TIME, METROLOGY AND FUNDAMENTAL PHYSICS WITH THE DEEP SPACE GATEWAY T. Marshall Eubanks[1], Demetrios Matsakis[2], Jose J.A. Rodal[3], Heidi Fearn[4], Charles F. Radley[5], [1]Asteroid Initiatives LLC, Clifton, VA 20124 USA; [2]U.S. Naval Observatory, Washington, D.C., USA;[3]Rodal Consulting, Research Triangle Park, NC, USA; [4]California State University, Fullerton, CA USA; [5]Leeward Space Foundation, Palm Bay, Florida 32907 USA; tme@asteroidinitiatives.com;

Introduction: The Deep Space Gateway (DSG) proposed for cis-lunar space offers an opportunity to both improve tests of fundamental physics and to develop chronometric navigation techniques for the human exploration of Mars and beyond. Here we outline how the DSG, equipped with highly accurate optical atomic clocks and optical phase coherent links with the Earth and other spacecraft, can used to develop and apply the science of chronometric geodesy and navigation, where the clock-spacecraft system is used to both position the spacecraft and measure adjacent gravitational fields.

It appears likely that the DSG will be placed in a lunar Near Rectilinear Halo Orbit (NRHO), which offers many advantages for access to the lunar surface and the Earth, while minimizing or even eliminating both solar eclipses and terrestrial communications blackouts [1, 2, 3]. For definitiveness, we assume a 4:1 synodic resonant Halo orbit with a perilune radius of 5600 km and an apolune radius of $\sim$75,000 km.

Development of Optical Communication and Navigation: Optical communications is becoming increasingly important in space exploration [4], to provide the increasing bandwidth needed to support the high data production rates of modern instrumentation; a Deep Space Optical Communication (DSOC) optical communications system is under active development at NASA [5]. Optical communications will also drive the development of Deep Space Optical Navigation (DSON), so that positioning can use the DSOC infrastructure. Recent developments in atomic clocks, and in particular the development of optical atomic clocks with fractional frequency stabilities at the 10^{-18} level [6, 7] and time transfer at the femtosecond level [8] will lead to the development of chronometric geodesy and navigation, causing profound changes in spacecraft operation. The DSG offers a near ideal installation for the development of these new technologies, offering in addition tests of fundamental physical laws and improvements in our knowledge of the solar system.

The ability to establish phase coherence between terrestrial clocks at a level of a few parts in 10^{-19} with fiber optics [9] allows for phase coherent arrays of optical transmitters, and thus for an optical navigation system analogous to the terrestrial Global Positioning System (GPS). A coherent laser array can send out interleaved timing pulses kept in synchronization at the 10^{-18} fractional frequency stability (ffs) level allowing the receiving spacecraft to infer the relative time of arrival of the different pulse trains at that level. Over cis-lunar distances, small telescopes and lasers (10 cm and 1 W, respectively), should be sufficient to allow phase coherence between the DSG clock and each element in the transmitting array. With a picosecond relative delay accuracy a continental laser array extending over 4000 km would allow a DSON receiver to position itself to within a formal error < 0.1 nanoradians, or better than 5 cm accuracy over a cis-lunar distance of 5×10^5 km.

Quantum Entanglement across Cis-Lunar Distances: At present, quantum-entangled photons have been distributed over Earth to space round trip distances of $\sim$2400 km [10]. With the lasers and optics needed for DSG DSOC and DSON, this range could be extended to cis-lunar distances, an increase of over two orders of magnitude. This is important for more than just establishing a new distance record. Current optical clock technology is approaching the classical limits for clock stability , and quantum clock-synchronization techniques have been proposed to improve the accuracy of time transfer beyond the classical limits [11, 12]. The DSG can be used to extend these techniques to cis-Lunar distances as a step towards their use in deep space, for example to establish a common quantum clock between the Earth and Mars. In addition, the large one-way travel time to the DSG and Earth will enable a new Earth-Moon test of Bell's Theorem and the foundations of quantum mechanics by expanding these tests to include human decision making across space-like separations, a test of quantum mechanics only possible with a crewed vehicle such as the DSG [13]

