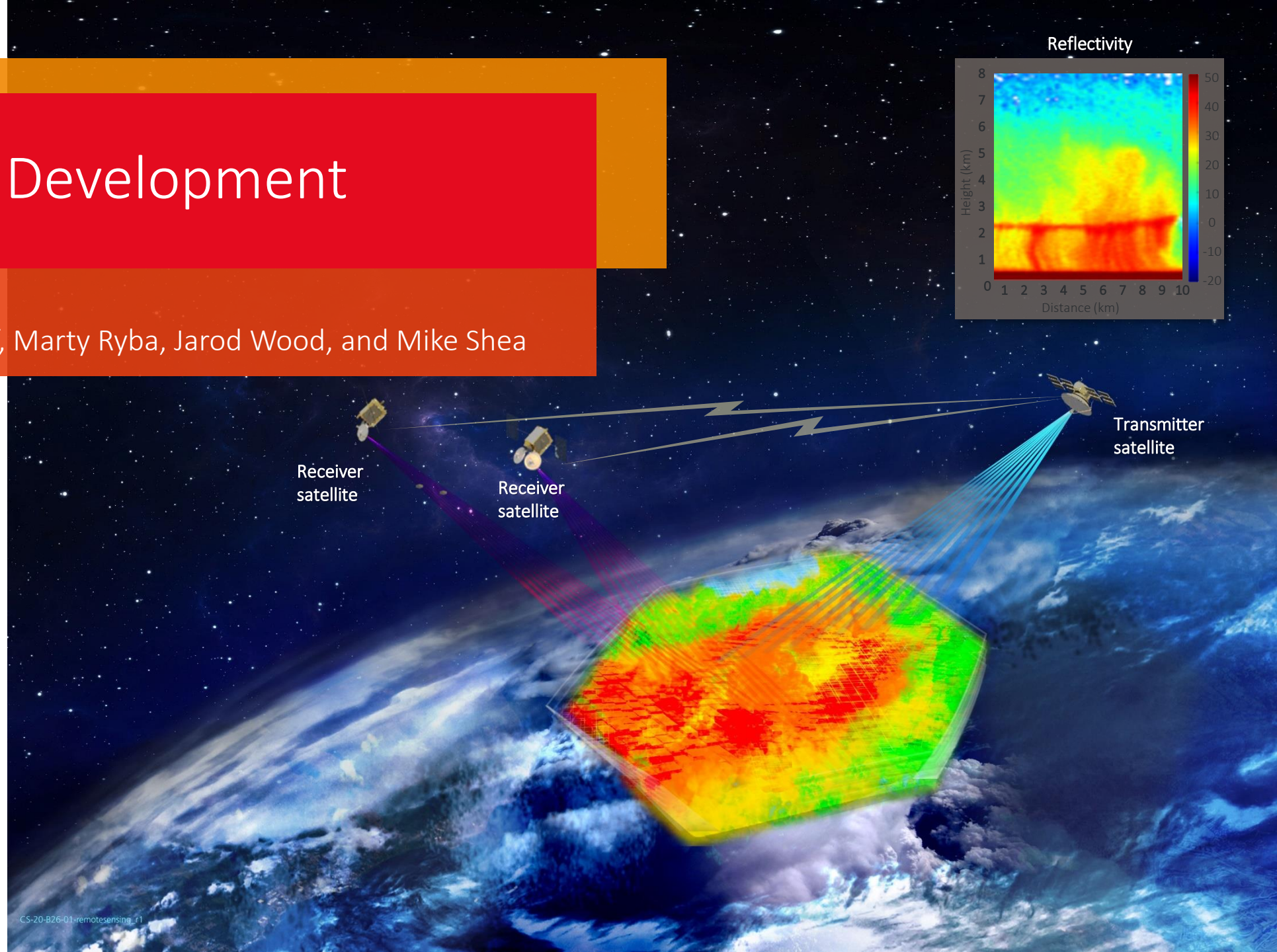
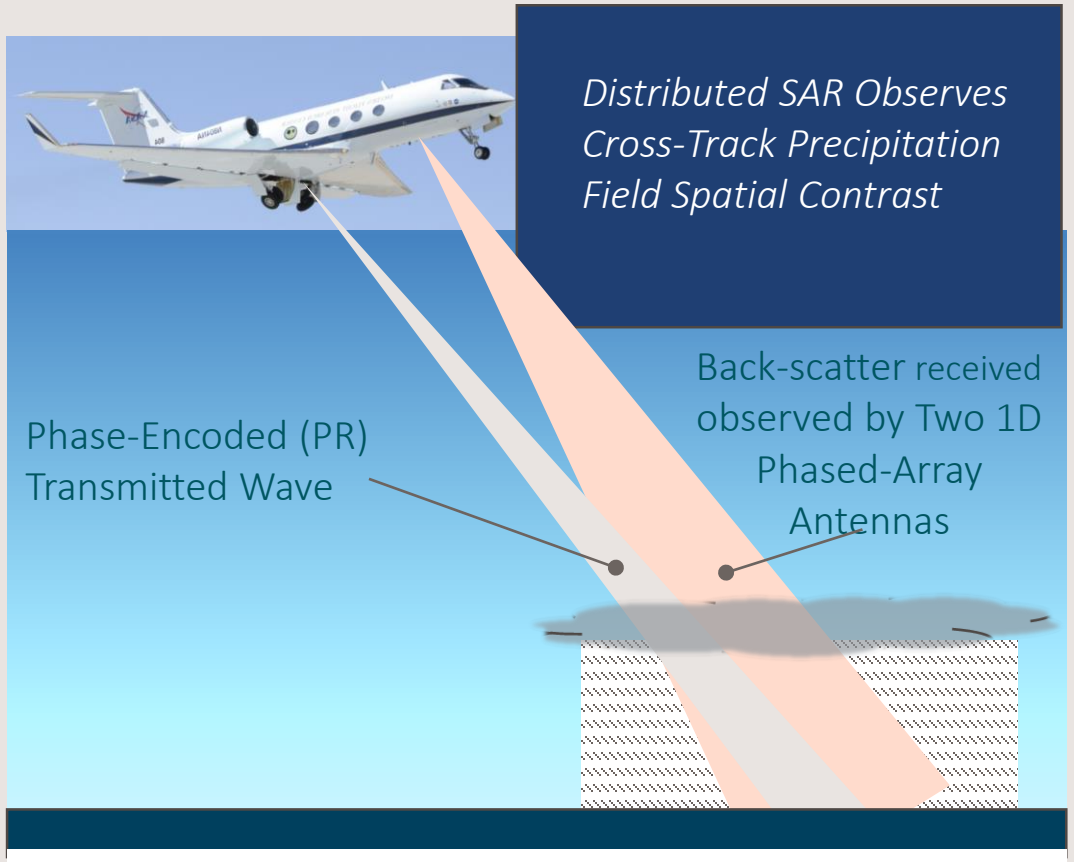
Airborne Test Development

Paul Hare, Kevin Maschhoff, Marty Ryba, Jarod Wood, and Mike Shea



Airborne Demonstration Concept of Operations



Airborne Precipitation Observation via Synthetic Aperture Radar Observation Enabled Under Certain Conditions

