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RainCube, the First Spaceborne Precipitation Radar in a 6U CubeSat

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ABSTRACT

RainCube (**Ra**dar **in** a **Cube**Sat) is a technology demonstration mission to enable Ka-band precipitation radar technologies on a low-cost, quick-turnaround platform. The RainCube instrument concept was conceived at the Jet Propulsion Laboratory. Initial technology development and demonstration paved the way to a mission concept to validate two key technologies in the space environment – a miniaturized Ka-band precipitation profiling radar that occupies ~3U and a 0.5m Ka-band deployable parabolic antenna stowed within 1.5U. RainCube was selected within NASA Science Mission Directorate's Research Opportunities in Space and Earth Science 2015 In-Space Validation of Earth Science Technologies solicitation. The spacecraft bus is developed by Tyvak Nanosatellite Systems, who is responsible for integration and test of the flight system and mission operations.

The radar and spacecraft were delivered on time for their scheduled ISS deployment on the ELaNa-23 launch in May 2018 from Wallops Flight Facility. The ultra-lightweight compact deployable Ka-band antenna was successfully deployed on July 28, 2018 and the radar made its first observation of precipitation on August 27, 2018. The mission continues to operate and has met all its Level 1 requirements through repeated observations of precipitation in the atmosphere. At the time of writing, the RainCube mission has been extended through August of 2019 with the spacecraft expecting to stay in orbit until summer 2020, and the potential for the mission to be extended through the end of the spacecraft's life.

This paper discusses the developments and results achieved by this novel technical approach, and its impact on mission concepts that may address the Clouds, Convection and Precipitation Designated Targeted Observable as defined in the 2017 Earth Science Decadal Survey.

INTRODUCTION

RainCube (Radar in a CubeSat) is a 6U CubeSat mission developed between the Jet Propulsion Laboratory (JPL) and Tyvak Nano-Satellite Systems (Tyvak). The objective of the mission is to develop, launch, and operate a 35.75 GHz nadir-pointing precipitation profiling radar payload to validate a new architecture for Ka-band radars and an ultra-compact deployable Ka-band antenna design in the space environment. RainCube has demonstrated the feasibility of a radar payload on a CubeSat platform. The radar payload is the evolution of two previous JPL research and development technologies – the miniaturized Ka-band atmospheric radar (miniKaAR) and the 0.5m diameter Ka-band radar parabolic deployable antenna (KaRPDA). JPL has contracted Tyvak to develop the spacecraft bus, complete system integration and testing of the spacecraft and radar, and operate the spacecraft and radar on-orbit.

The radar instrument in RainCube belongs to the class of precipitation radars that are capable of sending a signal that penetrates deep into the layers of a storm and measures the precipitation at those layers such that scientists can learn about the processes that make the storm grow or decay. The RainCube radar takes measurements similar to currently orbiting large spacecraft, such as Global Precipitating Monitoring (GPM), but its novel architecture has enabled the simplification and miniaturization of the radar subsystems such that they can fit within a CubeSat volume. This architecture also reduces the number of components, power consumption, and mass by over one order of magnitude with respect to the existing spaceborne radars, resulting in further cost savings.

