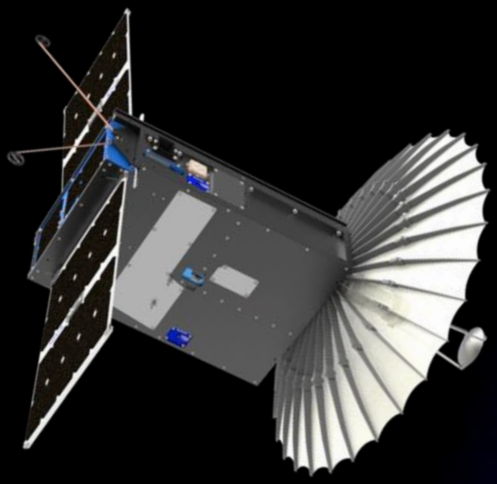
RainCube: Mission Overview of the First Radar in a CubeSat

Small Spacecraft Community of Practice
February 16, 2022



Shannon Statham, PhD
RainCube Project Manager

Jet Propulsion Laboratory,
California Institute of Technology, CA, USA

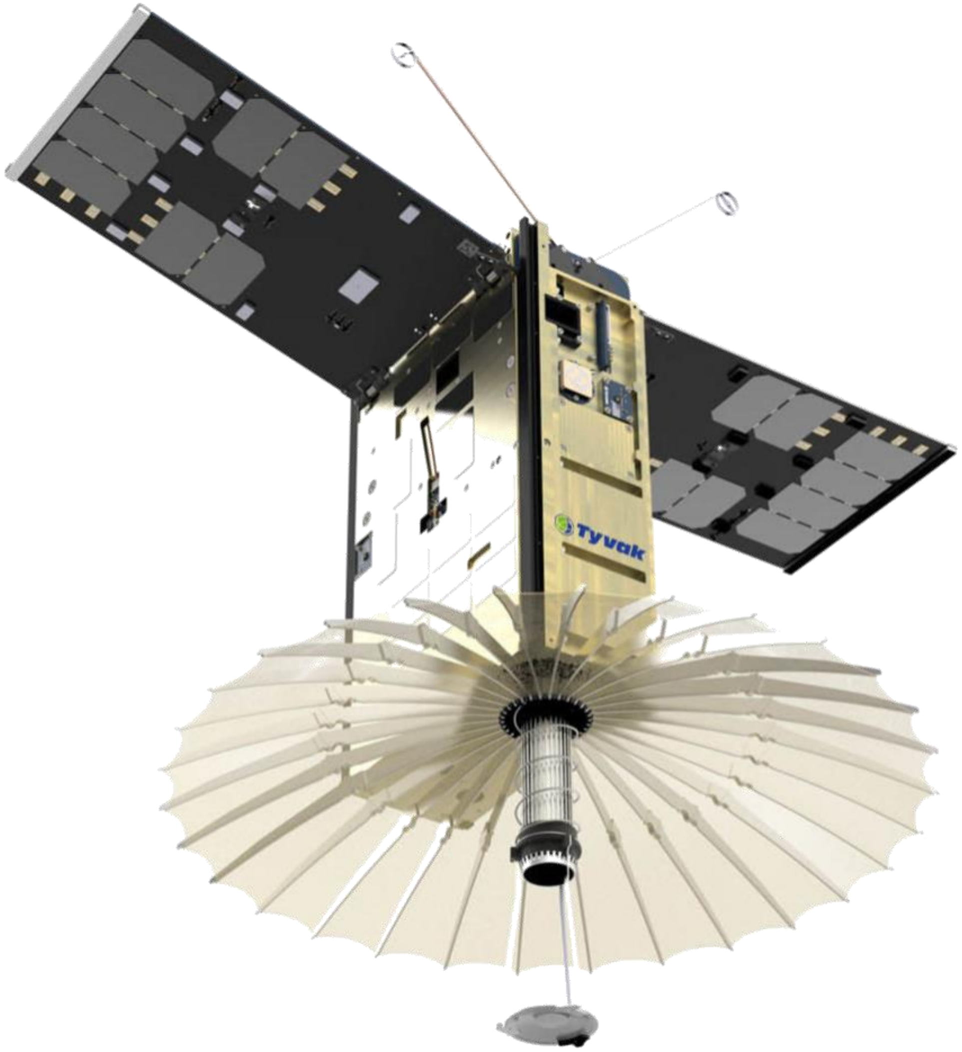
RAINCUBE OVERVIEW

RainCube – Radar in a CubeSat

RainCube is a ***technology demonstration*** mission to enable ***Ka-band*** precipitation radar technologies on a low-cost, quick-turnaround platform.

- **InVEST-15 Selection, ESTO**
  - Validate new Earth science technologies in space (TRL 4 to TRL 7)
- **Two Key Mission Objectives**
  - Demonstrate new technologies in Ka-band on a 6U CubeSat platform
    - Miniaturized Ka-band Atmospheric Radar for CubeSats (miniKaAR-C)
    - Ka-band Radar Parabolic Deployable Antenna (KaRPDA)
  - Enable precipitation profiling radar missions for Earth Science
- **Roles & Responsibilities**
  - NASA ESTO: Sponsor
  - JPL: Project Management, Mission Assurance, Radar Payload
  - Tyvak: Spacecraft Bus, System I&T, Mission Operations
  - CSLI / NanoRacks: Launch to LEO via ISS

RainCube in a Nutshell



Goal:

Demonstrate the first radar and active instrument in a CubeSat via a Ka-band precipitation radar

Success Criteria:

1. Detect precipitation
2. Capture vertical structure of storms
3. Operate for at least 3 months

RainCube was a Success!

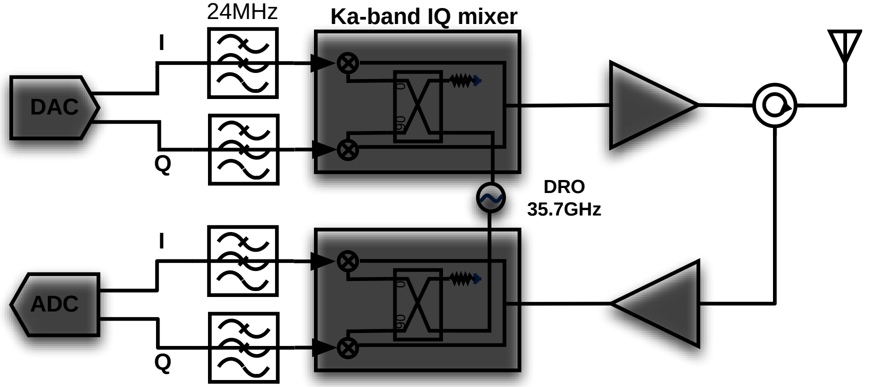
SPOILER ALERT

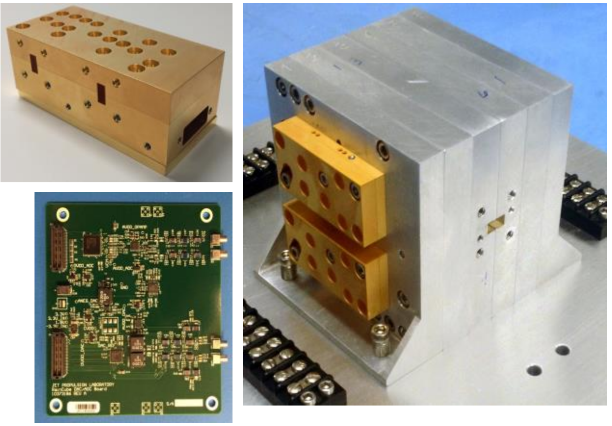
- Deployed from ISS in July 2018
- Detected precipitation in August 2018
  - First demonstration of a radar on a CubeSat
- Completed baseline mission in October 2018
- Coincident measurements of hurricanes & storms with TEMPEST-D
- Continued to operate until de-orbit in December 2020
  - Total of 2.5 years operating in space

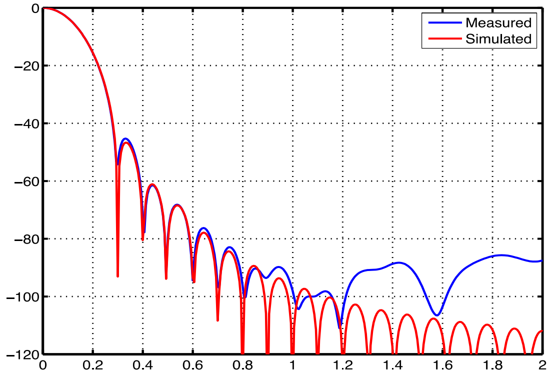
THE RAINCUBE STORY

Initial Radar Concept @ JPL

- **May 2013** – Brainstorming session
  - Earth Science Program Office and Radar Section
  - *Can a science-grade radar instrument be flown on a CubeSat?*
- **July 2013** – Initial concept developed
- **Dec 2013** – Test bed demo completed
- **July 2014** – Lab demo with prototype hardware

