Planetary Instrument Concepts for the Advancement of Solar System Observations Program
Abstracts of Selected Proposals
(NNH17ZDA001N-PICASO)

Below are the abstracts of proposals selected for funding for the PICASO program. Principal Investigator (PI) name, institution, and proposal title are also included. One hundred and six proposals were received in response to this opportunity. On April 11, 2018, 11 proposals were selected for funding.

Ricardo Arevalo/University of Maryland, College Park
Miniaturized Inductively Coupled Plasma Mass Spectrometer (ICPMS) for Trace Element Analysis

Trace elements, which are defined by abundances of <1000 ppmw in geological materials, serve as extraordinarily sensitive tracers of a variety of planetary processes including (but not limited to): i) biomineralization; ii) meteoritic infall (i.e., source of exogenous organic compounds); iii) hydrothermal activity and/or aqueous alteration; iv) weathering, erosion and sedimentation; and, v) magmatism, which in turn reflects local pressure, temperature and redox conditions in planetary interiors. In the commercial realm, trace elements are most commonly measured via inductively coupled plasma mass spectrometry (ICPMS) techniques, where a high-temperature (10,000 K) plasma effectively serves to atomize and ionize both solid (e.g., crystalline minerals or amorphous glasses) and liquid materials (e.g., water samples or chemical extracts). However, traditional modes of in situ chemical analysis available for planetary exploration, such as laser desorption mass spectrometry (LDMS; e.g., the MOMA investigation on the ExoMars rover) and laser-induced breakdown spectroscopy (LIBS; e.g., ChemCam on the Curiosity rover), are challenged to meet the limits-of-detection that enable the accurate quantitation of trace element abundances.

Here, we propose to develop a miniaturized ICPMS that integrates a novel, self-sustaining low-pressure plasma source with an advanced prototype quadrupole mass spectrometer (QMS) based on the heritage design of the LADEE NMS and MAVEN NGIMS spaceflight instruments. The low-pressure operation of the plasma will simplify the design of the interface between the source and quadrupole mass analyzer, as well as reduce pumping requirements, thereby circumventing the need for multiple differential pumping regions found in commercial instruments. A laboratory demonstration of the end-to-end system, which will deliver quantitative, ppmw-level measurements of large ion lithophile elements (e.g., Rb and Sr), high-field strength elements (e.g., the lanthanides), and other transition metals (e.g., redox-sensitive V and Cu) in synthetic (NIST reference materials) and natural silicate materials (Clay Mineral Society phyllosilicates and USGS basaltic glasses) will validate this concept as TRL 4 at the end

of the period of performance. The low maturity of the innovative ICP, and the unproven interface between this source and a spaceflight QMS system, define an entry TRL 1.

The mission-enabling capabilities that will be realized through this effort will support assessments of planetary habitability, provide context for geochronology measurements, and offer insights into the dynamics of planetary surfaces (including atmospheric inputs) and interiors (and potential tectonic activity). Thus, this technology addresses multiple mission focus areas described in the NASA Decadal Survey and Science Plan. As encouraged by the Planetary Science Division, this effort leverages an emerging technology supported by the Small Business Innovative Research (SBIR) program.

Shahid Aslam/NASA Goddard Space Flight Center
Advanced Net Flux Radiometer Focal Plane Assembly for Ice Giants

The recent Ice Giants Pre-Decadal Survey Mission Report, 2017 (IGPDS) recommended the scientific importance and high priority of sending a mission with an orbiter and a probe to one of the ice giants with preferential launch dates in the 2029-2034 timeframe. Such a mission will advance our understanding of the Solar System, exoplanetary systems, planetary formation and evolution. The IGPDS report identified twelve science objectives for ice giant exploration that are consistent with the Vision and Voyages Planetary Science Decadal Survey (NRC 2011). Highlighted in the report are two science objectives, of equal importance, that relate to the atmospheric (thermal) structure of these icy worlds: (i) determine the planet's atmospheric heat balance, and (ii) determine the planet's tropospheric 3-D flow. Key questions concerning the atmospheric structure arise: What are the altitudes/pressures and compositions of the cloud layers? How do the cloud layers interact with solar visible and planetary thermal radiation to influence the atmospheric energy balance? How does the energy balance contribute to atmospheric dynamics? Our unique Net Flux Radiometer (NFR) concept, onboard a probe descending deep into the atmosphere will contribute greatly to answering these questions by measuring the upward and downward radiation flux, in seven spectral channels, each with a 5-degree Field-Of-View (FOV) and in five sequential view (sky) angles as a function of altitude/pressure.

