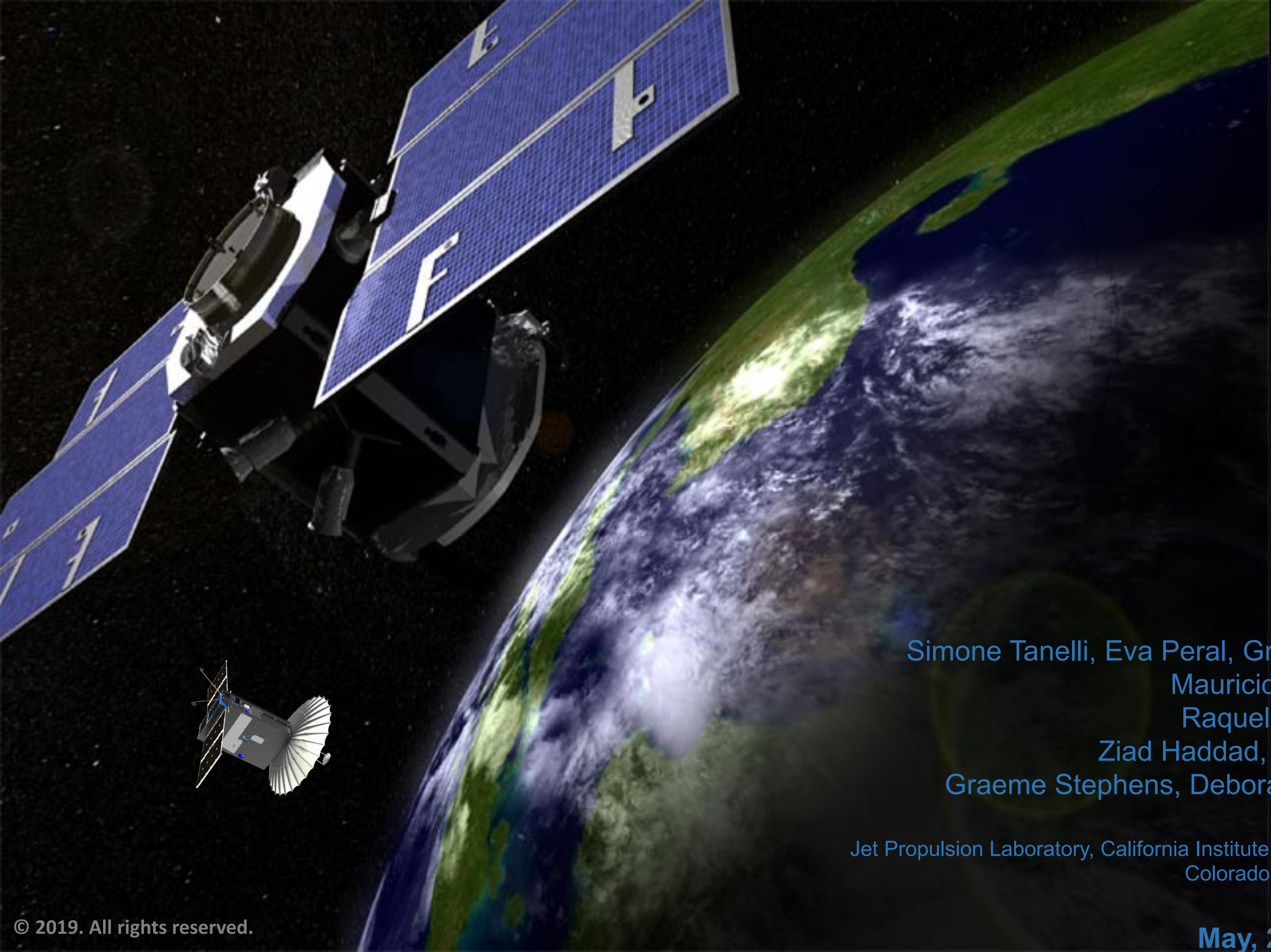


Jet Propulsion Laboratory
California Institute of Technology

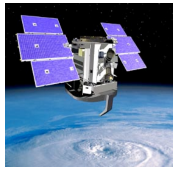
Evolution of radars for spaceborne observations of cloud and precipitation processes at JPL: from CloudSat to RainCube and beyond

Simone Tanelli, Eva Peral, Gregory Sadowy, Stephen Durden,
Mauricio Sanchez-Barbetty, Ken Cooper,
Raquel Rodriguez-Monje, Eastwood Im,
Ziad Haddad, Ousmane Sy, Matthew Lebsock,
Graeme Stephens, Deborah Vane, Susan van den Heever

Jet Propulsion Laboratory, California Institute Of Technology, Los Angeles, United States,
Colorado State University, Fort Collins, United States

May, 2019

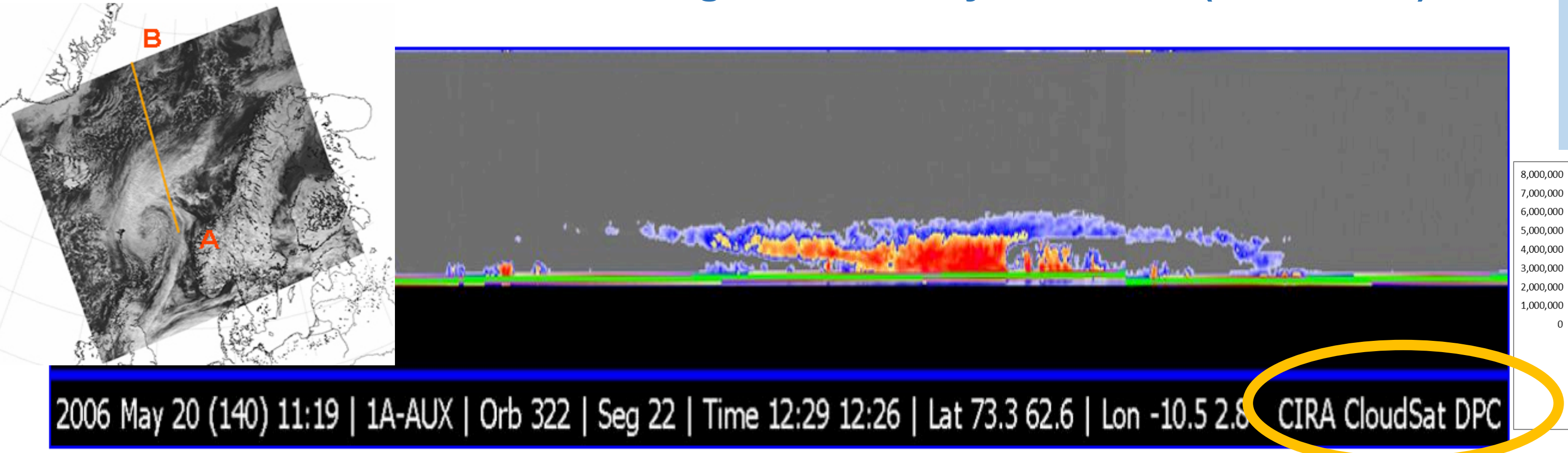
CloudSat’s Cloud Profiling Radar (CPR)



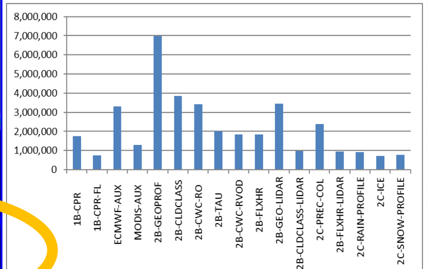
The first Spaceborne Cloud Radar is still a teenager:

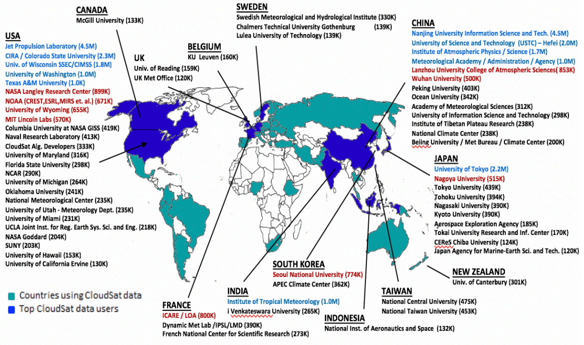
- radar sensitivity has dropped to about -26 dBZ mostly due to EIK aging after almost 13 years in orbit.
- Still on **primary EIK**, secondary has never been exercised in orbit.
- Mission performance and expected residual life limited mainly by the aging platform (at ~7x Mission Design life).

Warm Front Storm Over the Norwegian Sea: May 20th, 2006 (first cloud)

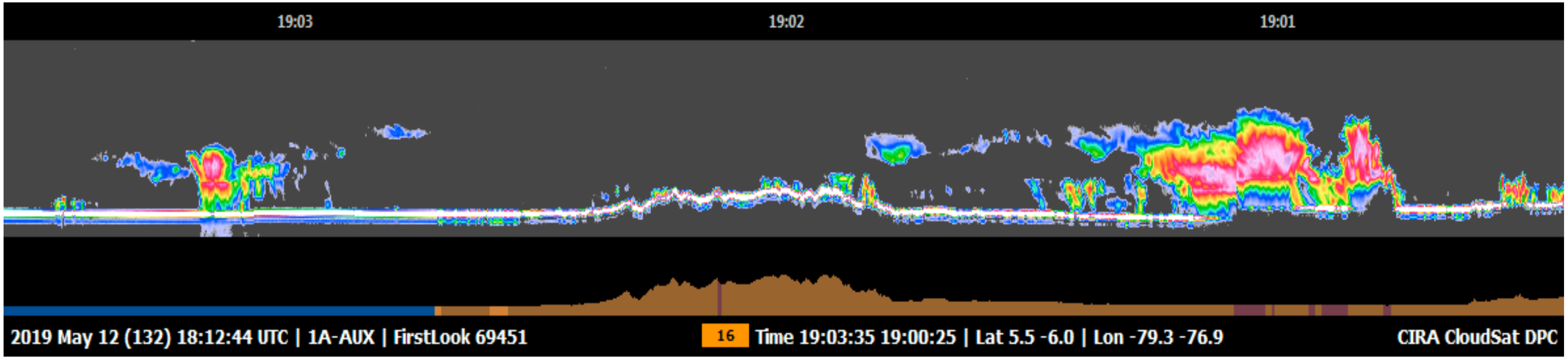


- PI-led (Graeme Stephens, JPL)
- 1st 94 GHz radar in space
- Launched April 2006, 22-month prime mission
- Flies in **A-Train** Constellation, 705km





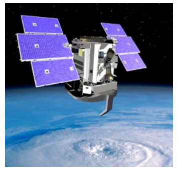
Tropical Convection in EastPac and SAmerica: May 12th, 2019 (most recent)



> 2000 peer-reviewed publications

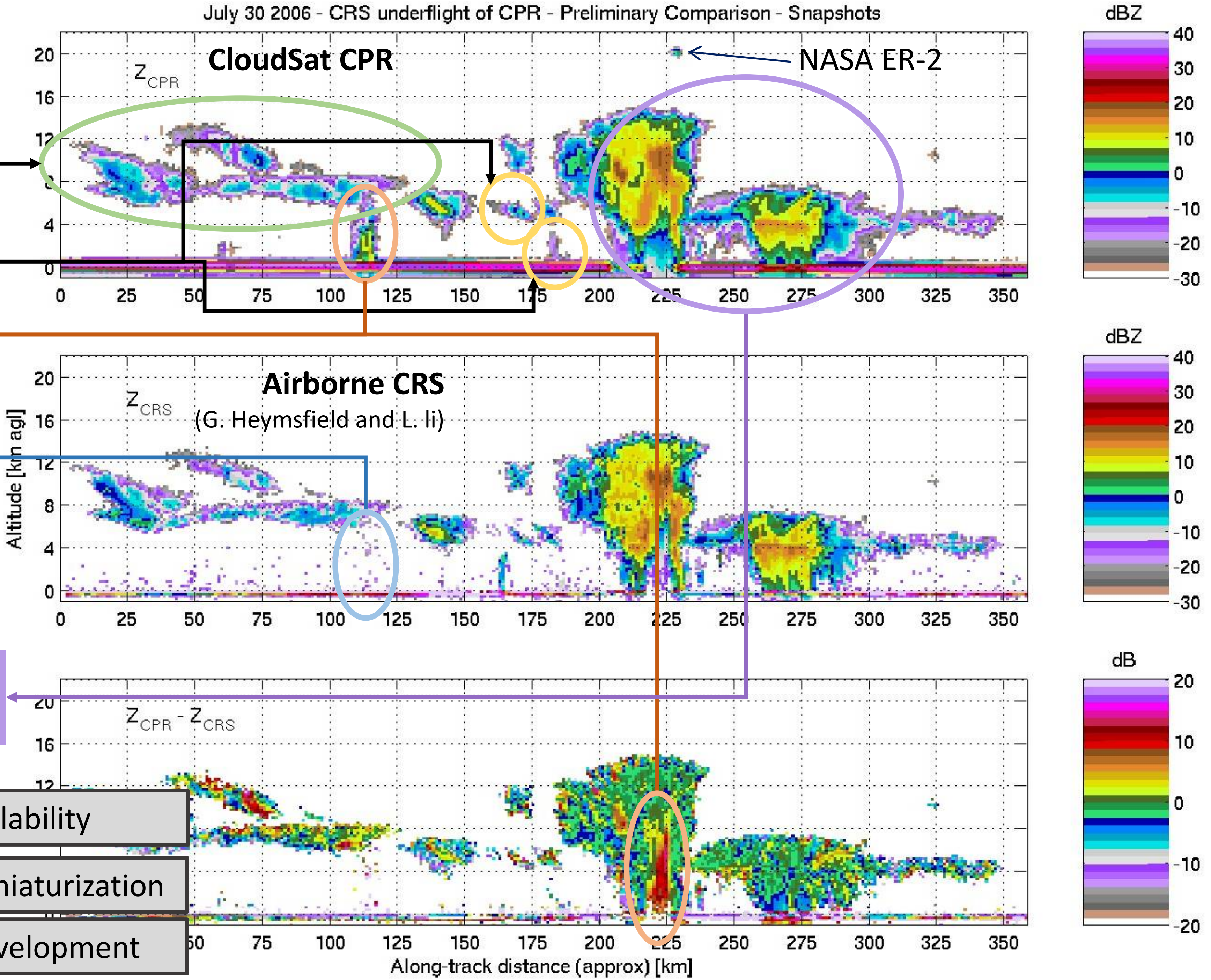
Demonstrated with CALIPSO value of W-band + LIDAR

Demonstrated usefulness of collocated, high resolution, coarsely calibrated Brightness Temperature measurements



CPR's legacy

(an oversimplified summary)



LIDAR ↔ SENSITIVITY

SURFACE CLUTTER ← VERT RES

NUBF ← HOR RES → Mult.Scatt.

