Jet Propulsion Laboratory
California Institute of Technology

RainCube the ~~a~~ precipitation profiling radar in a cubesat.

… and its legacy for the next generation of spaceborne cloud and precipitation radars

Simone Tanelli presenting
for the JPL & Tyvak RainCube Team

Jet Propulsion Laboratory, California Institute Of Technology, Pasadena, CA, United States,

ESTF Virtual Conference, May 27, 2021

The bittersweet conclusion of RainCube time in space

May 21st, 2018 – Dec 24th, 2021

Once the the altitude dropped below 320 km things deteriorated faster than expected

Some late mission experiments could not be completed

After solving so many challenges, we were finally “harvesting”

Come on…wasn’t 2020 already bad enough?

There isn’t really much we could have done about it

The job was done, and then some

Many successors of RainCube are already growing up

Yep, it was bad, and all this is nothing, considering.

RainCube in a nutshell

Technological goal (of the InVEST’15 tech demo):

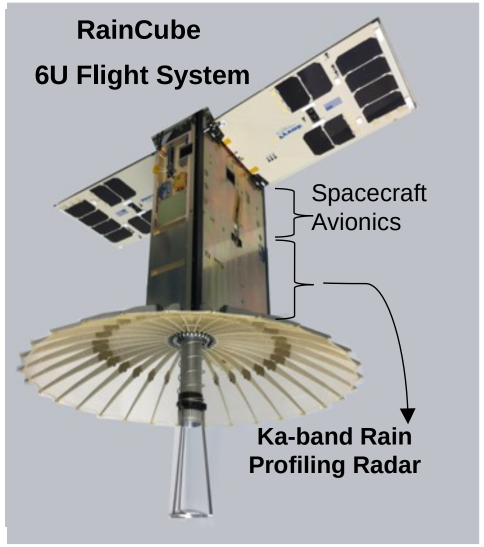
Demonstrate the first active remote sensing instrument in a CubeSat, via a Ka-band precipitation radar

Scientific goal (of a constellation or train):

To provide global observations of the temporal evolution of vertical structure and thermodynamic processes of storms.

Success criteria & relevance of the timeline:

Detect precipitation & capture vertical structure of storms.
Do so in a timely fashion to inform the
Cloud, Convection and Precipitation studies prompted by the 2017 Earth Science Decadal Survey.



RainCube

miniKaAR-C (radar electronics)

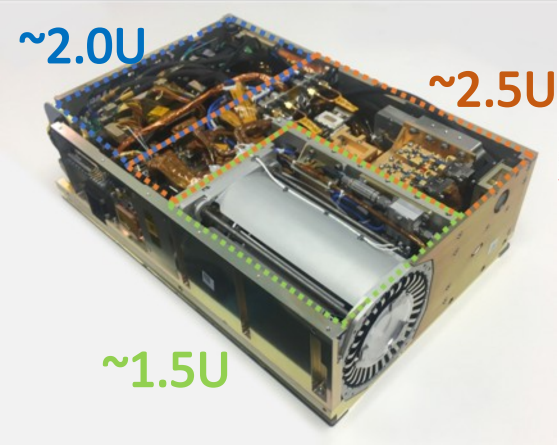
Reduced size, weight, and power by offset IQ with pulse compression modulation technique

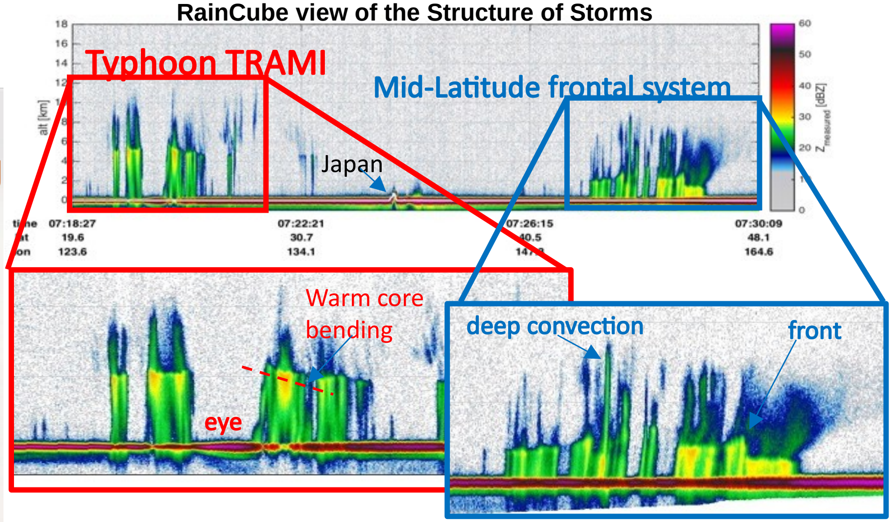
KaRPDA (antenna)

Half meter Ka-band lightweight deployable

Tyvak Bus:

Compact highly integrated bus providing 35W of power to the payload.





Peral E., S. Tanelli, S. Statham, S. Joshi, T. Imken, D. Price, J. Sauder, N. Chahat, A. Williams, “RainCube: the first ever radar measurements from a CubeSat in space,” J. Appl. Remote Sens. 13 (3), 032504 (2019), doi: 10.1117/1.JRS.13.032504.

System Architecture

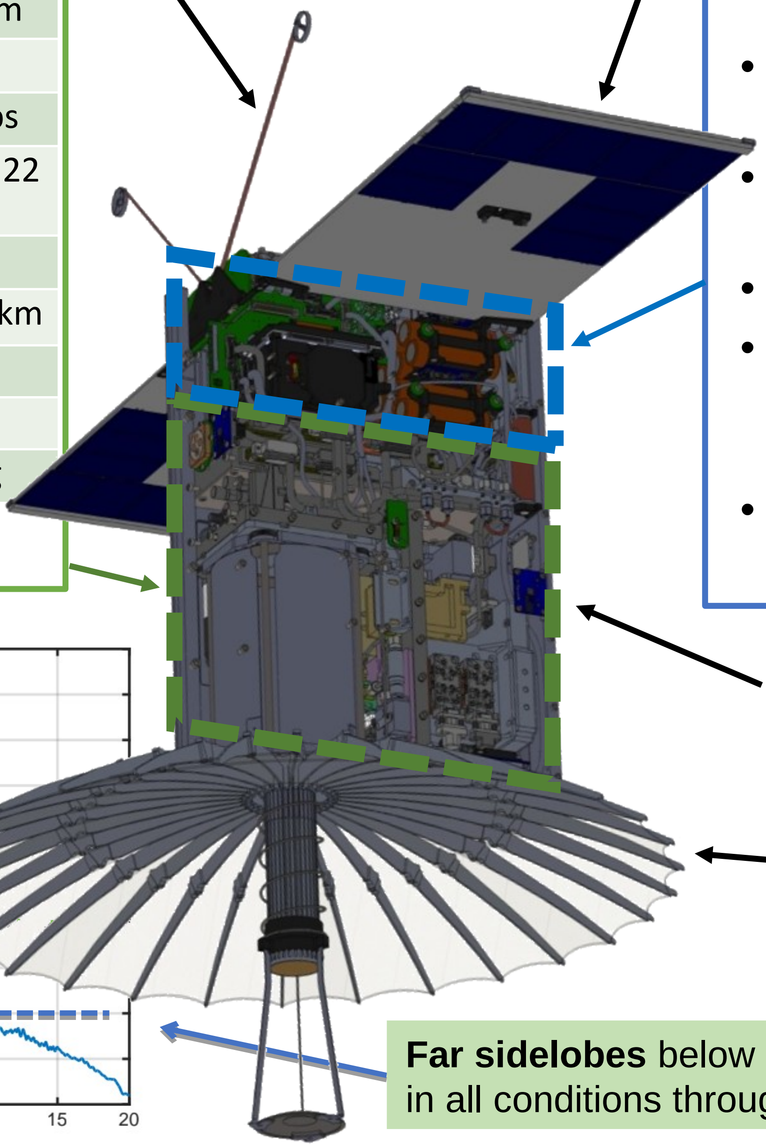
RainCube

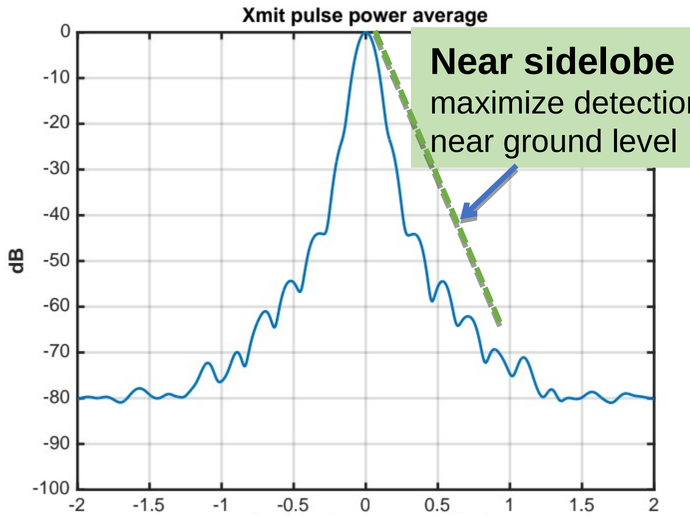
Radar Electronics & Antenna Reqs. (4U)

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

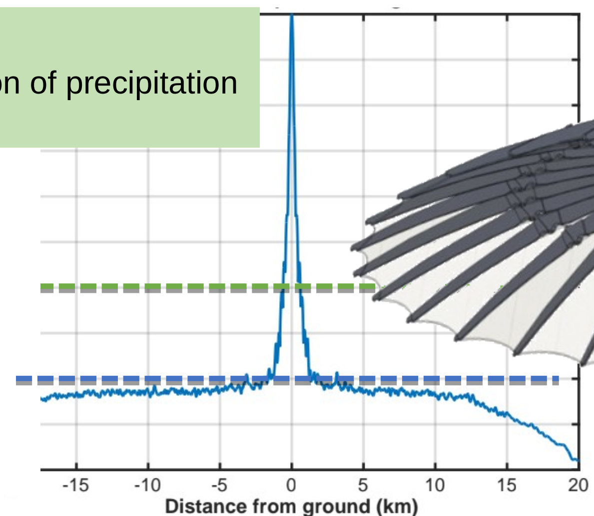
Bus Reqs. (2U)

