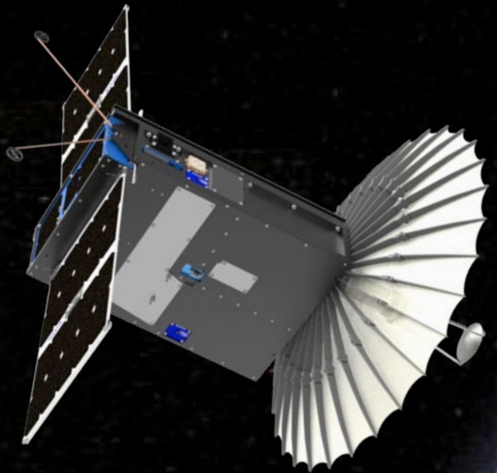
RainCube: First Spaceborne Radar in a CubeSat



IEEE BV MTTS Chapter Meeting
April 15, 2020
Virtual Presentation over WebEx

Presenter: Shivani Joshi
FPGA Engineer
RainCube Mission Operations Manager
Jet Propulsion Laboratory,
California Institute of Technology, CA, USA

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.

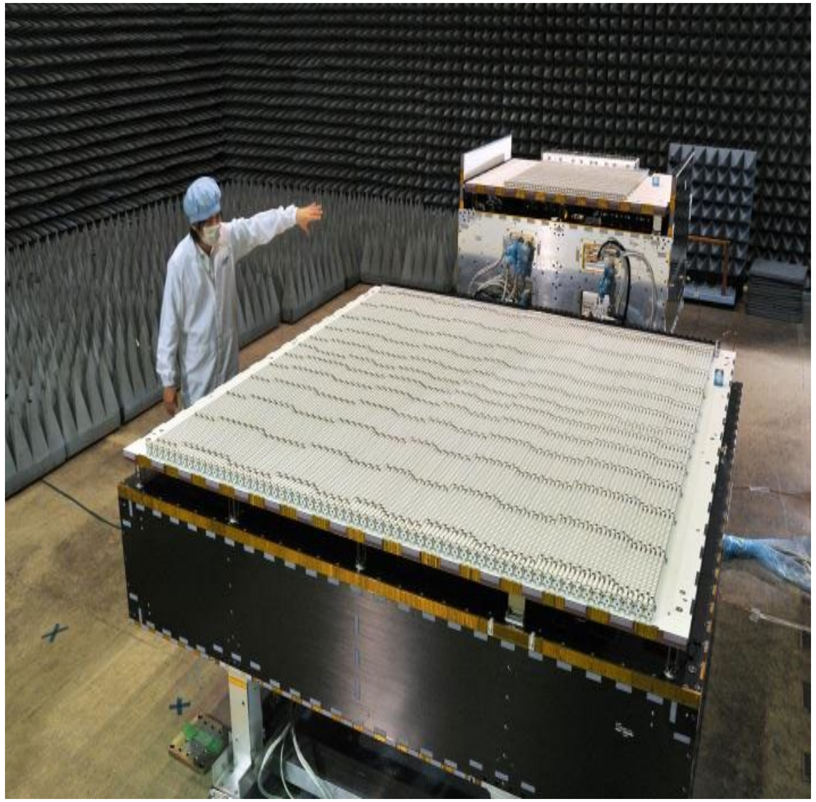
Prior to joining JPL, Shivani worked at Siemens Rail Automation for 4 years after graduating from USC with a Master's in Electrical Engineering. Her Bachelor's degree is in Electronics Engineering from Gujarat University in India.

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

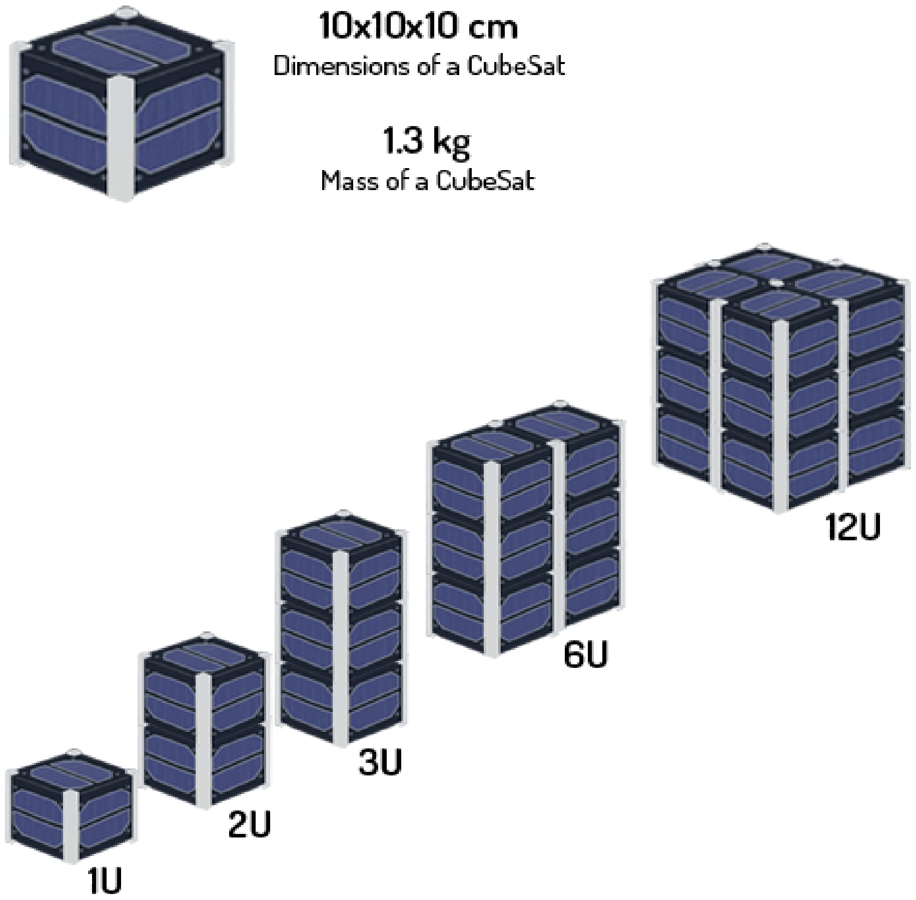


GPM – DPR
Dimensions – 13m x 6.5m x 5m with panels deployed
Mass – 3.8 tons
Image Credit – Simone Tanelli/GPM Team

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



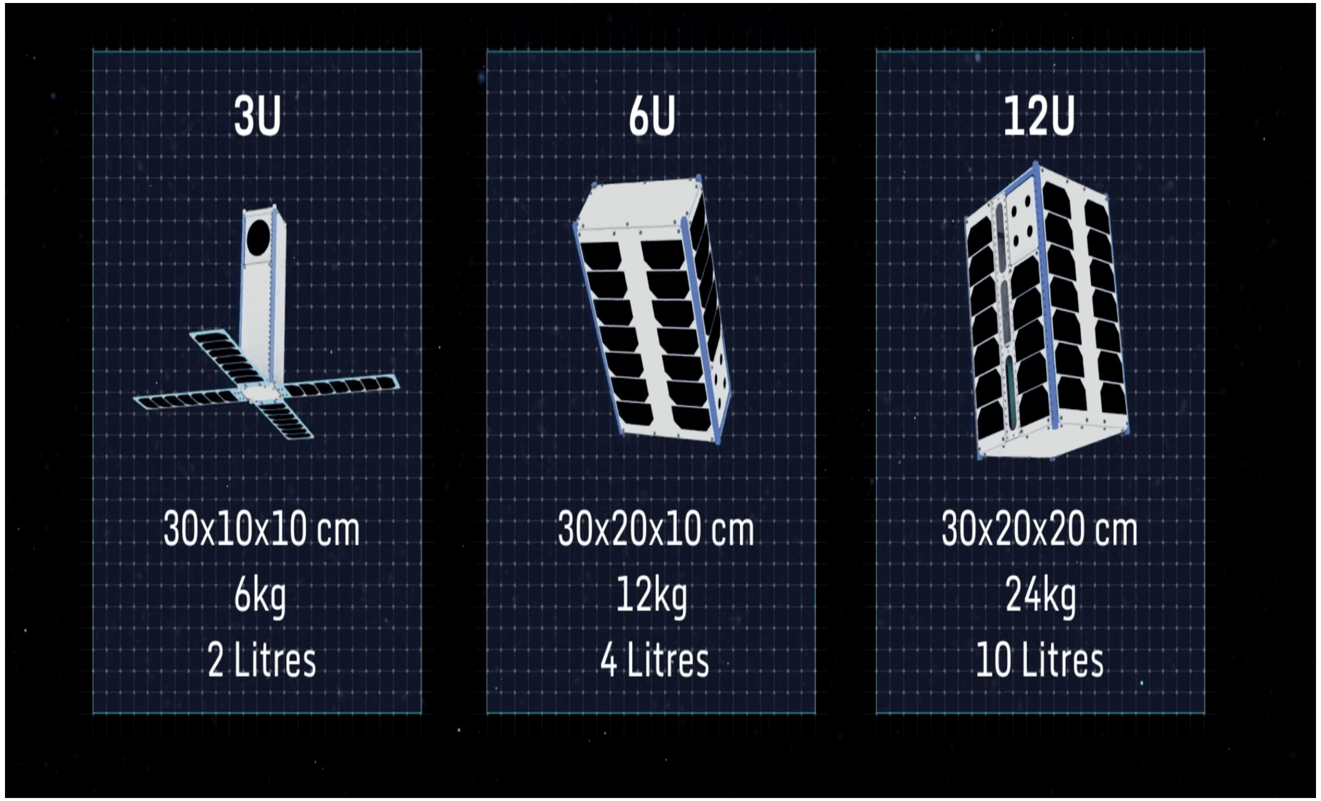
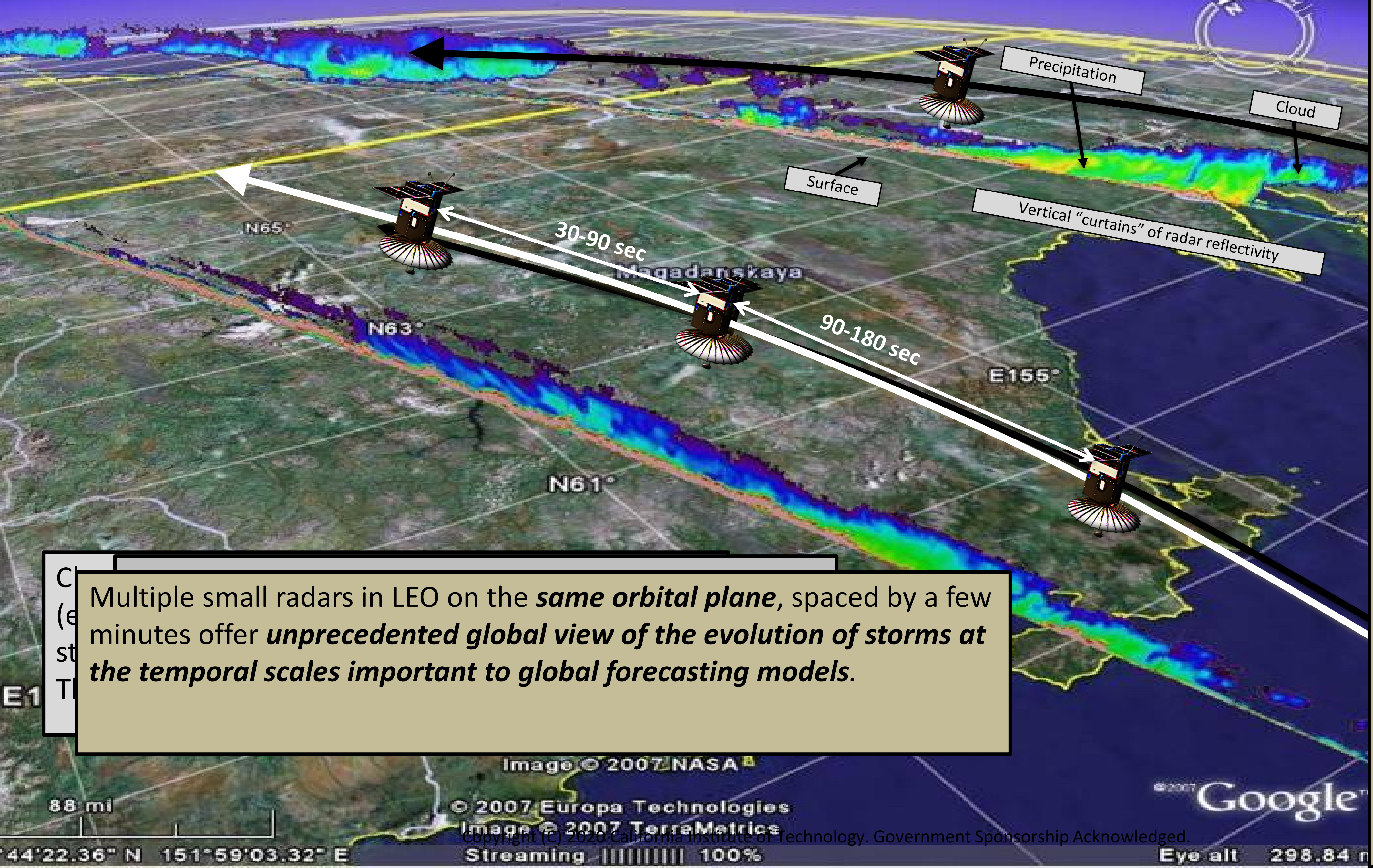