- Along-Track SAR with Range/Doppler TDI Observes Vertical and Along-Track Field Structure (2 of 3 Field Dimensions)
- Cross-correlation Observations, Some Using Spaced-Antenna/Shared Volume Methods Used to Observe Spatial Contrast in Third (cross-track) axis
  - Sensitive to Spatial Contrast Finer than Beam Size

Phased-Array Receivers Allow:

- Beam Steering to Control Receiver-Receiver-Beam Overlap
  - Defining Shared-Volume
- Simultaneous Beam Forming
  - Simultaneous Observation at Multiple Cross-Track Positions

High Resolution SAR Precipitation Radar Using BiStatic Geometry, and Continuous PR Phase-Encoded Waveform Transmission

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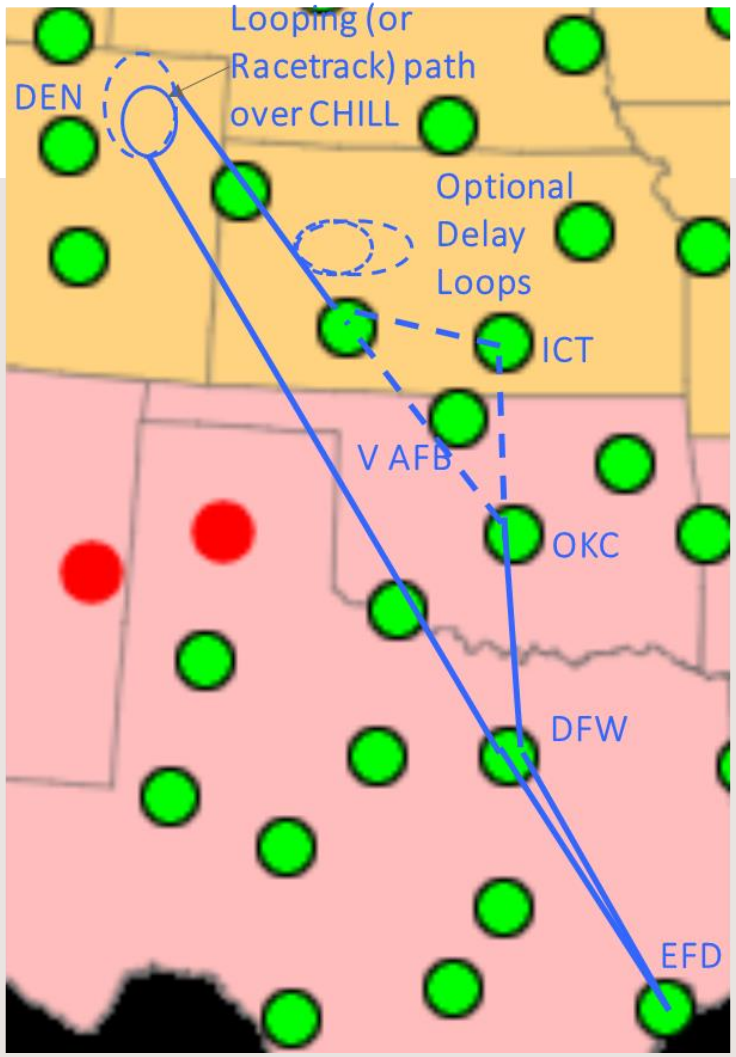
Airborne Demonstration Concept of Operations

- Launch Location : Ellington Field (EFD)
  - Home base for NASA GV,
  - Opportunity to tailor flight-day selection based on rain forecast
- Primary SToRM SAR Observation Site is near CSU CHILL Radar
  - Supporting Coherent, Coordinated X-band airborne and ground-based radar observations
- Secondary Observation way-points provide additional observation opportunities (in “Tornado Alley”)
  - Fly within range of >4 NOAA NEXRAD Doppler weather radars en-route to CHILL, with reasonable probability of severe storm activity in spring
- Way-point or Alternate areas may become Primary in case of precipitation forecast bust near CHILL site.
- Optional Delay Loops may adjust timing of GV CHILL overpass to coincide with peak precipitation-observation opportunity



Flight Path Supports Independent Observations by NEXRAD

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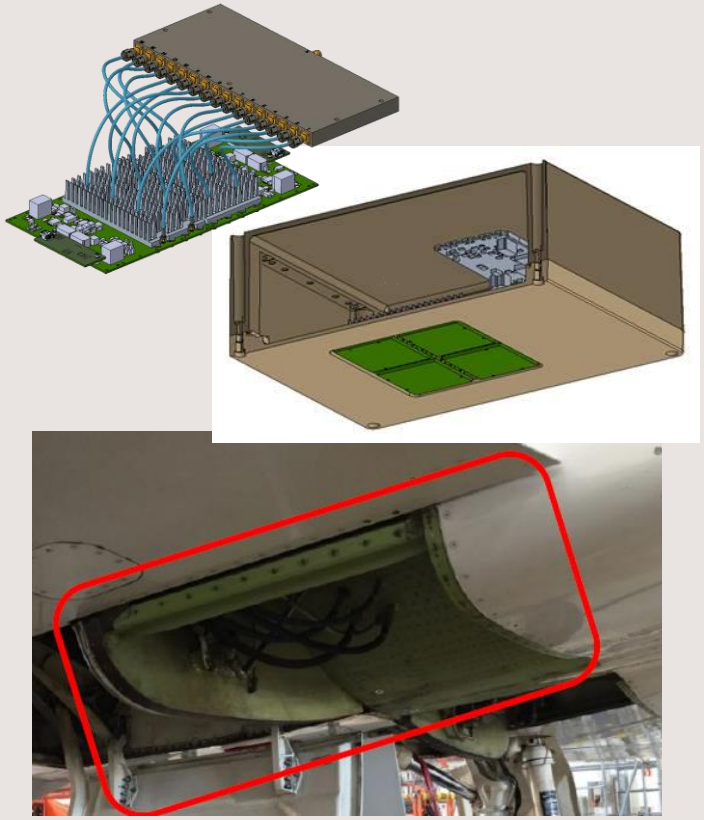
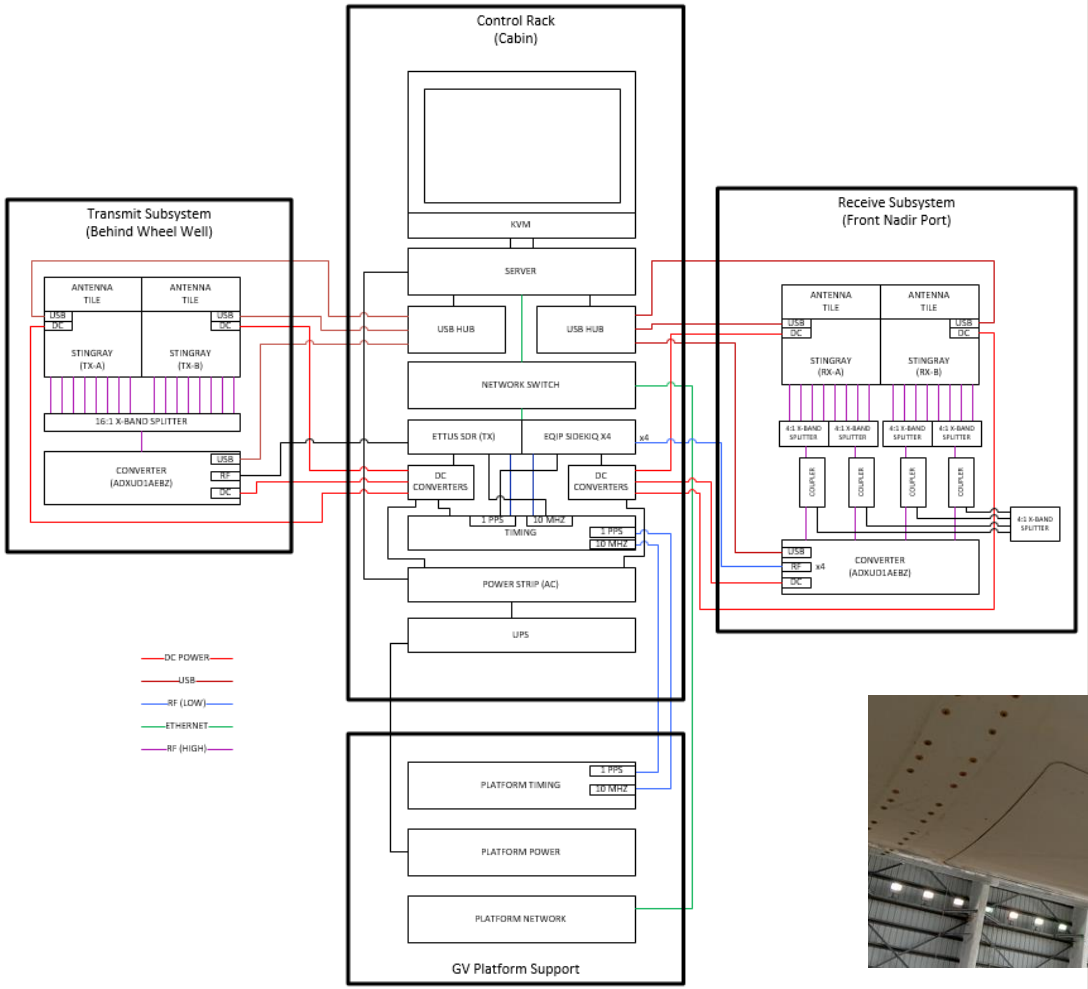
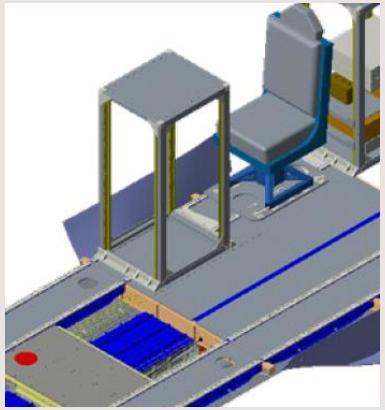
Subsystem Layout in GV