3D structure & advection ← NADIR

Coverage ← NADIR

Radiometers and Imagers

Ambiguity in μPhys Retrievals ← W-band CoPol, noDoppler

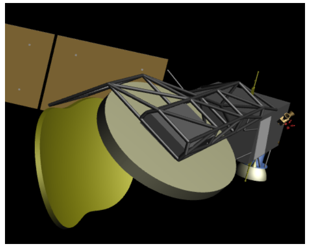
Ambiguity in retrievals of fluxes ← W-band CoPol, noDoppler

Limited : Antenna Size only	Scalability
Limited ← QOTL & EIK+HVPS	Miniaturization
Custom (pulsed, high power W)	Development

Cloud and Precipitation Radar Technology Development

at JPL from ACE (Decadal Survey ’07) to ACCP (Decadal Survey ‘17)

ACE did not occur as mission, but **was essential in focusing technology development efforts and in funding advancement of the state of the art in the US.** NASA Earth Science and Technology Office, JPL and GSFC funded technology development projects to enable the vision expressed in the DS’07.



ACERAD (IIP’09) — Demonstrate technologies to re-use the CloudSat-class solutions and meet the ACE requirments.

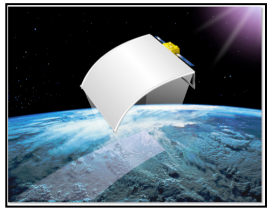
APR-3 (AITT’12) — Acquire Multi-Frequency, Doppler, Dual Polarization datasets to enable algorithm development and validation

RainCube
JPL R&TD, ACT, InVEST’15
- Demonstrate feasibility of very low cost Radar solution capable to contribute to the global sampling of diurnal cycle and to enable the dZ/dt measurement
- Demonstrate adoption of aggressive pulse compression and prediction of performance inclusive of Doppler effects
- Demonstrate ultra-compact radar architecture which can be reused also in higher performance systems

(EV Mission Concept)

airSWOT data (ACE SWG) — Demonstrate use of Displaced Phase Center Antenna for Distributed Targets to enable Doppler measurements with small radars

3CPR (IIP’13)

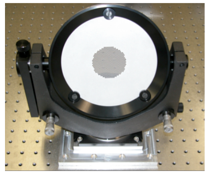


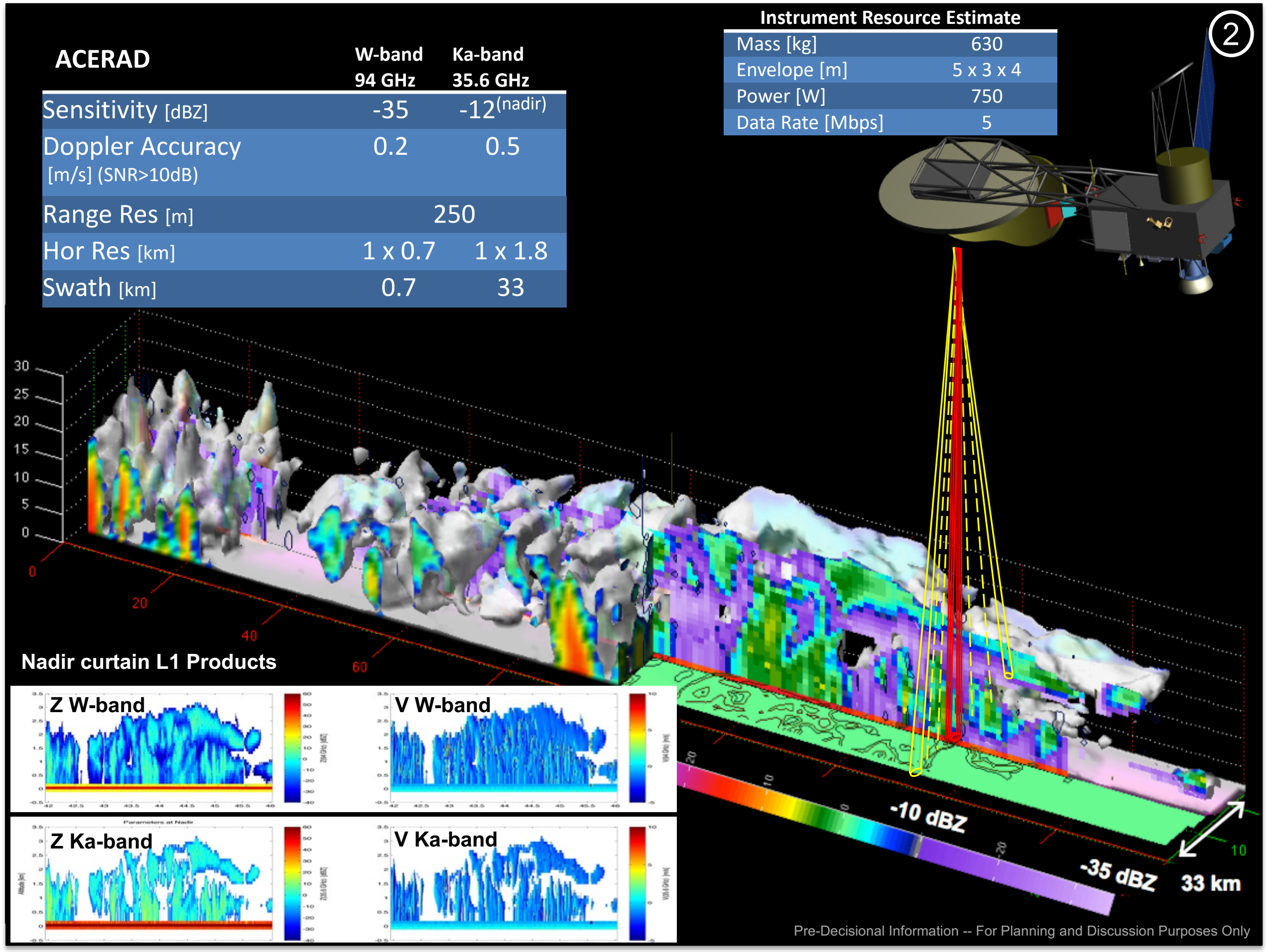
Enable W-band Electronic Scanning with an affordable technological solution and Ku, Ka and W-band Electronic Scanning with a single reflector

airMASTR (IIP’16) — Demonstrate (airborne prototype) the Integrated RainCube and 3CPR solutions in one extremely scalable instrument architecture (compatible with SmallSats and larger platforms)

ACERAD vs ACE Radar Requirements and Goals

- Dual Frequency Dual Pol Quasi Optical Transmission Line
- EIK at Ka and W-band, Short Pulse
- Dragonian Antenna Geometry (Ka scan, W nadir)
- Mature Technology, high efficiency
- High power density and high voltage, not scalable.





	PARAMETER	UNIT	REQUIREMENT	GOAL (#Priority)	ACERAD	Science Mnemonic
W-band, nadir	Min Det Sens	dBZ	-35	-40 (#3)	-35	EarthCARE level of detection.
	Doppler Acc	m/s	0.4	**0.2(#2)**	0.2	Precipitating/non-precipitating, sedimentation, cloud scale entrainment.
	Vert Res	m	250	**100 (#1)**	250	Melting layer, geometrically thin clouds, in-bin attenuation.
	Sfc Cltr max hgt	m	500	**250 (#1)**	400	Cloud base vs surface precipitation.
	Hor Res	km	1 x 1	--	0.7 x 1	CRM scale.
	Polarimetry (LDR)		--	YES (#5)	YES	Mixed phase and multiple scattering.
W-band, off-nadir	Swath Width	km	--	≥2 (#4)	--	Convective cell resolution (10km), radiometer footprint (25km). Ka-radar footprint (2km)
	Min Det Sens	dBZ	--	-20	--	All light precipitation, most large particle clouds.
	Doppler Acc	m/s	--	1	--	
	Vert Res	m	--	250	--	
	Hor Res	km	--	1 x 1	--	
Ka-band, nadir	Min Det Sens	dBZ	-10	**-20 (#2)**	-12	Most (all) light precipitation, some (all) large particle clouds.
	Doppler Acc	m/s	1	0.5 (#3)	0.5	Rain/no rain, convection.
	Vert Res	m	250	100 (#4)	250	
	Sfc Cltr max hgt	m	500	250 (#4)	400	
	Hor Res	km	2 x 2	1 x 1	1.8 x 1	CRM scale / matched beam.
	Polarimetry (LDR)		--	YES (#5)	YES	
Ka-band, off-nadir	Swath Width		--	**>25 (#1)**	33	Convective cell resolution, radiometer footprint. 100km would achieve meso-scale features.
	Min Det Sens	dBZ	--	-10	-10	
	Doppler Acc	m/s	--	1	1	
	Vert Res	m	--	250	250	
	Hor Res	km	--	2 x 2	1.8 x 1	

Requirement not met
Requirement met
Goal met

Airborne Precipitation and Cloud Radar 3rd Generation

Jet Propulsion Laboratory
California Institute of Technology

APR-3 supports the science of GPM, CloudSat, ACE, CCP, RainCube, SWOT.

ACR (1996)

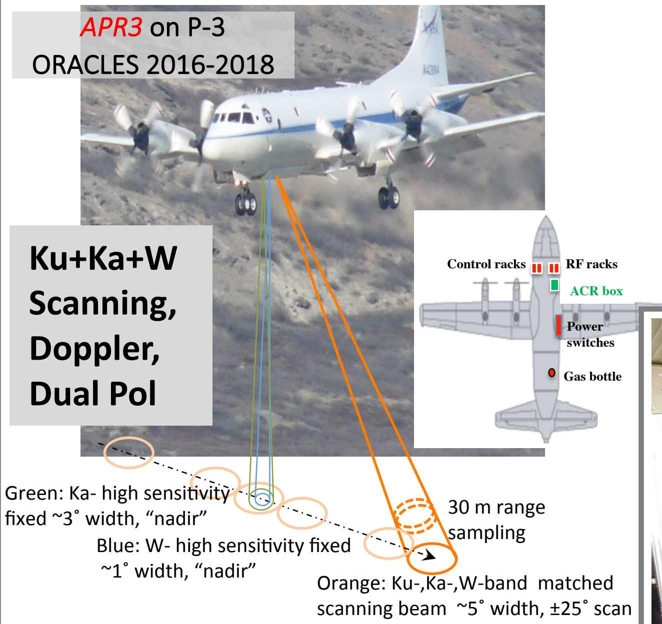
- W-band 94.9 GHz
- Doppler & Dual Pol

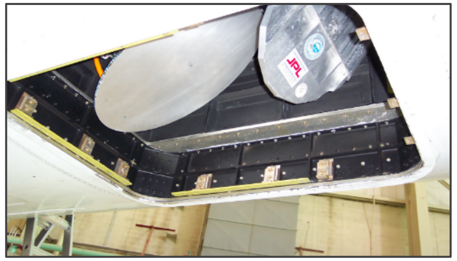
\+

APR2 (2001)

- Ku- 13.4 GHz & Ka- 35.6 GHz
- Scanning: +/- 25° cross track
- Doppler & Depolarization

