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Abstract. RainCube (Radar in a CubeSat) is a technology demonstration mission to enable Ka-band precipitation radar technologies on a low-cost, quick-turnaround platform. The 6U CubeSat, currently in orbit, features a radar payload built by the Jet Propulsion Laboratory and a spacecraft bus and operations provided by Tyvak Nano-Satellite Systems. Following the deployment of the half-meter parabolic antenna, the radar first observed rainfall over Mexico. The mission continues to operate and has met all requirements through repeated observations of precipitation in the atmosphere. RainCube is funded through the Science Mission Directorate's Research Opportunities in Space and Earth Science 2015 In-Space Validation of Earth Science Technologies solicitation. We report on the first radar observations of precipitation. © *2019 Society of Photo-Optical Instrumentation Engineers (SPIE)* [DOI: 10.1117/1.JRS.13.032504]

1 Introduction

RainCube (Radar in a CubeSat) is a 6U CubeSat mission developed between the Jet Propulsion Laboratory (JPL) and Tyvak Nano-Satellite Systems (Tyvak), which is the first ever radar instrument in a CubeSat.[1–4] 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 miniaturized architecture for Ka-band atmospheric radars and an ultracompact deployable Ka-band antenna design in the space environment, which are compatible with a 6U CubeSat platform. Through a competitive bid process, the RainCube JPL team selected Tyvak Nanosatellite Systems, LLC in Irvine, California, to develop the flight system, integrate the payload, and operate the payload on orbit.

The radar instrument in RainCube belongs to the class of atmospheric radars that are capable of sending a signal that penetrates deep into the layers of a storm and measures the precipitation at those layers, which provides a picture of the activity inside the storm such that scientists can learn about the processes that make the storm grow or decay. There is a network of ground-based weather radars that feed a large amount of information, which is currently used for weather forecasts. However, only developed countries are capable of supporting such networks, ocean ranges remain largely unreachable, and many mountain ranges present significant challenges; therefore, they cannot provide a global view. There are also weather satellites that provide a global view, but those only capture images of the top of the storms, and they do not provide much of the information that is needed to understand what is happening inside the storms. A couple of spacecrafts with downward looking cloud or precipitation radars, i.e., TRMM's PR (Tropical Rainfall Measurement Mission[5] Precipitation Radar), CloudSat's CPR (Cloud Profiling Radar[6,7]), and GPM's DPR (Global Precipitation Measurement mission, Dual frequency Precipitation Radar[8]), have enabled improved understanding of the structure and global

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distribution of storms, but these missions are usually expensive and thus cost prohibitive to launch a constellation for continuous global coverage. The RainCube radar takes measurements in a similar geometry, but its architecture has enabled the simplification and miniaturization of the radar subsystems such that they could fit within the volume, mass, and power constraints of small satellites, significantly reducing the cost to manufacture. Thus, the RainCube mission ultimately demonstrates the potential for an entirely new and different way of observing Earth with a constellation of low-cost small radars. This constellation would 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.

The RainCube mission is funded through NASA's Earth Science Technology Office (ESTO) in the Science Mission Directorate as a response to ESTO's InVEST-15 (In-Space Validation of Earth Science Technologies, 2015) solicitation.

RainCube was deployed from the ISS on July 13, 2018 and this paper reports on the first observations of precipitation. At the time of writing, the RainCube mission has been extended until May of 2019 with the spacecraft expecting to stay in orbit until mid-2019.

2 RainCube as an Earth Science Mission Enabler

Numerical climate and weather models depend on measurements from spaceborne satellites to complete model validation and improvements. Precipitation profiling capabilities pioneered by TRMM's PR and further advanced by CloudSat's CPR and GPM's DPR are currently limited to few instruments deployed in low Earth orbit (LEO). Therefore, their high-quality observations are sparse spatially and temporally with respect to the typical scales of weather phenomena (from tens of seconds to hours and from a few tens of meters to tens of km). These missions therefore are generally unable to observe the short-time evolution of weather processes, which is needed to validate and improve the current assumptions and skills of numerical weather models. The synergy with larger numbers of passive sensors (e.g., wide-swath microwave radiometers) mitigated this observational gap but only in the sense of coarse vertical profiling and increased uncertainties (specifically over land and ice), which do not provide observations for a large part of the processes driving the evolution of many types of weather systems. Projects to advance the technologies enabling the deployment of precipitation radars in geostationary orbit (GEO) have been successful on several fronts, but the state-of-the-art for very large lightweight deployable antennas and related cost considerations do not enable this approach yet. One alternative is to deploy several radars in LEO (as a convoy or constellation). This has not been realistically affordable for decades until the arrival of the CubeSat and SmallSat platforms, and the challenge moved to the capability to simultaneously miniaturize and reduce cost while preserving the fundamental performance requirements for this type of radar.

