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Terahertz Instruments for CubeSats

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***Abstract*— We have been developing terahertz high resolution spectrometers and radiometers on CubeSat platforms for astrophysics, planetary science, and Earth science applications. We are also developing millimeter-wave communications systems on CubeSat platform to provide communication link during entry-descent-landing (EDL) phase of Mars and other planetary missions. In this paper, we present an overview of the state of the millimeter-wave and terahertz instrumentation development for CubeSat platforms. We discuss the design and implementation challenges for these instrument developments. We also look into innovative packaging solutions, antenna technology, and low-power backend options for these instruments. We show that CubeSats and SmallSats will play a key role in future scientific space missions and also they will find increasing applications in commercial communication and other endeavors.**

Keywords—Terahertz; CubeSat; SmallSat; Spectrometer; Radiometer; Communication; Space; Instruments.

I. Introduction

CubeSats are shoe box size satellites with low-mass, low available power, and until recently had limited communication and instrumentation capability. The size of the CubeSats are referred in the unit of 'U', where one 'U' is a cube with 10 cm x 10 cm x 10 cm. In general, the development of CubeSats and its related instrumentation was primarily confined to undergraduate university research. National Aeronautics and Space Administration (NASA) supported the university CubeSat program by providing launching as secondary payloads.

In recent years, NASA has been actively looking into CubeSats and SmallSats as useable platforms to supplement main missions as well as using them for standalone scientific missions. Defense agencies are also exploring the possibility to use large and small satellites for surveillance and reconnaissance purposes. Even commercial players are getting into the business of SmallSats and CubeSats to provide wireless connectivity in remote areas.

To build instruments for SmallSats and CubeSats, one needs to think small, in every aspects – mass, power, and volume. The key design philosophy is to have high level of integration, and yet maintaining the capability of the instrument in its miniaturized format.

Majority of the NASA CubeSats are 6U in size. Approximately 2U of space is generally available for the scientific payload and the rest of the space is used for solar cells for power generation, star tracker for guidance, attitude control, communication, and other electronics. NASA's thinking is that

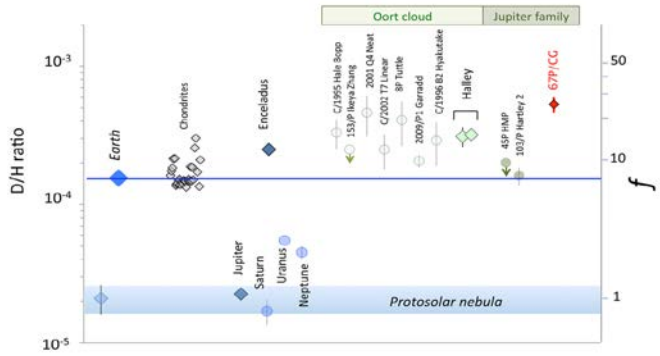

Fig. 1: Measured D/H ratio by different missions on planets and comets. Only a handful of measurements done so far [3]. A CubeSat based instrument will allow multiple missions for understanding D/H ratio variability in comets.

these CubeSat based flights will not only enable advancing proof of concept instruments to higher technology readiness level (TRL) by flying them in relevant environment, but also will allow to have multiple targeted flights with rich scientific data returns. Due to budget constraints, flying large missions are becoming more and more challenging. CubeSat and SmallSat platforms will provide the avenue to more scientific missions by flying multiple missions as they are much cheaper than large missions.

II. Science and Instruments On CubeSat Platforms

A. Science Drivers

One of the areas where the impact of CubeSat missions on scientific return will be enormous is in formation flying and targeted launching of constellation of CubeSats. This will enhance data throughput significantly and will also allow coverage of larger swath of area (for Earth science and planetary missions). For example, NASA is working on a CubeSat mission called TEMPEST (Temporal Experiment for Storms and Tropical Systems) where a constellation of five CubeSats will be deployed in such a way that they are certain distance apart from each other and will collect cloud data in a sequential manner to have better understanding of clouds, cloud processes, and precipitation on a global scale [1]. TEMPEST will a five-frequency millimeter-wave radiometer instrument covering the 90-183 GHz frequency band.

