

RainCube: First Spaceborne Radar in a CubeSat



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RainCube Mission Operations Manager
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California Institute of Technology, CA, USA

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Virtual Presentation over WebEx

ABOUT THE PRESENTER



Shivani joined NASA-Jet Propulsion Laboratory's Radar Science and Engineering section in 2015. She is an Electrical Engineer in Radar Digital Systems group.

RainCube was her first JPL mission. After working on the RainCube digital subsystem during development, Shivani has been serving as RainCube's mission operations manager since launch.

Prior to joining JPL, Shivani worked at Siemens Rail Automation for 4 years after graduating from USC with a Master's in Electrical Engineering. Her Bachelor's degree is in Electronics Engineering from Gujarat University in India.

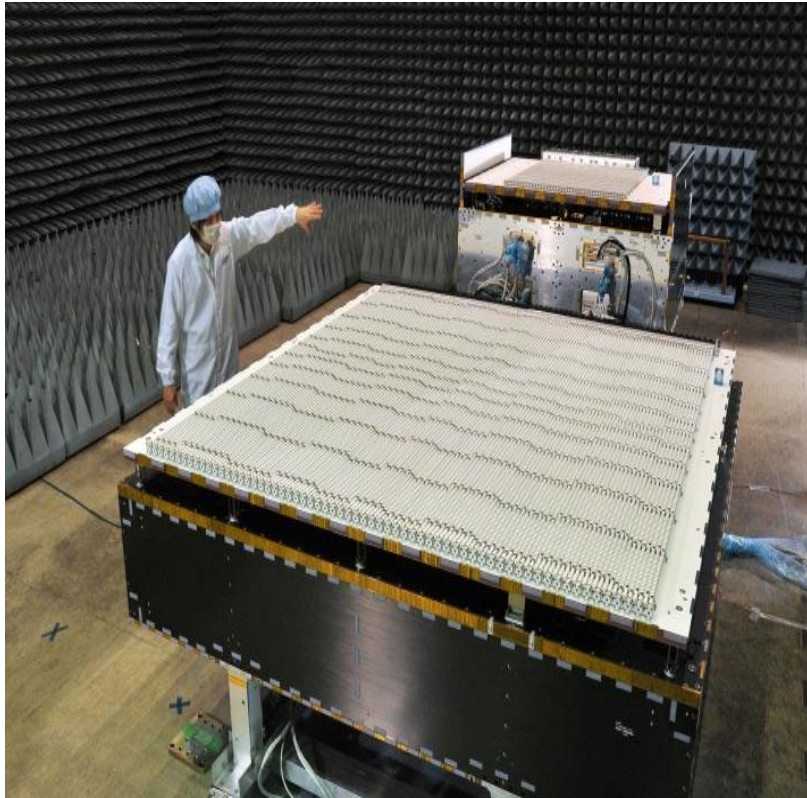
Other than RainCube, Shivani is part of the digital firmware team on Europa Clipper mission's REASON radar and a co-investigator on CloudCube IIP that has been selected as part of ROSES-2020 solicitation.



RAINCUBE – MISSION OVERVIEW

Rationale, Objectives and System Architecture

Traditional Radars for Measurement of Cloud, Convection and Precipitation



GPM – DPR

Dimensions – 13m x 6.5m x 5m with panels deployed

Mass – 3.8 tons

Image Credit – Simone Tanelli/GPM Team



CloudSat

Dimensions – 2.54m x 2m x 2.29m with panels deployed?

Mass – 700 kg (approx.)

Image Credit - <https://www.ball.com/aerospace/programs/cloudsat>

Traditional Form Factors used in CubeSats



10x10x10 cm
Dimensions of a CubeSat

1.3 kg
Mass of a CubeSat

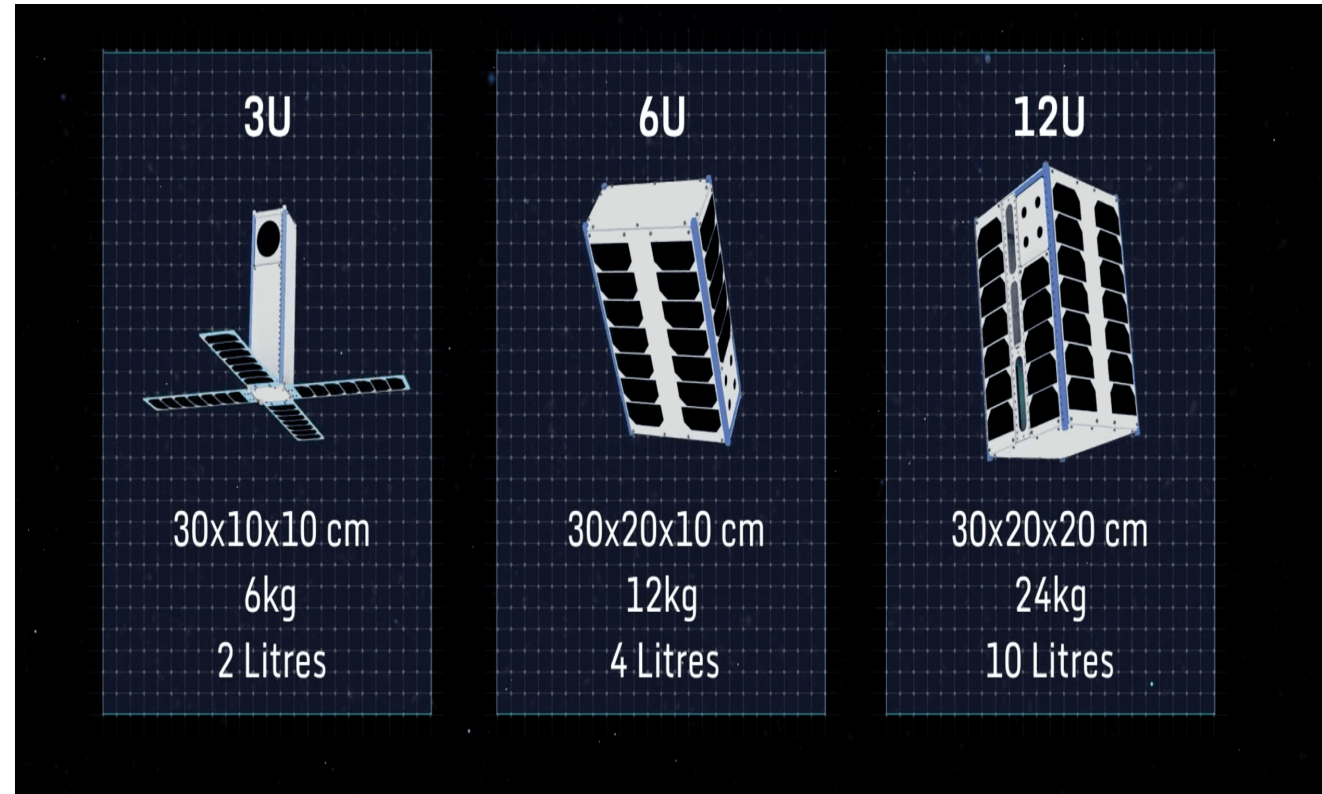
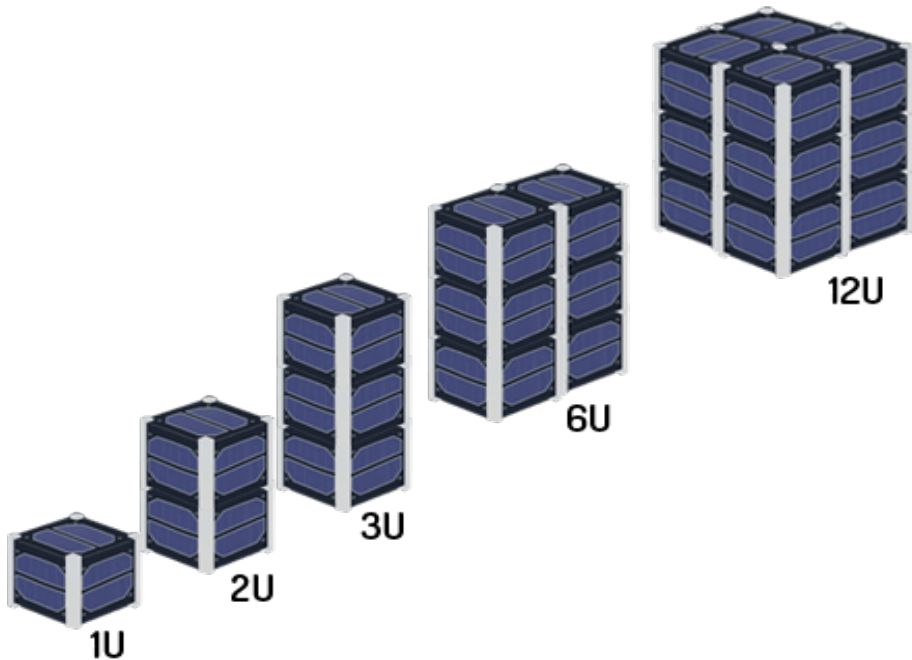
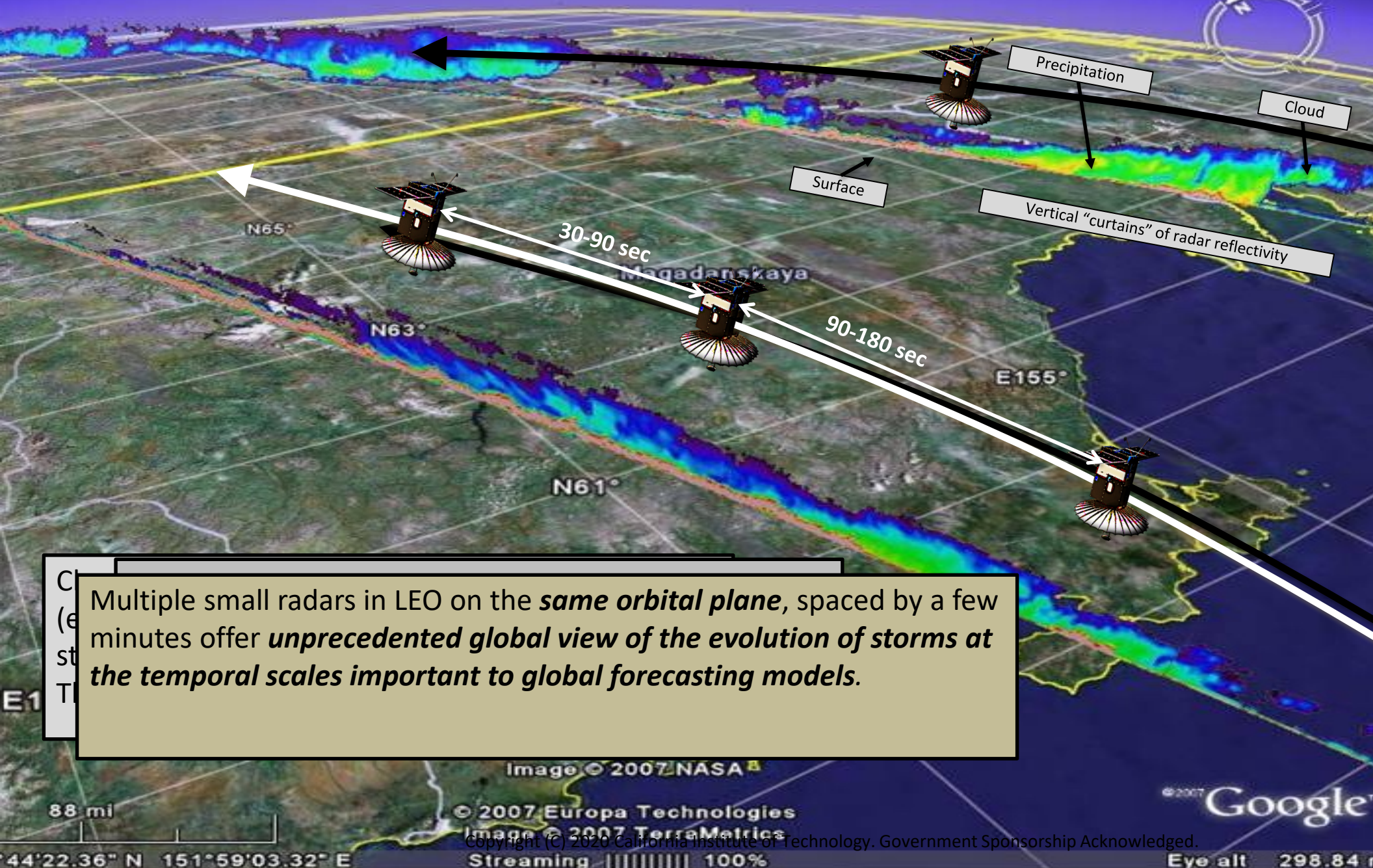


Image credit – <https://open-cosmos.com>

Image Credit - <https://alen.space/basic-guide-nanosatellites/>

Observing Cloud and Precipitation processes from space



Multiple small radars in LEO on the *same orbital plane*, spaced by a few minutes offer *unprecedented global view of the evolution of storms at the temporal scales important to global forecasting models*.

Inquiries for the feasibility of multiple cloud & precipitation radars in LEO were formulated during the development of TRMM and CloudSat (late 90's and early 00's).

Instrument and bus unit costs, and launch costs, didn't enable a realistic path to even propose such mission architectures... until the CubeSat (Nano, Micro, Small, ...) revolution.