The RainCube architecture reduces power consumption, mass, and the number of components, by more than one order of magnitude with respect to existing spaceborne radars. We can now seriously consider deploying a number of identical copies of the same instrument in various relative positions in LEO to address specific observational gaps left open by the current missions.[9–13] RainCube is the first demonstration of what could become a constellation of precipitation profiling instruments in small satellite form-factors.

3 RainCube's Radar Payload

RainCube's payload is a Ka-band nadir pointed precipitation profiling radar. The radar transmits a signal centered around 35.75 GHz, which is reflected back by precipitation particles as it travels through the atmosphere and eventually reaches the ground and reflects back. The magnitude of the received echo as a function of time, t, provides a measurement of the reflectivity at a vertical distance from the radar, $ct/2$, where c is the speed of light. At Ka-band, precipitation (and to a smaller extent water vapor and cloud liquid water) also attenuate the signal as it propagates through it. Thus, the RainCube radar measurement consists of a vertical profile of the reflectivity of the precipitation particles attenuated by the precipitation in the intervening path, followed by a measure of the surface echo attenuated by the entire column of precipitation.

These two measurements are typically used to retrieve the intensity and structure of the precipitation.

To fit a science-grade radar within the tight 6U CubeSat volume, RainCube takes advantage of a new architecture: the key innovation in this architecture is the modulation technique: offset IQ (in-phase and quadrature) with pulse compression.

Pulse compression is a well-known radar technique that reduces the peak power needed to achieve a certain sensitivity without losing resolution by sending a long pulse with a frequency modulation or chirp. However, pulse compression is rarely used for atmospheric radars and has never been used before in a spaceborne precipitation radar. The reason for that is the clutter introduced by the surface (that is, the surface backscatter spread in time t by the pulse compression filter response and the antenna pattern), which at near-nadir, especially over ocean, is highly reflective. Using standard pulse compression, the radar surface response exhibits high-range sidelobes that contaminate the echoes that arrive from the troposphere in the lowest layer that is within the pulse length above the surface (which may mean from a few km to the entire troposphere, depending on the length of the pulse). Previous spaceborne cloud and precipitation radars have adopted high power short monochromatic pulses to achieve the required sensitivity and range resolution such that measurements of clouds and precipitation are affected by surface clutter only within the time of the short pulse response (typically a few hundred meters to less than 2 km when pointing off nadir). This requires high-power amplifiers and either high-voltage power supplies or large power-combining networks, precluding small-size/low-power platforms. RainCube uses pulse compression with a long pulse (up to 166 μs) to achieve high sensitivity with off-the-shelf GaAs solid-state amplifiers. Through an optimal selection of the pulse shape and subsequent digital processing, the range sidelobes are suppressed to less than −55 dB at 500 m and −70 dB at 1 km above the surface, which is sufficient to accurately measure most relevant precipitation processes near the surface. Figure 1 shows the typical range compressed pulse response in dB computed from flight data using the calibration path. The low-near range sidelobes enable precipitation detection close to the surface, and the suppressed far range sidelobes (−90 dB beyond 2 km) ensure a clutter-free measurement for the complete troposphere. RainCube pulse bandwidth of 2.5 MHz and amplitude apodization with a Hanning window result in a range resolution of ~120 m, which is then averaged to 240 m to improve sensitivity and for consistency with state-of-the-art spaceborne precipitation mission data products.

The IQ (in-phase and quadrature) modulation scheme selected for RainCube reduces the number of RF components with direct up/downconversion from baseband to Ka band as shown in Fig. 2. However, IQ mixers are not ideal, and the residual LO (local oscillator) leakage and signal image can severely impact the radar response sidelobes. The range sidelobes produced by these spurious products are roughly equal to the image or LO suppression minus the range compression gain, which is defined as the pulse width times the bandwidth. State-of-the-art IQ mixers can easily achieve approximately −20 dB suppression for both LO leakage and image. However, with the 26-dB range compression gain of RainCube, the sidelobe level at −56 dB is not acceptable. There are techniques to suppress the image and LO even further,[14,15] but these are
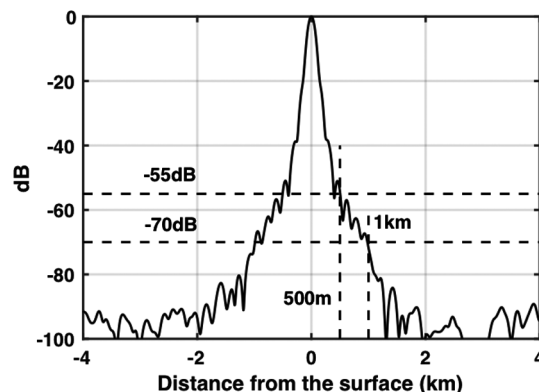