APR-3





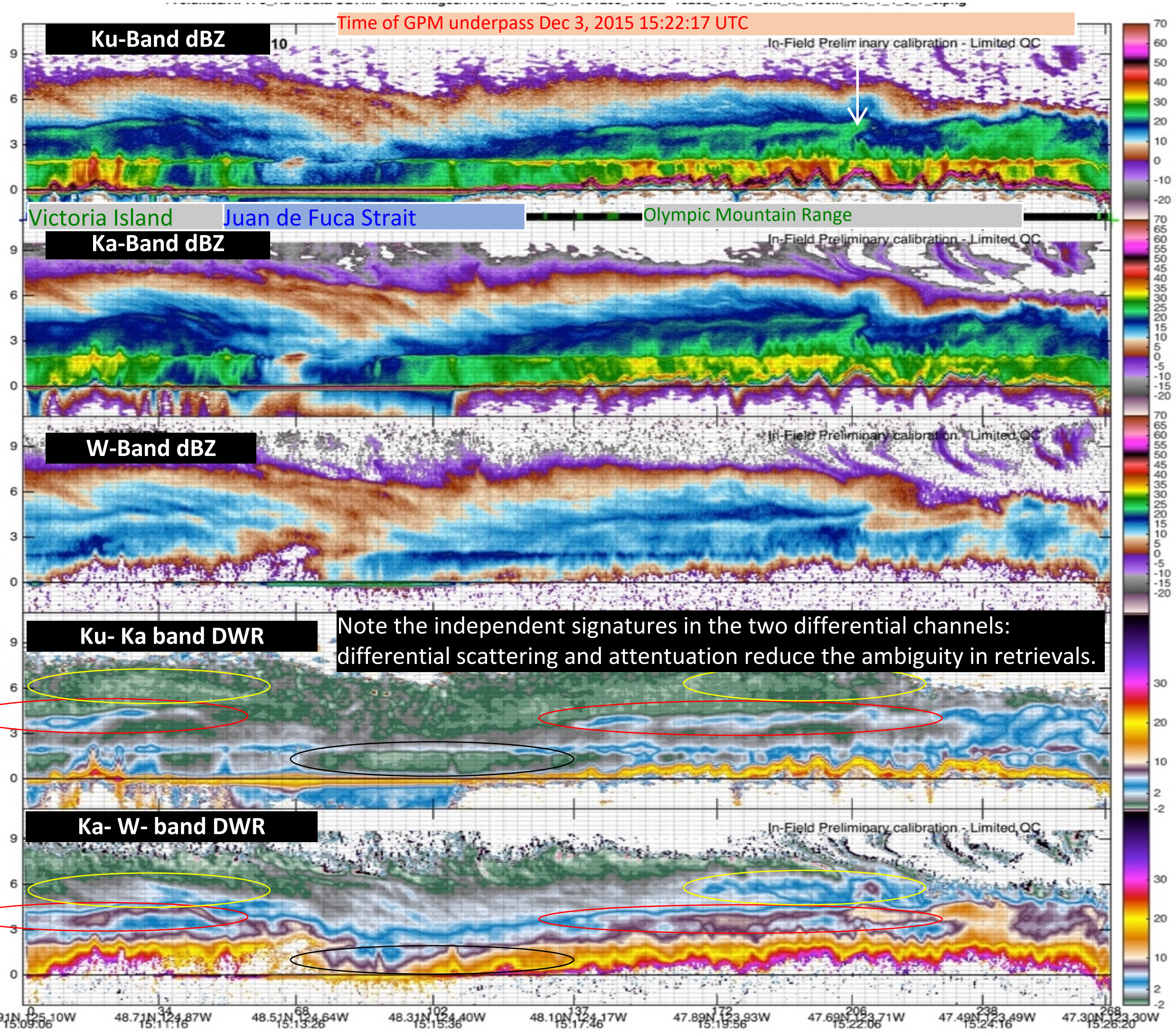
Ku-/Ka-W-band mechanically scanning antenna on NASA DC-8
(OLYMPEX/RADEX'15, radome removed)

Last Deployment : **ORACLES**, **Sao Tome**, **Sept. '18**

Next up: **CAMP2Ex**, **Philippines**, **Sept. '19**

2018 Digital Subsystem by RSS
Replaces two separate and obsolete digital systems for increased signal generation and processing capability.

2018 W-band RF
Completely new low power chains and new housing. ~50% mass & volume reduction. Interfaces with new digital.



Exmple of Multi-frequency Radar Observations of Clouds and Precipitation
being used by GPM, ORACLES, RainCube, EarthCARE, ACE and CCP study groups

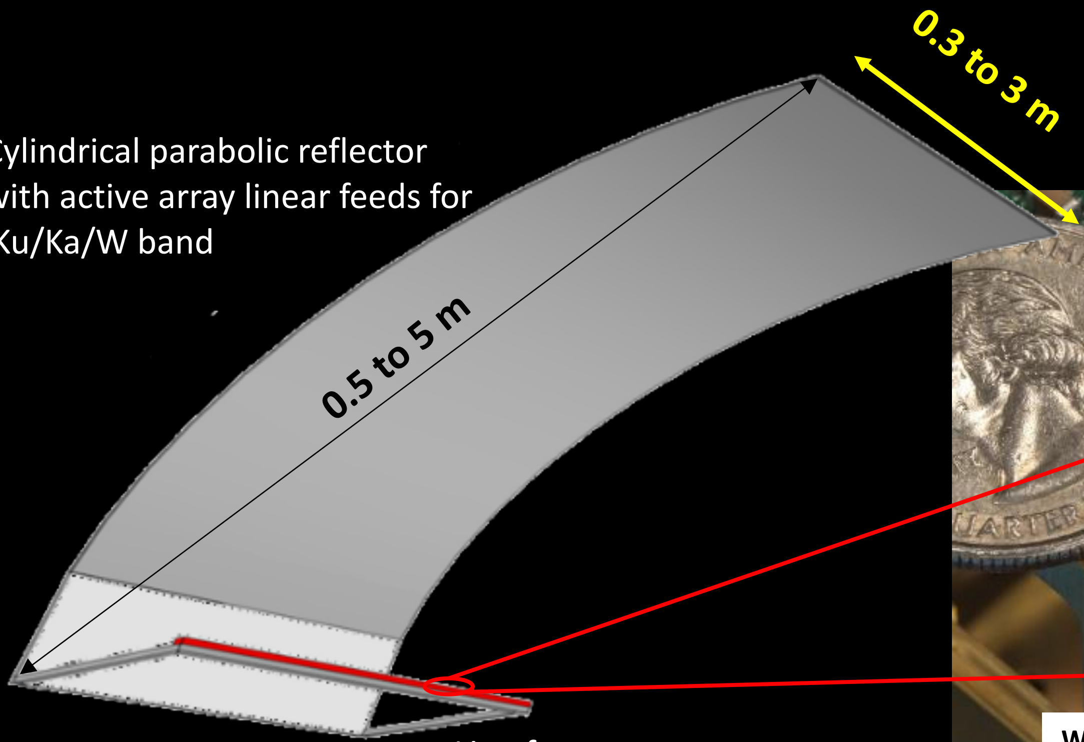
3-band Cloud and Precipitation Radar (3CPR)

(includes also C2D2 which is the Ka/W band version of 3CPR)

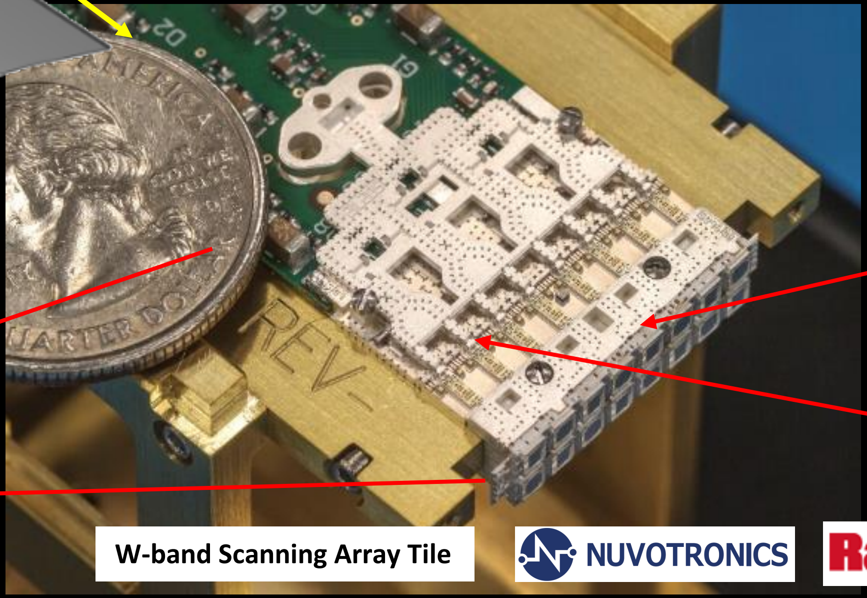
- NASA ESTO Instrument Incubator Program (2015-2018. PI: G. Sadowy).
- **Single Cylindrical parabolic reflector** provides high gain and cross-track scanning capability at Ku-band (13.4 GHz), Ka-band (35.6 GHz) and W-band (94 GHz)
- **Active Line Array Feed (ALAF)** consists of a line of Scanning Array Tiles : identical modules that include 8 interlaced Tx and Rx PolyStrata™ radiative elements and GaN – SiGe MMICs.
  - Tiles are assembled in ~30 cm subarrays,configurable with N-subarrays.

- **Eliminates** need for:
  - High Voltage Power Supplies
  - High Power Transmit Receive Switches
  - Localized high E field density in constrained power combiners
  - Lossy waveguides
- **1-D ALAF** has numerous advantages:
  - 3rd dimension available for close stacking and thermal dissipation
  - Scales linearly with cross track size
  - Along track size can be modulated independently

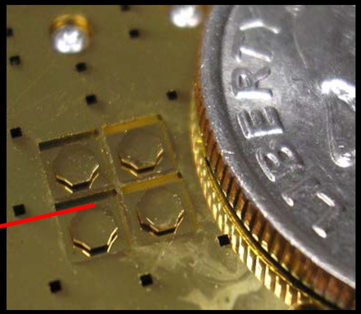
Cylindrical parabolic reflector with active array linear feeds for Ku/Ka/W band



