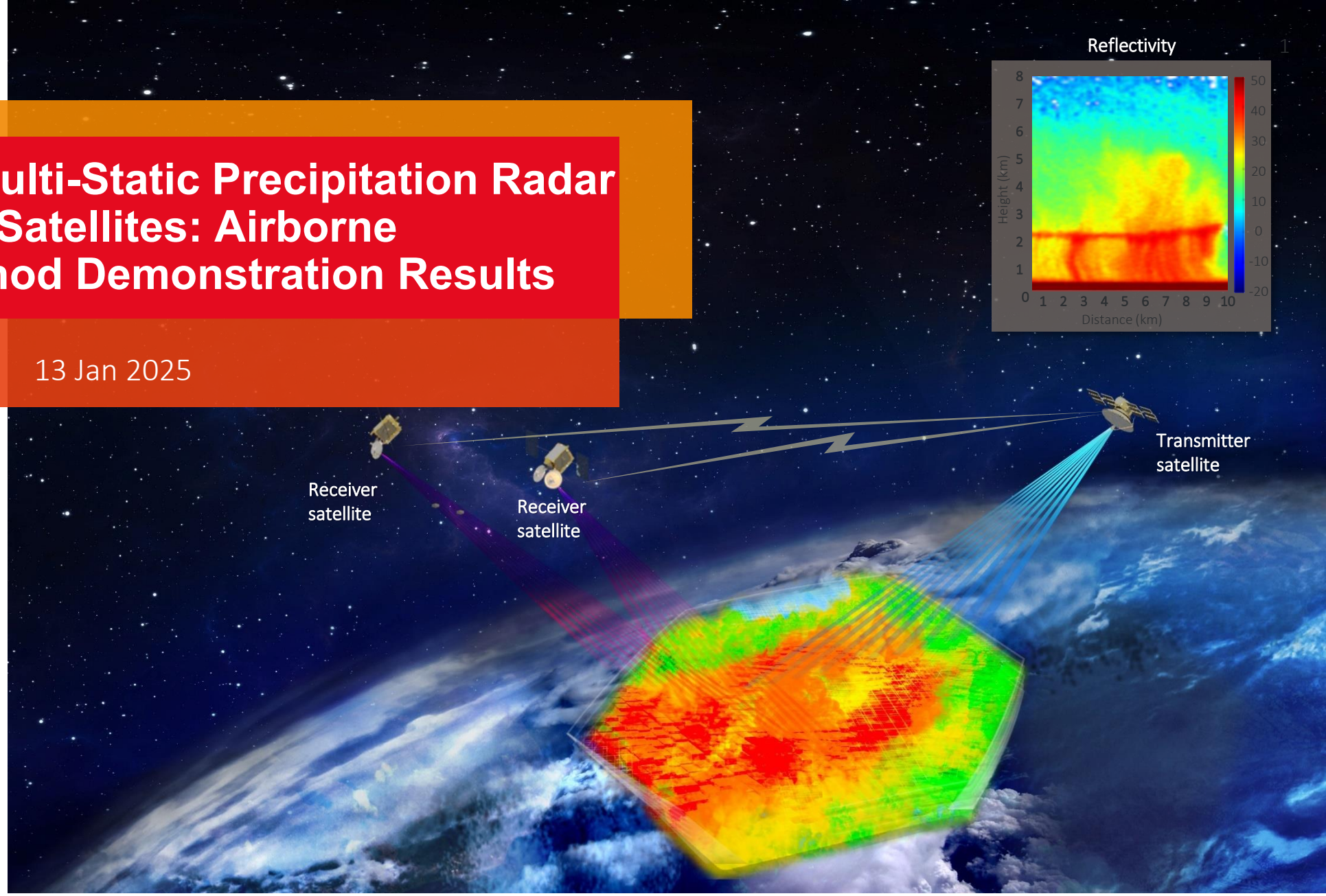
STORM SAR, A Multi-Static Precipitation Radar Hosted by Micro-Satellites: Airborne Observation Method Demonstration Results

15R2O Paper J1A.5 13 Jan 2025

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STORM SAR (Instrument Incubator)