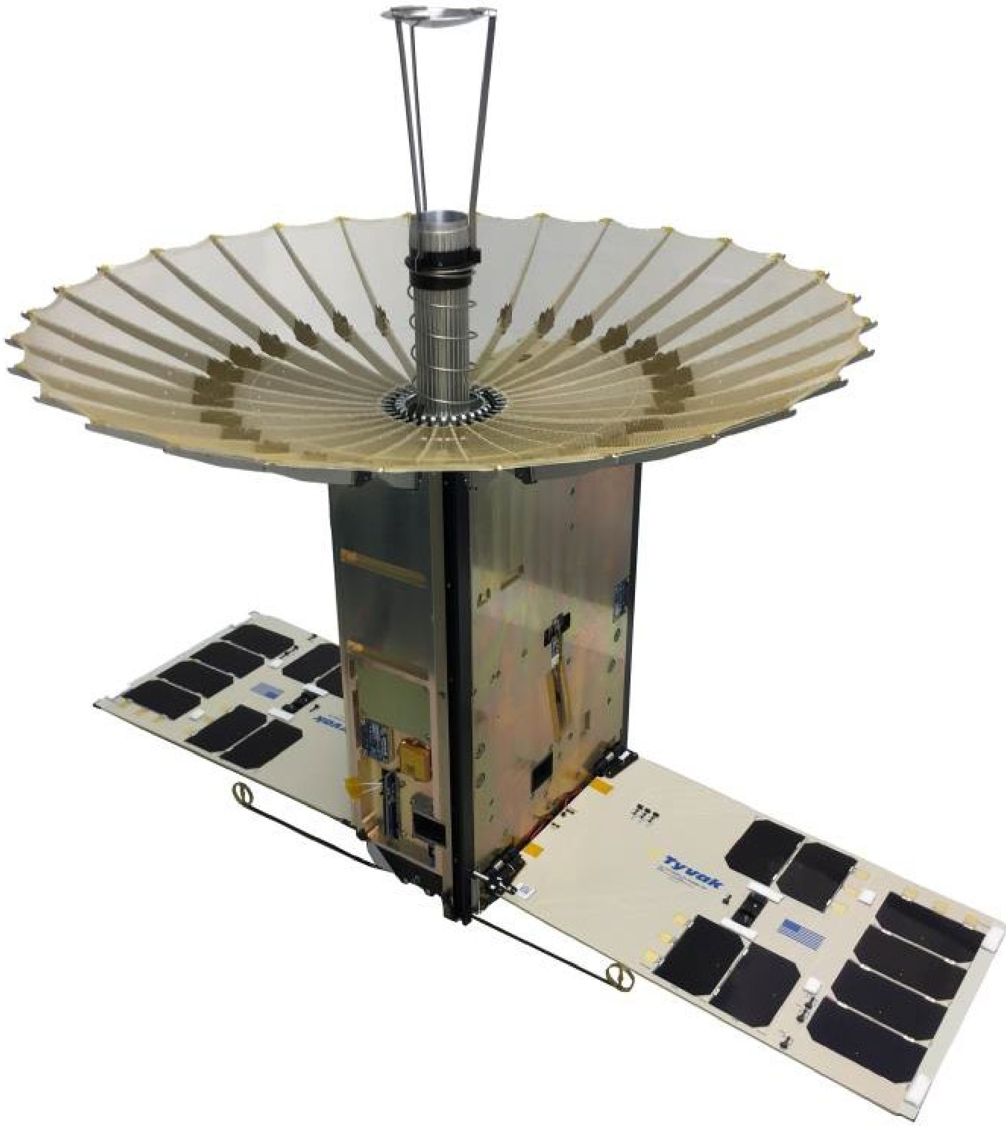

Figure 1. The RainCube 6U CubeSat fits the 0.5m antenna into 1.5U, the radar electronics into 1.5U, and the spacecraft bus into 2U. The vehicle has deployable solar panels and UHF antennas.

Thus, the RainCube mission demonstrates the potential for an entirely new and different way of observing Earth with a constellation of low-cost small radars. This constellation could provide the spatial and temporal coverage and sampling that is needed to improve our understanding of Earth's water cycle and eventually advance the numerical weather models that are used for weather forecasting.[1]

InVEST-15 Solicitation

The RainCube mission is funded through NASA's Earth Science Technology Office (ESTO) in the Science Mission Directorate. RainCube was proposed in May 2015 as a response to ESTO's InVEST-15 (In-Space Validation of Earth Science Technologies) solicitation. The goal of the solicitation is to raise the maturity of subsystem and instrument technologies from TRL 4-5 to TRL 7 through successful in-space demonstration. RainCube was selected in September 2015 with the CubeRRT, CIRAS, and CIRiS 6U CubeSat missions.[2]