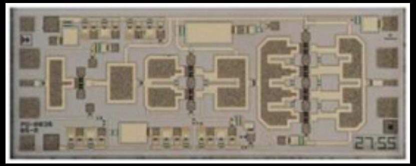
Line focus



NUVOTRONICS Raytheon



3 mm

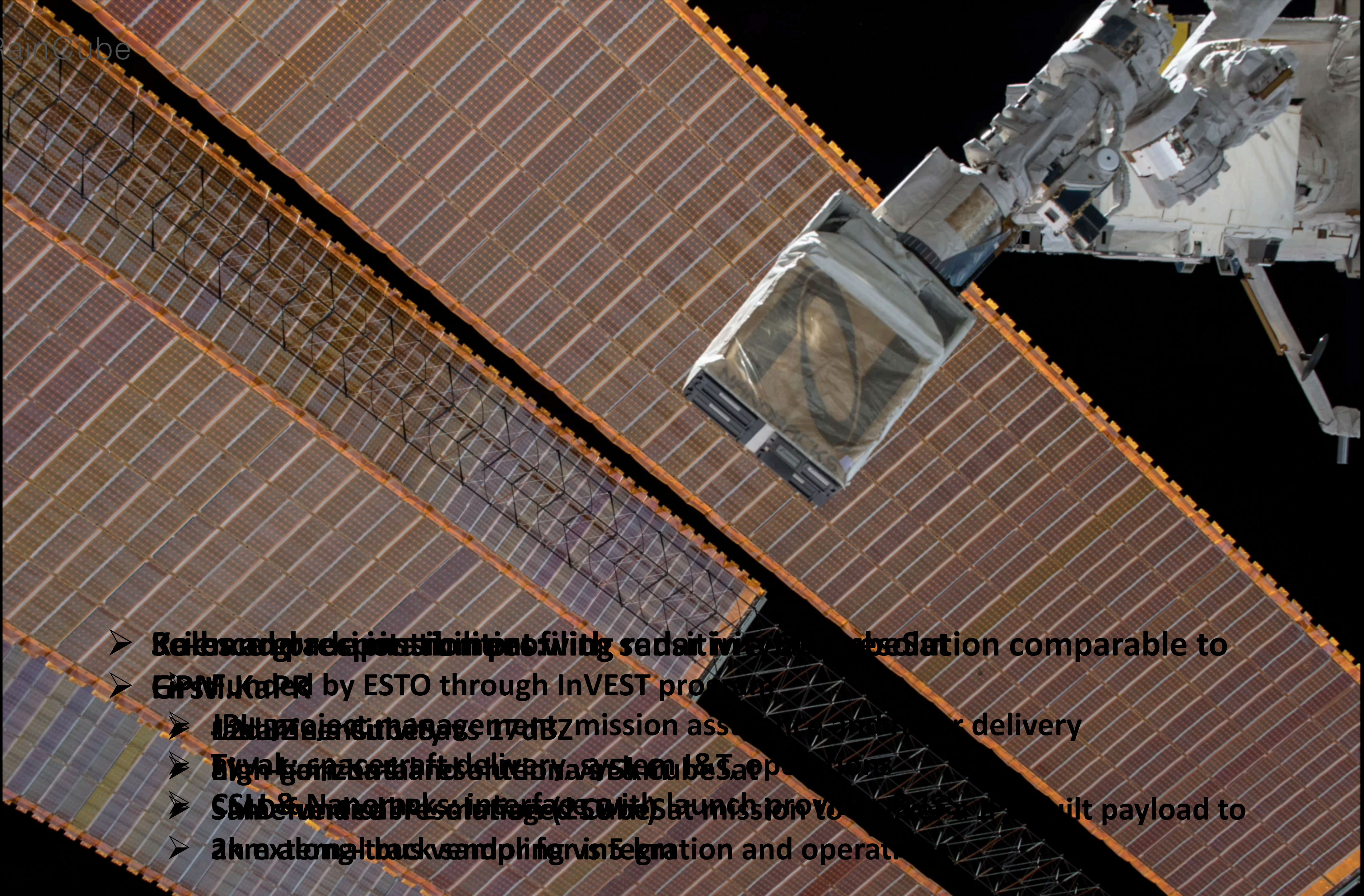


1 mm

GaN T & R MMICs

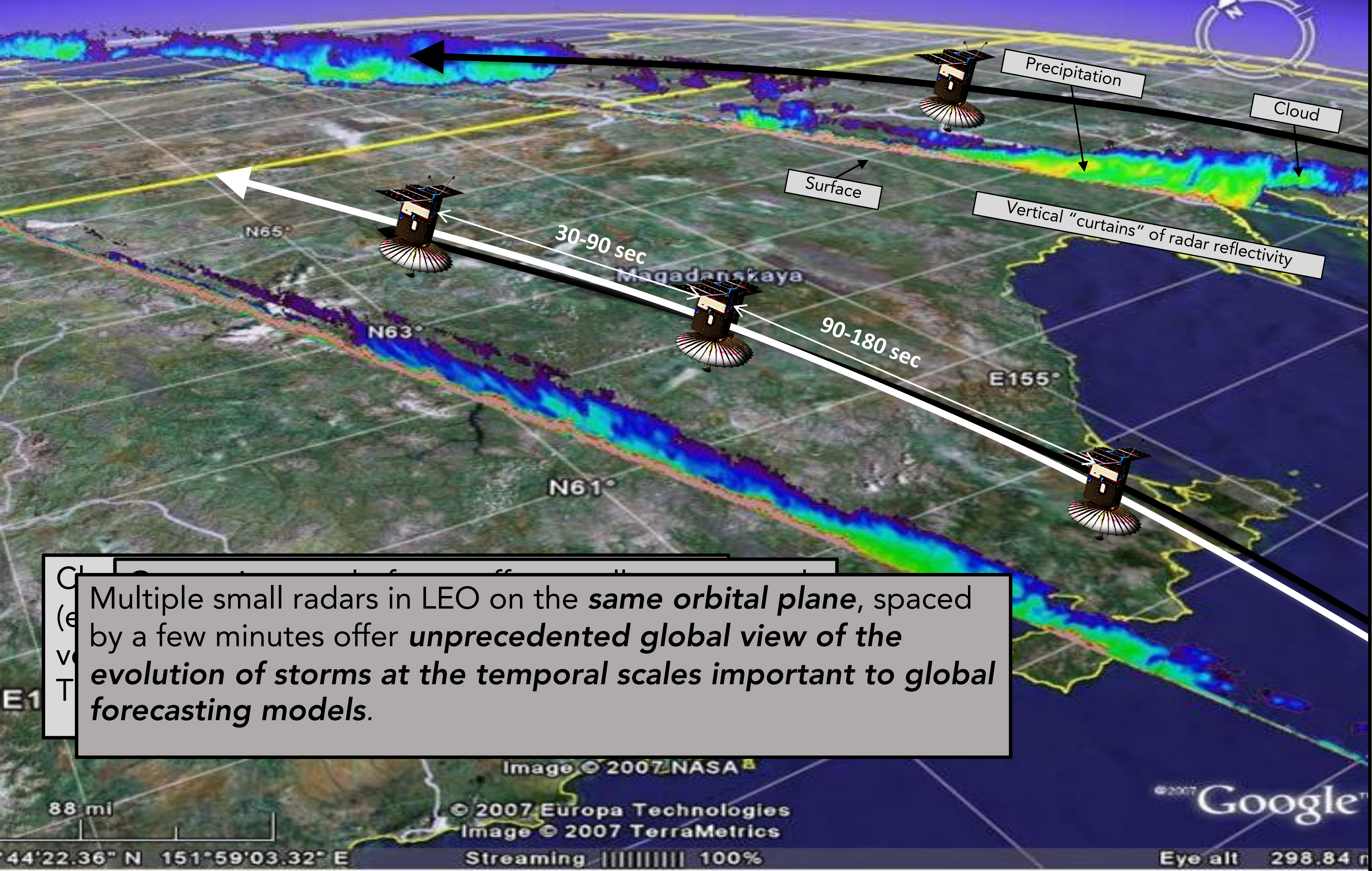

NASA
Jet Propulsion Laboratory
California Institute of Technology
RainCube Project Team
February, 2017
RainCube
RADAR FOR RAIN PROFILING
CubeSats
RainCube
ASTERIA
EXIT
RAINCUBE
CSLI
NASA/JPL
TYVAK

RainCube



- … comparable to GPM KaPR
- … by ESTO through InVEST pro…
  - JPL: project management, mission ass… delivery
  - Tyvak: spacecraft delivery, system I&T, ope…
  - CSLI & Nanoracks: interface with launch prov…
  - … payload to … integration and operat…

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.

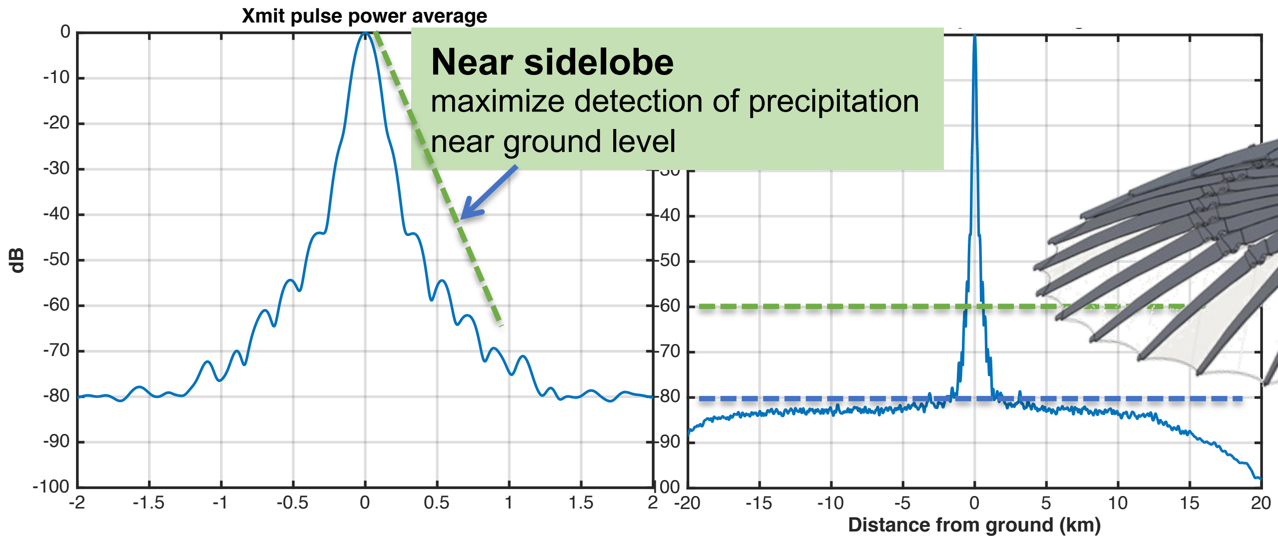
First challenge was posed with 1U and 3U (no-go). Then the 6U became an option…

System Architecture

RainCube

Radar Electronics & Antenna Reqs. (4U)

Req't Name	Requirement	Measured
Sensitivity @400km	20dBZ	11.0dBZ
Horizontal resolution @400km	10km	7.9 km
Nadir Data Window	0-18 km	-3 to 20 km
Vertical resolution	250m	250m
Downlink data rate (in transmit)	50 kbps	49.57 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 / 1.1dB	>39dBm
Antenna gain	42 dB	42.6 dB
Antenna beamwidth	1.2 deg	1.13 deg

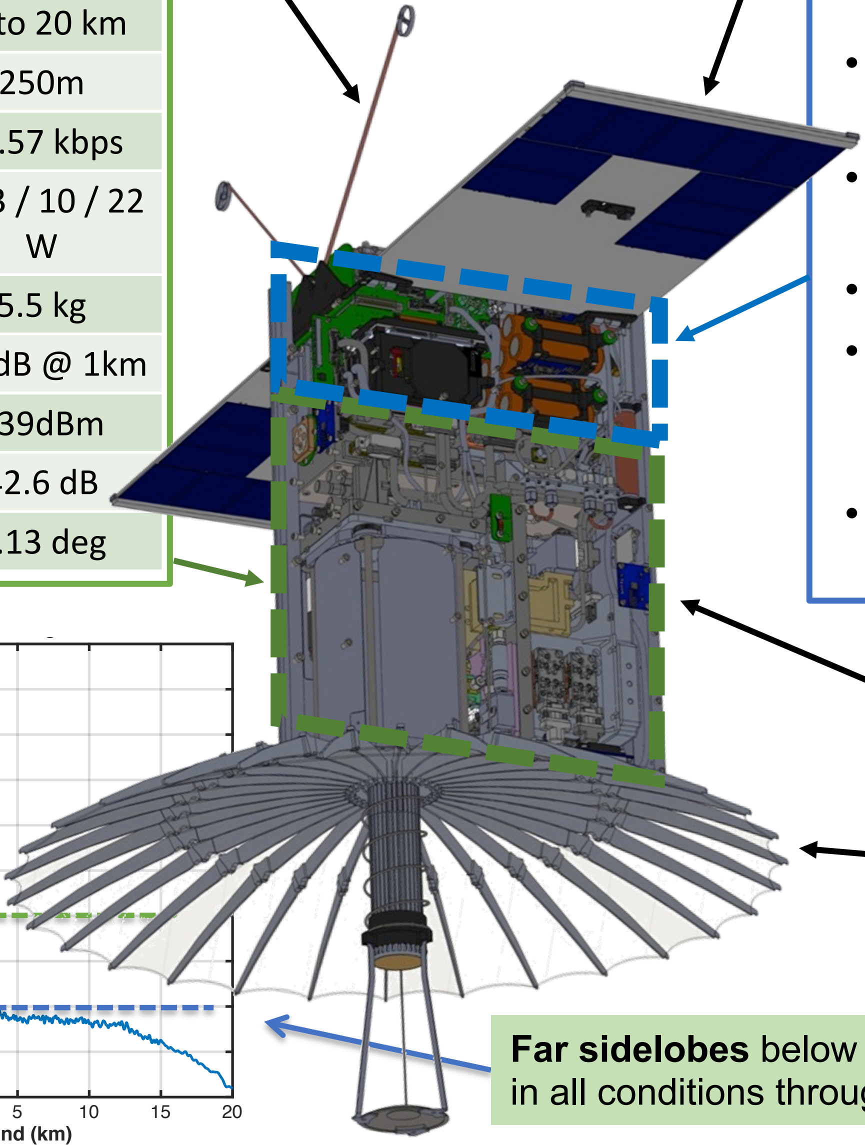


Deployable UHF Antenna

Deployable Solar Arrays

Bus Reqs. (2U)

- Provide 35 W for payload power in transmit mode
- Maintain a 25% radar duty cycle
- 12.1 Gb/week of payload data
- Maintain payload temperatures (-5C to +50C operational)
- GPS provides on-board altitude to radar

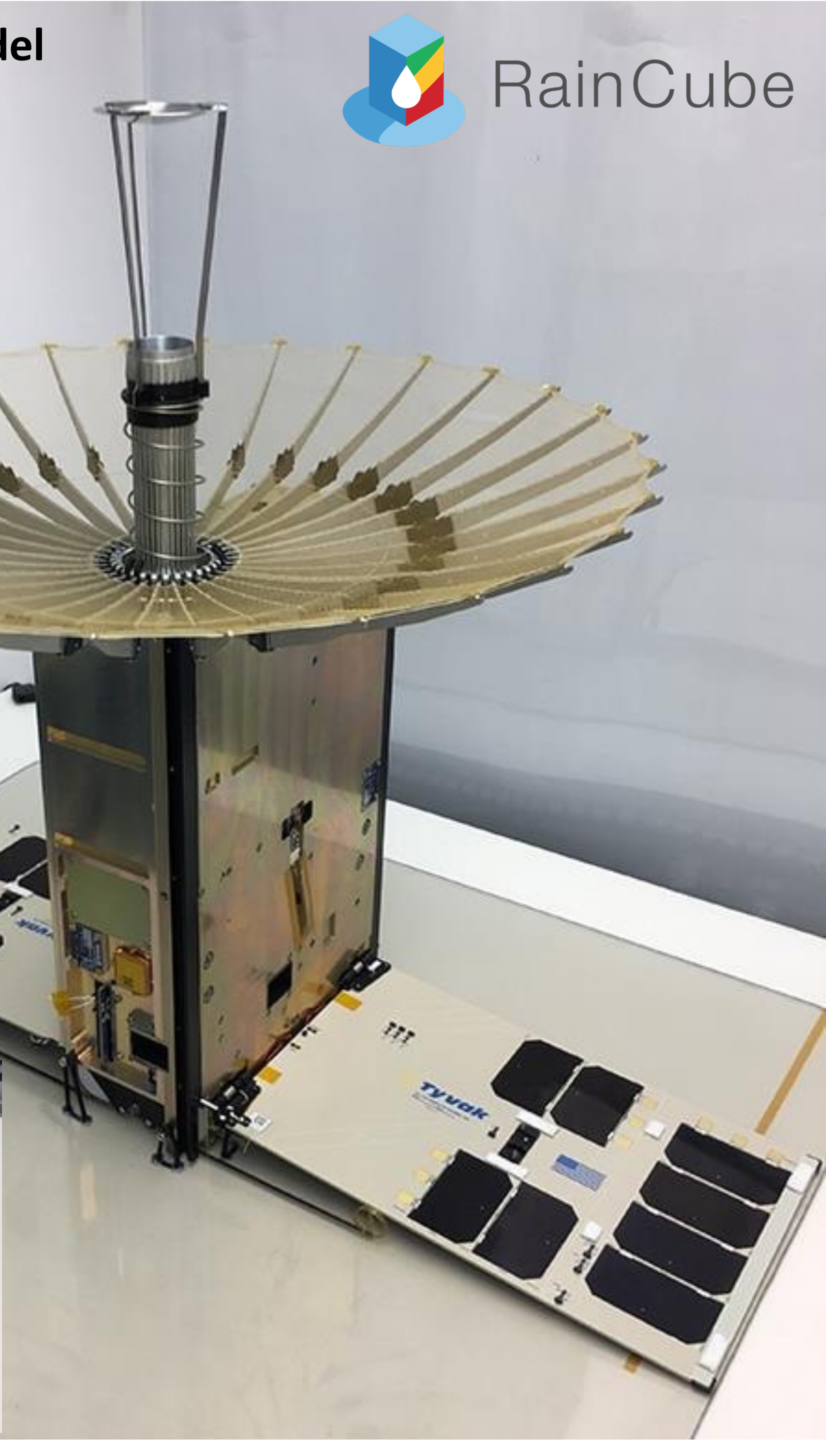


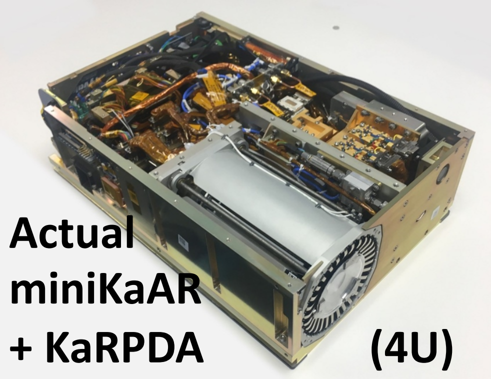
S-Band Patch Antenna & Transmitter

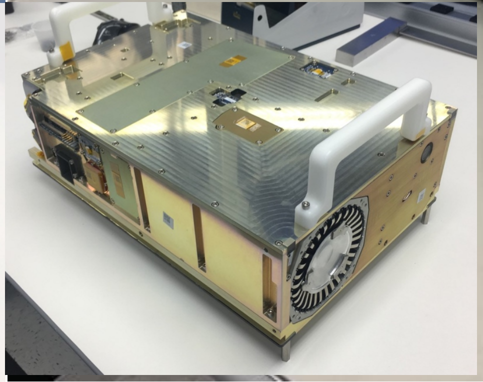
Deployable 0.5 m KaRPDA Radar Antenna

Far sidelobes below -60dB for clutter-free detection in all conditions throughout the troposphere