Satellite Tomography of Rain and Motion via Synthetic Aperture Radar

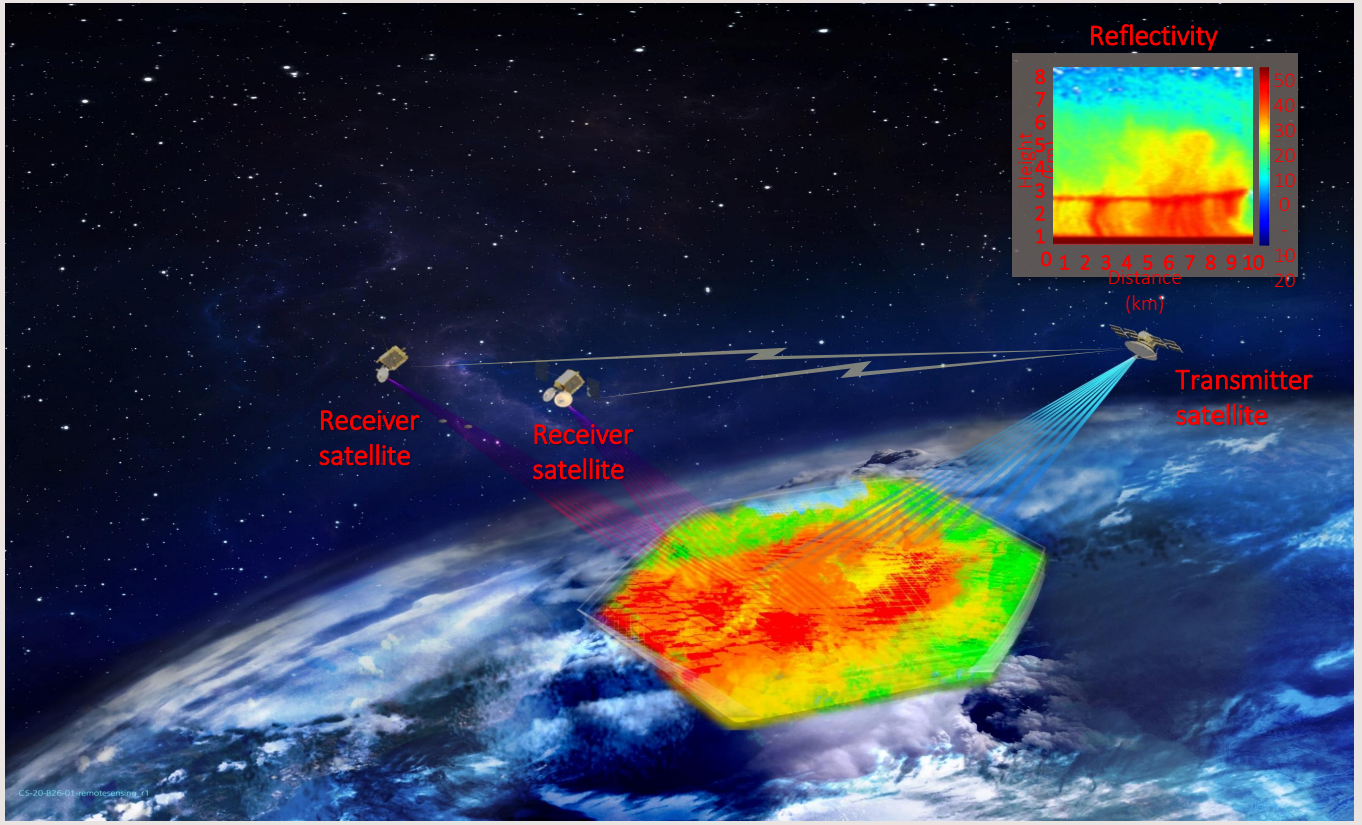
PI: Kevin Maschhoff , BAE Systems

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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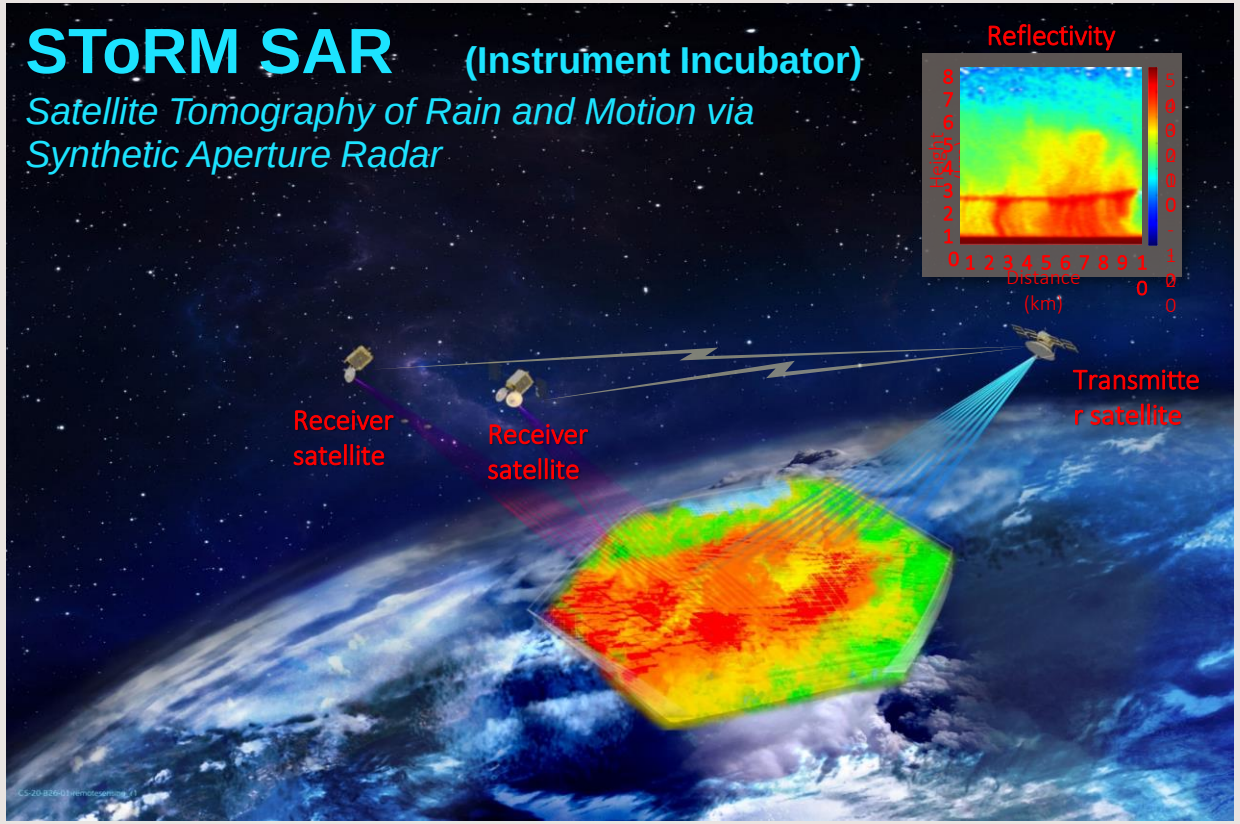
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SToRM SAR Methods Address Observation Needs Other Approaches Cannot Provide