Another science driver for CubeSat platforms is the microwave limb sounding (MLS) of Earth's atmosphere. Microwave limb sounding instruments make unique measurements of Earth's atmospheric composition from the

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upper troposphere through the stratosphere, including in the presence of aerosol and most clouds [2]. These measurements are essential for addressing key outstanding questions in climate, ozone layer stability, and air quality. The need for continuity of the limb sounding record is widely recognized in the Earth science community. However, constrained budgets mean that, in the absence of low cost (and hence low mass/power/volume) instruments, the looming "limb gap" is unlikely to be filled. Recent technological advances have enabled dramatic reductions in mass/power/volume for the receiver and spectrometer subsystems required for microwave limb sounder measuring atmospheric composition profiles, to the point where they could now be accommodated in a CubeSat form factor.

Measurement of water isotope ratios, D/H in particular, on planetary and cometary atmospheres is of high scientific importance to settle the question whether comets brought water to Earth, as shown in Fig. 1. Large missions such as Rosetta [3] which is making measurements on comet 67P/Churyumov-Gerasimenko has been widely successful but many more measurements are needed to settle the issue. High resolution terahertz spectrometer instruments which are at least an order of magnitude lighter, less volume, and consume less power will fit well on CubeSat platforms. Such CubeSat based instruments will allow multiple missions to different comets and allow us to understand the variability in comets.

B. Instruments and Technology for CubeSats

Developing scientific payloads for CubeSat platform poses a host of challenges. First, the instrument needs to be highly compact due to the lack of available space. Second, it has to be ultra-low power due to the severe restrictions on DC power availability. And finally, one has to be innovative in the design of antennas as traditional high gain reflector antennas (for scientific payload as well as for data communication) are not practical. Design and development of large aperture deployable antennas and other innovative structures are gaining a lot of attention in this regard.

Antennas are the heaviest and most space consuming part of many instruments and missions. Conventional reflector based quasi-optical antenna systems that are primarily used for large missions are not readily compatible with CubeSat/SmallSat platforms. There has been a lot of progress in recent years on novel patch array antennas that can be mounted on the side of the CubeSat, deployable parabolic mesh reflector based antennas that can be stowed inside the CubeSat, and deployable reflectarray antennas that can be folded on the side of the

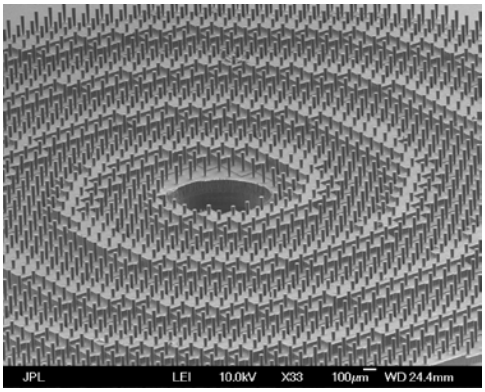

Fig. 2: SEM picture of a 300 GHz flat antenna fabricated using DRIE.

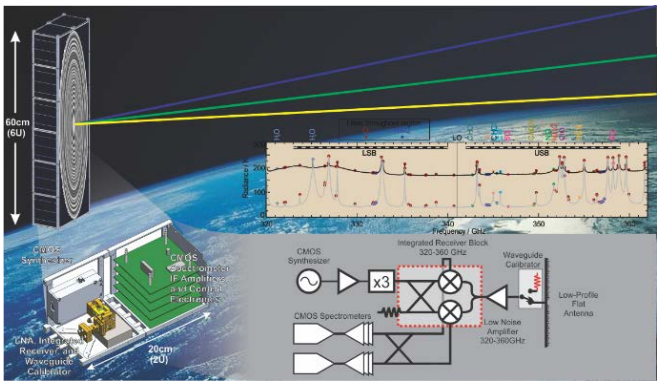

Fig. 3: Schematic of a microwave limb sounding (MLS) experiment implemented on CubeSat/SmallSat platform with a planar low-profile aperture antenna integrated on the sidewalls of spacecraft.