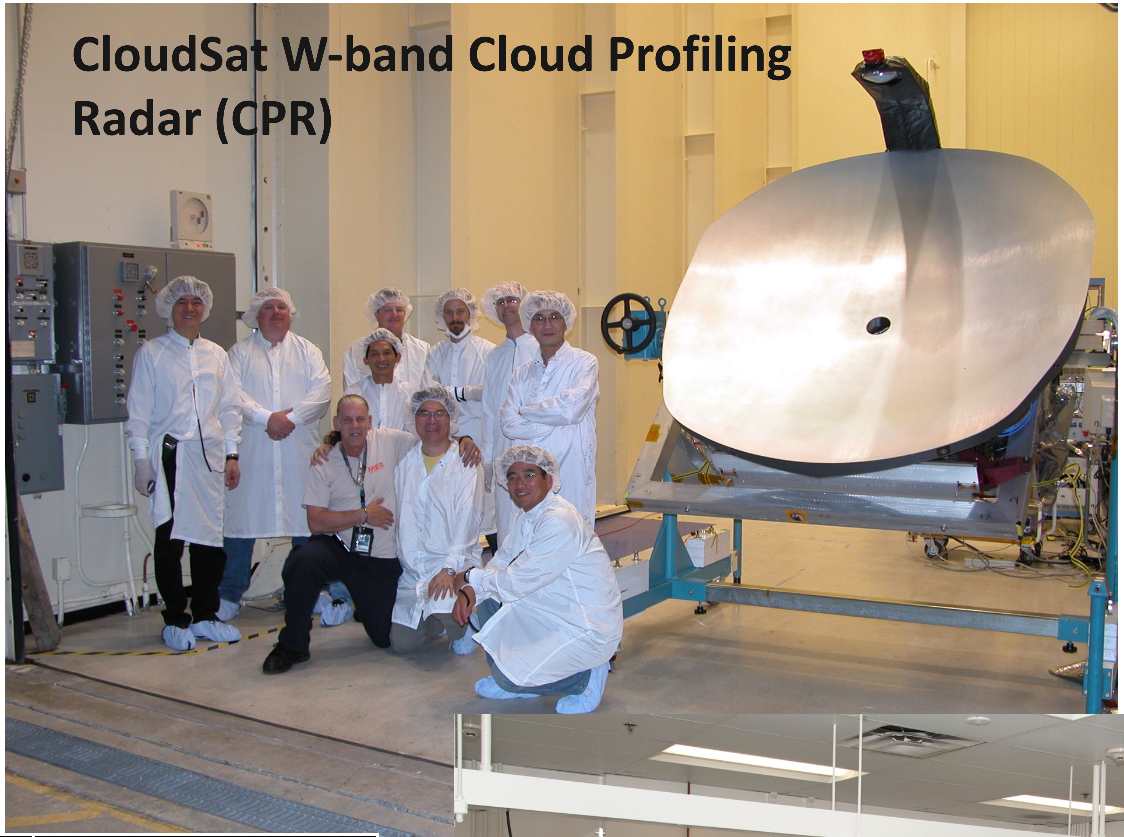

Radar in a Cubesat Concept

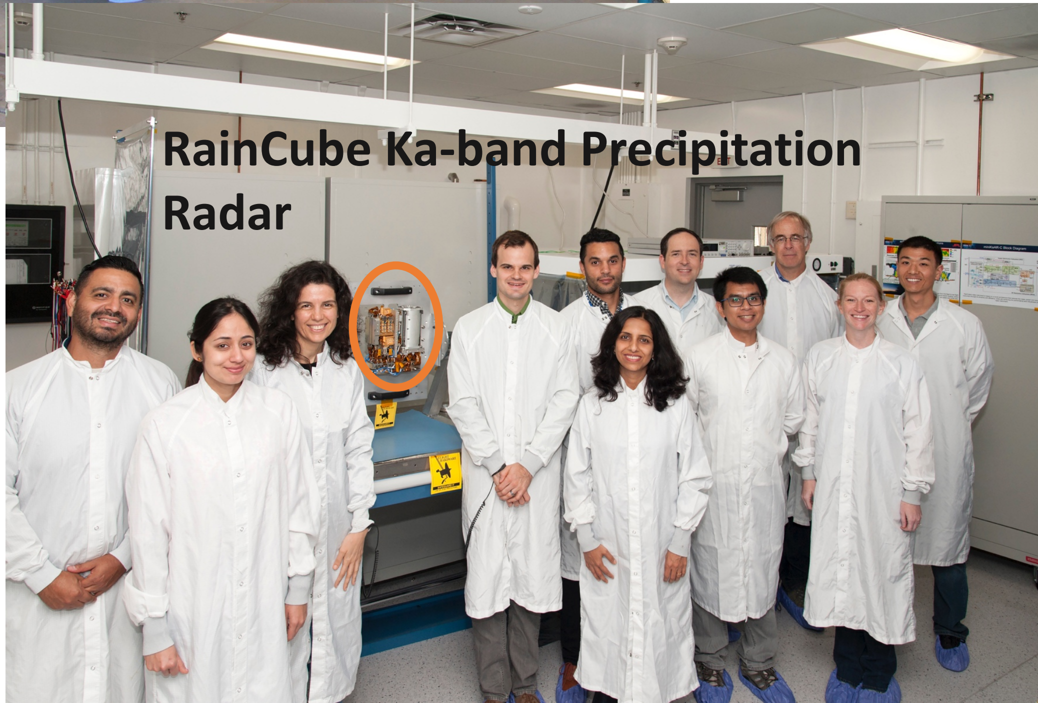

RainCube Flight Model
RainCube
Tyvak


Actual
miniKaAR
+ KaRPDA
(4U)



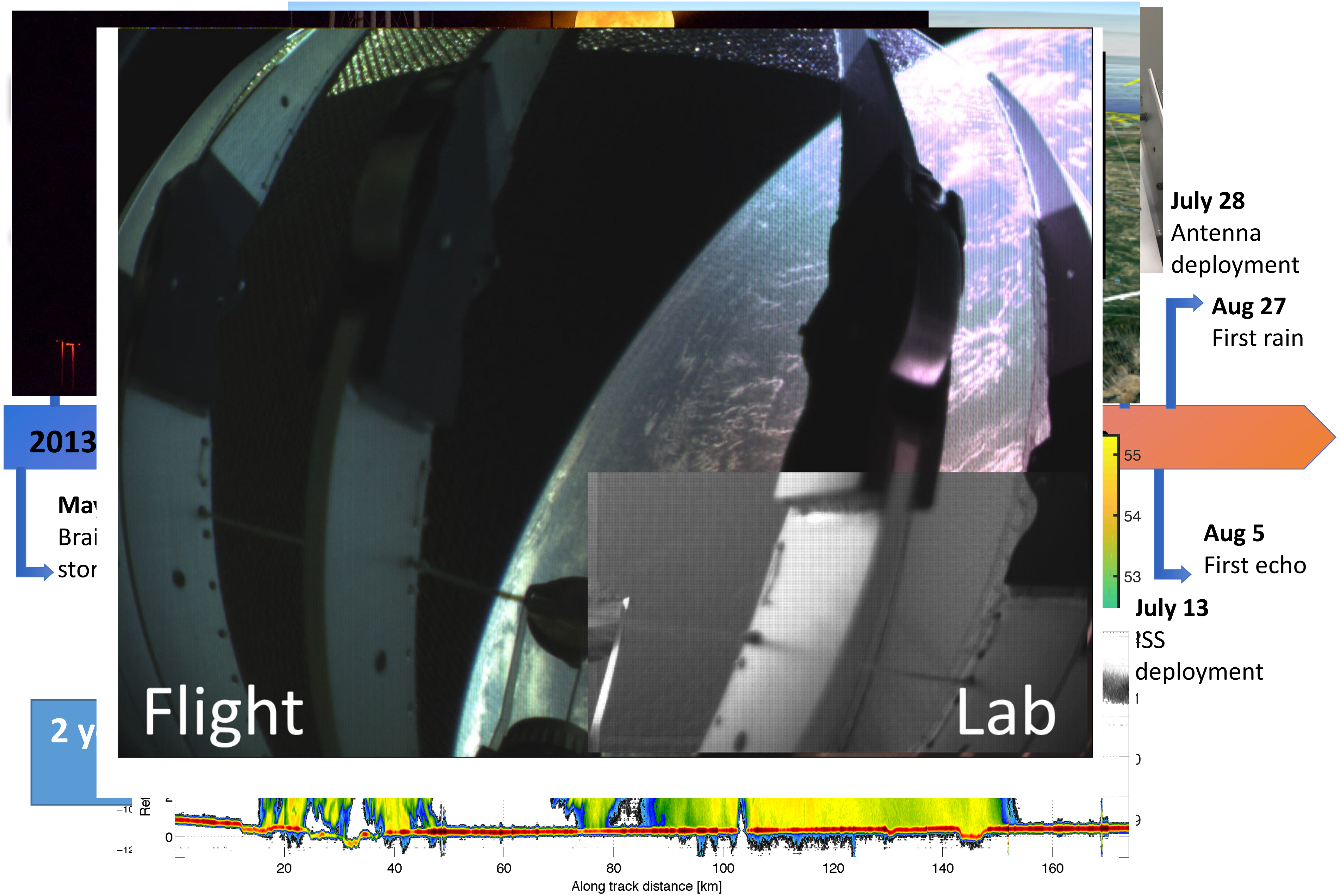
How small is RainCube. . .



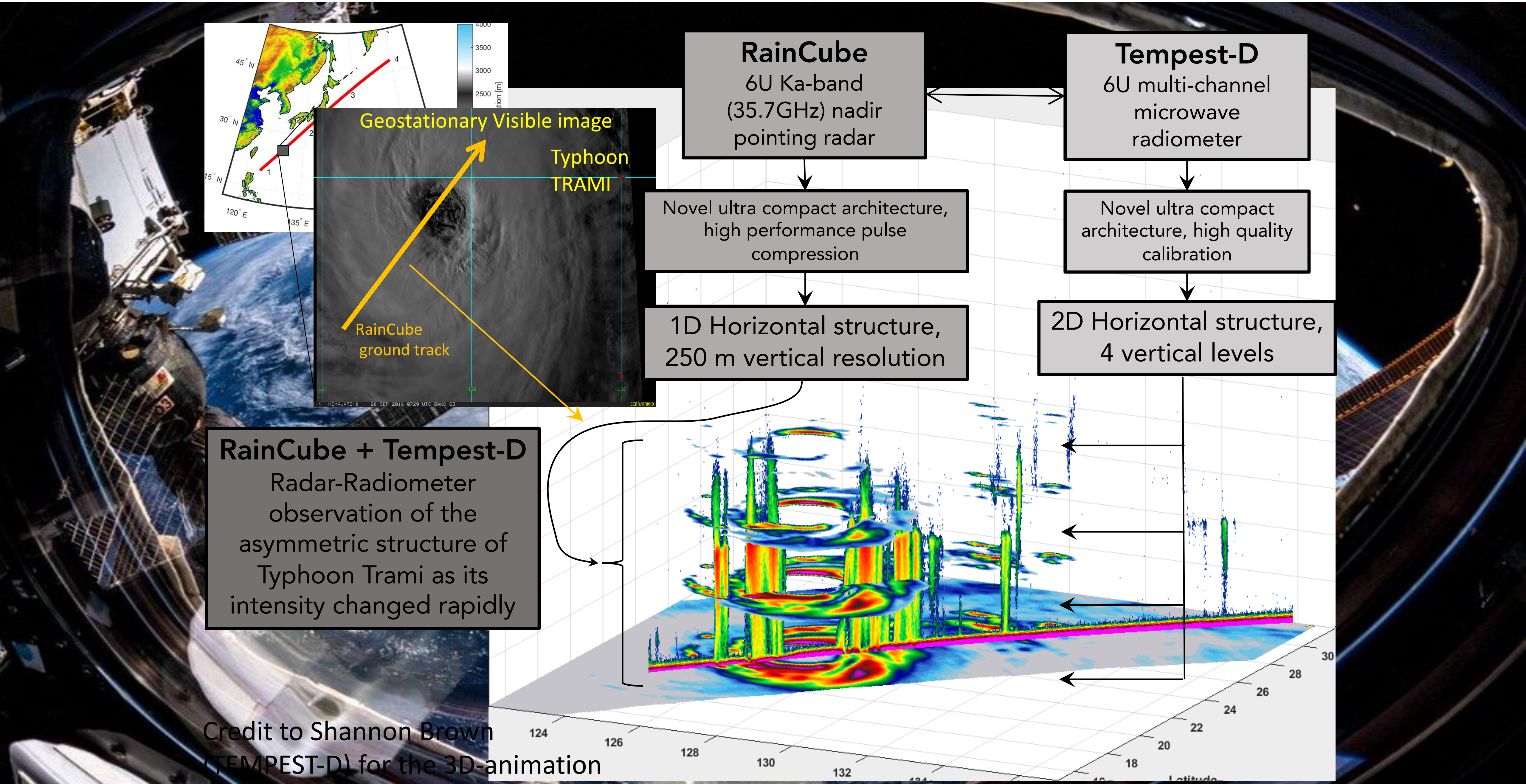


	CPR	KaPR	RainCube
Mass [Kg]	260	336	7
Power [W]	300	344	22
Volume [U]	4,356	1,210	4
Class	C	C	Tech demo
Frequency	W-band	Ka-band	Ka-band
Scanning	No	Yes	No
Sensitivity	-30 dBZ	+17 dBZ	+12 dBZ

RainCube Story : from TRL 2 to TRL 7 in 6 years



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

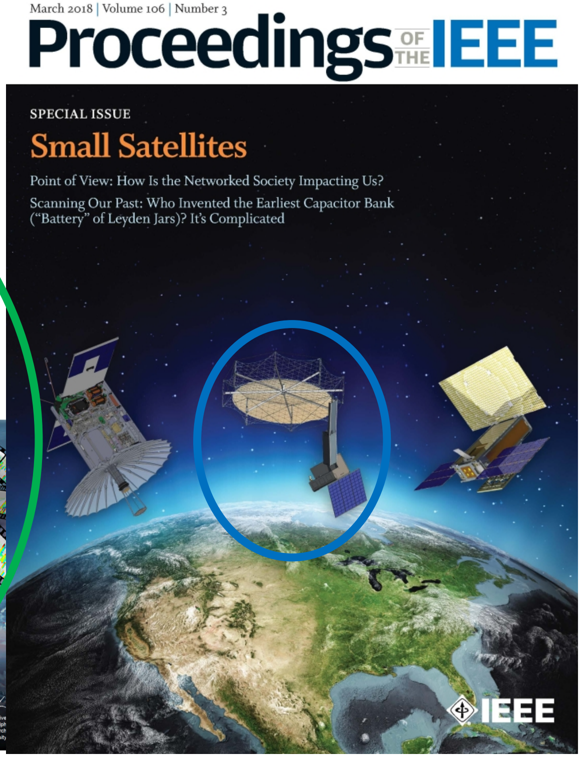


RainCube : What's next ?