- 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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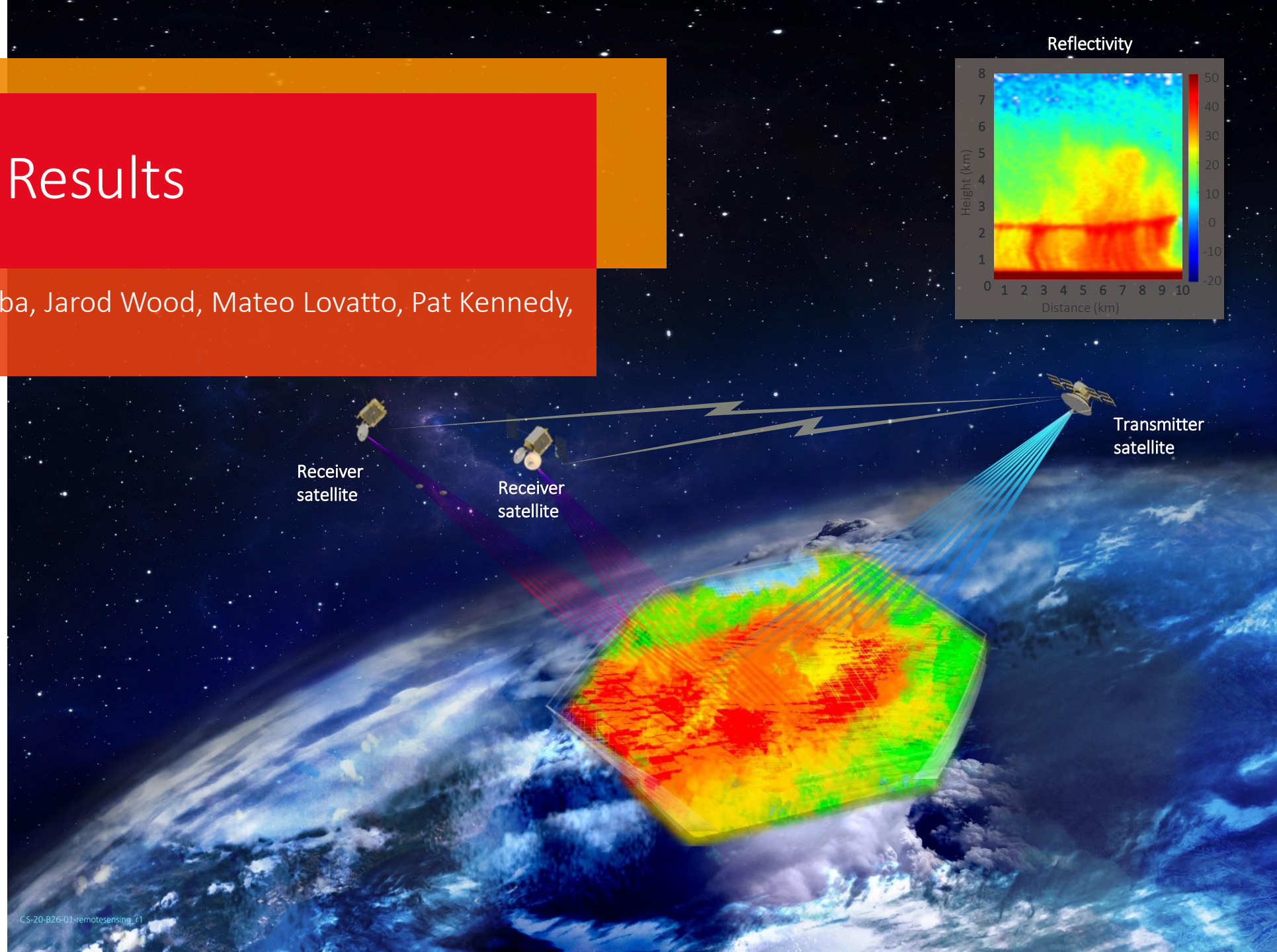
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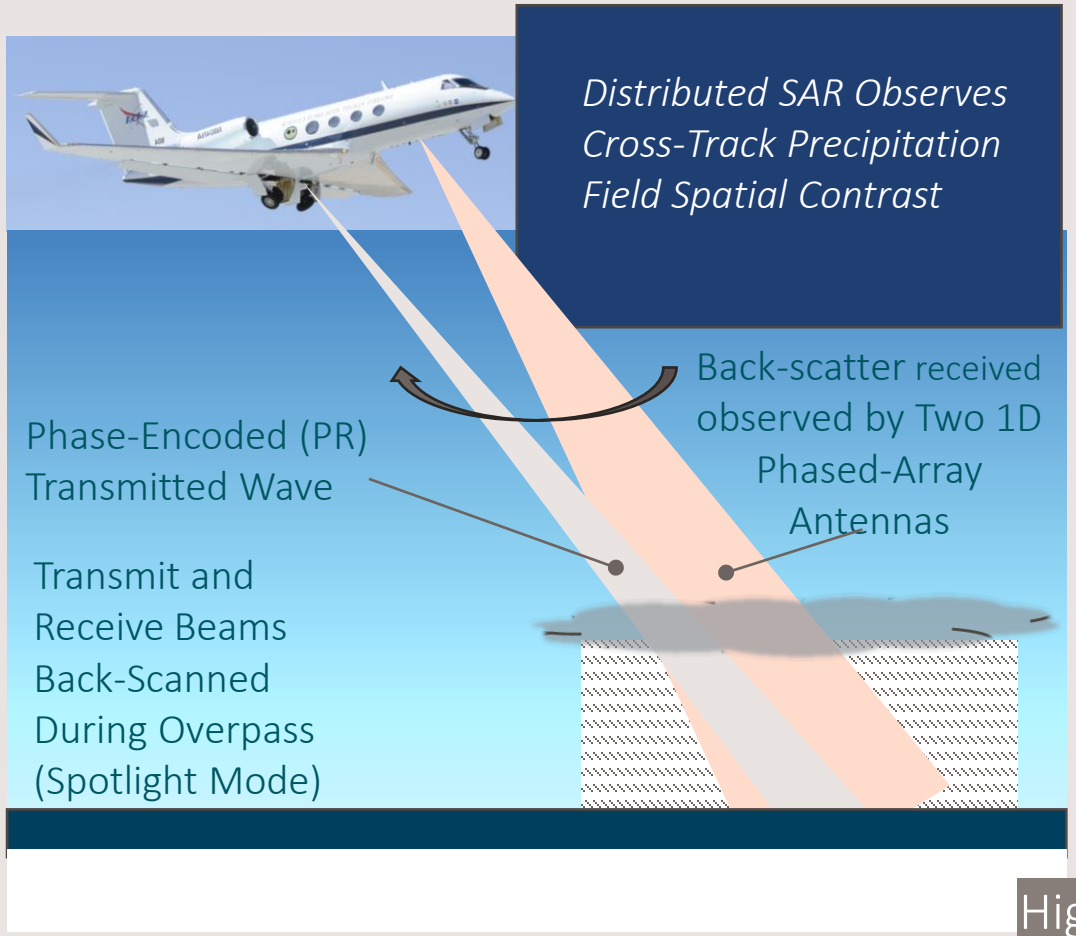
Airborne Test Results

Kevin Maschhoff, Marty Ryba, Jarod Wood, Mateo Lovatto, Pat Kennedy, and V Chandrasekar



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Airborne Demonstration Concept of Operations



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

- Along-Track SAR with Range/Doppler Aggregation Observes Vertical and Along-Track Field Structure (2 of 3 Field Dimensions)
- Cross-track Observations, Recovered from Multi-Angle Range/Doppler Views (Tomographic Reconstruction)
  - Sensitive to Spatial Contrast Finer than Beam Size

Phased-Array Receivers Allow:

- Beam Steering for Spotlight Mode Observations
  - Long Dwell over Selected Region
- Beam Steering Cross-Track for Off-Track Storm Observations
- 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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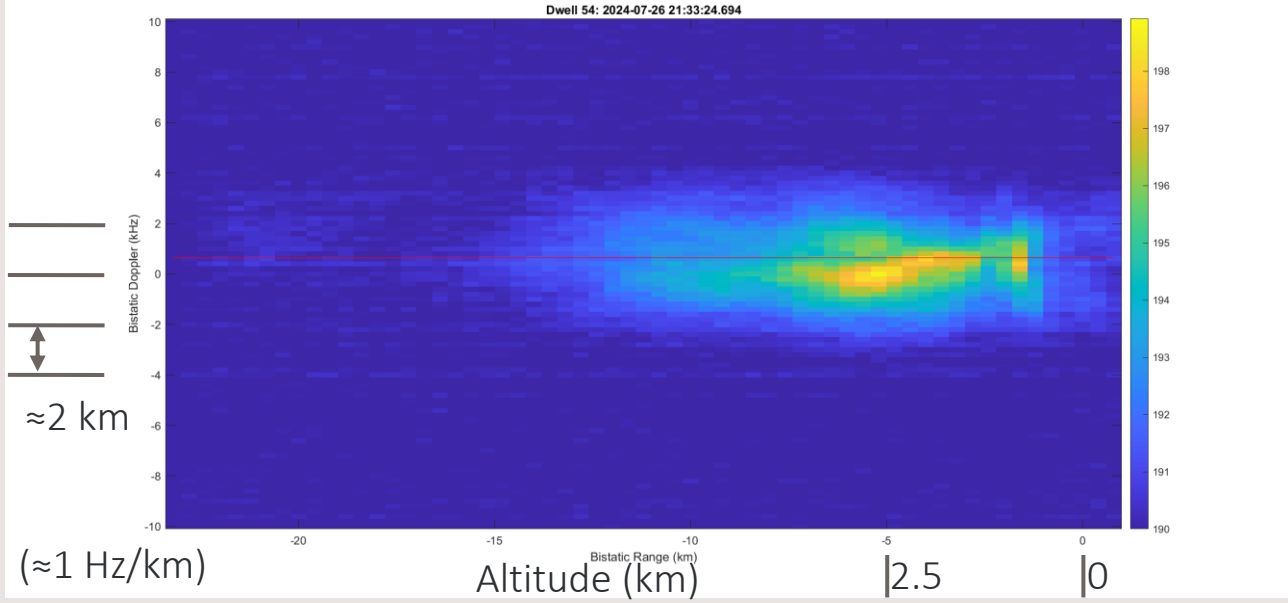
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Primary Finding: < 1 km Horizontal Resolution
(July 2024 Airborne Demonstration)