CubeSat. Even though these antennas has been successful, the frequency of operation for them has been limited to up to Ka band. There has been some work to push the frequency up to W-band, but to design them in the terahertz frequency range is extremely difficult due to surface accuracy requirements.

However, new technologies enable terahertz antennas to be constructed as a flat plate rather than a parabolic surface, enabling the development of terahertz instruments in a CubeSat. We are developing low-profile antenna technology at millimeter-wave and terahertz frequencies, opening up the possibility of future radar, radiometers, spectrometers, and communication instruments on CubeSat or SmallSat platforms.

As for the instrument front- and back-end, the main focus has been to have high level of integration of components to make the overall package compact. Generation of RF power at terahertz frequencies for local oscillator source has been one of the most challenging aspect of building terahertz instruments such as radars, radiometers, and high-resolution spectrometers [4]. Compounding that challenge is that available DC power on CubeSat platforms is limited. We have developed high performance CMOS based synthesizers as well as back-end digital spectrometers which consumes very little DC power. That is enabling us to make these terahertz instruments compatible with CubeSat platforms.

III. Terahertz Instruments On CubeSats

We are developing millimeter-wave and terahertz high resolution spectrometers and radiometers on CubeSat platforms for astrophysics, planetary science, and Earth science applications. We are also developing millimeter-wave communications systems on CubeSat platform to provide communication link during entry-descent-landing (EDL) phase of Mars and other planetary missions. In particular, our focus has been on the development of very high-resolution heterodyne spectrometer instruments for passive limb sounding (observing the atmosphere edge on) for observing Earth's troposphere at 350 GHz and 557 GHz instrument for measuring the D/H ratios on cometary atmospheres.

For these instruments we have developed a low-profile, high-gain, and ultra-light antenna which can be integrated on the side walls of the CubeSat/SmallSat. To that goal, we developed modulated metasurface antenna which consists of array of metallic cylinders placed on a ground plane. The antenna has been fabricated using silicon micromachining of

silicon wafers using deep reactive ion etching (DRIE) techniques and metallizing the structures [5]. Fig. 2 shows a scanning electron microscope (SEM) picture of the DRIE fabricated flat antenna developed at terahertz frequencies.

Both the 350 GHz and 557 GHz spectrometer instruments have similar receiver architecture. Fig. 3 shows a schematic of the 350 GHz limb sounding instrument, detailing the different atmospheric lines the instrument will measure in the 300-380 GHz frequency band. Inset shows a simplified block diagram of the instrument as well as how the system will be packaged in the 2U area of a CubeSat.

Fig. 4 shows schematic CAD model of different components of the 557 GHz instrument. The low-profile flat antenna is integrated on the sidewall of the CubeSat and fed by a rectangular waveguide connected to a calibration switch. These receivers require calibration to relate the measured response to a known brightness temperature, enabling comparison between the various species being observed. In addition, because of long-term (10-100 seconds) gain drift inherent in the electronic components, the receiver needs to be regularly calibrated. We developed a MEMS based low-loss waveguide calibration switch that is low-mass and volume, ideal for calibration on a CubeSat platform. The local oscillator signal generations starts with a very low-power CMOS system on chip (SoC) based digital synthesizer in the W-band [6] followed by GaAs Schottky diode based frequency multipliers [4] to generate the required pump power at the operating frequency. The CMOS SoC approach allows a drastic reduction in size, weight, and power by a factor of 10-100 each compared with a traditional dielectric resonance oscillator (DRO) typically employed by terahertz receivers. Other RF components such as GaAs Schottky diode mixers are integrated on the same waveguide block as the frequency multipliers, providing highly integrated packaging. The back-end electronics such as the IF amplifiers and spectrometers are integrated on separate packages and printed circuit boards. We also have developed SoC processors capable of providing the necessary back-end signal processing for heterodyne spectrometer instruments. The 3 GHz (6 GS/s) spectrometer chip has 4000 channels, providing 750 KHz spectral resolution which is sufficient for these instruments. The control electronics for instrument control such as synthesizer frequency setting, bias settings for frequency multiplier and mixer, and monitor the health of the instrument are done by means of a custom-built ASIC chip assembled on a separate printed circuit board.