First challenge was posed with 1U and 3U (no-go). Then the 6U became an option...



NASA ESTO and InVEST PROGRAM

- **ESTO** = Earth Science Technology Office
- ESTO funding initiatives to promote science and technology advancements –
 - IIP – Instrument Incubation Program
 - ACT – Advanced Component Technology
 - AIST – Advanced Information Systems Technology
 - **InVEST** – In Space Validation of Earth Science Technologies
- RainCube was an InVEST – 2015 selection
- InVEST – 2015 is part of NASA-ROSES solicitation
 - (**ROSES** = Research Opportunities in Space and Earth Sciences)

NASA ESTO and InVEST PROGRAM CONT..

- **Rationale for InVEST**
 - Advance the readiness of existing Earth Science technology (i.e., TRL advancement)
 - No research or development of new technology
 - Reduce risks to future Earth Science missions
- **Key requirements to be selected for the InVEST solicitation were**
 - Entry TRL (Technology Readiness Level) must be at least 5 = already demonstrated on Earth either as an airborne mission or in lab environment
 - Must validate technology in space within 1 year of launch
 - Implied use of “*U-Class*” small satellites that are of 3U to 6U form-factor
 - For access to space, recommended that proposers submit a proposal to the annual NASA CubeSat Launch Initiative (CSLI)

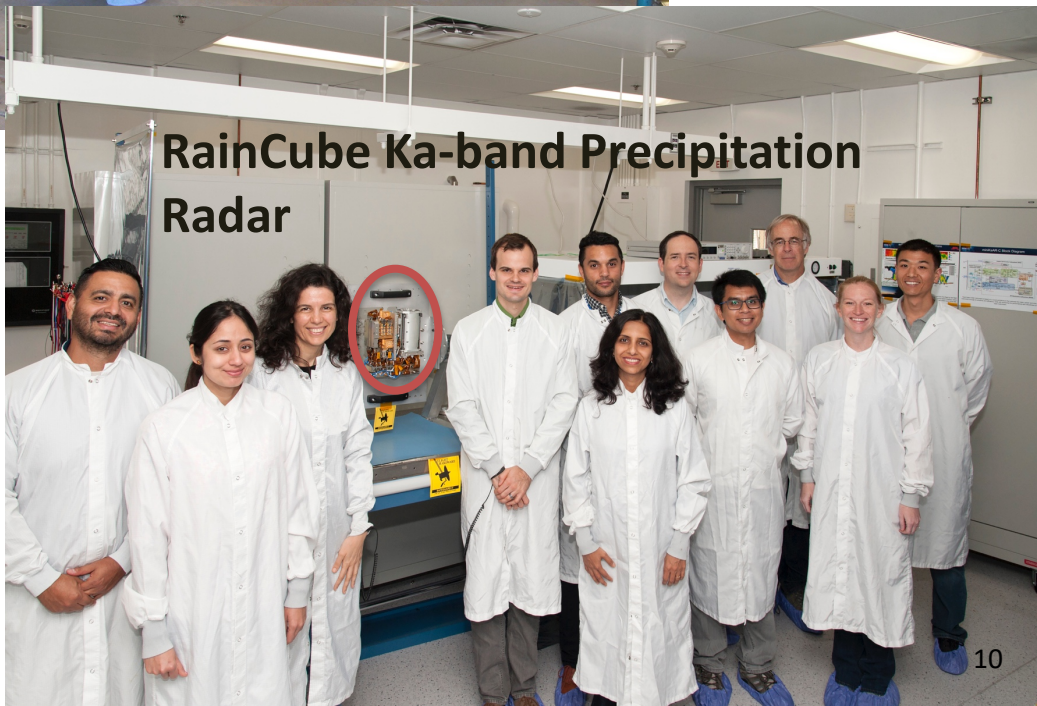
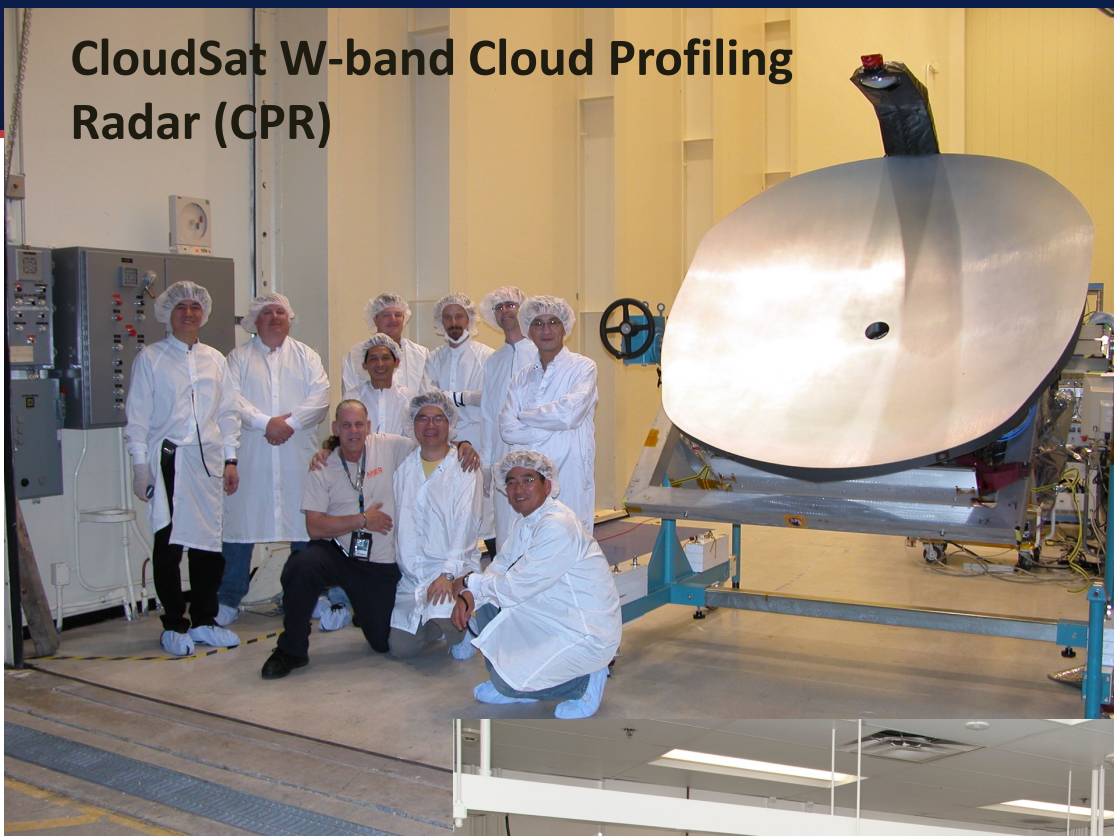
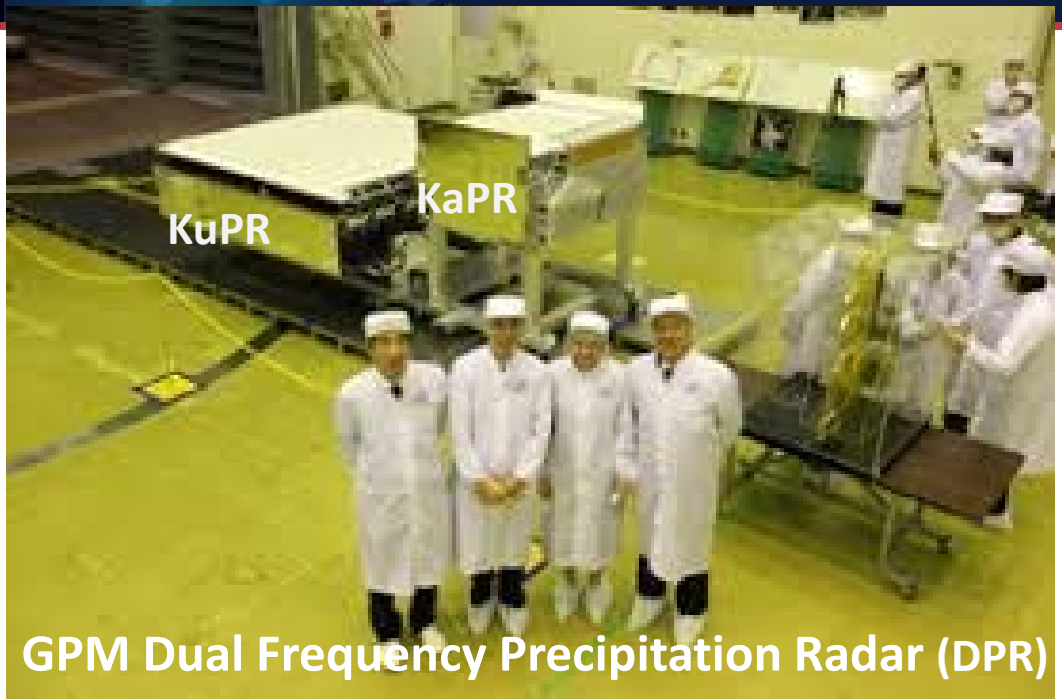


RainCube – Radar in a CubeSat

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 5 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 Delivery
 - Tyvak: Spacecraft Delivery, System I&T, Mission Operations
 - CSLI / NanoRacks: Provide launch to LEO via ISS

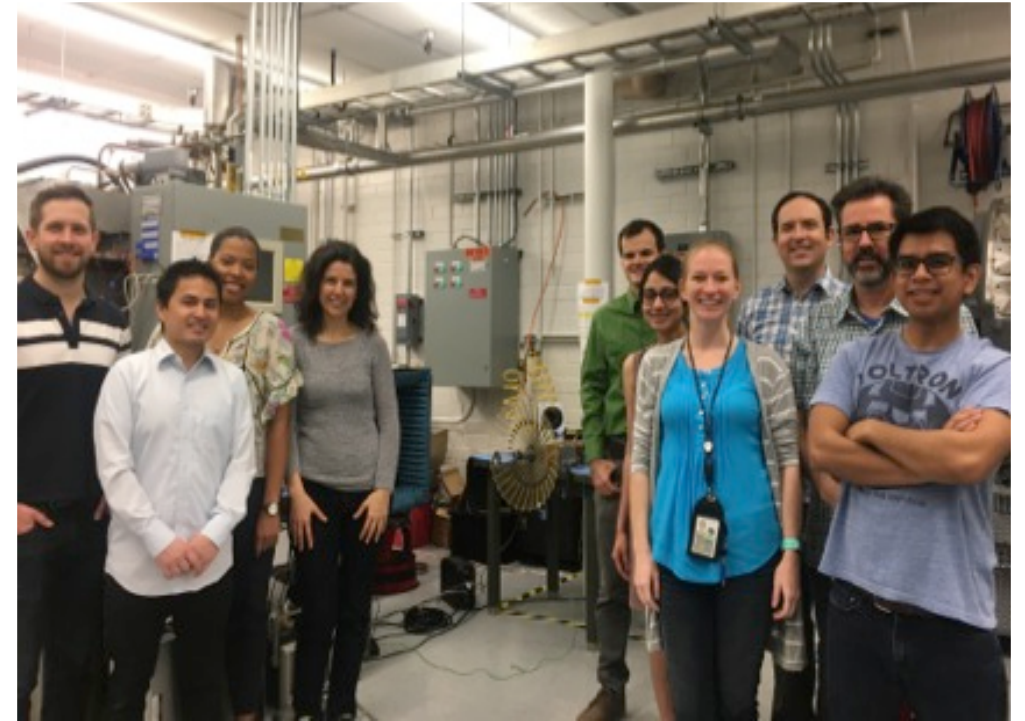
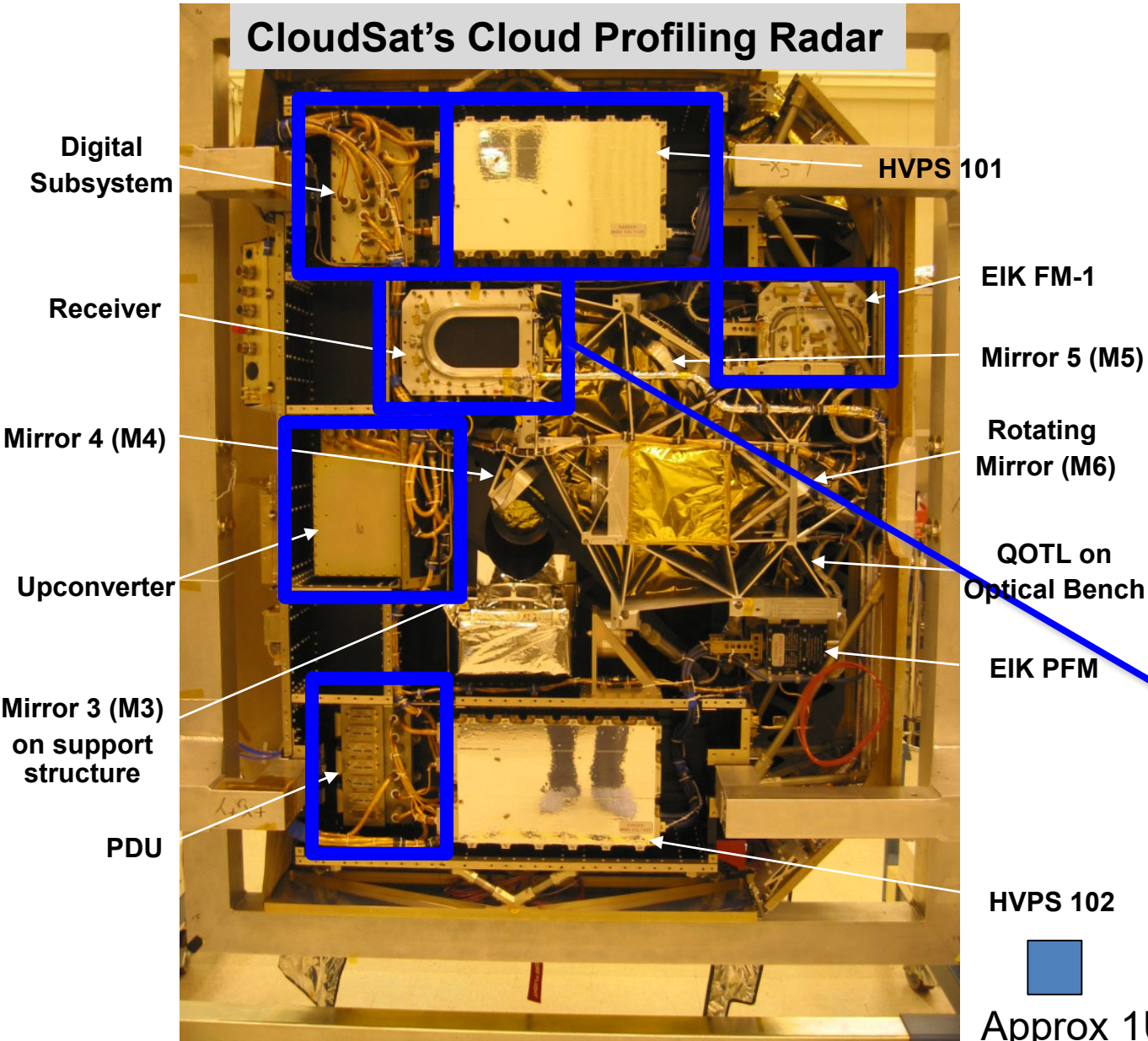
How small is RainCube...