Toward Aircraft

SToRM Airborne Demonstration Bi-Static Radar Payload Observed a Convective Storm with < 0.5 km Along-Track Resolution

- Transmitter Beam width ~ λ/D =0.25 rad (≈ 14° FWHM)
  - Beam Projection on Ground from 13 km ≈ 3.25 km
- Along-Track Doppler Frequency Extent of Features < 400 Hz
  - *Ground-projection of finest features < 400 meters*
- GV speed (~ 240 m/s) drives along-track resolution
  - *Along-track resolution from space would be even finer*
- This resolution achieved with convective storm with core Reflectivity Factor > 50 dBZ (for 4 km-core vertical extent)
  - *Observation of this storm from above at Ka-band and higher frequencies would be severely attenuated*



A 1-second "Dwell" airborne observation from above of X-band Reflectivity of a storm over NE Colorado on 26 July near 21:33Z. 1 kHz Doppler shift ~ 1 km. Horizontal sampling = 200 Hz. Bi-Static Range resolution = 400 m. (chip rate of 2.3 MHz → fundamental vertical height resolution ~ 66 m). 0 range is approximately ground level. Doppler shift is relative to ground aim point). Color scale is power (dBW per 200 Hz bin)

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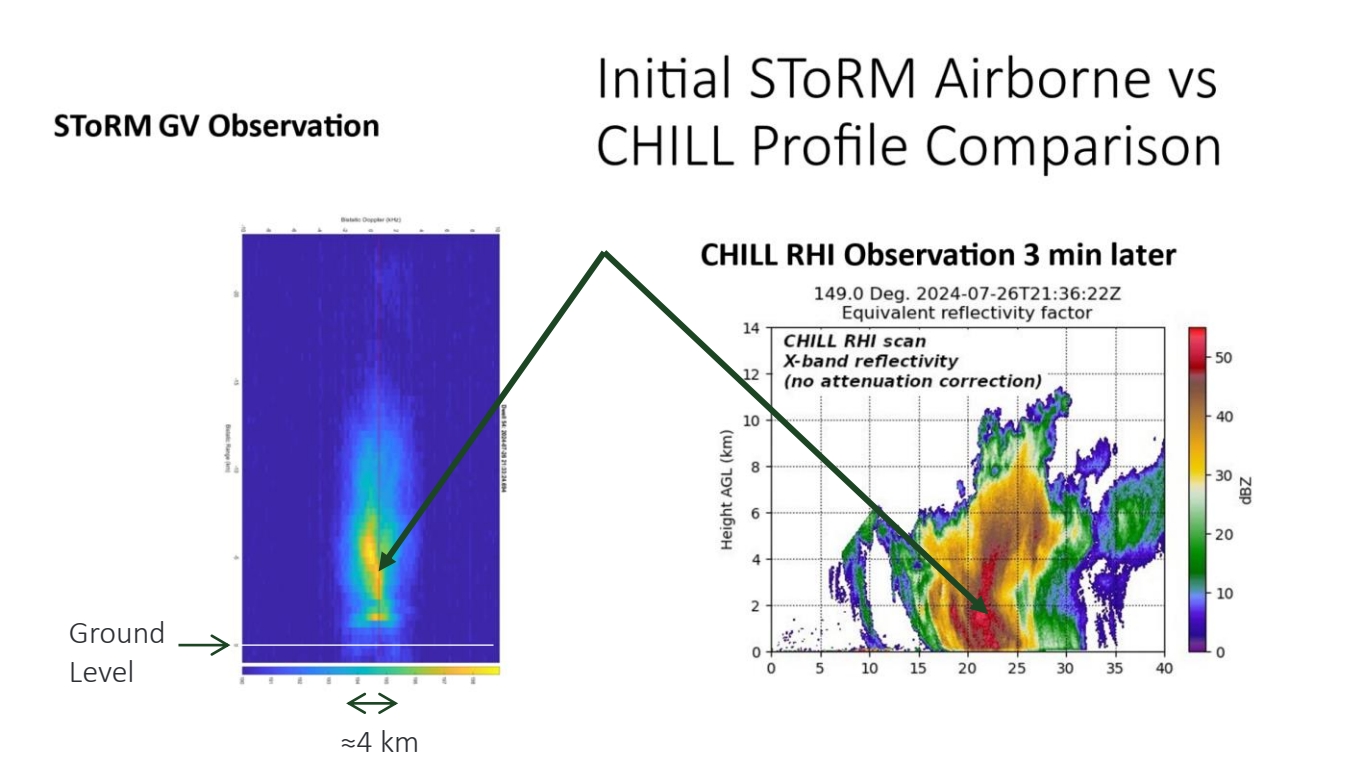
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Primary Finding: Reflectivity Similar to Ground Radar Obs.
(July 2024 Airborne Demonstration)

Airborne Demonstration Bi-Static Radar Precipitation Observations Compare Reasonably with High Resolution Ground-Based X-Band Precipitation Radar Observations of Same Storm by CSU-CHILL

- Both Observations are in X-Band (9.3 GHz)
- SToRM Airborne observed a portion of a storm field also observed by CHILL
- NOTE—Pose Angle Differs between SToRM profile and CHILL profile---by ~ 90 degrees
  - SToRM Observation Target Center only 23 km from CHILL



Range/Doppler Aggregation Observations for a 1-second Dwell (left) Compare well with CHILL Elevation Scan (RHI) observation of same storm central region