Solar, Lunar and Planetary Redshifts and Other Tests of Relativity: The basic relativity tests enabled by a highly accurate spacecraft clock are described in [14] for the ACES experiment on the ISS; it should be possible to improve these tests by orders of magnitude with the DSG. In particular, the DSG solar potential change (see Table 1) is large enough that the second Post-Newtonian (PN) order change should be observable. The DSG thus could be the first platform able to access second order PN effects in the solar system, enabling a new class of tests of relativity. The redshifts from the Earth, Moon and Jupiter could be determined to a part per million (for the Moon) to a part per thousand (for Jupiter), allowing for improved redshift tests with a variety of compositions. Redshift changes of these magnitudes will be noise for any chronomet-

Body	δPotential	Notes
Sun	5.7×10^{-11}	Full to New Moon
	1.4×10^{-18}	Second PN Order
Moon	9×10^{-12}	Apo- to Perilune
Earth	6×10^{-13}	Apo- to Perigee
Jupiter	2×10^{-15}	At opposition
Venus	9×10^{-16}	At opposition
Saturn	10^{-16}	At opposition
Other planets	$< 10^{-16}$	

Table 1: Gravitational redshifts in the default DSG orbit.

ric navigation system, which will rely on its ability to separate target potential changes from the time-varying background. The DSG will offer the opportunity to develop techniques to account for the gravitational background, and thus to actually make it possible to deliver chronometric navigation using a 10^{-18} ffs clock.

Chronometric Observation of Gravitational Radiation with frequencies ∼1 Hz: Highly accurate optical clocks in space, together with phase coherent optical laser links between spacecraft, will enable the detection of gravitational waves with metric amplitudes comparable to the clock stability and wavelengths comparable to the clock separation [15, 16]. The chronometric detection of gravitational radiation offers advantages over the interferometric gravitational wave detectors, such as LIGO and the planned eLISA, which look for changes in the light travel time between end-points, instead of changes in clock phase. Modeling of the long-period gravitational wave background will also become important for chronometric navigations at distances $\gg$ 1 AU, where gravitational radiation is likely to become a significant source of clock, and thus navigation, errors.

An extended gravitational wave instrument is most sensitive for waves with wavelengths twice the projected length of the size of the instruments (or $\lesssim 2.56$ light seconds for the DSG-Earth combination). It happens that this wavelength is too long for effective detection by LIGO and will be too short for eLISA; the DSG with a good clock could thus help to fill in a hole in the gravitational wave frequency spectrum. A DSG chronometric gravitational wave detector would thus be a valuable addition to the Earth and space based gravitational wave detection instruments, capable of sensing large binary masses with orbital periods of a few seconds (for the larger masses, shortly before they merge into a single black hole). Figure 1 shows the detection range as a function of mass for orbital periods of 1 seconds assume a clock fractional frequency stability of 10^{-18}. For total masses of order 3000 solar masses (M_{Sun}), where the merger happens at an orbital period ∼1 second, the DSG could be competitive with both eLISA and LIGO.

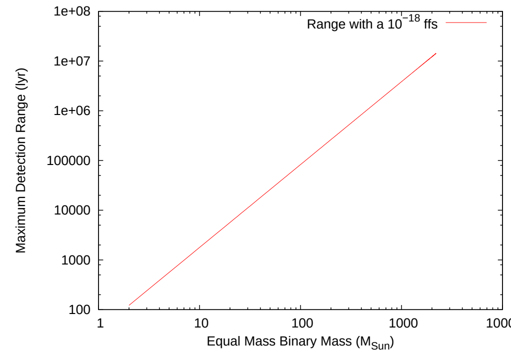

Figure 1: Maximum Detection Range using the DSG for an equal mass binary with a 1 second orbital period.

Basic Tests of Existing Positioning Techniques: The DSG will be at the lunar distance, and thus can be ranged by existing Lunar Laser Ranging (LLR) facilities. New technology corner cubes [17] could thus be tested on the DSG before deployment on the lunar surface; this would assist future LLR work and provide an auxiliary source of navigation data. The DSG will also be within range of the GPS satellites (either the main-lobe or side lobes) and should be equipped with a sensitive GNSS receiver capable of operation in cis-lunar space [18] to allow for tests of GPS / GNSS performance in a cis-lunar Space Service Volume.

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