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RainCube, a Ka-band 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. As of the publication date, the 6U CubeSat is in the assembly, integration, and test phase leading towards an expected delivery to storage in September 2017. The mission is manifested for an ISS deployment on the ELaNa-23 launch, currently scheduled in the first half of 2018.

Radar instruments have often been regarded as unsuitable for small satellite platforms due to their traditionally large size, weight, and power. The Jet Propulsion Laboratory has developed a novel radar architecture compatible with the 6U form factor. The RainCube mission will 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. The spacecraft bus is developed by Tyvak Nanosatellite Systems, who is responsible for integration and test of the flight system and mission operations. RainCube is funded through the NASA Science Mission Directorate's Research Opportunities in Space and Earth Science 2015 In-Space Validation of Earth Science Technologies solicitation with the goal of raising the instrument TRL to 7.

INTRODUCTION

RainCube (Radar in a CubeSat) is a 6U CubeSat mission 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 will also demonstrate 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 parabolic deployable antenna (KaPDA). JPL has contracted Tyvak to develop the spacecraft bus, integrate the payload, and operate the spacecraft. RainCube is currently in integration and test with an expected ready-for-delivery date of September 2017.

To fit a radar within the tight 6U CubeSat volume, RainCube takes advantage of a novel architecture enabled by the simplification and miniaturization of the radar subsystems. 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. Successful demonstration of the RainCube technology may lead to advances in numerical climate and weather models using small satellites like CubeSats. Precipitation profiling capabilities are currently limited to a few instruments deployed on large LEO vehicles. While these instruments are sensitive, they cannot provide the temporal resolution necessary to observe the evolution of weather phenomena at short time-scale and ultimately improve weather models. RainCube is the first demonstration of what could become a constellation of precipitation profiling instruments in small satellite form-factors.