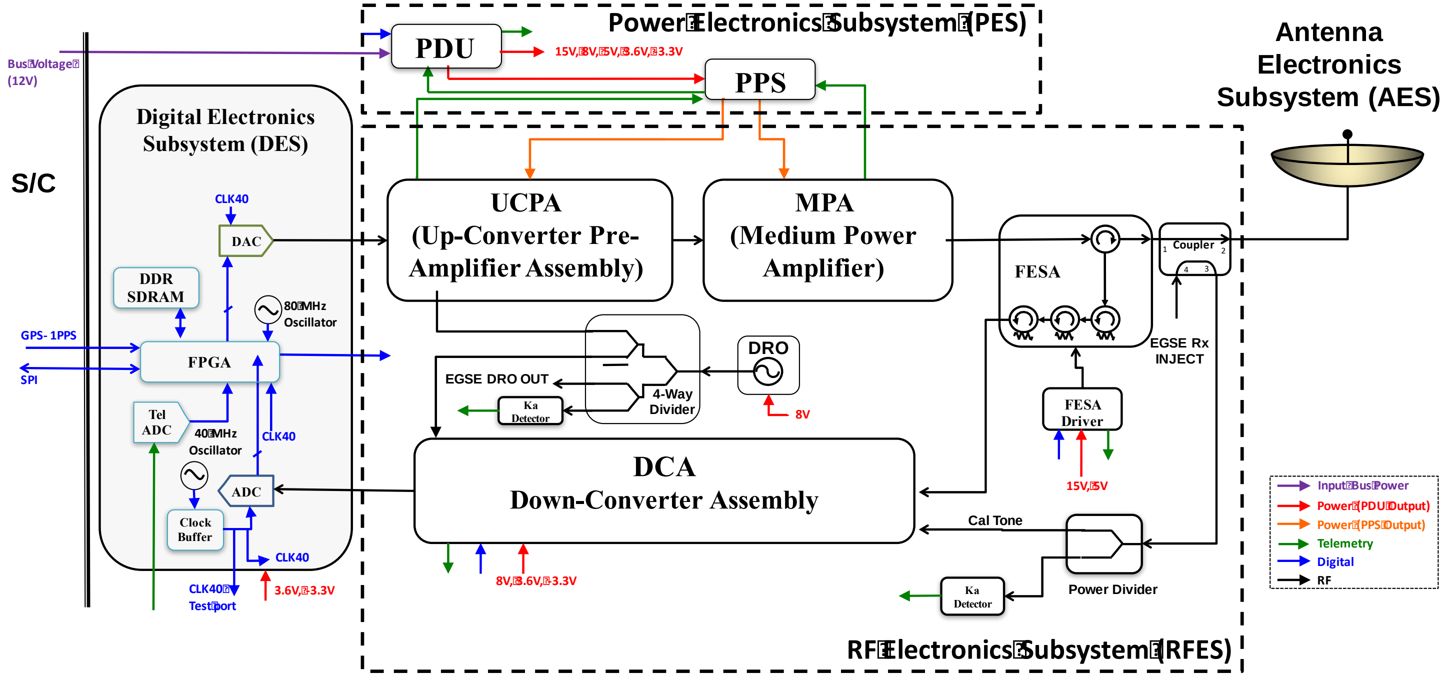






Radar Electronics – miniKaAR-C

- Novel radar architecture that greatly reduces size, mass, and power
  - Only 5 unique RF active components
  - One Ka-band and one 40 MHz oscillator
  - One digital board for control, timing, on-board processing, SC digital interface, etc.



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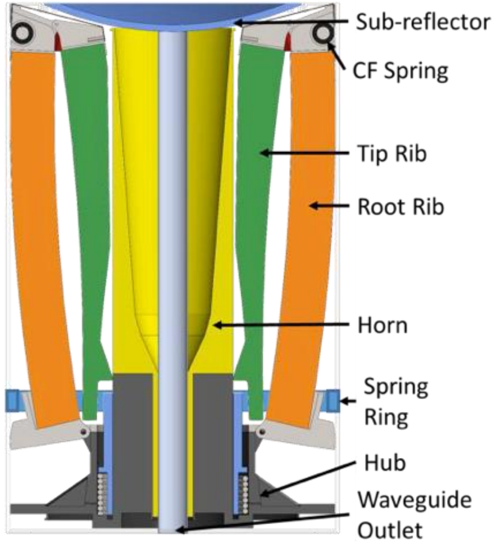
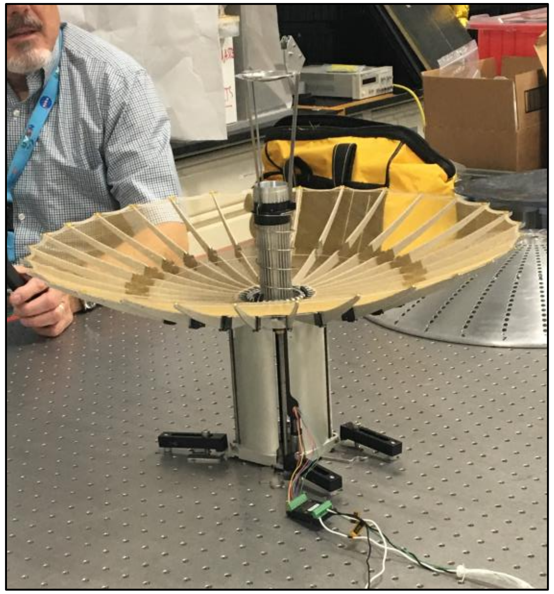
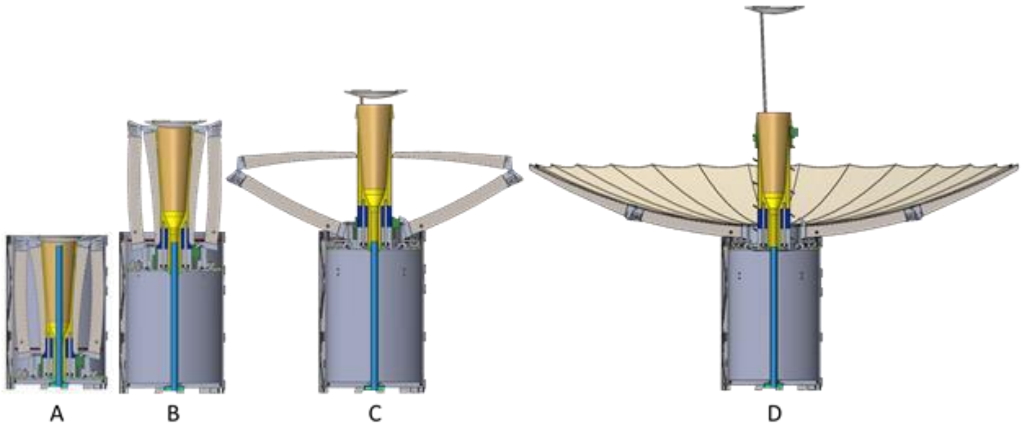
Radar Antenna – KaRPDA

- Telecom antenna concept for higher data rates on CubeSats
  - Ka-band parabolic deployable antenna
  - Cassegrain architecture
  - Motorized system with spring-loaded ribs and sub-reflector
  - 0.5 meter dish that stows in ~1.5U



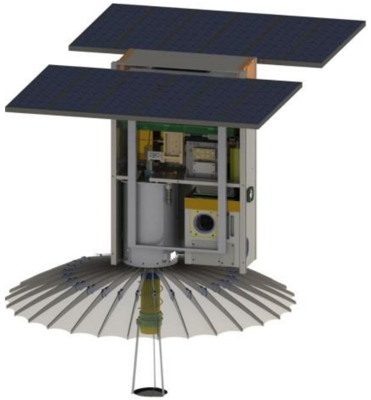


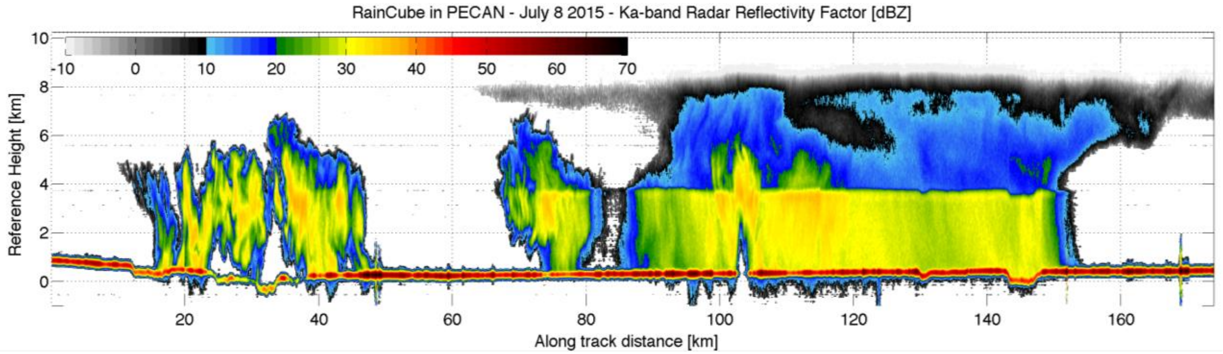


Small Satellite Radar Science Drivers

Pre-Phase A Study & InVEST Selection

- **Jan 2015** – Feasibility study
  - *Is a mission like RainCube feasible with current SOA CubeSat technologies?*
  - *If so, how much would it cost?*
- **May 2015** – Ground demo of miniKaAR-C prototype
- **May 2015** – InVEST-15 proposal
  - Single 6U CubeSat tech demo of new radar technologies ($7 million)
- **July 2015** – Airborn demo of miniKaAR-C prototype
- **Nov 2015** – RainCube is selected for InVEST-15