Image credit – https://open-cosmos.com

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

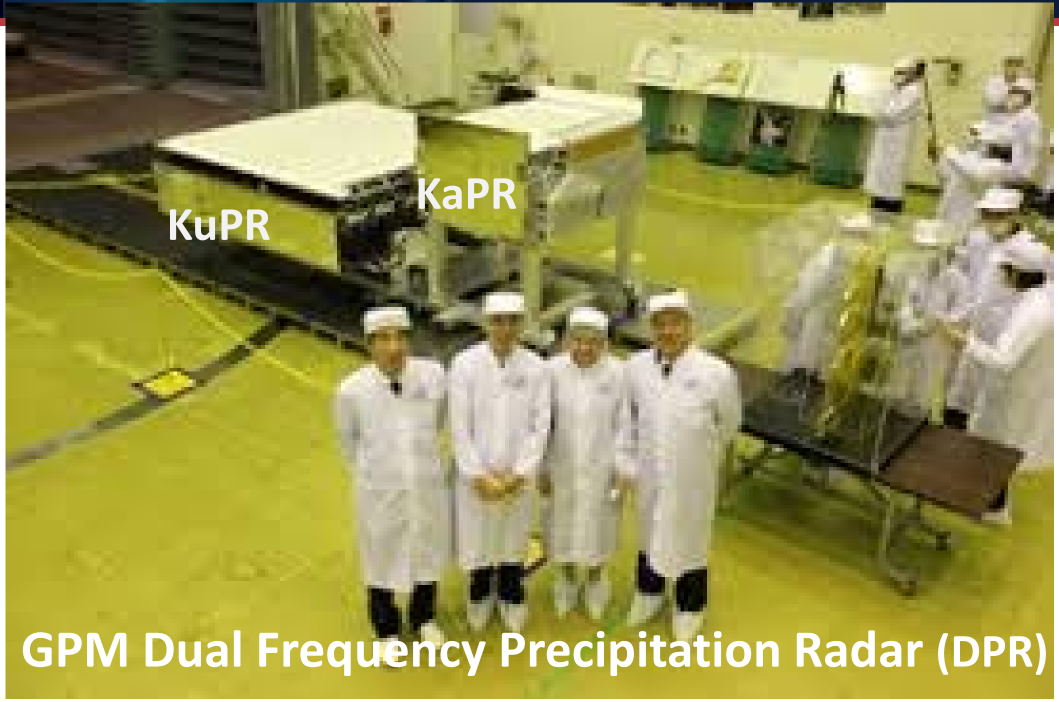
- **Key requirements to be selected for the InVEST solicitation were**
  - Entry TRL (Technology Readiness Level) must be at least 5 = already demonstrated on Earth either as an airborne mission or in lab environment
  - Must validate technology in space within 1 year of launch
  - Implied use of *“U-Class”* 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)

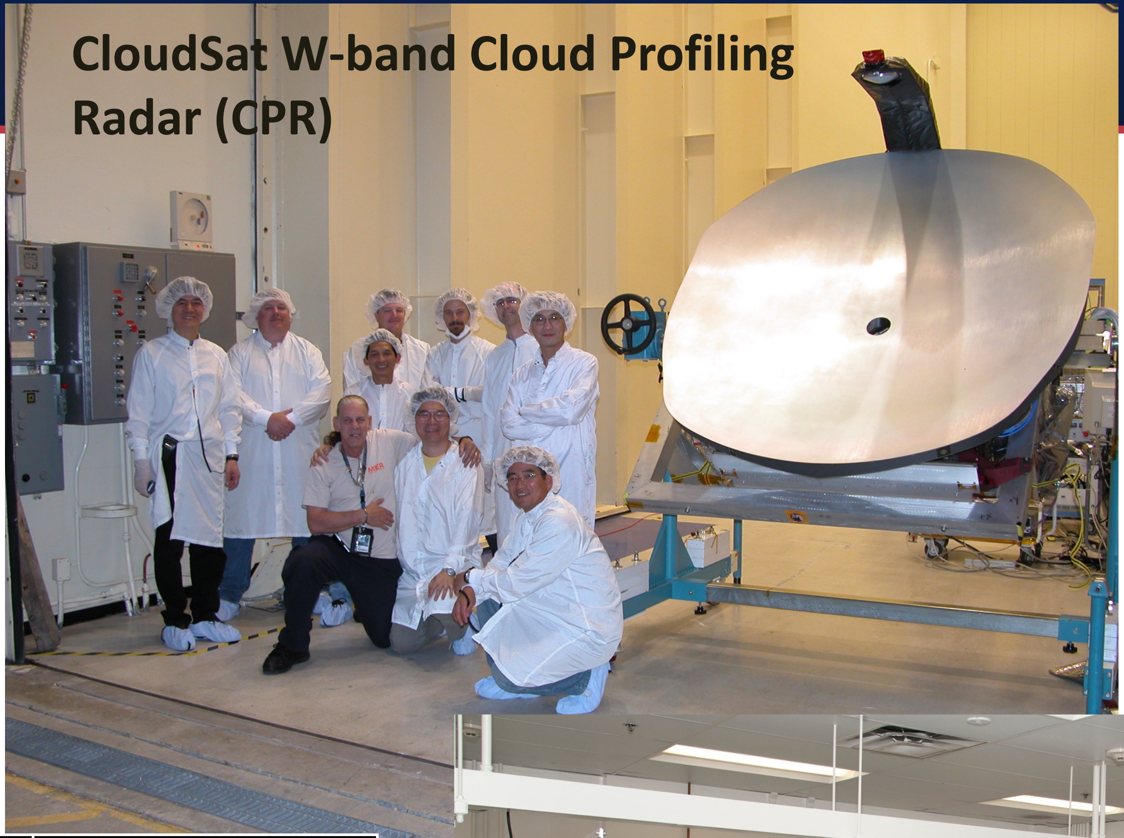
RainCube – Radar in a CubeSat

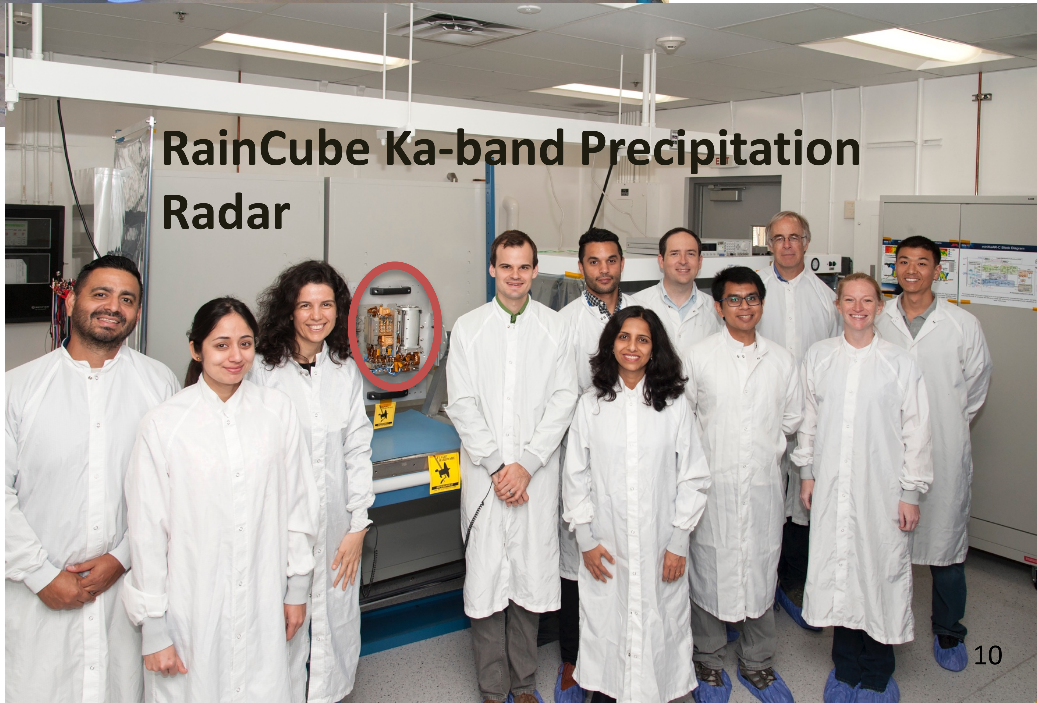
RainCube is a ***technology demonstration*** mission to enable ***Ka-band*** precipitation radar technologies on a low-cost, quick-turnaround platform.

- **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. . .

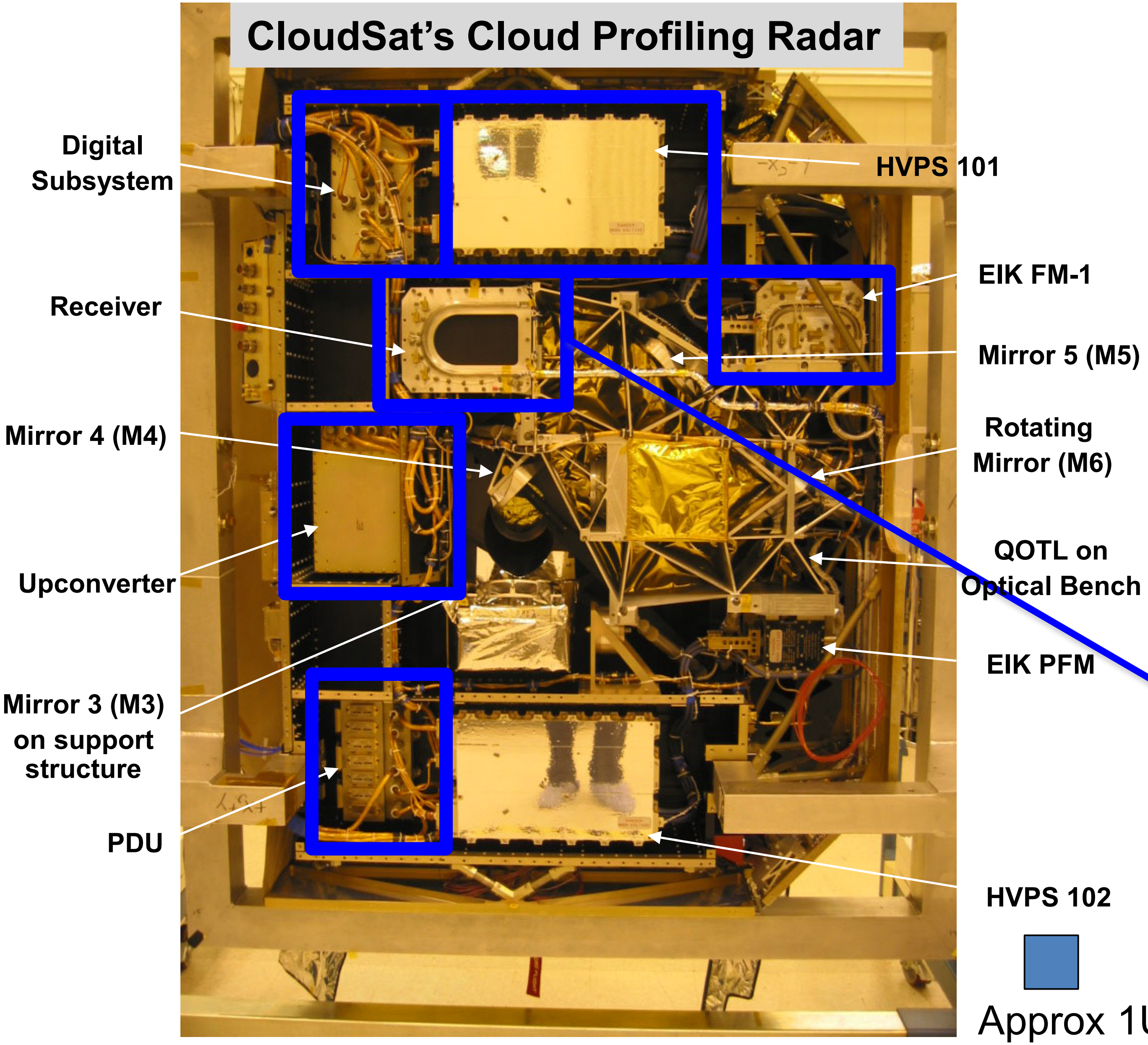




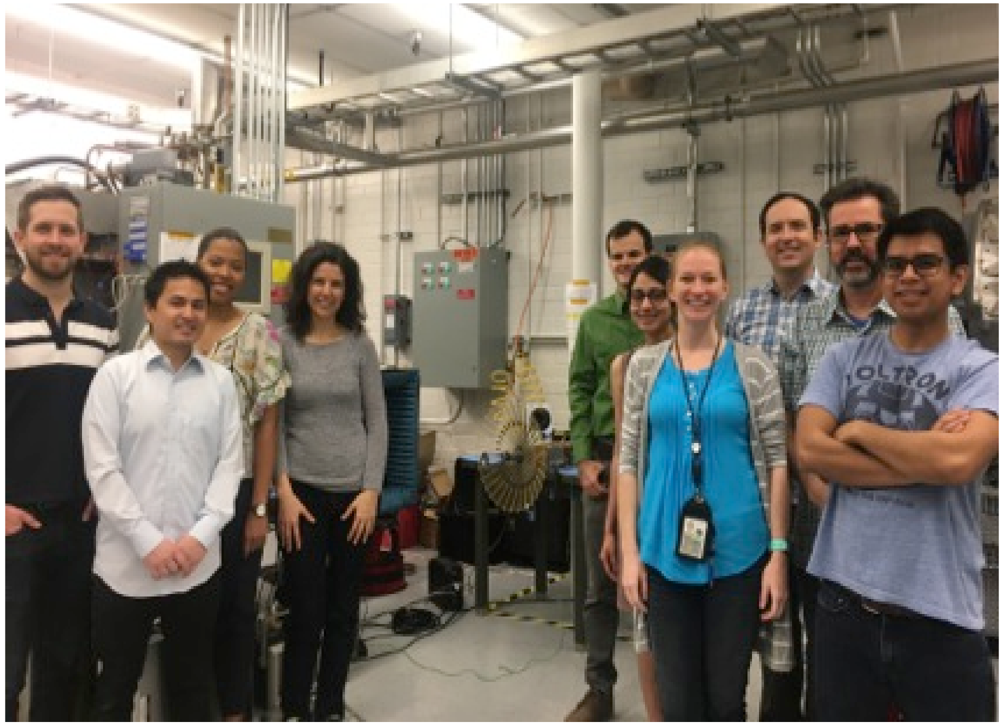


	CPR	KaPR	RainCube
Mass [Kg]	260	336	7
Power [W]	300	344	22
Volume [U]	4,356	1,210	4
Class	C	C	Tech demo
Frequency	W-band	Ka-band	Ka-band
Scanning	No	Yes	No
Sensitivity	-30 dBZ	+17 dBZ	+12 dBZ

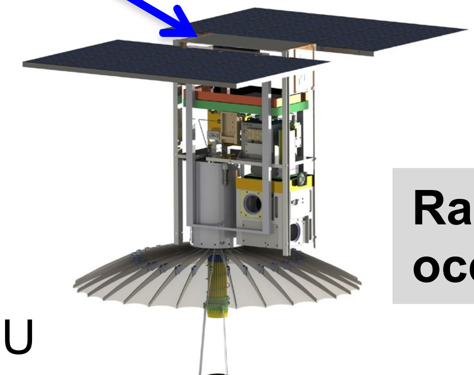
Radar In a CubeSat - The key is to miniaturize . . .