Fig. 1 RainCube's flight pulse response obtained from in-orbit calibration data.
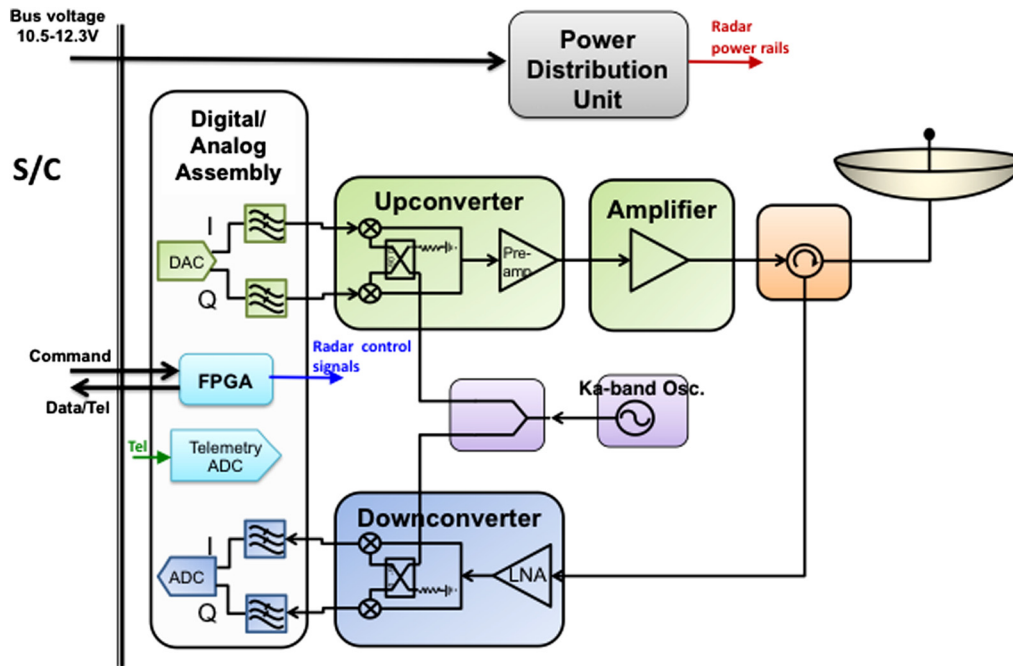
Fig. 2 RainCube's radar block diagram. Abbreviations: S/C, spacecraft; Osc, oscillator; DAC, digital-to-analog converter; ADC, analog-to-digital converter; FPGA, field programmable gate array; Pre-amp, preamplifier; LNA, low noise amplifier; Tel, telemetry.

temperature and aging sensitive, and they are not sufficiently robust for a low-cost flight mission. RainCube uses an offset IQ technique, in which the baseband signal is offset in frequency sufficiently to avoid contamination from the LO leakage and image by a combination of analog and digital techniques. It has been demonstrated that RainCube's performance is not impacted even if the image/LO suppression is highly degraded; therefore, it is a very robust modulation technique that does not require adjustments or tuning.

RainCube's digital subsystem is highly simplified compared to similar radars, and it consists of a single board that includes low power complementary metal-oxide-semiconductor digital-to-analog conversion (DAC), analog-to-digital conversion (ADC) and telemetry ADC chips, and a single commercial-grade flash-based field-programmable gate array (FPGA) performing all control, timing, telemetry acquisition, data formatting, S/C bus communications, and on-board processing (OBP). The radar raw data capture rate is ~425 Mbps and includes a science window, as well as noise and calibration windows, to capture receive only noise and a replica of the transmit chirp. Since it would be prohibitively expensive to downlink this amount of data, RainCube's radar relies on extensive OBP to reduce the data rate by almost four orders of magnitude to ~50 kbps in transmit mode, which is in line with current CubeSat technology capabilities. The radar also supports a receive-only mode (radar is not transmitting), and a standby mode, where only basic health and telemetry functions are available at lower data rates (<10 kbps). The radar OBP algorithm includes data filtering, range compression, power computation, and along-track averaging for a given integration time. It also performs averaging of the calibration signal. Given the simplicity of the algorithm, and the large amount of resources in commercial FPGAs, triple mode redundancy (TMR) is used for all critical functions and most noncritical functions, including most of the OBP, and error detection and correction (EDAC) is used for critical memory functions. In addition, rad-hard hardware interlock circuits are implemented for all critical signals that could result in radar damage in the event of a single-event-upset. The digital board reports telemetry faults in the interlock circuits, TMR voter logic and EDAC, both correctable and uncorrectable.