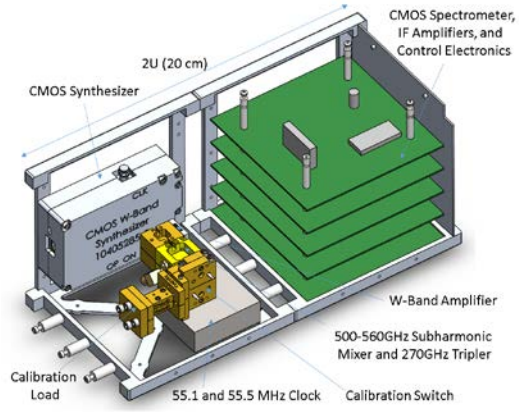

Fig. 4: Model of the major components for the 557 GHz spectrometer instrument showing the packaging of the RF and back-end components.

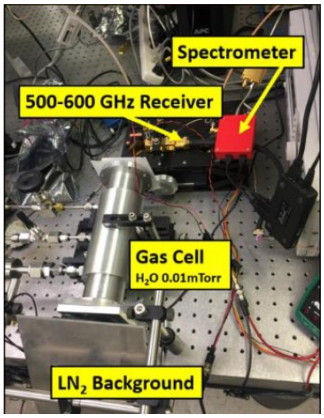

Fig. 5: Photo of our 557 GHz gas cell test set up in the laboratory.

We assembled a 557 GHz spectrometer instrument in the laboratory and performed gas cell tests to evaluate performance of the system. Fig. 5 shows the test set up. We measured less than 4000 K double sideband system noise temperature of the instrument. We also took gas cell data at 557 GHz water line.

IV. Conclusion

We are developing terahertz instruments compatible with the requirements on a CubeSat platform. High level of integration, low-power, and compact form factor along with low-profile antennas that can be integrated on the side walls of the spacecraft makes it possible to make them the instrument of choice for future CubeSat missions.

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References

[1] S. C. Reising, *et al*., "Overview of Temporal Experiment for Storms and Tropical Systems (TEMPEST) CubeSat Constellation Mission," *Proc. IEEE MTT-S Intl. Microwave Symp*, Phoenix, AZ, May 2015.

[2] J. W. Waters, *et al*., "The Earth Observing System Microwave Limb Sounder (EOS MLS) on the Aura Satellite," *IEEE Trans. Geosci. Remote Sens.*, vol. 44, no. 5, pp. 1075–1092, May 2006.

[3] K. Altwegg, *et al*., "67P/Churyumov-Gerasimenko, a Jupiter Family Comet with a High D/H Ratio," *Science*, vol. 347, issue 6220, January 2015.

[4] G. Chattopadhyay, "Technology, Capabilities, and Performance of Low Power Terahertz Sources," *IEEE Trans. THz Sci. Tech.*, vol. 1, no. 1, pp. 33-53, September 2011.

[5] D. Gonz´alez-Ovejero, C. Jung-Kubiak, M. Alonso-delPino, T. Reck, and G. Chattopadhyay, "Design, Fabrication, and Testing of a Modulated Metasurface Antenna at 300 GHz," *Proc. 10th European Conf. Ant. and Prop. (EuCAP)*, Paris, France, April 2017.

[6] A. Tang, T. Reck, Y. Kim, G. Virbila, G. Chattopadhyay, and M-C F. Chang, "A 65nm CMOS 88 -105 GHz DDFS Based Fractional Synthesizer for High Resolution Planetary Exploration Spectroscopy," *Proc. IEEE MTT-S Intl. Microwave Symp*., San Francisco, May 2016.