Approx 1U



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

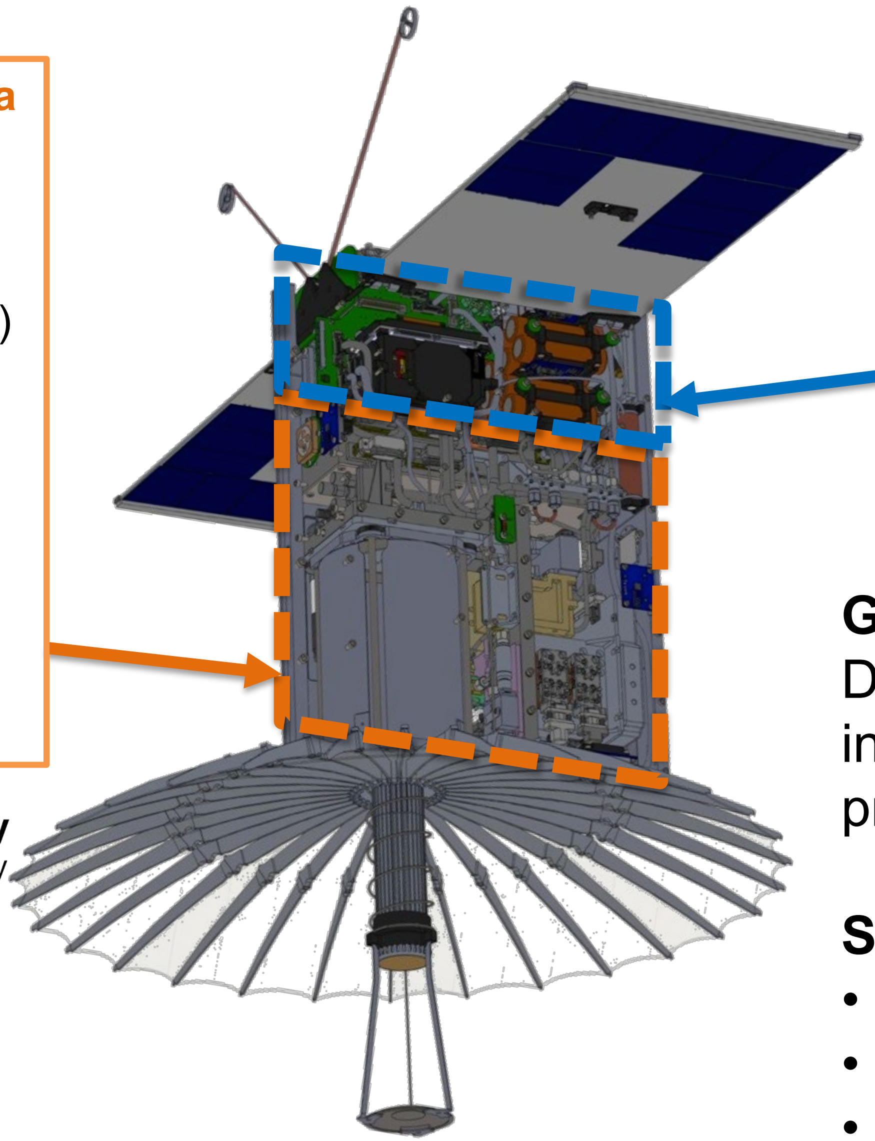
- Constellation paves way for precipitation measurements over smaller time scales to better understand evolution of many weather systems.

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)

Jet Propulsion Laboratory
California Institute of Technology



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

Tyvak
A Terran Orbital Corporation

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.

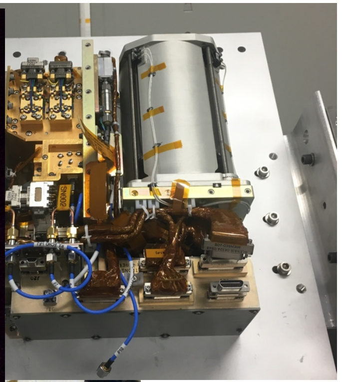
Tyvak Bus:

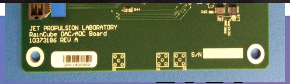
Compact highly integrated bus providing 35W of power to the payload – 2U

RAINCUBE – MISSION TIMELINE

From TRL-0 to TRL-9

Timeline from TRL0 to TRL 9





May 21
Launch to
ISS

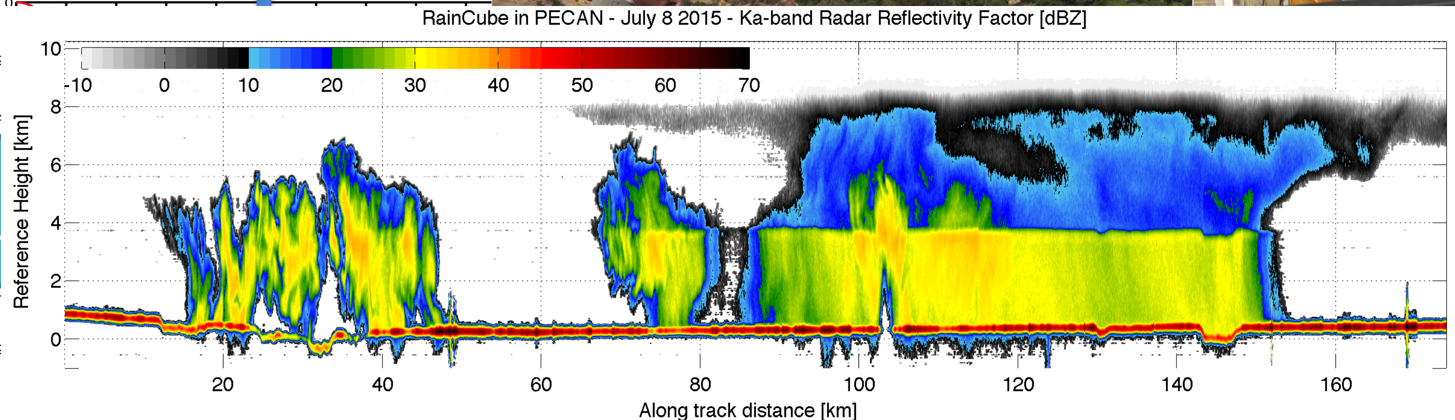
2013 | 2014 | 2015 | 2017 | 2018

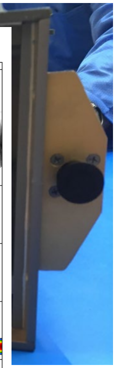
May ’13
Brain-
storming

Dec ’13
Test bed
demo

Ju
Ai
de

eb’18
elivery to
anoracks

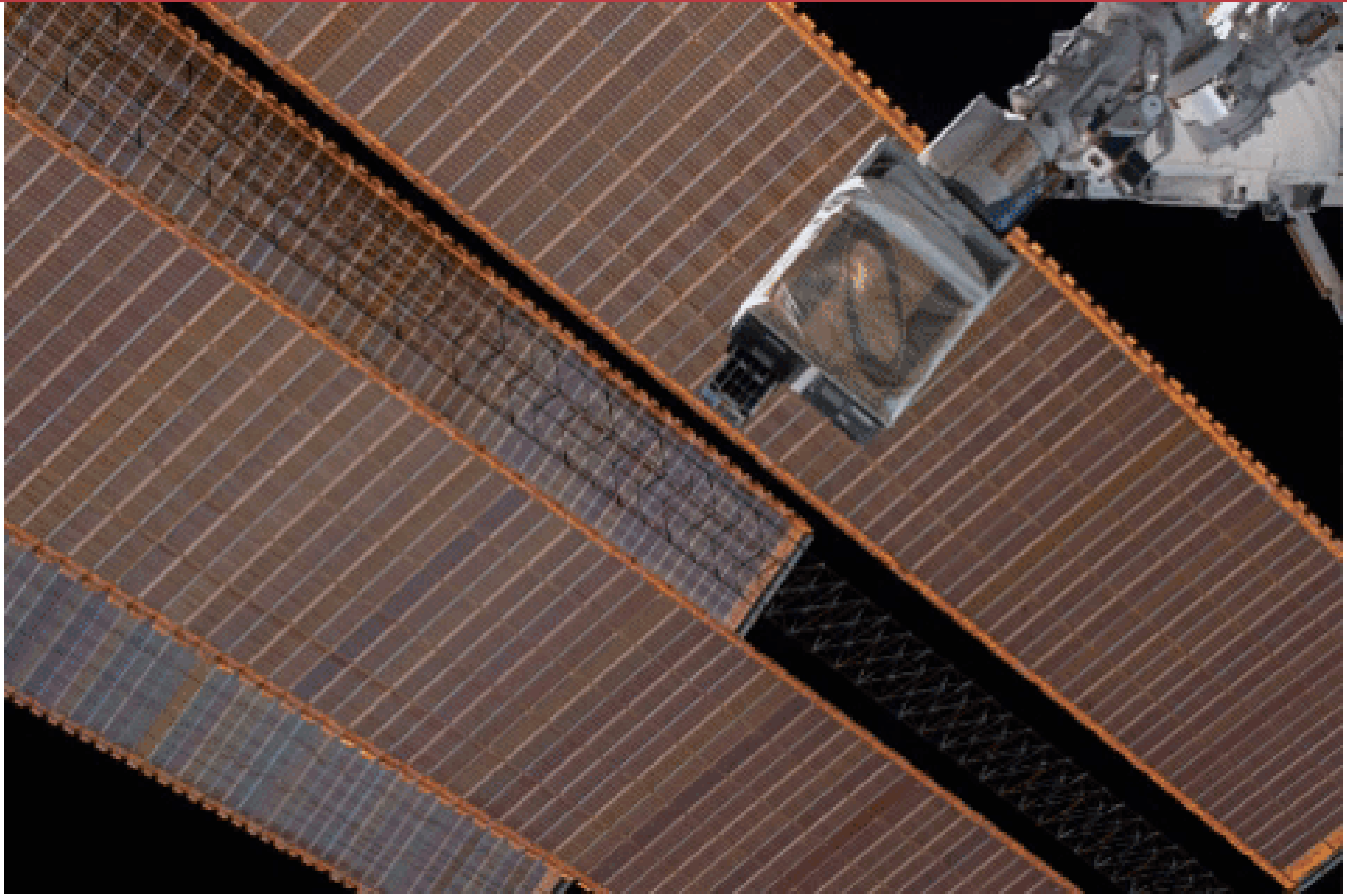




2 yea
0

ged.