We will develop a prototype advanced Focal Plane Assembly (FPA) housed in a vacuum micro-vessel, a key sub-system of our NFR. The design, build and validation of this sub-system will mature this technology from TRL-2 to TRL-4. We propose to develop an advanced NFR FPA, comprising integrated detector and Winston cone sub-assemblies, housed inside a vacuum micro-vessel. The vacuum micro-vessel is required to help mitigate the effects of rapid changes in temperature of the FPA that the instrument will experience during a probe descent into either a Uranus or a Neptune atmosphere. The FPA will be integrated with a fold mirror sub-assembly and assembled into a vacuum micro-vessel to mature this technology from TRL-2 to TRL-4. Our proposal team collectively has decades of experience in designing and building mid-infrared to far-infrared instrumentation and are uniquely qualified to carry out this work.

Mahmood Bagheri/Jet Propulsion Laboratory
Electrically pumped mid-IR optical frequency combs for dual frequency spectroscopy

In this work, we propose to develop a fully integrated mid-Infrared optical frequency comb source that spans over 200 nm spectral bandwidth at 3-4 micrometer. Combining revolutionary advances in dual frequency comb spectroscopy (DFCS) with the developed semiconductor mid-IR frequency comb, we will develop a powerful new tool for understanding the origin and evolution of the Solar System and habitability therein. This new in-situ measurement concept will provide a miniature and low power instrument for in-situ measurements of trace gas and stable-isotope compositions on the Moon, Venus, Mars, and Titan as well as such measurements on returned Martian, lunar, and cometary samples.

Our team has recently demonstrated the first semiconductor-based mid-IR optical frequency comb by passive mode-locking an interband cascade laser (ICL)[1]. Our demonstrated ICL-based comb is the first true mode-locked semiconductor laser at mid-IR that can access 3-6 micrometer with broad coverage and high efficiency. However, we have identified the modal dispersion in these combs limit the stable operating conditions to a narrow range [2]. In this work, we propose to extend the emission bandwidth and stable operating conditions of the ICL combs by dispersion compensation engineering of the laser gain medium and the waveguide. The proposed optical frequency comb will span over 200 nm with a center wavelength at 3.3 micrometer. By taking advantage of a multi-heterodyne architecture where two nearly similar optical combs are interfered on an optical detector, we will enable a multi-species massively parallel optical detection scheme with part-per-billion (ppb) sensitivity at sub-second acquisition time [3]. Therefore, the proposed dual comb spectrometer is suitable for simultaneous detection of a series of target molecules such as CH4, H2S, N2O, NH3, C2H2, C6H6 (benzene) and many other volatile compounds. The innovative combination of high-efficiency ICL combs and small cavity dimensions will be applicable throughout the 3 to 6 micrometer range.

The incumbent state-of-the-art in in-situ detection of planetary volatiles is GC-MS (mass spectrometry coupled with a gas chromatographic column). Typical detection limits of GC-MS instruments that are compatible with planetary exploration are approximately a few ppb to 10 ppb. Our proposed instrument will have comparable or better sensitivity. Moreover, IR spectroscopy is inherently compound-specific and isotope-specific, thereby eliminating isobaric interferences associated with mass-spectrometric techniques. Consequently, unlike mass spectrometry, our proposed DFCS instrument does not require sample preparation, pre-concentration, pre-separation (e.g. by gas chromatography), or pre-conversion, resulting in reduced instrument overhead and complexity and avoids issues associated with sample contamination and damage.