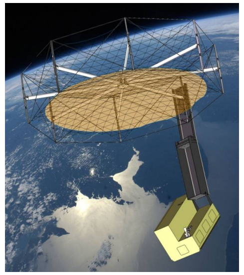
Pre-Decisional Information -- For Planning and Discussion Purposes Only

- Constellation of RainCube's "as is"
  - Analyzing the current dataset to demonstrate the potential and the limitations of the current system in addressing science questions

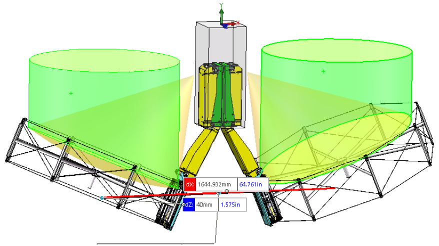
- Constellation with improved antennas & electronics
  - To address a larger set of science questions
  - Development of **technologies** and of **mission concepts** is ongoing
  - **Extension to W and G-band for cloud & precip.**
  - **DPCA** for Doppler, **Larger Size** for improved resolution and sensitivity, **multi-feed** for scanning



RainCube 1.0 m in 12 U



RainCube 1.0 m DPCA in 24U



TENDEG

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

- 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

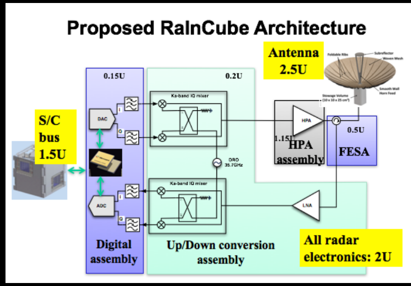
Multi-Application SmallSat Tri-band Radar (MASTR)

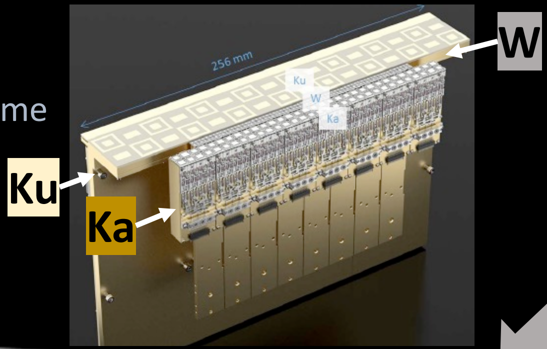
Pre-Decisional Information -- For Planning and Discussion Purposes Only

miniKaAR's back end
reduce # of parts
Simple

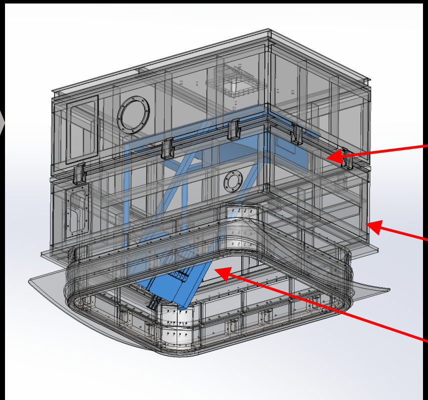
+

3CPR antenna scheme
scanning
Agile





Airborne Prototype
airMASTR
ESTO IIP – 2017/19 – PI: M. Sanchez-Barbetty



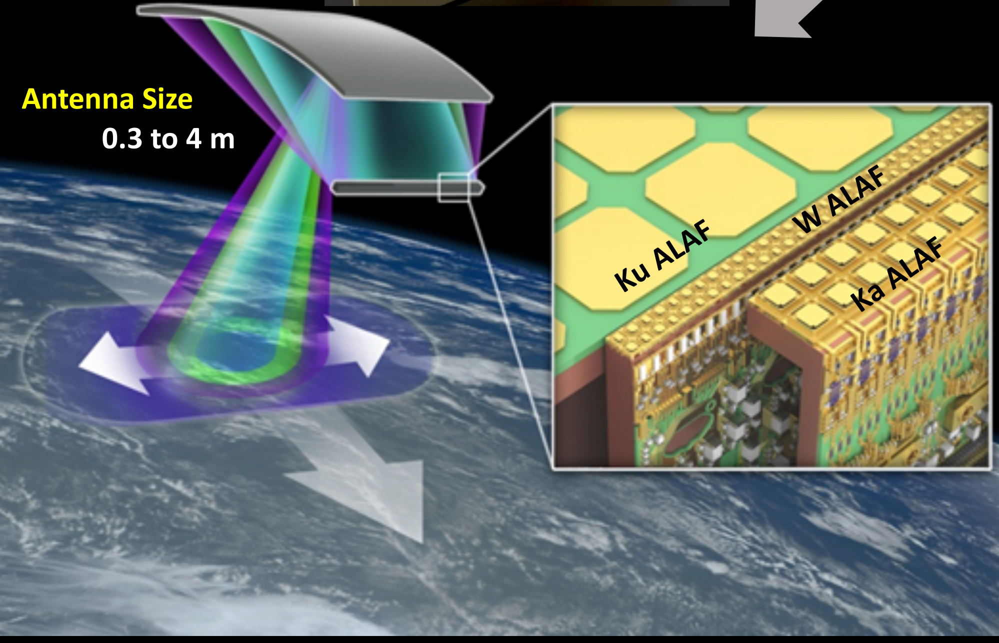
Planned first flight Spring 2020

Reflector (3CPR EM)

NASA DC-8 Pressure box (same position as APR-3)

Triple Frequency Phased Array Feed (30 x 4 x 20 cm)

Low Bandwdith Mode: **high sensitivity** (Clouds and Precipitation, Scatterometry)
High Bandwdith Mode: **high range res** (Altimetry, Snow Depth, Sea Ice freeboard)
Long / Short Pulse: Compatible with either, multi PRI for staggered Doppler and adaptive vertical coverage, programmable
Swath Width: Swath width baselined at ~20 km based on ACCP preliminary SATM, but electronics can scan to 5˚ (W-band) or more (Ku and Ka).



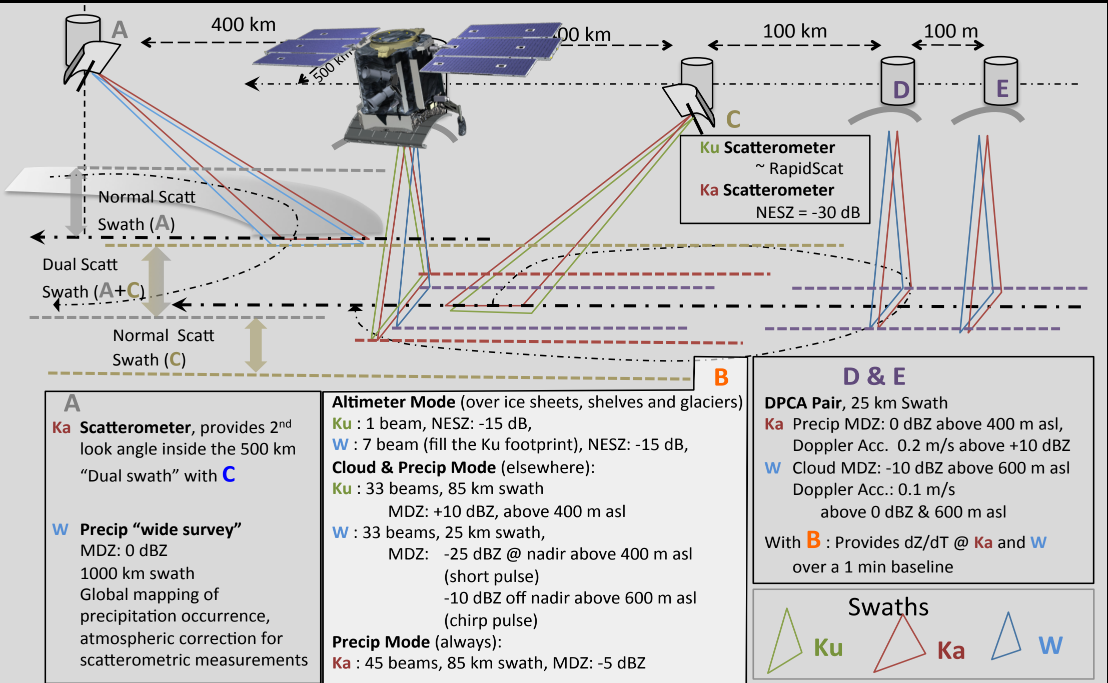
ULTRA SCALABLE

Minimum size: compact back end can be scaled down to RainCube size

Any or all bands: Each of the 3 bands can be activated independently, or not even be integrated

X-Track size: Line feed array composed of N subarrays of 0.3 m each for manufacturability

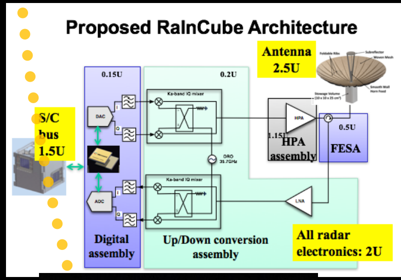
Along Track size: Simple 2D GO Design for Reflector based on Gain, Resolution and Doppler Requirements. Doesn't affect electronics.



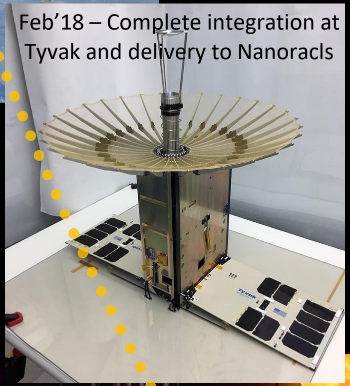
Precipitation and Cloud Radars for Small Satellites

Jet Propulsion Laboratory
California Institute of Technology

2013 – Initial Concept: Ka-band profiling radar to fit in a 6U spacecraft
High Gain Ultra Compact deployable antenna
Novel Radar Architecture
High Performance Pulse Compression



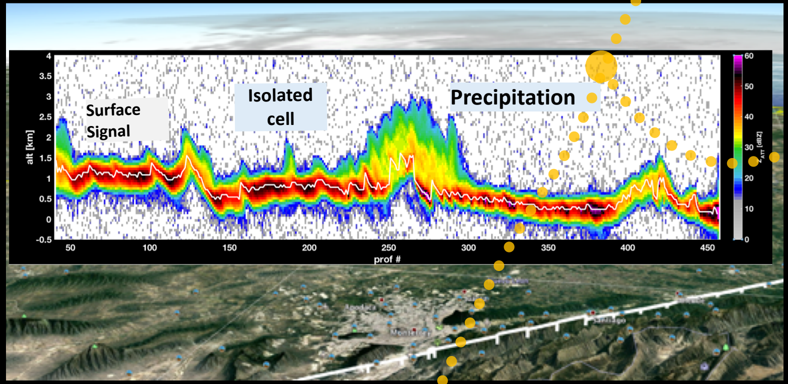
ESTO InVEST'15
PI: E. Peral

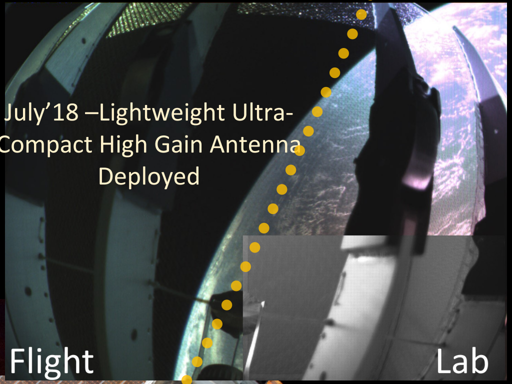


Feb'18 – Complete integration at Tyvak and delivery to Nanoracks

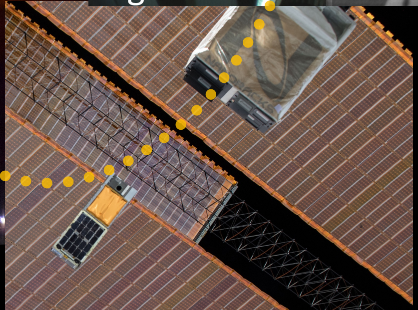
May'18 –Launch from Wallops Flight Facility