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

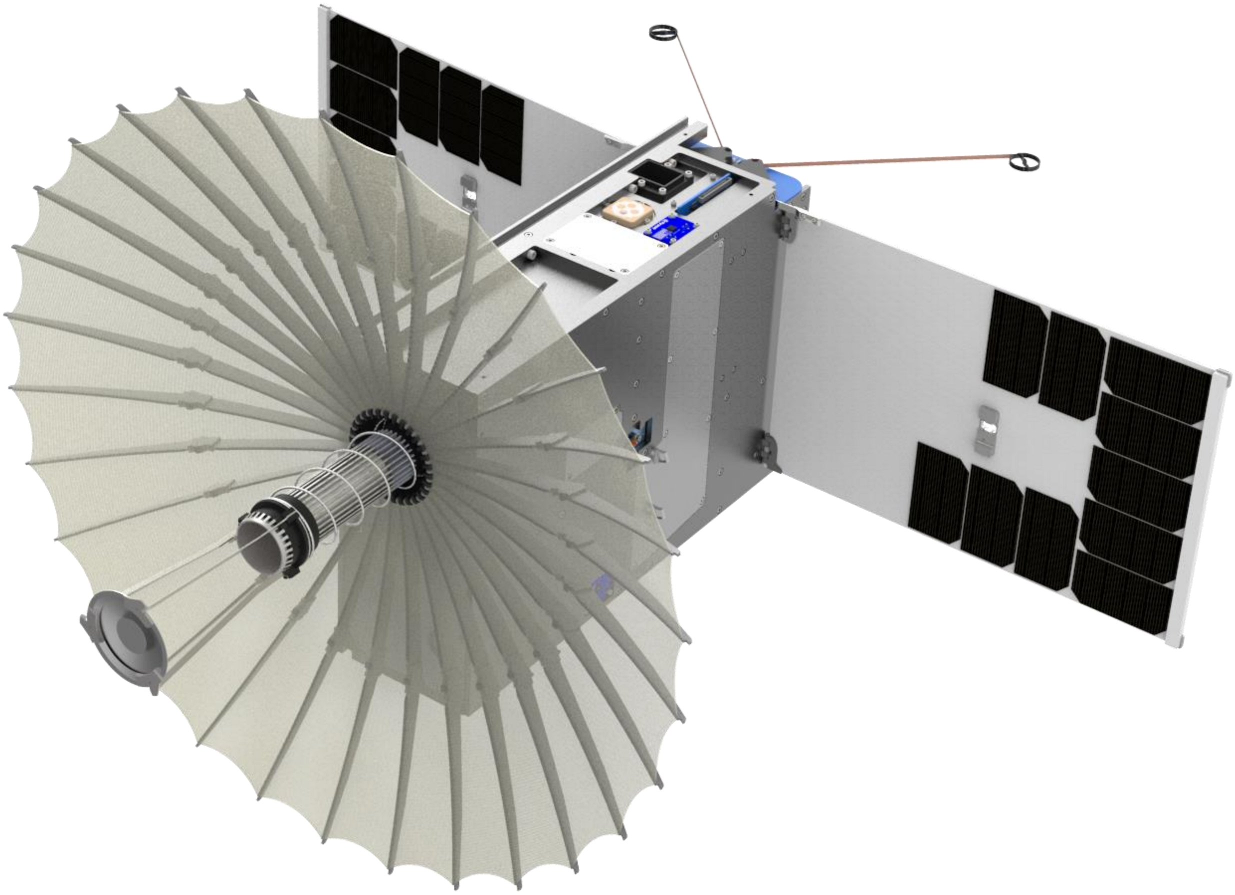

Figure 1. The RainCube 6U CubeSat fits the 0.5m antenna into 1.5U, the radar electronics into 3U, and the spacecraft bus into 1.5U. The vehicle has deployable solar panels and UHF antennas.

demonstration. RainCube was selected in September 2015 with the CubeRRT, CIRAS, and CIRiS 6U CubeSat missions. [1]

MISSION CONCEPT

RainCube will launch no earlier than April 2018 to the International Space Station. In the months after delivery, RainCube and other NanoRacks payloads will be moved through an ISS airlock and deployed at the ISS's altitude of about 400 km. Tyvak is responsible for operating the RainCube mission, with JPL involvement for radar commissioning activities and subsequent technical support and guidance. The first month of flight is allocated for the commissioning phase where the vehicle will deploy its solar panels and UHF antennas (seen in Figure 1), undergo subsystem checkouts, and power on and exchange telemetry with the radar in standby mode. About two weeks into the commissioning phase, the radar's Ka-band antenna will be deployed, also seen in Figure 1. This deployment is the mission's only planned critical event. Deployment of the antenna will take about three minutes and could be done during an operator-in-the-loop ground pass. To supplement the antenna's own deployment sensors, Tyvak has integrated a camera on the spacecraft bus to image the antenna during and after deployment. With the antenna deployed, the remaining commissioning time will be used to check out the radar in both receive and transmit modes.

With a healthy spacecraft and payload, RainCube will transition to a one-month payload operations phase. During this phase, the radar will be operated with a 25% transmit-mode (active) duty cycle and with continuous operation in this mode for at least a full, 90-minute orbit. This allows the spacecraft bus to use the next three orbits to recharge the batteries, dissipate payload thermal energy, and downlink payload data and spacecraft telemetry via UHF or S-band. When in transmit-mode, the radar will collect vertical precipitation profiles between 0 and 18 km altitude above Earth, with a horizontal resolution <10 km and a vertical resolution <250m. Even with onboard compression of the raw measurements, the payload will generate up to 1.73 Gb of data per day, excluding bus telemetry. Tyvak will downlink and deliver this data to JPL for processing within seven days of onboard collection.

With the 25% transmit-mode duty cycle, there is a 6-sigma certainty that the mission will fly over precipitation within the first two days of payload operations. Including commissioning and decommissioning, the mission expects to have no more than twelve months of flight time before atmospheric drag causes the spacecraft to re-enter the atmosphere. The radar can continue to collect data down to an altitude of about 310 km, where the CubeSat will be imminently close to reentering the atmosphere.

SPACECRAFT SYSTEMS

RainCube is made up of two main sections, the radar payload and the spacecraft bus. The radar payload (shown assembled in Figure 2) 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. 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 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

