A Status of U-class Earth Science Instruments at JPL

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Abstract: With advancements in CubeSat technologies and low-cost launch opportunities, CubeSats could play a role in meeting NASA's key Earth science measurement objectives, especially in extreme weather and ecosystem processes. In this paper, we discuss the development of "science grade" hyperspectral imager, microwave spectrometer, IR sounder, and Ka-band radar instruments at JPL. They are scheduled to launch in early to late 2018 while the hyperspectral imager is being developed for airborne flights and for space in the future. The limitations in power, mass, and volume imposed by the CubeSat platform required the identification of new technologies in order to miniaturize instruments into a specific form factor. In conclusion, we will summarize strategies to implement small and low-cost instruments and suggest an architecture for enabling a constellation of U-class instruments.

1. INTRODUCTION

Since our initial assessment of CubeSat related technologies six years ago, we have established a CubeSat instrument program at JPL and have been successfully implementing miniaturized instruments for flight. The motivation of this paper is to describe capabilities of the "science grade" hyperspectral imager (Snow and Water Imaging Spectrometer (SWIS)), microwave spectrometers (TEMPEST-D/MASC), IR sounder (CIRAS), and Ka-band radar (RainCube) for a 6U CubeSat, and seek international partnerships in establishing potential constellations of these instruments for enabling new sciences. The term "science grade" refers to an equal or better spectral resolution or gain, depending on instrument types, compared with existing flight instruments. They are scheduled to launch in early to late 2018 via the NASA CubeSat Launch Initiative (CSLI) while SWIS is targeted for an airborne application and eventually could be a candidate for space. Our team has developed future mission concepts based on these radiometers, radars, and hyperspectral imagers along with a new GNSS receiver. Key technology gaps were identified while developing these concepts: instrument cross calibration, satellite capability, deployable structures, thermal management, miniature components, and communication. In conclusion, we will summarize strategies to implement small and low-cost instruments and suggest an architecture for a constellation of these instruments in order to provide either high temporal resolution or heterogeneous measurements for advancing forecast models and enabling process-oriented new sciences.

2. JPL U CLASS INSTRUMENTS

2.1 Temporal Experiment for Storms and Tropical Systems Technology Demonstration (TEMPEST-D/MASC)

TEMPEST-D is a mission to validate the performance of a CubeSat microwave radiometer designed to study precipitation events on a global scale. The notional TEMPEST constellation of 6U CubeSats would be designed to sample convective precipitation events, from cloud formation, through ice formation and precipitation to cloud dissipation. In addition, the Microwave Atmospheric Sounders on CubeSats (MASC) performs passive atmospheric sounding using the oxygen line at 118 GHz and the water line at 183 GHz. These soundings provide temperature and humidity profiles through the atmosphere. While the science objectives are different, many aspects of the instrument are shared including the optical design, calibration methodology and receiver front-end technologies.

2.1.1 Mission concepts

For both TEMPEST-D and MASC, the instrument observes the Earth through a cross-track scanning antenna. The scan mirror rotates through 360° observing a calibration target inside the CubeSat, a cold-space reference and an Earth view of ±45°, corresponding to a ground swath of 1000 km from an altitude 450 km. TEMPEST, for which TEMPEST-D is a demonstration, is intended to sample convective systems with a time resolution of 5 minutes. This is accomplished by deploying five CubeSats in a single orbital plane, using differential atmospheric drag to space the satellites and maintain the required separation. At a nominal orbital inclination of 52°, the TEMPEST constellation will revisit a point on Earth within a day. In contrast, 24 MASC satellites in high inclination orbits, provide global coverage with revisit times of less than two hours. That can be compared with the current suite of sounders which have closer to six-hour revisits.

2.1.2 Key instrument technology and design

Both TEMPEST-D and MASC use low-noise Indium Phosphide (InP) monolithic microwave integrated circuit (MMIC) high electron mobility transistor (HEMT) technology developed in collaboration with Northrop Grumman. The instrument has a receiver at 89 GHz and 4 channels from 165-182 GHz. After RF amplification and passive filtering, the signals are directly detected, resulting in an exceptionally low-power design, well suited to the CubeSat power limitations. With higher resolution sounding channels, MASC requires a heterodyne architecture, where the RF signals are down converted to a lower frequency, filtered and detected. This down conversion requires a stable local oscillator with an additional 1-2 watts in the design. A comparison of the system characteristics is shown in Table 1.