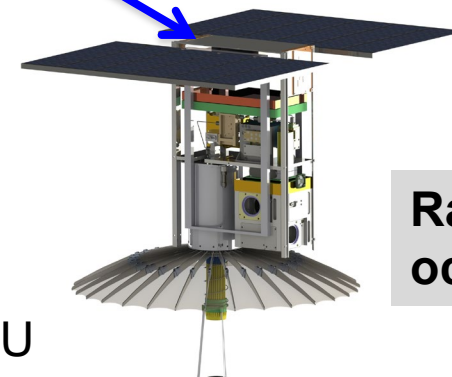
	CPR	KaPR	RainCube
Mass [Kg]	260	336	7
Power [W]	300	344	22
Volume [U]	4,356	1,210	4
Class	C	C	Tech demo
Frequency	W-band	Ka-band	Ka-band
Scanning	No	Yes	No
Sensitivity	-30 dBZ	+17 dBZ	+12 dBZ

Radar In a CubeSat - The key is to miniaturize . . .

CloudSat's Cloud Profiling Radar



These two images are approximately to scale



RainCube Instrument occupies 4.0 U



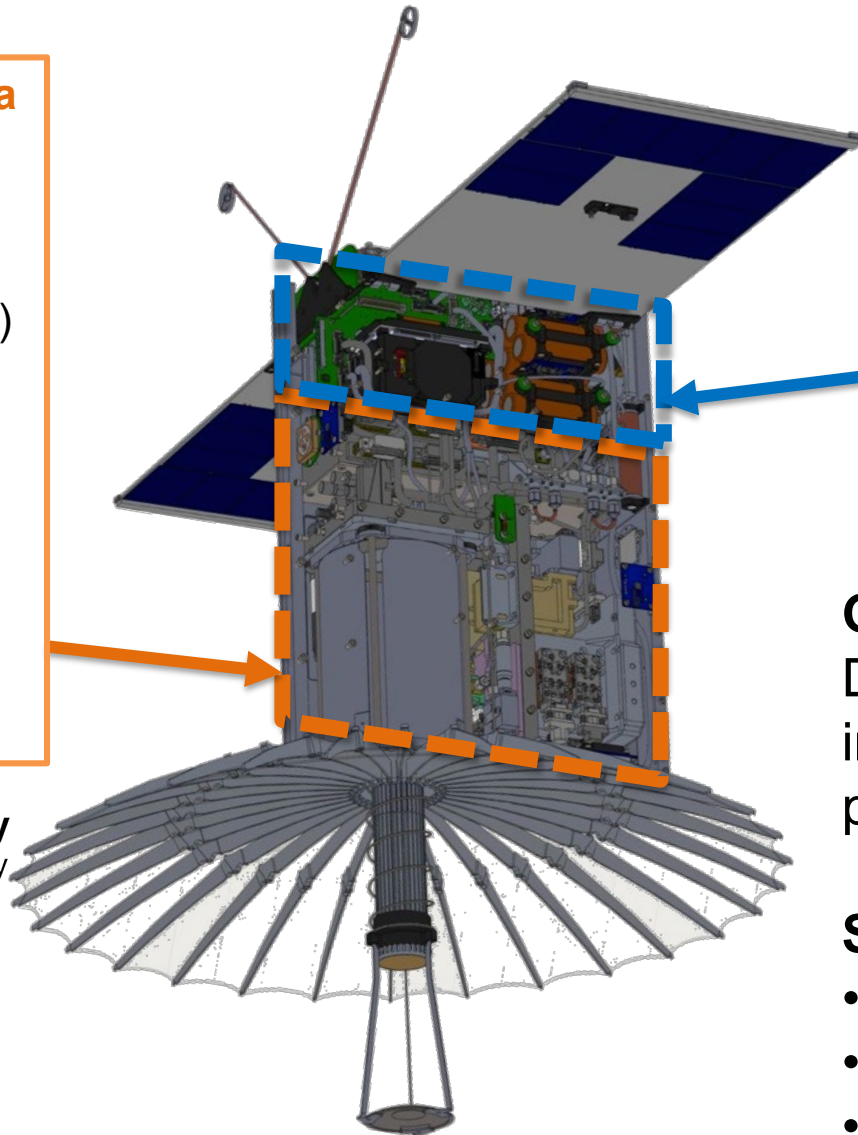
What do we gain from miniaturization?

- Reduce number of components, power consumption and mass by over an order of magnitude wrt the existing spaceborne radars – **Thereby reducing complexity and cost**
- CubeSats use COTS components and rapid development which further **reduces cost of development and testing**
- By using standard CubeSat form factor (such as 1U, 3U, 6U or 12U), we can partner with industry bus vendors thereby **further reducing cost and time of I&T**
- **Constellation paves way for precipitation measurements over smaller time scales to better understand evolution of many weather systems.**

System Architecture

Radar Electronics & Antenna (4U)

- 35.75 Ghz (Ka-Band) Operation
- 20dBZ sensitivity (10 dBZ)
- Vertically profile in 0-18 km altitudes
- 10 km horizontal resolution (8km)
- 250 m vertical resolution
- 35W in transmit (22W)



SC Bus (2U)

- Provide 35 W for payload power in transmit mode
- Maintain payload temperatures (-5C to +50C operational)
- GPS provides on-board altitude to radar
- 3 month operational requirement



Goal:

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

Success Criteria:

- Detect Precipitation
- Capture Vertical Structure of Storms
- Mission Life of 3 Months

Enabling Features for RainCube

miniKaAR-C:

Reduced size, weight, and power by offset IQ (in-phase and quadrature) with pulse compression modulation technique – 2.5U

KaRPDA:

Half meter deployable high frequency antenna stowing in 1.5U.

Tyvak Bus:

Compact highly integrated bus providing 35W of power to the payload – 2U





RAINCUBE – MISSION TIMELINE

From TRL-0 to TRL-9

Timeline from TRL0 to TRL 9



May 21
Launch to
ISS



2013

2014

2015

2017

2018

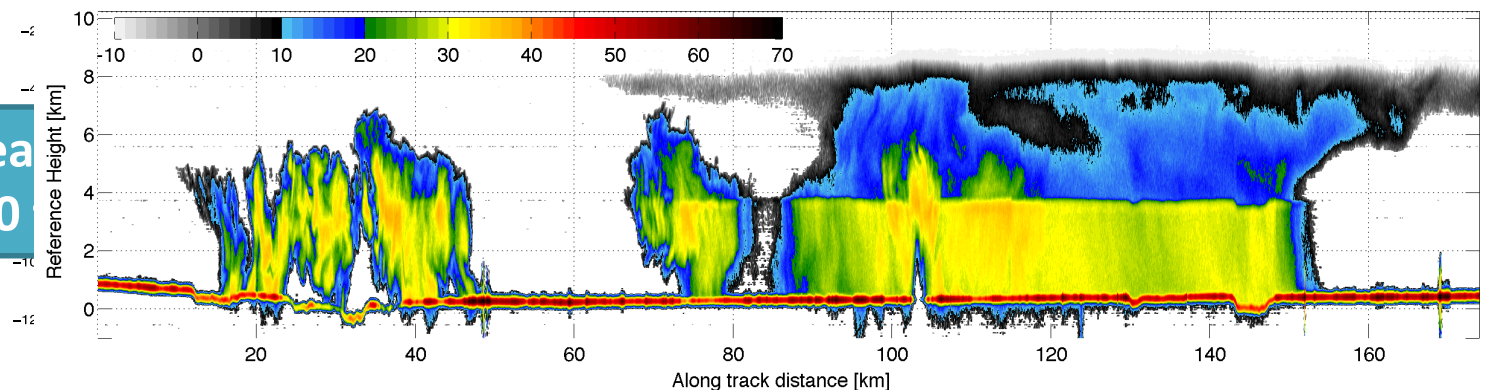
May '13
Brain-
storming

Dec '13
Test bed
demo

Jul
Air
de

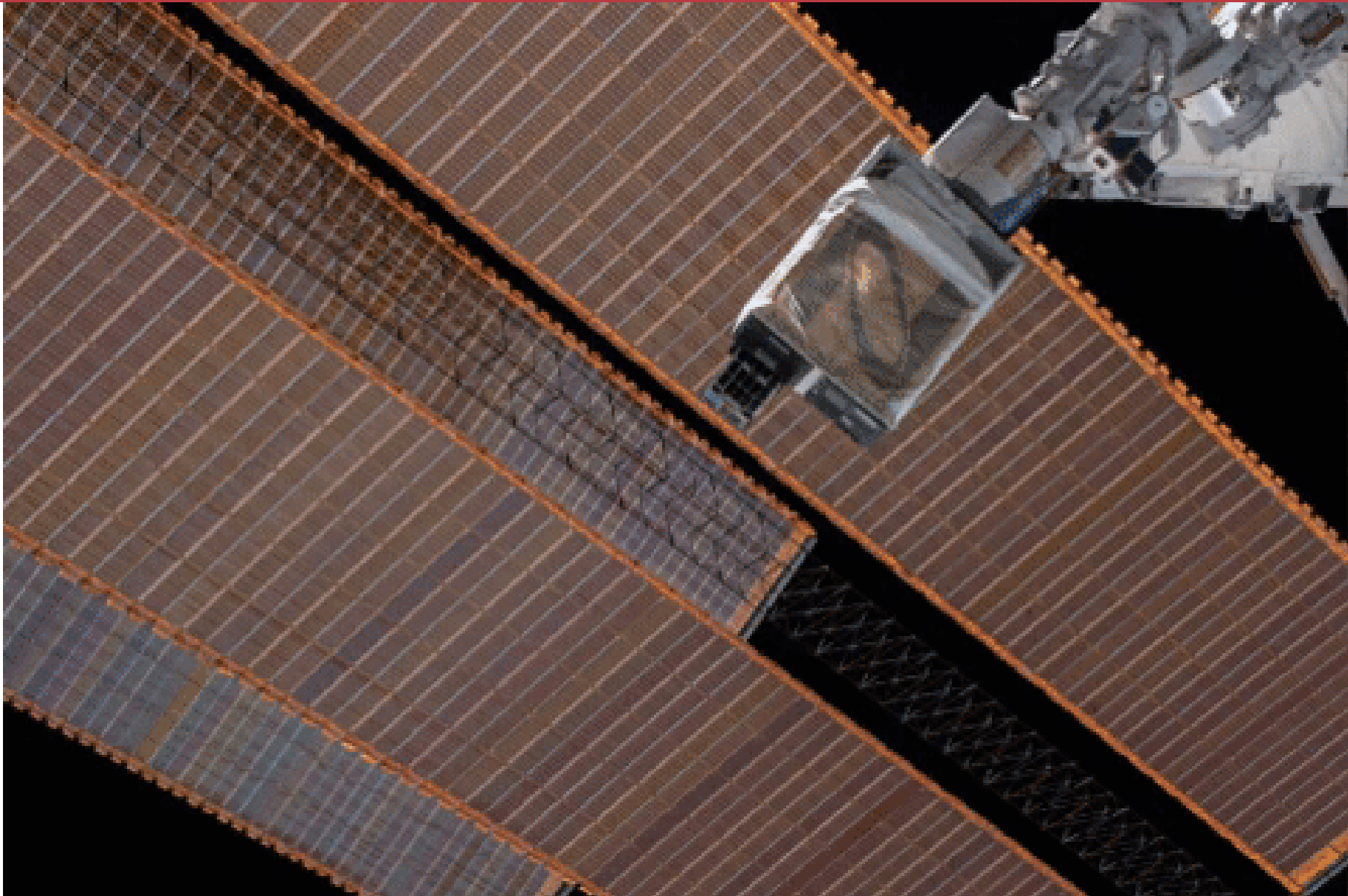
Feb '18
Delivery to
anoracks

RainCube in PECAN - July 8 2015 - Ka-band Radar Reflectivity Factor [dBZ]