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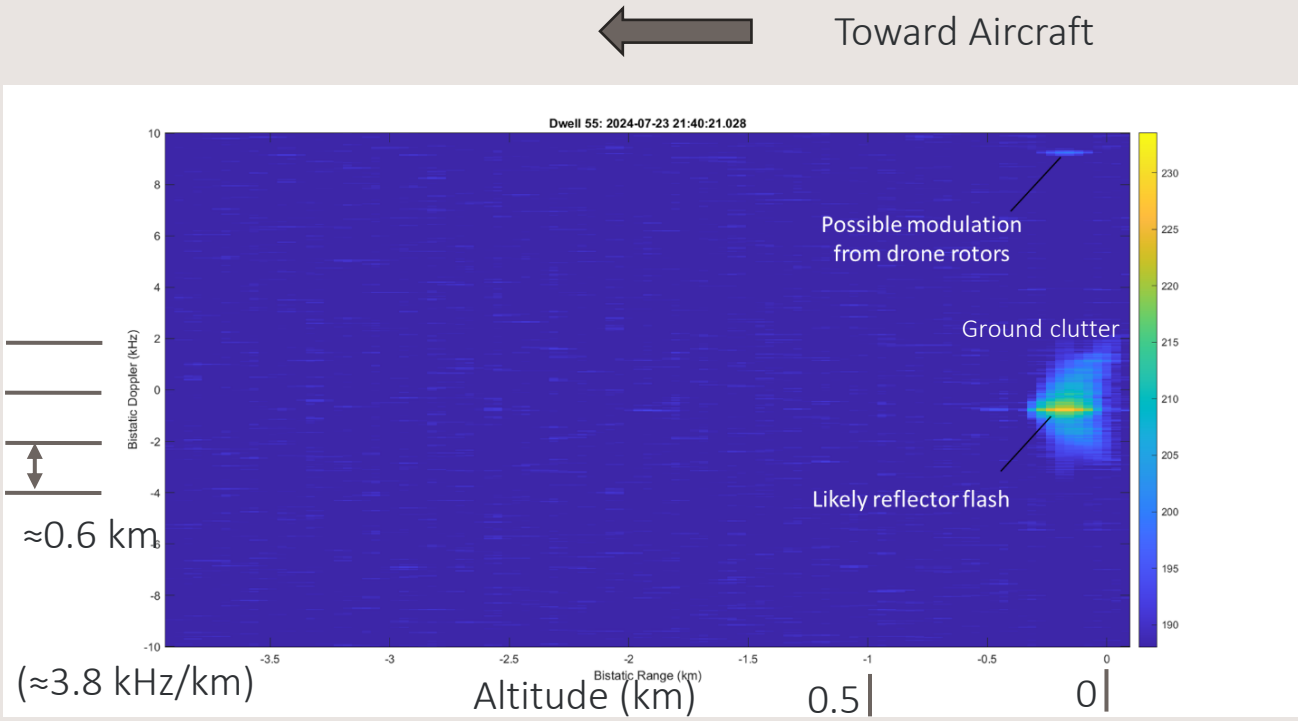
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Calibration Target Observation Illustrates Sharpness of Along-Track Response

- The drone-lofted corner-cube was over-flown to provide a point reflectivity target lifted out of the ground clutter.
- Two race-track over-passes at 10,000 ft AGL were performed while the CSU drone team flew a corner-cube target, suspended below the drone over the CSU drone center at 500 ft AGL.
- IRC chat between the on-board team and the drone team ensured that the over-flight happened during the drone's relatively brief battery-limited flight period.
- Overflight observations by SToRM are being assessed. A preliminary aggregated image (Dwell) showing what we believe to be the reflection of the SToRM radar from the drone-lofted corner cube is shown in Figure

Corner-Cube Target Suspended from Drone Provides Experimental Observation of SToRM SAR Point Spread Function



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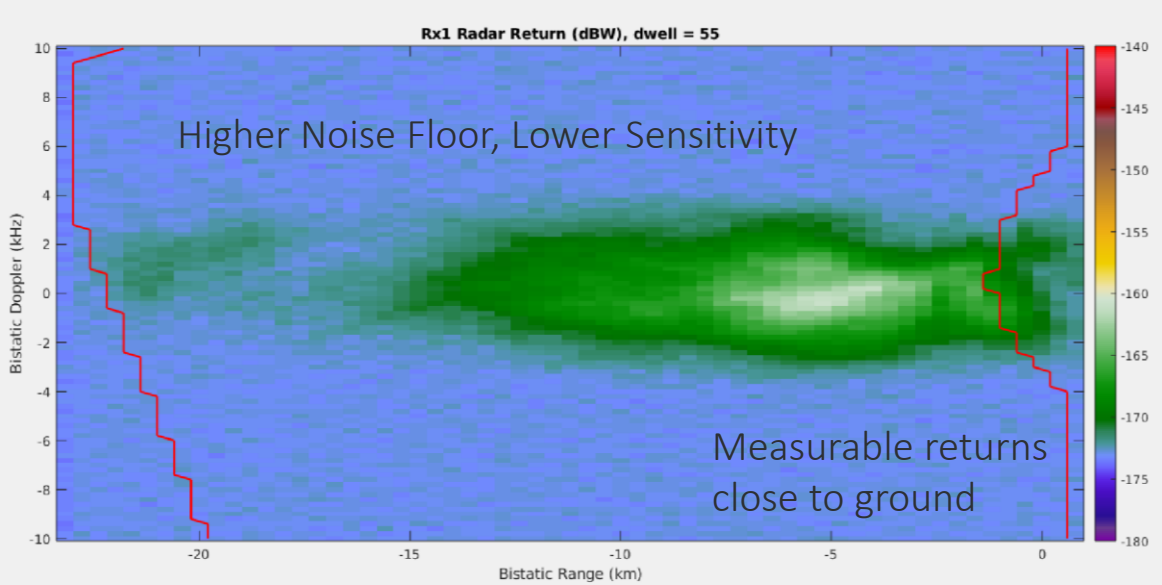
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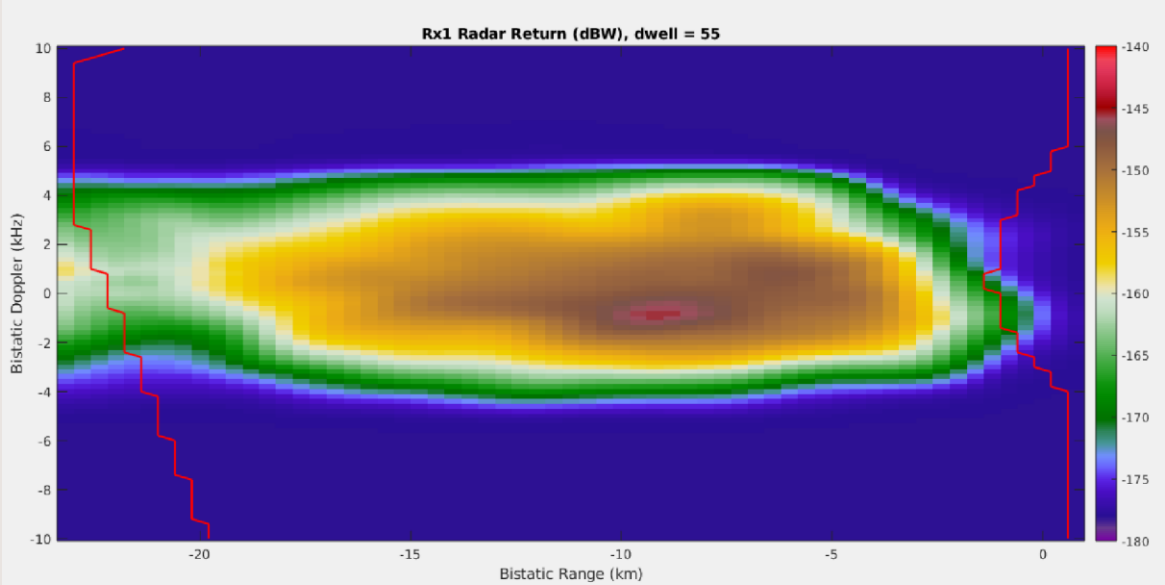
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Radar Returns Comparison—SToRM Observation, and Ground Radar Data-used to view same region

