Silicon Micromachined High-Resolution Terahertz Spectroscopic Instrument for Planetary Missions

G. Chattopadhyay[1], T. J. Reck[1], A. Tang[1,2], C. Jung-Kubiak[1], C. Lee[1], J. V. Siles[1], E. Schlecht[1],
M-C F. Chang[2], and I. Mehdi[1]

[1]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109
[2]Department of Electrical Engineering, University of California, Los Angeles, CA 90095
goutam@jpl.nasa.gov

Abstract: Using newly developed silicon micromachining technology that enables low-mass and highly integrated receivers, we are developing a state-of-the-art terahertz radiometer/spectrometer instrument for planetary orbiter missions to Mars, Venus, Titan, and the Galilean moons. Our flexible receiver architecture provides a powerful instrument capability in a light-weight, low-power consuming compact package which offer unprecedented sensitivity performance, spectral coverage, and scalability to meet the scientific requirements of multiple missions. The instrument will allow a large number of chemical species, such as water, NO_2, N_2O, NH_3, SO_2, H_2S, CH_4, and HCN, among others, in the atmospheres of Mars, Venus, and Titan to be detected at concentrations below a part per billion. It will also be able to pinpoint their location in latitude, longitude, and in altitude. The maturation of this terahertz instrument will have an immediate impact on other areas such as multi-pixel focal plane heterodyne arrays for astrophysics and terahertz imagers and radars for a variety of national security applications.

Introduction: High-resolution terahertz planetary instruments rely on heterodyne receivers for detection and measurements. In such instruments, the incoming radio frequency (RF) signal from the telescope is mixed with an on-board generated local oscillator (LO) signal. The beat signal, known as the intermediate frequency (IF), is much lower in frequency than the signal, is then processed for data. All information in the incoming signal is present in the IF signal.

Space-based terahertz heterodyne radiometry/spectrometry has already been established as an important technique for planetary, terrestrial, and interstellar remote sensing. Heterodyne techniques at these frequencies have proven useful for measuring trace constituent abundances and physical properties under all climate conditions, including high dust loading [1]. The terahertz transitions of polar molecules permit detection of numerous trace species at parts per trillion to parts per billion sensitivity. As an emission measurement, observations are carried out continuously in a passive mode without the need for any time restricted event such as a solar occultation. At these wavelengths, a moderate-sized antenna (30-cm effective) can yield high-spatial resolution measurements ($\lambda/D \approx 1.8\text{x}10^{-3}$ at 550 GHz), while ultrahigh spectral resolution ($\lambda/\Delta\lambda > 10^6$) provides clear line separation and well-defined line profiles. Submillimeter-wave measurements are an ideal complement to infrared measurements of thermal inertia. Moreover, they offer several advantages over the infrared (IR) measurements: (i) much higher spectral resolution ($>10^6$) is possible because of the smaller absolute Doppler line broadening at lower frequencies, (ii) terahertz measurements are not blinded by aerosols or dust because the wavelengths are much longer than dust grain/aerosol size, eliminating scattering, (iii) some constituents (*such as nitriles*) have much stronger line intensities at submillimeter wavelengths, thus making possible detection at much lower concentrations, and (iv) radiometry allows characterization of surface properties by measuring thermal emission from dielectric surfaces.

The capabilities of microwave observations for retrieval of atmospheric parameters have been widely demonstrated for both Earth and Mars. Among numerous examples, the Microwave Limb Sounder (MLS) on the Upper Atmosphere Research Satellite (UARS) [2] and the EOS Aura spacecraft [3], [4] demonstrate the value of microwave limb sounding for trace constituent detection and wind [5]. In March 2004, MIRO (Microwave Instrument for Rosetta) was launched on the Rosetta spacecraft that had its rendezvous with Comet 67–P/Churyumov-Gerasimenko [6] recently.

Ground-based and Earth-orbit microwave observations have monitored the behavior of Mars' climate for years. For example, the Submillimeter Wave Astronomy Satellite (SWAS) used the rotational transition of H_2O (557 GHz) and ^{13}CO (551 GHz) to derive the

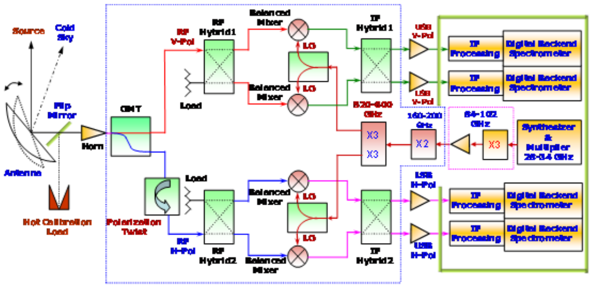

Fig. 1: Schematic block diagram of a 520-600 GHz dual-polarized sideband separating receiver with two sideband outputs in each polarization for radiometry and spectroscopy applications.

temperature structure and altitude distribution of water vapor on Mars [7]. More observations of the Martian atmosphere have been performed from the ESA Herschel Submillimeter Telescope [8]. However, all these previous instruments have either been limited by the tunable and instantaneous bandwidth, sensitivity, and single polarization capability of the receivers, and were narrowly focused on a small number of lines or too heavy for planetary missions.