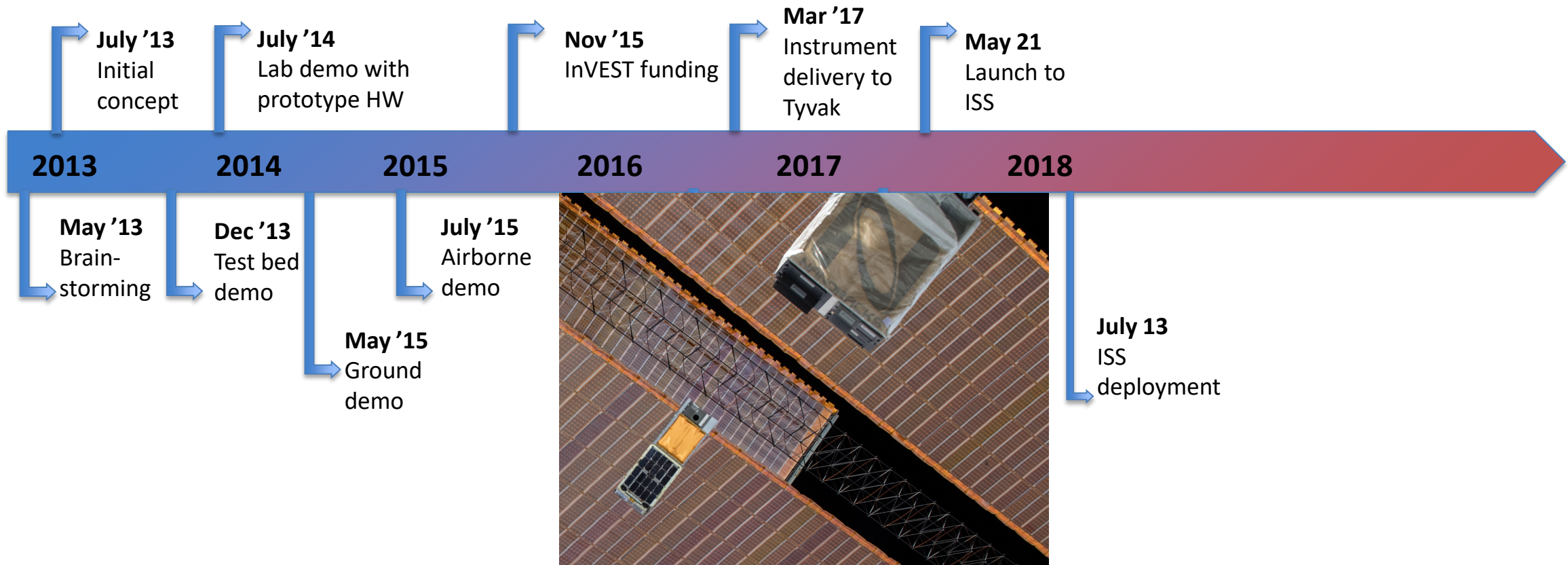
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ISS Deployment: July 13th, 2018