Measurement



Simulation from Ground Data





SToRM SAR Airborne Antenna Sizes are Modest (xmtr < 10 cm square)



Not shown is expected improvement, cross track resolution from beamforming

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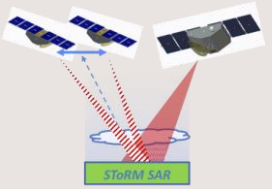
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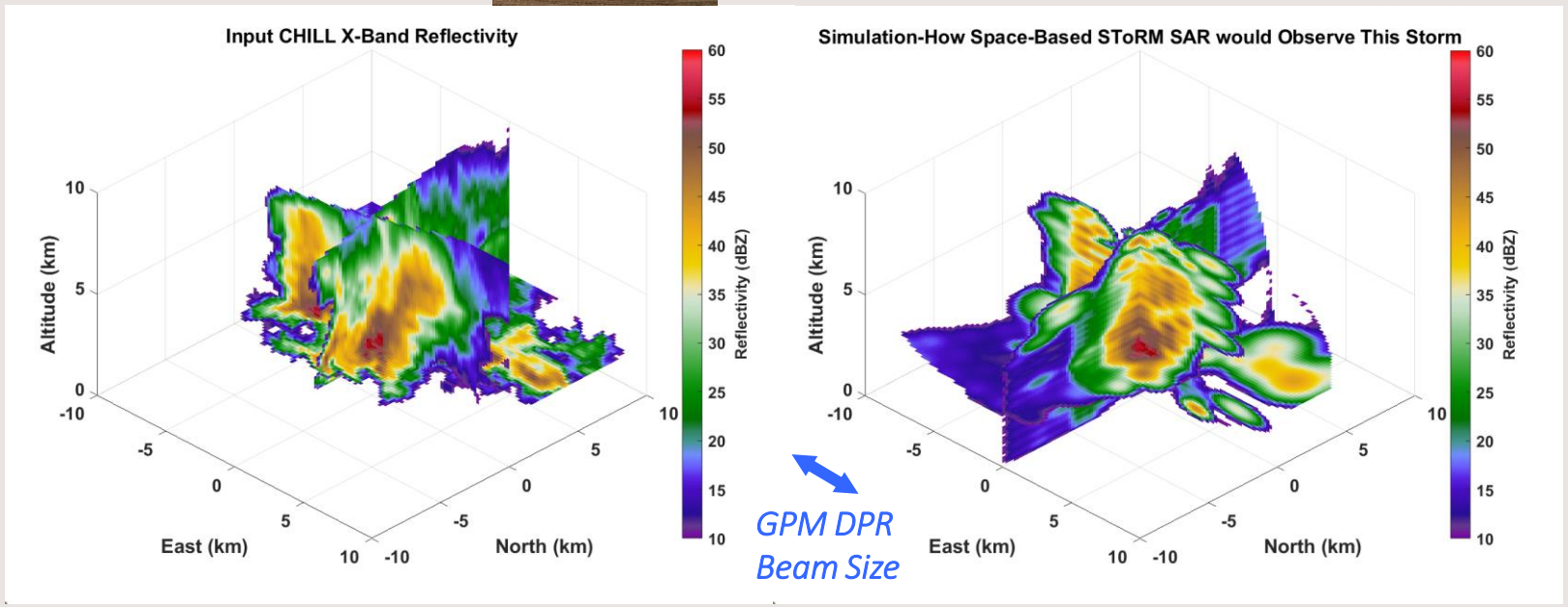
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Simulation of SToRM SAR Observation from Space—Using Reflectivity of a Recent Colorado Summer Storm as Input





- CHILL radar densely sampled a storm close by (< 25 km from CHILL) using multiple RHI scans
  - Horizontal resolution ~ 200 m
- Space-based multi-static observation by SToRM SAR “fly-over” is simulated:
  - 400 km altitude, transmitter path offset by 100 km from ROI, two receivers offset from Xmtr by 50 km, 1 m apertures, ~ 100 W transmitter
  - Range/Doppler & Aggregation for multiple angles during fly-over,
    - Receiver noise added,
    - GM Model-based retrieval, 1 km grid



Simulated SToRM SAR Observation of Reflectivity Field from a storm recently observed by a ground-based precip. Radar (CHILL) captures fine (< 1 km) structure

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SToRM SAR Airborne Team

- Marty Ryba, Mateo Lovato, and Jared Wood on the GV (and Mateo with calibration equipment)





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SToRM SAR Ground Team

- Kevin at CHILL, observing flight path, weather radar, and communicating candidate storm target location candidates to the on-board payload team
- CSU research staff member Pat Kennedy, operating the CHILL radar during SToRM flights near by.
-





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Summary and Recommended Follow-on Steps for SToRM SAR

- **Summary:**
  - Observation Method Can Provide High Horizontal Resolution (< 1 km) Vertical Profiles in Moderate to Severe Storms from LEO
    - Supported by model simulations, ground, and airborne tests of Range/Doppler Aggregation Method
  - Observation Method can be Implemented in a low-Cost Multi-Static LEO Constellation
    - Payload Hardware TRL>6+
    - ESPA-Class Micro-satellite for Transmitter, 20U-Class Satellite for Receivers
- **Recommended Next Steps**:
  - SToRM X-Band Airborne Payload Performance Improvements and Re-Flight over Summer T-Storms
    - Modify Payload to Reduce RF Packaging Loses, and Replace SDR (intermittent sync issues)
    - Verify Upgraded Radar Performance in Ground (upward-looking) tests at CSU-CHILL
    - Can Re-Fly Payloads on GV (over Colorado) with these improvements in Summer 2025
  - Develop Ka-Band Modules for Airborne Demonstration—together with Current X-Band Payload—OR—add other Polarization at X
  - Rehost X-Band Airborne Payload on NASA Boeing 777, Configure to Support Airborne Science Missions, and Fly Demonstration/Verification→ Providing Improved Tx/Rx Separation and Enable 3D Reflectivity Retrieval

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Acknowledgement

Thanks to NASA Earth Science Technology Office for Supporting This Work Under the Instrument Incubator Program