- 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





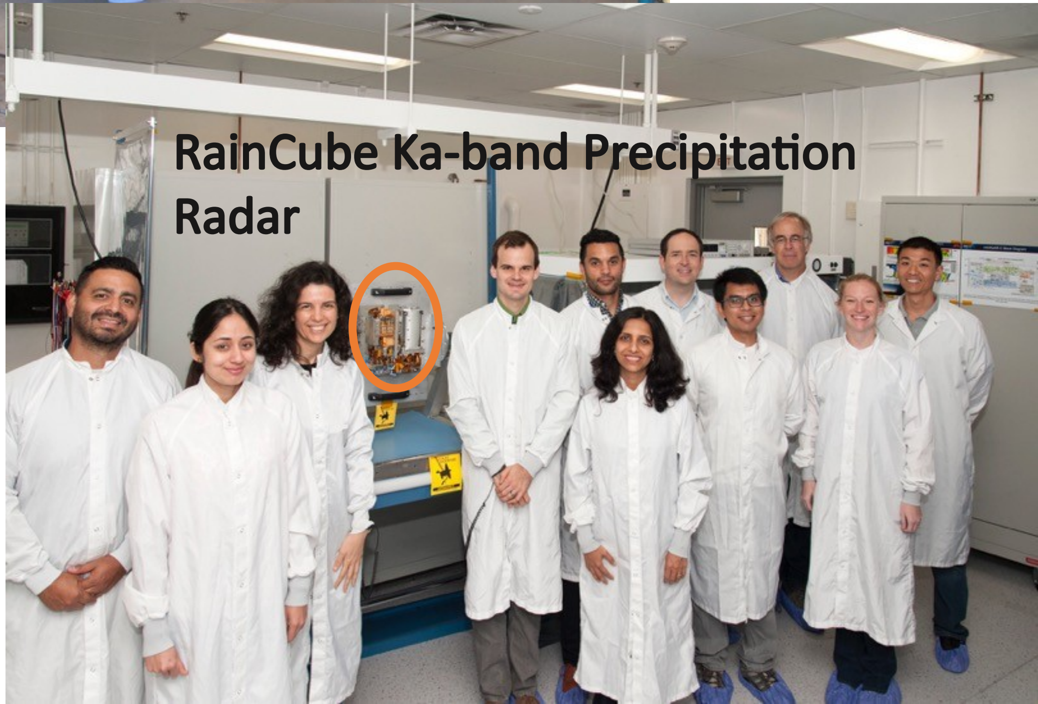
Near sidelobe
maximize detection of precipitation near ground level



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

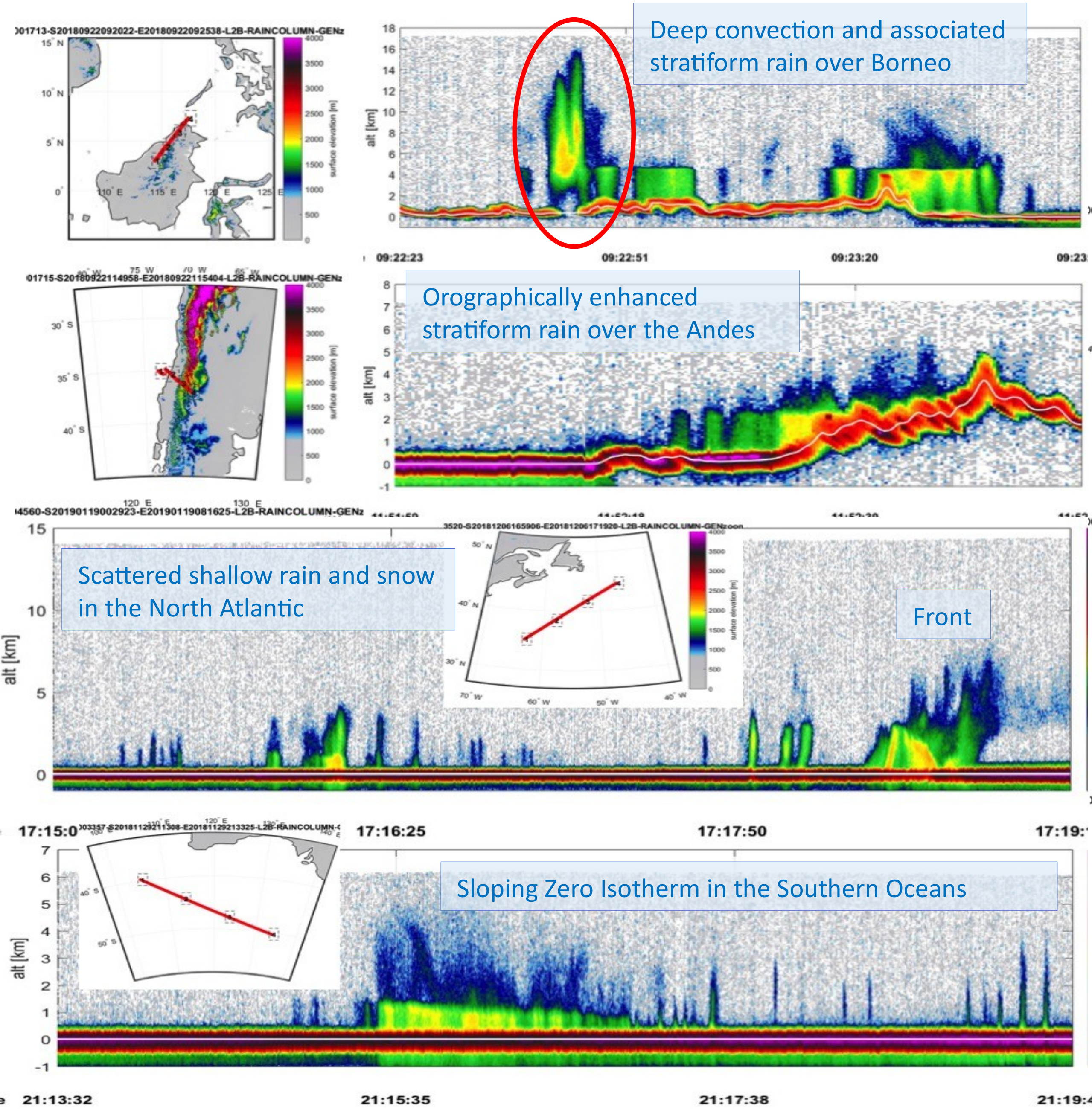
How small is RainCube. . .

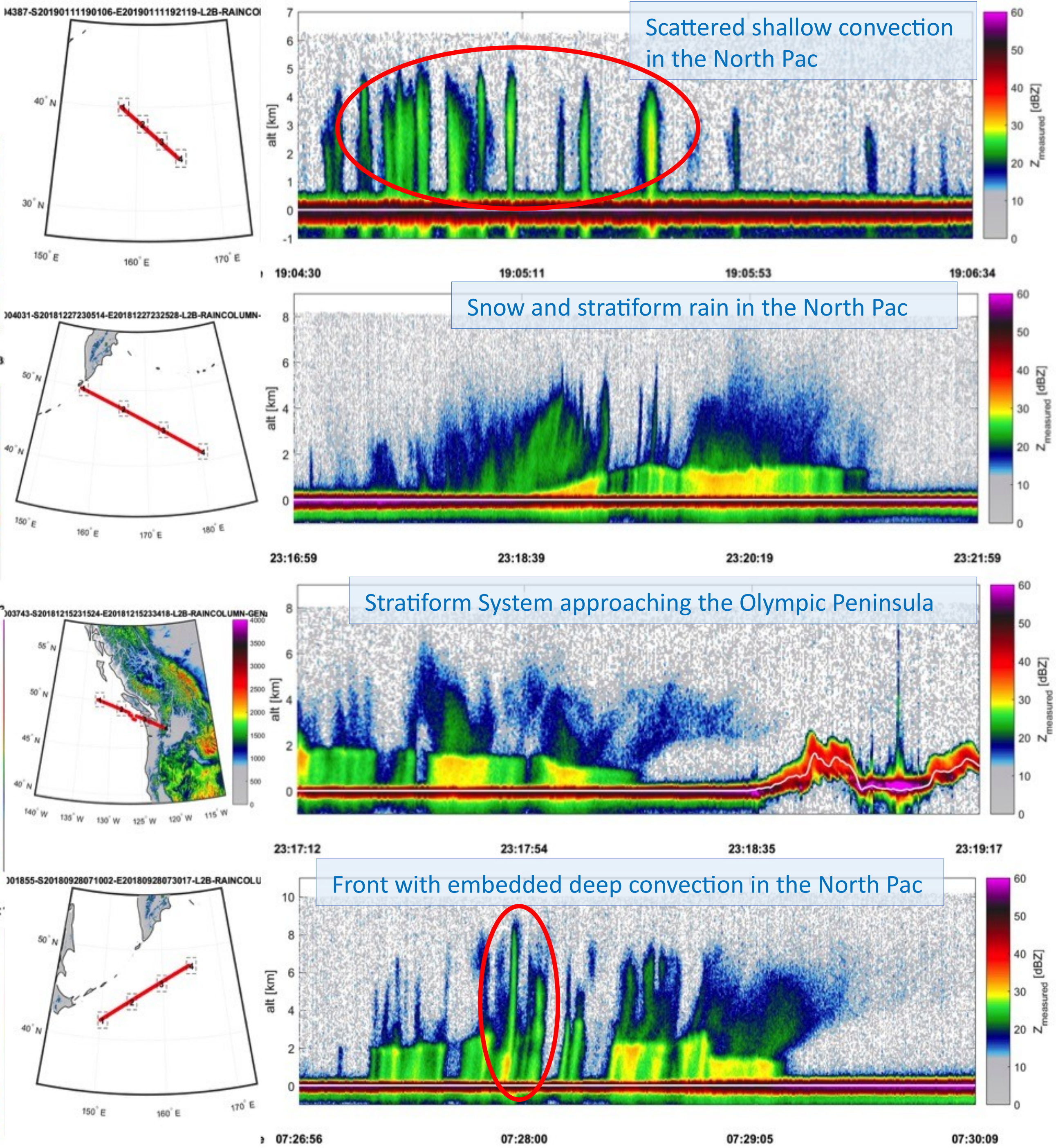
	CPR	KaPR	RainCube
Mass [Kg]	260	336	7
Power [W]	300	344	22
Volume [U]	4,356	1,210	4
Class	C	C	Tech demo
Frequency	W-band	Ka-band	Ka-band
Scanning	No	Yes	No
Sensitivity	-30 dBZ	+17 dBZ	+12 dBZ