Timeline from TRL0 to TRL 9

Slide credit – Simone Tanelli, Jonathan Sauder

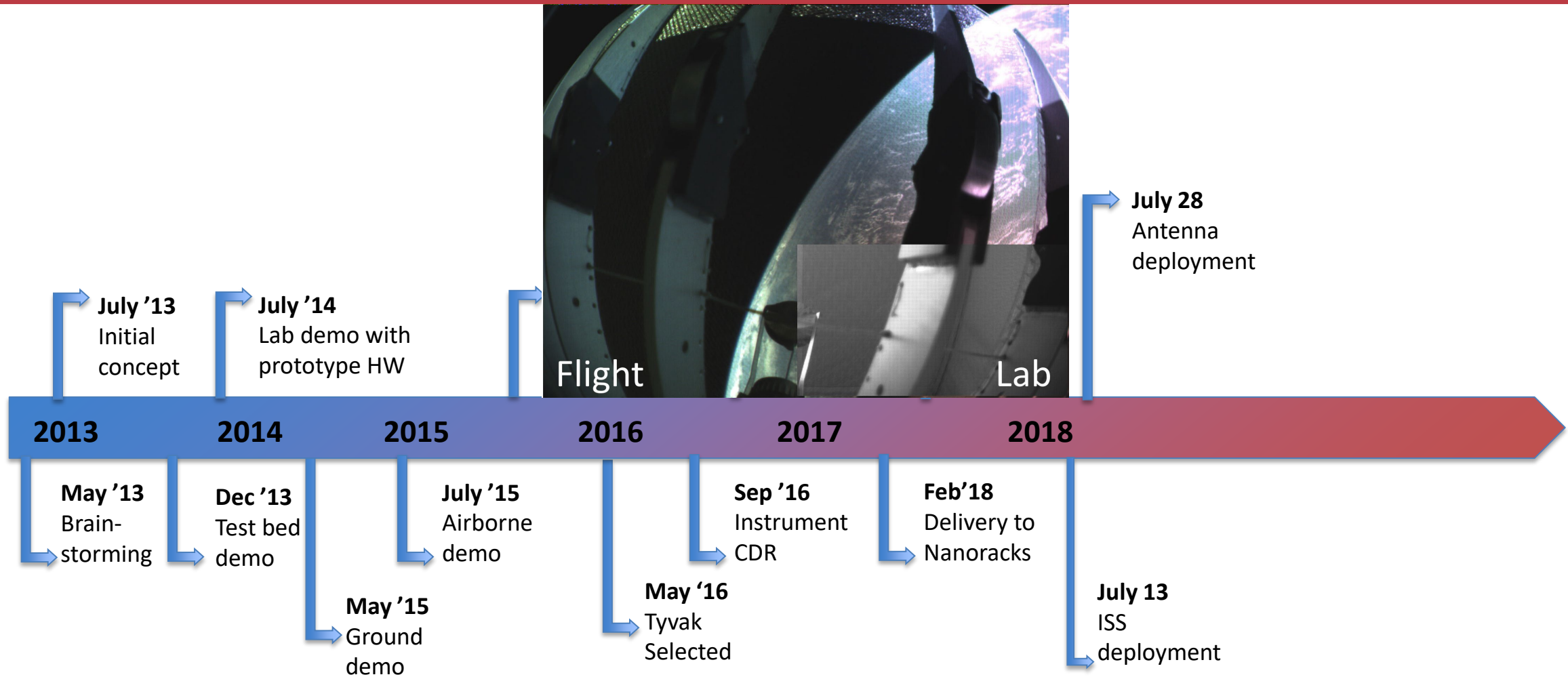




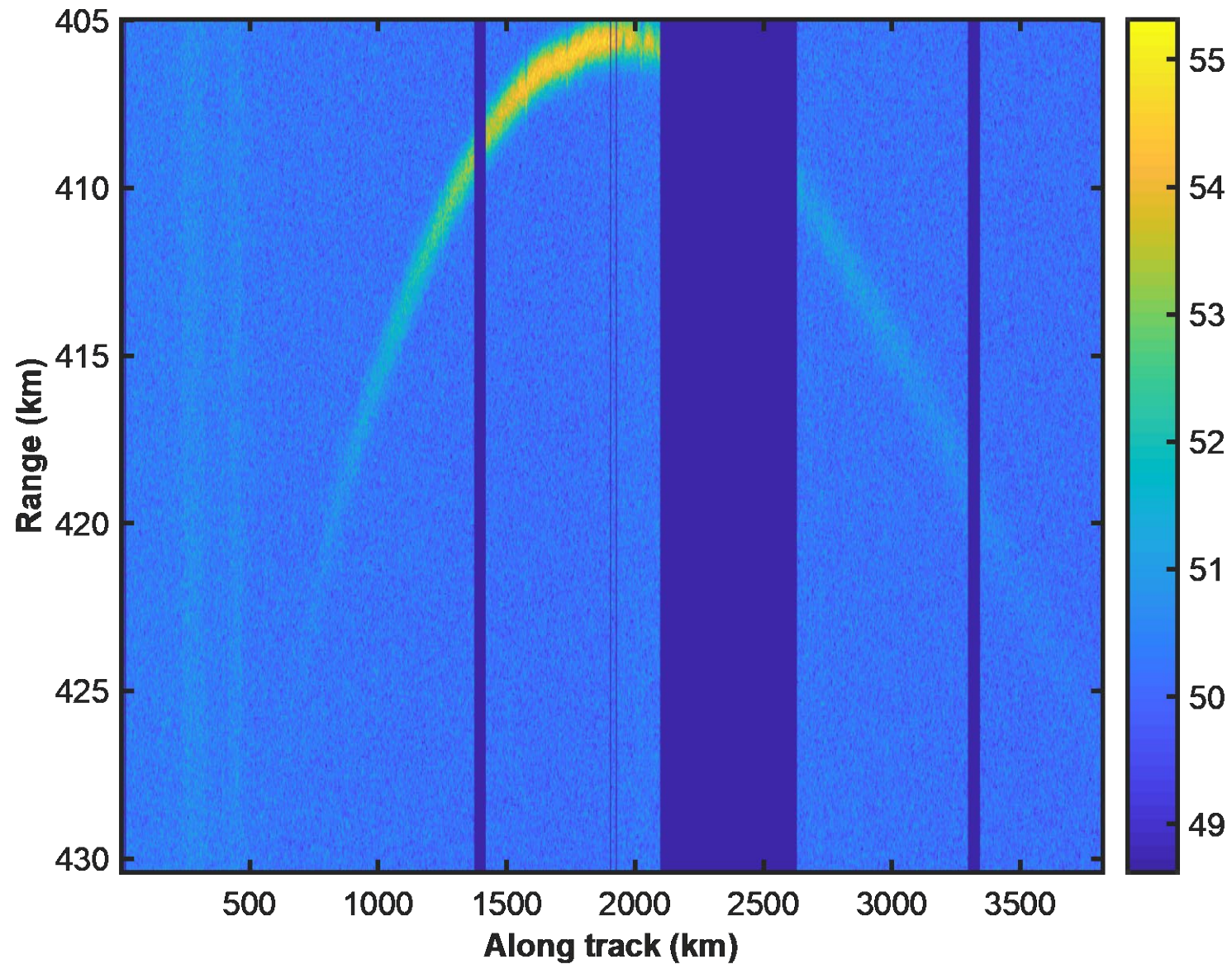
Antenna Deployment: July 28th, 2018



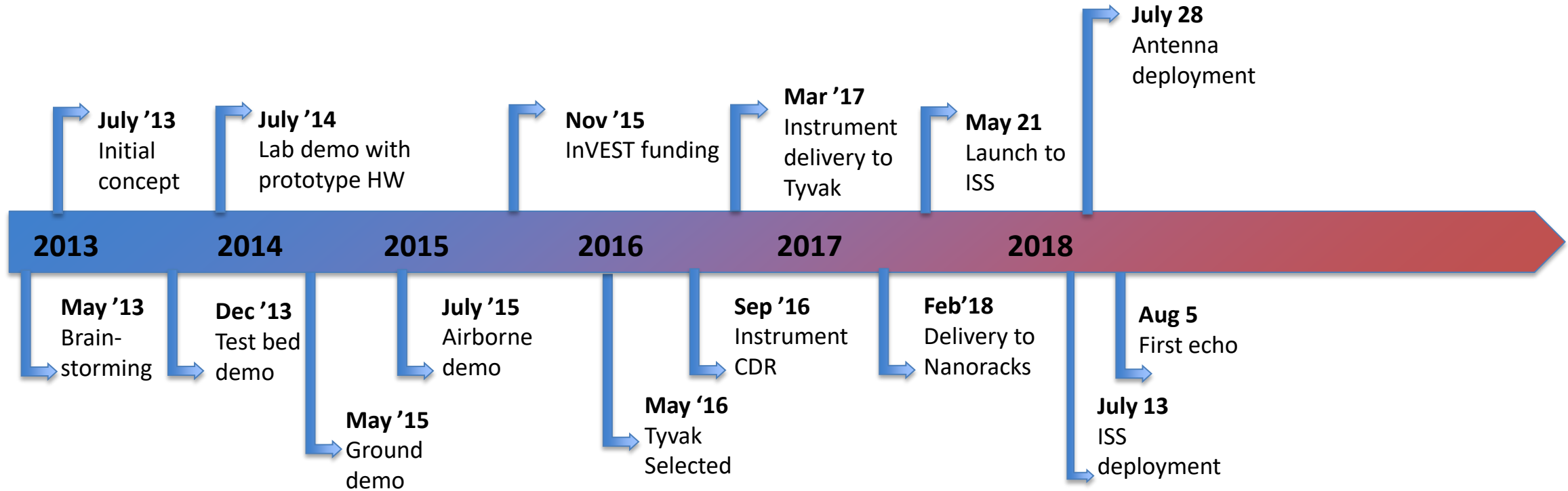
Timeline from TRL0 to TRL 9



First Echo: 8/5/18

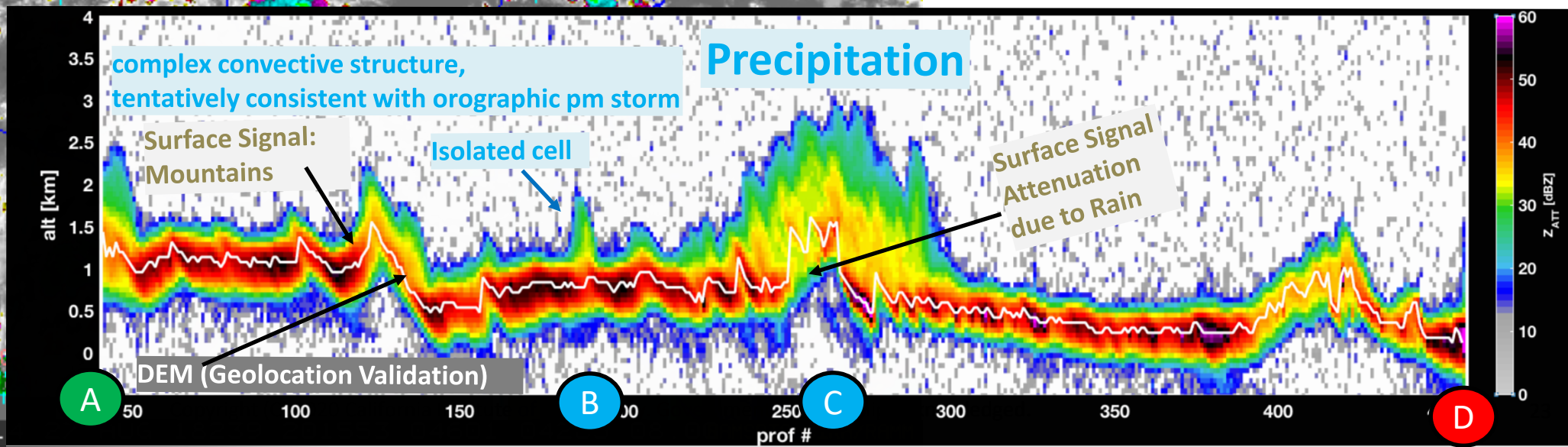
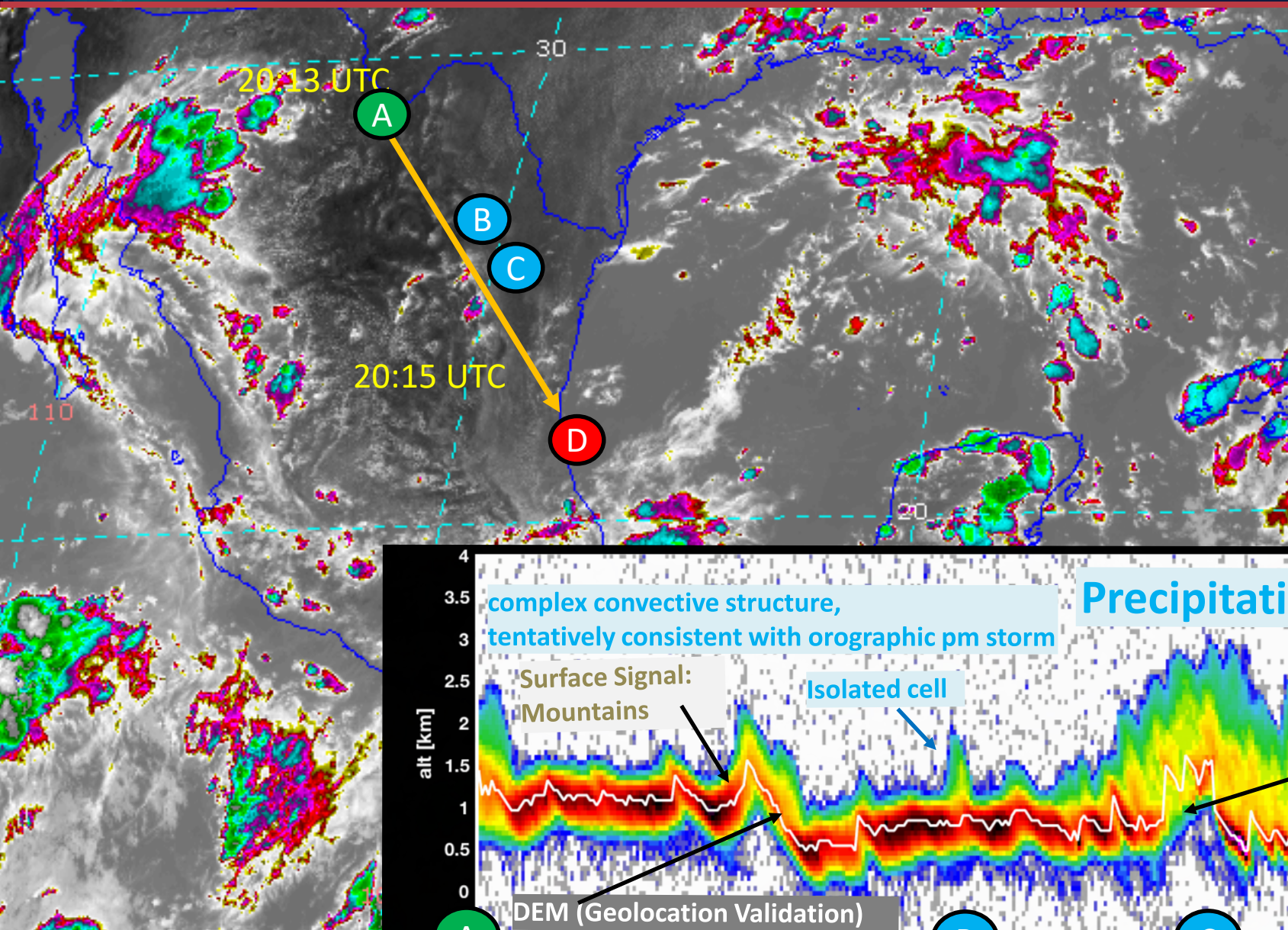


Timeline from TRL0 to TRL 9

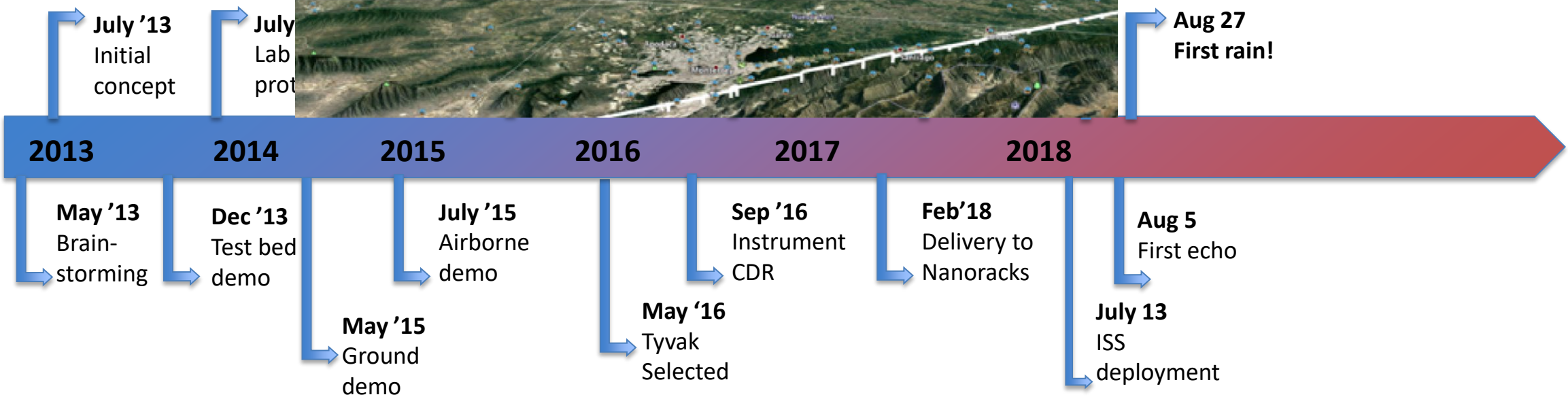
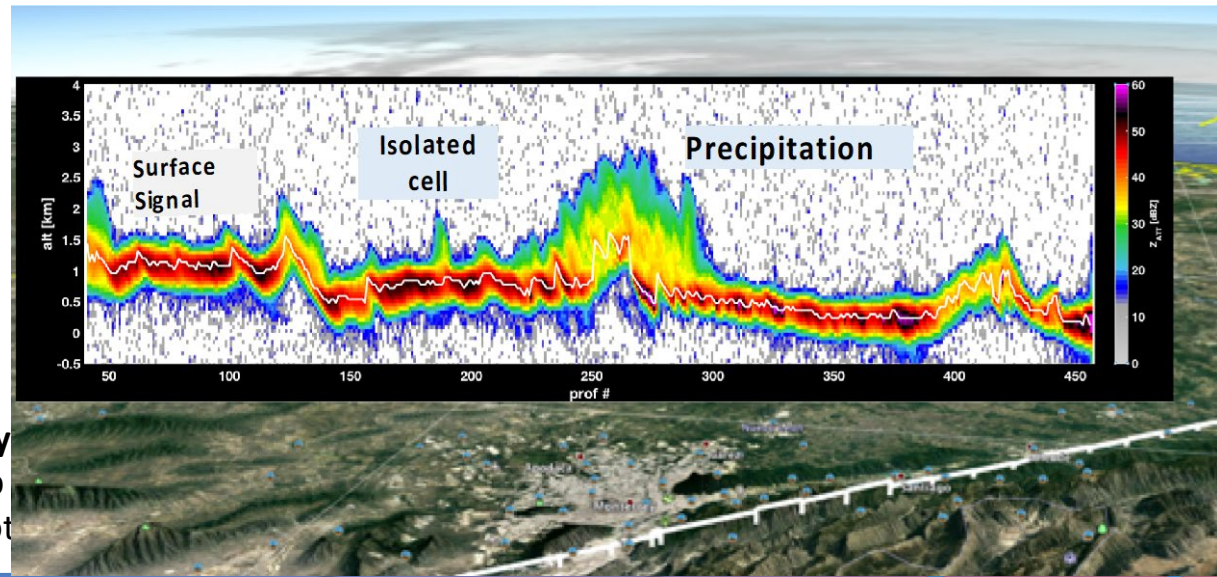


First Rain for RainCube

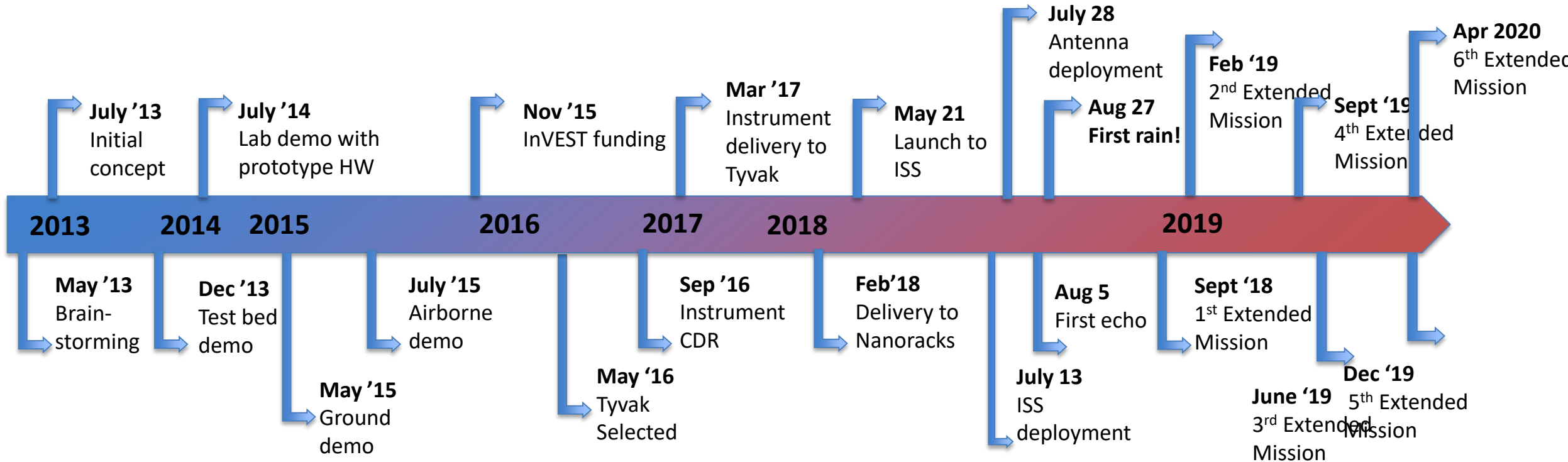
Mission Success over Sierra Madre Oriental (near Monterey Mexico) on 8/27/18 at 20:14 UTC



