Space Sci Rev (2017) 212:1433–1451
DOI 10.1007/s11214-017-0424-y

Survey of Capabilities and Applications of Accurate Clocks: Directions for Planetary Science

**Véronique Dehant[1] · Ryan Park[2] · Dominic Dirkx[3] ·
Luciano Iess[4] · Gregory Neumann[5] · Slava Turyshev[2] ·
Tim Van Hoolst[1]**

Received: 29 December 2016 / Accepted: 19 September 2017 / Published online: 16 October 2017

Abstract For planetary science, accurate clocks are mainly used as part of an onboard radioscience transponder. In the case of two-way radio data, the dominating data type for planetary radioscience, an accurate spacecraft clock is not necessary since the measurements can be calibrated using high-precision clocks on Earth. In the case of one-way radio data, however, an accurate clock can make the precision of one-way radio data be comparable to the two-way data, and possibly better since only one leg of radio path would be affected by the media. This article addresses several ways to improve observations for planetary science, either by improving the onboard clock or by using further variants of the classical radioscience methods, e.g., Same Beam Interferometry (SBI). For a clock to be useful for planetary science, we conclude that it must have at least a short-time stability ($< 1{,}000$ s) better than 10^{-13} and its size be substantially miniaturized. A special case of using laser ranging to the Moon and the implication of having an accurate clock is shown as an example.

Keywords Radioscience · Atomic clock · Positioning

High Performance Clocks with Special Emphasis on Geodesy and Geophysics and Applications to Other Bodies of the Solar System
Edited by Rafael Rodrigo, Véronique Dehant, Leonid Gurvits, Michael Kramer, Ryan Park, Peter Wolf and John Zarnecki

---

✉ V. Dehant
v.dehant@oma.be

[1] Royal Observatory of Belgium, Uccle, Belgium

[2] Jet Propulsion Laboratory/California Institute of Technology, Pasadena, USA

[3] Delft University of Technology, Delft, The Netherlands

[4] University of Rome, Rome, Italy

[5] NASA Goddard Space Flight Center, Greenbelt, USA

Table 1 Ranges of different frequency bands used in radioscience

Frequency band	uplink	downlink
UHF	[390 MHz, 405 MHz]	[435 MHz, 450 MHz]
S-band	[2.026 GHz, 2.11 GHz]	[2.2 GHz, 2.29 GHz]
X-band	[7.145 GHz, 7.19 GHz]	[8.4 GHz, 8.45 GHz]
Ka-band	[34.2 GHz, 34.7 GHz]	[31.8 GHz, 32.3 GHz]

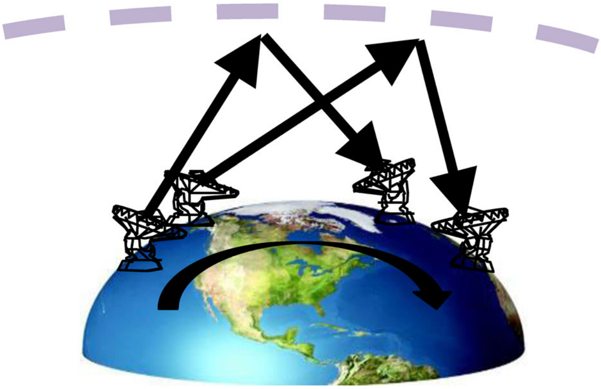

Fig. 1 Illustration of two-way radio measurements over a particular integration time

1 Survey of Capabilities of Accurate Clocks and Transponders in Space Science

Planetary science instruments/measurements using clocks or equivalent frequency standards are mainly for radioscience and laser instruments.

1.1 Radioscience

Radioscience instruments provide gravity, tide, and rotation measurements, from which the interior property of Solar System bodies can be deduced (see e.g. Folkner et al. 1997; Kuchynka et al. 2013, 2014; Le Maistre et al. 2012; Dehant et al. 2009, 2010, 2012a; Park et al. 2013, 2016). These observations are typically obtained using radio frequencies in UHF, S-band, X-band, or Ka-band. The frequency ranges for these radio bands as reserved for space radio links are presented in Table 1.

The measurements used to achieve the geodesy objectives are the Doppler shifts (i.e., for measuring line-of-sight velocity) and time of flight (i.e., for measuring distance) as measured at NASA Deep Space Network (DSN) stations or ESA ESTRACK tracking stations on Earth. These ground stations consist of 34 m/35 m and 70 m antennas. Similar 65 m antennas exist as well in Russia. Other equivalent stations (35 m and 64 m) are existing in China and Japan.