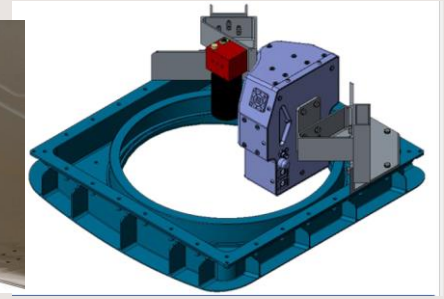
Tx Subassembly
Behind Rear Wheel Well
(Mini Portal Modification)



Control Rack
(Cabin)



Rx Subassembly
Front Nadir Port



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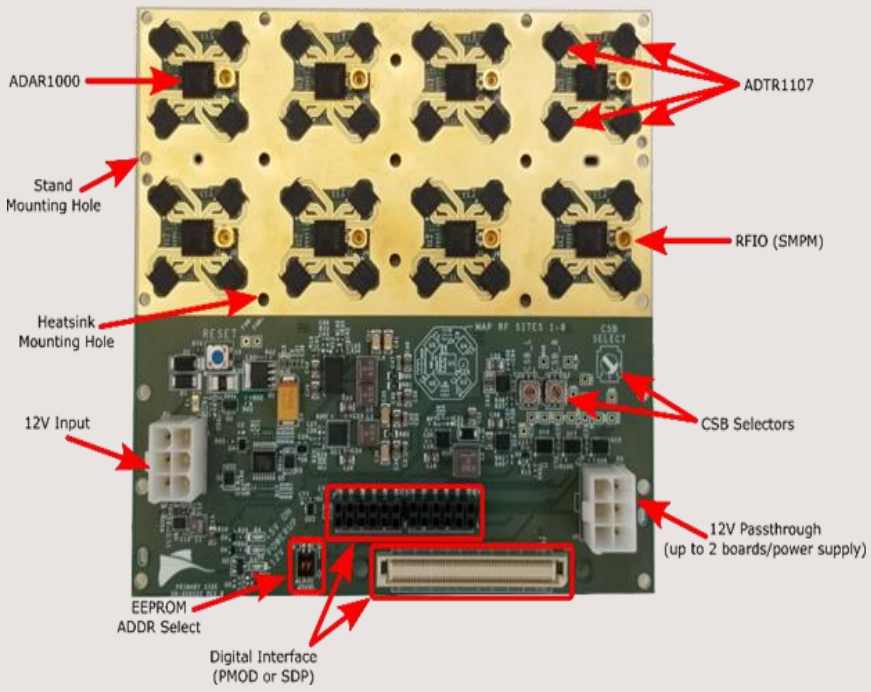
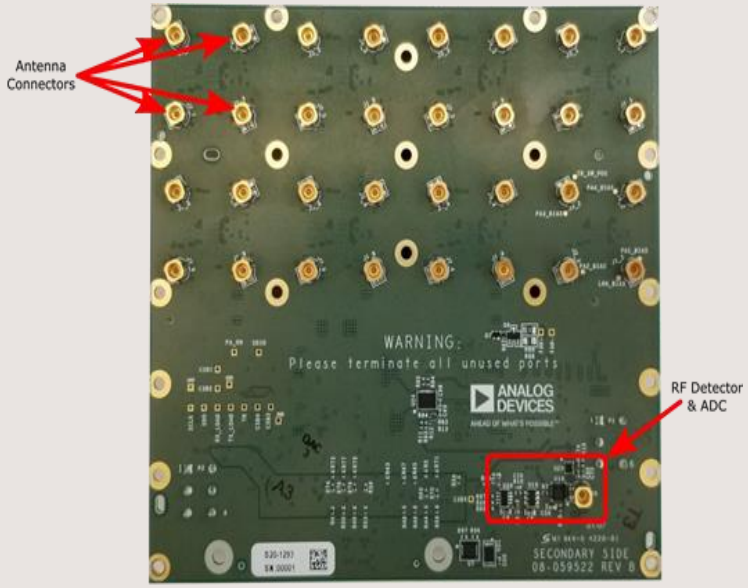
Airborne Demonstration
ADI Stingray Hardware

- Baseline for this SToRM Airborne employs the **32-element Stingray X-band phased-array** assembly from Analog Devices.
- The Stingray assembly exemplifies this trend. Its **critical components** include the ADAR1000 quad beam-forming IC and ADTR1107 quad TR IC, fabricated in a SiGe BiCMOS process, at TRL-7, **and in production**.
- These are integrated into a modular assembly (8x4) extensible in increments of 8 elements in the long dimension (and **can be butted for a 2x expansion**).
- The receiver antenna for the space implementation is approximately 1.5 meters in the cross-track direction, and much less in the along-track direction, and the **planar modular phased array antenna geometry meets the need.**