RainCube Phase A/B & C

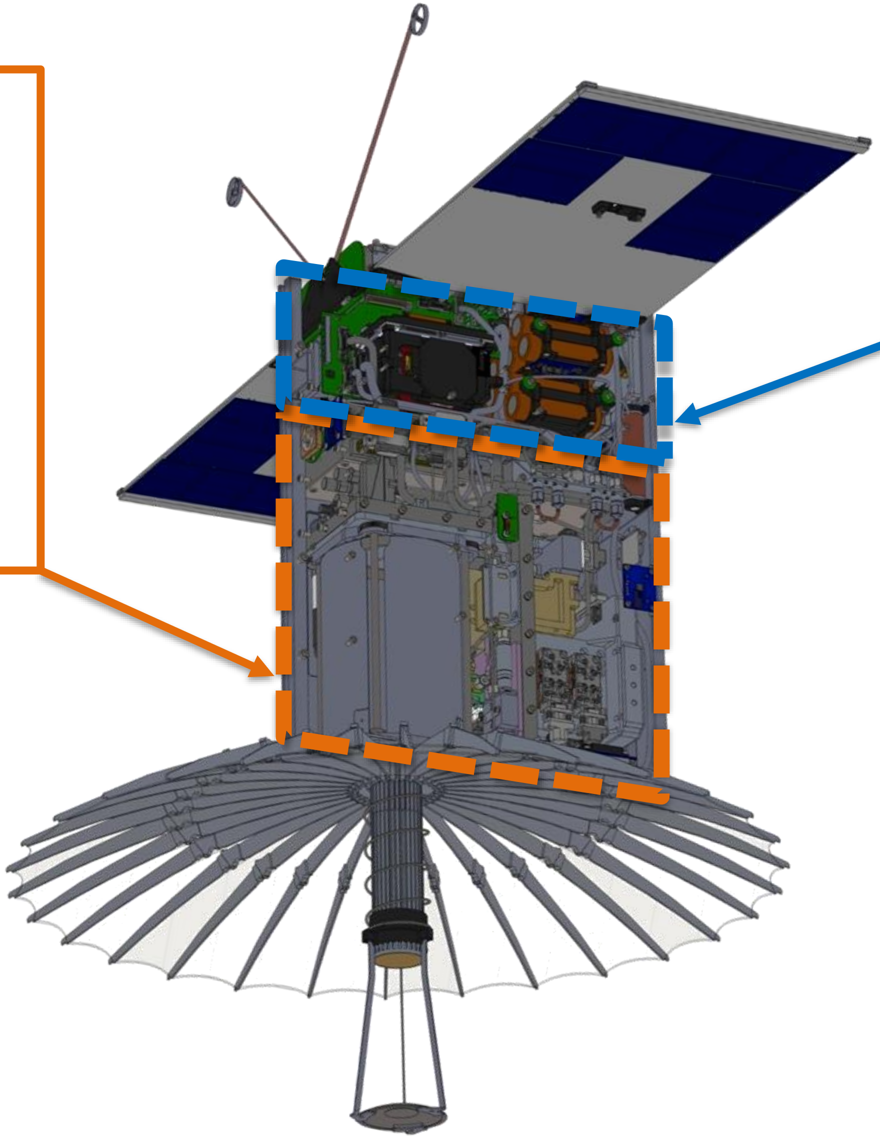
- **Dec 2015** – RainCube project kick-off
- **May 2016** – Tyvak selected for RainCube Spacecraft provider
- **Sept 2016** – Project Critical Design Review (CDR)

RainCube System Architecture

Radar Electronics & Antenna

- **35.75GHz** center frequency
- **20dBZ** sensitivity
- Vertically profile **0-18 km altitudes**
- **10km** horizontal resolution
- **250m** vertical resolution
- **35W** max power draw

Jet Propulsion Laboratory
California Institute of Technology



Spacecraft Bus

- Provide **35W** for payload power in transmit mode
- Maintain payload temperatures **(-5C to +50C operational)**
- Provide **on-board altitude** to radar via GPS
- Provide high payload data downlink via **S-Band** radio

Tyvak
A Terran Orbital Corporation

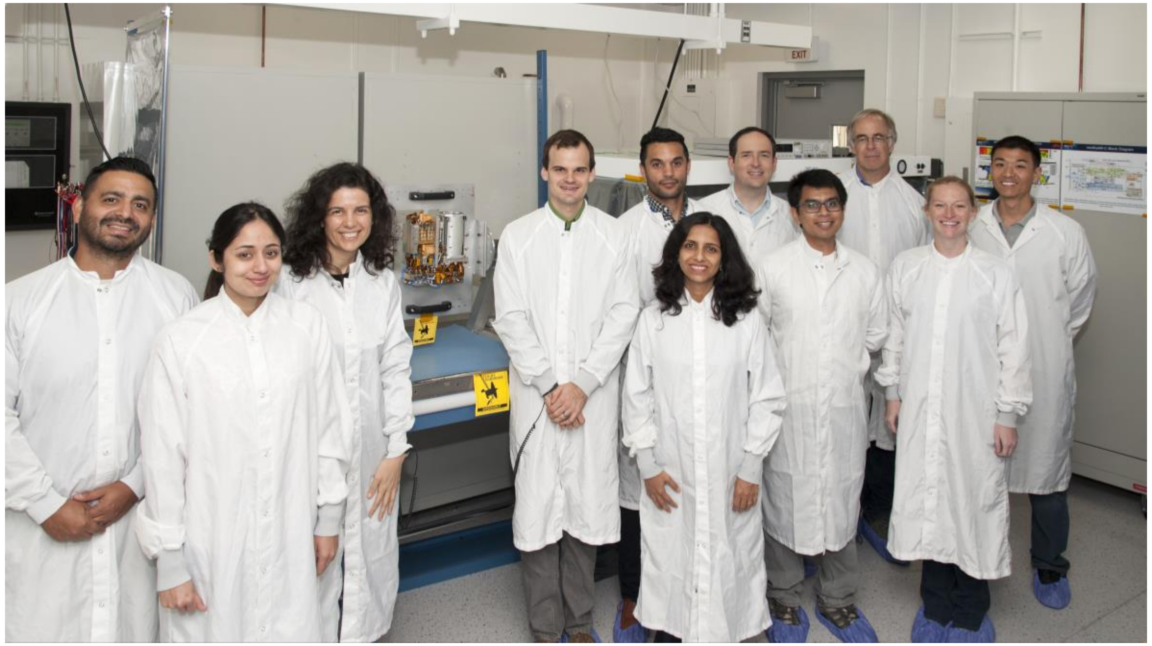
RainCube Phase A/B & C

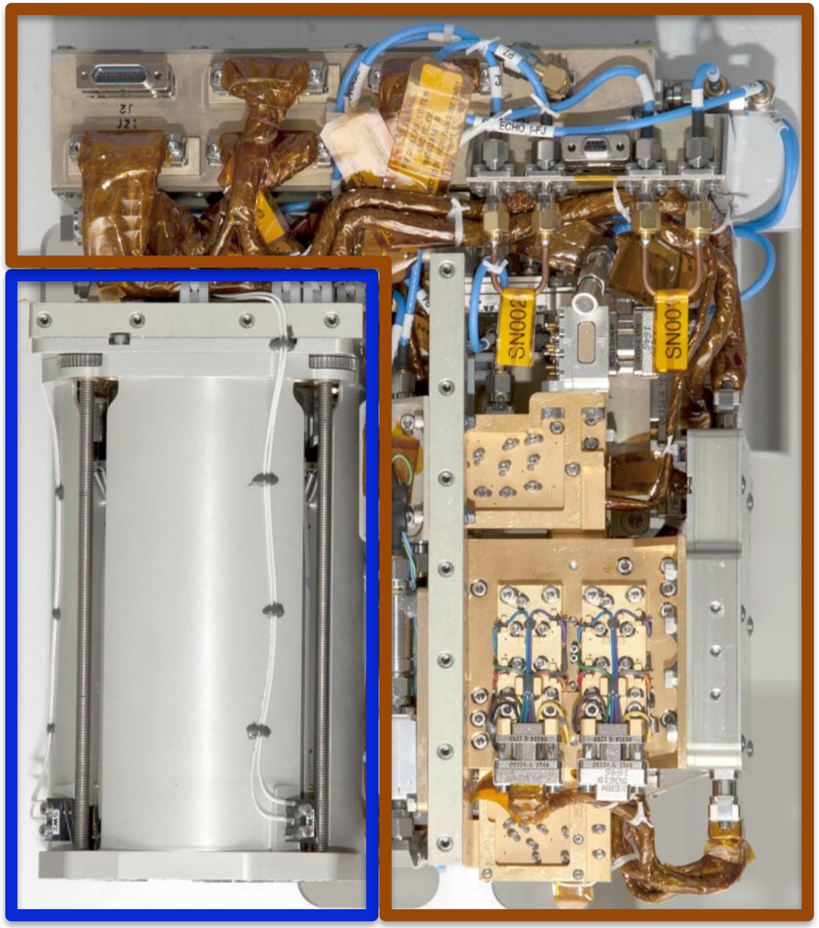
- **Dec 2015** – RainCube project kick-off
- **May 2016** – Tyvak selected for RainCube Spacecraft provider
- **Sept 2016** – Project Critical Design Review (CDR)
- **Jan 2017** – Radar I&T begins
- **Apr 2017** – System Integration Review (SIR)