Storms as seen by RainCube

8 examples out of almost 2000 processed scenes





What an in-orbit technology demonstration could do in 2 years

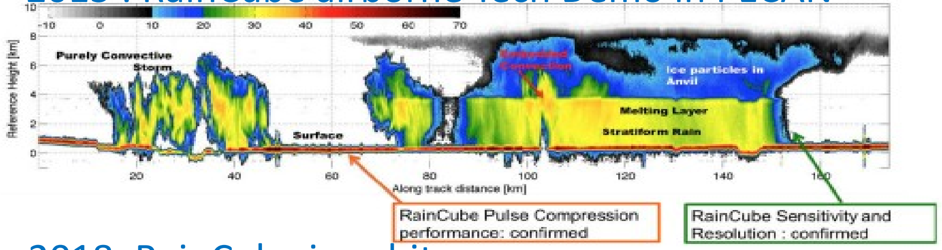
- RainCube operated in space between Aug 2018 and December 2020
  - It re-entered the atmosphere on Dec 24th, 2020 with the Radar still fully functional
- Assumed additional scope as soon as the prime objective was completed
  - Mission success could be claimed after the first storm detection
  - Past that milestone, risks associated with additional objectives could be evaluated
    - Operating the mostly-COTS radar over the SAA
    - Scheduling data takes to target specific storms based on forecast
    - Acquiring data in proximity of GPM for cross comparison and validation
    - Devising a new ADCS algorithm solution to maintain fine pointing with only 2 remaining reaction wheels.
    - Adopting the Amazon Web Services for global downlink capability
    - Designing and implementing new waveforms to validate end-to-end performance models
- Operated with a very small team to achieve the desired goals
  - Many early career team members could benefit of invaluable experience somewhere between “technology development” and “flight project”, and with a rewarding short turnaround.
- Enabled and sometimes forced creative solutions throughout its lifecycle.
- Demonstrated a number of technology solutions which in turn enabled a number mission and instrument concepts where either all or only one of them are necessary.
  - Inspired a number of groups, worldwide, to pursue similar challenges and bring it to the next level.
- Provide science data (Available on: https://tcis.jpl.nasa.gov/data/raincube/)

Main outcomes

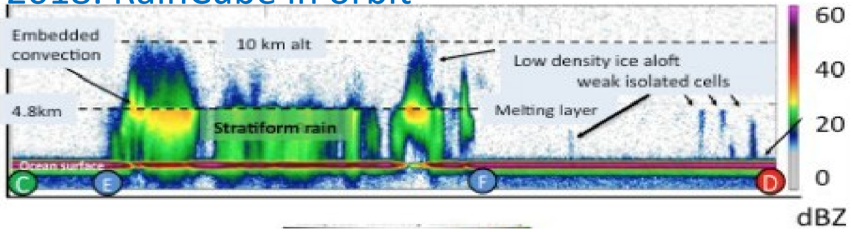
RainCube

Demonstration of feasibility of mission concepts involving multiple radar platforms

2015 : RainCube airborne Tech Demo in PECAN



2018: RainCube in orbit



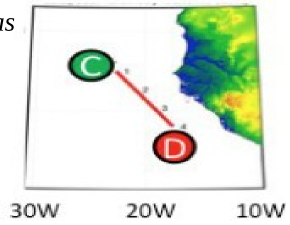
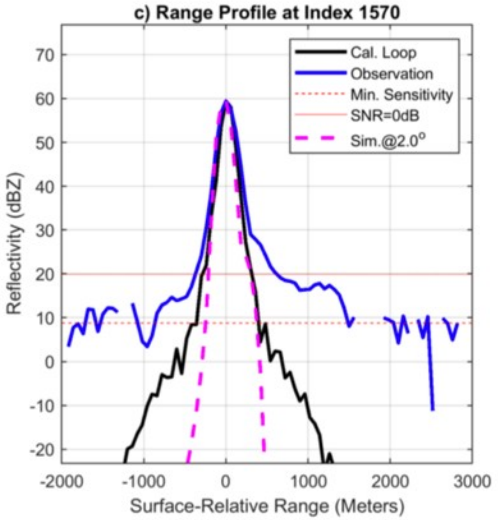


Fig. 2. (a) MiniKaAR-C data from the airborne campaign as a part of the PECAN campaign (June 28–July 15, 2015) showing the profile of radar reflectivity Z. The reflectivity color scale is in dBZ. The expected on orbit sensitivity of Raincube of ∼10 dBZ is emphasized with the color scale chosen. (b) MiniKaAR-C reflectivity profiles of rain falling from the nascent hurricane florence.

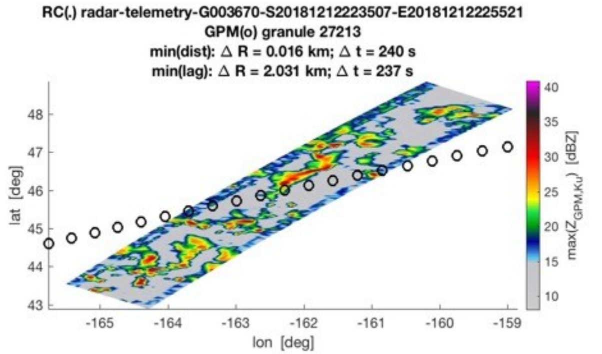
Stephens G.L., S.C. van den Heever, Z. S Haddad, D J Posselt, R L Storer, L D Grant, O O Sy, T. Narayana Rao, S. Kumar, S. Tanelli and E. Peral, “A distributed small satellite approach for measuring convective transports in the Earth’s atmosphere”, IEEE TGRS, Print ISSN: 0196-2892; Online ISSN: 1558-0644; doi: 10.1109/TGRS.2019.2918090

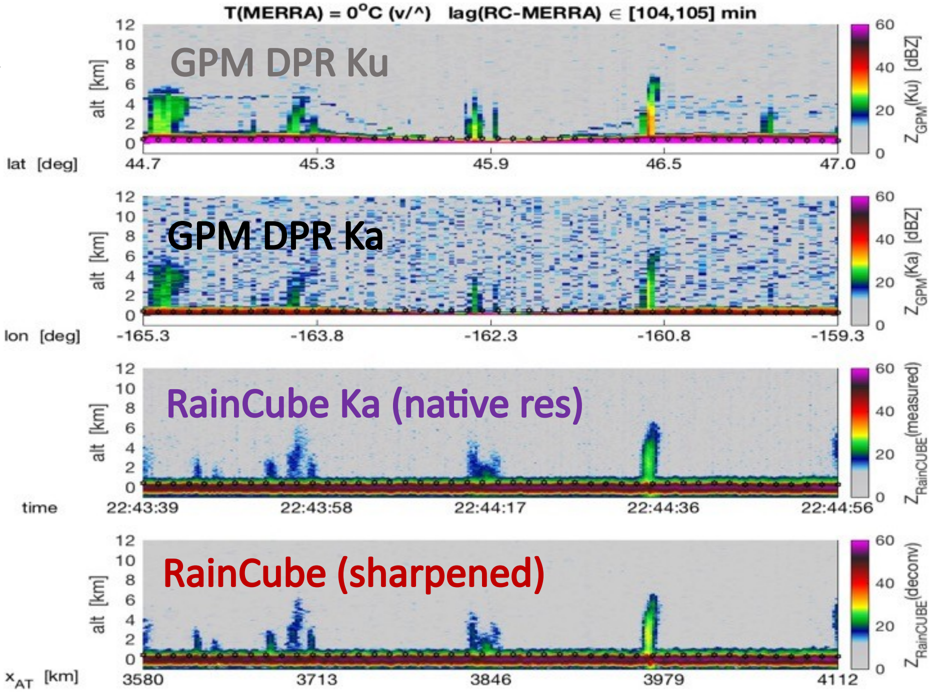
Validation of accurate modeling of pulse compression performance for Precipitation Radars from Low Earth Orbit



Beauchamp R.M., S. Tanelli and O.O. Sy, 2020: Observations and Design Considerations for Spaceborne Pulse Compression Weather Radar, *in IEEE Transactions on Geoscience and Remote Sensing, vol. 59, no. 6, pp. 4535-4546, June 2021, doi: 10.1109/TGRS.2020.3013164.*

Along-track resolution sharpening for nadir-pointing Spaceborne Precipitation Radars: validation with GPM and NEXRAD





O.O. Sy, S.Tanelli, G.S. Sacco, E.Peral, 2021: RainCube: first Cubesat demonstrator of deconvolution for spaceborne cloud and precipitation radar measurements, in IEEE Transactions on Geoscience and Remote Sensing, doi: 10.1109/TGRS.2021.3073990.