We are currently developing a terahertz spectroscopic sounder for possible use on Mars, Venus, Titan, Jupiter, Europa, and Ganymede. In this paper, we will describe the new capabilities of the instrument along with the technological advancements that is enabling this instrument development.

Instrument Concept and Capabilities: The low-power, low-mass, and low-volume terahertz instrument is a combined radiometer and spectrometer. It features a dual-polarized, sideband separating, and balanced mixer receiver backed by a high-speed digital spectrum analyzer. In exploring planets and their moons from orbit, this instrument will gather data on the thermal structure, dynamics and composition of planetary atmospheres and surfaces. Fig. 1 shows the block diagram of the instrument under development.

The radiometer part of the instrument is capable of measuring the polarized thermal emission which encodes key thermophysical properties such as the planetary surface's dielectric constant and temperature, revealing aspects of its chemical composition and physical state.

The spectrometer part of the instrument investigates the sources and sinks of trace gases and enabling global characterization of the planetary atmospheres with the high spectral, spatial, and temporal resolution that is uniquely available through terahertz spectroscopy. It will also measure wind speeds, temperature, pressure, and key constituent concentrations in the planetary atmospheres with a higher precision than any other available technology.

The current state-of-the-art instrument at terahertz frequencies for planetary sciences is the Submillimeter-Wave Instrument (SWI) which has been selected for the ESA's JUpiter ICy Moon Explorer (JUICE) mission. SWI will study Jupiter and its magnetosphere, as well as the physical characteristics, composition and geology of the Galilean satellites, with a resolution and coverage far beyond what was achieved by Galileo. However, the SWI instrument will need to reorient the entire spacecraft to make polarization measurements. Therefore, it will not be feasible to map the full surfaces of the satellites in 2 or 3 polarization orientations because of the time it will require to make the maps, and hence has to be restricted to limited regions on the surfaces. Moreover, since single polarization measurements will be done in each pass of the spacecraft, similar to the Cassini measurements, there is a strong possibility that the measurement of the two linear polarizations might be of non-overlapping regions.

The instrument we are developing does not suffer from these limitations because it will have an integrated dual-polarized receiver which will make two linear polarization measurements simultaneously. Compared to SWI, this instrument is also capable of providing a factor of two increase of the spectrometer's usable instantaneous bandwidth by separating sidebands, improved sensitivity by using balanced mixers to reject local oscillator noise and separating sidebands to reject noise from the image sideband, and improved calibration accuracy by eliminating sideband imbalance error and rejecting flux from the image sideband. Dual-polarized outputs for the spectrometer instrument will improve the sensitivity of our instrument by a factor of $\sqrt{2}$ compared to SWI. Moreover, the instrument uses, for the first time, silicon micromachined waveguide packaging for a higher level of component integration in a low-mass package.

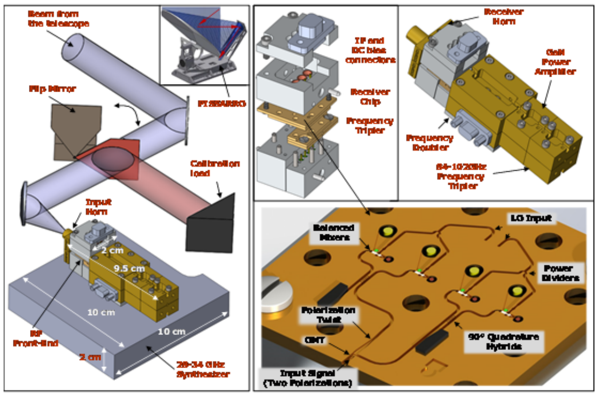

Fig. 2: Schematic of the instrument concept showing the optical path from the telescope to the front-end receive (left). Silicon micromachined integrated front-end components in a low-mass package (right-top). Details of the micromachined components in the silicon wafer (right-bottom).