Timeline from TRL0 to TRL 9



Timeline from TRL0 to TRL 9





RAINCUBE – MISSION OPERATIONS, SCIENCE RESULTS AND LESSONS LEARNED



RainCube Mission Operation

- RainCube Mission Ops center is located at Tyvak Nano-satellite Systems, Inc, Irvine, CA.
- The Tyvak ops team lead by Chris Shaffer operates RainCube and schedules and transfers collected L0 science data to JPL server.
- So far, the mission has generated > 10,000 science data files of precipitation measurement.
- The longest sample duration collected so far is 40 mins.
- Nominal duration of collections is 10 to 20 mins of nadir pointed data taken during Umbra orbit.
- The mission underwent major SC anomalies since deployment – mainly 1) aperiodic system level reboots, 2) failure of 1 of 2 MPPTs and 3) loss of the Z-axis reaction wheel
- The ops team has to carefully plan operations to ensure mission safety in presence of these anomalies

Science Operations Planning

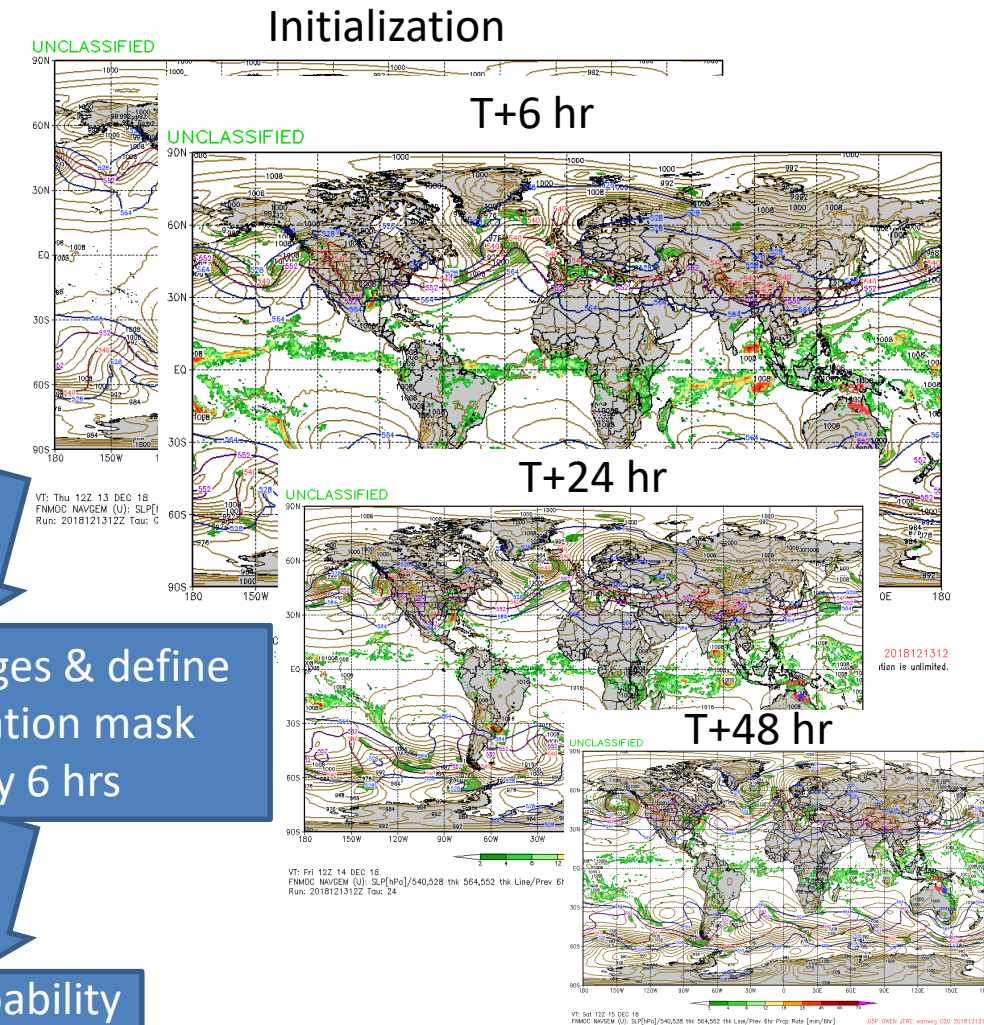
After primary mission success, and due to aforementioned SC anomalies, we wanted to carefully plan targeting of forecasted precipitation and collocated measurements with other missions. In order to improve efficiency of mission operations towards this goal, we increased automation starting with automating the planning of events in a prioritized way

- **Constraints for automation**

- a. Maximum of 6 20 minute Radar Acquisitions per day (Imposed by spacecraft power system)
- b. No operations on consecutive orbits (Imposed by spacecraft power system)
- c. No operations in umbra (Preferred because of higher occurrence of reboots in umbra)

- **Target Priorities**

- Forecasted presence of precipitation
- CONUS – for NEXRAD
- GPM – for DPR
- Storms of interest



Parse images & define precipitation mask every 6 hrs

Calculate local probability of precipitation along the predicted orbit of RainCube

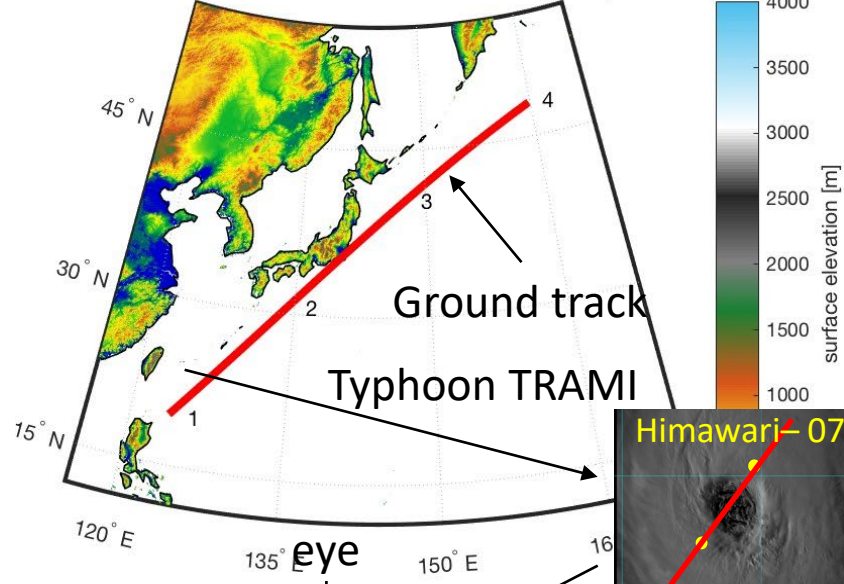
Prioritize close approaches with GPM and passes over GPM GV sites (CONUS, Japan, Australia)

KEY SCIENCE RESULTS/OBSERVATIONS

Sept 28, 2018 – RainCube Observation of Typhoon TRAMI

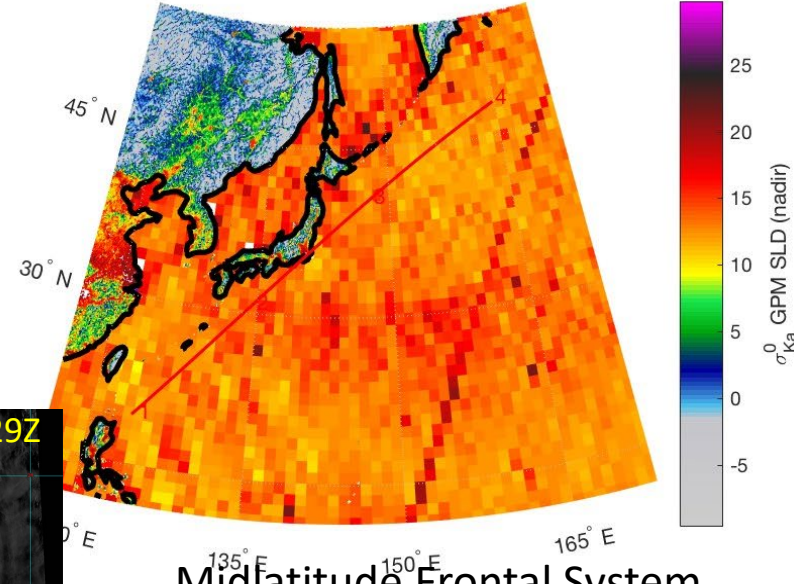
CloudSat-DEM based on NASA-DEM

data(S20180928071011-E20180928073009)



GPM σ^0 reference

320100920071011-E20180928073009
2018/9/28 @ 7:18:28 --> 2018/9/28 @ 7:30:10

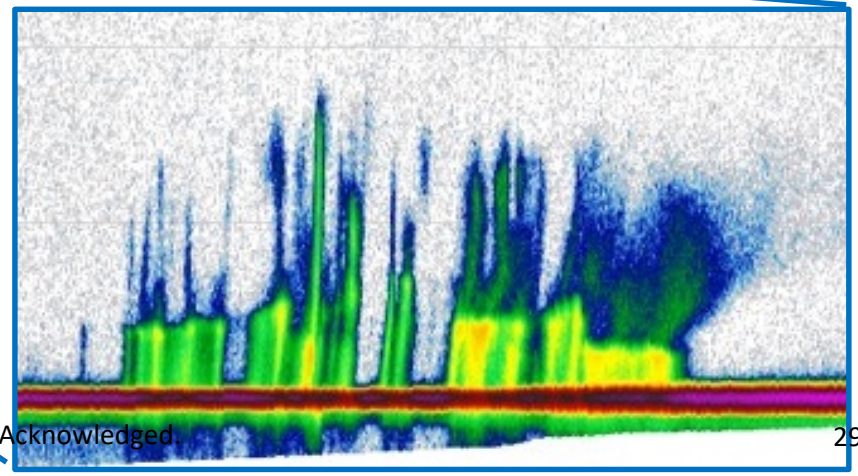
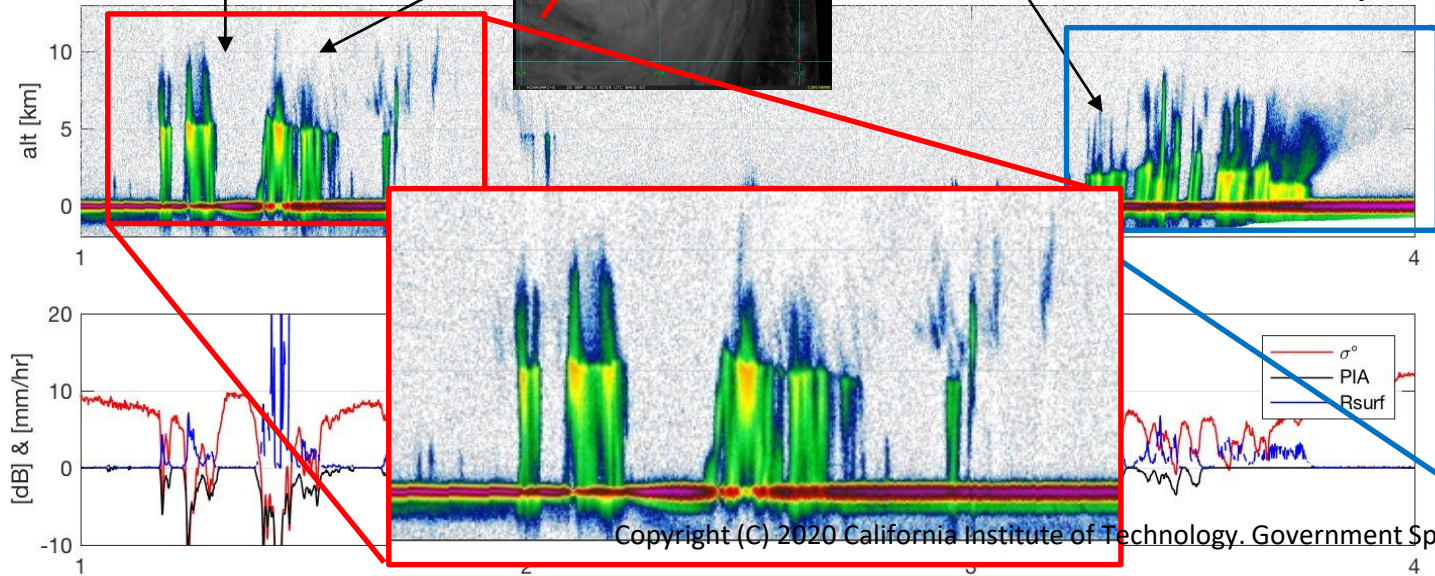
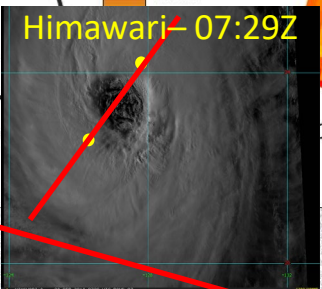