SPACECRAFT SYSTEMS

RainCube is made up of two main sections, the radar payload and the spacecraft bus (shown assembled in Figure 2). The radar payload consists of the radar electronics, miniKaAR-C, and the deployable Ka-band antenna, KaRPDA. The spacecraft bus is developed using Tyvak's Endeavour avionics platform and provides power, data, and thermal interfaces to the payload.

miniKaAR-C

The miniaturized Ka-band Atmospheric Radar for CubeSats (miniKaAR-C) is demonstrating an enabling radar technology that can fit within a small satellite form factor. Radar instruments are typically not suitable for small satellite platforms due to their large size, weight, and power (SWaP). A novel architecture for a Ka-band precipitation profiling radar has been developed at JPL, the miniKaAR, which reduces the number of components, power consumption, and mass by over an order of magnitude with respect to the existing spaceborne radars, and it is compatible with the capabilities of low-cost satellite platforms such as SmallSats or CubeSats.

The key enabler to reduce SWaP in miniKaAR is the modulation technique: offset IQ (in-phase and quadrature) with pulse compression. Previous spaceborne cloud and precipitation radars have adopted high power short monochromatic pulses to achieve the required sensitivity with low range sidelobes (to avoid contamination of the tropospheric echoes by the surface response). This requires high-power amplifiers and either high-voltage power supplies or large power-combining networks, precluding small-size/low-power platforms. Pulse compression is used to achieve the required sensitivity with off-the-shelf Gallium Arsenide (GaAs) solid-state amplifiers Pseudomorphic High Electron Mobility Transistor (pHEMT) chips. Optimal selection of the pulse shape minimizes the range sidelobes.

The digital subsystem consists of a single board that includes low power CMOS digital-to-analog conversion (DAC), analog-to-digital conversion (ADC), telemetry ADC chips and a single commercial-grade flash-based FPGA performing all control, timing, and on-board processing (OBP). The radar OBP algorithm consists of data filtering, range compression, power computation and along-track averaging. Triple mode redundancy is used for all critical functions and most non-critical functions. In addition, rad-hard interlock circuits are used for all critical signals that could result in radar damage in the event of a single-event-upset.

These advances make the miniKaAR-C practical with the inherently limited resources of the CubeSat form factor. When operating in transmit-mode, the radar requires 22W of power (with up to 1W RF out) and produces a data stream of up to 50 kbps. Receive-only and standby modes only consume 10W and 3W respectively and have lower data rates (<10 kbps). Including the antenna, the radar (Figure 2) has a flight mass of 5.5kg and the single 'H-frame' chassis allows heat to be transferred to thermal radiating faces on the spacecraft bus. [3]