Tanelli S., E. Peral, O. O. Sy, G. F. Sacco, Z. S. Haddad, S. L. Durden, S. Joshi, "RainCube: How can a CubeSat radar see the structure of a storm?," Proc. SPIE 11131, CubeSats and SmallSats for Remote Sensing III, 1113106 (30 August 2019); https://doi.org/10.1117/12.2531150

RainCube returns to nadir

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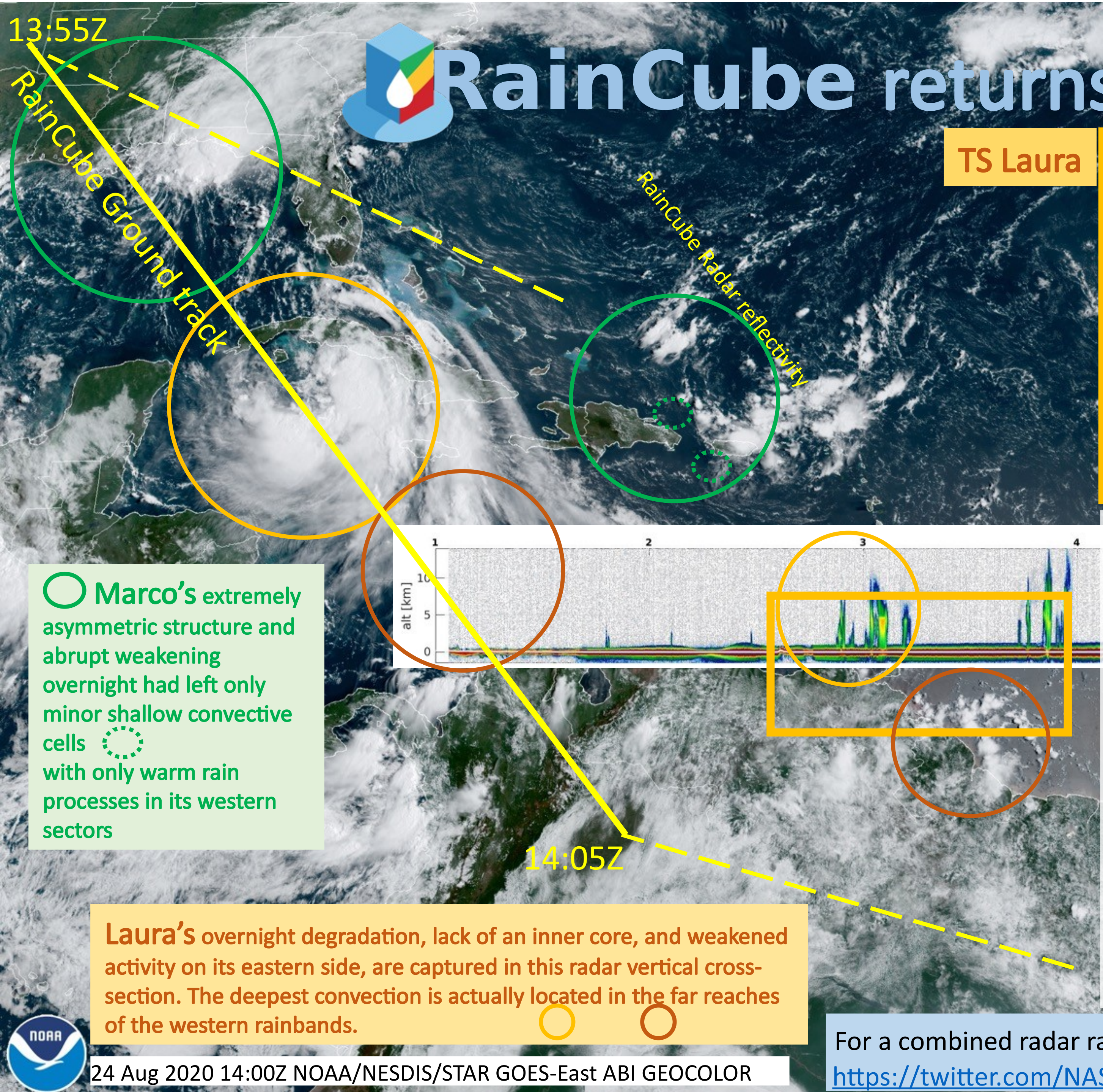
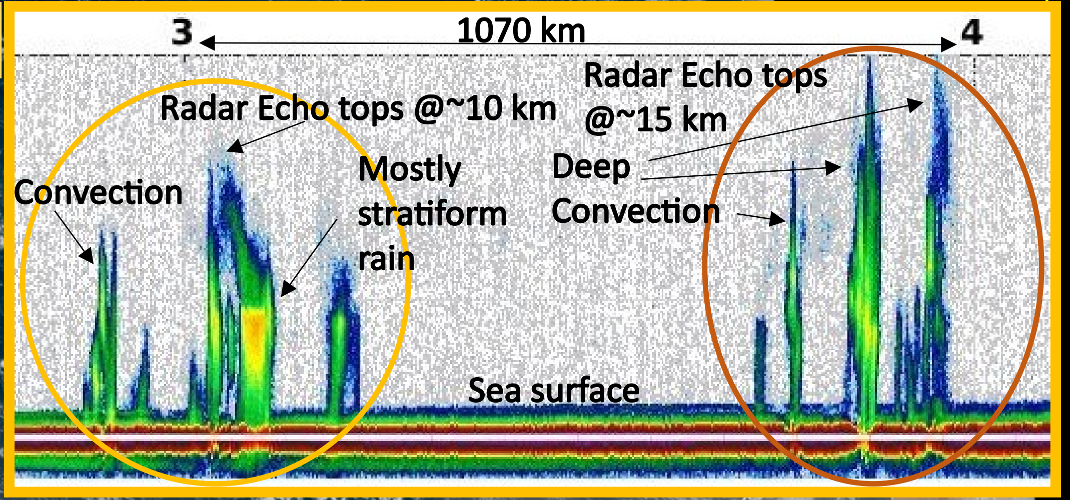




Marco's extremely asymmetric structure and abrupt weakening overnight had left only minor shallow convective cells with only warm rain processes in its western sectors

Laura's overnight degradation, lack of an inner core, and weakened activity on its eastern side, are captured in this radar vertical cross-section. The deepest convection is actually located in the far reaches of the western rainbands.

In 2019 RainCube lost one of its 3 tiny reaction wheels.

Since then, it had been operating at reduced capacity, with low reliability pointing, and only in umbra.

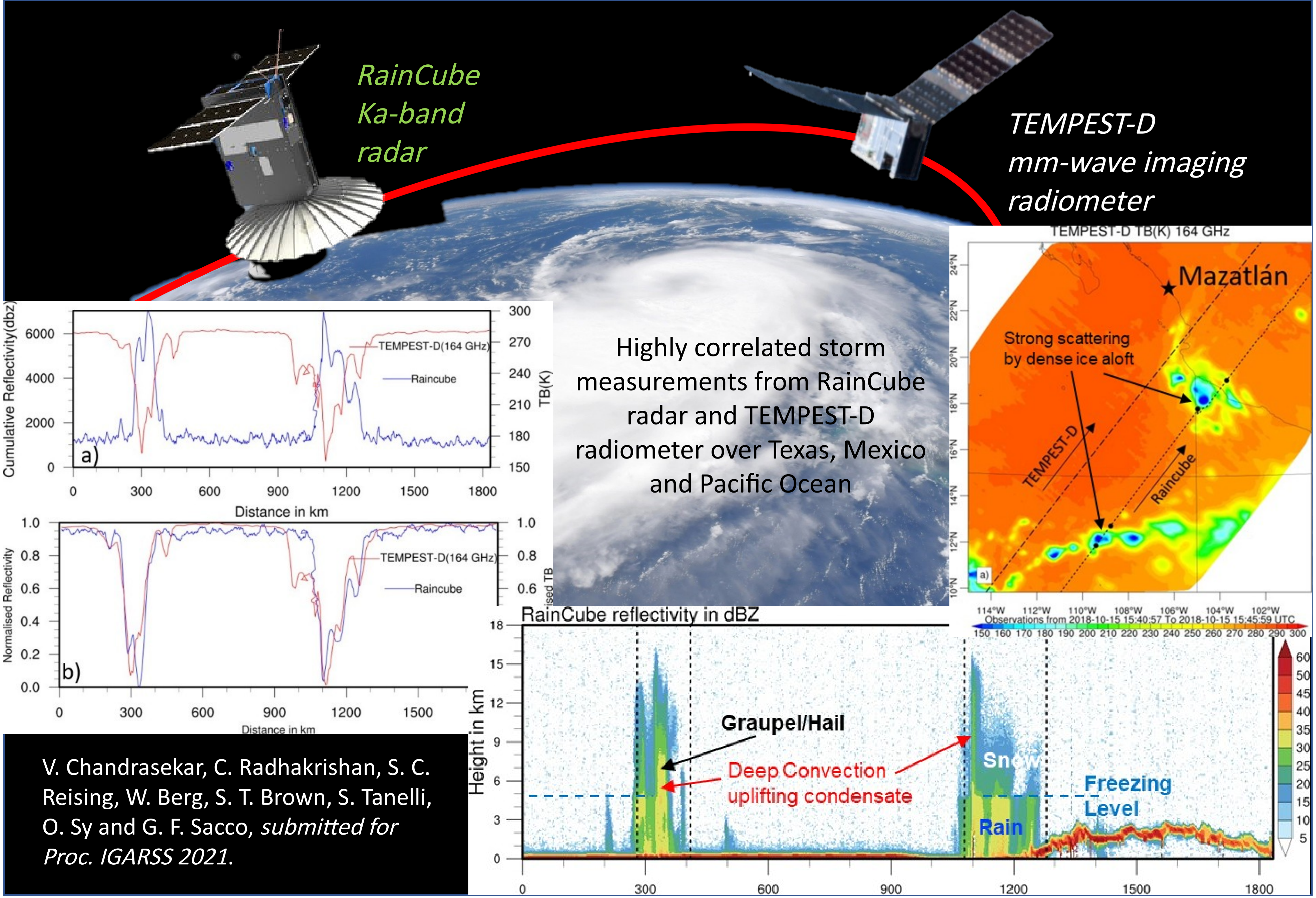
Between March and July 2020, Tyvak ADCS and Ops teams completed successfully the design, implementation and upload of a new ADCS algorithm that uses only 2 reaction wheels and the torque rods to maintain the radar pointed at nadir.

Preliminary tests conducted in August 2020 indicate that **RainCube can now be operated again with satisfactory pointing performance in both umbra and daytime and can target weather systems of interest.**

While quantitative assessments, radar validation, and statistics of performance improvement are being accumulated, on August 24th RainCube was activated during an overflight of the locations of named storms **Marco** and **Laura.**

For a combined radar radiometer highlight of the same event see:
https://twitter.com/NASAEarth/status/1299403554923458560

24 Aug 2020 14:00Z NOAA/NESDIS/STAR GOES-East ABI GEOCOLOR



RainCube
Ka-band
radar
TEMPEST-D
mm-wave imaging
radiometer
Highly correlated storm measurements from RainCube radar and TEMPEST-D radiometer over Texas, Mexico and Pacific Ocean
Cumulative Reflectivity(dbz)
TB(K)
TEMPEST-D(164 GHz)
Raincube
a)
Distance in km
Normalised Reflectivity
b)
TEMPEST-D TB(K) 164 GHz
Mazatlán
Strong scattering
by dense ice aloft
TEMPEST-D
Raincube
Observations from 2018-10-15 15:40:57 To 2018-10-15 15:45:59 UTC
RainCube reflectivity in dBZ
Height in km
Graupel/Hail
Deep Convection
uplifting condensate
Snow
Rain
Freezing
Level
V. Chandrasekar, C. Radhakrishan, S. C. Reising, W. Berg, S. T. Brown, S. Tanelli, O. Sy and G. F. Sacco, *submitted for Proc. IGARSS 2021*.

