NEXT-GENERATION PLANETARY GEODESY: RESULTS FROM THE 2021 KECK INSTITUTE FOR SPACE STUDIES WORKSHOPS.

J. T. Keane[1](james.t.keane@jpl.nasa.gov), M. M. Sori[2], A. I. Ermakov[3], A. Austin[1], J. Bapst[1], A. Berne[4], C. J. Bierson[5], B. G. Bills[1], C. Boening[1], A. M. Bramson[2], S. D'Amico[6], C. A. Denton[2], A. J. Evans[7], D. Hemingway[8], S. Hernandez[1], K. Hogstrom[1], K. Izquierdo[2], P. B. James[9], B. C. Johnson[2], M. Kahre[10], H. C. P. Lau[3], T. Navarro[11], M. Neveu[12,15], F. Nimmo[13], J. G. O'Rourke[5], L. Ojha[14], H. J. Paik[15], R. S. Park[1], P. Rosen[1], M. Simons[4], D. E. Smith[16], S. E. Smrekar[1], K. M. Soderlund[17], G. Steinbrügge[1], S. M. Tikoo[6], S. D. Vance[1], N. Wagner[9], R. C. Weber[18], H. Zebker[6], and M. T. Zuber[16]. [1]Jet Propulsion Laboratory, California Institute of Technology; [2]Purdue University; [3]University of California, Berkeley; [4]California Institute of Technology; [5]Arizona State University; [6]Stanford University; [7]Brown University; [8]Maxar Technologies; [9]Baylor University; [10]NASA Ames Research Center; [11]McGill University; [12]NASA Goddard Space Flight Center; [13]University of California, Santa Cruz; [14]Rutgers University; [15]University of Maryland, College Park; [16]Massachusetts Institute of Technology; [17]University of Texas at Austin; [18]NASA Marshall Space Flight Center.

Introduction: Measurements of gravity, topography, and deformation are powerful tools to investigate planetary formation, evolution, interior structure, and active processes. Such geodetic measurements thus have the capability to address some of the highest priority questions in planetary science. The power of geodesy is best demonstrated in the Earth-Moon system, where data from space missions has transformed geodesy from a purely geophysical tool into one that unlocks advances in geology, hydrology, climate change, and more. However, despite their utility, geodetic measurements have been sparse beyond the Earth-Moon system (**Fig. 1**). This paucity of modern geodetic observations motivated our Keck Institute for Space Studies (KISS) workshops (**Fig. 2**), where we identified the scientific advances that could be unlocked by future geodetic measurements across the Solar System.

Next-Generation Geodesy at Ocean Worlds: Ocean Worlds, such as Europa, Enceladus, and Titan, are some of the most fascinating and important objects in the Solar System. Their subsurface liquid water oceans may provide habitable environments. Ocean Worlds also display astonishing levels of geologic complexity and activity, making them exciting for studying fundamental geologic processes, and the coupled thermal/orbital evolution in giant planet systems. We identified three driving science questions that new geodetic data can address:

What are the interior structures of Ocean Worlds? The interior structures of Ocean Worlds provide the basic context necessary for understanding their origin, evolution, and habitability [1]. Important considerations include: lateral variations in ice shell thickness; mechanisms for topographic support; thickness, composition, and circulation patterns of the ocean; mechanical properties of the deep interior and rocky core.

What are the sources, sinks, and transport mechanisms of mass and energy within an ocean world? Geodetic data are uniquely suited to determine how the tidal heating is partitioned between the icy shell, ocean, and rocky interior [2, 3]. Cross-analyzing geodetic data with other datasets (e.g., geologic mapping, radar sounding, thermal observations) can shed light on the thermal history of Ocean Worlds.

Where are the habitable environments within an ocean world, and how long do they persist? Qualitatively, habitability requires clement conditions (temperature, pressure, etc.), a liquid solvent (water), an energy source, and key elements (CHNOPS). Geodetic measurements provide a powerful technique for characterizing the energy and material fluxes that result in habitability [e.g., 4]. For example: deformation measurements (e.g., InSAR) can characterize present-day activity and ice shell recycling rates, and static