Program Manager: Parminder Ghuman

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Supplementary Material

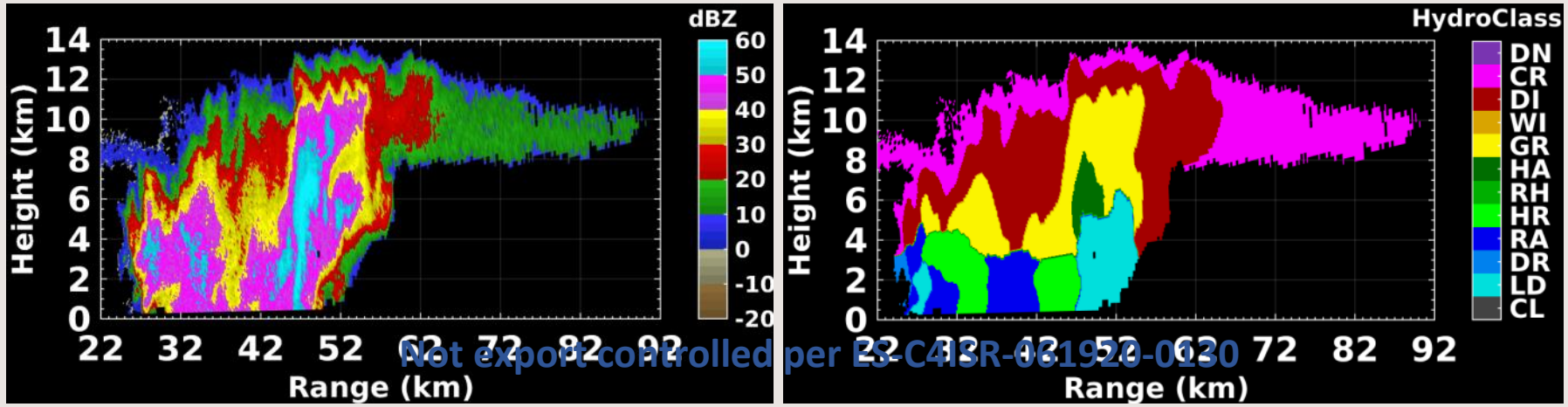
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What Spatial Resolving Power Is Needed to Observe Intense Mid-Latitude Storms From Space?



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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

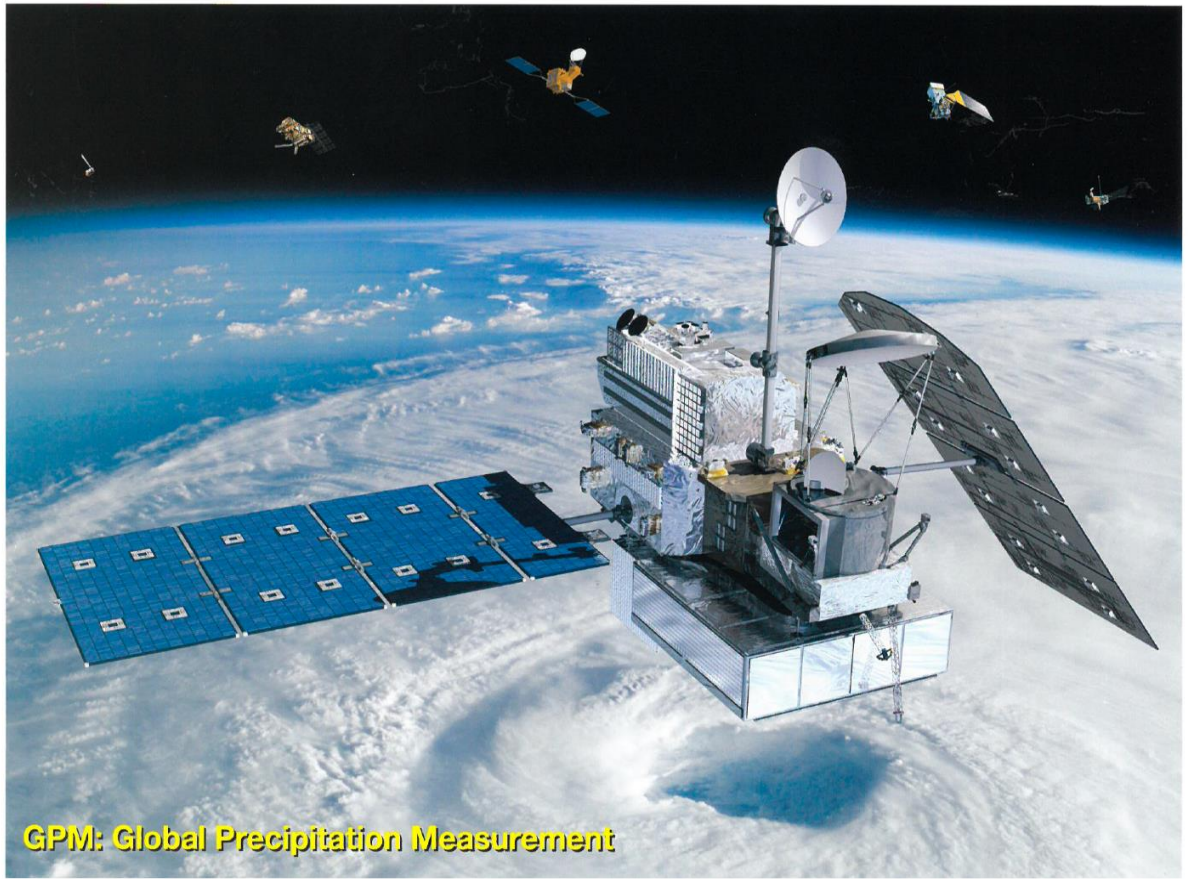
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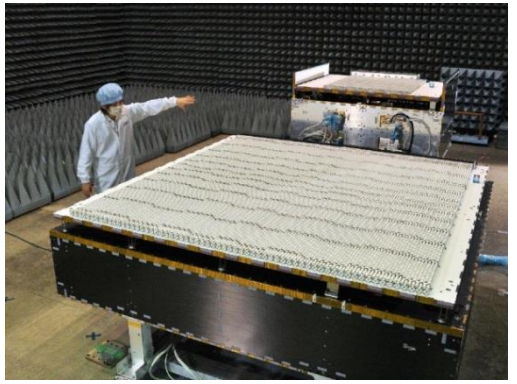
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Problem to Solve-Providing 1 km Horizontal Resolution Precipitation Observations from Space