The instrument details are shown in the mechanical layout along with the optical path in Fig. 2. The radiation collected by the reflector telescope goes through a collimation mirror to an ellipsoidal mirror which focuses the beam to the receiver horn antenna. For normal observations, the flip mirror does not block the optical path. However, for calibration purposes, it directs the signal from the temperature stabilized hot-load to the receiver horn antenna, as shown in Fig. 2. The heterodyne instrument uses a widely tunable locally generated signal (LO) and mixer to convert a band of frequencies down to a frequency range of 1-5 GHz where it is analyzed in detail by the back-end digital spectrum analyzer. The front-end is a dual-polarized, sideband-separating balanced receiver using an orthomode transducer (OMT) to separate the polarizations of the incoming radiation. A polarization twist brings both the polarizations to the same plane. A combination of two 90° RF quadrature hybrids, three local oscillator 3-dB power dividers, four Schottky diode balanced mixers, and two 90° IF quadrature hybrids provide two pairs of sideband-separated outputs, one for each polarization. The front-end of the receiver is being micromachined on a silicon substrate using deep reactive ion etching (DRIE) enabling technology, as shown in Fig. 2 (right) [9], [10]. The volume of the entire silicon micromachined front-end is only 0.5 cm^3. The mixer is pumped at a frequency near the observation frequency by a solid-state local oscillator (LO) subsystem tunable over a 15% bandwidth. The LO signal is generated by a chain of components starting with a 28 to 34 GHz synthesizer. This frequency is then multiplied by 18 to the 520 to 600 GHz range by a combination of commercial and existing JPL components. To optimize the power requirement for the LO chain and overall instrument, we have designed and fabricated an ASIC based bias circuit board that reduced mass and power of control and monitor circuits by a factor of five.

Recent Technological Advances: The key technology advancements for this instrument development are Deep Reactive Ion Etching (DRIE) based silicon micromachining process and silicon CMOS based synthesizer, spectrometer, and control and monitor ASIC chip design and fabrication.

<u>DRIE-based silicon micromachining:</u> For this instrument, we developed a unique enabling silicon micromachining process that has never been used for any planetary instruments before. Using JPL's micro device laboratory (MDL), we fabricated a highly integrated terahertz receiver front-end entirely on a silicon substrate [11]. This is a breakthrough in relevant to terahertz instrument designs for planetary missions. Fig. 3 shows the photographs of the fabricated terahertz receiver front-end assembled for testing.

The micromachined silicon blocks for terahertz waveguide circuits must meet a number of requirements. The waveguide and device channels need very smooth etched surfaces in order to minimize ohmic losses. The cross-

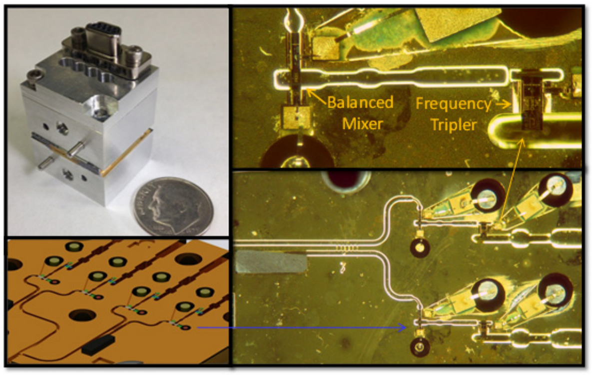

Fig. 3: Photo of the assembled terahertz receiver front-end (top left). The thin gold section in the middle of the two aluminum pieces is the silicon micromachined RF front-end. Bottom left shows the 3-D drawing of the silicon micromachined pieces with the waveguide circuits. Bottom right shows the close-up of the waveguide circuits and top right shows the close up of the devices mounted inside the silicon micromachined waveguides.

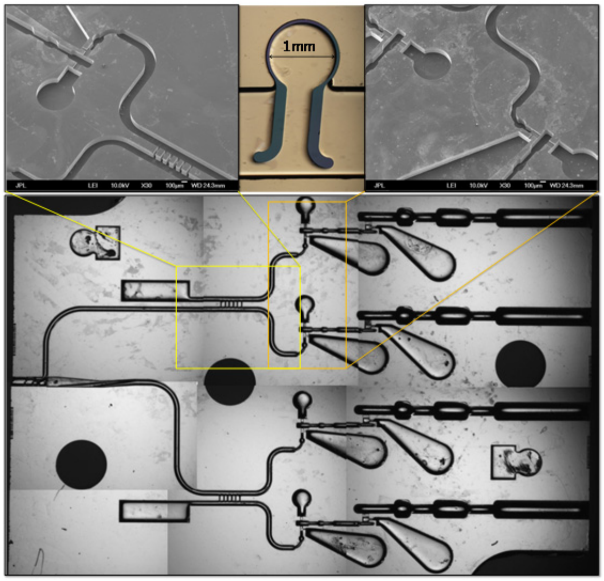

Fig. 4: SEM pictures of micromachined terahertz receiver front-end components on silicon wafer. Center top shows silicon compression pin used for aligning two silicon block halves.