Commercial (5G/SATCOM) RF Technology Provides Basis for SToRM Hardware Implementation

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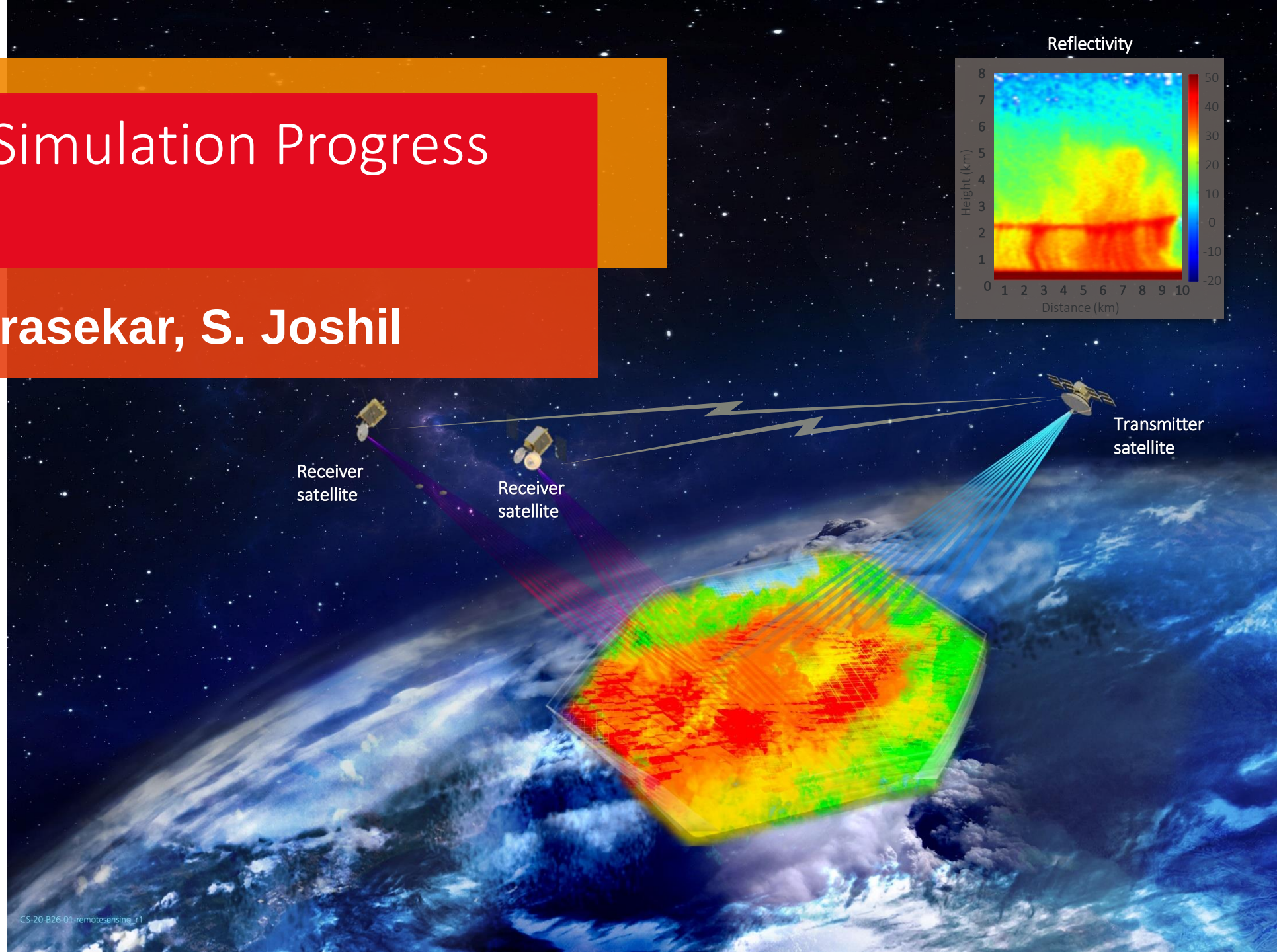
Precipitation Simulation Progress