The RainCube radar commanding interface was designed to support variable pulse repetition interval, pulse width, and pulse amplitude parameters. In order to simplify the testing, a fixed pulse repetition interval of 1660 μs was selected. However, the pulse width, pulse chirp

bandwidth, and amplitude, in addition to various parameters that determine the pulse shape, peak power, and image/LO rejection, remain programmable flight parameters.

When operating in transmit-mode, the radar requires 22 W of power (up to 1 W average RF output power with a 10% transmit duty cycle). Receive-only and standby modes only consume 10 and 3 W, respectively. Including the antenna, the radar has a flight mass of 5.5 kg.

Even with this modest power consumption for a radar, thermal management has been a significant part of RainCube's design since the beginning of the mission. RainCube has a passive thermal design (except for survival heaters) with the subsystems mounted on a single plate that allows heat to be transferred to thermal radiating faces on the spacecraft bus. Detailed analyses have been performed on all analog, RF, digital boards, and their components following standard practices of higher-class flight missions, to ensure appropriate margins exist for the components and materials given the expected mission environment.

RainCube's radar payload uses mostly commercial off-the-shelf components that have been carefully selected to withstand an LEO radiation environment. For critical functionality, such as where single event upsets could result in damage to the radar or unpredictable behavior, radiation hardened components are used.

RainCube is a real aperture nadir pointing radar, that is, the horizontal resolution is directly related to the aperture of the antenna. RainCube uses an antenna whose aperture size is larger than the bus longest dimension. The Ka-band Radar Parabolic Deployable Antenna (KaRPDA) is a 0.5-m antenna that stows in ∼1.5U.[16–25] 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 subreflector below the focal point of the antenna. This enables the antenna to be stowed in a tight volume.

Figure 3 shows a picture of the as-built radar payload prior to integration with the spacecraft (S/C) bus. The radar's RF, analog, and digital electronics occupy a volume of ∼2.5U of the spacecraft's 6U volume. These components are tightly packaged around the mission's 0.5-m deployable antenna, which is stowed in a canister that occupies about 1.5U volume (top left corner of Fig. 3).

Table 1 summarizes the key specifications of the RainCube radar instrument.

4 RainCube's Flight System

The standardized CubeSat form factor pushes payload developers and spacecraft bus providers to maximize capability in a limited volume. The very compact RainCube radar design still leaves
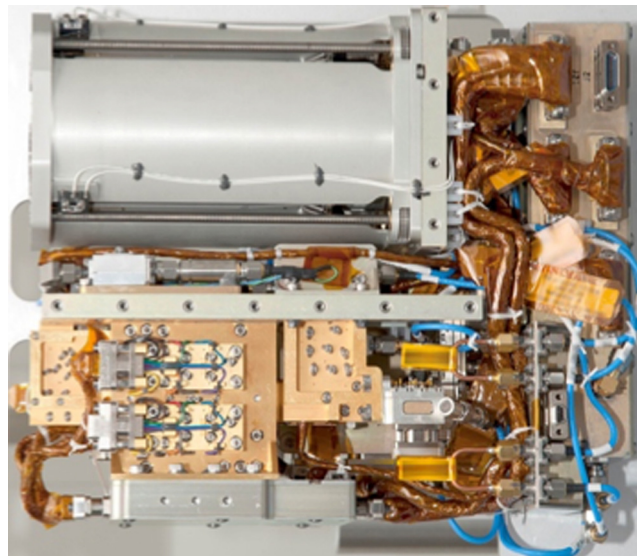

Fig. 3 The radar electronics (bottom and right) and deployable antenna (top left) integrated into the flight chassis.

Table 1 Key RainCube performance metrics.