ISS Deployment: July 13th, 2018



Timeline from TRL0 to TRL 9

Slide credit – Simone Tanelli, Jonathan Sauder

2013

- **May '13** Brain-storming
- **July '13** Initial concept
- **Dec '13** Test bed demo

2014

- **July '14** Lab demo with prototype HW

2015

- **May '15** Ground demo
- **July '15** Airborne demo
- **Nov '15** InVEST funding

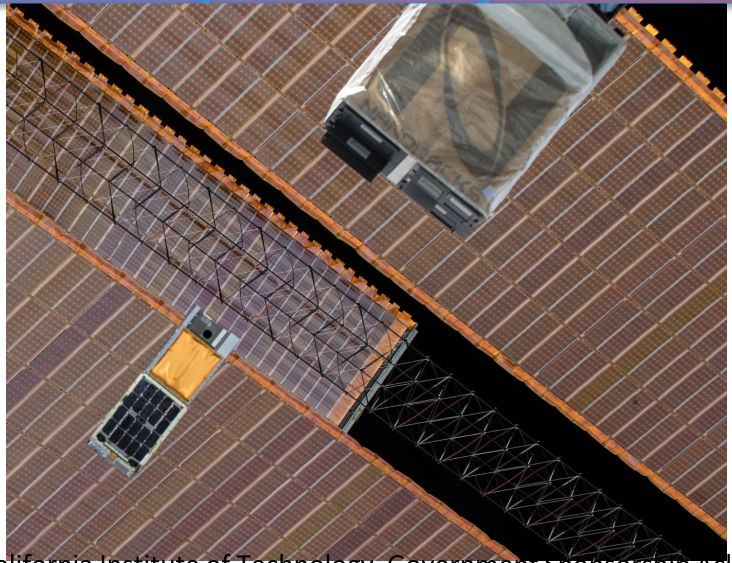
2016

2017

- **Mar '17** Instrument delivery to Tyvak

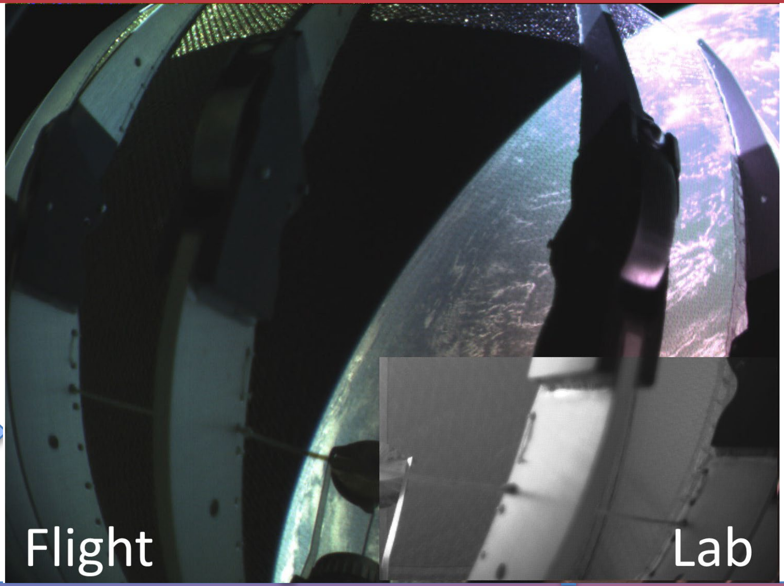
2018

- **May 21** Launch to ISS
- **July 13** ISS deployment



Antenna Deployment: July 28th, 2018

Timeline from TRL0 to TRL 9



2013 2014 2015 2016 2017 2018

May '13
Brain-storming

July '13
Initial concept

Dec '13
Test bed demo

July '14
Lab demo with prototype HW

May '15
Ground demo

July '15
Airborne demo

May '16
Tyvak Selected

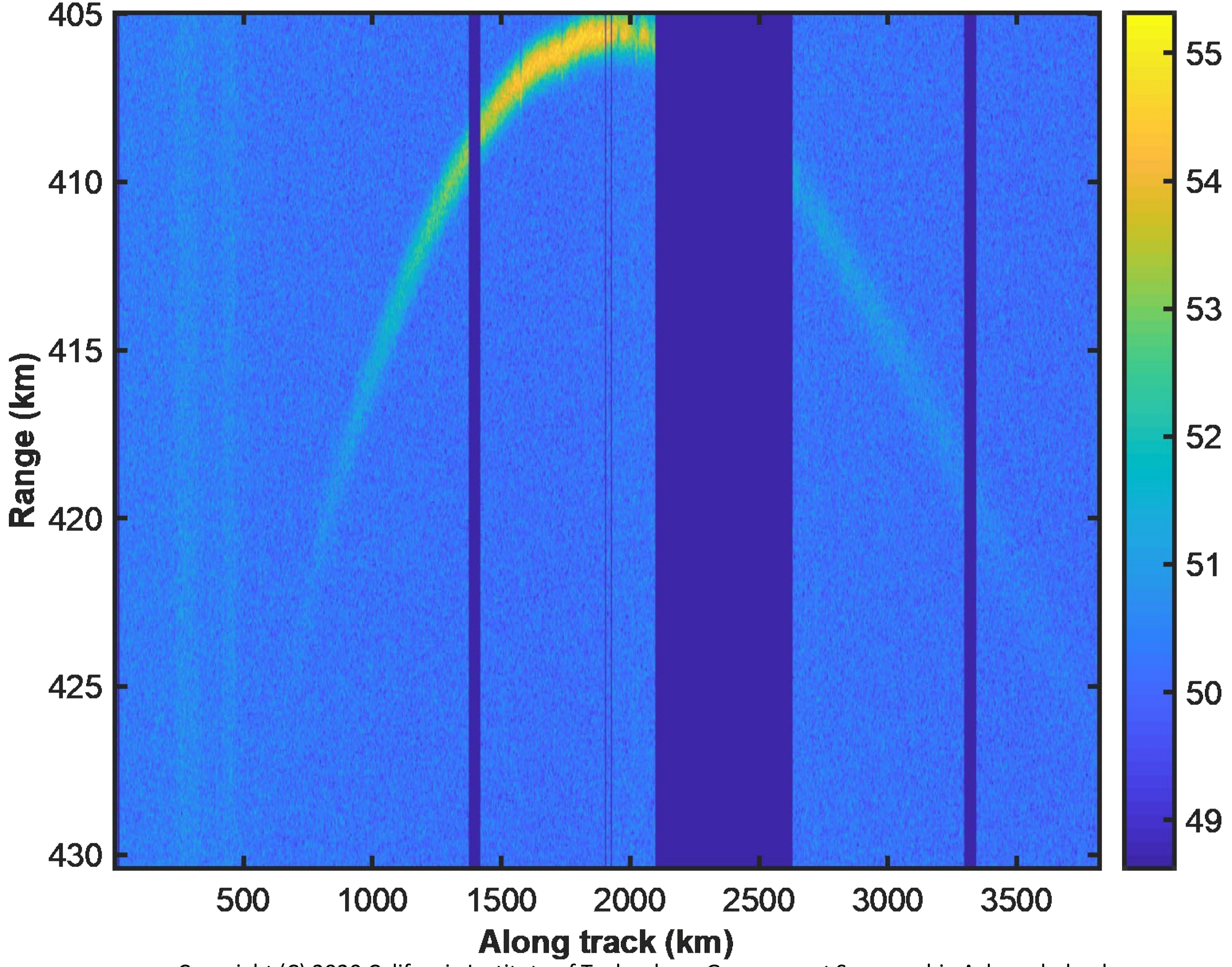
Sep '16
Instrument CDR

Feb'18
Delivery to Nanoracks

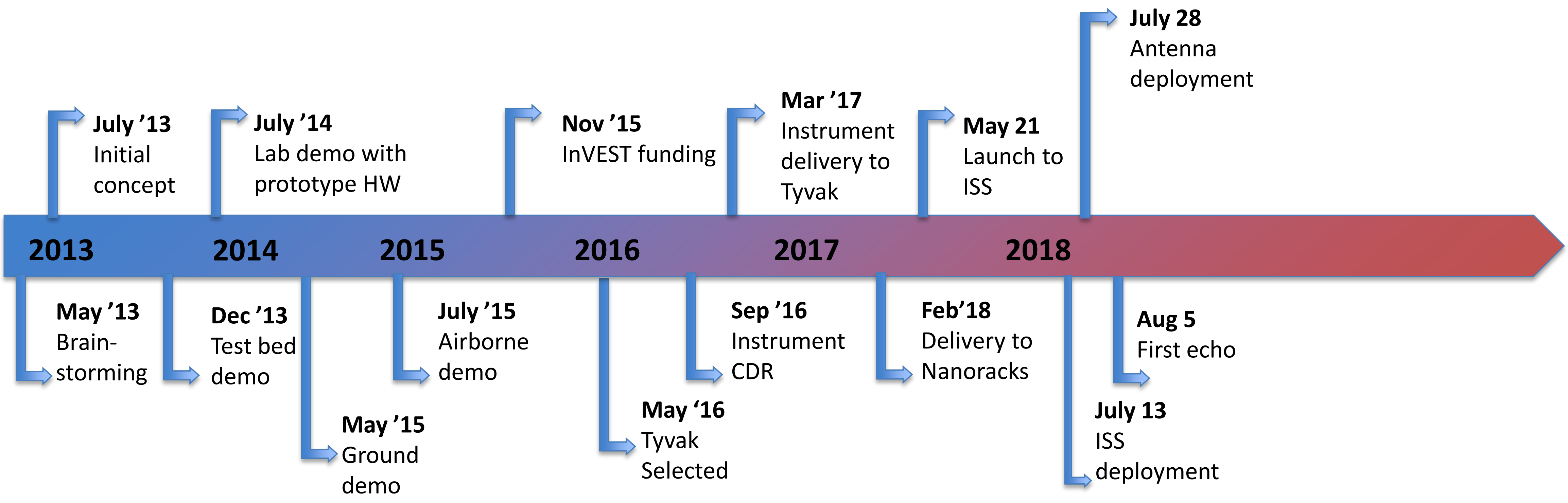
July 13
ISS deployment