CSU- **V. Chandrasekar, S. Joshil**



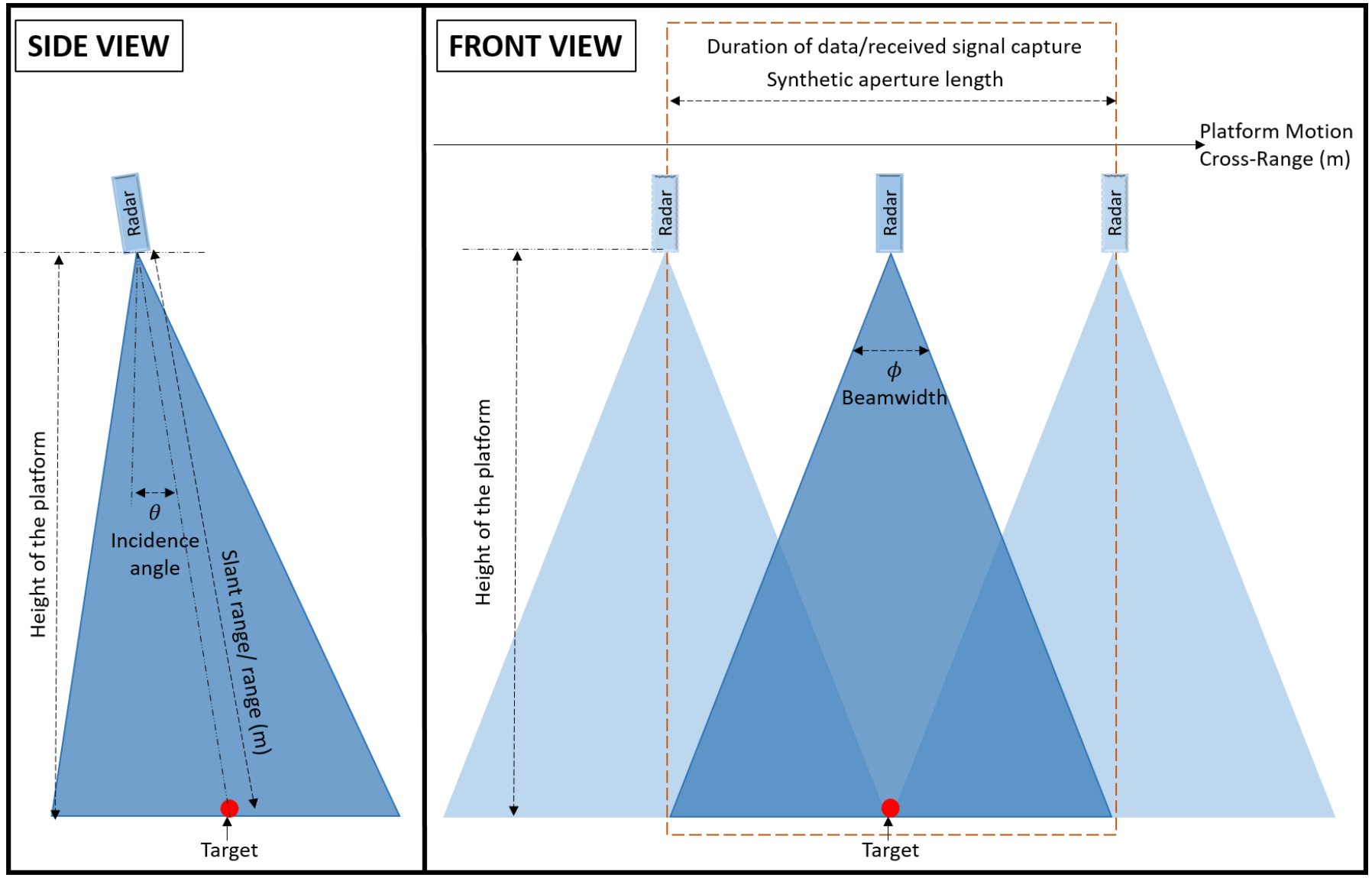
Simulation Architecture and Parameters

SAR Simulation Parameters

Frequency	= 13.9 GHz
Platform height	= 400 km
Baseline distance	= 10 km
Incidence angle	= 0.716 deg
Slant range= 400.03 km	
Antenna size	= 1.74 m
Azimuth resolution	= 0.87m
Bandwidth	= 50 MHz
Pulsewidth	= 1 us
PRF	= 18 kHz
Sampling frequency	= 200 MHz
Velocity of platform	= 7670 m/s
Target	= Fixed/Weather

Antenna pattern is 1 in the entire beam illumination region

Tx and Rx Platform in [X, Y, Z] are at [5 km, 0 km , 400 km]
Target is at
[0 m, 0 m, 0 m]



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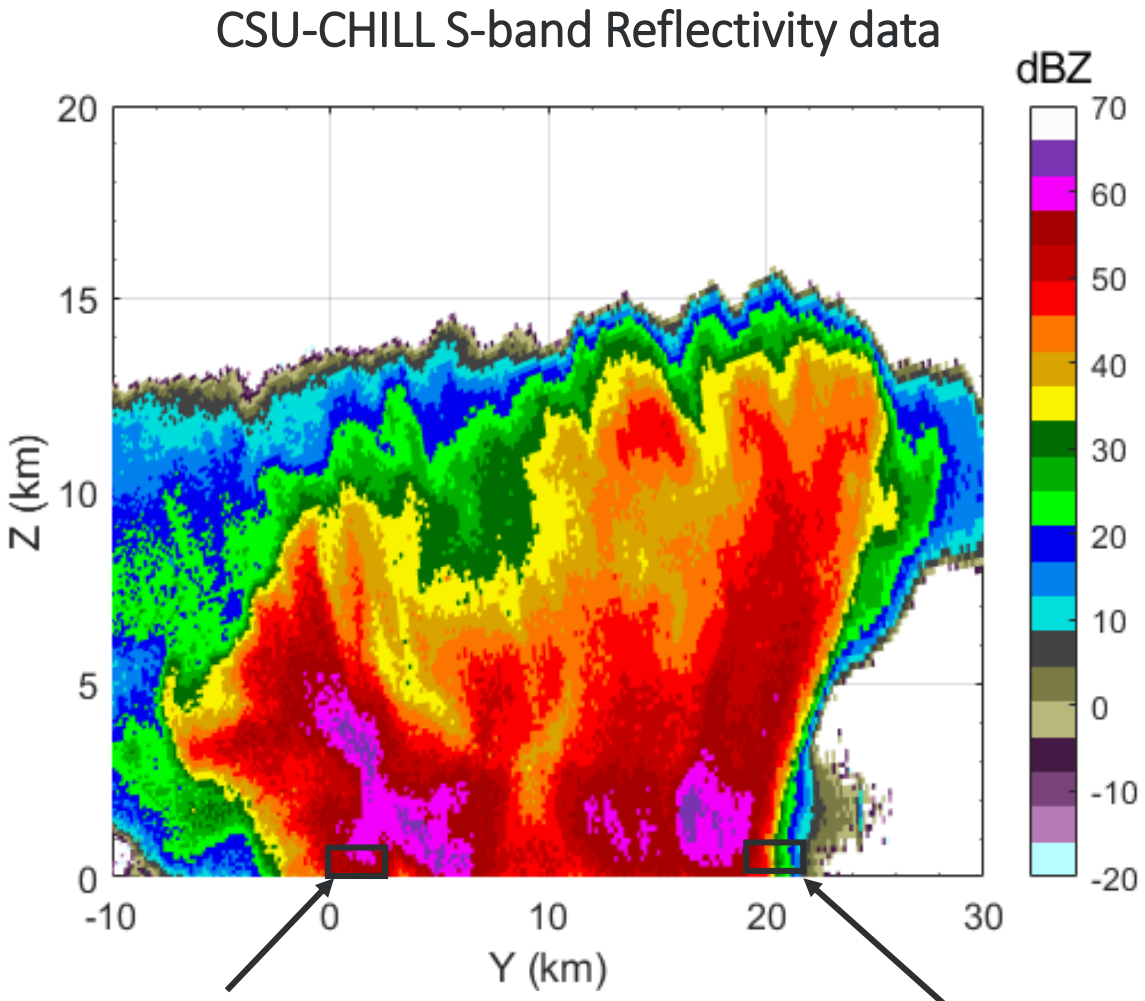
Simulation Examples Case1,2

- Precipitation case from CSU-CHILL S-band radar
- RHI data scan collected on 26th June 2006 at 21:38 UTC
- RHI plot converted to XYZ reference frame
- The reflectivity points are provided as input to the simulation module