The Decadal Survey [4] identifies specific goals and objectives for the New Frontiers Saturn Probe mission, that include determining the noble gas abundances and isotopic

ratios of H, C, N, and O in Saturn's atmosphere and determining the atmospheric structure at the probe descent location. In a Saturn Probe configuration, our proposed DFCS would be able to measure both Nitrogen/ammonia (lambda = 3.3 micrometer) and Carbon/methane (lambda = 3.27 micrometer) simultaneously where as other technologies such as tunable laser spectroscopy would require individual channels (2 lasers) for each gas under investigation.

[1] M. Bagheri, et al., "Electrically pumped mid-infrared optical frequency combs," submitted to Nat. Comms. (2017).
[2] L. Sterczewski, et al., "Dispersion and modelocking properties of interband cascade lasers," in prep.
[3] L. Sterczewski, et al., "Multiheterodyne spectroscopy with interband cascade lasers," Opt. Eng. 57 (2017).
[4] Vision and Voyages for Planetary Science in the Decade 2013-2022, National Research Council, The National Academies Press, Washington, D. C., 2011.

Don Banfield/Cornell University
Saltation Sensor

On any planet with an atmosphere and granular material on the surface, wind-driven grain movement is a fundamental process of sediment transport and deposition, and landscape transformation. Wind moves the finest particles ("dust") in suspension, resulting in dust devils and dust storms observed on Earth and Mars. Somewhat coarser grains ("sand") cannot become suspended and instead are driven downwind in a series of hops across the surface called "saltation." Saltating sand accumulates into drifts, ripples, and the dunes seen on Earth, Mars and Titan. These saltating sand grains, because of their coarseness and the speed with which they are driven across the surface, have significant potential to abrade materials they impact against. This can have effects not only on geomorphology, but is also a serious engineering hazard for both manned and robotic planetary explorers.

Saltation has proven to be a difficult process to study and understand, partly because of its dynamic character. The first fundamental question about saltation involves determining the minimum wind strength required to mobilize sand, under the various conditions on Earth, Mars or Titan. A second fundamental question involves the actual flux of saltating grains (their speed and number density), and how this depends on the grain and atmosphere characteristics, gravity, wind speed, and height above the ground. Most state-of-the-art sensors for measuring saltating grain movements are unsuitable for robotic missions, requiring complex servicing to extract measurements. The most viable candidate for remote application, the "Sensit" instrument (commonly used in terrestrial field studies), only yields the grain impact rate and an estimate of the typical energy impacting the sensor over an interval at its single sensing height (i.e., with no vertical resolution on the flux). Impacts from small, high-speed grains cannot be distinguished from lower-speed impacts of larger grains. We have developed a science traceability

matrix establishing what is required to advance our general understanding of saltation in planetary environments. None of the existing instrumentation can fulfill these measurement requirements, especially considering the accommodation requirements for planetary instrumentation. We propose a technical approach to an instrument that would meet these measurement requirements and be well-suited to accommodation on a wide variety of planetary landers, rovers or aircraft.

We propose to adapt capacitive ultrasonic transducers (as used in our Martian Sonic Anemometer) to instead passively detect grain impacts. We have completed a preliminary proof-of-concept showing that we can extract information separately about impact energy and impact momentum from the signal generated during each impact. We have also demonstrated a conceptual approach to add position sensing to such a grain impact transducer to yield also each impact location. We propose to mature these transducer designs to optimize their ability to determine separately impact energy, momentum and position and to ensure durability of the sensors in the erosive saltating sand flux. We also propose developing the signal processing instrument back-end to handle the data stream from an array of such impact sensing transducers, and digest it to efficient and economically-sized information in light of limited spacecraft downlink availability. We anticipate no planetary protection hurdles for this heat- and disinfectant-tolerant instrument. The saltation sensor is currently at TRL ~2, but we expect to mature it up to TRL ~5 by the end of this work, poising it well to be proposed to space flight opportunities.