Metric	Value
Mass	5.5 kg
Volume (full assembly)	24.8 cm × 21.5 cm × 9.7 cm
Power (standby/Rx/Tx)	3 W/10 W/22 W
Resolution	7.9 km (horizontal) 120 m (vertical)
Sensitivity	13 dBZ
Integration time	Science data: 0.28 s Calibration data: 0.85 s
Radar peak transmit power	10 W
Pulse width	166 μs (nominal)
Pulse chirp bandwidth	2.5 MHz
Pulse repetition interval	1660 μs
Data generation	Science mode: 50 kbps
	Standby and receive mode: 10 kbps
Antenna deployment power	4.5 W peak, 2.2 W average for a 3 min deployment
Antenna gain	42.6 dBi

only 2U or, equivalently, one-third of the remaining flight system volume for all of the bus's subsystems and components (Fig. 4). The JPL radar instrument mechanical team and the Tyvak mechanical team worked in close collaboration to meet the tight volume constraints (Fig. 5 shows pictures of the as-built RainCube satellite).

The flight system was designed to have enough power generation and energy storage capability to operate the radar in transmit mode for a continuous, 90-min orbit. Though designed for a 35-W power consumption, the final radar consumption was significantly lower. In addition, the flight system had to achieve an overall transmit-mode duty cycle of 25%, effectively allocating one orbit for the radar in transmit mode and the following three orbits for the spacecraft bus to recharge the batteries, radiate waste heat, and downlink the expected 1.7 Gb daily payload data volume with the radar in standby mode.

To meet these challenges within the 6U CubeSat form factor, the spacecraft bus takes advantage of several key and enabling technologies. First, the solar panels are designed to deploy to maximize the area that can face the Sun. While CubeSat-class solar panel gimbals exist, the RainCube panels take a simpler approach by featuring solar cells on both panel sides [seen in Fig. 5(b)] to maximize power generation while keeping the radar pointed at nadir. The spacecraft bus utilizes compact high energy density (>200 W-Hr/kg) batteries to allow the radar to operate through eclipse and meet operations requirements. The spacecraft bus also features three-axis attitude control using a suite of reaction wheels, star trackers, sun sensors, magnetometers, and a GPS. While the RainCube radar only requires 0.75-deg pointing control when operating, the bus can quickly and optimally reorient to recharge batteries, track ground stations during S-band downlinks, and orient the radiators to deep space.

5 RainCube Mission Operations

Tyvak is responsible for operating the RainCube satellite in orbit, with JPL involved for radar commissioning activities and subsequent technical support and guidance. Tyvak maintains UHF ground stations at their Mission Operations Center (MOC) in California and in Italy. These
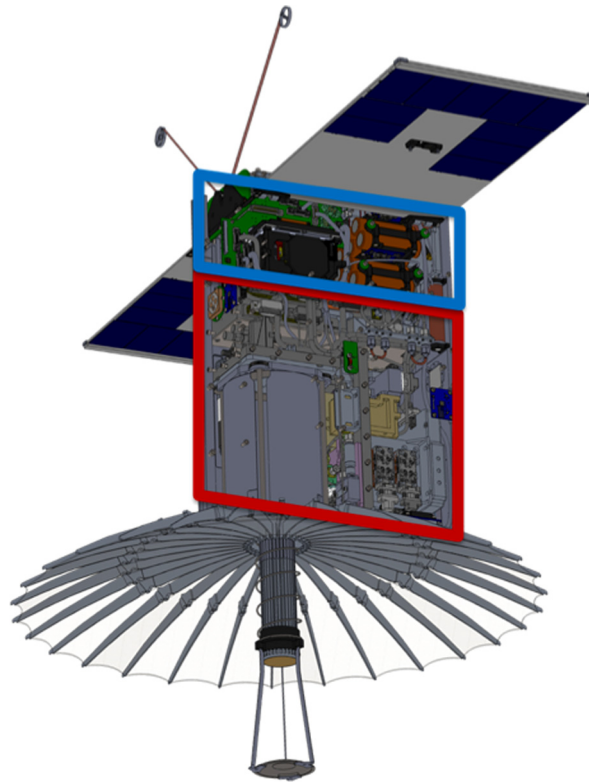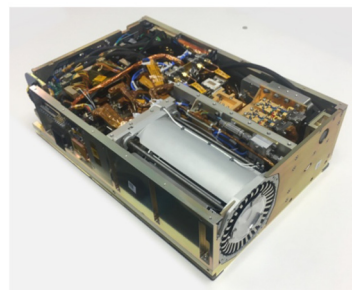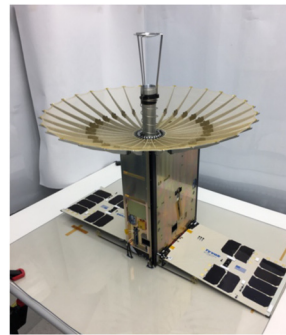
Fig. 4 The radar payload (red) uses most of the flight system's volume. The remaining volume is for the spacecraft bus (blue), housing the computer, attitude control, communications, and power subsystems.