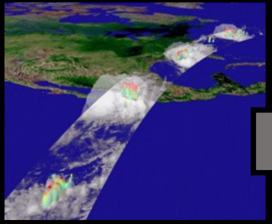
Spaceborne "Atmospheric Radar" landscape (20~~20~~ 21)

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

= Notional accommodation concept among several possible

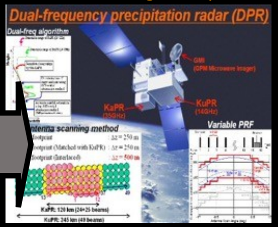
The 4 "predecessor" Spaceborne Cloud & Precipitation Radars

TRMM/PR – NICT/JAXA
Ku, Scanning , Tropical Rain



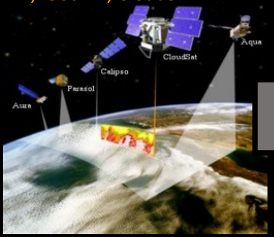
1997-2015

GPM/DPR – NICT/JAXA
Ku/Ka, Scanning, Precipitation



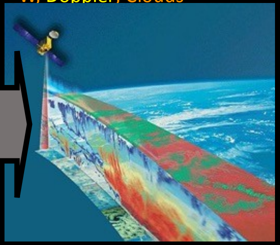
2014-Today

CloudSat/CPR
JPL/NASA/CSA
W, -30dBZ , Clouds



2006 -Today

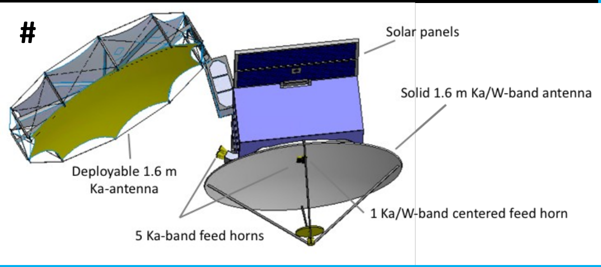
EarthCARE/CPR
NICT/JAXA
W, Doppler, Clouds



NET 2023

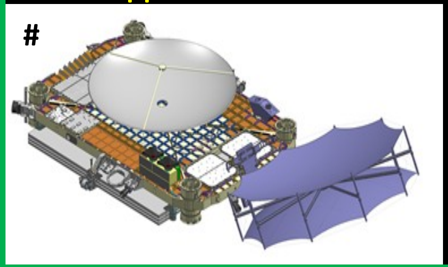
IIP 2019: CloudCube
Ka/W/G, Scanning Ka, **DPCA Doppler**,
SmallSat

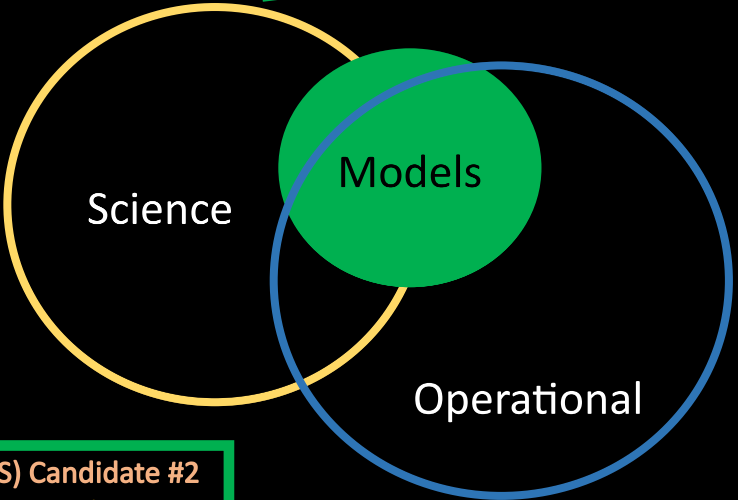
#



*** ACCP (AtmOS) Candidate #1**
Ku/W, Narrow Scanning Ku,
DPCA Doppler Ku

#

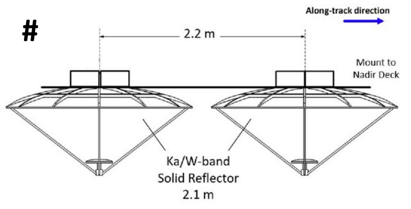




RainCube
JPL/NASA InVEST Tech Demo
Ka-band, Precipitation,
6U CubeSat
2018 – 2021

*** ACCP (AtmOS) Candidate #2**
Ka /W, Narrow Scanning Ka,
DPCA Doppler Ka & W

#



NOAA Architecture Studies

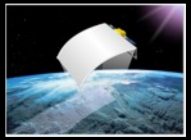
International developments in EU and Asia

Commercial endeavors

IIP 2019: VIPR (in-cloud Vapor profiling) & PBL radar *

IIP 2016: MASTR
Ku/Ka/W, Scanning,
Doppler, SmallSat

#



ES DS 2007: ACE Mission Concept Radars *
and their evolution towards a wholistic cloud/precipitation mission concept
Ku, Ka, W, ***Doppler***, **Scanning**

Strengths:

- unprecedented view of the vertical structure of weather systems
- Improved quantitative precipitation estimates on a global scale
- Synergy with other instruments (radiometers, lidars, etc.)
- As ensemble: sufficient dynamic range to cover from non-precipitating clouds to severe storms.

Weaknesses:

- Limited **temporal** coverage (singles in LEO)
- Limited **spatial** coverage (narrow or no swath, singles

RainCube's legacy

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

RainCube
Ka-band / 0.5 m

Ka-band
1.6 m Antenna
SmallSat

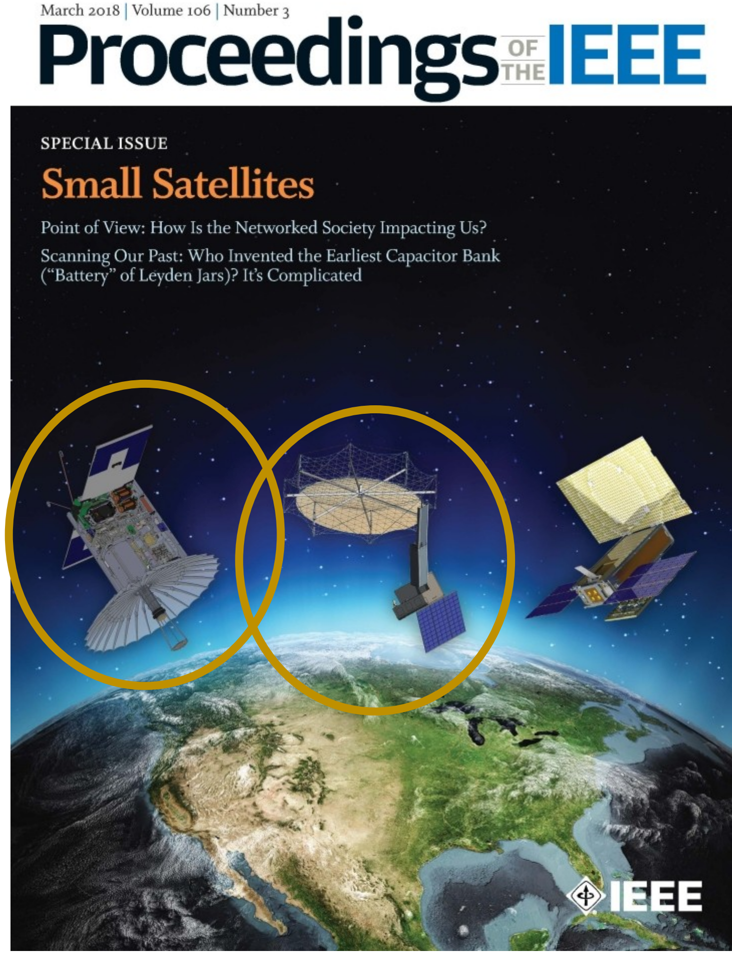
CloudCube

Ka-/W-band
Dual
2.1 m Antenna

Ku-/W-band
Dual
2.1 m Antenna
("SmallSat")

Ka-/W-/G-band
1-2 m Antenna
(SmallSat)

		# of sats
Operational monitoring (Combined w. Radiometers)	Inspired: NOAA Architecture + International Efforts + Commercial Enterprises	11-100
Diurnal Cycle sampling (Operational model validation)		6-10
EV-class concept *Convective Mass Flux in Tropical Storms*		2-5
Tech Demo 2018-2020	**ACCP Candidate Radar For polar component** *Broad cloud/precipitation dynamics*; **ACCP Candidate Radar For inclined component** *Deep Tropical convection dynamics*; **Next gen** *Cloud microphysics and dynamics*	1



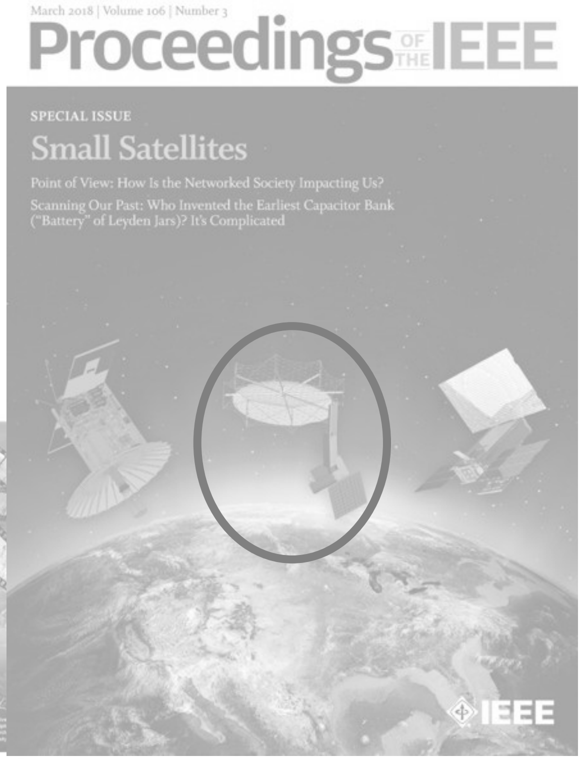
RainCube has opened up the spectrum of possible cloud and precipitation radar solutions to adapt to a vast array of mission concepts

RainCube : What's next ?