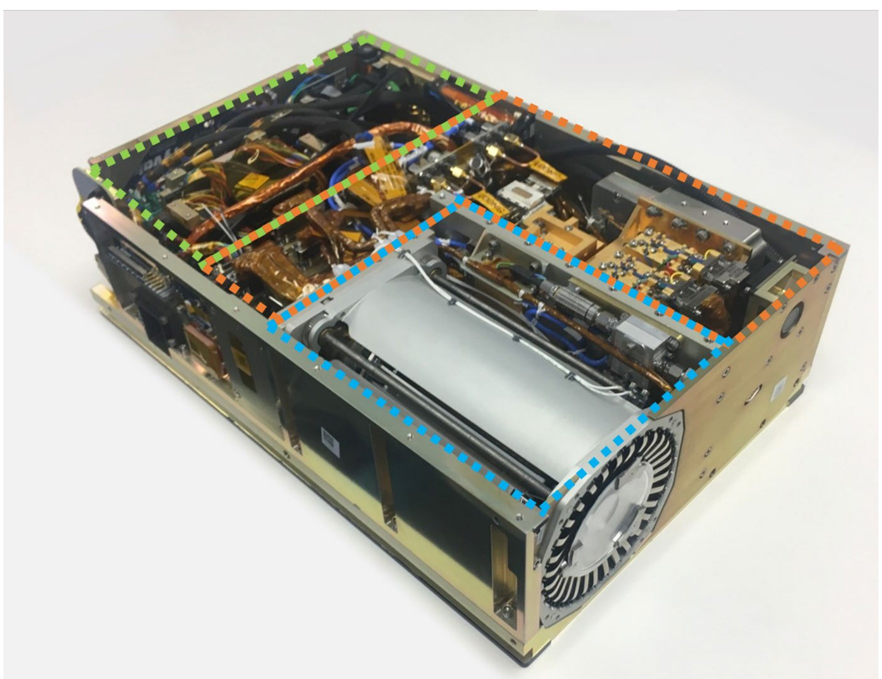

Figure 2. The mini-KaARC radar electronics (orange line), KaRPDA deployable antenna (blue line), and spacecraft bus (green line), integrated into the flight chassis, prior to launch

Radar Antenna – KaRPDA

The radar's resolution is directly related to the aperture of the antenna. RainCube is using an antenna that is larger than its longest dimension. The Ka-band Radar Parabolic Deployable Antenna (KaRPDA) is a 0.5-meter antenna that stows in 1.5U. This antenna is optimized for the radar frequency of 35.75 GHz and is measured to produce a gain of 42.6 dBi (over 50% efficiency) in the flight configuration. The antenna uses a Cassegrain architecture as it places the sub-reflector below the focal point of the antenna, allowing the antenna to stow in a tight volume.[4] The mesh antenna surface is supported by deep ribs, which provide high structural rigidity to stretch the mesh to a precise parabolic shape. These ribs provide another advantage by allowing the hinges to have precision stops located approximately one half inch from the pivot point. This ultimately minimizes the influence of manufacturing tolerances. The tip ribs are tapered near the end, where stiffness is not required, to maximize stowed space. The ribs are connected at the bottom of the root rib to a hub, which also supports the horn and secondary reflector. The hub supports all 30 ribs on the antenna.

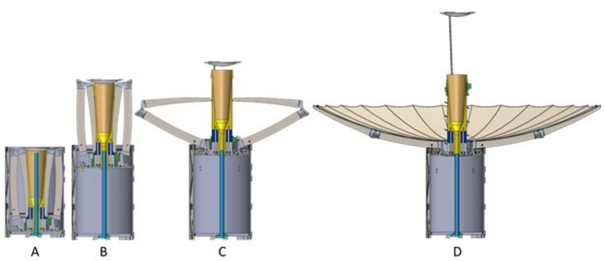

Figure 3: The deployment sequence unfurls the 0.5m antenna from a 0.1m diameter cylinder.

To deploy, the hub is driven upwards by four lead screws attached to nuts in the hub, pushing the antenna upwards (images A/B in Figure 3). As the hub begins to reach the top, the spring ring, which is attached to the root rib hinges, catches on a detent in the top of the antennas stowed canister and the ribs begin to deploy (B/C). The tip ribs reach a point where they no longer interfere with the horn, and they are deployed by the constant force springs located in the mid rib hinge (C). After the ribs have cleared the horn the sub-reflector is released by a latching feature on the root rib hinges and is held in place by a spring (C/D). The hub continues to travel upwards until the root ribs have fully deployed (D). After the antenna is fully deployed, it is locked in place with the lead screws, and the root ribs are preloaded by the spring ring.[5]

Spacecraft Bus

The radar payload is integrated into a spacecraft bus provided by Tyvak. The majority of hardware, and all the software used for RainCube is designed, developed, and tested by Tyvak in their Irvine, CA facility. This 'one-stop-shop' approach simplifies the overall development and gives greater control of design accommodations, schedule, cost, and risk management by eliminating third party interfaces and troubleshooting. RainCube is based off of Endeavour technology base, which includes Command and Data Handling (C&DH), Electrical Power System (EPS), Attitude Determination and Control (ADCS), and Communication Systems. To meet the specific requirements of the mission, the bus is tailored around the payload with minimal non-reoccurring engineering. Only small changes are needed to the structure, fixed solar panels, and electronics backplane between programs to accommodate internal mounting, instrument aperture locations, and payload interface thermal requirements.