(a)   (b)

Fig. 5 (a) The integrated radar payload and flight avionics in the 6-U bus chassis. (b) The fully integrated RainCube satellite including the solar panels and the deployed radar antenna.

ground stations provide both uplink and downlink support for RainCube and are primarily used for spacecraft command and telemetry. To handle the radar's daily data volume of 1.73 Gb, Tyvak is interfacing with the KSAT ground station network for S-band downlink. KSAT's large and distributed ground station network affords RainCube many potential downlink passes per day. All spacecraft operations and data are routed through servers in Tyvak's MOC, and the radar payload data are delivered to JPL using a secure VPN.

For launch, RainCube was part of the ELaNa-23 mission, which manifested seven CSLI (CubeSat Launch Initiative) missions on the Orbital OA-9 ISS resupply mission. The RainCube satellite was integrated into a NanoRacks "doublewide" (2U × 6U) CubeSat dispenser and shared the volume with the HaloSat satellite. RainCube was launched to ISS from Wallops Island on May 21, 2018 and ejected to LEO on July 13, 2018 at the scheduled time of 08:05:00 GMT (Fig. 6).

Fig. 6 RainCube (left) and HaloSat (right) following ISS deployment. Solar panel deployment occurred 5 min after ejection followed by UHF antenna deployment 30 min later and first beaconing (credit to NASA).

Tyvak detected RainCube energy on the first pass over the Irvine station in California about 1 h after deployment from ISS and verified that the spacecraft was responding to commands. After a few passes, it was confirmed that the UHF and solar panel had successfully deployed and that all subsystems including communications, power and attitude control, and determination were healthy.

The first weeks after deployment were used to commission the spacecraft, including attitude determination and control subsystem calibration, deployment camera verification, and first S-band downlink. The first radar operation in standby mode was completed with ground-in-the-loop during a UHF pass window on July 25, 2018. Radar telemetry confirmed nominal temperatures and power draw. The radar antenna deployment occurred on July 28, 2018 after a short commissioning phase of the antenna motor controller to confirm health telemetry. Immediate feedback from four deployment switches on the radar antenna indicated successful deployment. In addition to the deployment switches, a payload camera on the spacecraft bus captured images of the antenna during and after deployment, and the photos were downlinked on July 29, 2018 (Fig. 7).

Radar commissioning was completed after the successful antenna deployment. Standby mode telemetry was verified on August 1, 2018 followed by receive-only mode operation on August 3, 2018 while the spacecraft was in coarse Sun-pointing mode, where the S/C solar panels are steered toward the Sun. Receive-only mode data verified nominal values in voltages, currents, and temperatures, but it also provided the first experimental confirmation that the radar RF receiver chain was functioning as expected. The radiometric signal showed an excursion of about 0.5 dB, consistent with the predicted change in brightness temperature between an oceanic scene and a land scene, and the transitions were coarsely correlated with crossing of Sumatra and Malaysia (Fig. 8).

The first radar echo returns from Earth's surface were obtained on August 5, 2018 while the spacecraft was still in coarse Sun-pointing mode. As the antenna slewed toward nadir, the
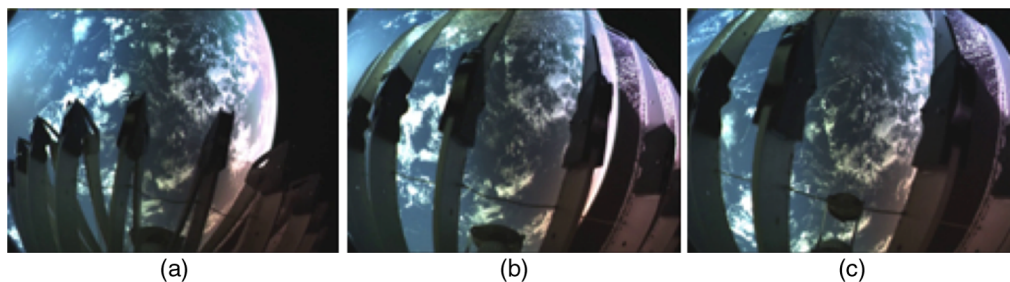