16 months from funding to flight instrument delivery

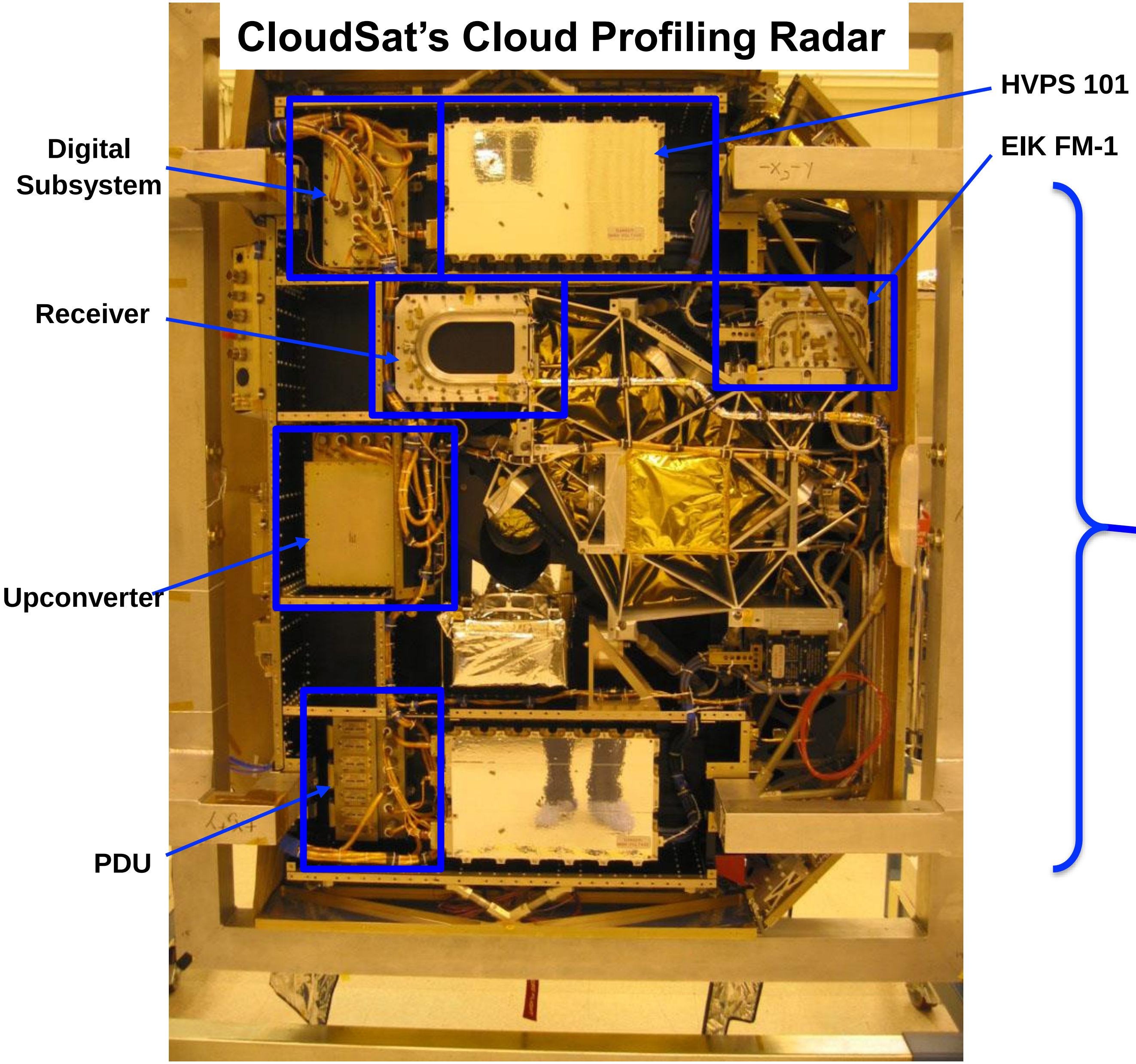
Radar Payload

- Radar payload comprises of miniKaAR-C and KaRPDA flight assemblies
- Three radar operational modes:
  - Standby, Receive Only, and Transmit
- Final power draw in transmit mode is 22W



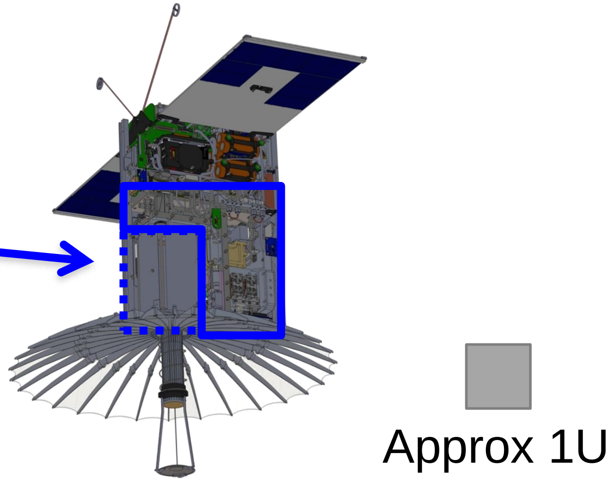


Enabling Technologies are Key to Miniaturization



RainCube radar instrument occupies < 4U in stowed state

- **miniKaAR-C ~2.5U**
- **KaRPDA ~1.5U**

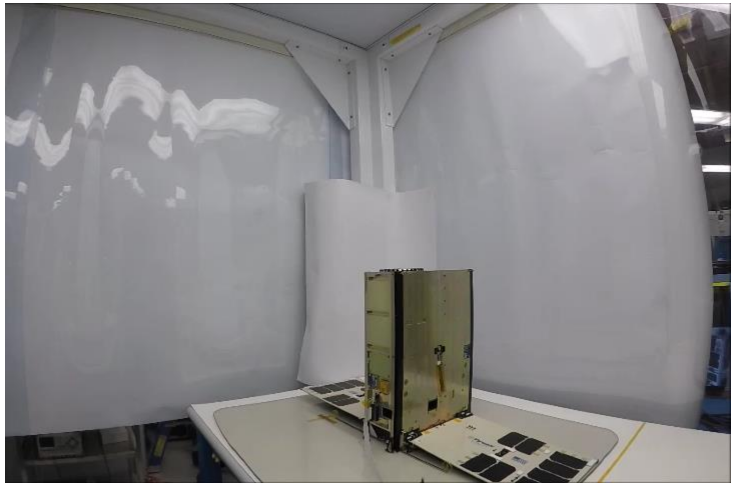


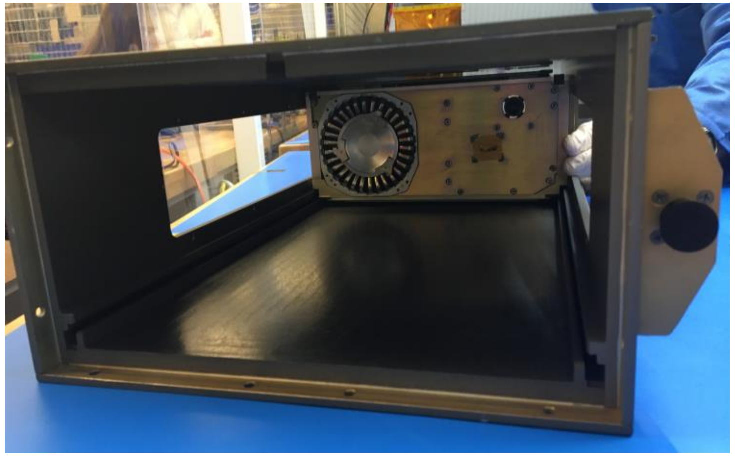
Note: these two images are approximately to scale

RainCube Phase D

- **Aug 2017** – System I&T begins
- **Nov 2017** – Self-compatibility test complete
- **Jan 2018** – System vibe test complete
- **Feb 2018** – System TVAC test complete
- **Mar 2018** – Launch delivery to NanoRacks

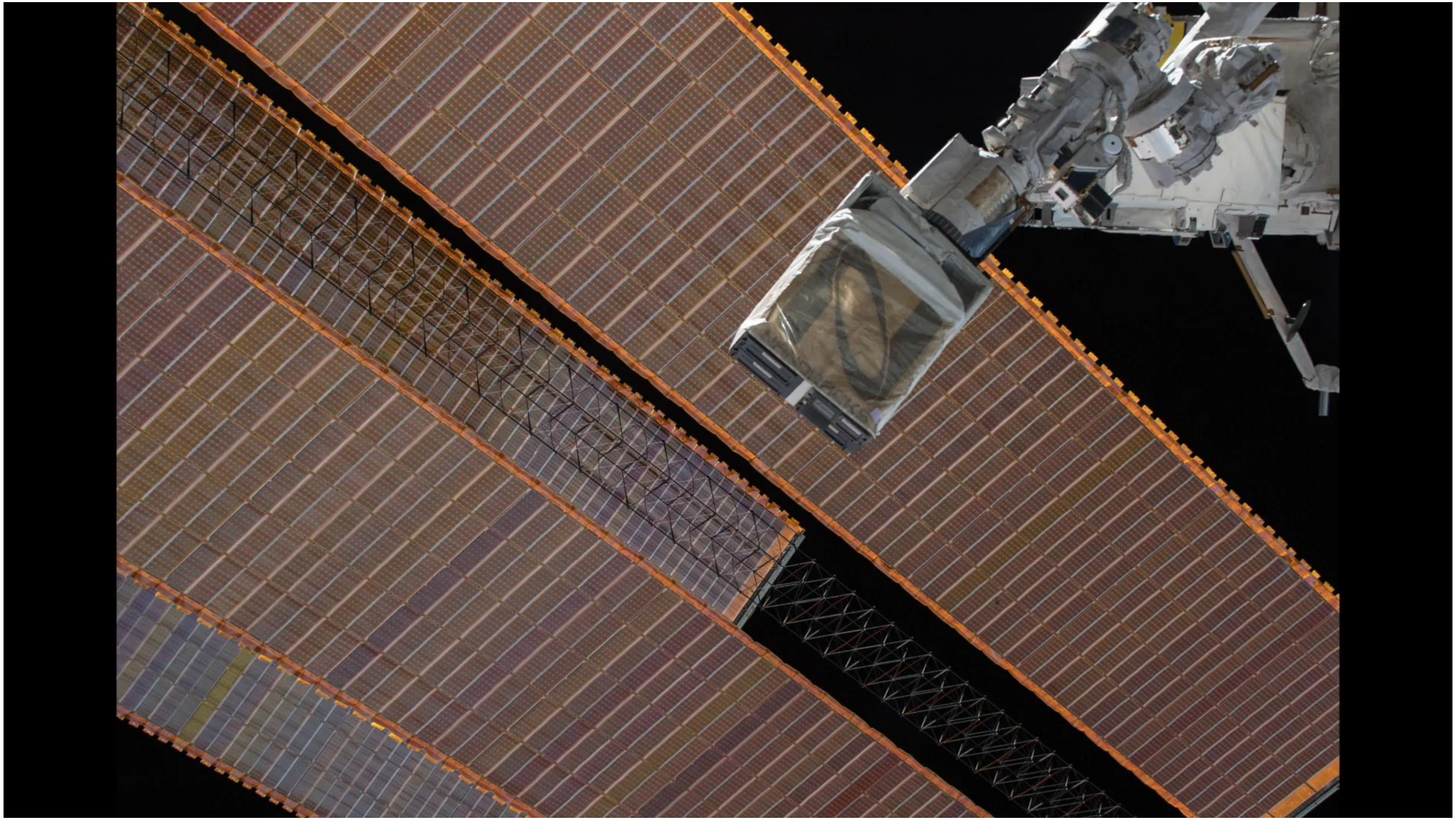
Antenna Deployment Video (actual deployment time is ~3 minutes)



