RainCube, a precipitation profiling radar in a cubesat. … and its legacy for the next generation of spaceborne cloud and precipitation radars.
The bittersweet conclusion of 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.

**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

**Tvyvak Bus:**
Compact highly integrated bus providing 35W of power to the payload.

---

**Radar Electronics & Antenna Reqs. (4U)**

<table>
<thead>
<tr>
<th>Req’t Name</th>
<th>Requirement</th>
<th>Measured</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sensitivity @400km</td>
<td>20dBZ</td>
<td>11.0dBZ</td>
</tr>
<tr>
<td>Horizontal resolution @400km</td>
<td>10km</td>
<td>7.9 km</td>
</tr>
<tr>
<td>Nadir Data Window</td>
<td>0-18 km</td>
<td>-3 to 20 km</td>
</tr>
<tr>
<td>Vertical resolution</td>
<td>250m</td>
<td>250m</td>
</tr>
<tr>
<td>Downlink data rate (in transmit)</td>
<td>50 kbps</td>
<td>49.57 kbps</td>
</tr>
<tr>
<td>Payload power consumption (AntDeployment/STDBY/RXOnly/TXScience)</td>
<td>10 / 8 / 15 / 35 W</td>
<td>5 / 3 / 10 / 22 W</td>
</tr>
<tr>
<td>Mass</td>
<td>6 kg</td>
<td>5.5 kg</td>
</tr>
<tr>
<td>Range sidelobe suppression</td>
<td>&gt;60dB @ 5km</td>
<td>&gt;65dB @ 1km</td>
</tr>
<tr>
<td>Transmit power &amp; Transmit loss</td>
<td>10W / 1.1dB</td>
<td>&gt;39dBm</td>
</tr>
<tr>
<td>Antenna gain</td>
<td>42 dB</td>
<td>42.6 dB</td>
</tr>
<tr>
<td>Antenna beamwidth</td>
<td>1.2 deg</td>
<td>1.13 deg</td>
</tr>
</tbody>
</table>

**System Architecture**

- **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

**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...

<table>
<thead>
<tr>
<th></th>
<th>CPR</th>
<th>KaPR</th>
<th>RainCube</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass [Kg]</td>
<td>260</td>
<td>336</td>
<td>7</td>
</tr>
<tr>
<td>Power [W]</td>
<td>300</td>
<td>344</td>
<td>22</td>
</tr>
<tr>
<td>Volume [U]</td>
<td>4,356</td>
<td>1,210</td>
<td>4</td>
</tr>
<tr>
<td>Class</td>
<td>C</td>
<td>C</td>
<td>Tech demo</td>
</tr>
<tr>
<td>Frequency</td>
<td>W-band</td>
<td>Ka-band</td>
<td>Ka-band</td>
</tr>
<tr>
<td>Scanning</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Sensitivity</td>
<td>-30 dBZ</td>
<td>+17 dBZ</td>
<td>+12 dBZ</td>
</tr>
</tbody>
</table>
Storms as seen by RainCube

8 examples out of almost 2000 processed scenes

- Deep convection and associated stratiform rain over Borneo
- Orographically enhanced stratiform rain over the Andes
- Scattered shallow rain and snow in the North Atlantic
- Front
- Sloping Zero Isotherm in the Southern Oceans
- Front with embedded deep convection in the North Pac
- Scattered shallow convection in the North Pac
- Snow and stratiform rain in the North Pac
- Stratiform System approaching the Olympic Peninsula
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

Demonstration of feasibility of mission concepts involving multiple radar platforms

2015: RainCube airborne Tech Demo in PECAN

2018: RainCube in orbit

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

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


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
Highly correlated storm measurements from RainCube radar and TEMPEST-D radiometer over Texas, Mexico and Pacific Ocean.

Spaceborne “Atmospheric Radar” landscape (2020)

The 4 “predecessor” Spaceborne Cloud & Precipitation Radars

- TRMM/PR – NICT/JAXA
  Ku, Scanning, Tropical Rain
- GPM/DPR – NICT/JAXA
  Ku/Ka, Scanning, Precipitation
- CloudSat/CPR
  JPL/NASA/CSA
  W, -30dBZ, Clouds
- EarthCARE/CPR
  NICT/JAXA
  W, Doppler, Clouds

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 in LEO)

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

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

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

NOAA Architecture Studies
International developments in EU and Asia
Commercial endeavors

IIP 2019: MASTR
Ku/Ka/W, Scanning, Doppler, SmallSat

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

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

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

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

# = Notional accommodation concept among several possible

* Pre-Decisional Information – For Planning and Discussion Purposes Only
RainCube’s legacy

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

RainCube
Ka-band / 0.5 m

---

Operational monitoring
(Combined w. Radiometers)

Diurnal Cycle sampling
(Operational model validation)

EV-class concept
*Convective Mass Flux in Tropical Storms*

---

# of sats

11-100

6-10

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*

---

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

• 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

<table>
<thead>
<tr>
<th>Ka-band</th>
<th>ESTO InVEST and ACT programs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Antenna size [m]</td>
<td>0.5</td>
</tr>
<tr>
<td>Sensitivity [dBZ]</td>
<td>15</td>
</tr>
<tr>
<td>Hor Resolution [km]</td>
<td>8</td>
</tr>
<tr>
<td>Range Res [m]</td>
<td>250</td>
</tr>
<tr>
<td>Beams</td>
<td>1</td>
</tr>
<tr>
<td>RF Power [W]</td>
<td>10</td>
</tr>
</tbody>
</table>
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.

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.
• 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
  - 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

• Constellation with other Radars and Radiometers:
  - A study team in the Earth Science Decadal Survey 2017 is considering 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 : What’s next?
Pre-Decisional Information -- For Planning and Discussion Purposes Only

<table>
<thead>
<tr>
<th>Ka-band ESTO InVEST and ACT programs</th>
<th>6U</th>
<th>12 U</th>
<th>50 kg</th>
</tr>
</thead>
<tbody>
<tr>
<td>Antenna size [m]</td>
<td>0.5</td>
<td>1.0</td>
<td>2.0</td>
</tr>
<tr>
<td>Sensitivity [dBZ]</td>
<td>15</td>
<td>5-10</td>
<td>0-5</td>
</tr>
<tr>
<td>Hor Resolution [km]</td>
<td>8</td>
<td>4</td>
<td>2</td>
</tr>
<tr>
<td>Range Res [m]</td>
<td></td>
<td></td>
<td>250</td>
</tr>
<tr>
<td>Beams</td>
<td>1</td>
<td>1-3</td>
<td>1-5</td>
</tr>
<tr>
<td>RF Power [W]</td>
<td>10</td>
<td>10-20</td>
<td>10-40</td>
</tr>
</tbody>
</table>
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

---

Displaced Phase Center Antenna error budget analyses

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

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 3rd 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)
Independent performance analyses are being carried out in the context of the ACCP Designated Observable Mission Architecture studies. This example is 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.

Simulations confirm absence of NUBF-induced biases which would be otherwise affecting the measurement in a single-antenna configuration (see [3-8])
• 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 DPCA in 24U

• Constellation with other Radars and Radiometers:
  - A study team in the Earth Science Decadal Survey 2017 is considering 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 1.0 m in 12 U

TENDEG

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