| (a) | (b) | (c) |

Fig. 7 On-orbit pictures captured during the 3-min deployment sequence: (a) the ribs unfurl as the antenna is nearly extended, (b) ribs open, and (c) final dish shape tensioning and subreflector separation.
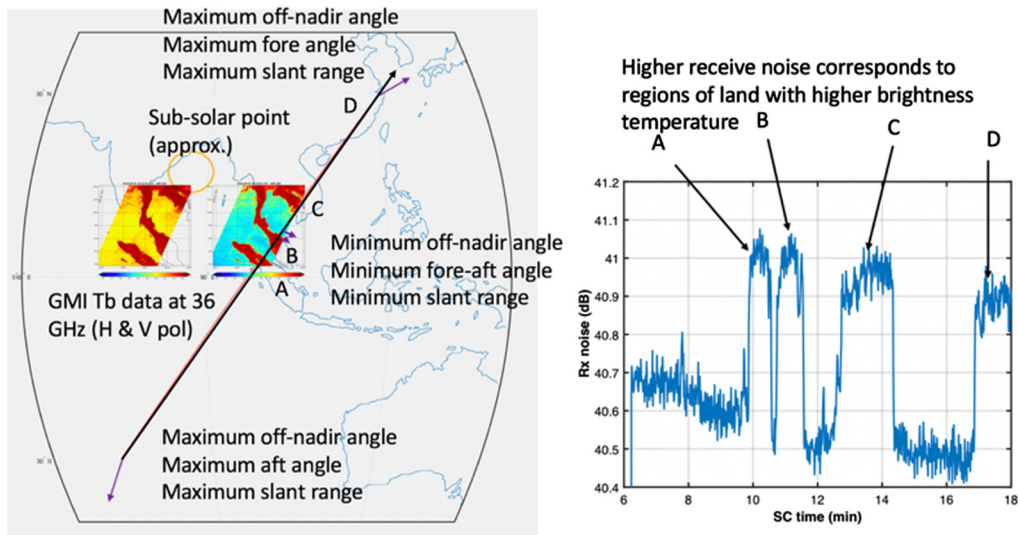
Fig. 8 First receiver noise only measurements from RainCube (in logarithmic uncalibrated units). Purple arrows indicate approximate estimated look directions in coarse Sun-pointing mode, and the approximate Sun subpoint area is indicated by the yellow circle. Over a limited region the radar antenna was pointing close to nadir and it was verified that the receiver RF chain of the radar was functioning nominally.
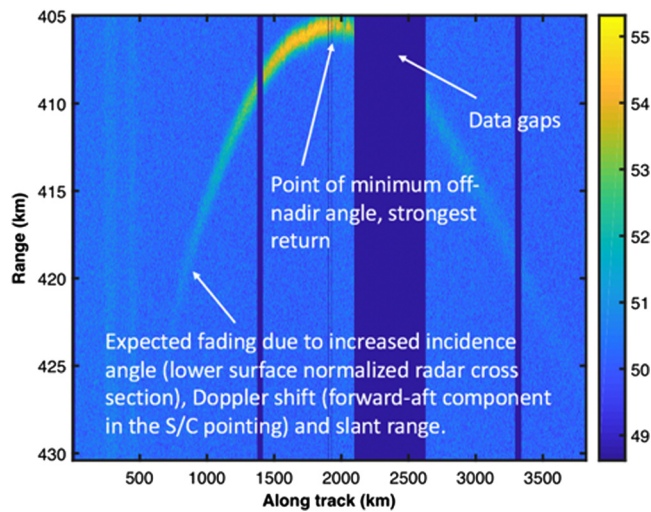

Fig. 9 First radar echo reflectivity measurements from RainCube (in logarithmic uncalibrated units) as a function of along-track distance and range. The spacecraft is in coarse Sun-pointing mode. The data gaps were a temporary issue that was resolved, and data collected after this data set has no gaps.

strongest returns were obtained, and, as expected, faded as the incidence angle, slant range, and Doppler shift increased (Fig. 9). These measurements validated the RF transmit chain and the overall health of all the radar subsystems.