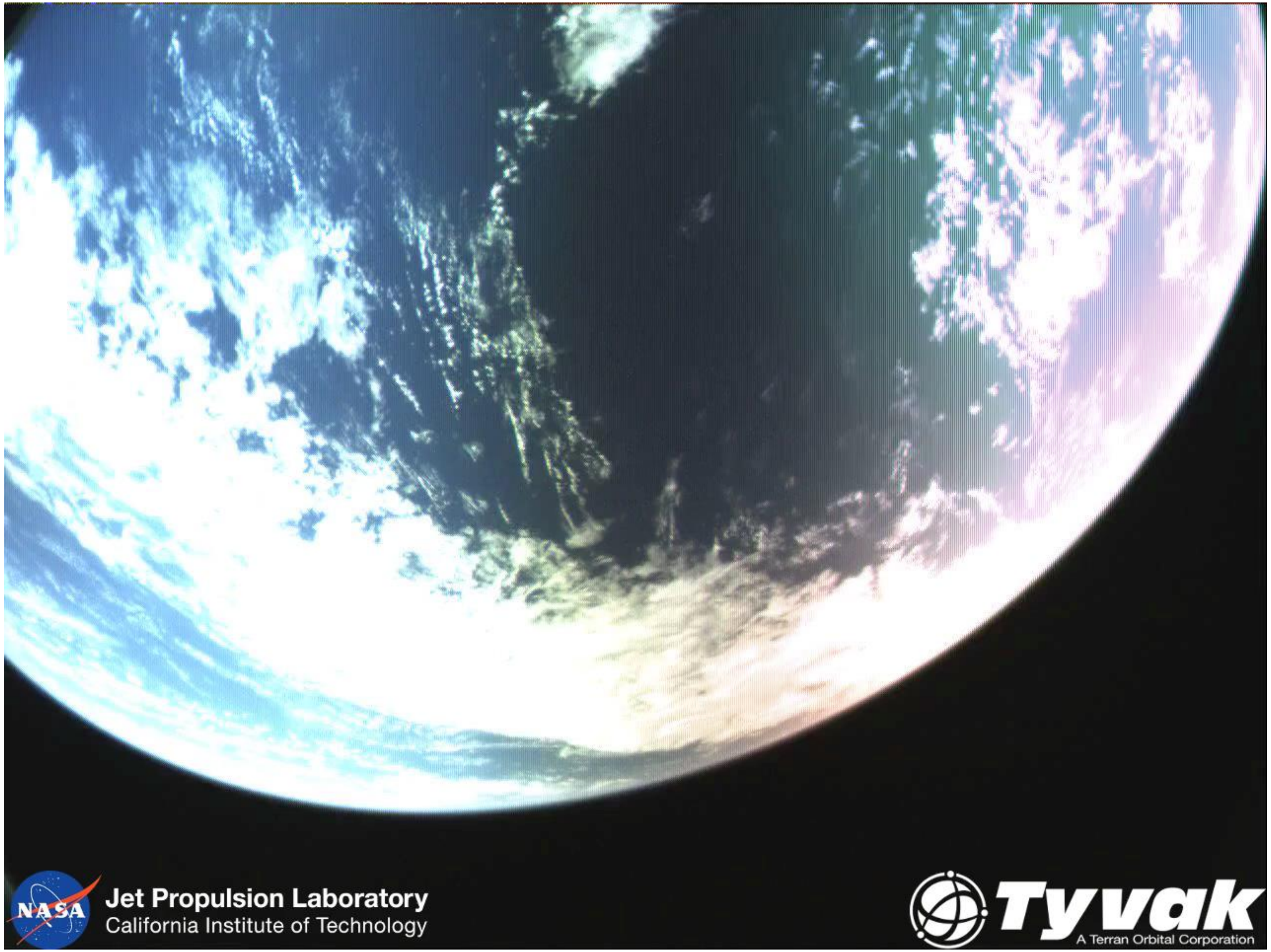


- Cygnus OA-9E ISS Commercial Resupply Services Mission, Wallops

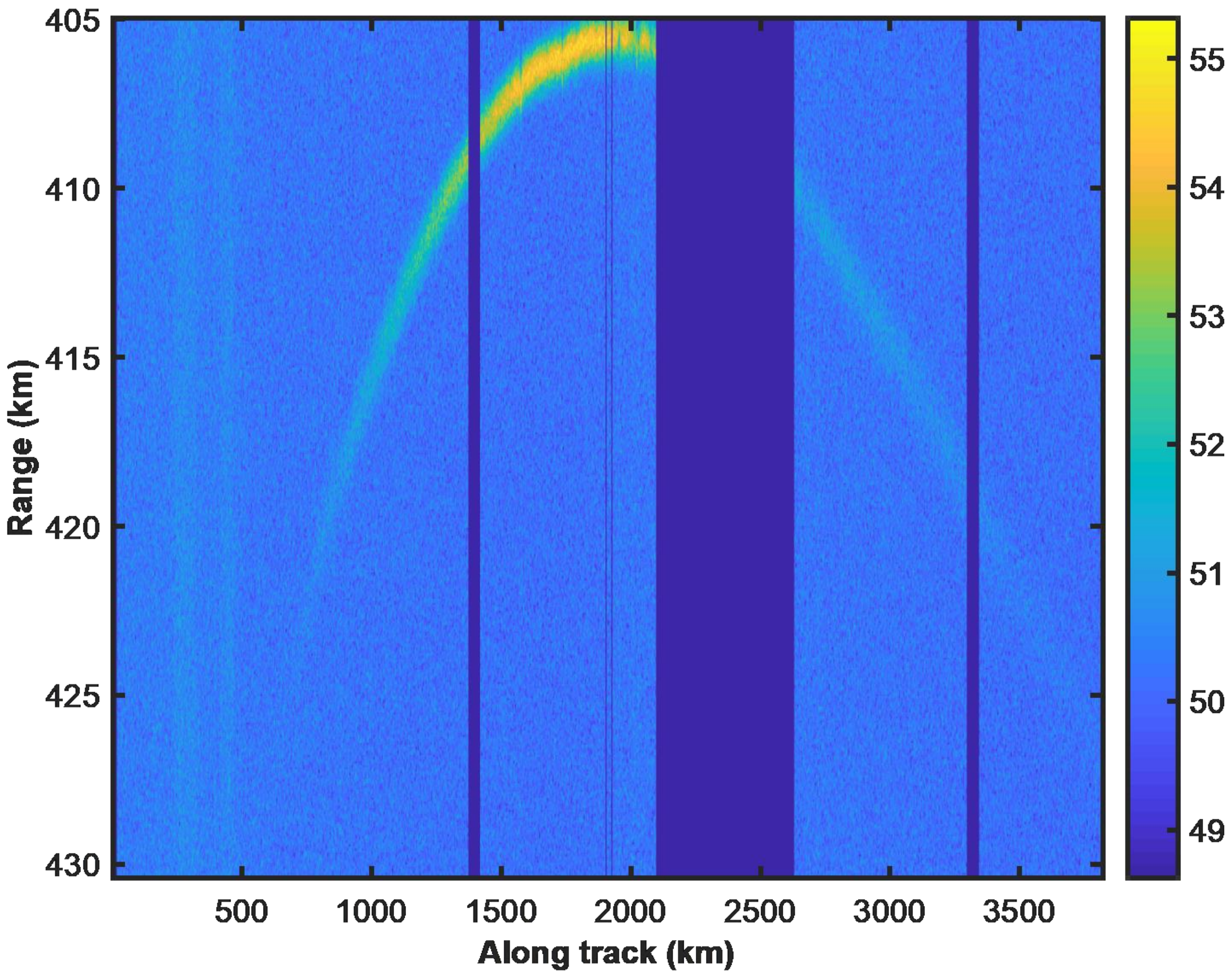
ISS Deployment: July 13th, 2018



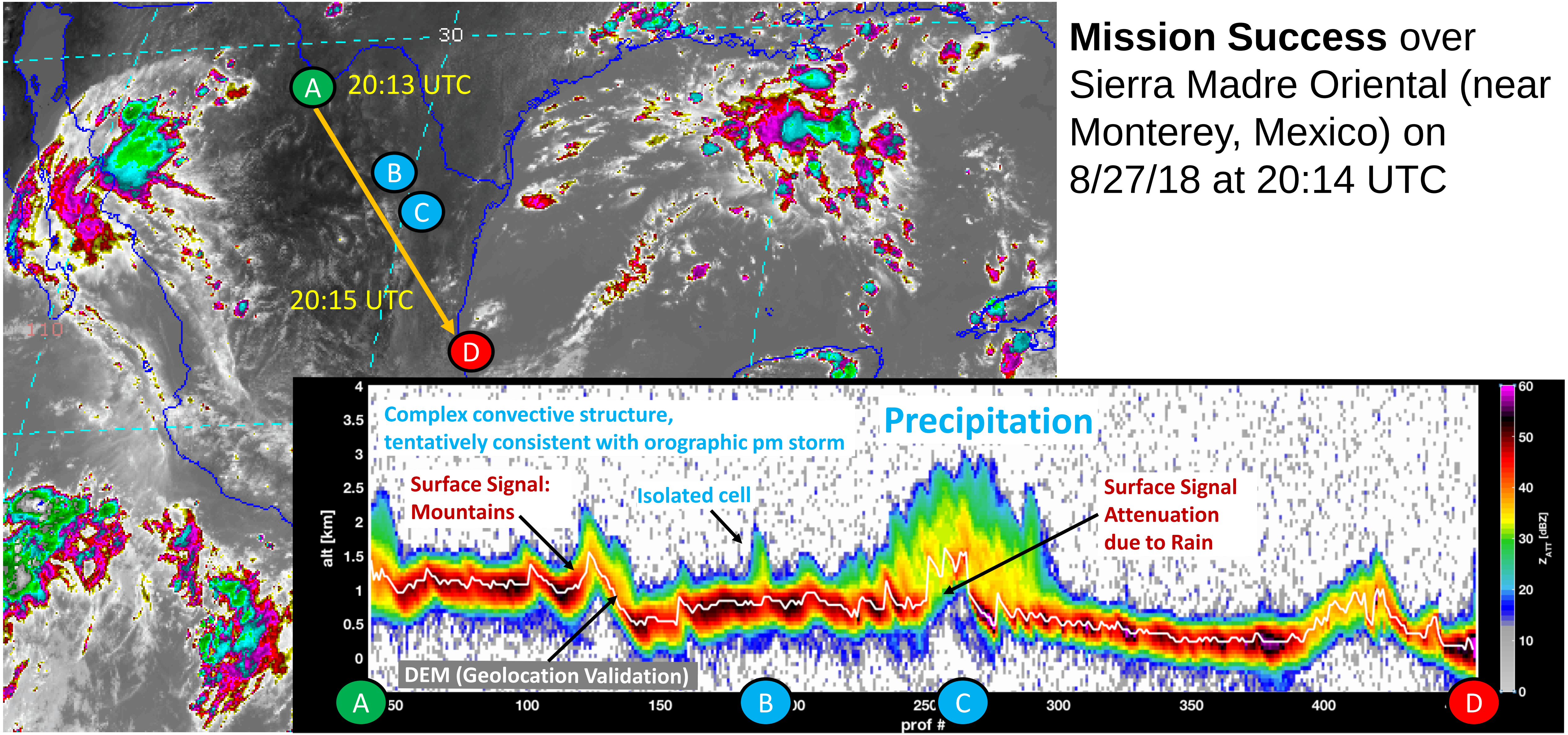
Antenna Deployment: July 28th, 2018



First Echo: August 5th, 2018

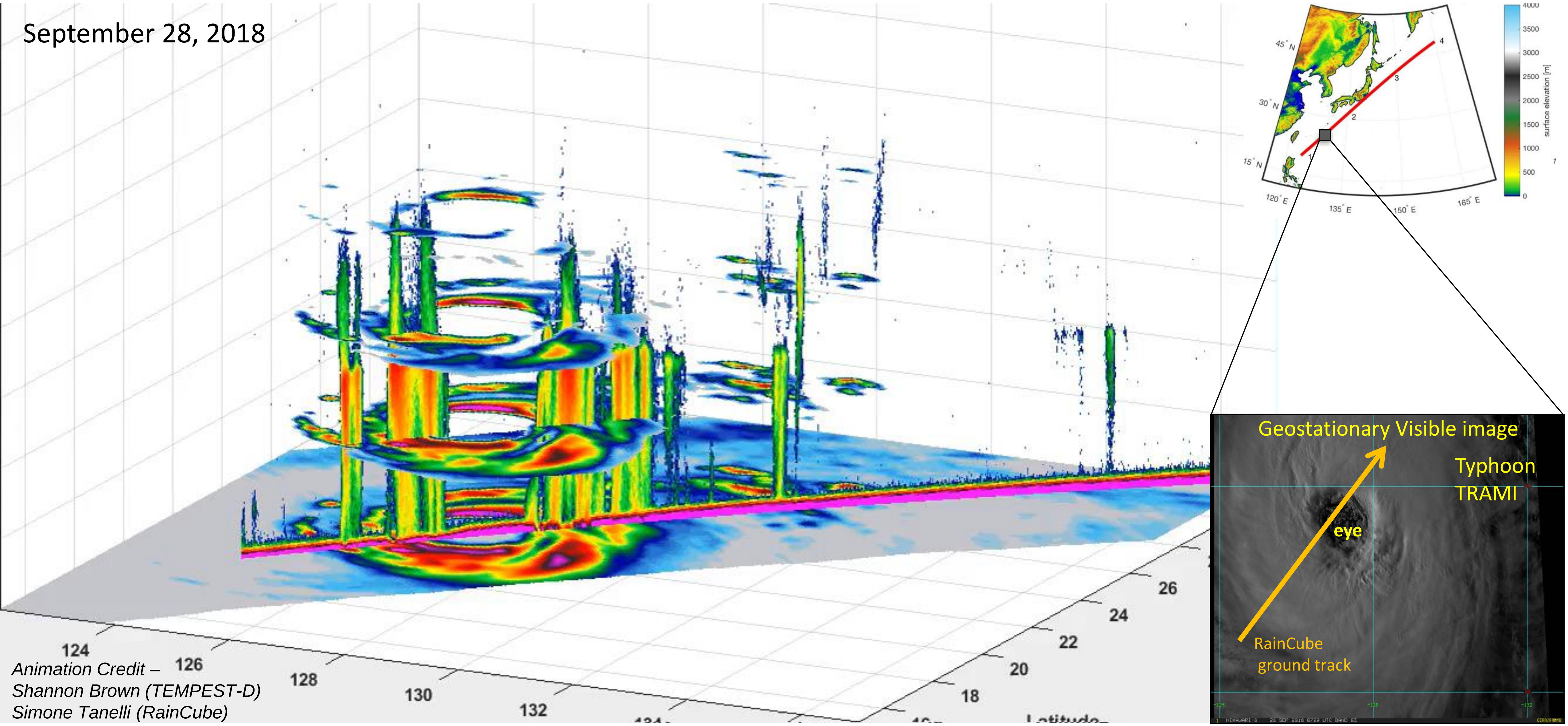


First Rain Measurement: August 27th, 2018