Aug'18 -First vertical curtain of Precipitation from RainCube





July'18 –Lightweight Ultra-Compact High Gain Antenna Deployed

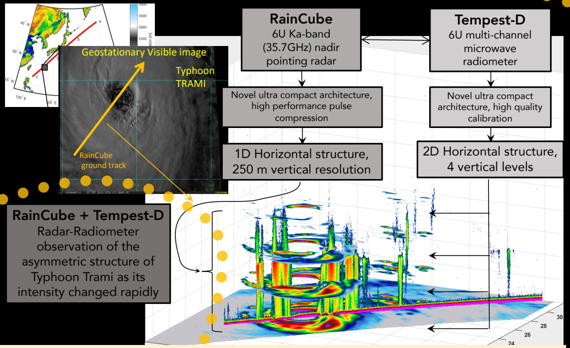


July'18 –Deployment from ISS NanoRacks

RainCube & MASTR enable concepts of constellations of Small Satellites with Active and Passive microwave instruments (*)

RainCube back end

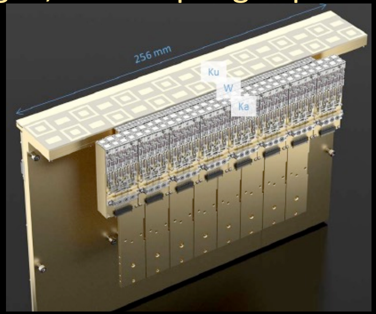
Digital and Up-Down RF Conversion
reduce # of parts, simple



Sept'18 – Combined observations of Typhoon TRAMI with TEMPEST-D (passive mm-wave)

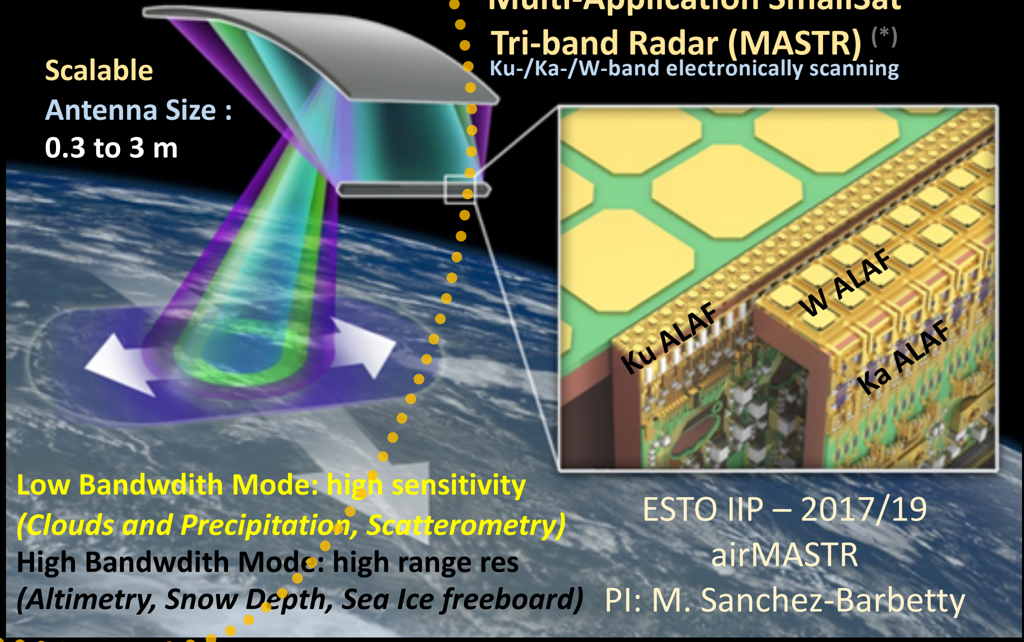
ACE 3CPR front-end (*)

singly-curved parabolic antenna and line feed array electronic cross-track scanning at Ku-/Ka-/and W-band
Agile, 3D sampling capability



Multi-Application SmallSat Tri-band Radar (MASTR) (*)

Ku-/Ka-/W-band electronically scanning



Scalable Antenna Size : 0.3 to 3 m

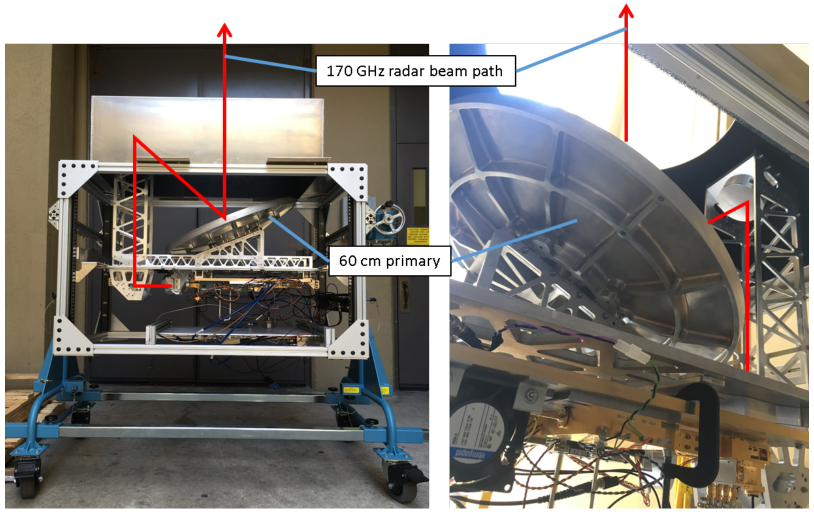
Low Bandwdith Mode: high sensitivity
(Clouds and Precipitation, Scatterometry)
High Bandwdith Mode: high range res
(Altimetry, Snow Depth, Sea Ice freeboard)

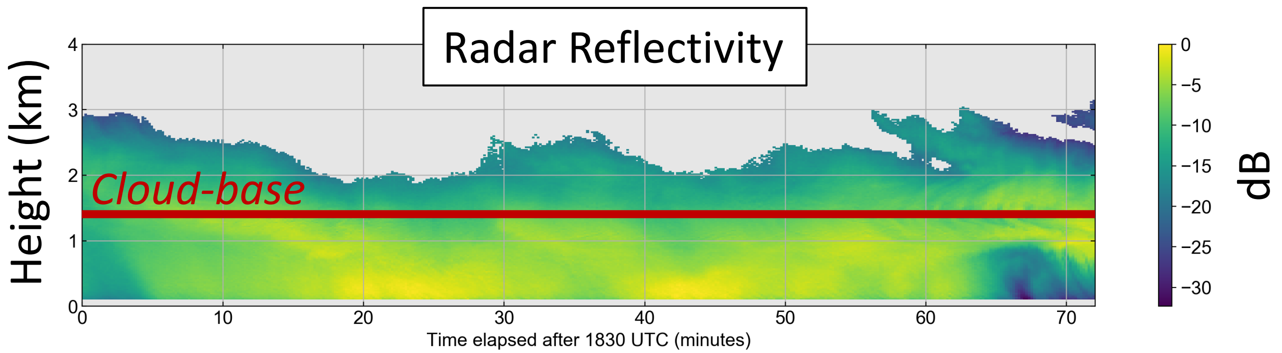
ESTO IIP – 2017/19
airMASTR
PI: M. Sanchez-Barbetty

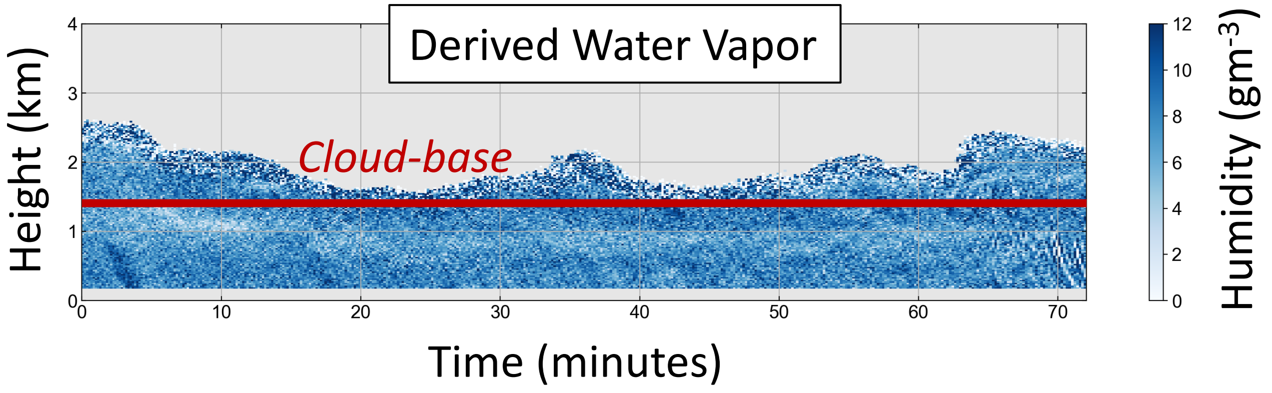
(*) = Pre-Decisional Information -- For Planning and Discussion Purposes Only

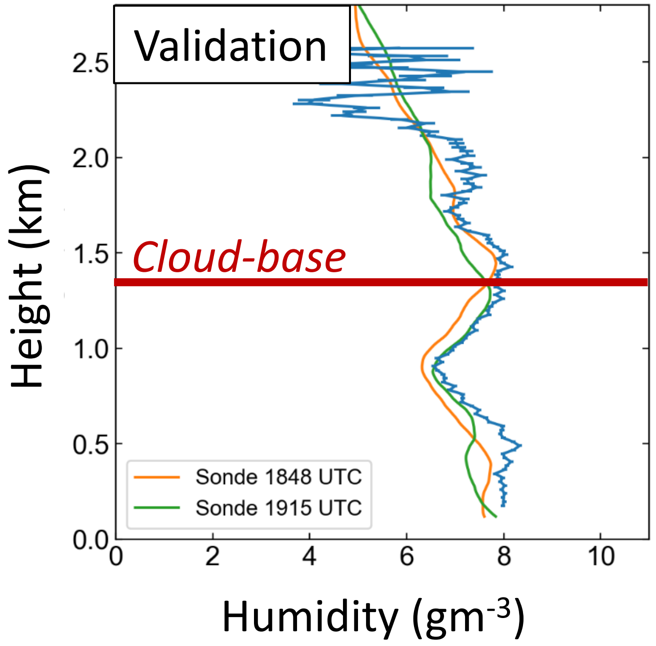
Vapor In-Cloud Profiling Radar (VIPR)

- ESTO funded (IIP-16) G-band (~170 GHz) differential absorption radar
- **First-ever** approach to remotely sense **water-vapor in-cloud/precipitation**
- Validation below shows **RMSE < 10%** @200 m vertical resolution
- Frequencies tuned to **planetary boundary layer** but can be extended to upper atmosphere





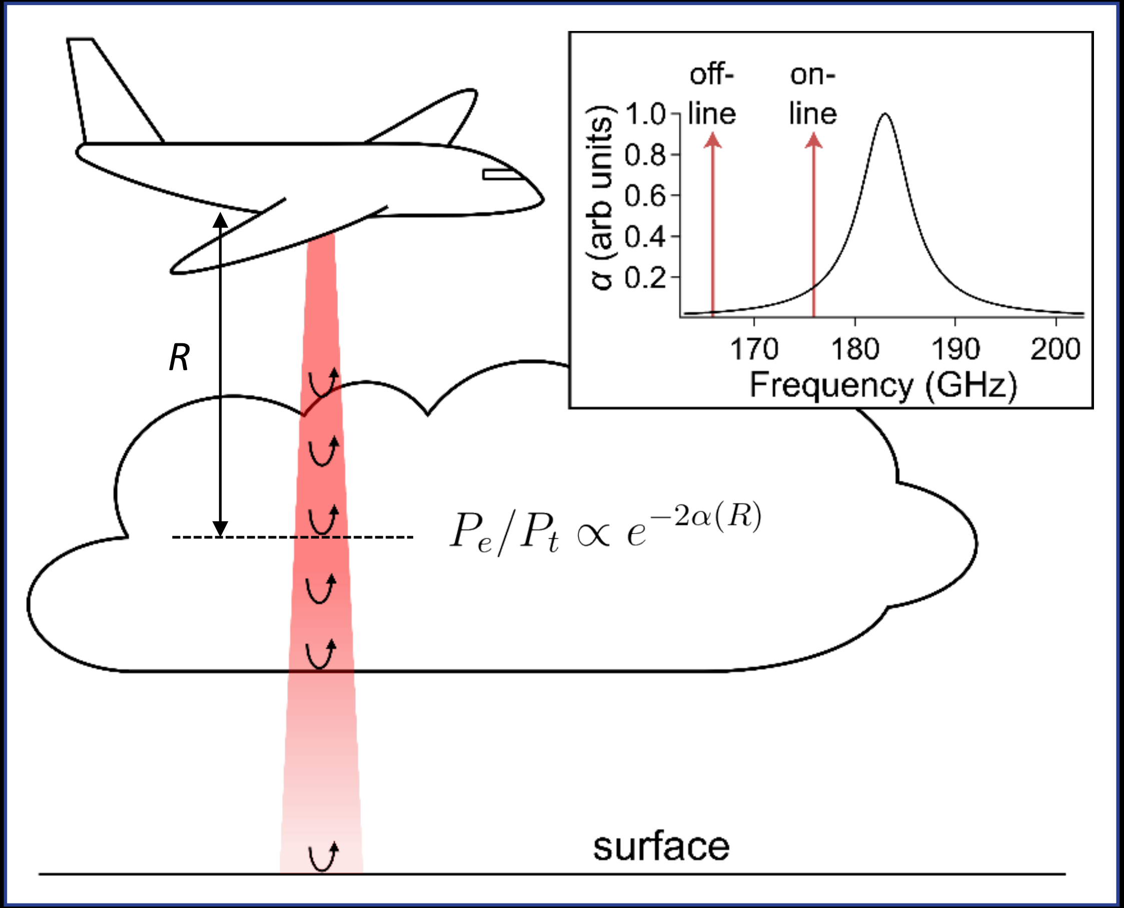




Thank you

Vapor In-cloud Profiling Radar (VIPR)