July 28
Antenna deployment

First Echo: 8/5/18

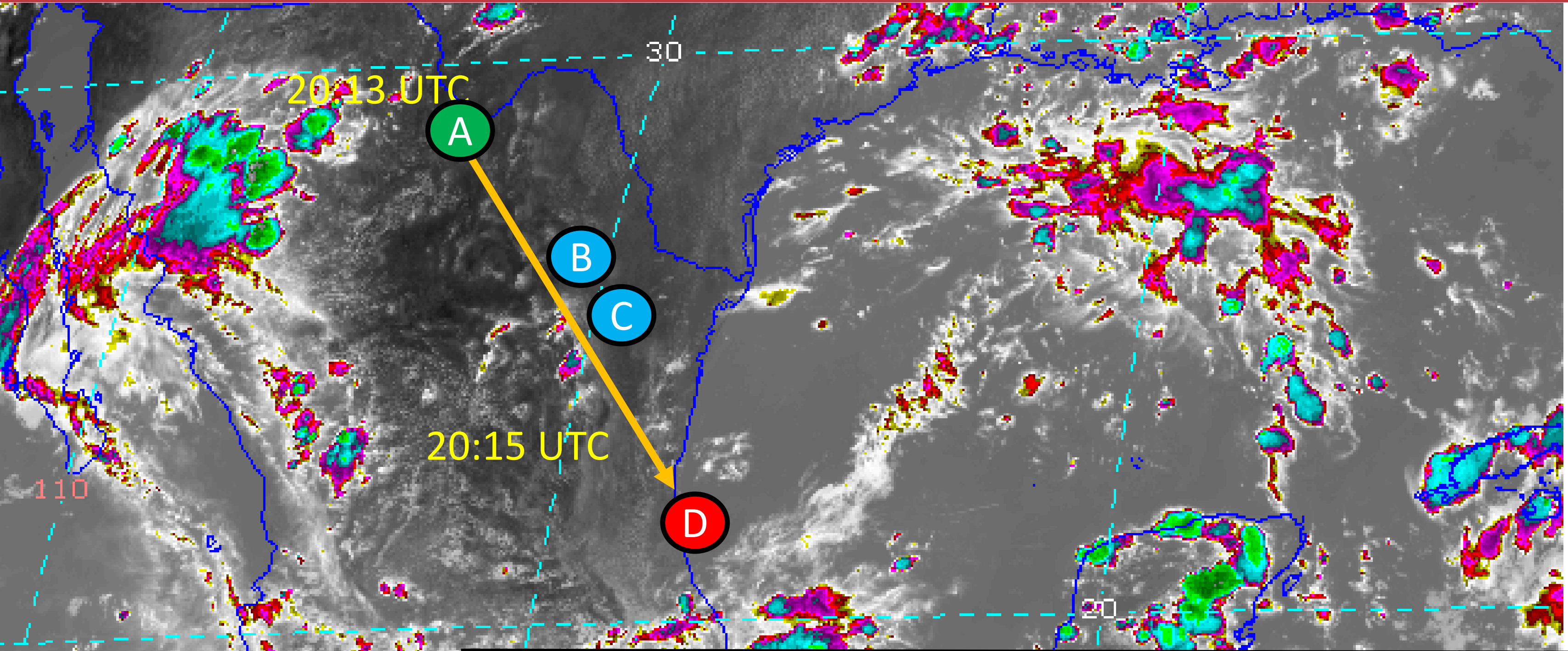


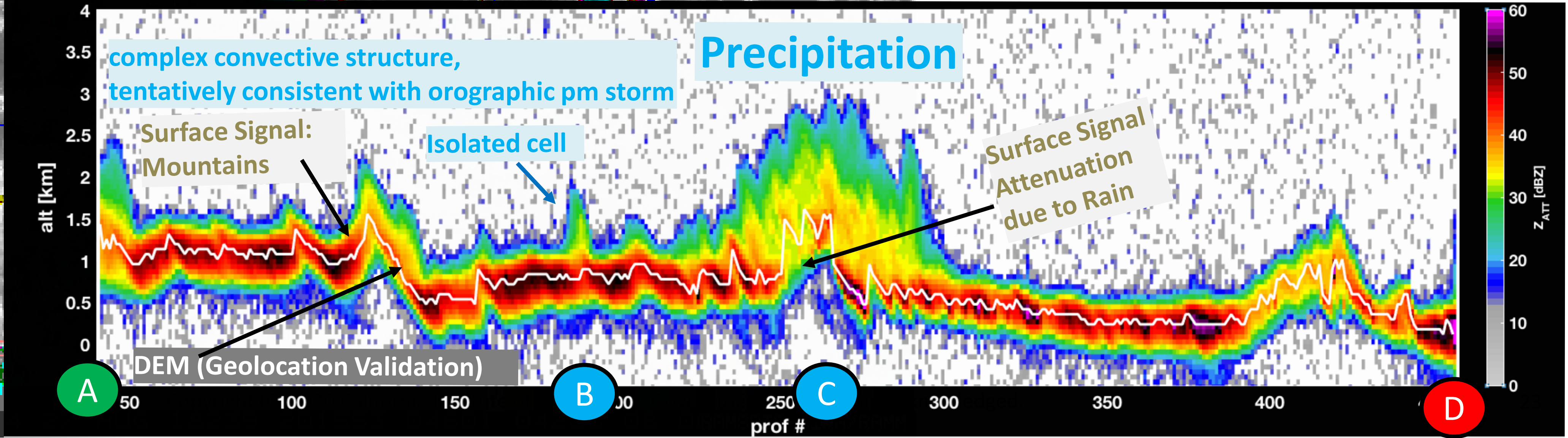
Timeline from TRL0 to TRL 9



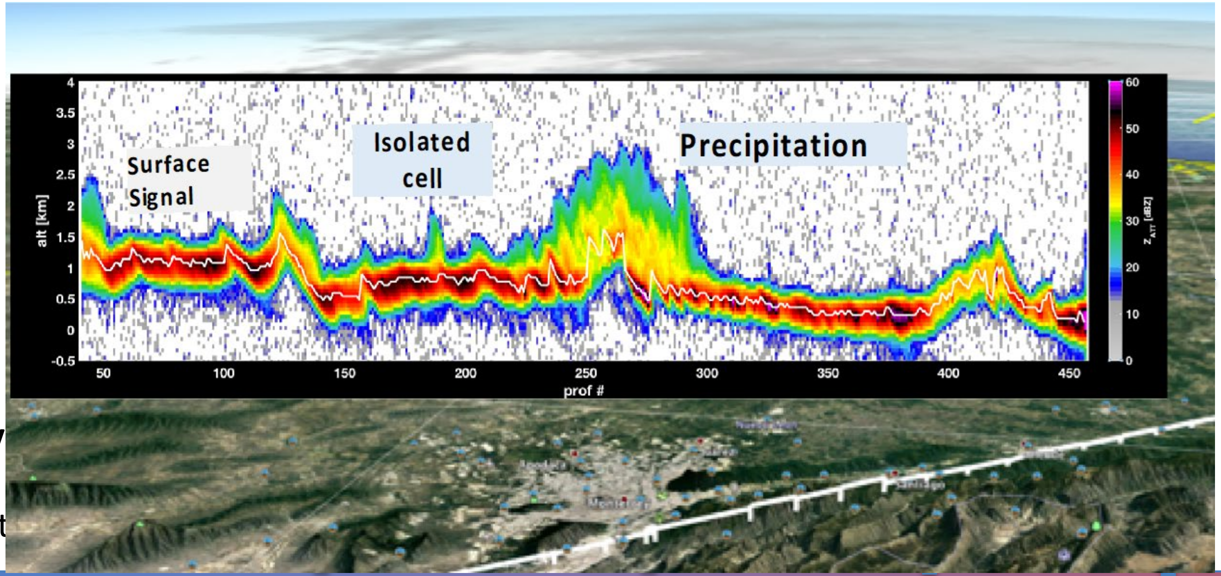
First Rain for RainCube

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





Timeline from TRL0 to TRL 9



2013 · 2014 · 2015 · 2016 · 2017 · 2018

May '13
Brain-storming

July '13
Initial concept

Dec '13
Test bed demo

July
Lab prot

May '15
Ground demo

July '15
Airborne demo

May '16
Tyvak Selected

Sep '16
Instrument CDR

Feb'18
Delivery to Nanoracks

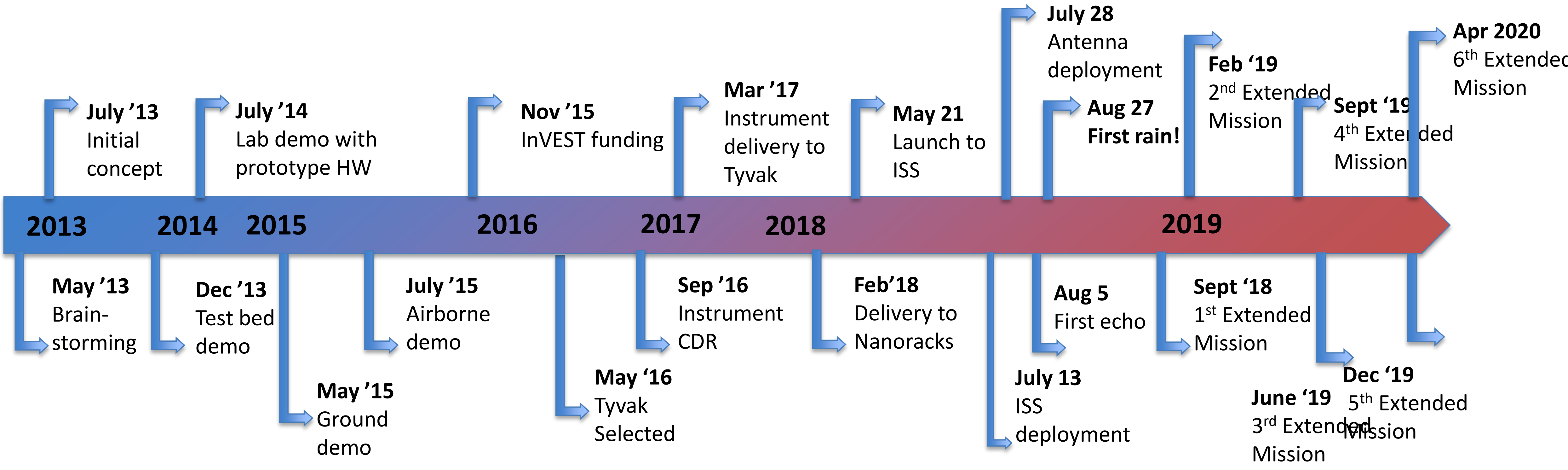
July 13
ISS deployment

July 28
Antenna deployment

Aug 5
First echo

Aug 27
First rain!

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

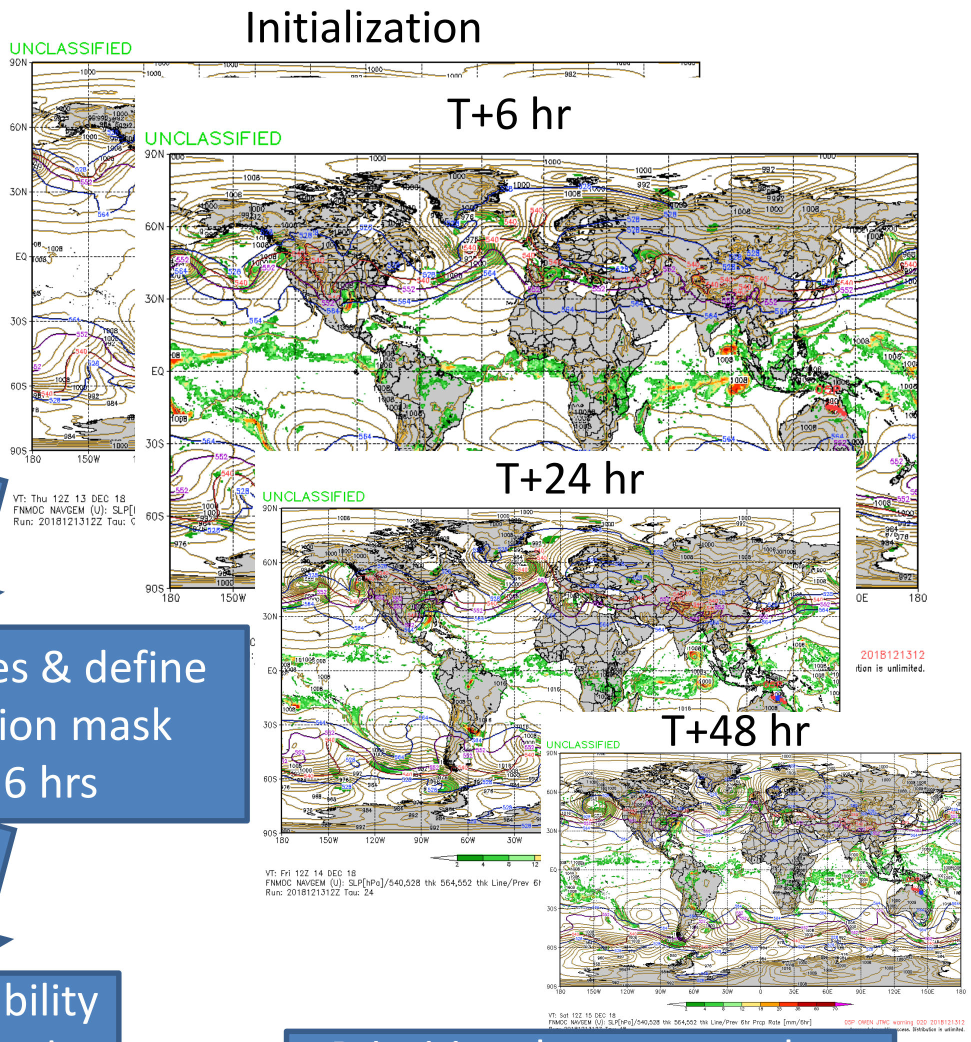
- **Constraints for automation**

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



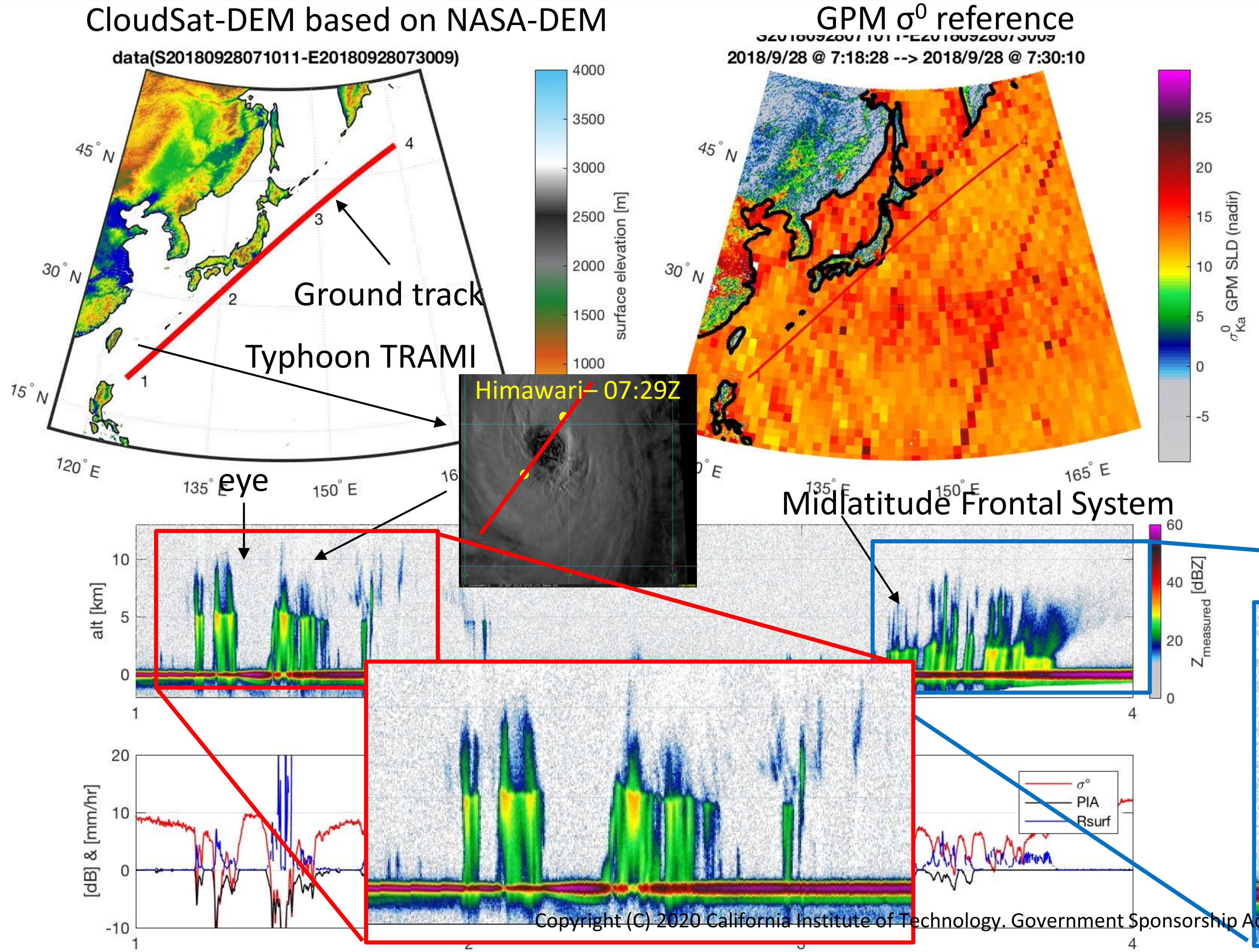
Parse images & define precipitation mask every 6 hrs