Howard Drew/University of Maryland, College Park
A millimeter/submillimeter heterodyne sensor for spectroscopy and imaging of cold planetary objects in the outer solar system

We propose to develop a tunable millimeter/submillimeter-wave antenna coupled graphene mixer-based heterodyne sensor on future missions to icy moons (Titan, Enceladus, and Europa) of the outer planets of our solar system. The proposed technology is focused on the "Ocean Worlds" mission theme and will enable to address challenge questions - significance of abiological synthesis of organics, i.e., hydrocarbons, their derivatives, and ions (carbocations and carbanions) - in the origin of life on Earth. Investigating this abiotic chemistry is a necessary step in the quest to understand the origin of life and habitability context. The goal of planetary exploration research is the identification of molecules of prebiotic importance (e.g. the aromatic rings, heterocycles, nucleic acid bases, and amino acids) in space through rotational spectroscopy, and the elucidation of their chemical structures using the proposed heterodyne detection technique. The detector system is based on non-linear 2 wave mixing of the weak THz radiation and a THz local oscillator in a graphene photo-thermo-electric detector (Cai et al., Nature Nanotechnology 9(10) 814 (2014)). This results in a heterodyne response for the weak THz signal with the difference frequency relative to the local oscillator. The noise temperatures of noncryogenic graphene mixers are expected to fall between

respective values of superconducting SIS heterodyne detectors and hot electron bolometer HEB square law mixers and require less local oscillator power than Schottky diode mixers. We expect to bring this technology from TRL1 to TRL4.

Besides hydrogen and water (as water ice), methane and methanol constitute as the major molecular matter in our solar system. We identified "Olah's nonclassical carbonium ion chemistry" as preferred chemical pathway for abiotic synthesis of organic compounds on Titan, and this pathway begins by the conversion of most abundant methane to methonium ion CH5+ (Ali et al., P & SS, 109-110 (2015) 46; Puzzarini et al., AstronJ. 154: 82(2017)). Because of the observed higher reactivity of methanol with respect to methane, a feasible new pathway has recently been proposed for the conversion of methanol to various extraterrestrial abiological organics together with a possible connection with methonium ion-based chemistry (Olah et al., JACS. 138 (2016) 1717). If methanol (a derivative of methane) indeed has been delivered by meteorites or comets to the icy surface of Europa in the chemistry of formation of our solar system, it is suggested that the radiation- catalyzed surface chemistry of Europa could also mimic the observed prebiotic chemistry on Titan by the Cassini-Huygens mission. Rotational spectroscopy in space from future orbiting spacecrafts (Titan and Europa Orbiter) would provide important information of atmospheric and surface-assisted prebiotic chemistry using the proposed heterodyne sensor. On the detection of any biological process or chemical markers for extraterrestrial life, spectroscopy of representative building blocks of life in the Ocean Worlds of the outer solar system (e.g. spectrum of Enceladus plume composition) is an important step.

The proposed graphene mixer-based sensor will also enable the measurements of winds with high velocity resolution from Doppler shift studies of optically thin rotational lines. In addition, this technology will permit a sensitive array receiver configuration for thermal imaging of surfaces of cold planetary bodies in the outer solar system with spectral resolution. A major breakthrough in technical challenges on the design and development of the sensor proposed will put studies of spectroscopy, chemistry and dynamics of the environments of icy moons of outer planets in our solar system, and will provide a lasting impact on the "relevance and significance of extraterrestrial abiological hydrocarbon chemistry" in the origin of life as stated in the Planetary Science Decadal Survey (2013-2022).

Brian Drouin/Jet Propulsion Laboratory
Two Spectrometers on a Chip

The promise of miniaturized millimeter-wave (mmw) spectrometers to provide sensitive and highly specific detections of volatile materials in normal and extreme environments has recently been demonstrated in the Spectrometer-on-a-Chip (SpecChip) project. These efforts show that specific organic and inorganic species are readily identified and quantified utilizing a miniaturized Fabry-Perot cavity coupled to a single circuit board containing the mmw production and detection circuitry. These efforts also quantified the sensitivity of the system, the bandwidth, and identified the limiting technologies.