Characteristic	TEMPEST-D	MASC
Optics scan/resolution	±45°, 15 km (at 182 GHz)	
Channels	89, 165, 174, 178, 182 GHz	119, 120, 125,126, 175, 176,181,182 GHz
Noise Temperature	<500 K (89), <800 K(182)	<600 K (119), <800 K(182)
Data Rate	9 kbps	15 kbps
Mass	4.2 kg	~5 kg
Power	5.2W	7W

Table 1. TEMPEST-D and MASC Instrument Characteristics

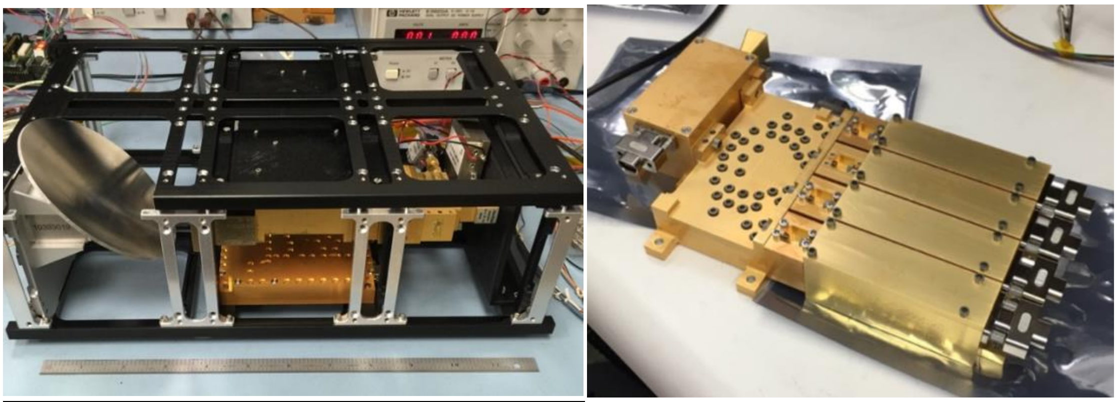

Figure 1. (Left) MASC Instrument in 6U bus structure. The scan mirror is on the left and the receiver (gold) on the right. (Right) The integrated high frequency flight receiver with channels 165, 174, 178 and 182 GHz on the bench and ready for testing.

2.2 Snow and Water Imaging Spectrometer (SWIS)

SWIS would produce spectral data with high-SNR and high radiometric accuracy, that provide information about water status and constituents to enhance the understanding of aquatic ecosystems and aid the management of ecosystems and aquifers impacted by snow melt.

2.2.1 Mission concepts

SWIS provides a spatial sample of ~150 m from a 520 km orbit, with a swath of 90 km, covering the spectral band 350-1650 nm with 5.7 nm sampling. SWIS data could be used in several potential mission concepts; for example 5-6 CubeSats could provide daily or frequent coverage of selected areas to determine snow conditions and assess melt rate, or over a selected coastal area impacted by runoff, algal blooms or other episodic or chronic conditions. With one CubeSat, a near-daily coverage of one arctic and Antarctic location at sun elevation above 20^{o} could determine glacier melt and impact in aquatic ecosystem. Furthermore, a repeat coverage of specified areas to determine seasonal and interannual variability in aquatic photosynthetic communities and the impact of stress due to climate or human activities could be observed.

2.2.2 Key instrument technology and design

SWIS is a miniature, fast (F/1.8) and high-uniformity Dyson spectrometer coupled to a three-mirror anastigmatic telescope with a 10^{o} field. It integrates several critical technologies in its design: an extended-response, polarization insensitive diffraction grating made by E-beam lithography, a black Si slit, an extended response HgCdTe detector with linear variable anti-reflection coating, and a combined solar calibration/dark frame mechanism. The combination of fast readout rate and high throughput provides the high dynamic range required to handle both highly reflective and dark targets (calm water). Thermal modeling shows that the required thermal stability can be achieved with passive cooling and small (< 1W) heaters to the focal plane and spectrometer.