Data points considered for simulations, Case 1

Case 2

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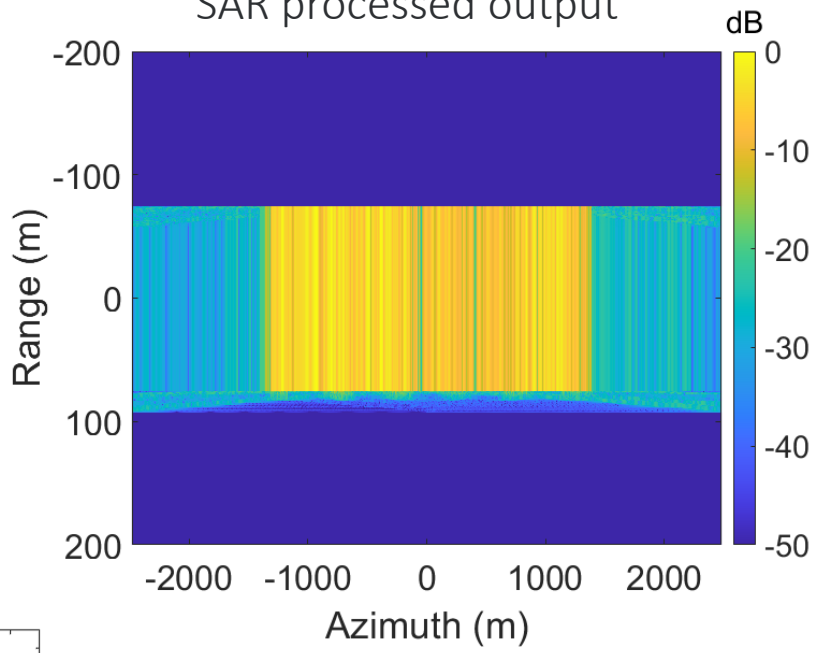
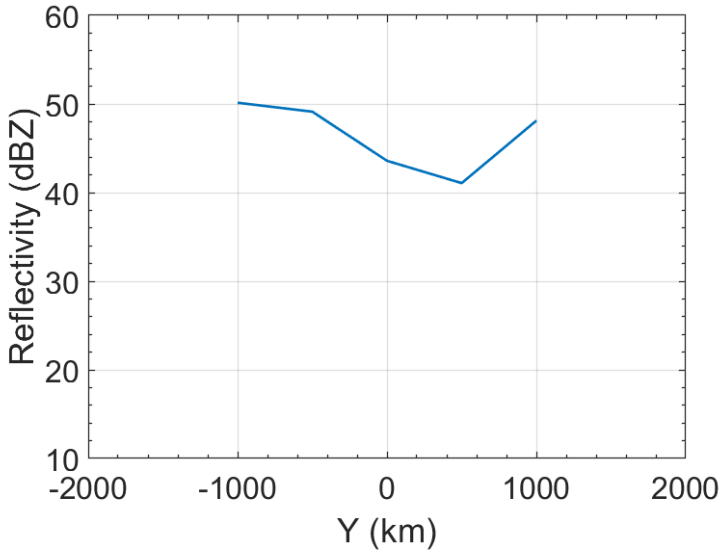
SAR simulation results – Case 1

SAR processed output



Input reflectivity data

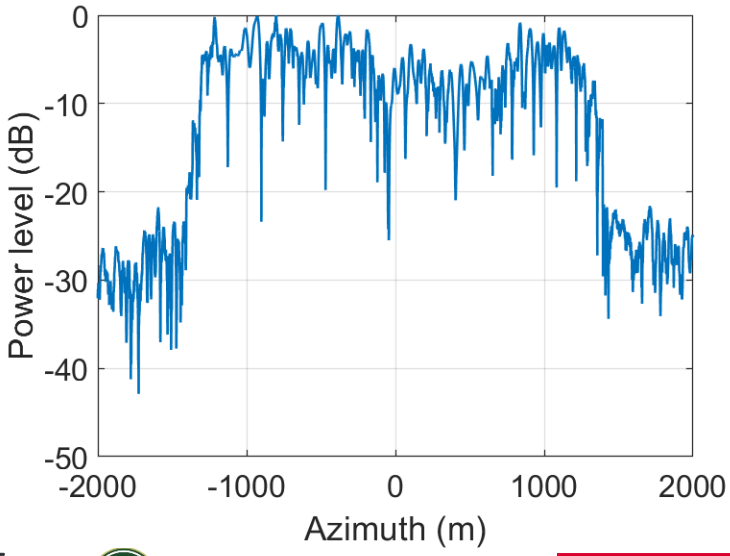


Precipitation parameters:

Velocity = 0 m/s

Spectral Width = 1 m/s

SAR processed output data



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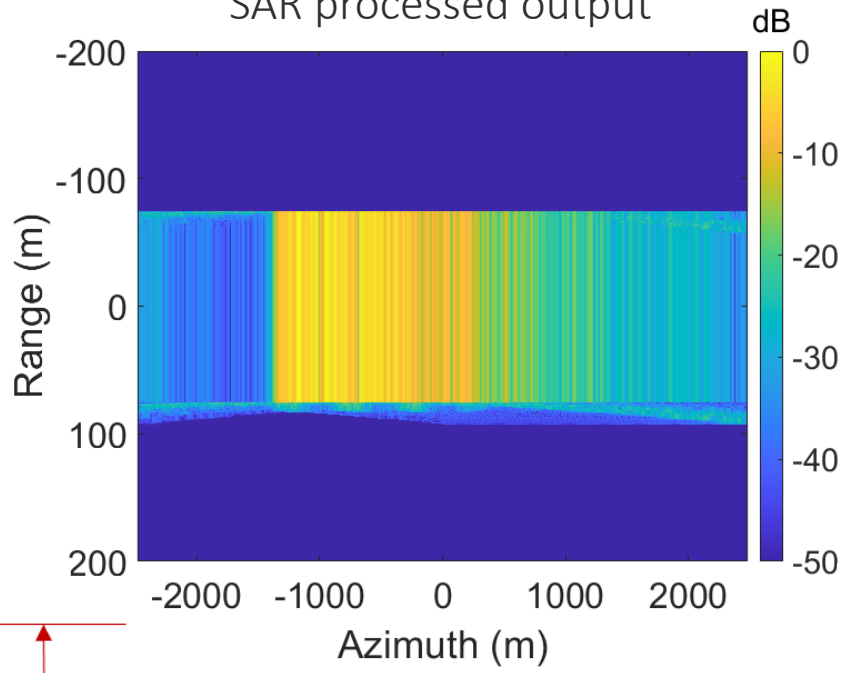
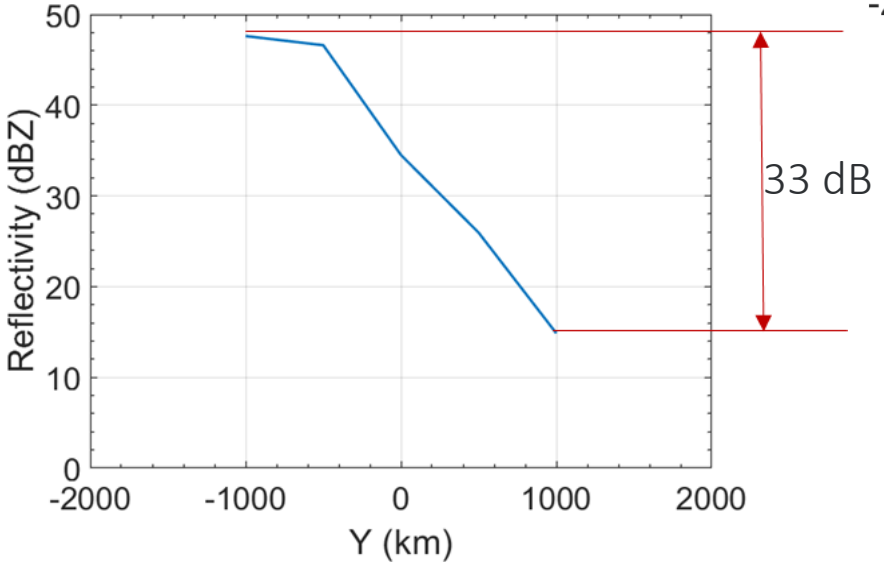
SAR simulation results – Case 2