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

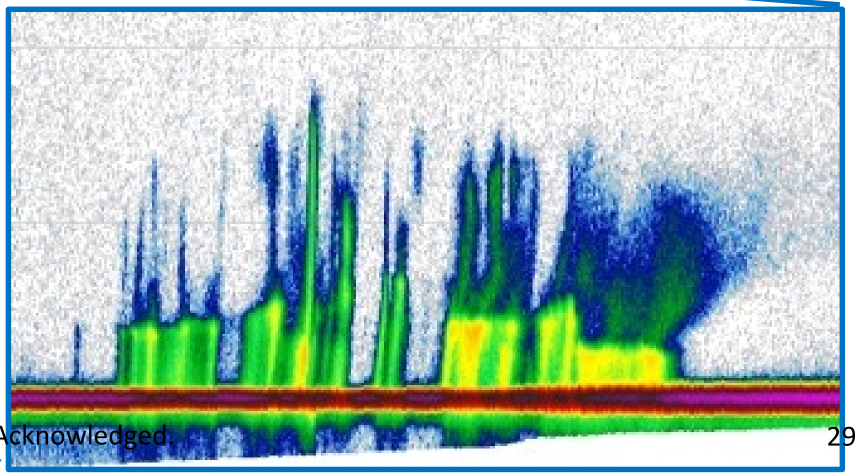


Structure of Typhoon TRAMI

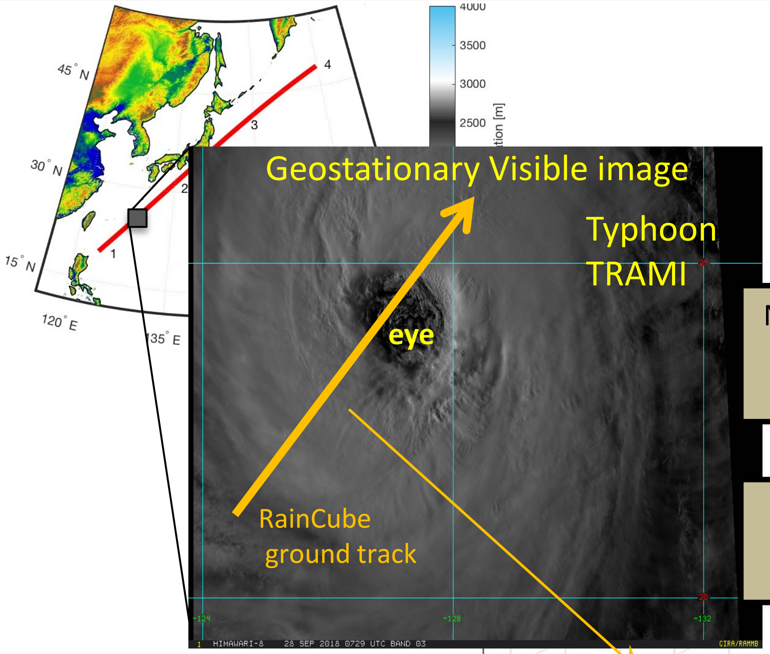
Shortly after it had weakened from Cat 5 to Cat 2. The SW-NE cross section shows very little convective activity along the eyewall (mostly located in the SE sector at that time).

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



RainCube
6U Ka-band (35.7GHz)
nadir pointing radar

~5 min apart

Tempest-D
6U multi-channel
microwave radiometer

Novel ultra compact architecture, high performance pulse compression

Novel ultra compact architecture, high quality calibration

1D Horizontal structure, 250 m vertical resolution

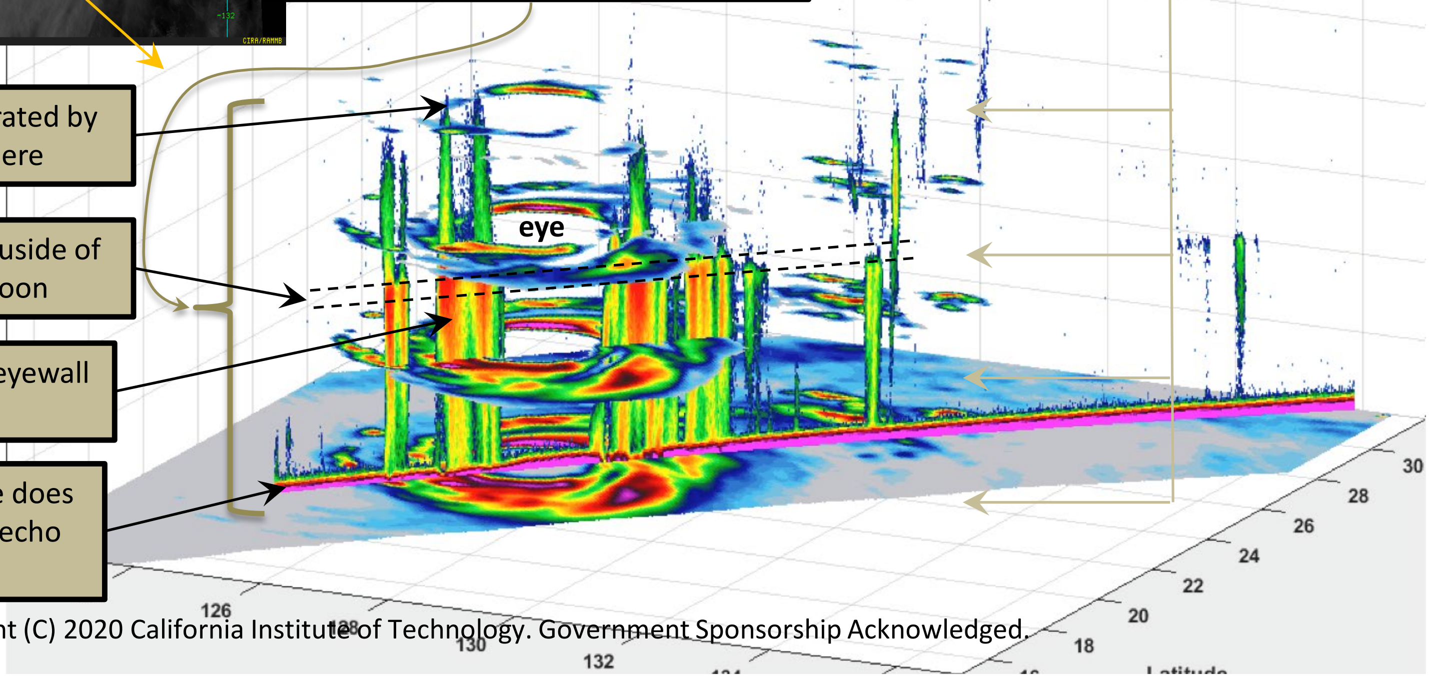
2D Horizontal structure, 4 vertical levels

Extent of penetration of ice generated by convection in upper troposphere

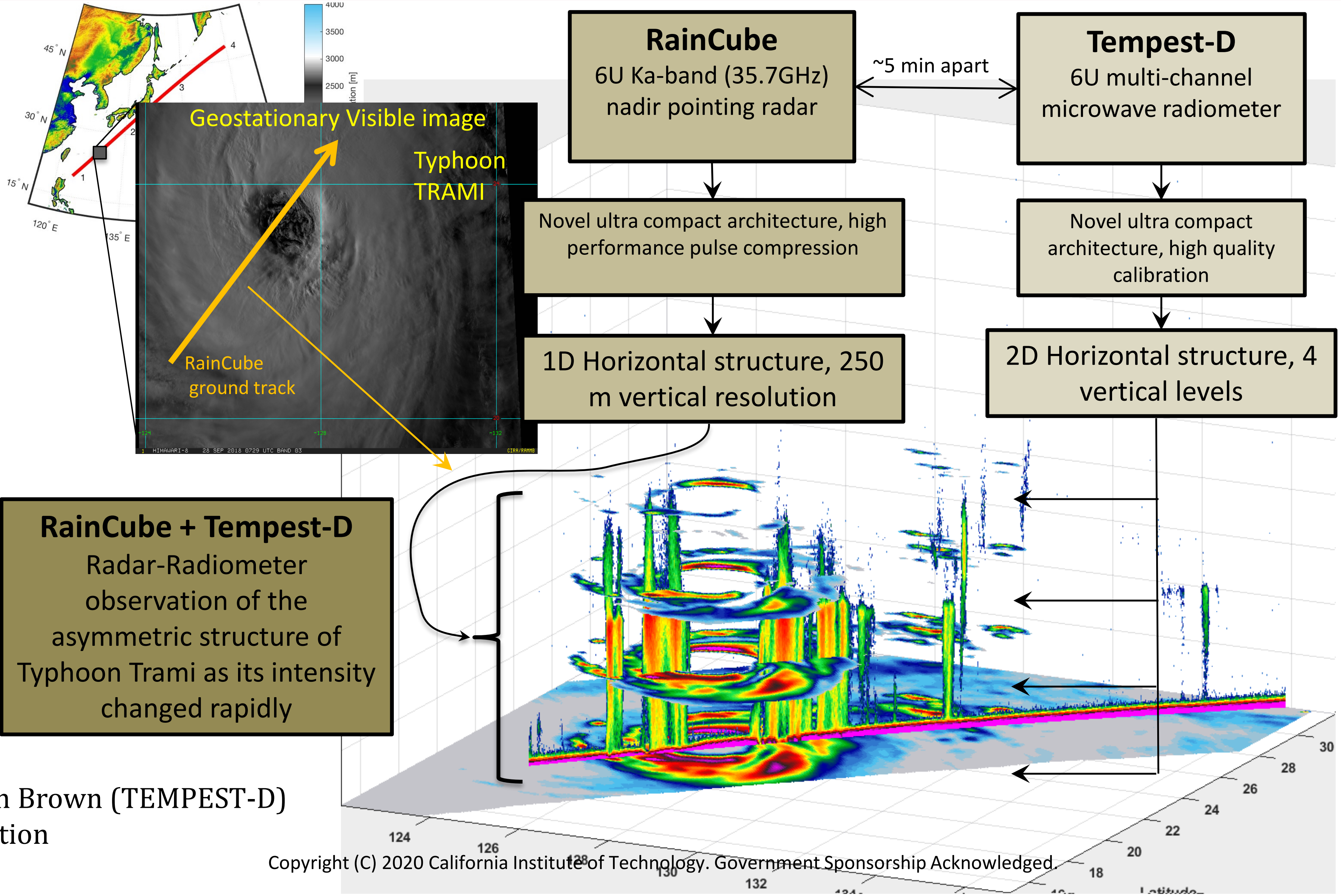
Melting Layer : ~4.8 km altitude ouside of TRAMI, raised inside the Typhoon

Intensity of precipitation in the eyewall and rainbands

Strong echo from ocean surface does not contaminate precipitation echo



RADAR + RADIOMETER MINI CONSTELLATION



RainCube
6U Ka-band (35.7GHz) nadir pointing radar

~5 min apart

Tempest-D
6U multi-channel microwave radiometer

Novel ultra compact architecture, high performance pulse compression

Novel ultra compact architecture, high quality calibration

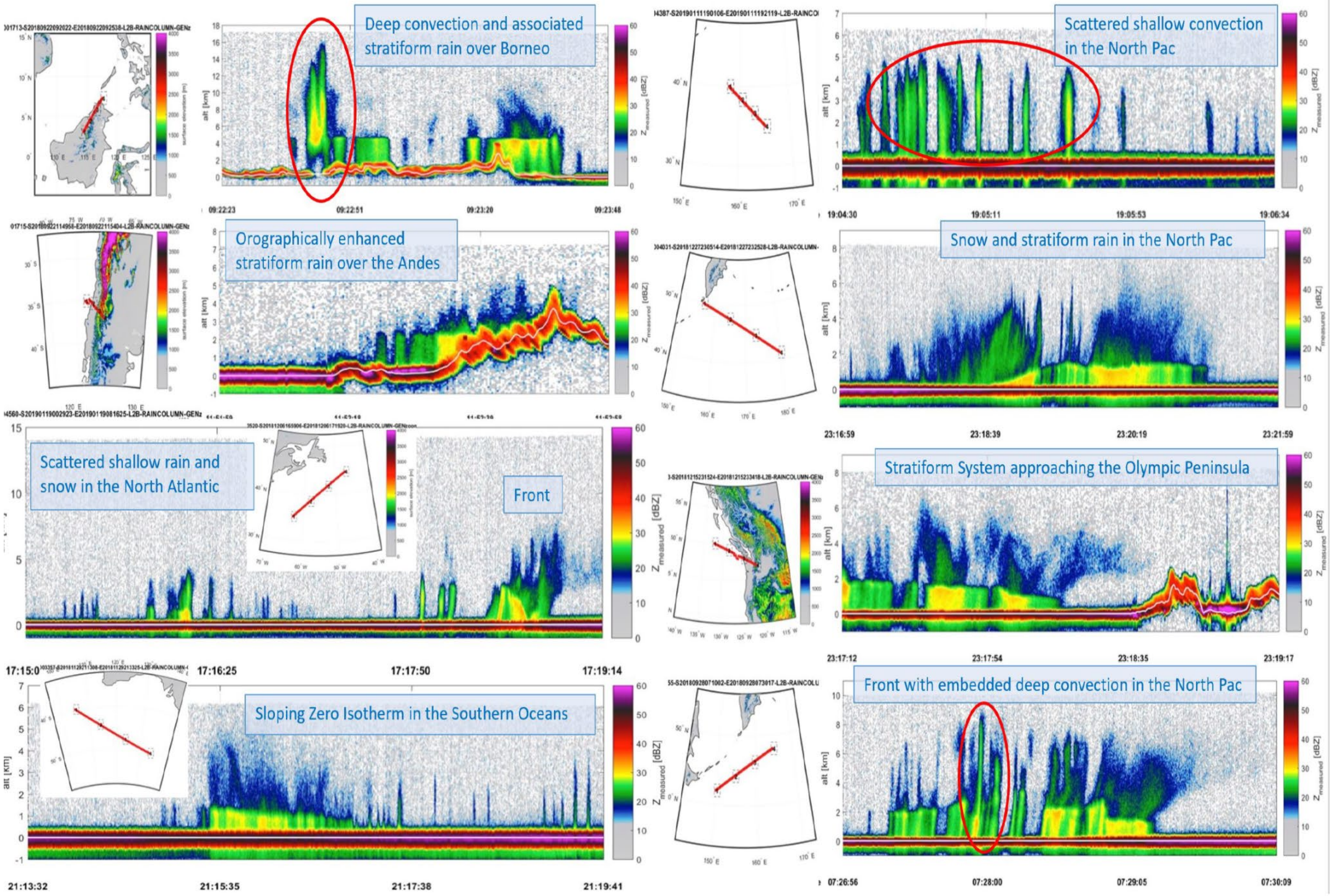
1D Horizontal structure, 250 m vertical resolution