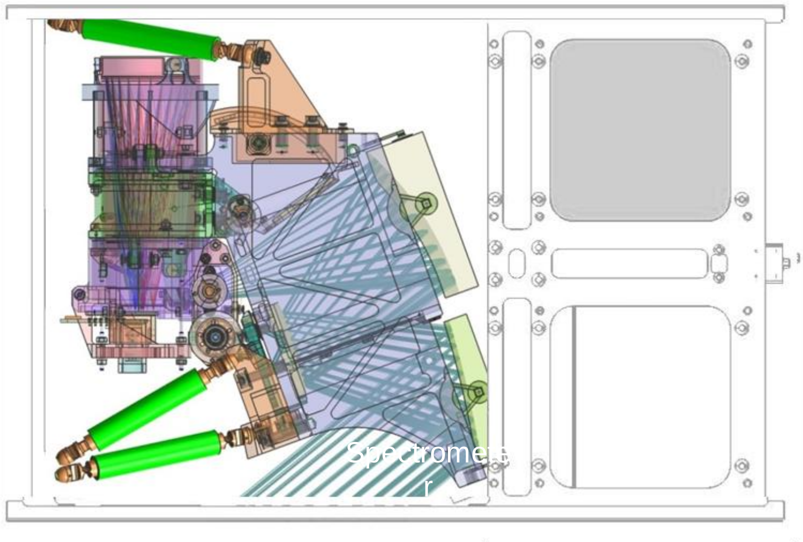

Figure 2. SWIS opto-mechanical and calibration subsystems shown in a 6-U frame.

2.3 CubeSat Infrared Atmospheric Sounder (CIRAS)

Key objectives of CIRAS are to demonstrate technologies for reducing the cost of future IR sounders, help mitigate a gap in hyperspectral IR sounder coverage in the event of a loss of one of the current IR sounders, offer the opportunity for IR sounding data from new orbits, and maintain continuity of current IR sounders into the future.

2.3.1 Mission concepts

The CIRAS measures temperature and water vapor profiles using hyperspectral infrared from 4.08-5.13 µm with spectral resolution of 3.35 nm using 625 channels. CIRAS has two scan modes: 1) Global Mode: Scans ±49.6º cross track (covers > 1500 km from an orbit altitude of 600 km), at a spatial resolution 13.5 km. 2) Zoom mode: Scans ±7.7º cross track (covers > 145 km from an orbit altitude of 600 km), at a spatial resolution 3.0 km. The zoom can occur anywhere in the ±49.6º scan range. NOAA has identified the Earth Observation Nanosatellite-Infrared (EON-IR) as a valuable element in their future program architecture and could be a candidate for a gap mitigation of the Cross-track Infrared Sounder (CrIS) instrument. Current IR sounders with one or two CIRAS sounding units could improve this by a factor of two or more to improve Numerical Weather Prediction worldwide, or to study the diurnal properties of hydrothermodynamic processes in the lower troposphere. Also, three CIRAS instruments flown in formation and separated in time by 5-10 minutes would allow measurement of the data needed to produce 3D Atmospheric Motion Vector (AMV) winds in much the same way GOES and MODIS provide AMV winds using broad (“total column”) water vapor channels

2.3.2 Key instrument technology and design

CIRAS consists of a 2D array of High Operating Temperature-Barrier Infrared Detector (HOT-BIRD), selected for its high uniformity, low cost, low noise and higher operating temperatures. An MWIR Grating Spectrometer (MGS) is designed with no moving parts and an immersion grating to reduce the volume and reduce distortion, with a contribution from Ball Aerospace. The other key technologies include an infrared blackbody with black silicon, a commercial cryocooler, and an integrated Dewar cryocooler assembly and camera electronics developed with IR Cameras in Santa Barbara. The spacecraft is built by Blue Canyon Technologies in Boulder Colorado.