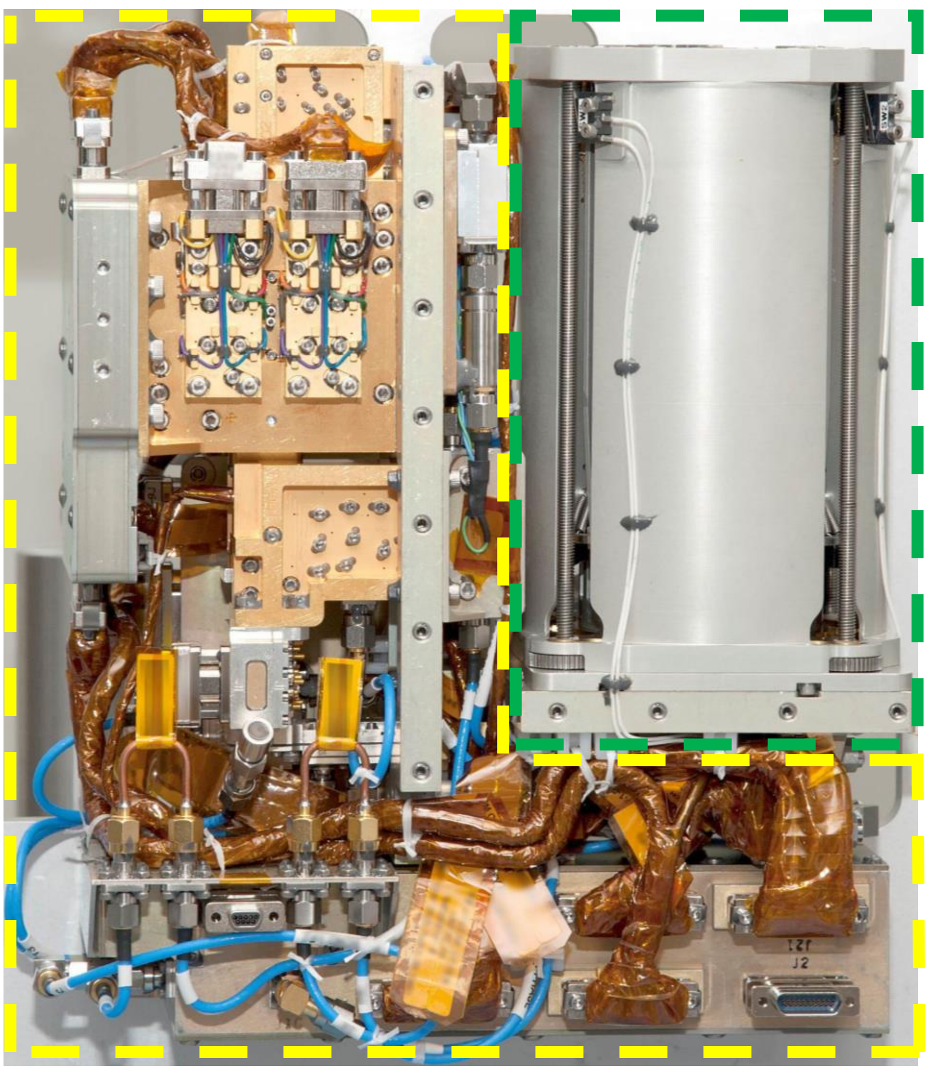

Figure 2. The radar electronics (yellow) and deployable antenna (green) integrated into the flight chassis. The payload has undergone qualification vibe and t-vac testing at JPL.

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 a custom amplifier fabricated with off-the-shelf GaAs solid-state 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 providing 24 channels of telemetry, 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 10W peak, 1W average 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 bolted interface allows heat to be transferred to thermal radiating faces on the spacecraft bus.

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 the spacecraft's 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. [2] The design for KaRPDA is shown in Figure 3. 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.

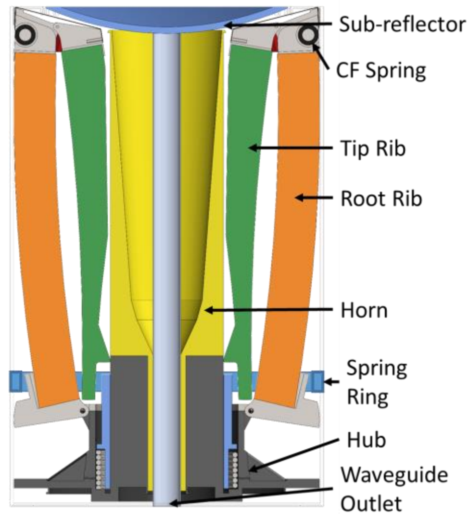

Figure 3: Illustration of key KaRPDA components

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 4). 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. [3]

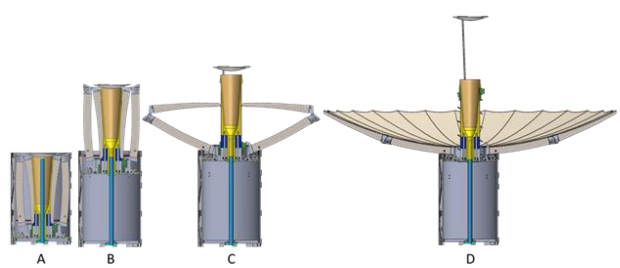

Figure 4: The deployment sequence unfurls the 0.5m antenna from a 0.1m diameter cylinder.