Building upon this success, we propose here to improve the extend the bandwidth and range of the supporting CMOS technology to support science goals. We push the boundary of two technological limiting factors for mini-mmw spectrometers (1) to extend the coverage in W-band (covering HDO at 80.6 GHz) and (2) to provide frequency coverage up to G-band (for H2O at 183 GHz). The two chipsets will be shown to operate in a single system, the SpecChip^2. These developments enable the highly desirable science targets of quantifying both water (H2O) and deuterated water (HDO). These measurements in tandem enable H/D ratio measurements in water/ice samples and expand the existing ability to detect and quantify organic and inorganic volatiles. The improvement in frequency range and bandwidth also expands the applicability of CMOS spectrometers to enantiomeric specific measurements.

The demonstrated low-mass, low power millimeter wave system with CMOS components covers 89-104 GHz and gas detections of CH3OH, CH3CHO, N2O, OCS, CH3CH2OH, CH3CN, CH3CH2CN, (CH3)2CO, NaCl and KCl have been made. The demonstrations are limited by sample availability and are only a fraction of the gases detectable with such a system. However, there are key species of scientific interest whose target transitions are at higher frequencies, particularly H2O at 183 GHz (in G-band 140-220 GHz) and HDO at 80.6 GHz (in W-band 75-110 GHz). Thus far, 65 nm CMOS tunable devices with sufficient (> 1 mW) power to pump a mixer or a molecular transition, have not been demonstrated above 140 GHz. For infusion of this technique into space missions, we must be able to achieve detections for the highest-value science targets, therefore we propose to develop, fabricate and test the necessary circuitry in 28 nm CMOS, an architecture that is showing improvements for upper frequency limits. Through creation of the specific W-band and G-band circuitry necessary for planetary science instrumentation, we provide a broadly useful new instrument with a premier science capability for water H/D ratio measurement.

Christine Hartzell/University of Maryland, College Park
In-Situ Cohesion Quantification and Sample Collection Through Electrostatic Lofting

The proposed investigation will explore the feasibility of collecting a regolith sample from the surface of an asteroid and measuring the cohesion of the regolith through electrostatic lofting. Due to the very low mass of asteroids, dust grains are bound to the surface primarily due to inter-granular cohesion, rather than gravity. Additionally, the surficial regolith grains are charged due to their interaction with the solar wind plasma. It has been hypothesized that dust grains may be detached from the surface of a small body simply due to the electrostatic force. We propose to use the physics of electrostatic lofting to characterize the cohesion of the surficial regolith and collect sample of an undisturbed small body surface.

We propose to evaluate the feasibility of cohesion measurement and sample collection by an instrument that will be able to accurately control its distance above the surface and its electric potential. By changing its distance from the surface and electric potential, the instrument will change the local plasma environment. When the electrostatic force (produced by the interaction of the grain charge with the local electric field in the plasma sheath) is sufficient to overcome gravity and cohesion, dust grains will detach from the surface and approach the instrument. Through accurate knowledge of the instrument's position and potential, and the size of the grains lofted, it is possible to calculate the cohesion between the surficial dust grains. Additionally, the grains may adhere to the spacecraft, providing a novel, controllable method of sample collection.

This technology is currently at TRL 2. We will bring this technology to TRL 4 by the end of the performance period.

Philippa Molyneux/Southwest Research Institute
Development of far-UV-sensitive silicon imaging arrays for compact UV instrumentation