2D Horizontal structure, 4 vertical levels

RainCube + Tempest-D
Radar-Radiometer observation of the asymmetric structure of Typhoon Trami as its intensity changed rapidly

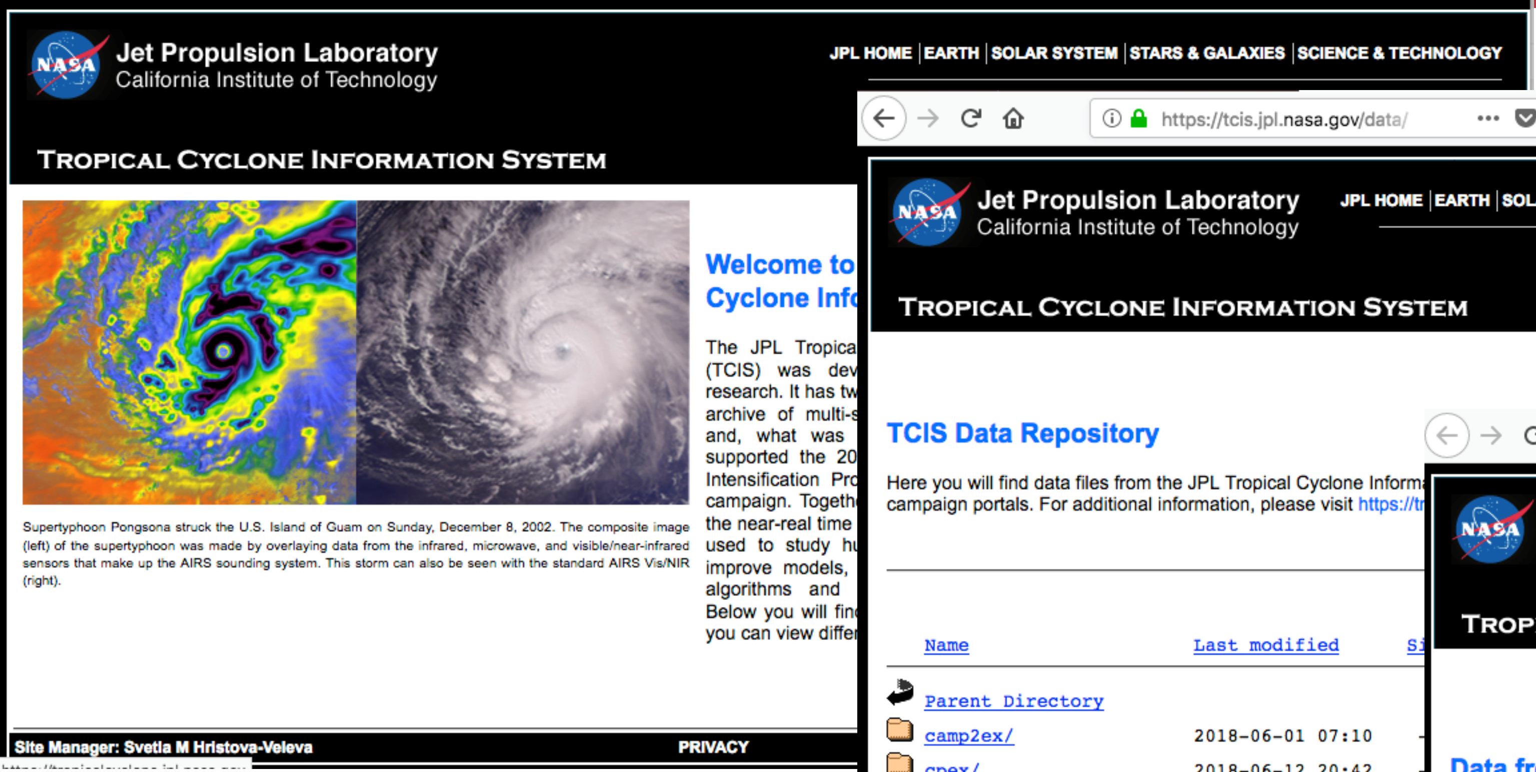
Credit to Shannon Brown (TEMPEST-D) for the 3D-animation

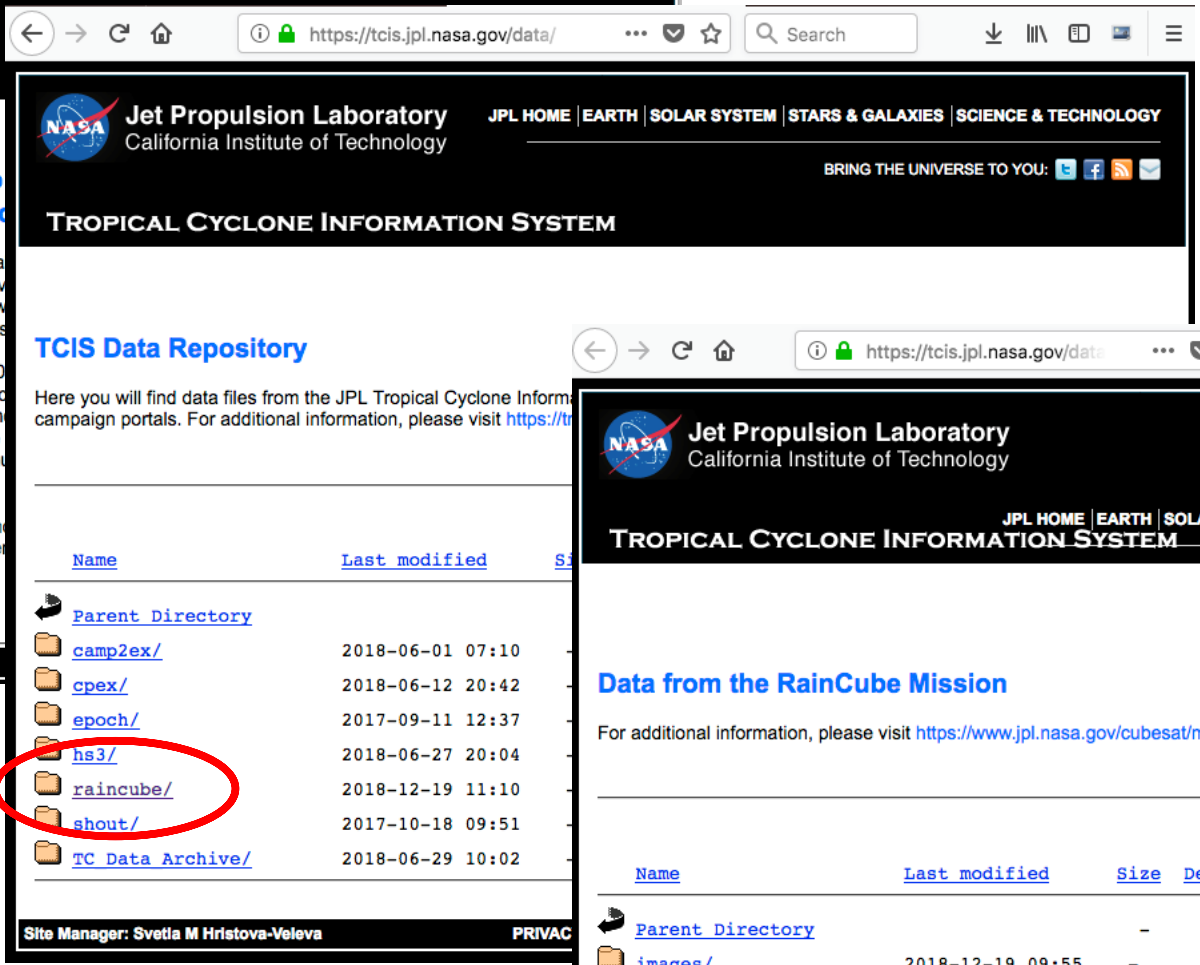
A Collection of RainCube Storms

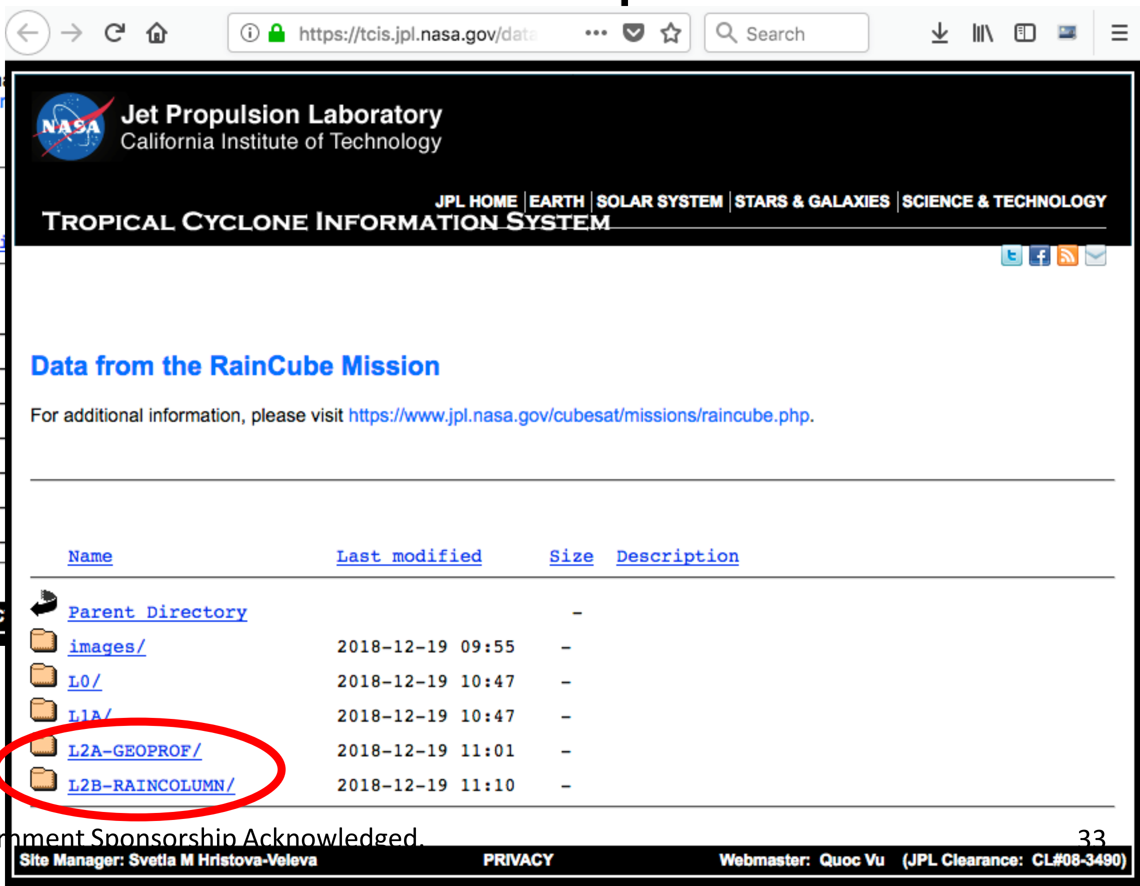


Slide credit:
Ousmane Sy (JPL)

TCIS portal will host RainCube data







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 L0 and L1 data to the public.