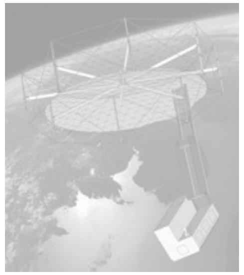
Pre-Decisional Information -- For Planning and Discussion Purposes Only

- 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

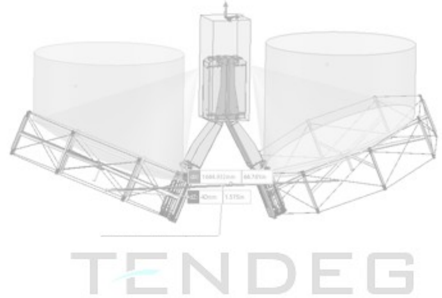
- Constellation with improved antennas & electronics
  - To address a larger set of science questions
  - Development of **technologies** and of **mission concepts** is ongoing
  - **Extension to W and G-band for cloud & precip.**
  - **DPCA** for Doppler, **Larger Size** for improved resolution and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



RainCube 1.0 m in 12 U



RainCube 1.0 m DPCA in 24U

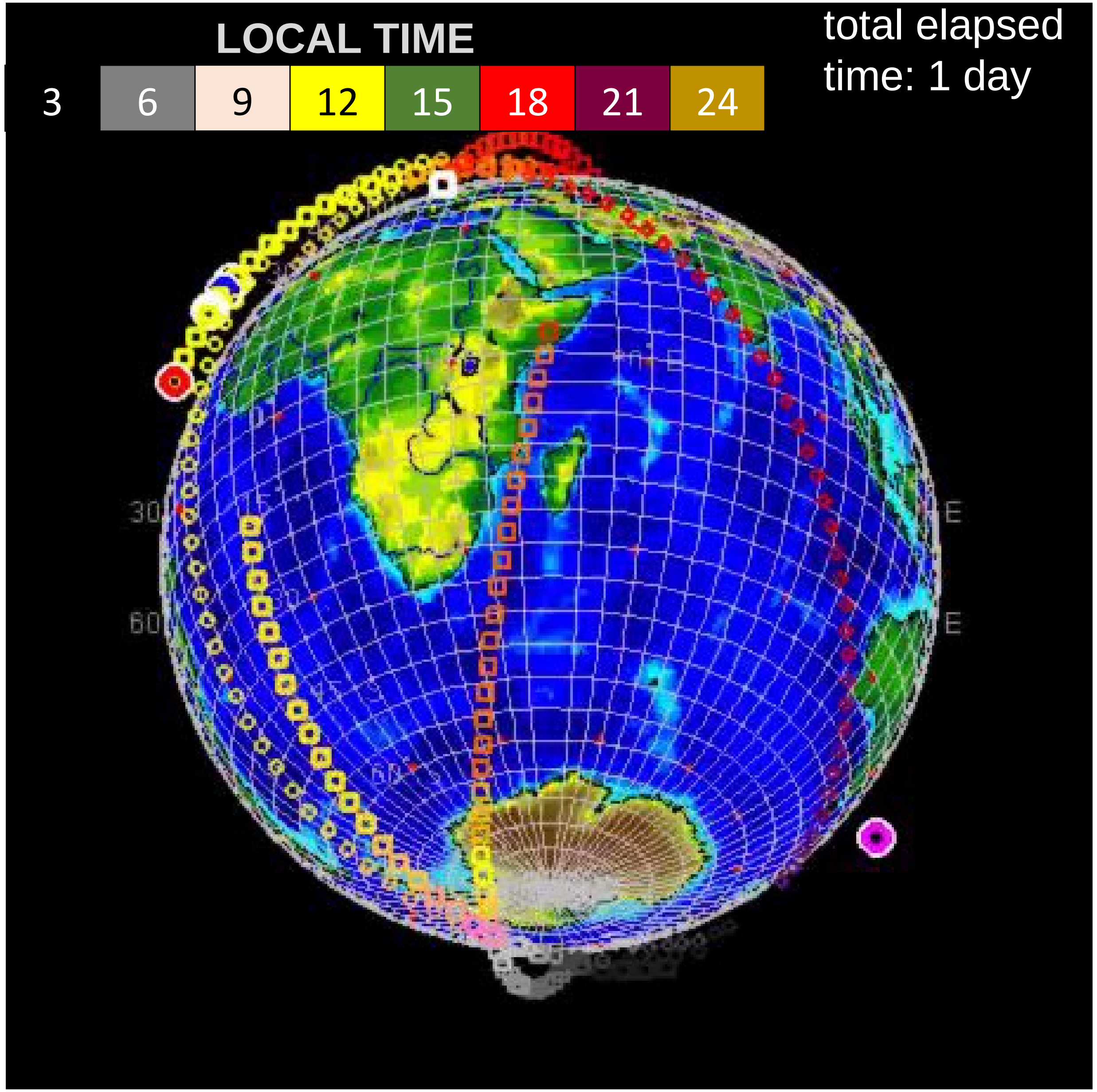


Ka-band ESTO InVEST and ACT programs

	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

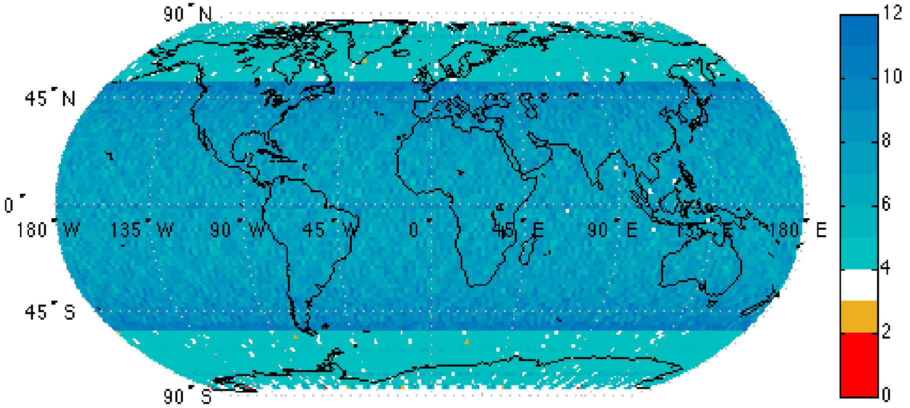
- Constellation with other Radars and Radiometers:
  - A study team in the Earth Science Decadal Survey 2017 will consider RainCube-like constellations for measurements of convection and precipitation
  - Higher frequency versions of RainCube for cloud and water vapor observations
- Planetary applications
  - An evolution of this instrument could support altimetry and cloud and precipitation on planetary targets

RainCube InVEST'15 "as is" : strength in numbers



Global sampling of the **diurnal cycle** of precipitation can be conducted effectively with a small number of simple radars.

The notional mission concept adopted in this particular simulation involves 3 distinct orbital planes.



Number of different hours of day in local time that a given 2° x 2° box was visited within a **16 day** period.

Almost everywhere in the globe, each box was visited at least at four different hours of the day.

This class of radar enables not only new research but can have an **application**-oriented role for operational weather agencies, as well as commercial sector enterprises.

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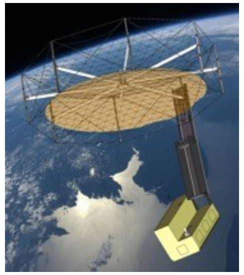
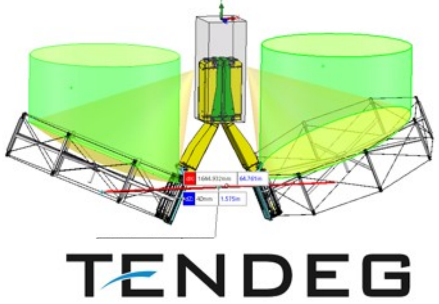
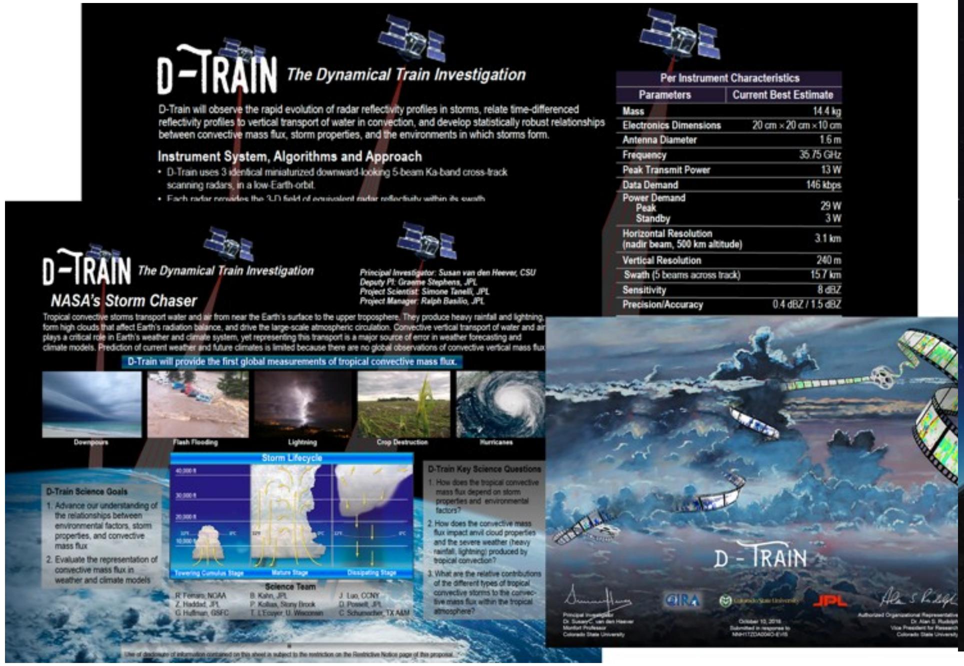
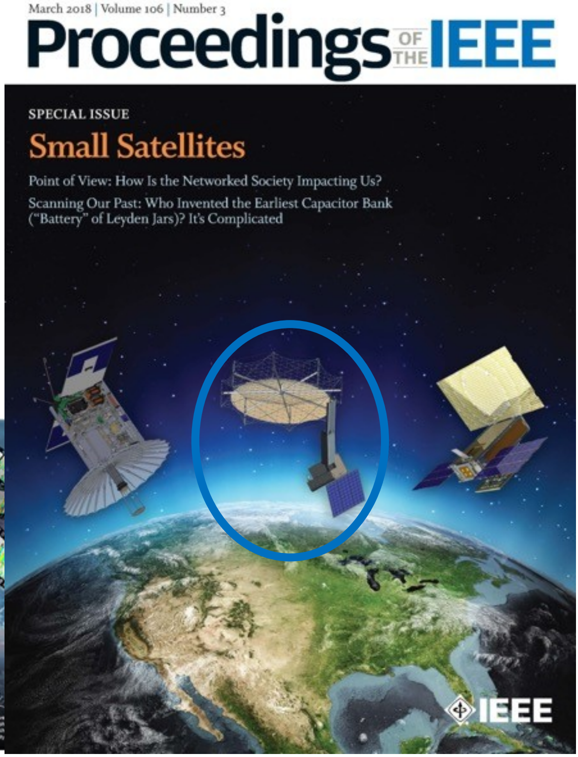
RainCube 1.0 m in 12 U