Mission Success over Sierra Madre Oriental (near Monterey, Mexico) on 8/27/18 at 20:14 UTC

RainCube & TEMPEST-D Coincidental Measurement of Typhoon Trami



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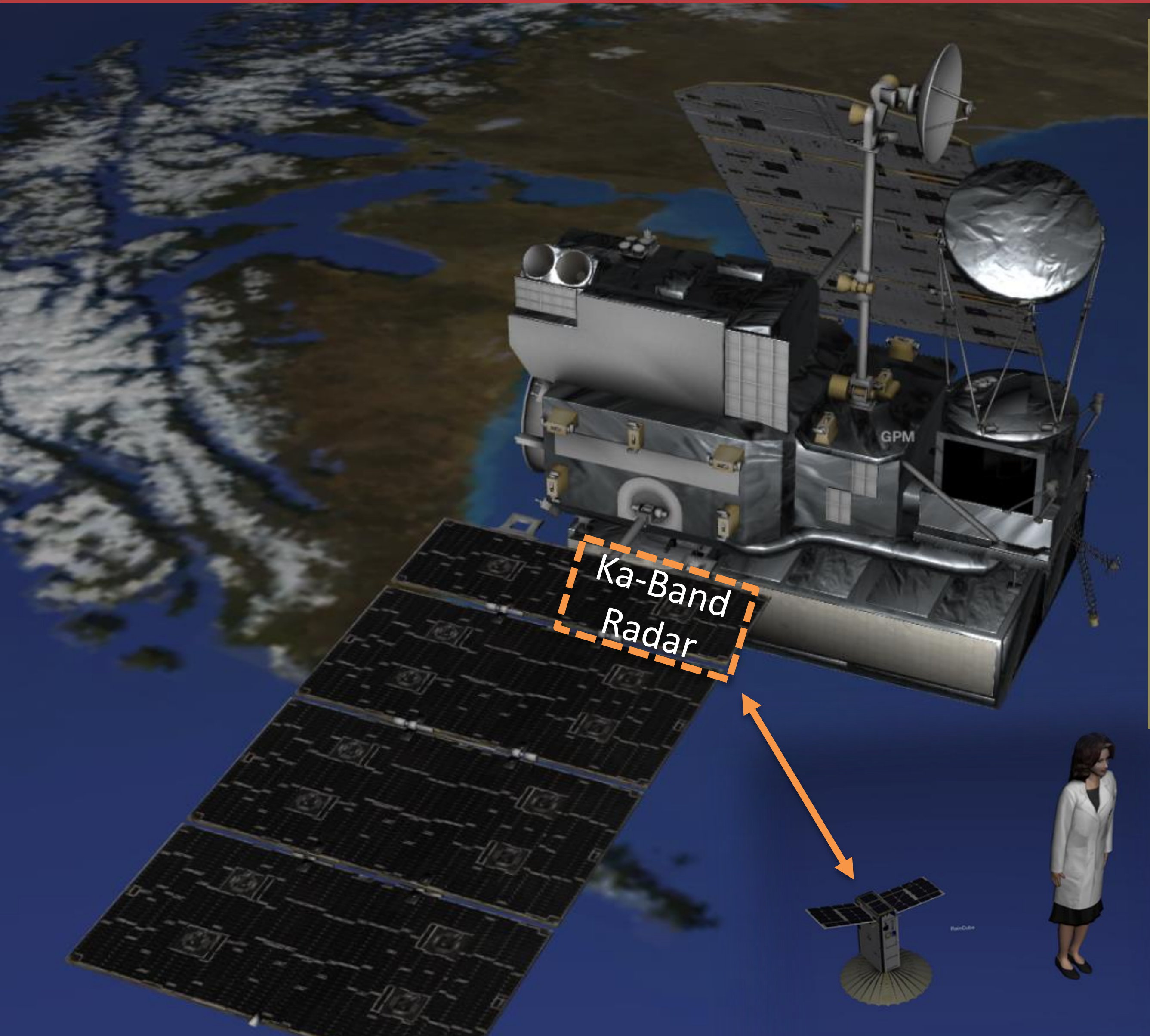
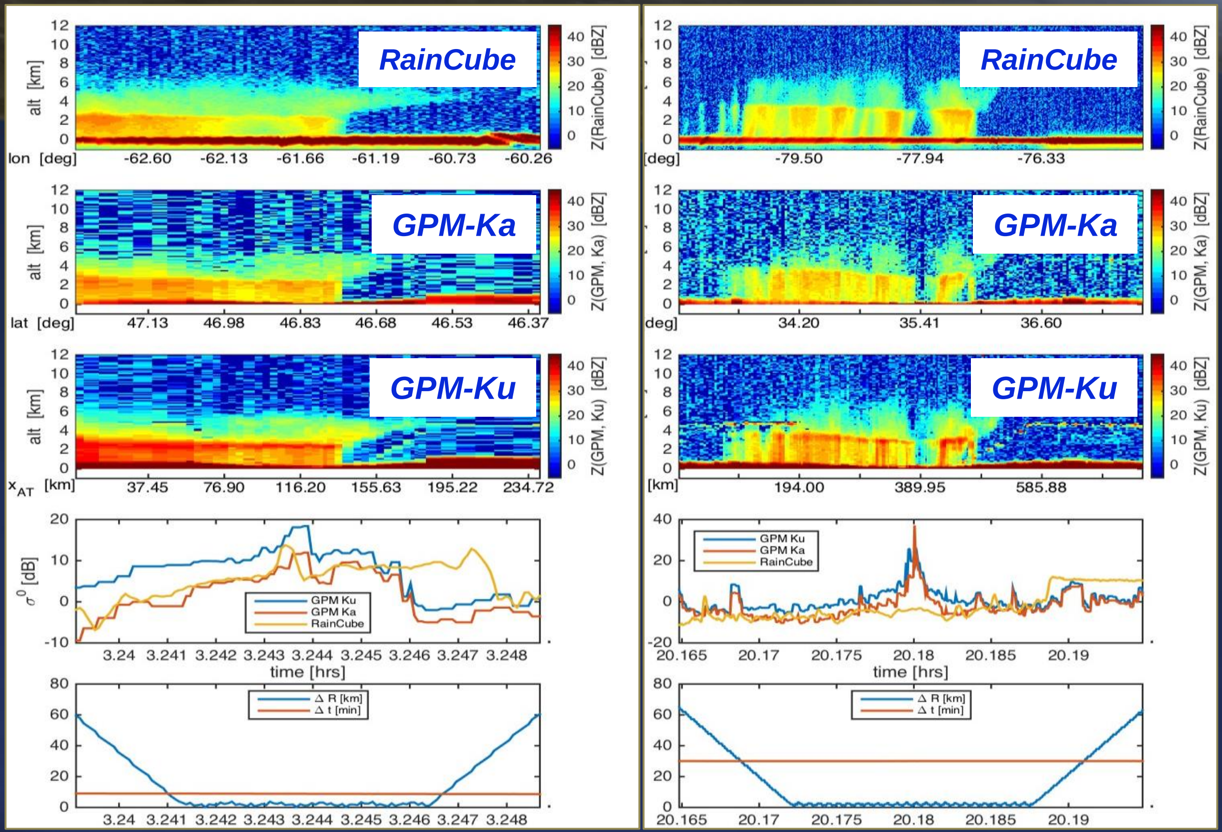
Comparison of RainCube and GPM/DPR Measurements