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, 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-recurring engineering. Only small changes are needed to the structure, deployable 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, highlighted in Figure 5. The battery module is scalable and has been configured into a single 70W-Hr pack that supports RainCube's high peak charge currents and 90-minute payload operations in transmit-mode. The spacecraft's 1U x 3U faces provide area 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 lead 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 has both a UHF (Rx/Tx) and S-Band (Tx) link. Lastly, the large, fixed-angle deployable solar arrays close the power budget with the vehicle operating in Local Vertical Local Horizontal attitude for one continuous orbit of radar operations and three orbits of sun-pointing to recharge. 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 Ka-band radar antenna deployment.

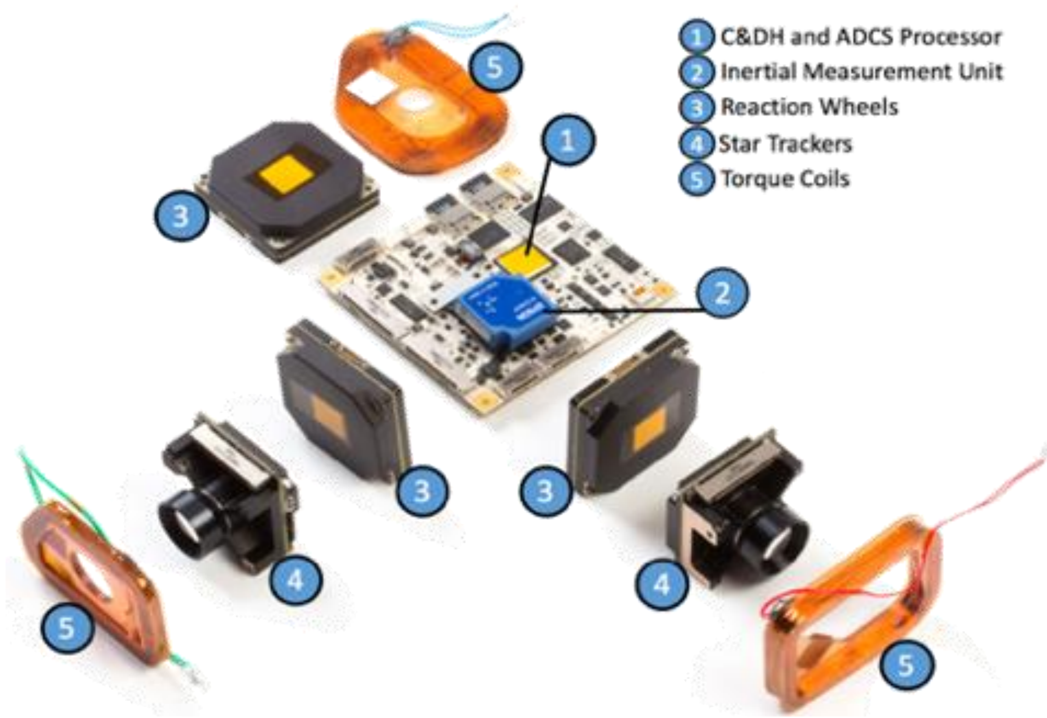

Figure 5. An exploded view of the Tyvak avionics shows the Core Command and Data Handling and Attitude Determination and Control System. For RainCube, the torque coils are replaced with torque rods for improved torque authority at lower altitudes.

INTEGRATION, TEST, LAUNCH, AND OPERATIONS

Integration and test of the radar was completed in March 2017 with all payload requirements verified and validated. Radar integration began in January 2017 with a 'flat-sat' to connect and operate the flight radar subsystems. The radar electronics were then assembled in the flight configuration and calibrated over temperature in thermal-ambient testing. The stowed flight antenna was installed in February, and the fully assembled radar payload went through workmanship vibe and thermal-vacuum testing (including antenna deployment) in March. The assembled payload is 5.5 kg and will be delivered to Tyvak in June.

Integration and testing of the full RainCube vehicle, illustrated in Figure 6, will be completed at Tyvak. Upon delivery, the radar payload is mounted to one of the 2U x 3U structural walls, which also acts as a radiator. After subsystems are tested together on the flight flat-sat, they are installed into the flight vehicle with planned functional checkouts at specific assembly steps. The flight system will then undergo end-to-end hardware performance characterization, including the first flight system-commanded deployment of the radar antenna, and EMI self-compatibility testing. Following this, the final flight build of the software will be loaded and the flight system will complete a random vibration test, with a test dispenser provided by NanoRacks, and thermal-vacuum to bake-out the system and perform a thermal balance test. The solar panels, UHF antennas, and radar antenna will deployed one final time before the flight system is placed into a planned storage in September 2017.