The Endeavour Avionics Board provides a data recorder and processing for the C&DH and ADCS systems, along with interfaces to the Inertial Reference Module that contains two star cameras, three orthogonal reactions wheels, and three torque rods. The battery module is scalable and has been configured into a single 70W-Hr pack that supports RainCube's high peak charge currents and orbit-long payload operations. The spacecraft's 1U x 3U faces provide volume for electronics routing, GPS antennas, the S-Band patch antenna, and coarse sun sensors. The broad 2U x 3U faces of the structure act as primary radiating surfaces for thermal management and have a silver Teflon coating. The radar operational temperature range led to a thermal design that includes survival heaters and tuned optical properties of the structure to ensure the flight system stays within allowable flight temperatures over the duration of the mission.

The communication systems are UHF (RX/TX) and S-Band (TX). Tyvak operates two UHF ground stations, one in San Diego, near their Mission Operations Center (MOC) in Irvine, CA, and one in Italy. The UHF link is primarily used for commanding the spacecraft, and the S-band link, which uses KSAT's expansive ground station network, is used for higher downlinking rates required for the payload data volume. This enabled Tyvak to downlink 1.73 Gb of radar per day. All spacecraft operations and data were routed through servers in Tyvak's MOC where the payload data will be delivered to JPL using a secure VPN.

Lastly, the large, fixed-angle deployable solar arrays close the power budget with the vehicle operating in

Local Vertical Local Horizontal (LVLH) attitude for one continuous orbit of radar operations and three orbits of sun-pointing. Operations of the vehicle will utilize Tyvak's C2D2 ground software in their local Mission Operations Center (MOC) in Irvine, CA. The bus also hosts a 3MP color imager with a fish-eye lens mounted at an optimal angle to capture images of the KaRPDA deployment on-orbit.[3]

INTEGRATION, TEST, AND LAUNCH

The integration of the payload began with building up the miniKaAR-C components on a thick aluminum plate to which the instrument and antenna were attached, in January of 2017. The thickness of this plate was driven by the radar thermal requirements as opposed to structural concerns. A scope was then connected to the waveguide output, and instrument performance was tested in an ambient pressure, thermal environment. This enabled performance characterization of miniKaAR-C prior to further payload assembly.

Once the functional and performance of the radar electronics were verified, KaRPDA, in the stowed state, was installed at the end of the instrument waveguide. The fully assembled payload subsequently underwent a workmanship vibration test at 7.2 G_{RMS} and a protoflight thermal vacuum test. The thermal vacuum test began with an abbreviated burn-in followed by deployment of KaRPDA and standby characterization of the miniKaAR-C instrument. To obtain comparative payload data with the integrated antenna, the test chamber was returned to room temperature and pressure and a custom, close fitting waveguide was installed in the horn of the antenna. A waveguide to coax-connection was installed on top of the waveguide, and the coax cable was routed outside of the chamber through a feedthrough. The chamber was then re-sealed, and the radar payload performance was characterized in vacuum over the protoflight operational temperatures. All testing of the payload was completed in March of 2017. The 5.5 kg assembled and qualified payload was delivered to Tyvak in June of 2017.

Upon delivery to Tyvak, the radar payload was mounted to one of the 2U x 3U structural walls, which also acts as a radiator. After an initial build up and fit checks, the flight system underwent functional characterization under a number of test scenarios to verify the radar and spacecraft interfaces. Prior to the system-level vibe test, the fully integrated RainCube satellite was functionally tested end-to-end, a full deployment of KaRPDA was demonstrated, and a self-compatibility test with all spacecraft and radar operating modes in an EMI chamber was completed. A system-level protoflight random vibration test was completed in a NanoRacks dispenser in early 2018 followed by a system-level bake-out and thermal balance test. Due to volume constraints, KaRPDA was not deployed in the system thermal-vacuum test. This was deemed as low mission risk given the previous deployments in thermal vacuum and ambient conditions.

