TESTING FUNDAMENATL GRAVITY WITH INTERPLANETARY LASER RANGING. S.G. Turyshev, M. Shao, and I. Hahn, Jet Propulsion Laboratory, 4800 Oak Grove Drive, Pasadena, CA. turyshev@jpl.nasa.gov

Introduction: Lasers—with their spatial coherence, narrow spectral emission, high power, and well-defined spatial modes—are highly useful for many space applications. While in free-space, optical laser links would have an advantage as opposed to the conventional radio-communication methods. Laser optical links would provide not only significantly higher data rates, it would also allow a more precise navigation and attitude control. In fact, precision navigation, attitude control, landing, resource location, 3-dimensional imaging, surface scanning, formation flying and many other areas are thought of in terms of laser-enabled technologies [1-2]. Deployment of laser instruments on the Deep Space Gateway (DSG), may lead to advances in many science areas. In particular, high-precision laser ranging may offer very significant improvements deep-space navigation & in many areas of relevant science investigations.

We propose the development of the Interplanetary Laser Ranging Terminal (ILRT) on the DSG. The ILRT will enable advances in gravitational and fundamental physics experiments performed in the solar system. By conducting very accurate range measurements, the ILRT will push high-precision tests of astrophysics and fundamental gravity into a new regime. It will explore the physics of the universe by measuring the curvature of space around the Sun, as represented by the parameterized-post- Newtonian (PPN) Eddington parameter γ, reaching the measurement accuracy of better than 2.0×10^{-7} (today's best accuracy is 2.3×10^{-5}, achieved by the Cassini mission to Saturn). Such a test would provide a crucial information to separate the modern scalar-tensor theories of gravity from general relativity, to probe possible ways for gravity quantization, and to test modern theories of cosmological evolution [3-7].

Other science objectives of the ILRT include measurements of (i) the time-rate-of-change of the gravitational constant, G; (ii) the non-linearity of gravity (as given by another PPN parameter β); and would test (iii) the gravitational inverse square law at interplanetary scales; and also (iv) the Equivalence Principle by using either spacecraft or celestial bodies of the solar system. The ILRT will improve the current results in many of these tests by a factor 10-50; in some cases, improvements by a factor of 100 are expected. In addition, the ILRT could be used for precision laser-enabled navigation of any laser-bearing spacecraft (either laser ranging or astrometry) at heliocentric distances of up to 3 AU.

Measurement concept: The ILRT will conduct high-precision measurements of the distance between the DSG and several types of laser instruments that could be either the set of passive laser corner-cube retro-reflector arrays currently on the lunar surface (deployed by the Apollo missions) and/or yet to be deployed in the near future. It can also work with several other types of instruments, such as active laser transceivers on a spacecraft in the solar system (for instance, on a smallsat in orbit around (or landed on) Phobos/Mars or asteroid).

The LIRT could be developed to operate in two different regimes – incoherent (i.e., measuring the time of flight) and coherent (i.e., measuring the phase of the received signal) ones. In an incoherent mode ILRT will rely on a moderate-power CW laser modulated at GHz frequencies to allow for <1 mm range accuracy for distances of up to 3 AU. In a coherent mode, ranging to an asset within 50 Earth-Moon distances could be done with a precision better than 1 μm (precision of 1 nm is possible for quasi-drag-free operations using an onboard accelerometer or differential operations).

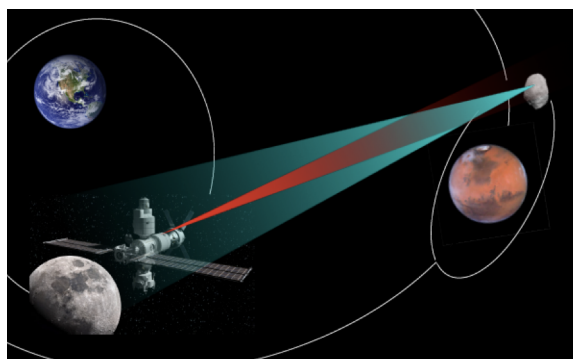

Fig. 1. The concept of interplanetary laser ranging to Phobos with a laser transceiver delivered to Phobos by a separate small-sat-class misison (currently being developed at JPL).

Instrument description: After launch from Earth and arriving to DSG, the ILRT will be deployed on its exterior surface, including a 30 cm diameter telescope, a medium-power (~10-50W) CW laser, an array of fast photo-detectors, imaging system, and a precision timing. The instrument will be on a gimbal to allow poining towards a laser target. For 1 hr/day or more the ILRT will transmit laser signal to, and receive laser signals from, a laser ranging instrument involved in the experiment (i.e., deep-space, Phobos or the moon).

The instrument data, consisting of time intervals between photon transmissions/ detections will be analyzed onboard or directly sent to the Earth via an RF link or a dedicated lasercomm facility. The timing measurements will be processed to give the DSG-s/c range accuracy of <1 mm. ILRT will take tracking passes of 0.5 hr/day for nominal 3 years of operations.