SAR processed output



Input reflectivity data



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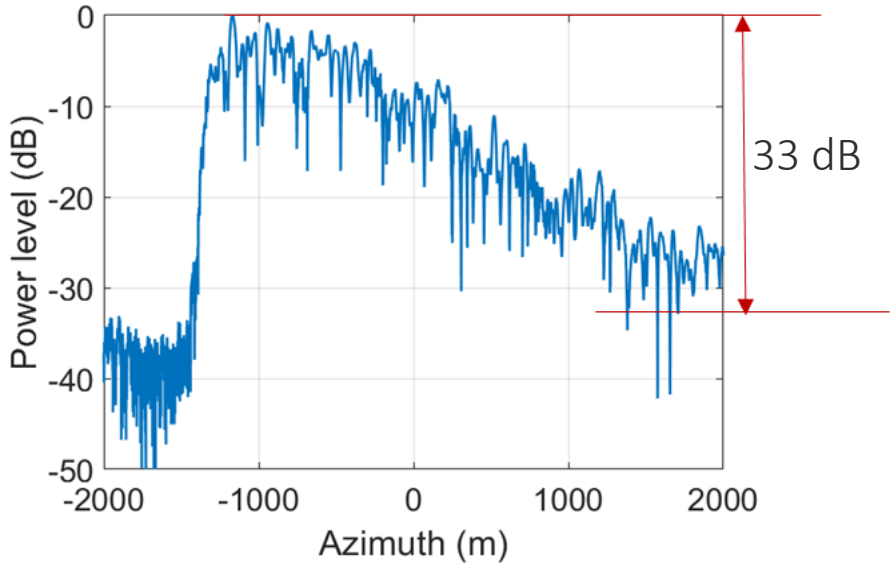

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Summary and Next Steps

- *Successful Demonstration of GPS-Synchronized Bi-Static Coherent Precipitation Radar !*
  - Ground-Based Field Observation of Precipitation Field using BAE's Bi-Static Range/Doppler/Aggregation Method with Small Receiver Antennas Receivers and CHILL Pulsed CW Transmitter Closely Matches Independent CHILL Observations
- SAR Processing of an Observed Reflectivity Extended Field (by CHILL) Combined with "weather target" Behavior Yields a Reflectivity Retrieval matching CHILL Observations
  - *First Demonstration of SAR-type processing recovering reflectivity for Extended Target*
- Preparations for Airborne Demonstration of Observation Method for June 2024 Flights
  - Instrument Payload Control Software Developed
  - Payload hardware integration and laboratory testing-nearly complete
  - Phased Array Antenna Characterization/Calibration—Summer 2023
  - Airborne ECO Flight planning refinement and flight safety verification—ongoing with JSC

Key Preparations now focused on airborne demonstration

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Supplementary Material

SToRM Airborne Observation Requirements

Key Performance Requirements

- Along-Track Spatial Resolving Power- < 1 km
  - > 1 kHz Doppler Shift per along-track km
- Cross-Track Spatial Resolving Power- < 1 km
  - Resolving spatial features 2x to 4x below beam width
- Vertical Resolving Power < 0.25 km
  - 6dB Width of Impulse Response
- Size of Transmitter-Illuminated Field > 5 km
- Frequency: X-band (~ 9 GHz- for weather radar)
- Reflectivity Resolution: <20 dBZ

G-V Flight Conditions (Example Platform)

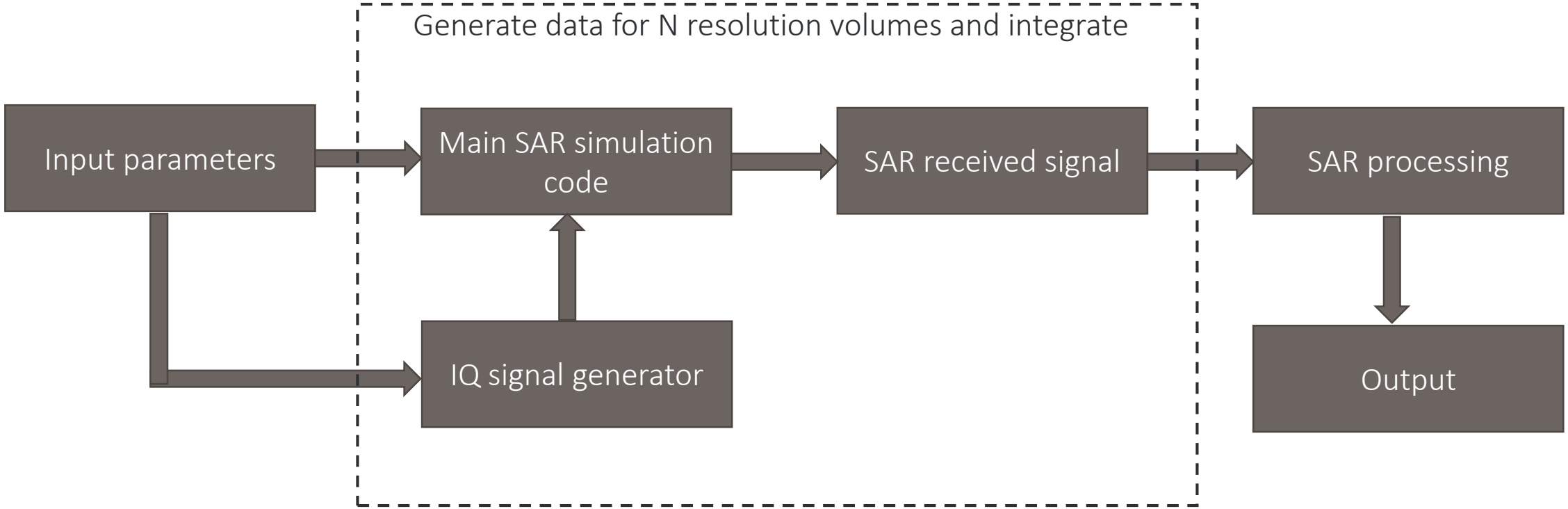
- Nominal Altitude: 15-20 km
- Nominal Air Speed: 200-250 m/s
- Flight Duration: > 6 hours
- Flight Telemetry: (Current ER2 telemetry for air speed, attitude, etc)

Target Scene Requirements:

- Near a Ground-Based X-Band Precipitation Radar
  - e.g. NSF CHILL facility in Greely, CO
  - e.g. Norton Bay (San Francisco Bay area)
  - e.g. Dallas/Fort Worth Area, Houston Area

Simulation Code Architecture

- Code for simulations of multiple resolution volumes is developed
- Simulations are carried out using realistic scenario