Structure of Typhoon TRAMI

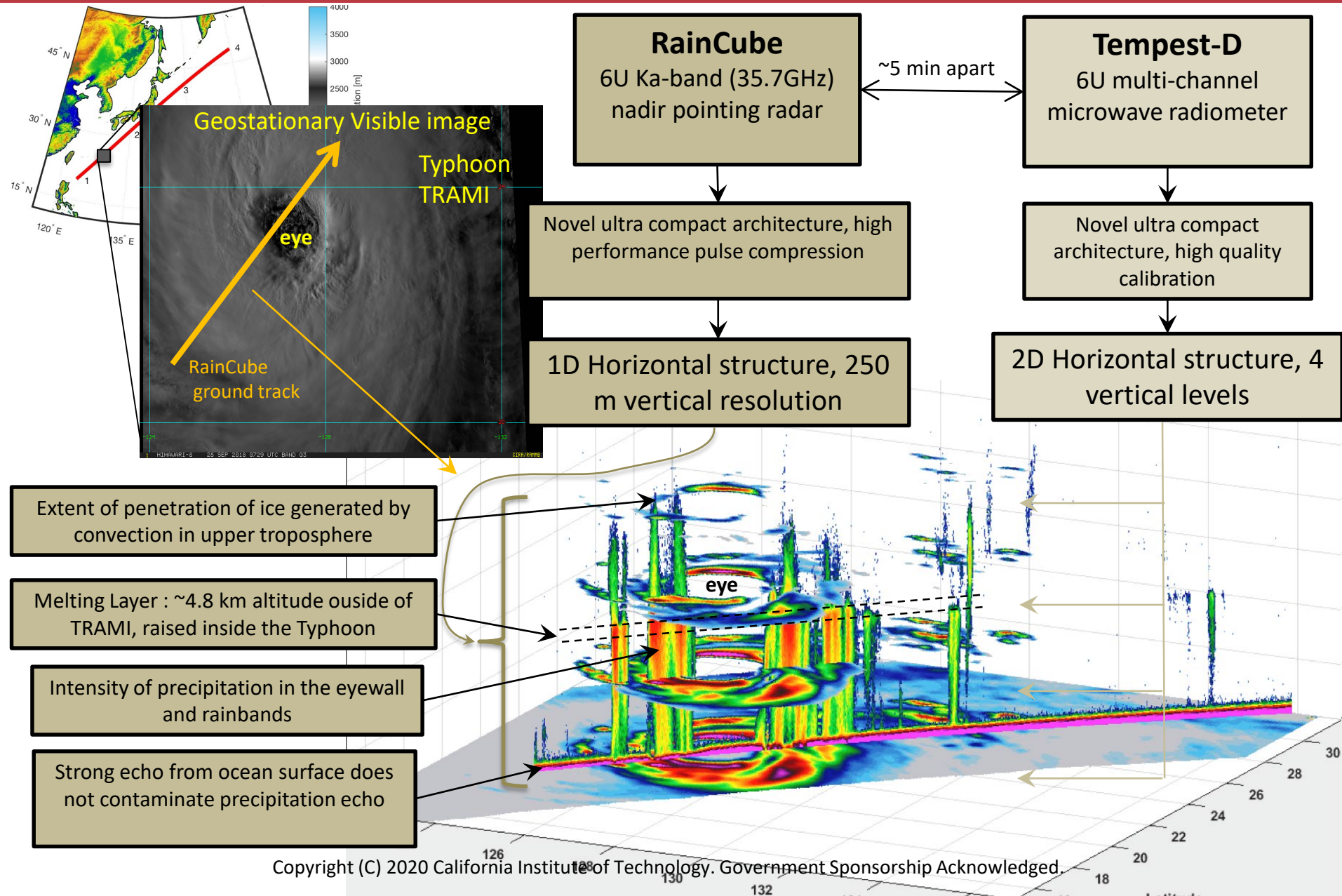
Shortly after it had weakened from Cat 5 to Cat 2. The SW-NE cross section shows very little convective activity along the eyewall (mostly located in the SE sector at that time).

Mid-Latitude system with deep convection

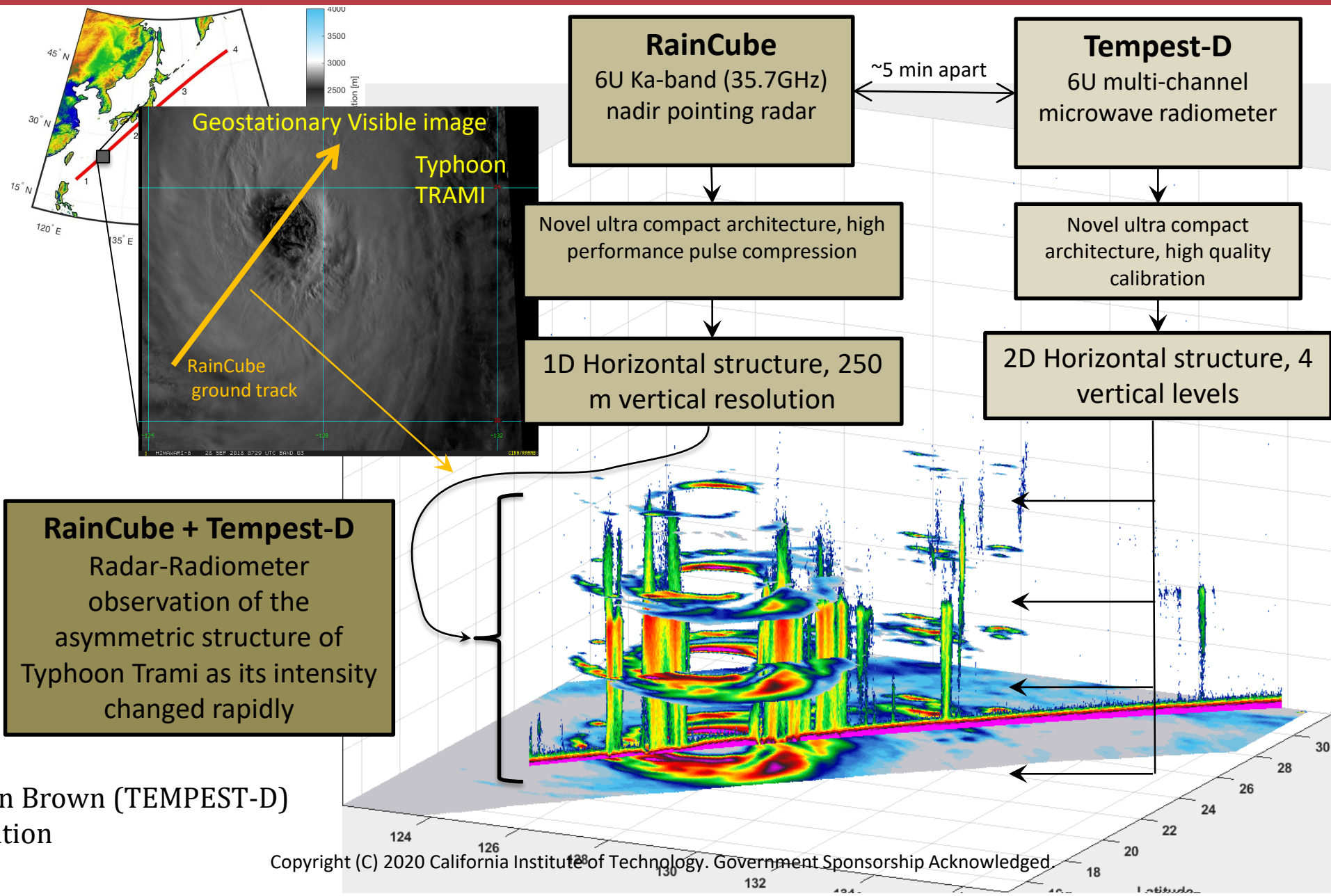
The complex structure of this frontal system propagating NW from Japan includes deep convective towers reaching almost 9 km and sharp gradients of the zero isotherm height.



RainCube and TEMPEST-D observe Typhoon Trami on Sept. 28, 2018

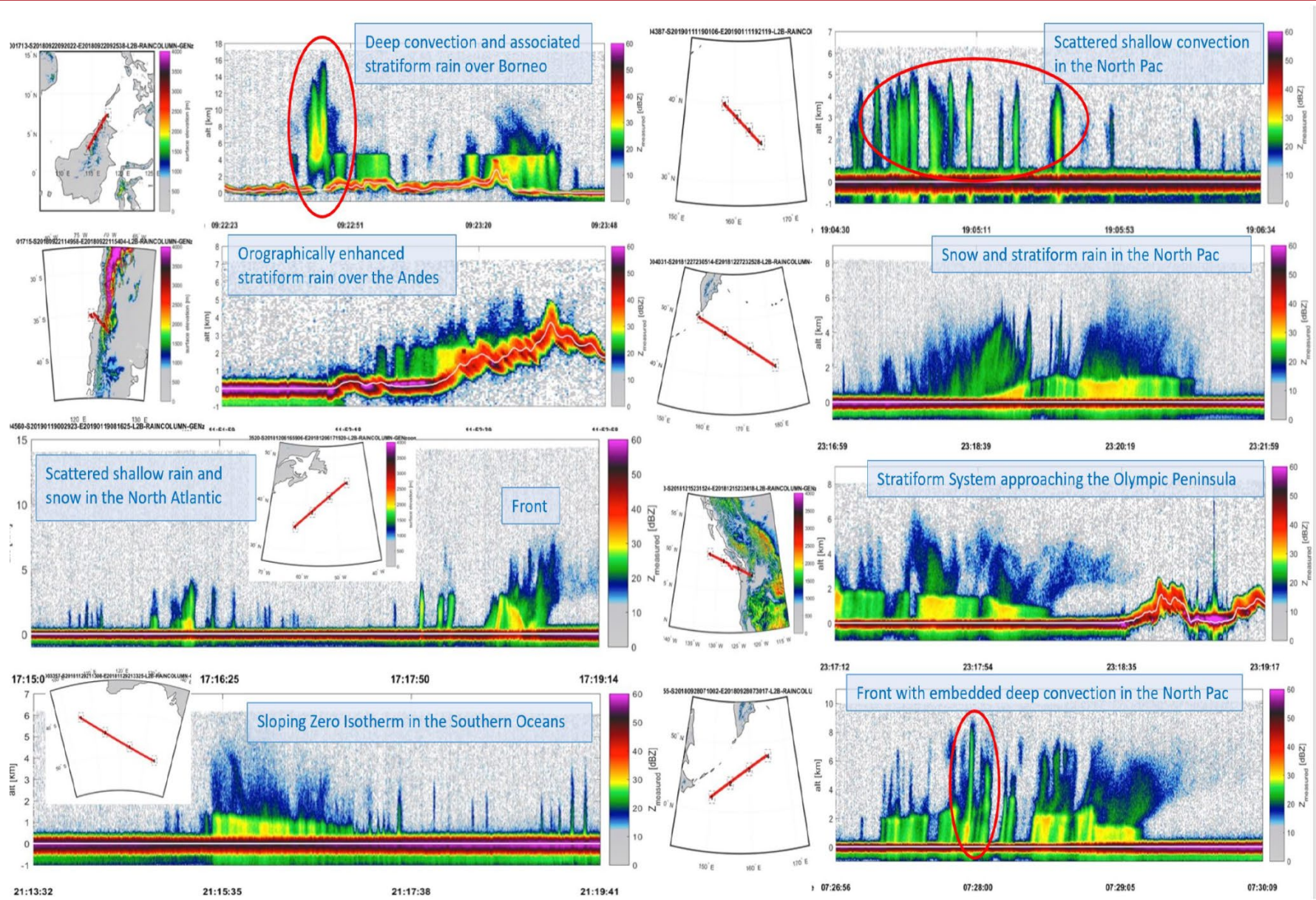


RADAR + RADIOMETER MINI CONSTELLATION



Credit to Shannon Brown (TEMPEST-D) for the 3D-animation

A Collection of RainCube Storms



Slide credit:
Ousmane Sy (JPL)

TCIS portal will host RainCube data

Jet Propulsion Laboratory
California Institute of Technology

TROPICAL CYCLONE INFORMATION SYSTEM

Welcome to Cyclone Info

The JPL Tropical Cyclone Information System (TCIS) was developed for tropical cyclone research. It has two main components: a multi-sensor archive of multi-sensor data and what was supported the 2002 Intensification Process Campaign. Together, they provide the near-real time data used to study hurricanes, improve models, algorithms and data products. Below you will find links to the data you can view differently.

Supertyphoon Pongsona struck the U.S. Island of Guam on Sunday, December 8, 2002. The composite image (left) of the supertyphoon was made by overlaying data from the infrared, microwave, and visible/near-infrared sensors that make up the AIRS sounding system. This storm can also be seen with the standard AIRS Vis/NIR (right).

Site Manager: Svetla M Hristova-Veleva

JPL HOME | EARTH | SOLAR SYSTEM | STARS & GALAXIES | SCIENCE & TECHNOLOGY

https://tcis.jpl.nasa.gov/data/

Jet Propulsion Laboratory
California Institute of Technology

TROPICAL CYCLONE INFORMATION SYSTEM

BRING THE UNIVERSE TO YOU: [Twitter] [Facebook] [RSS] [Email]

TCIS Data Repository

Here you will find data files from the JPL Tropical Cyclone Information System. For additional information, please visit <https://tcis.jpl.nasa.gov>

Name	Last modified	Size
Parent Directory		
camp2ex/	2018-06-01 07:10	
cpex/	2018-06-12 20:42	
epoch/	2017-09-11 12:37	
hs3/	2018-06-27 20:04	
raincube/	2018-12-19 11:10	
shout/	2017-10-18 09:51	
TC Data Archive/	2018-06-29 10:02	

Site Manager: Svetla M Hristova-Veleva

https://tcis.jpl.nasa.gov/data/

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TROPICAL CYCLONE INFORMATION SYSTEM

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Data from the RainCube Mission

For additional information, please visit <https://www.jpl.nasa.gov/cubesat/missions/raincube.php>.