RainCube's ride to space is through NASA's CubeSat Launch Initiative. The mission was selected in 2016 and is currently manifested on the ELaNa-23 flight with eight other CSLI CubeSat missions. [4] The specific mission/vehicle has not yet been determined and the launch is not expected before April 2018. Tyvak will deliver the assembled RainCube spacecraft to NanoRacks for integration into their 'doublewide' (2U x 6U) dispenser. The canisterized CubeSats will be delivered to the ISS as soft-stowed cargo in the pressurized volume with one of the Station's resupply missions. RainCube and the other NanoRacks payloads expect to be deployed within a few months after arrival to the ISS.

Mission operations will be managed and completed by Tyvak. Tyvak maintains a UHF ground station at their facility in Irvine, CA. This ground station provides both uplink and downlink support for RainCube and is

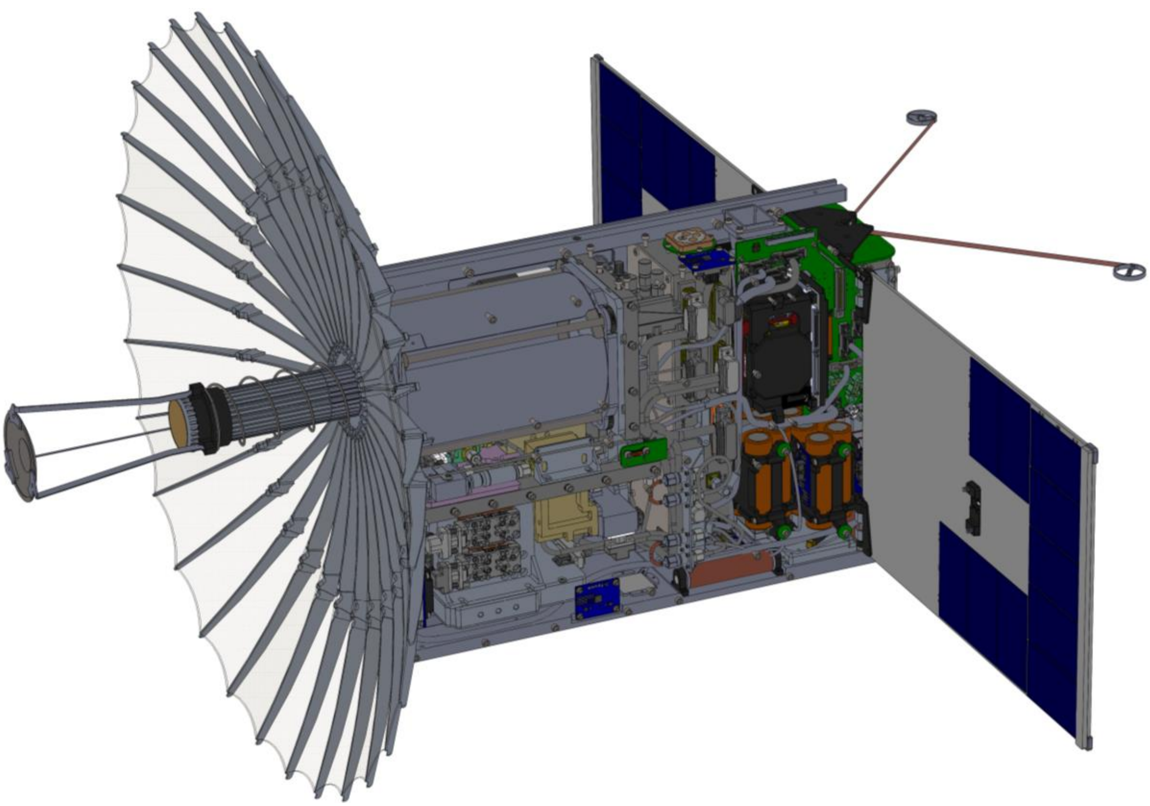

Figure 6. No extra volume is wasted in the final pre-fabrication CAD rendering! The spacecraft is assembled by first installing the integrated radar (left), followed by the bus avionics (right), and finally closing out the system with remaining structure and deployable solar panels.

primarily used for spacecraft TT&C. 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 will afford RainCube many potential downlink passes per day. All spacecraft operations and data will be routed through servers in Tyvak's MOC where the payload data will be delivered to JPL using a secure VPN.

CONCLUSION

JPL has developed a novel Ka-band precipitation profiling radar architecture that can fit within a 6U CubeSat volume. Paired with Tyvak's performant spacecraft bus, the RainCube mission will be one of the first CubeSats with an active sensing payload. 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. Flying multiple groups in different planes could investigate diurnal cycle variability. The compact radar and deployable antenna technologies on RainCube opens a new realm of possibilities for scientific discoveries.

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.

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Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not constitute or imply its endorsement by the United States Government or the Jet Propulsion Laboratory, California Institute of Technology.

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