Recent advances in the UV responsivity of silicon-based imaging arrays motivate us to develop and test a fully UV-optimized CMOS-detector focal-plane array (FPA) prototype. Notable innovations in silicon-based FPAs have led to the development of detectors with quantum efficiencies at mid-UV wavelengths (200-300 nm) that are competitive with state of the art microchannel plate (MCP) technology (e.g., Bai et al., SPIE, 2008; Nikzad et al., 2011) with the added advantage that, unlike MCPs, they do not require high-voltage power supplies. Hence, the utilization of these innovative detectors in future UV spectrographs or imagers will reduce the power, mass and complexity of such instruments over their current equivalents, making them well-suited for future low-cost planetary missions including those based on CubeSats and other SmallSat platforms. In previous studies we characterized the far-UV (100-200 nm) performance of UV-optimized n-type silicon devices at SwRI (Davis et al, SPIE 2012) and began to develop methods of enhancing the far-UV response by doping thinned-silicon wafers with antimony using Molecular Beam Epitaxy (MBE) (Retherford et al., JATIS, 2015). This work demonstrated that the MBE process is feasible for silicon wafers with thicknesses as little as 100 microns; an important result, given the short absorption depth of far-UV photons in silicon. Methods of cleaning the wafers prior to MBE were investigated at MIT Lincoln Laboratory, and the MBE process was optimized through a series of experiments in which the target doping concentrations, growth temperatures and epitaxial-silicon thicknesses were varied. Exploiting this initial success, we intend to (1) complete the optimization of the MBE process for n-type backside-illuminated CMOS hybrid arrays from Teledyne, (2) expand the assessment to include MBE process on state-of-the-art p-type CMOS monolithic arrays made using ~10-micron epitaxial-wafers from Teledyne e2v, and investigate options for anti-reflectance coatings to reject longer wavelength light, and (3) fabricate and test UV-optimized photodiodes, analyzing their

response to wavelengths from far UV to the visible. We will also develop a full prototype FUV-optimized CMOS FPA taking advantage of flight-heritage array formats such as HAWAII-1RG. For the component technologies developed in this program, the entrance TRL of 3 will be raised to TRL 4 or higher upon exiting the program. Once developed, these UV-optimized devices will enable highly capable SmallSat investigations of lunar polar volatiles, Venusian upper atmosphere composition and dynamics, water vapor plumes at Enceladus and/or Europa, and other targeted science measurements detailed within the Vision and Voyages Planetary Decadal Survey.

Rachel Obbard/Dartmouth College

Mars In Situ Tomography System (MISTS) Development for Characterizing the Stratigraphy of Polar Layered Deposits

We propose to miniaturize an X-ray microcomputed tomography (microCT) system for in situ analysis of layered martian ice. The Micro In Situ Tomography System (MISTS) will provide the microstructural information we would seek from an ice core: millimeter scale stratigraphy of impurity layers and micron scale particle size, shape, and position.

OBJECTIVE

Mars has layered subsurface ice and polar layered deposits that contain a climate record relevant to studies of past habitability and climate science more generally.

MicroCT provides non-destructive three-dimensional visualization and characterization of the internal features of multiphase materials with spatial resolution down to several microns. It has been used extensively in the study of depositional processes in sedimentary rock (e.g. Falvard and Paris, 2017) and more recently in ice (Obbard et al., 2009; Iverson et al., 2017). MicroCT can measure micron scale layer stratigraphy, particle size, shape, volume concentration, pore size, shape and distribution, all as a function of depth. The use of microCT to differentiate and identify depositional layers based on particle size and shape distribution in the ice has been demonstrated in the West Antarctic Ice Sheet (WAIS) core were used to identify the type and source of specific volcanic eruptions (Iverson et al., 2017).

Application of the technique has been growing in part due to rapid advances in instrumentation technology and accessibility through commercially available benchtop systems. Typically a microCT system is located in a laboratory; however, in some situations it may be preferred (e.g. transport and curation of frozen samples) to bring the microCT to the samples. We propose to develop a miniaturized microCT system that can be used robotically to examine stratigraphy and sediment distribution in martian ice cores.

TECHNICAL APPROACH

The MISTS will be a two-step process. Immediately following collection, an ice core will be placed between source and detector and X-ray attenuation images collected. One of the challenges we foresee is the need to withdraw and image fractured cores. The ice coring drill will employ Honeybee Roboticsý eccentric tubes core breakoff and retention technology, a metal bit with an internal breakoff and caching tube(s) made of an X-ray transparent polymer (Zancy, 2014). As the caching tube and core is drawn from the hole, it will pass though a surface mounted microCT system, which will image the sample in situ in the tube. Data (bitmap X-ray attenuation image files, vertical and azimuthal position, and X-ray source statistics) will be transferred to Earth, where tomographic images will be reconstructed.