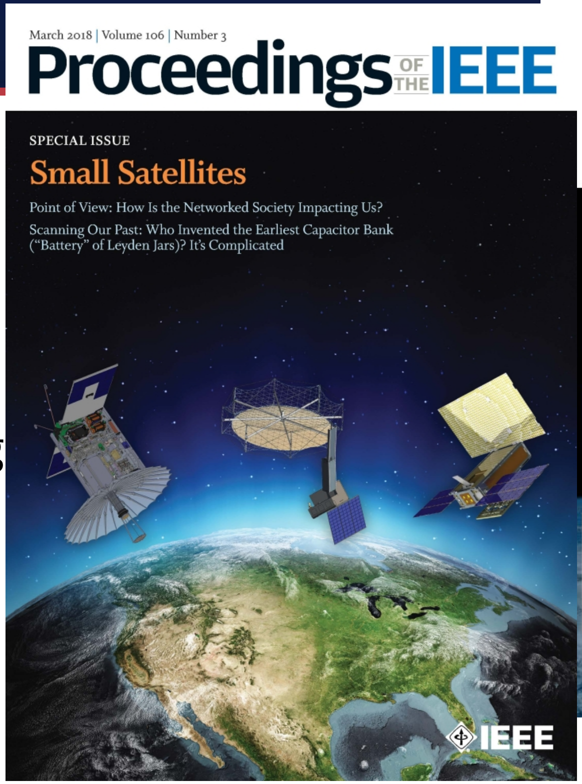
Lessons Learned

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

Ka-band ESTO InVEST and ACT programs

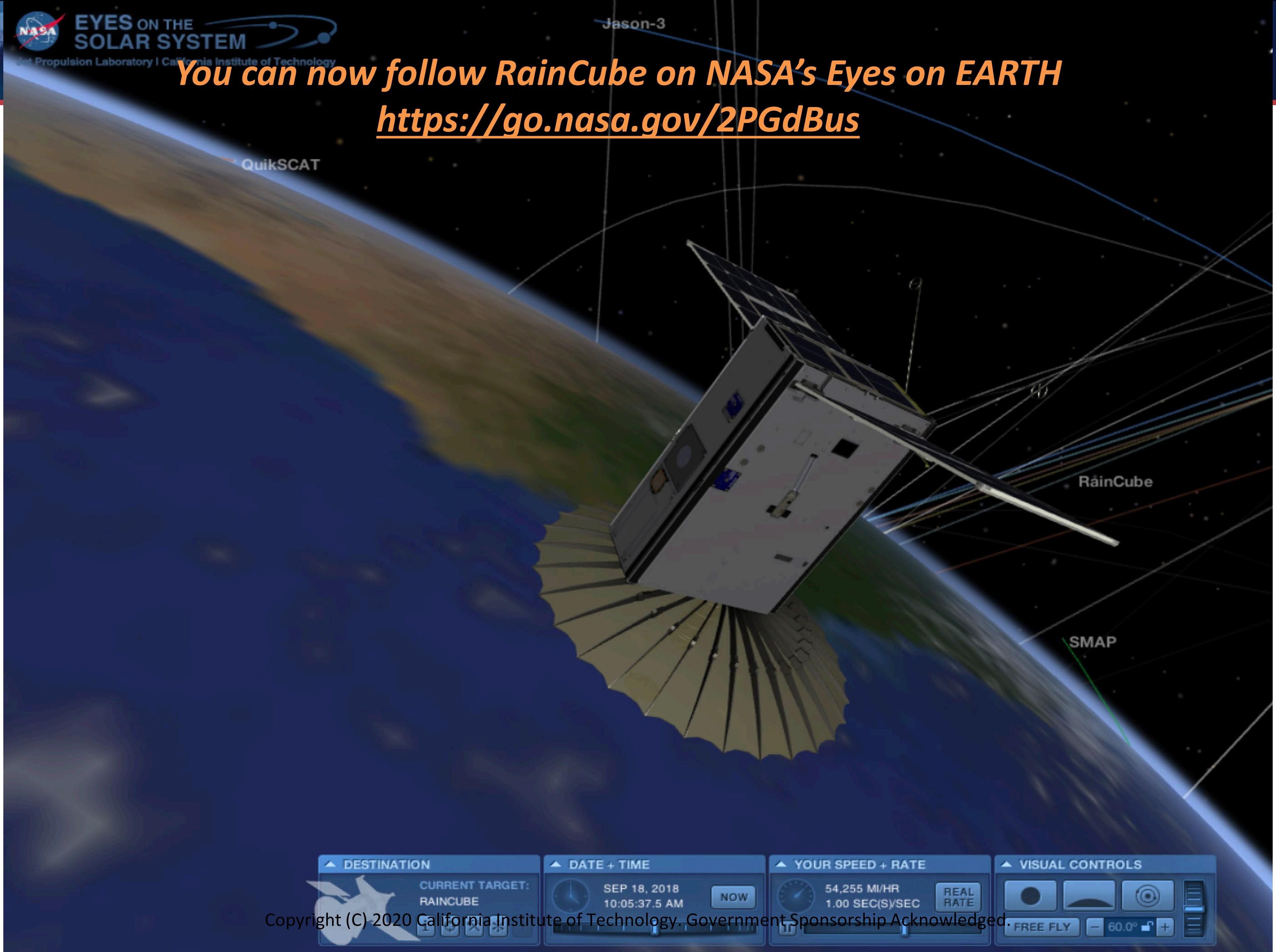
	6U	12 U	50 kg
Antenna size [m]	0.5	1.0	2.0
Sensitivity [dBZ]	15	5-10	0-5
Hor Resolution [km]	8	4	2
Range Res [m]	250		
Beams	1	1-3	1-5
RF Power [W]	10	10-20	10-40

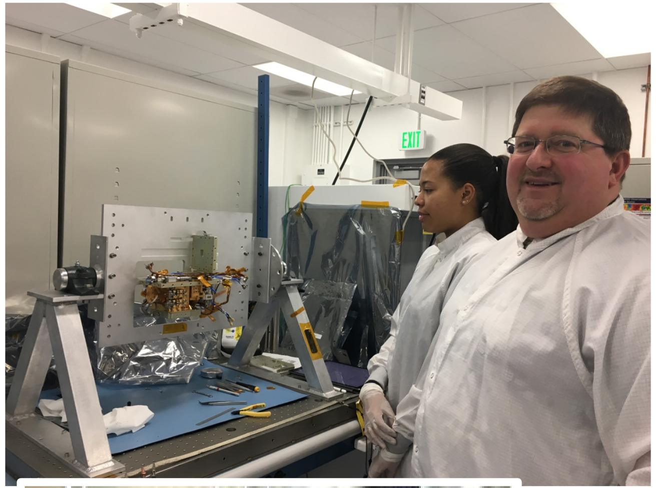
CloudCube – IIP Selection

- 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.

You can now follow RainCube on NASA’s Eyes on EARTH

https://go.nasa.gov/2PGdBus



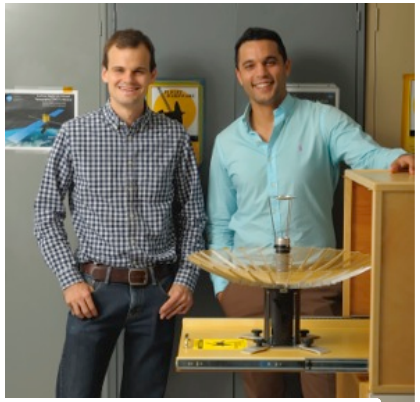

EXIT

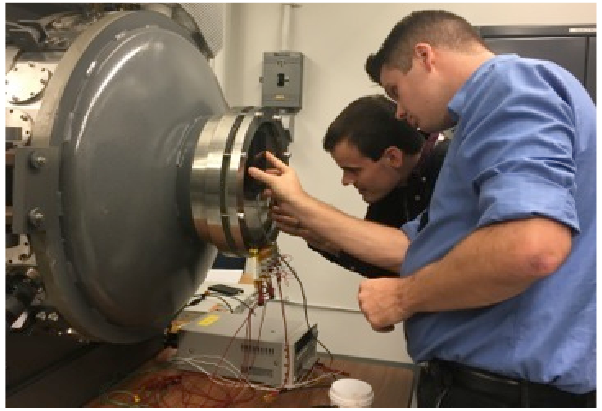

(RainCube)
(ASTERIA)

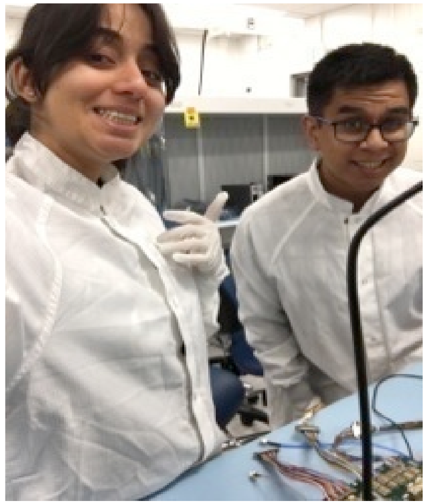

OA-9 CRS Launch
@orbital_atk
NASA Wallops Flight Facility
7,385 likes
Go Antares! Go Cygnus!
#OA9 #Antares #Cygnus

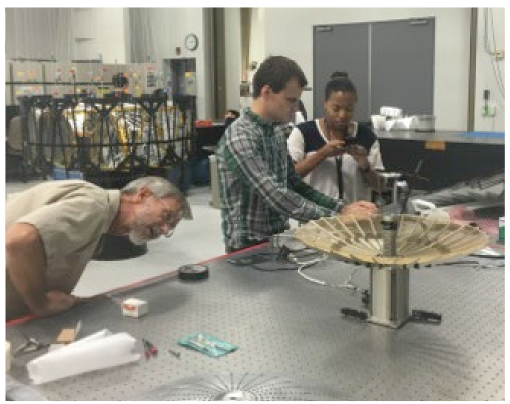

RainCube
RADAR FOR RAIN PROFILING

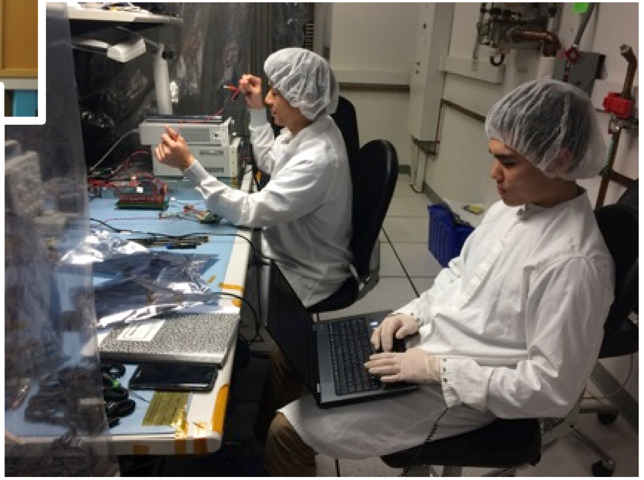

RainCube Project Team
February, 2017



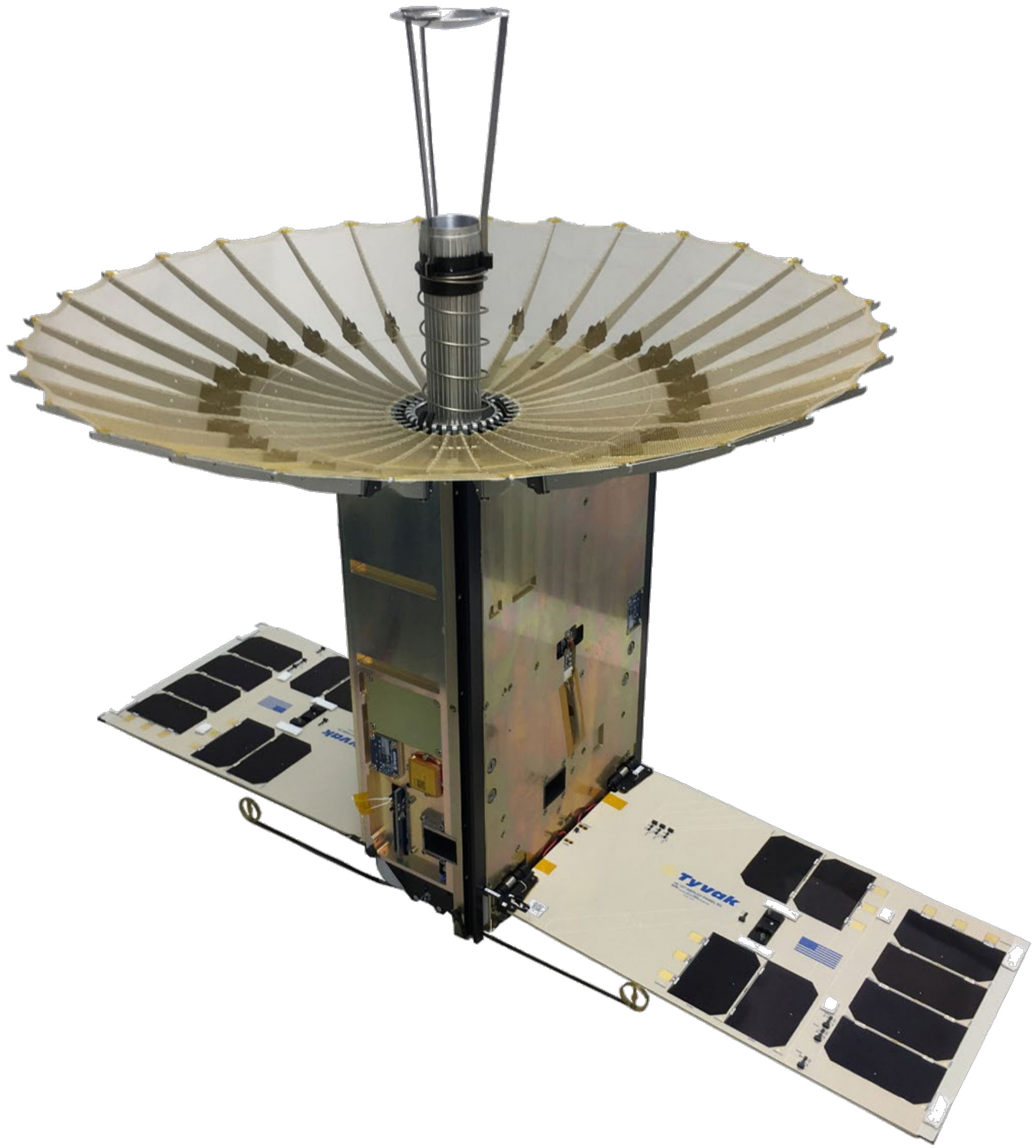








Thank You!



- NASA/JPL-Caltech Team members
  - Eva Peral, Simone Tanelli, Shannon Statham, Jonathan Sauder, Shivani Joshi, Douglas Price, Travis Imken, Nacer Chahat, Chaitali Parashare, Alessandra Babuscia, Elvis Merida, Marvin Cruz, Carlo Abesamis, Macon Vining, Joseph Zitkus, Richard Rebele, Mary Soria, Arlene Baiza, Stuart Gibson, Greg Cardell, Brad Ortloff, Brandon Wang, Taryn Bailey, Dominic Chi, Brian Custodero, John Kanis, Kevin Lo, Mike Tran, Nazilla Rouse, and Miguel Ramsey.
- Tyvak Team Members
  - Austin Williams, Chris Shaffer, Ricky Prasad, Ehson Mosleh, Jeff Mullen, Jeff Weaver, Sean Fitzsimmons, Nathan Fite, John Brown, John Abel, Craig Francis, Kari Kawashima, Lauren Fitzgibbon, Steven Sundin and Marco Villa.
- Funded by NASA ESTO InVEST