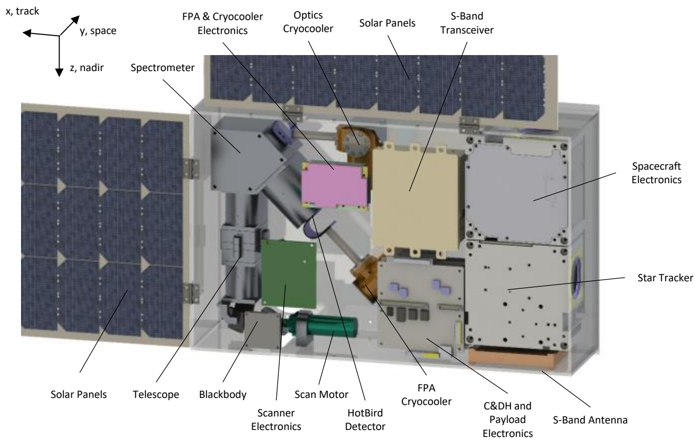

Figure 3. The CubeSat Infrared Atmospheric Sounder.

2.4 Radar in a CubeSat (RainCube)

Precipitation profiling capabilities pioneered by TRMM's PR (Tropical Rainfall Measurement Mission [1] Precipitation Radar) and further advanced by CloudSat's CPR (Cloud Profiling Radar [2], [3]) and GPM's DPR (Global Precipitation Measurement mission, Dual frequency Precipitation Radar [4]) are currently limited to few instruments deployed in LEO. As such, their high-quality observations are sparse in time with respect to the typical time-scale of weather phenomena (tens of seconds to hours). These missions therefore are generally unable to observe the short-time evolution of weather processes, which is necessary to validate and improve the current assumptions and skills of numerical weather models. A novel architecture compatible with the 6U class (or larger) has been developed at JPL and will be demonstrated in an upcoming mission called RainCube (Radar in a CubeSat). The key lies in the simplification and miniaturization of the radar subsystems. Therefore, it opens up a new realm of options for low-cost satellite platforms such as CubeSats, with obvious savings not only on the instrument implementation (especially beyond the first unit) but also the spacecraft and launch costs. The importance of these measurement gaps has been addressed at several recent NASA workshops of the Weather Focus Area (April 2015) and the Atmospheric Composition, Chemistry, Dynamics and Radiation Focus Area (May 2014, e.g., "One of the primary inhibitors in understanding how convective processes vary around the globe is the lack of time resolution in observations from space." [5]).

2.4.1 Mission concepts

A constellation of only four RainCubes would populate the precipitation statistics in a distributed fashion across the globe and across the times of day, and therefore, would enable substantially better sampling of the diurnal cycle statistics while providing a high-resolution vertical profiling capability. One could extend this scheme by adding more RainCubes in each of the orbital planes, and phase them once in orbit so that they would be separated by an arbitrary amount of time among them. Wide separations (say 20-30 min) would further extend the sampling of the diurnal cycle to sub-hourly scales. Narrower time separations between RainCubes would allow studying the evolution of convective systems at the convective time scale in each region of interest and would reveal the dominant modes of evolution of each corresponding climatological regime.

2.4.2 Key instrument technology and design

Two key technologies will be validated in the space environment: a miniaturized Ka-band precipitation profiling radar that occupies a 2.5U volume and a 0.5m Ka-band parabolic deployable antenna that stows in a 1.5U volume [7]. The RainCube architecture reduces the number of components, power consumption and mass by over one order of magnitude with respect to the existing spaceborne radars. The baseline instrument configuration for the RainCube concept is a fixed nadir-pointing profiler at Ka-band with a minimum detectable reflectivity factor better than +20 dBZ (CBE 11dBZ) at 250m range resolution. The footprint size (i.e., horizontal resolution) is determined by the antenna size. For a nominal orbital altitude of 400 km, the RainCube antenna produces approximately an 8.5 km footprint.