sections of the waveguide walls also have to be precisely rectangular in order to minimize scattering from geometric inhomogeneity and to permit successful integration of the MMIC amplifiers, frequency multipliers, and mixers. Finally, a very precise and accurate alignment method is needed to assure good impedance matching across vertical wafer-to-wafer waveguide transitions.

For micromachined fabrication, the silicon wafers are processed with conventional ultra violet (UV) photolithography, and DRIE techniques using photoresist and silicon dioxide (SiO_2) as etching masks. By optimizing the Bosch process of DRIE fabrication, we were able to achieve excellent surface roughness (better than 15 nm rms) and vertical edges for deep trenches. Fig. 4 shows scanning electron microscope (SEM) pictures of the silicon micromachined terahertz receiver front-end wafer.

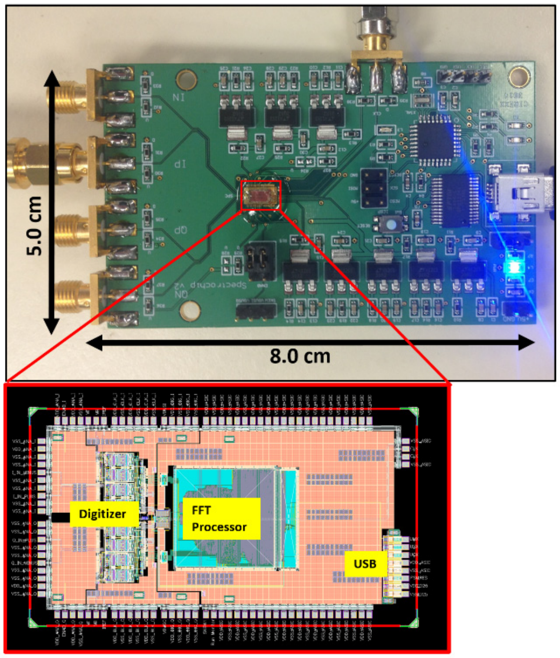

Fig. 5: CMOS based spectrometer processor chip and PCB containing all digitization and digital spectral processing functions necessary for a spectroscopic instrument.

High-speed digital Spectrum Analyzer: Rapid advances in silicon system-on-chip technology have enabled a whole new class of space-qualifiable, high-speed, wideband spectrometer back-end. Previously, wide-bandwidth digital spectrometer processors were implemented as auto-correlators architectures [12] or chirp-transform spectrometers (CTSs) [13]. These components have been massive and power hungry. Due to the much higher circuit speeds available from modern sub-micron CMOS technology, it is now possible to construct a much lighter and low-power consuming system-on-chip (SoC) circuits replacing even FPGA based spectrometers. Fig. 5 shows SoC layout of a full 2 GS/s spectrum analyzer chip in advanced 65nm CMOS. The chip has integrated 7-bit digitizers, channel offset self-calibration, interleaving functions, clock management system, and vector accumulation. Currently it has a 512 channel quadrature output with integrated USB 2.0 controller. The entire back end including support PCB is 5cm x 8cm x 1cm and consumes only 200mW of total power. A higher speed 10 GS/s SoC chip with 8K channels is also under development.

Future Prospects: Terahertz heterodyne instruments are versatile and can be applied to disparate environments in which emission features are saturated as well as barely measureable. Water, and other strong emitters, are known to be trace components of the Martian and Titanian atmospheres. The high sensitivity of terahertz spectrometry to these emission features is enough to; (1) trace molecular origins and chemistry through isotopologue ratios (2) determine wind speeds and (3) determine vertical profiles or column densities. Exospheres, such as those in the Enceladus, Europa and Ganymede systems (EEGs), are expected to have water as a bulk component and trace organic and inorganic components. The radiometric sensitivity will be sufficient to detect column abundances of 10^{11} molecules/cm^2. This is sufficient to characterize sputtering and sublimation regions. Weaker water isotopologue signals will be important gauges for the optical depth. The high spectral resolution of the ballistic profiles will also reveal the nature of the ballistic velocities (winds) in detail. Due to the large bandwidth vs. resolution, and the common origin of rotational spectra, the discovery potential of an orbiting submillimeter spectrometer is tremendous. EEGs ice can be studied through bulk and trace gas measurements of the ballistic exosphere. Rheological models indicate that the surface composition will change if the ice layer is broken or fractured, and flows of upwelled material will contain clues to the subsurface composition. Thus, the presence of a super-compact terahertz instrument at these objects will enable ground-breaking surface science.