Tasks:
1. Determine optimal core diameter by weighing competing requirements such as sample size, tomographic spatial resolution, drilling and microCT power, and weight.
2. Specify X-ray source strength, integration time, detector resolution.
3. Identify microCT geometry, components (i.e. source and detector) and design.
4. Make design changes to current core breakoff and retention system, including the caching/analysis tube(s).
5. Build and test microCT system on caching tubes containing ice and sediment in the lab at cold temperatures.

The proposed work is relevant to NASA PICASSO because we aim to design and develop a new miniaturized instrument to be used for in situ science in a planetary context. Under this project, the proposed instrument will advance from TRL 2 to TRL 4.

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Xiaoli Sun/NASA Goddard Space Flight Center
Linear Mode Photon Counting HgCdTe Avalanche Photodiode Arrays for Multi-beam Laser Altimeters

We propose to develop a 2x30 and a 7x8 pixel linear mode photon counting (LMPC) HgCdTe avalanche photodiode (APD) array for future planetary laser altimeters and infrared laser absorption spectrometers. These new detectors can detect single photon

event and are about 100 times more sensitive than the silicon APDs and photomultiplier tubes used in current laser altimeters in space. The higher sensitivity and pixelated detectors will enable us to increase the number of beams by a factor of 10 compared to the current multi-beam laser altimeter, such as the Lunar Orbiter Laser Altimeter (LOLA) without increasing the laser power. The spectral response of these new detectors spans from 0.4 to 4.3 micrometers, which broaden the choice of laser wavelengths to enable penetrating atmosphere at one of the spectral transmission windows of certain planetary bodies, such as Titan. The new detectors can also be used in atmosphere backscattering lidars and laser absorption spectrometers with near quantum limited performance. These detectors are based on the recent HgCdTe APD technology developed by DRS Technologies supported by the NASA Earth Science Technology Office (ESTO). We have already developed a prototype device with 2x8 pixel in a micro cryo-cooler. Here we proposed to develop a mid-sized LMPC HgCdTe APD array for multi-beam laser altimeters with at least 10 times more beams than the current technology and pave the way for even larger pixel arrays for future 3-D imaging lidar.

Laser altimeters, or lidar, have been used in numerous space missions to measure surface topography, global shape, orbit, and surface reflectance at the laser wavelength. Early planetary laser altimeters, such as the Mars Orbiter Laser Altimeter (MOLA), used a single laser beam to measure the surface elevation profile one per orbit. LOLA is the first multi-beam laser altimeters and shows the great benefit and potential of multi-beam measurements. Besides a much finer and denser ground coverage, it measures the surface slope and roughness from a single laser pulse. It also gives orders of magnitude more cross-over points for orbit and laser beam pointing determination. However the number of laser beams are now limited by the detector sensitivity, size, and the available laser power. The LMPC HgCdTe APD arrays which we propose to develop will have single photon sensitivity and combine individual detector packages into a focal plane array (FPA) to enable a LOLA sized instrument to have 10 times more beams. The United States Defense Advanced Research Projects Agency (DARPA) has already funded DRS after NASA ESTO to produce a large size focal plane array (FPA) but with a simplified read-out integrated circuit (ROIC) for ground-based flash lidar demonstration. We will leverage these investments to develop and demonstrate a 2x30 and a 7x8 pixel array detector (60 and 56 pixels) with full pulse waveform outputs. We will also study the use a single laser with microlens array to illuminate ground surface in a pattern that matches the detector pixel format.