RainCube 1.0 m DPCA in 24U







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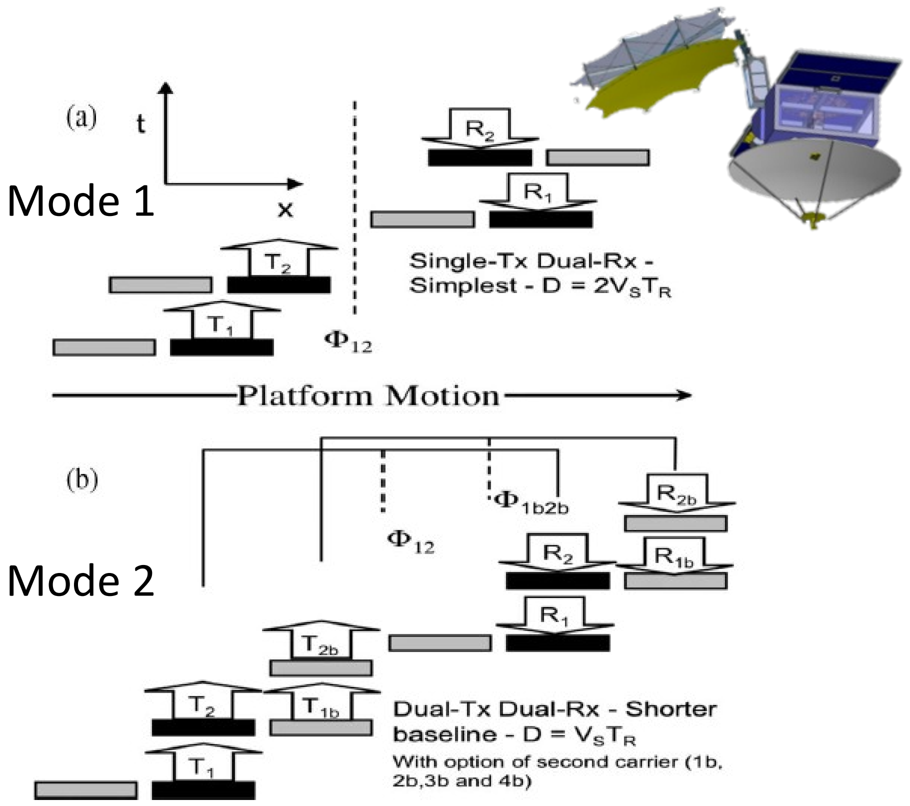
  - Higher frequency versions of RainCube for cloud and water vapor observations
- Planetary applications
  - An evolution of this instrument could support altimetry and cloud and precipitation on planetary targets

Displaced Phase Center Antenna
for high accuracy Cloud and Precipitation Doppler estimates

One upgrade in CloudCube wrt RainCube is that it can Tx and Rx alternatively from a Fwd and and Aft antenna to adopt the **DPCA technique** [1,2].

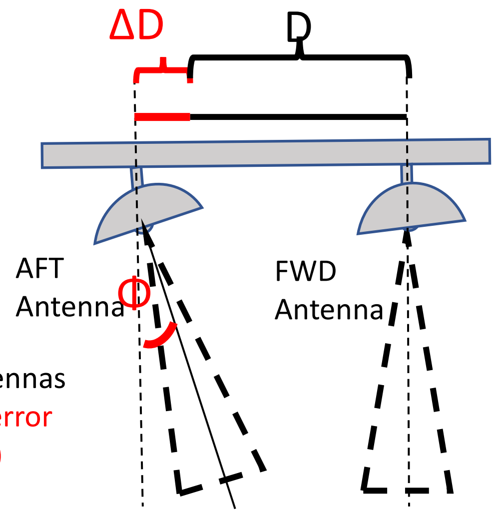
DPCA effectively cancels (or reduces by one or more orders of magnitude) the effective platform velocity contribution to signal broadening:

- Reduction of spectral broadening
  - improvement in mean Doppler estimation precision
  - Improvement in estimation of the target's natural Doppler spectral width (i.e., turbulence, shear, hydrometeor size spread)
- Reduction in Non-Uniform Beam Filling biases [3-8]
  - improvement in mean Doppler estimation accuracy

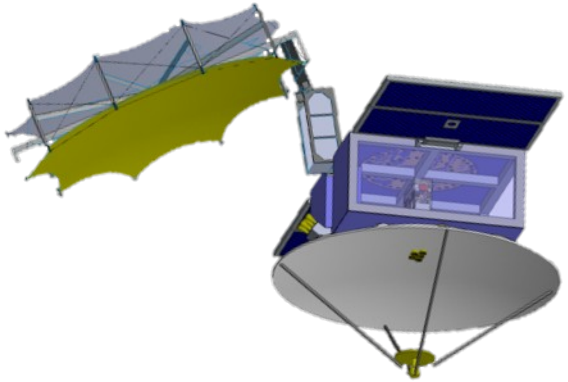


1. **Durden, S. L.**, **Siqueira, P. R.,** & Tanelli, S. (2007). On the use of multiantenna radars for spaceborne doppler precipitation measurements. IEEE Geoscience and Remote Sensing Letters, 4(1), 181–183.
2. Tanelli, S., Durden, S. L., & Johnson, M. P. (2016). Airborne Demonstration of DPCA for Velocity Measurements of Distributed Targets. IEEE Geoscience and Remote Sensing Letters, 13(10), 1415–1419. [4] Tanelli, S., Im, E., Durden, S. L., Facheris, L., & Giuli, D. (2002). The effects of nonuniform beam filling on vertical rainfall velocity. Journal of Atmospheric and Oceanic Technology, 19(7), 1019–1034
3. Tanelli, S., Im, E., Kobayashi, S., Mascelloni, R., & Facheris, L. (2005). Spaceborne Doppler Radar Measurements of Rainfall: Correction of Errors Induced by Pointing Uncertainties. Journal of Atmospheric and Oceanic Technology, 22(November), 1676-1690.
4. Schutgens, N. A. J., 2008: Simulated Doppler Radar Observations of Inhomogeneous Clouds: Application to the EarthCARE Space Mission. J. Atmos. Oceanic Technol., 25,26–42, doi:10.1175/2007JTECHA956.1.
5. Battaglia, A; Tanelli, S., "DOMUS: DOppler MUltiple-Scattering Simulator", IEEE Trans. Geoscience and Remote Sensing, vol.49, no.1, pp.442,450, Jan. 2011
6. Kollias, P., S. Tanelli, A. Battaglia, A. Tatarevic, (2014): Evaluation of EarthCARE Cloud Profiling Radar Doppler Velocity Measurements in Particle Sedimentation Regimes. J. Atmos. Oceanic Technol., 31, 366–386. doi: http://dx.doi.org/10.1175/JTECH-D-11-00202.1
7. Sy, O.O.; Tanelli, S.; Takahashi, N.; Ohno, Y.; Horie, H.; Kollias, P., (2014). Simulation of EarthCARE Spaceborne Doppler Radar Products Using Ground-Based and Airborne Data: Effects of Aliasing and Nonuniform Beam-Filling. Geoscience and Remote Sensing, IEEE Transactions on, vol.52, no.2, pp.1463,1479, Feb. 2014. doi: 10.1109/TGRS.2013.2251639
8. Sy, O.O.; Tanelli, S.; Kollias, P.; Ohno, Y., 2014b, "Application of Matched Statistical Filters for EarthCARE Cloud Doppler Products", IEEE Trans. Geoscience and Remote Sensing, vol.52, no.11, pp.7297,7316, Nov. 2014

Displaced Phase Center Antenna error budget analyses



DPCA enables high quality Doppler measurements with 2 Antennas of less than L = 2.5 m diameter.



D = Distance between antennas
ΔD = Separation distance error
Φ = mis-pointing (degrees)

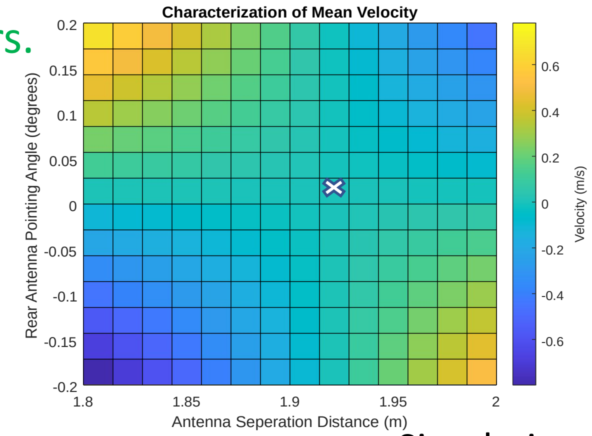
Compared to a single antenna solution with an antenna of say 5 m diameter:

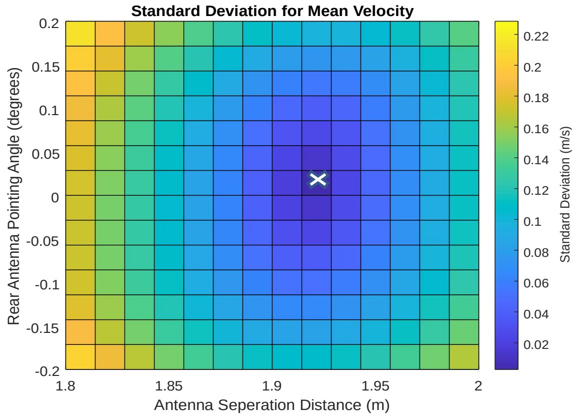
PROS:

1. Eliminates need to manufacture very large mm-wave reflectors.
2. Reduces significantly the 3^{rd} antenna dimension (driven by f, via f/L).
3. Eliminates NUBF biases.