The ILRT relies on a medium power (~50-100W) CW laser and uses a telescope with 30 cm aperture to conduct precision laser ranging. The instuemnt could weigh 40-45 kg, including a gimbal for pointing. It may also need a ~30 kg thermal radiator to keep the ILRT at a room temperature. The instrument would occupy an estimated volume of ~0.7 m^3 and must be located one the exterior surface of the DSG. If a ~100W laser is used to operate the ILRT (in incoherent mode), < 300W electrical power is needed to operate the instrument. For the coherent mode of operation, a less-powerful laser could be used, reducing power requirements.

The primary data generated by the instrument will be the time-stamps of the transmitted and received signals (for incoherent mode) and/or phase measurements (for coherent mode), together with the environmental data, and relevant auxiliary information. This would result in the estimated lifetime data volume of ~10 GB.

The ILRT will be mounted on a gimbal on the exterior surface of the DSG. The instrument will be thermally insulated from extremal mounting; it needs to radiate heat to cool down the laser. In general, stable thermal environment is desired. An ideal orbit for the instrument will allow for the links between DSG and Phobos, and between DSG and the Earth. If the Earth-facing side of the moon is also available (even part of the orbit) it opens up the possibility of clock transfer, precision navigation, and optical communication.

The unit may have an three-axis accelerometer to decouple it from the non-gravitational noise contribution anticipated from the DSG. In this regard, the most accurate measurements will be achieved when the DSG is not occupied by a crew. Thus, the ILRT needs to be capable of remote operations. The instrument design is based on existing laboratory lasers and an array of photo-detectors which will be ruggedized to operate in space. JPL's Table Mountain Observatory, CA (TMO) is already equipped with a high-power (1.1 kW, average) laser for the lunar laser ranging (LLR, discussed below), that will be used in conjunction with the ILRT.

The ILRT development cost of $53M (FY 2017 $) was estimated, including ruggedization of the laser and the detector system for 16-month Phase A/B, 40-month Phase C/D, and 3 years of science operations. ILRT could be started in 2018 for launch in 2022.

Relevant facilities at JPL: ILRT will benefit from the existing high-power laser ranging facility recently constructed at the TMO. This facility uses a CW fiber amplifier laser with a 1.1 kW average power ouptut to conduct very precise measurements between the Earth and the retro-reflectors currently on the Moon. We amplitude-modulate the laser to conduct differenced LLR measurements accurate to 30 μm (atmosphere limited).

The logic for the optical schematic of our DLLR facility is as follows: For transmission, a seed laser is first phase-modulated to broaden the linewidth to ~10-20 GHz to avoid the spontaneous Brillion scattering (SBS) in the fiber amplifier, then amplitude/frequency-modulated with a chirping waveform (50-500MHz), which provides the absolute ranging information. This seed source is then fed into the fiber amplifier. The high power laser beam (~1.1kW) is then collimated in free space and propagate into the telescope. On return, a CCD is used to roughly point the telescope. A narrow bandpass and a Fabry-Perot filters are used to limit the IR detectors to the laser bandwidth. A high quantum efficiency IR camera provides the fine pointing information. We use a commercial IR photo-multilier tube detector with ~1-nsec time resolution. The return flux from the Moon is estimated to be ~1e4 photons/sec.

With high photon flux, the fundamental limitation of the accuracy of the LLR is then no longer sqrt(N), but the atmospheric delay. The delay from Earth's atmosphere (~2.3 m at zenith) produces a ranging uncertainty of ~8 mm after correction using the temperature, pressure, and humidity. However, the differenced delay error from OCTL to two or three sets of lunar corner-cube retro-reflectors can be as little as ~30 μm.

We expect a similar class performance from the ILRT which would open many areas for laser-enabled science investigations and precision navigation.

Conclusion: The deployment of laser transceivers in space will provide new opportunities for highly improved tests of the Equivalence Principle and measurements of various parameters of fundamental gravity. While in free space, the laser links allow for a very precise trajectory estimation and control to an accuracy of the order of 1 mm at distances up to ~5 AU. With their anticipated capabilities, interplanetary transponders will also lead to significant advances in the tests of fundamental physics and could discover a violation and/or extension of general relativity, and/or reveal the presence of an additional long-range interaction in physical laws. As such, these devices should be used for the next steps in lunar and planetary exploration and also to the future interplanetary missions to explore the solar system.

References: [1] Turyshev S.G., Williams J.G. (2007) *IJMP D 16, 2165-2179*. [2] Turyshev S.G., Yu N., Toth V.T. (2016) *Phys.Rev. D 93, 045027*. [3] Turyshev S.G., Sazhin M.V., Toth V.T. *(2014) Phys. Rev. D 89, 105029*. [4] Turyshev S.G., Toth V.T., Sazhin M.V. (2013) *Phys.Rev. D 87, 024020*. [5] Turyshev S.G, (2008) *Ann.Rev.Nucl.Part.Sci. 58, 207-248*. [6] Turyshev S.G. et al. (2010) *Exp.Astr. 28(2), 209-249*. [7] Turyshev S.G. et al. (2007) *IJMP D 16, 1879-1925.*