Name	Last modified	Size	Description
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L1A/	2018-12-19 10:47	-	
L2A-GEOPROF/	2018-12-19 11:01	-	
L2B-RAINCOLUMN/	2018-12-19 11:10	-	

Site Manager: Svetla M Hristova-Veleva

The Tropical Cyclone Information System will host RainCube data. Huge thank you to PI : Svetla Hristova-Veleva, Site Administrator Quoc Vu, and Data Manager Brian Knosp)

Tested posting data and accessing through url. L2 Data will be made public when QC is satisfactory.

No plan to open up and (1) data to the public. Government Sponsorship Acknowledged.



Lessons Learned

1. Extended Formulation Phase
2. Tailored versions of NASA and Institutional Flight Practices
3. Clearly define roles and responsibilities of each organization at the time of contract formation
4. 6U form factor is useful for standardized dispenser and tech demo but consider larger form factor for ease of cable and thermal design
5. Revise flight mass growth contingency for CubeSat and SmallSat missions – the 5-30% margin reserved for flight missions is too strict for CubeSats
6. Value of pre-operations ORT aka Rehearsal
7. Value of Anomaly Response Team during commissioning
8. Value of excellent EGSE flat-sat for both radar and SC
9. Prioritized mission objectives well beyond primary objectives



WHAT'S NEXT?

What's next ?

- **Constellation of RainCube's "as is"**
 - Analyze the current dataset to demonstrate the potential and the limitations of the current system in addressing specific science questions.
- **Constellation with a larger/scanning antenna**
 - To address a larger set of science questions
 - Development of **technologies** and of **mission concepts** is ongoing
- **Constellation with other Radars and Radiometers:**
 - A study team in the Earth Science Decadal Survey 2017 will consider RainCube-like constellations for measurements of convection and precipitation
 - Higher frequency versions of RainCube for cloud and water vapor observations
- **Planetary applications**
 - An evolution of this instrument could support altimetry and cloud and precipitation on planetary targets

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Proceedings OF THE IEEE

SPECIAL ISSUE
Small Satellites

Point of View: How Is the Networked Society Impacting Us?
Scanning Our Past: Who Invented the Earliest Capacitor Bank ("Battery" of Leyden Jars)? It's Complicated

IEEE

D-TRAIN The Dynamical Train Investigation

D-Train will observe the rapid evolution of radar reflectivity profiles in storms, relate time-differenced reflectivity profiles to vertical transport of water in convection, and develop statistically robust relationships between convective mass flux, storm properties, and the environments in which storms form.

Instrument System, Algorithms and Approach

- D-Train uses 3 identical miniaturized downward-looking 5-beam Ka-band cross-track scanning radars, in a low-Earth-orbit.
- Each radar provides the 3-D field of convective radar reflectivity within its swath.

Per Instrument Characteristics

Parameters	Current Best Estimate
Mass	14.4 kg
Electronics Dimensions	20 cm x 20 cm x 10 cm
Antenna Diameter	1.6 m
Frequency	35.75 GHz
Peak Transmit Power	13 W
Data Demand	146 kbps
Power Demand	
Peak	29 W
Standby	3 W
Horizontal Resolution (nadir beam, 500 km altitude)	3.1 km
Vertical Resolution	240 m
Swath (5 beams across track)	15.7 km
Sensitivity	8 dBZ
Precision/Accuracy	0.4 dBZ / 1.5 dBZ

NASA's Storm Chaser

Tropical convective storms transport water and air from near the Earth's surface to the upper troposphere. They produce heavy rainfall and lightning from high clouds that affect Earth's radiation balance, and drive the large-scale atmospheric circulation. Convective vertical transport of water and air plays a critical role in Earth's weather and climate system, yet representing this transport is a major source of error in weather forecasting and climate models. Prediction of current weather and future climates is limited because there are no global observations of convective vertical mass flux.

D-Train will provide the first global measurements of tropical convective mass flux.

D-Train Science Goals

1. Advance our understanding of the relationships between environmental factors, storm properties, and convective mass flux
2. Evaluate the representation of convective mass flux in weather and climate models

Science Team

R. Ferraro, NOAA
B. Kahn, JPL
Z. Haddad, JPL
G. Huffman, GSFC

J. Lun, CSU
D. Posselt, JPL
C. Schumacher, TX A&M

D-Train Key Science Questions

1. How does the tropical convective mass flux depend on storm properties and environmental factors?
2. How does the convective mass flux impact anvil cloud properties and the severe weather (heavy rainfall, lightning) produced by tropical convection?
3. What are the relative contributions of the different types of tropical convective storms to the convective mass flux within the tropical atmosphere?

Principal Investigator: Susan van den Heever, CSU
Deputy PI: Graeme Stephens, JPL
Project Scientist: Simone Tanelli, JPL
Project Manager: Ralph Basilio, JPL

Submitted in response to NASA/DSD/DC-18-016

Ka-band ESTO InVEST and ACT programs

	6U	12 U	50 kg
Antenna size [m]	0.5	1.0	2.0
Sensitivity [dBZ]	15	5-10	0-5
Hor Resolution [km]	8	4	2
Range Res [m]	250		
Beams	1	1-3	1-5
RF Power [W]	10	10-20	10-40



CloudCube – IIP Selection

- The success of RainCube is generating much interest among the weather radar science and engineering community.
- The miniaturized radar architecture of RainCube is the backbone of recent selection to ESTO's IIP (Instrument Incubation Program) called CloudCube
- CloudCube is a multi frequency millimeter-wave radar system that will consist of an ultra-compact 35/94/238 GHz multi-frequency radar with Doppler capabilities at the lower frequency band.
- The instrument will enable unprecedented mission concepts that would fill existing gaps in the observation of a variety of cloud and precipitation processes.



Jason-3

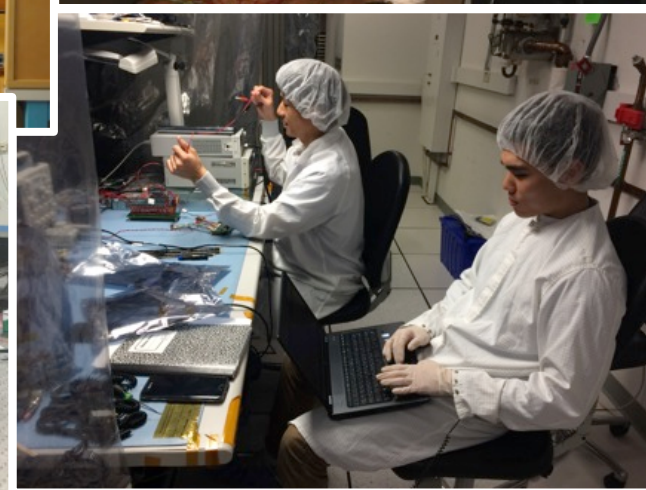
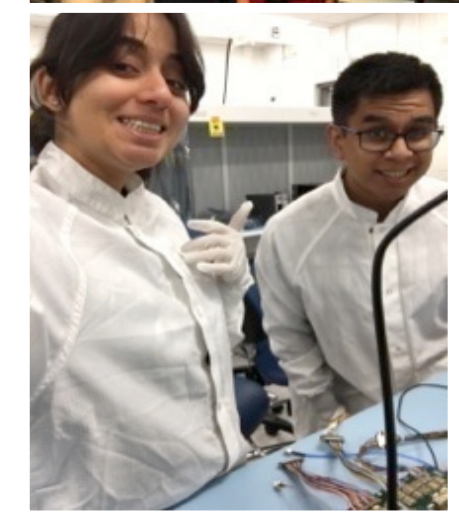
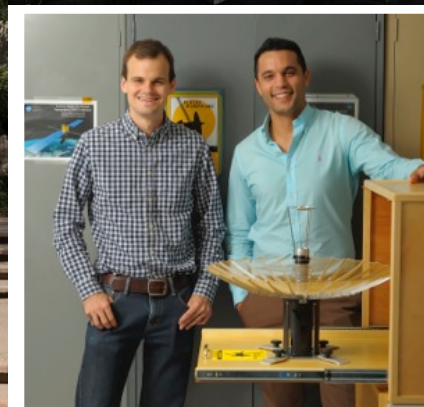
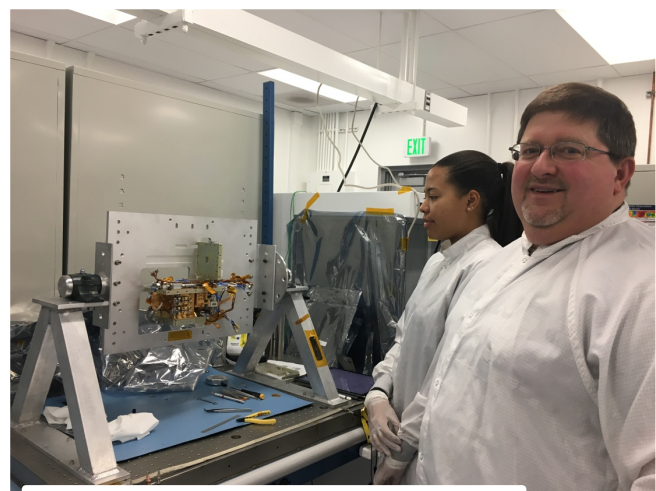
You can now follow RainCube on NASA's Eyes on EARTH
<https://go.nasa.gov/2PGdBus>

QuikSCAT

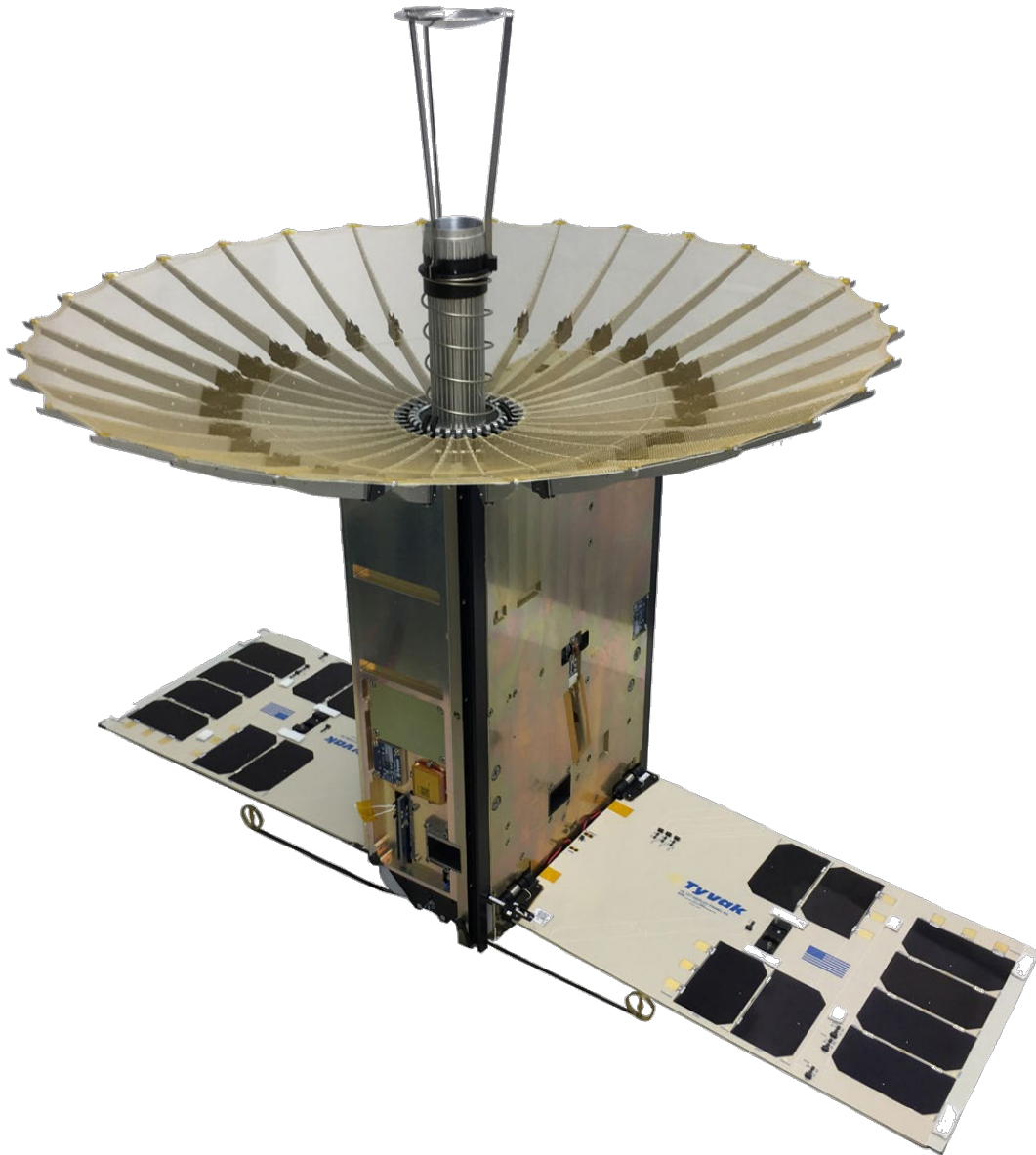
RainCube

SMAP

DESTINATION	DATE + TIME	YOUR SPEED + RATE	VISUAL CONTROLS
CURRENT TARGET: RAINCUBE	SEP 18, 2018 10:05:37.5 AM NOW	54,255 MI/HR 1.00 SEC(S)/SEC REAL RATE	<input type="radio"/> <input type="radio"/> <input checked="" type="radio"/> <input type="radio"/> <input type="radio"/> FREE FLY - 60.0° +



Thank You!



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