In the last decade the underlying technology for submillimeter-wave instruments has seen a resurgence. Consequently, while instruments like MIRO and MLS were detecting only a few lines, future missions will utilize tunable local oscillator sources, much like the HIFI instrument. Electronically tunable sources make it possible to detect a number of different molecules, tremendously increasing science output and allowing the instruments to detect several species of interest. In addition to the trace gas detection, the versatility of such an instrument is demonstrated by its ability to (1) make temporal maps, (2) measure wind velocities with resolution down to <10m/s with appropriate optimization, (3) probe winds within dust storms to provide unique insights into the atmospheric impact of dust storms, and (4) measure the lower branch of the global Hadley cell circulation within the boundary layer providing direct measurements of circulation patterns and thus allowing calculation of the transport of water as it sublimates off the polar cap.

The current generation of instruments capable of carrying out these measurements requires too much power (more than 50 W) and weighs too much (more than 20 kg). The instrument we are developing will make a big difference in those both counts and will be able to provide an instrument weighing only 10 kg and requiring less than 20 W of power.

Acknowledgements: The research described herein was carried out at the Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, USA, under contract with National Aeronautics and Space Administration.

References:

[1] M. A. Janssen, Atmospheric Remote Sensing by Microwave Radiometry, Wiley, New York, 1993.

[2] J. W. Waters, *et al.*, "The UARS and EOS Microwave Limb Sounder (MLS) Experiments," *Journal of the Atmospheric Sciences*, vol. 56, 194-218, 1999.

[3] M. J. Filipiak, *et al.*, "Carbon Monoxide Measured by the EOS Microwave Limb Sounder on Aura: First Results," *Geophysical Research Letters*, vol. 32, 2005.

[4] J. W. Waters, *et al.*, "The Earth Observing System Microwave Limb Sounder (EOS MLS) on the Aura satellite," *IEEE Trans. Geoscience And Remote Sensing*, vol. 44, no. 5, pp. 1075-1092, May 2006.

[5] D. L. Wu, *et al.*, "Mesospheric Doppler Wind Measurements from Aura Microwave Limb Sounder (MLS)," *Advances in Space Research*, vol. 42, 1246-1252, doi:10.1016/j.asr.2007.06.014, 2008.

[6] S. Gulkis, *et al.*, "Remote sensing of a comet at millimeter and submillimeter wavelengths from an orbiting spacecraft," *Planet Space Sci.* 55, 1050-1057, 2007.

[7] M. A. Gurwell, *et al.*, "Submillimeter Wave Astronomy Satellite Observations of the Martian Atmosphere: Temperature and Vertical Distribution of Water Vapor," *Astrophysical Journal*, vol. 539, L143-L146, 2000.

[8] P. E. Hartogh *et al.*, "Water and Related Chemistry in the Solar System. A Guaranteed Time Key Program for Herschel," *Planetary and Space Science*, vol. 57, 1596-1606, 2009.

[9] G. Chattopadhyay *et al*, "Deep Reactive Ion Etching Based Silicon Micromachined Components at Terahertz Frequencies for Space Applications," Proceedings of the *33rd Intl. Conf. on Infrared, Millimeter, and Terahertz Waves*, Pasadena, CA, September 15-19 2008.

[10] T. Reck, *et al.*, "Measurement of Silicon Micromachined Waveguide Components at 500-750 GHz," *IEEE Trans. THz Sci. Tech*, vol. 4, no. 1, pp. 33-38, January 2014.

[11] C. Jung-Kubiak, *et al.*, "Silicon Microfabrication Technologies for THz Applications," *Proc. IEEE Silicon Nanoelectronics Workshop*, Honolulu, Hawaii, June 2012.

[12] B. Klein, *et al.*, "A new generation of spectrometers for radio astronomy: fast Fourier transform spectrometer," *Proc. of the SPIE*, Volume 6275, p. 627511, 2006.

[13] P. Hartogh, "A multiband chirp transform spectrometer for the microwave remote sensing of middle atmospheric trace gases," *SPIE*, vol. 2583, p282, 1995.