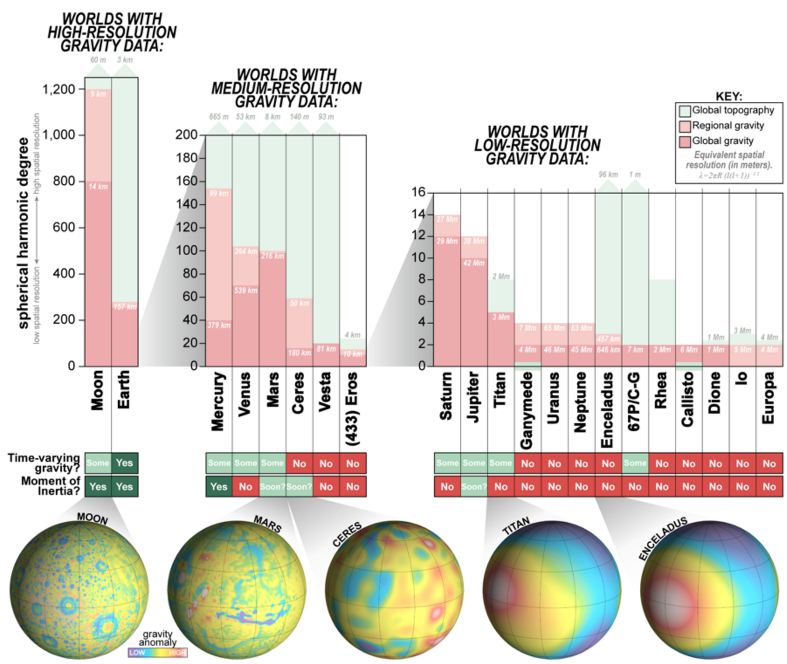

Fig. 1. Current knowledge of topography and gravity across the Solar System from orbital spacecraft. Resolution is plotted in terms of spherical harmonic degree, and labeled with equivalent spatial resolution in meters, kilometers, or megameters. Figure adapted from [20].

gravity measurements can characterize the seafloor and rocky interior, informing the conditions at which water and rock interact.

Next-Generation Geodesy at Mars: New geodetic data have the potential to address a wealth of outstanding scientific questions at Mars, falling under two broad themes: geodynamics and climate.

What is the geodynamic and tectonic history of Mars, and how and why does it differ from Earth's? The global north-south dichotomy in topography, geology, and other datasets is the largest, oldest, and most fundamental geophysical feature of Mars—yet there is still no consensus in how the dichotomy was formed [5]. Hypotheses include endogenic and exogenic processes, and combinations therein [e.g., 6–9]. A critical factor in testing dichotomy origin hypotheses is determining whether Mars has a global asymmetry in crustal thickness, crustal density, or both [10–11]. A confident distinction between these possibilities is not feasible with current datasets, but higher-resolution gravity measurements could disentangle these hypotheses, as was demonstrated at the Moon with GRAIL [12].

Additionally, the existence of ancient plate tectonics-like processes on Mars has been speculated [13], but not verified. Sufficiently accurate high-resolution gravity data would allow for investigation of this idea.

How do planetary climates respond to orbital forcing? On Earth, gravity has proved to be one of the most valuable datasets in the study of climate. At Mars, the available data has enabled some insights [14–15], but only scratches the surface. A higher-resolution static gravity field would allow for testing of the total water volumes present in the mid-latitudes, especially in areas where ice content is debated [e.g., 16–17], with implications for future human exploration [18].

Time-variable gravity would be a particularly powerful dataset for studying Martian climate. On Earth, time-variable gravity has allowed direct observation of ice sheet mass balance, hydrological cycles, and sea level change [19]. Gravitational monitoring over multiple Mars years could be used to study sources and sinks of water, dust cycle, and more.

Compelling Mission Concepts: Based on our exploration of next-generation planetary geodesy, we identified four mission concepts that would provide the most transformative advances in planetary science. Those mission architectures are, in no particular order:

- Enceladus Geophysical Orbiter: Characterize the interior structure and habitability of Enceladus, with an emphasis on probing the plumbing of the Tiger Stripes and their origin and evolution.
- Europa Geophysical Orbiter: Characterize the interior structure of Europa, building on Europa Clipper.
- Mars Gravity Mapper and InSAR: Characterize present day activity on Mars, particularly Mars's climate, atmospheric mass transport, volatile and dust cycles, and surface deformation.

Fig. 2. *Poster for the 2021 KISS Workshop for Next-Generation Planetary Geodesy, showing a hypothetical, GRAIL-like mission to Mars.*

- Mars Geophysical Helicopter: Characterize Mars's key geologic terrains (e.g., intense magnetic anomalies in the southern highlands, dichotomy boundary), filling a critical data gap between global-scale orbital measurements, and local-scale rover measurements.

New Technologies: Next-generation geodesy can be accomplished without new technologies, although new technologies have the potential to unlock additional transformative investigations. Examples include: SmallSats and radio beacons to make simultaneous and distributed gravity measurements; superconducting gravity gradiometers; advancement of onboard processing, particularly for large data volume experiments (e.g., InSAR).

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