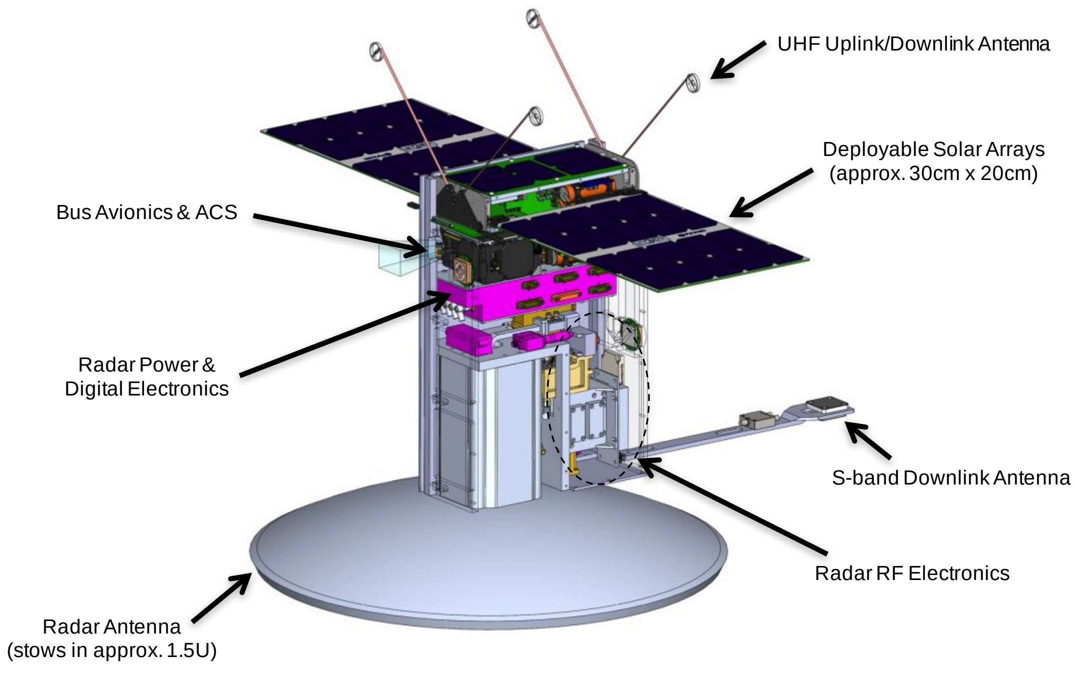

Figure 4. RainCube

3. CONCLUSION

One of the key benefits of CubeSat has been the standard form factor. The U-class form factor has enabled a miniaturization of instruments to a specific dimension. The volume, mass, and power requirements helped to determine key gaps in instrument technologies and to trade technology options for affordability. With the standardized instrument form factor, they can be easily accommodated in Cubesats and Smallsats without the high cost of a spacecraft modification. In order to enable a constellation of U-class instruments, some key challenges must be overcome: cross calibration of passive instruments, ability to mass-produce, ground communication terminals, and OSSE (Observing System Simulation Experiments) analysis of temporal sampling and sensitivity of instruments. For inter-satellite precision and absolute precision of instruments, internal calibration systems and cold-sky observing strategies needed to be developed; thus, a constellation of these instruments should behave as if measurements are made by a single instrument. New mechanical design principles and fabrication approaches such as additive manufacturing and multi-function structure would enable cost effective ways to mass-produce instruments. Furthermore, the processes of validation and verification of space qualification need to adopt industry quality control practices, as traditional methods would add a significant cost. Whether they consist of a homogeneous or heterogeneous set of instruments, a partnership with international agencies would speed up populating a constellation. For less than one hour of revisit time anywhere on the globe, an order of 30 to 40 satellites are required. In order to establish a reliable ground communication, a virtual network of commercial and international ground stations should be negotiated. These instruments could be also hosted on a smallsat via a standard interface; this would allow a heterogeneous set of instruments to provide measurements of different species and vertically resolved measurements coincidentally. Lastly, OSSE needs to be developed to fully understand the benefits of high temporal sampling over a high spectral resolution and a high-gain measurement with a high pointing knowledge. We would like to acknowledge the funding supports from NASA Earth Science Technology Office for developments of all the instruments discussed in this paper. The research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

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