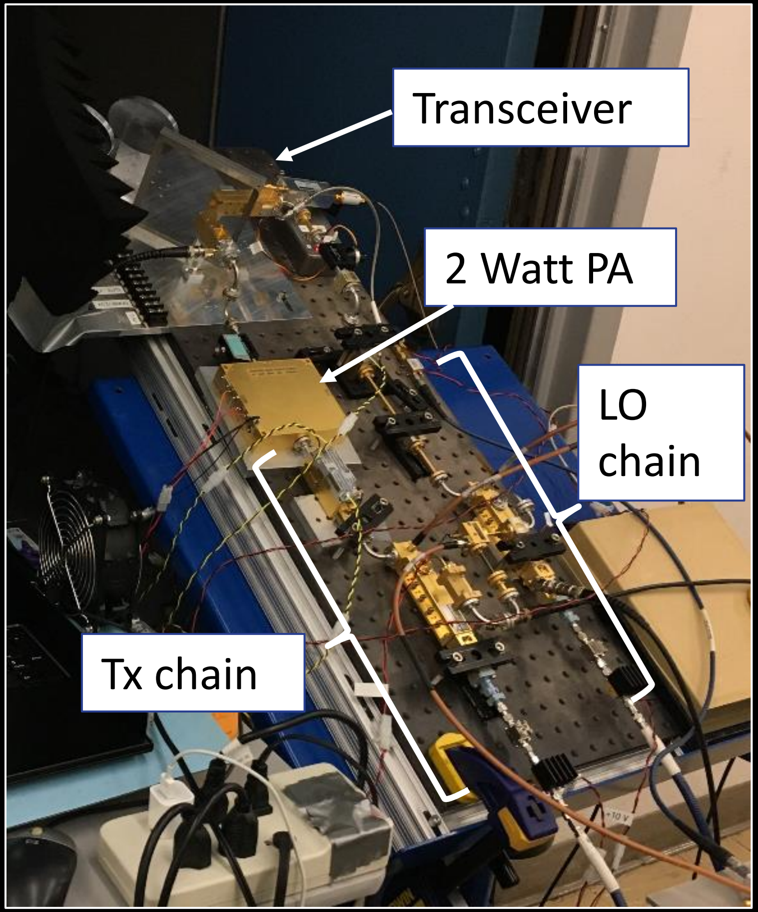
- Use widely tunable transmitter with ~500 mW transmit over ~5% bandwidth
- *Important assumption*: Reflectivity and extinction from hydrometeors independent of frequency
- Frequency dependence from hardware cancels out (common mode)
- Airborne platform demo
  → Surface echoes (total column water)

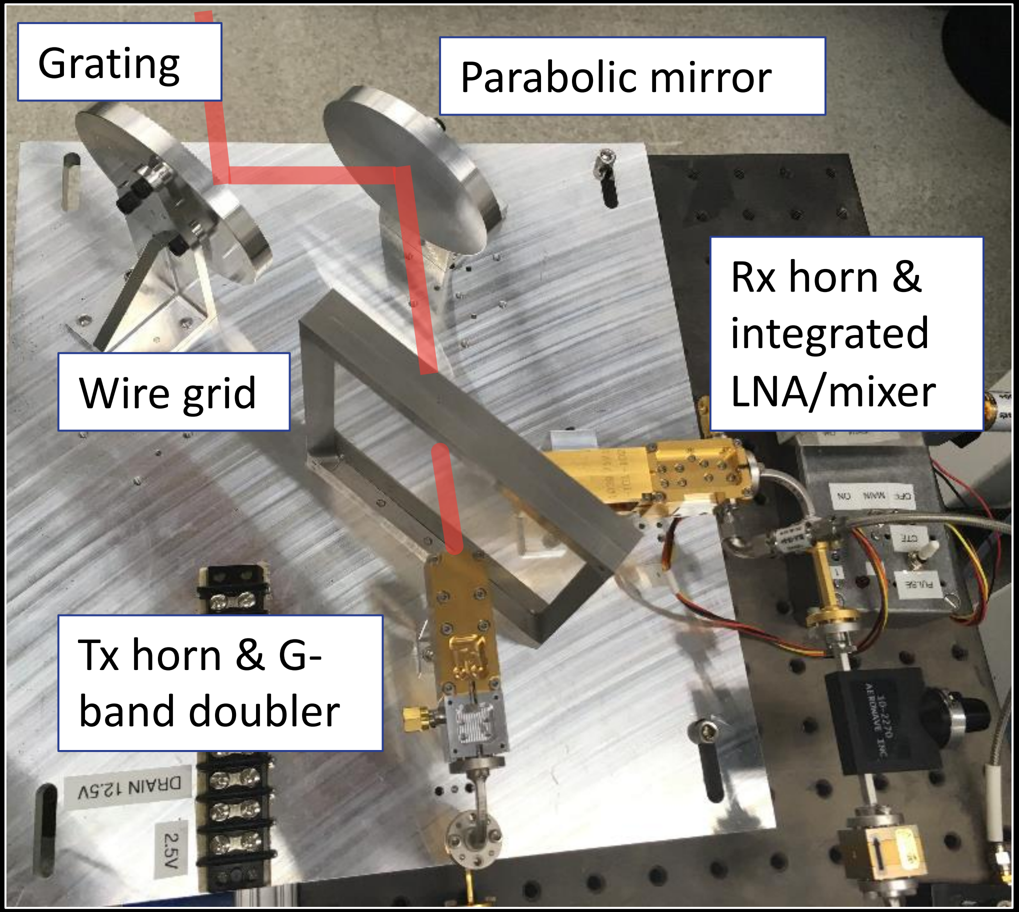


Vapor In-cloud Profiling Radar (VIPR)

FMCW radar is appropriate for low-power source components

Challenging but possible to achieve necessary T/R isolation

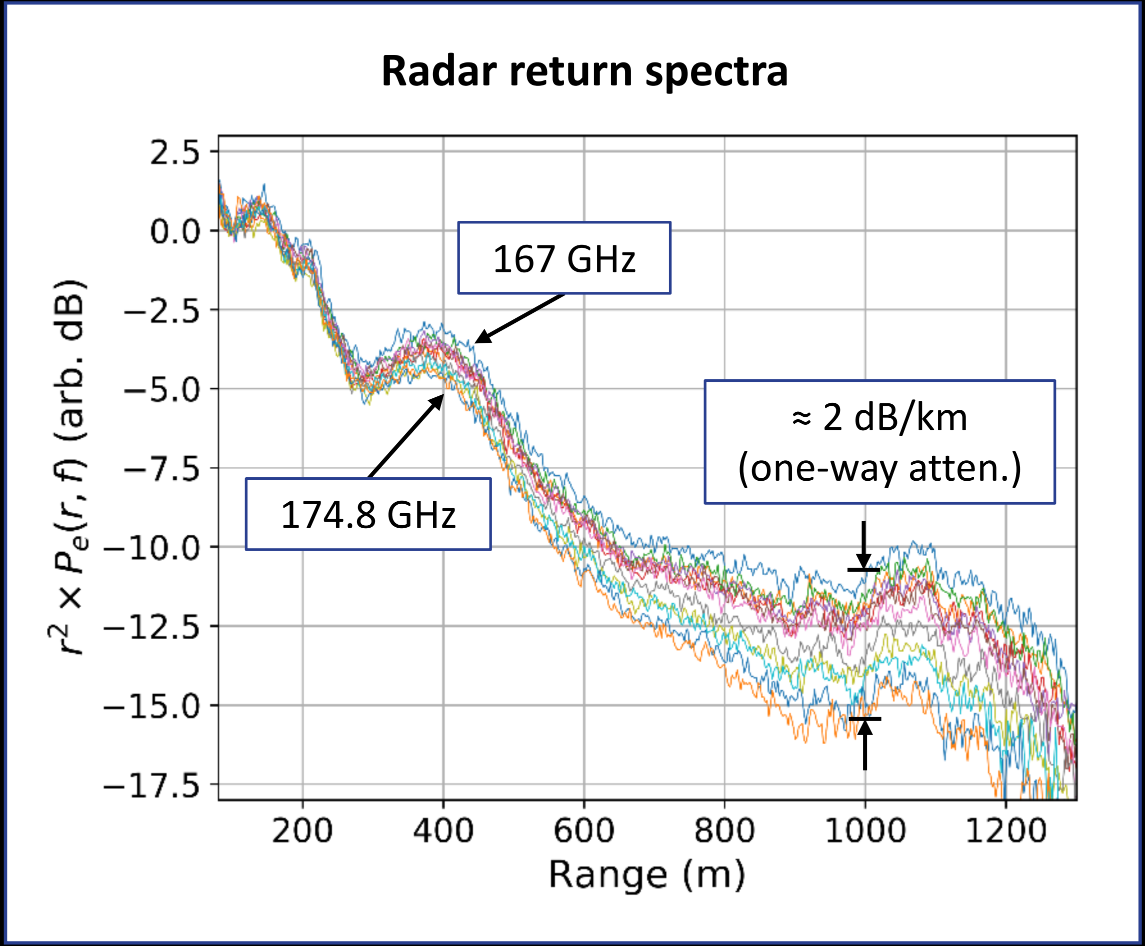


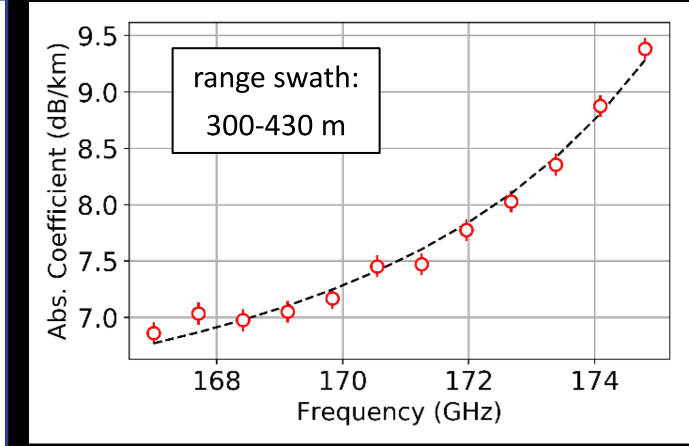


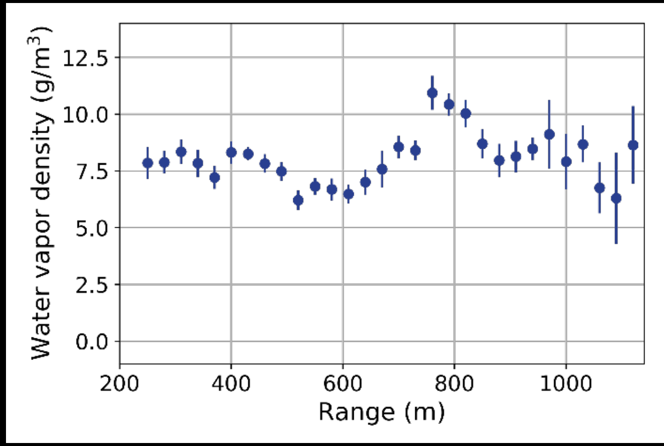
Vapor In-cloud Profiling Radar (VIPR)

Pre-Decisional Information -- For Planning and Discussion Purposes Only

Precipitating Cloud Measurements







3CPR System Design

- Supports either:
  - ACE decadal survey mission concept (Ka- / W-band)
  - Cloud and Precipitation Processes Mission (CaPPM) concept. (Ku-, Ka-, W-band)
- ***Most precious resources:***
  - ***Sampling time***
  - ***Transmitted power***
- Pulse-to-pulse beam agility and optimized timing enable optimization of performance WRT certain science requirements
- One point design was chosen for 3CPR system study
  - High-sensitivity nadir measurements
  - Significant swath at all three bands
- Hardware is highly adaptable to changes in measurement priorities or resource limitations.
- Supports adaptive scan strategies and pulsed compression if required by application

3CPR Key Parameters

Parameter	Value (Ku/Ka/W)
Reflector Size	5 m x 3 m
Feed Array Length	2.5 / 2.87 / 2.87 m
Feed elements (each for TX / RX)	160 / 480 / 1152
Transmit Power (peak)	3200 / 1600 / 1267 W
Pulse length	1.5 μs
Scan angle (+/-)	4.5 / 12 / 3.5 degrees

3CPR Predicted Performance

		NADIR			SWATH		
		Ku	Ka	W	Ku	Ka	W
EFOV (along x across)	km	4 x 4	2 x 1.5	1 x 0.6	4 x 4	2 x 2	1 x 1
Clutter Free MDS	dBZ	-5	-20	-35	+2	-10	-22
Clutter Free hgt	M	300	300	300	500	850	500
Near Surface MDS	dBZ	+12	-5	-20	+12	0	-10
Near Surface hgt	M	250	250	250	400	500	300
Doppler 0 SNR	dBZ	+12	-5	-18	+12	N/A	*-13*
Doppler Prec.	m/s	0.3	0.2	0.1	0.5	N/A	*0.5*
Swath	km	--	--	--	60	195	50
Max Scan Angle	deg	--	--	--	4.5	12	3.5
# Beams		1	1	1	18	96	48
Polarization		FULL	LDR	LDR	FULL	LDR	LDR

Legend	ACE	Req Met	**Goal Met**	IWSSM	Req Met	CaPPM (Tent.)	Req. Met

IWSSM = International Workshop on Space-based Snowfall Measurement
CaPPM = Cloud and Precipitation Processes Measurement mission concept group

Pre-Decisional Information -- For Planning and Discussion Purposes Only