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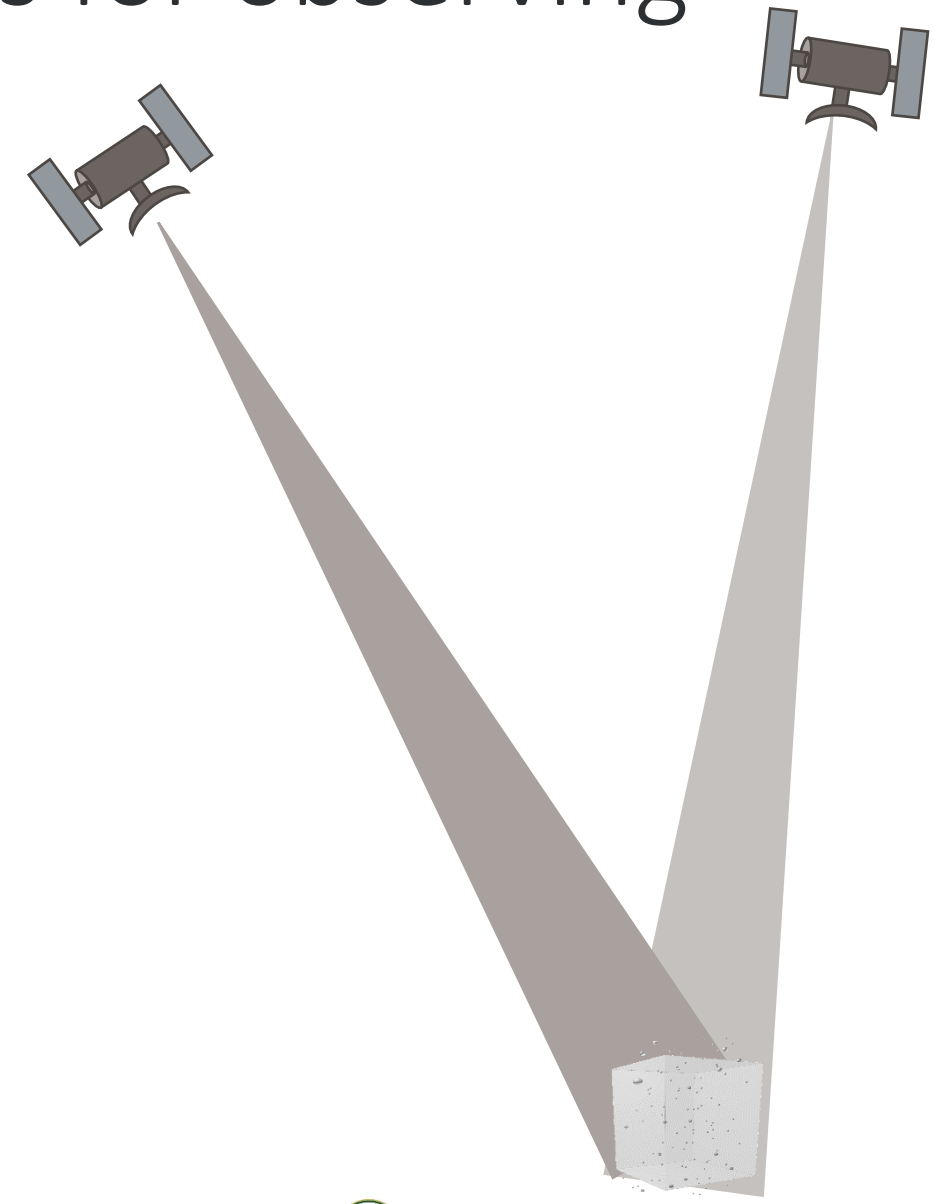
Spaceborne SAR simulations for observing precipitation



- **Simulations of the SAR signals will aid in understanding the influence of various parameters of precipitation such as velocity of hydrometeors on the received SAR signal**
- A spaceborne SAR simulation code was developed for monostatic and bistatic cases.
- The simulation parameters for spaceborne are considered based on GPM Ku-band radar.
- Results of various simulation cases for monostatic and bistatic were discussed previously.

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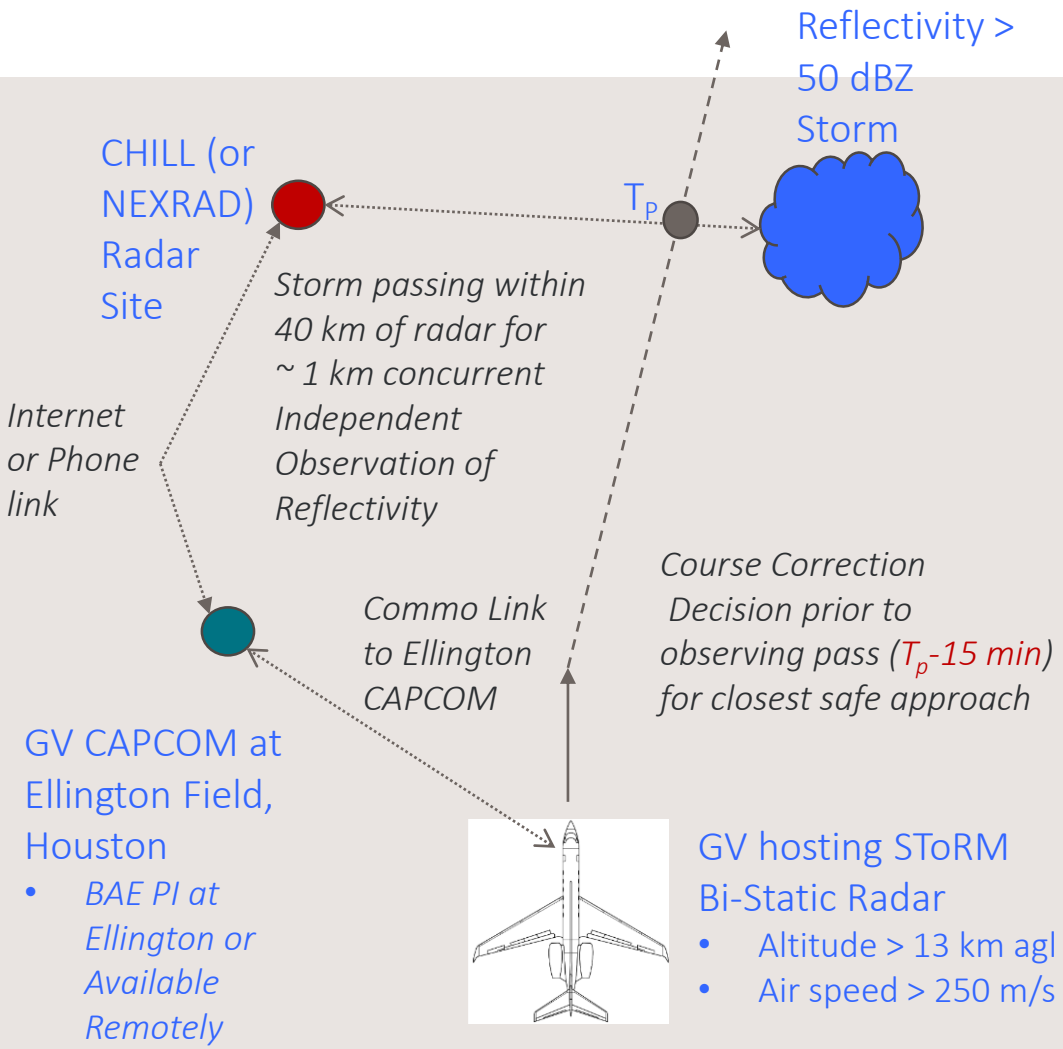
Airborne Demonstration Concept of Operations

- **Beam Navigator**
  - Uses NRT Weather Information, Platform Position, and Velocity to Guide Selection of Targeting of the Beam Angle and Angle Change Rate
    - **Will be in communication with Ground** for real time weather radar guidance on routes and observation targeting
  - Payload Team Communicates Route **Update Requests to Pilot**
  - Communicates Radar Operation Guidance to Radar Operator
- **Radar Operator**
  - **Configures Radar** for planned observations and confirms on ramp while **on ground** power to confirm equipment ready for flight. Power—Off
  - Brings up radar on ramp after **switch-over to on-board power** and confirms readiness for flight
  - **Operates equipment** during flight, as guided by Beam Navigator
  - **Transfers Data** collected during airborne operations for ground analysis



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