Our work plan is to (a) develop a 2x30 and a 7x8 pixel LMPC HgCdTe APD FPA with ROIC for single photon sensitivity linear outputs; (b) integrate the FPA in a low-cost liquid nitrogen Dewar system and characterize the detector performance; (c) investigate the signal waveform processing techniques that are efficient and can later be integrated in the ROIC, and (d) develop a laser transmitter beam formation technique to match the detector pixel patterns. The entry TRLfor the detector and the laser transmitter are TRL-2. We propose a 3-year research and development program to bring them to TRL-4. The target applications are multi-beam laser altimeters and atmosphere backscattering lidar for Mars and other planetary bodies, mid-wave infrared laser spectral absorption lidar for the Moon and asteroids, and proximity operation lidar for asteroid mapping and sample returns.

Karl Yee/Jet Propulsion Laboratory
Universal MEMS Seismometer

In the coming decades NASA will launch missions to explore Ocean Worlds in search of conditions for life in the outer Solar System. In addition, landed mission concepts to study rocky bodies (the Moon, Mars, Venus and asteroids) are likely to be proposed. Seismometers are a common threshold instrument to most landed mission concepts, as they are the most efficient and proven tool to explore a planetary body's interior. Yet, since 1976 (Viking 2) no seismometer has been included in any of NASA's lander or rover missions. The main reason for this lies in the complexities in launching, landing, and emplacing intricate, highly sensitive, and delicate seismometers on extra-terrestrial bodies. This fact was highlighted by the complexities encountered by the InSight mission that will launch in May of 2018 (originally planned for 2016). To enable a simple implementation of geophysical exploration of deep planetary interiors in future missions NASA is in dire need for a small, robust, yet sufficiently sensitive seismometer that can be realized in multiple mission architectures.

Currently, high-performance seismology is dominated by large, pendulous mass, instruments. Micro Electro-Mechanical System (MEMS) based seismometers offer the advantages of small volume and mass, low power, and reduced cost through batch fabrication; however, MEMS seismometers have traditionally suffered from lower performance. The sensitivity of a resonant vibratory sensor is limited by its thermal mechanical noise floor. A seismometer's noise floor is minimized by maximizing the resonator MTQ product (i.e. Mass x Period x Quality factor). Thus, high sensitivity is usually achieved by using a large proof mass and a very soft suspension system; this combination makes for a large, fragile instrument. A frequency tuning technique commonly used for MEMS resonators is to apply a voltage across a capacitor spanning the length of the spring, resulting in electrostatic spring softening. Increasing this voltage results in electrostatic frequency nulling (i.e. large T), enabling high sensitivity with a reduced proof mass. This has been demonstrated in the macro cryo-seismometer being developed by the University of Maryland and JPL. However, utilization of this technique is something that has not been exploited at micro length scales, but is a natural fit, as very small capacitive gaps can be micro machined in, substantially reducing the high voltages needed at macro length scales to exploit the effect.

The objective of the proposed effort is to utilize electrostatic spring softening to develop a state of the art MEMS seismometer, unique in the ability to deliver broad-band sensitivity (~1ng/rt-Hz at 0.1-100Hz). High shock tolerance is easily achieved with a smaller proof mass by caging it. Furthermore, with the smaller proof mass, increase of the sensor bandwidth through negative force feedback can be accomplished capacitively, instead of inductively as utilized by macro seismometers; thus, the sensor becomes easier fabricate, is of homogenous construction (i.e. silicon with no metallic magnetic coils), and thus able to tolerate extremes in temperatures (e.g. -160C for Europa to 460C for Venus). Finally, the resonator quality factor will be maximized through construction out silicon, a material with low thermoelastic damping (i.e. low intrinsic losses), and the sensor will be vacuum packaged in a COTS leadless chip carrier. This will be a compact

sensor, easily incorporated into any lander with minimal impact to spacecraft size, weight and power; this device would also enable the low-cost deployment of a seismic network through the use of penetrators.

Enabling the integration of a small sensitive seismometer onto future rovers, soft and hard landers, as well as onto impactors, will add a valuable geophysical facet to most future planetary surface missions without the complexity and associated costs that a dedicated geophysical mission demands.