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



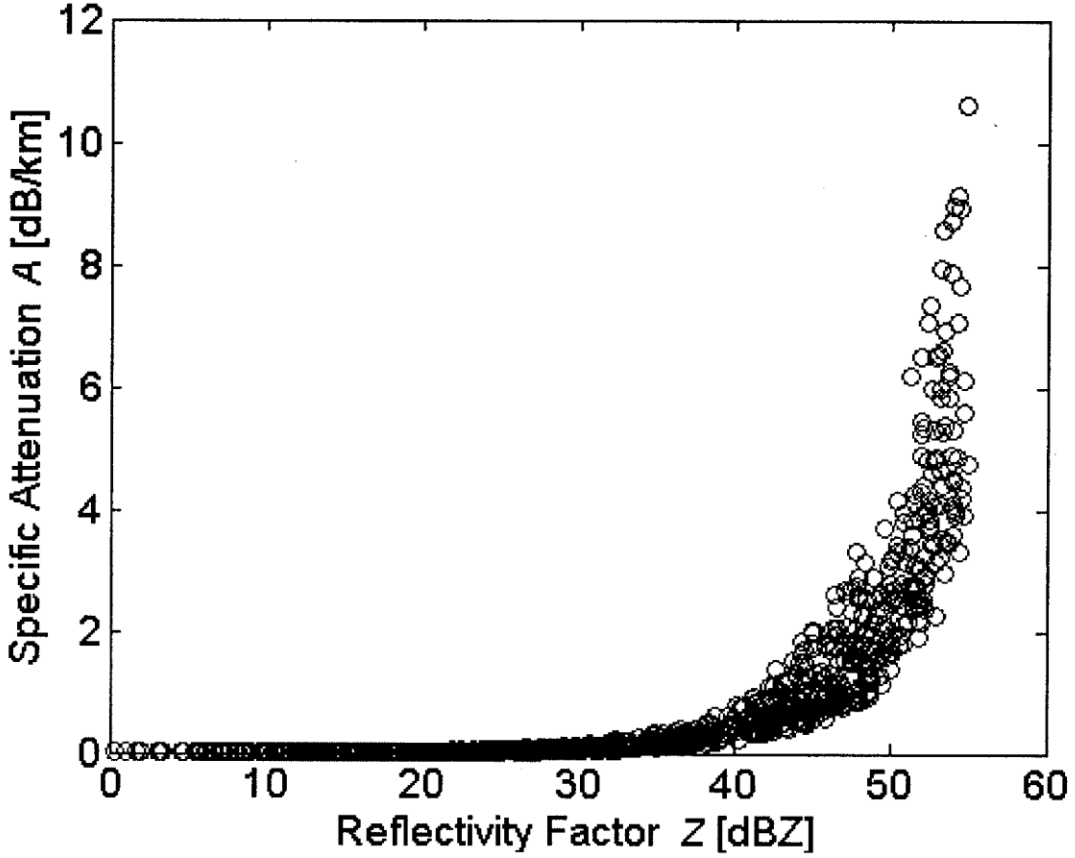
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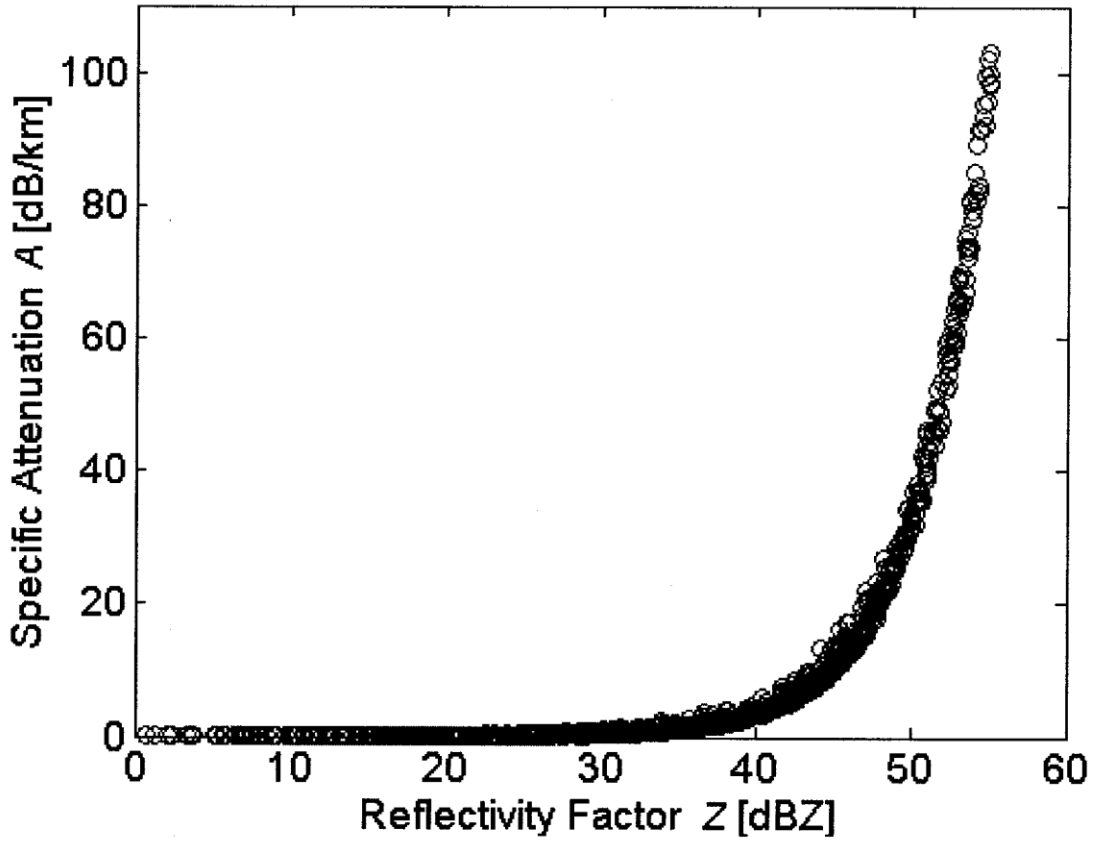
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Specific Attenuation at Ka and Higher Frequencies Limits Vertical Profiling of Intense Convective Storms





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

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Recommended Follow-on Steps

- SToRM X-Band Airborne Payload Performance Improvements and Re-Flight over Summer T-Storms
  - Modify Xmtr and Receiver Assembly Housing to:
    - Include High-X-Band Transmission Lower Windows (Anticipate 6 dBZ Improvement)
    - Include Metal Sides (improved RF Isolation)
  - Replace SDR showing sync problems with Alternate (reuse from ground test HW) and verify operation in airborne test env.
  - Fix firmware in 4-channel receiver, or go to single beam (in which one side/sub-array showed intermittent behavior) (6dBZ Impr.)
  - Verify Upgraded Radar Performance in Ground (upward-looking) tests at CSU-CHILL
  - Re-Fly Payloads on GV (over Colorado) with these improvements in Summer 2025
- Develop Ka-Band Modules for Airborne Demonstration—together with Current X-Band Payload
  - Commercial Phased-Array Modules
  - Demonstrate Dual-Band Detection within this new lower-cost paradigm
- Rehost X-Band Airborne Payload on NASA Boeing 777, Configure to Support Airborne Science Missions, and Fly Demonstration/Verification→ Providing Improved Tx/Rx Separation and Enable 3D Reflectivity Retrieval

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Summary of Remaining Challenges

- Correlations between SToRM Airborne Observations and Detailed CHILL/NEXRad Challenging-
  - Impact: Limiting High Resolution Reflectivity Comparisons (no example of fully 3D Comparison)
  - Multiple Causes: Narrow SToRM Transmitter Beam and CHILL RHI's often not well aligned spatio/temporally, Only Partly Overlapping Vertical Coverage with NEXRAD (upper), and Lower (CHILL)
  - Possible Improvements: More Observations! (More flights)
- Airborne Payload Hardware Issues Interfered with /Degraded Some Observations
  - Lower Tx and Rx Signal Levels (polycarbonate absorption)→Higher Threshold dBZ than Expected, Limited number of Obs
  - SDR Timing Sync Lock Loss, Requiring re-alignment in post processing → Substantial Delay—well after flight period-- before Observation quality could be assessed
    - Intermittent sync issue with one of 4 sub-arrays in receiver phased array---interferes with cross-track beam-forming & 3D Reflectivity Recovery
- Large Impact by Direct-Path transmitter signals at off-nadir angles →Limits useful angle range, and 3D recovery
  - Could be improved by greater Tx/Rx baseline separation (Larger—e.g. 777 platform)

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