For final system verification, day-in-the-life testing was performed in an EMI chamber, which included all mission scenarios from dispenser deployment to spacecraft commissioning to KaRPDA deployment and radar payload operation. This test verified the mission sequencing and flight software scripts and radar performance prior to launch delivery. The RainCube satellite was transported to Houston, Texas in March 2018 for integration into a NanoRacks 'doublewide' (2Ux6U) dispenser, which was shared with the HaloSat satellite.

RainCube was manifested on the ELaNa-23 flight with six other CSLI CubeSat missions [6]. On May 21st, 2018, RainCube was launched on OA-9's ISS resupply mission as part of the soft cargo. After launch, RainCube and the other CSLI CubeSats remained unpowered on-board the ISS until a deployment window became available. In the interim, the JPL and Tyvak teams performed several spacecraft operation rehearsals including off-nominal scenarios.

COMMISSIONING, OPERATIONS AND SCIENCE RESULTS

On July 13th, 2018 at 1:05 AM PDT, RainCube and HaloSat were jettisoned from the ISS. Initial contact with the RainCube spacecraft was made on the first ground station pass, about one hour later, which confirmed solar panel and UHF antenna deployment. During the next two weeks, general spacecraft commissioning occurred, which included attitude

Figure 4. KaRPDA successfully deployed on orbit on July 29th over the South Pacific

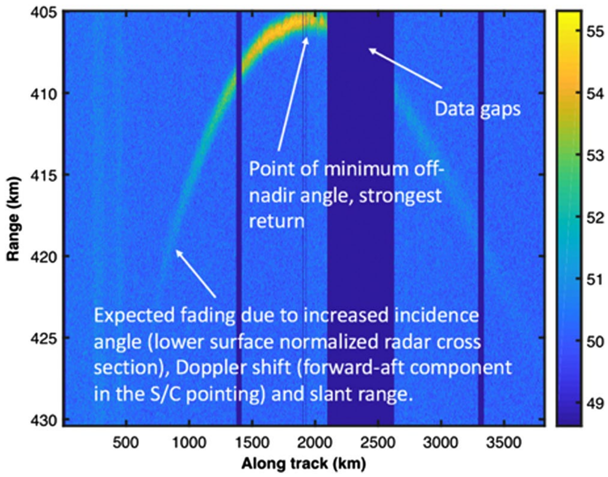

Figure 5: First Echo from RainCube

control system calibration, deployment verification, camera performance, and S-band downlink.

After initial spacecraft commissioning, on July 25th, the radar was tested in standby mode during a ground-in-the-loop UHF pass. This was to verify basic functionality of miniKaAR-C prior to antenna deployment. On July 28th, KaRPDA was commanded to deploy, and telemetry downlinked via the UHF indicated a successful deployment. On July 29th, photos from the payload camera were downlinked (Figure 4), which provided visual verification that KaRPDA had successfully deployed.

To further exercise the radar, standby mode was again verified on August 1st followed by a receive-only mode check on August 3rd. The first transmit mode pulses were sent and received on August 5th, shown in Figure 5. As the spacecraft was in course sun pointing mode, this measurement provided confidence in the radar operation, but it was not sufficient to fully verify the radar performance on-orbit.

Over the next three weeks, spacecraft commissioning was completed, which included transitioning from course sun pointing to fine pointing of the ADCS. On August 27th, while in fine pointing mode, RainCube observed a thunderstorm near Monterrey Mexico (Figure 6). This measurement verified the radar functionality and performance on-orbit, and it marked the first active measurement and the first radar measurement from a CubeSat.