While encouraging, these first radar measurements were not sufficient to fully validate the RainCube radar performance. The next three weeks were spent completing the radar and spacecraft commissioning to obtain the attitude control calibrations necessary for fine nadir-pointing and to improve the robustness of the data downlinks. Finally, on August 27, 2018, RainCube observed precipitation for the first time when it acquired a thunderstorm in fine nadir pointing mode over the Sierra Madre Oriental, near Monterrey, Mexico. A fast-growing orographic precipitation developed shortly before RainCube's pass, which overflew its north-eastern edge as later confirmed by analyzing visible satellite imagery. Figure 10 illustrates several aspects typical
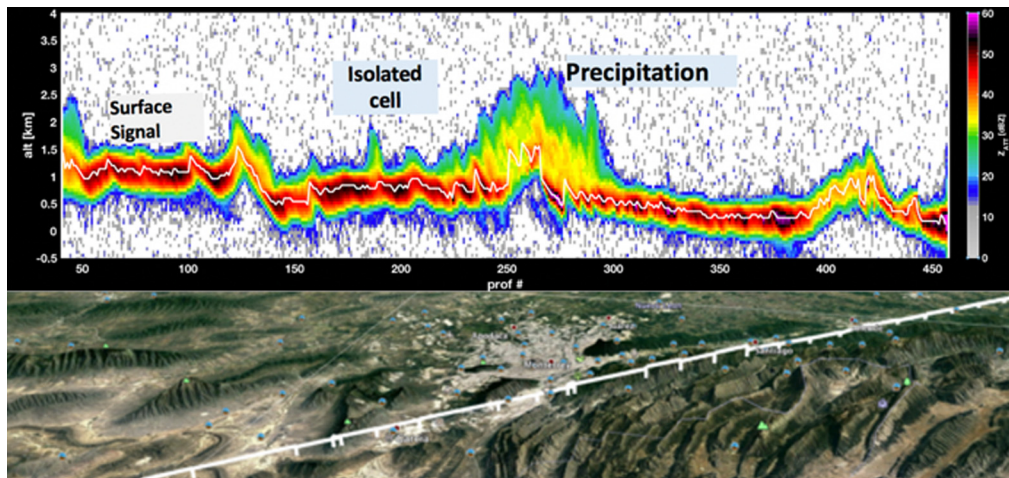
Fig. 10 First RainCube radar precipitation measurements on August 27, 2018 over Mexico in fine nadir pointing mode. The radar reflectivity, calibrated to be expressed in dBZ and as a function of radar profile number and altitude, is shown over a Google Maps image of the terrain. (Image credit: NASA/JPL/Caltech—Google).

of precipitation radar returns. The radar reflectivity as a function of acquired radar profile number and altitude is shown calibrated to be expressed in dBZ, the weather radar standard measure of precipitation reflectivity. The background image is a Google Maps image of the terrain, with the white line showing RainCube satellite's track. The brightest return (in red colors) comes from Earth's surface and the white line follows the peak of the return, and as such it tracks the topography. The surface response jaggedness is explained by the peculiar orography in this particular region, with high peaks corresponding to mountains. The returns above the surface are due to precipitation. For strong precipitation, the signal is attenuated and the surface return is no longer visible in the data. The visible satellite imagery confirmed not only the main storm but also the isolated rain cell that was observed before that.

During the first few weeks of the mission, the RainCube team self-imposed a requirement to only acquire data between ± 30 deg latitude to limit operations in low radiation regions. This set of data has been used to validate the radar performance, which is in solid agreement with on-the-ground predictions (see Table 1). Since then, RainCube's operations have been expanded to encompass the full orbit, including the South Atlantic Anomaly. The on-board fault telemetry has not reported any errors in the interlock logic, the TMR voting logic or the EDAC, which demonstrates the radar design's robustness to radiation.

6 Conclusion

RainCube has validated in-space two new technologies: a miniaturized architecture for Ka-band atmospheric radars and an ultracompact deployable Ka-band antenna. As such, RainCube has introduced a new paradigm to observe weather processes as it opens up the possibility of a constellation of small precipitation radars, enabling unique science. This paper reports on the path to RainCube's successful mission, the demonstration of its performance requirements, and the first measurements ever acquired by a radar in space on a CubeSat platform.

At the time of writing, RainCube has collected more than 90 h of radar data, including near simultaneous measurements with Tempest-D,[26] a multifrequency radiometer in a CubeSat, and measurements collocated with the Global Precipitation Measurement (GPM) mission.[27] These results are outside the scope of this paper and will be the subject of future publications. The RainCube spacecraft and radar remain healthy. The radar power and thermal subsystems continue operating within expected limits with steady voltages and temperatures, and the radar RF performance remains nominal. RainCube is expected to stay in a stable orbit until July 2020 (2 years after ISS deployment).

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