CONS / MITIGATIONS:

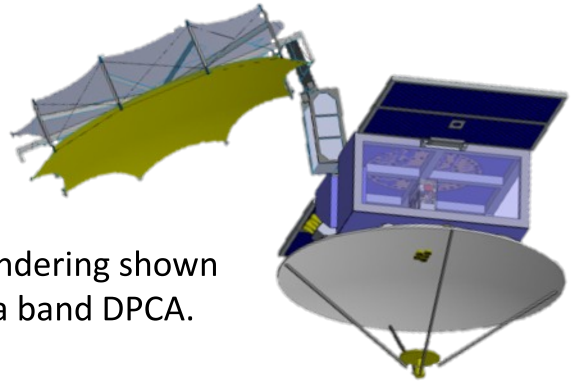
1. Requires PRI to match k*Vs*D
    1. Gentle degradation, adjustable PRI in orbit
2. Requires Antennas to be co-aligned
    1. Gentle degradation, only halving of standard antenna alignment tolerance
3. For specific combinations and sets of requirements, it can result in slow PRF which is then more prone to Doppler aliasing
    1. Coherency supports standard de-aliasing techniques (as in Ground Based Doppler Weather Radars)
    2. Selection between Mode 1 and Mode 2 enables multiple options with the same hardware.





Simulations by : **S. Graniello** (CSU/JPL, 2020)

Displaced Phase Center Antenna independent error analyses

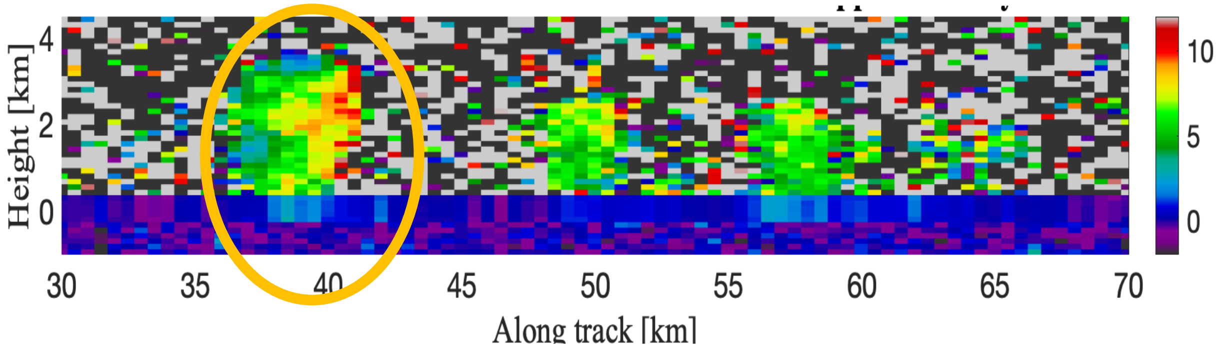


Independent performance analyses are being carried out in the context of the ACCP Designated Observable Mission Architecture studies. This example is of of warm rain convective processes (Courtesy: **P. Kollias**, Stony Brook U.).

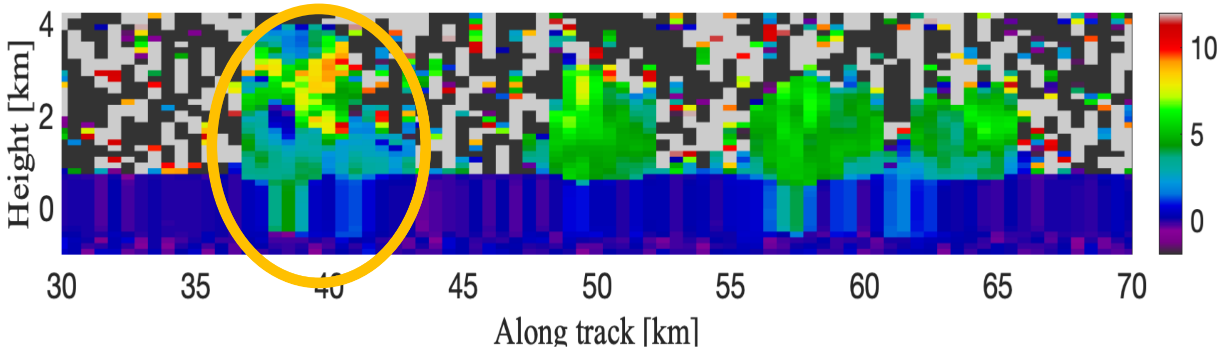
Note the notional graphic rendering shown here supports only Ku and Ka band DPCA.

W-band DPCA is currently analyzed only for 2 non-deployable antenna configurations.

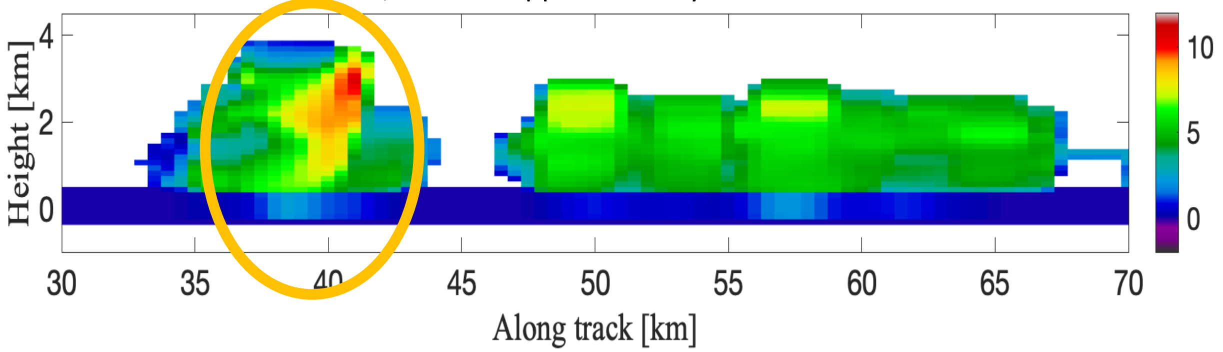
Ka-band **measured**, quality-controlled Doppler velocity



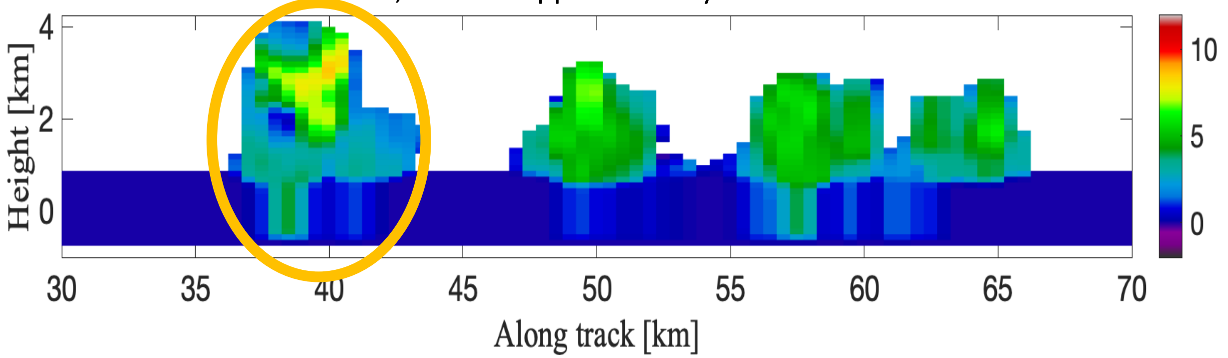
W-band **measured**, quality-controlled Doppler velocity



Ka-band **model**, 'truth' Doppler Velocity at the radar resolution



W-band **model**, 'truth' Doppler Velocity at the radar resolution



Simulations confirm absence of NUBF-induced biases which would be otherwise affecting the measurement in a single-antenna configuration (see [3-8])

RainCube : What’s next ?

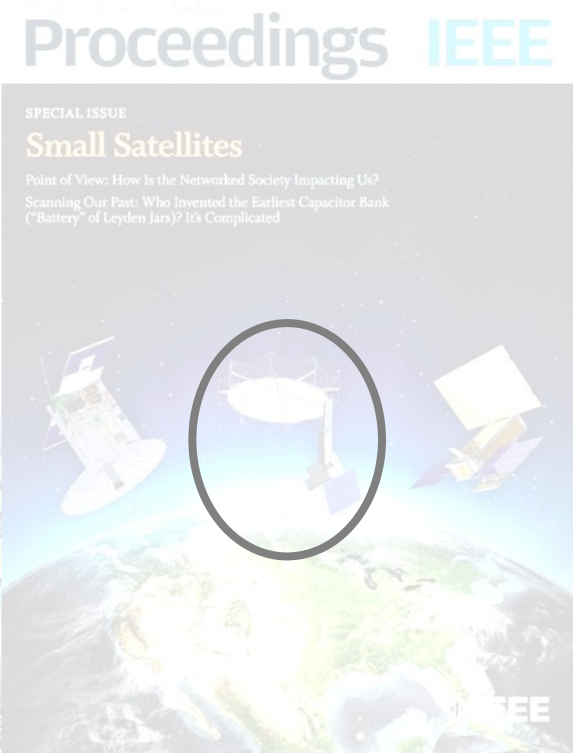
Pre-Decisional Information -- For Planning and Discussion Purposes Only

- 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, G, and Ku 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



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

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- Planetary applications
  - An evolution of this instrument could support altimetry and cloud and precipitation on planetary targets


NASA
Jet Propulsion Laboratory
California Institute of Technology
RainCube Project Team
February, 2017
RainCube
RADAR FOR RAIN PROFILING
CubeSats
(RainCube)
(ASTERIA)
RAINCUBE