RainCube continues to collect precipitation data in Lower Earth Orbit. On Sept. 28th, RainCube and TEMPEST-D (a CubeSat radiometer developed by JPL that also launched on ELaNa-23) both observed Typhoon Trami from orbit. This enabled overlapping of RainCube's radar data with TEMPEST-D's radiometer data (Figure 7), illustrating the potential opportunities for future missions to coordinate constellations of CubeSat or SmallSat instruments to collect more holistic Earth science data [7]. This is just a glimpse of the future Earth observations that could be made possible by the next generation of Earth Science CubeSats and SmallSats.

CONCLUSION

JPL has validated two new technologies through in space operations with the RainCube mission, the KaRPDA and miniKaARC. The novel Ka-band precipitation profiling radar architecture and highly constrained parabolic deployable antenna can fit within a 6U CubeSat volume. Paired with Tyvak's spacecraft bus, the RainCube mission has been the first CubeSat with an active sensing payload, ushering in a new generation of Earth science focused CubeSat missions. The demonstration of RainCube's technology could enable a future constellation mission of many precipitation profiling radars. Grouping multiple vehicles in a 'train' could show the evolution of precipitation processes at the minute-level scale and improve forecasting models. The first steps of creating such a 'train' were evidenced by the RainCube/TEMPEST-D observations of Typhoon Trammy. Flying multiple groups in different orbital planes could show diurnal cycle variability. The

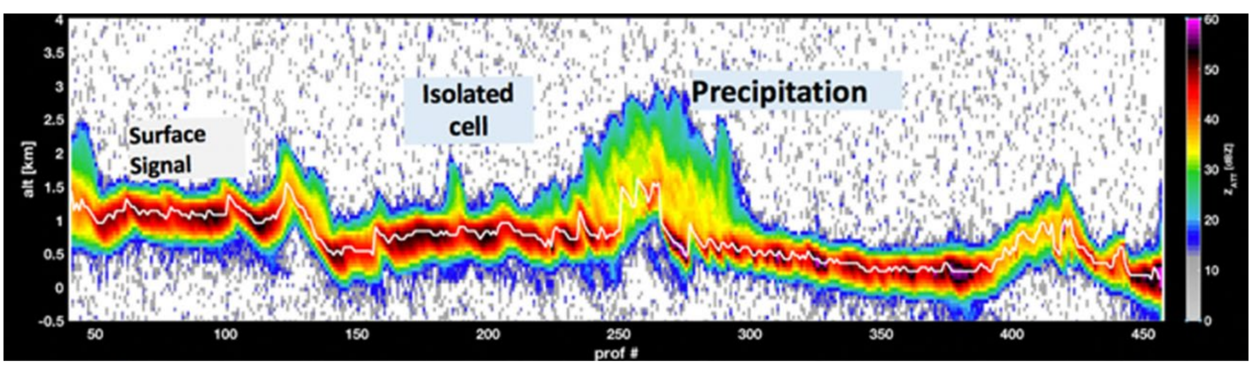

Figure 6: First Precipitation Data from RainCube

compact radar and deployable antenna technologies on RainCube will open a new realm of possibilities for scientific discoveries.[8]

To follow the status of this mission through launch and operations, please visit the official RainCube website at http://www.jpl.nasa.gov/cubesat/missions/raincube.php.

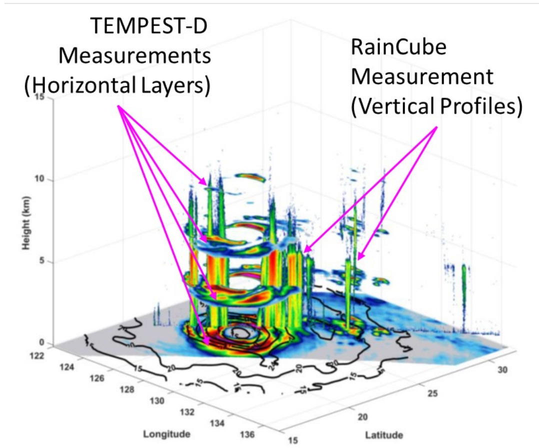

Figure 7: TEMPEST-D and RainCube co-observed Typhoon Trami

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