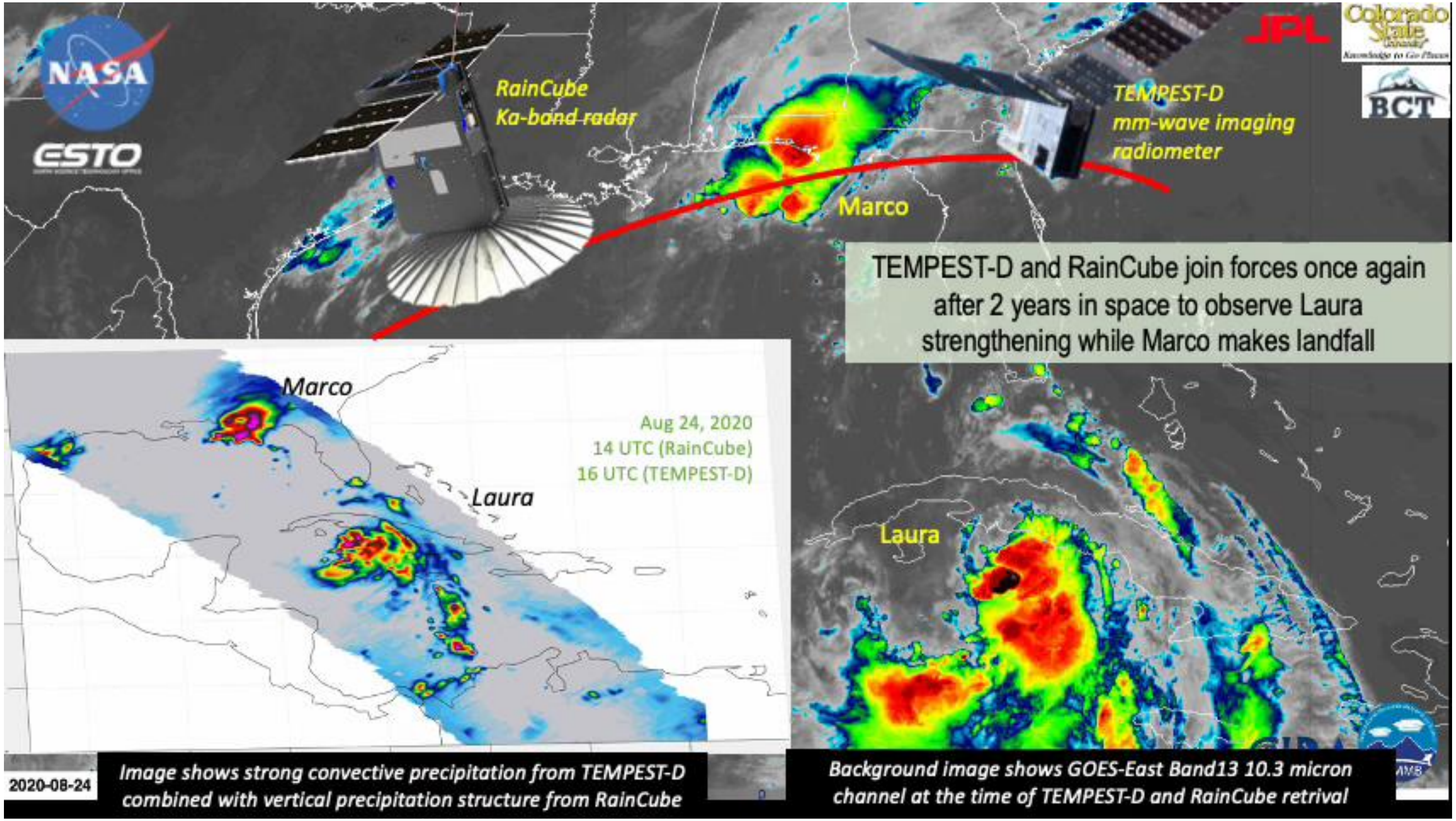
Two measurements from RainCube and GPM/DPR*

**Just one of many GPM measurements.*
Extracted from 3D scanned cross-track.
Data Credit: Ousmane Sy (JPL)
Image Credit: NASA Eyes on Earth

Final Months of Ops

- **July 2020** – Regained fine pointing control with new GNC algorithm
- **Aug 2020** – Measurements of Hurricanes Laura & Marco

RainCube Captures Hurricanes Laura & Marco



Final Months of Ops

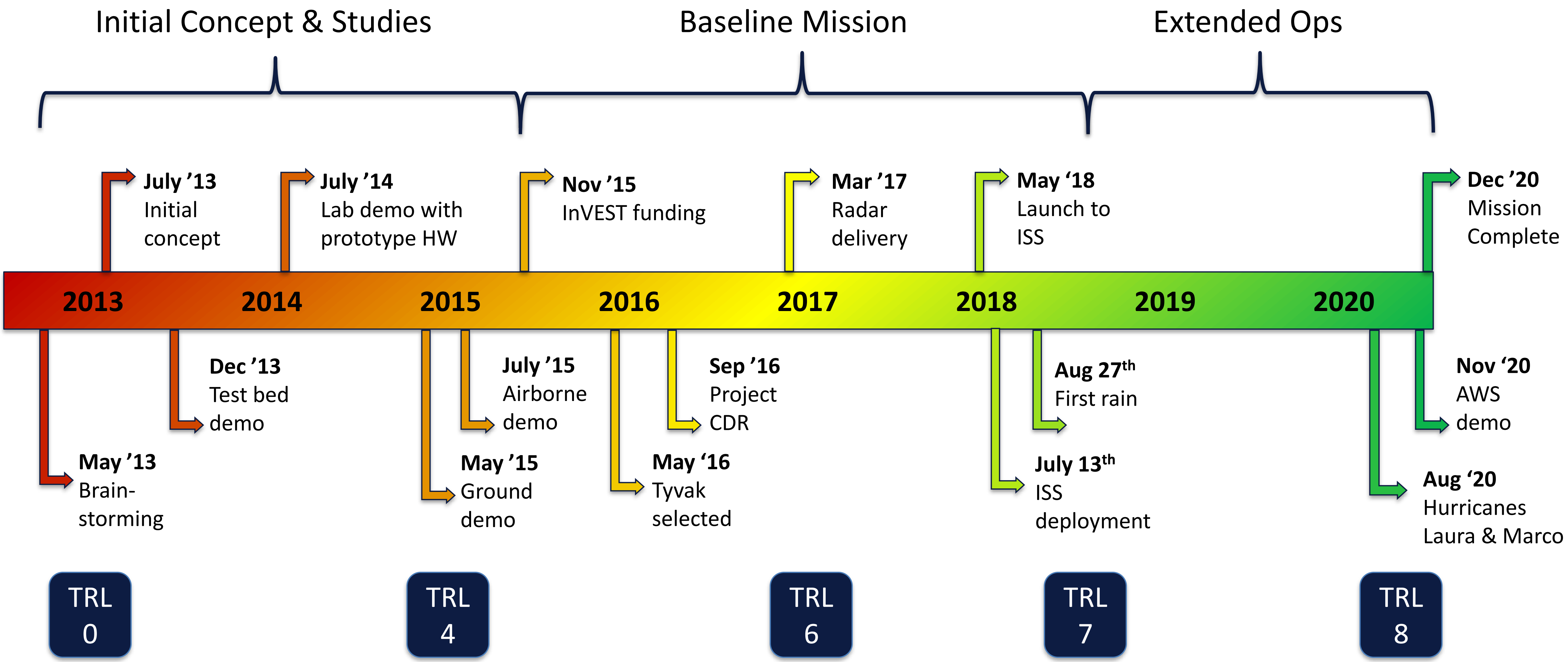
- **July 2020** – Regained fine pointing control with new GNC algorithm
- **Aug 2020** – Measurements of Hurricanes Laura & Marco
- **Sept/Oct 2020** – Continued to collect in-orbit radar measurements with varying pulse compression parameters
- **Nov 2020** – S-band downlink demo with AWS International Ground Network
- **Dec 2020** – Antenna second motion operation completed
- **Dec 2020** – RainCube de-orbits on Christmas Eve

RainCube operated for 2.5 years on-orbit

Radar Performance Metrics

Performance Parameter	Requirement	Measured
Sensitivity @400km	20 dBZ	**11.0 dBZ**
Horizontal resolution @400km	10 km	**7.9 km**
Nadir data window (above sea level)	0 to 18 km	**-3 to 20 km**
Vertical resolution	250 m	250 m
Downlink data rate (in transmit)	50 kbps	49.6 kbps
Payload power consumption (AntDeployment / STDBY / RXOnly / TXScience)	10 / 8 / 15 / 35 W	**5 / 3 / 10 / 22 W**
Mass	6 kg	**5.5 kg**
Range sidelobe suppression	> 60dB @ 5km	**> 65dB @ 1km**
Transmit power & transmit loss (10W / 1.1 dB)	38.9 dBm	> 39 dBm
Antenna gain	42 dB	**42.6 dB**
Antenna beamwidth	1.2 deg	1.13 deg

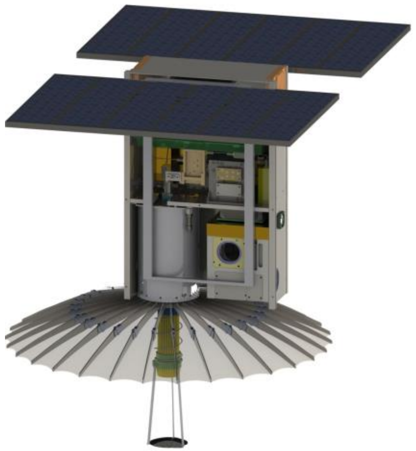
Timeline from TRL 0 to TRL 8



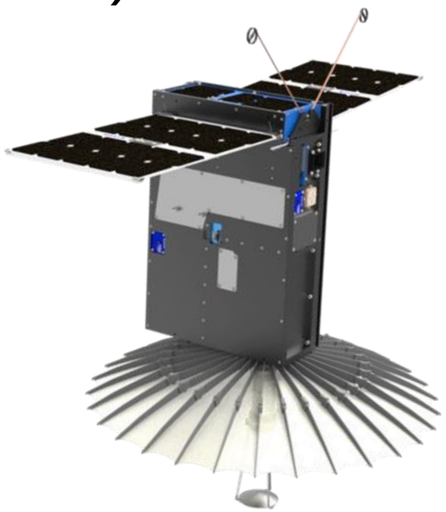
LESSONS LEARNED

Thorough & Peer-Reviewed Formulation Phase

- Early studies & focused table-top reviews
  - Pre-Phase A Study (design trades with subsystem engineers)
  - Budget Review (workforce, schedule, and costs)
  - Feasibility Review (technology and design maturities)
  - Requirements Reviews (baseline vs threshold)



- Request for Information (RFI) versus Request for Proposal (RFP)
  - Assess and tailor flight system requirements based on supplier inputs



Collaborative Tailoring & Review Process

- Embrace institutional practices & tools in a value-added philosophy
  - Assess applicability of institutional req'ts for a 3-month, tech demo mission with $7m budget
- Open dialogues with JPL institutional stakeholders
  - Class D Technical Advisory Board
  - Safety & Mission Assurance
- Formulation of a Technical Advisory Board from the project beginning
  - Subject matter experts for all major subsystems
  - Experience with low cost, high risk missions
  - Attended specific technical meetings and tabletop reviews
  - Maintained awareness of project progress throughout implementation phases
  - Formal project review boards were comprised of TAB members

CubeSat Form Factor Constraints

- Volume versus access to space
  - 6U was *just* big enough for RainCube
  - Many design trades & compromises due to volume
- Mass growth and margin standards
  - Many design compromises due to mass assumptions
  - Often overestimate & then require ballasts
  - Problematic for orbit life and other mission aspects

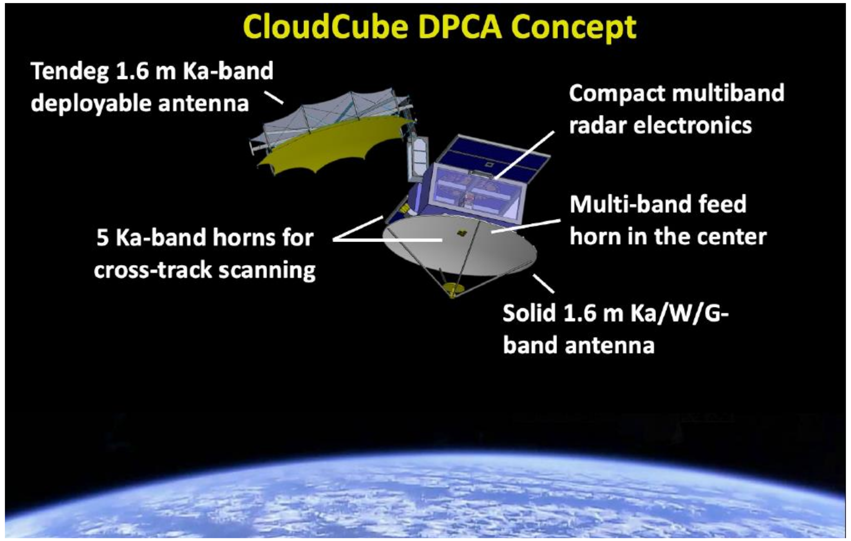
RAINCUBE LEGACY

Implications for Future Earth Science Missions

- **RainCube has enabled unique opportunities for Earth Science missions**
  - Science-grade precipitation profiling radar on a small satellite platform is possible!
  - New technologies can be flown on a variety of platforms
- **Multi-satellite missions are now practical**
  - Cost-effective approach for building multiple satellites for a single mission / objective
  - Significantly improve revisit times of weather phenomena using constellations
  - Compliment large weather satellite observations with temporal measurements
- **Manage mission risk and reliability through numbers**
  - Alternative to large, multi-instrument satellites
  - Avoid “all eggs in one basket” and the resulting conservative risk posture
  - A more sustainable approach to reduced budgets and cost-constrained missions

IIP-19: CloudCube

- Selected by NASA ESTO Instrument Incubator Program (IIP) 2019
- Compact, multi-frequency mm-wave radar instrument
  - Ka-band, W-band, and G-band
- Doppler capabilities at Ka-band
- Modular design for different frequency subsets and small satellite designs
- miniKaAR-C architecture is backbone of CloudCube design



EVM-3: INCUS

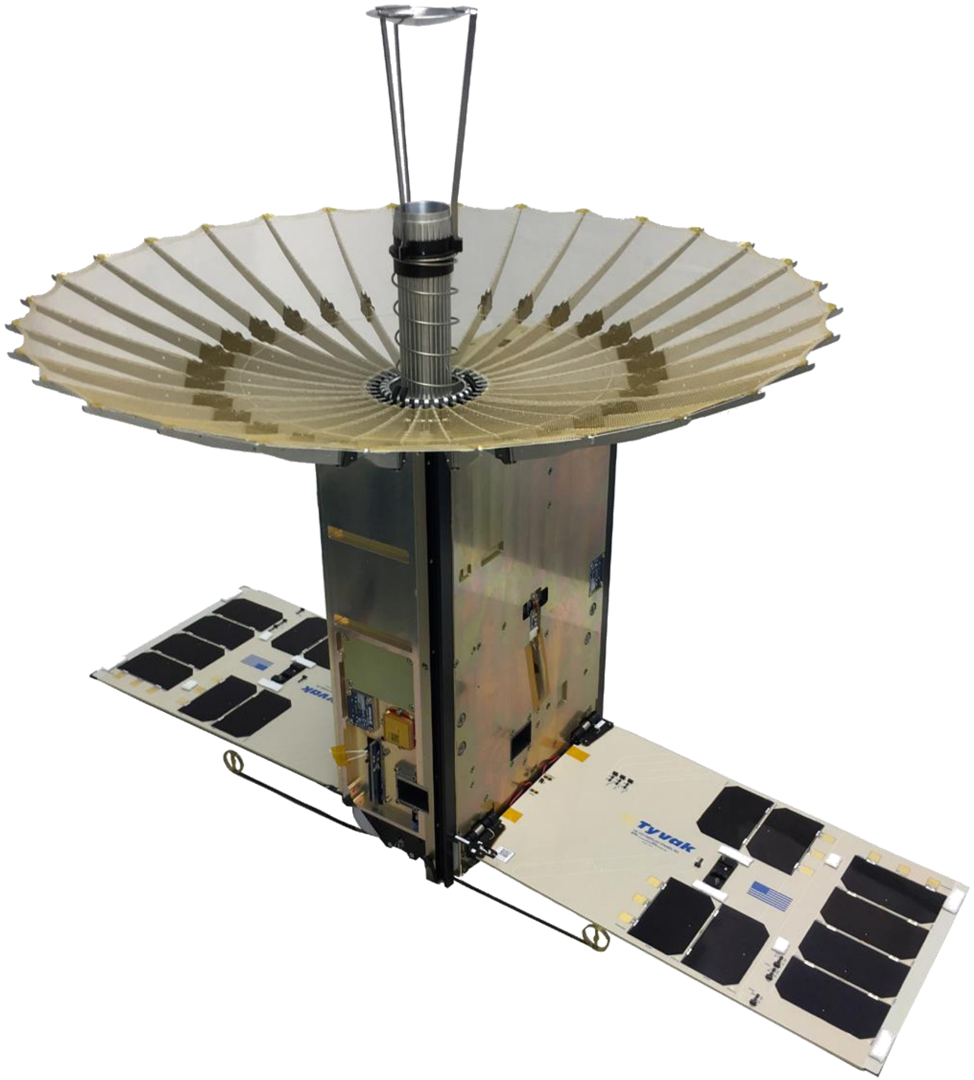
- **In**vestigation of **C**onvective **U**pdraft**s** (INCUS)
  - "… three SmallSats, flying in tight formation,… to directly address why convective storms, heavy precipitation, and clouds occur exactly when and where they form."
  - https://climate.nasa.gov/news/3128/nasa-selects-new-mission-to-study-storms-impacts-on-climate-models/

- Selected in November 2021
- $177 million approximate cost (not including launch costs)
- Launch expected in 2027

Summary

- RainCube successfully demonstrated the first radar on a CubeSat
- Novel radar architecture increased from TRL 0 to TRL 7 in just over five years
  - First brain-storming session in May 2013
  - Rain detected from orbit in August 2018
  - Extended mission concluded in December 2020 (TRL 8)
- Enabling technologies for unique Earth Science missions
  - Improve weather and climate modeling

Special Thanks



- JPL RainCube Team Members
- Tyvak RainCube Team Members
- JPL Earth Science Program Office
- NASA Sponsors

RainCube Team in Pictures