For two-way link between a spacecraft and an Earth's station (see Fig. 1), the measured Doppler shift can be written as (Moyer 2000):

$$\Delta f = \frac{f_T(t_1)}{cT_c}\big[\rho(t_2) - \rho(t_1)\big] \tag{1}$$

where f_T is the frequency transmitted at the spacecraft, c is the speed of light, and $\rho(t_1)$ and $\rho(t_2)$ are the spacecraft-station ranges at the start-time (t_1) and end-time (t_2) of the

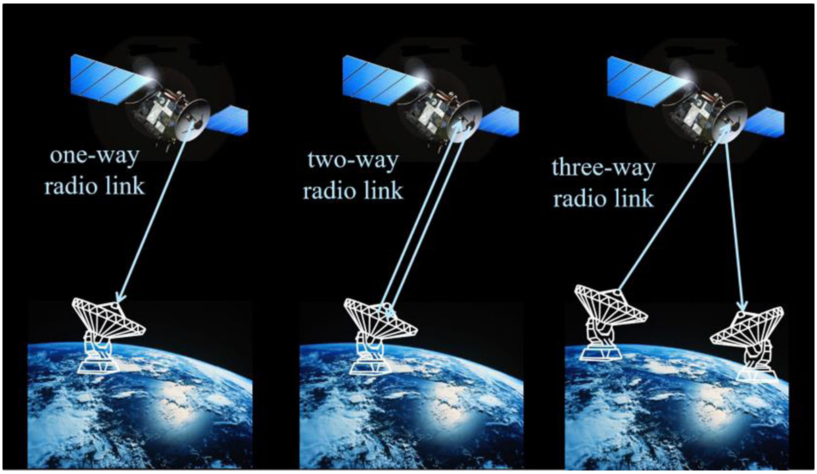

Fig. 2 Representation of the one-way, two-way and three-way radio-links

Doppler count time T_c, respectively. The ranging measurements consist of time differences between the signal sent to the spacecraft and received at the ground station. The geometry, or equivalently the orientation of the line-of-sight direction, changes over the sample time. From these measurements, one can reconstruct the motion of a spacecraft around a planet or moon (or on its way to the target celestial object) or of a lander or a rover on a planet or moon surface with respect to the Earth. One can as well measure the relative motion of a lander or a rover with respect to a spacecraft. The radio signals are often used as a “two-way” signal (see Figs. 1 and 2). For a two-way measurement, the reference frequency is provided on an Earth station, the signal is transmitted from the station, received at a spacecraft, and transmitted back coherently to the same Earth station. In this configuration, the same Earth station is used for transmission and reception of the signal. The “three-way” configuration is sometimes used, in which case, the receiving station is different from the transmitted station (see Fig. 2). The “three-way” data needs to be corrected for an offset between the clocks at the two stations, which is a well-understood practice and its accuracy is comparable to two-way data. Obviously, in these configurations, the reference clocks are calibrated on Earth and an onboard clock is not needed as long as the data is acquired coherently. The ESTRACK or DSN ground stations use hydrogen maser as their references (at the level of 10^{-15} stability). However, for the transponders to be coherent (retransmitting at a fixed ratio with respect to the reference frequency with no phase lag induced from the instrument), they are usually based on phase-lock loops and involve an internal oscillator. This oscillator must be as stable as possible but practically a quartz is sufficiently stable.

On the other hand, one could equivalently use an Ultra Stable Oscillator (USO) onboard the spacecraft and receive on Earth, or vice-versa; this is the so-called “one-way” radio tracking (see Fig. 2). The precision of the one-way measurements is mainly limited by the stability of an onboard USO, usually at the intrinsic stability level of 10^{-13}. In practice, two-way Doppler and ranging are mainly used for radioscience applications since present-day USOs are very sensitive to thermal environment and it is hard to achieve the intrinsic instrument stability (Asmar et al. 2005). In addition, a spacecraft must have a transponder for communication purposes, thus there always exists a two-way capability.

Presently the radioscience observation allows us to provide information on the global orbit of the spacecraft and its changes in space and time (precise orbit positioning), on gravitational and non-gravitational perturbations on the spacecraft trajectory and their time variations, including tidal or seasonal atmospheric effects, on the acceleration undergone by the spacecraft at a particular space and time (gravity above particular targets), on the orientation and rotation parameters of the planet or moon around which the spacecraft is in orbit or flies by. Two-way Doppler and ranging are used at present. If precise clocks are available on the spacecraft, one-way measurements could supplement these measurements. A benefit for one-way measurements in planetary missions can also be found when using it for atmospheric occultation, which can be used to determine atmospheric properties of a target body.

1.2 Interplanetary Laser Ranging

A laser altimeter enables distance measurements from a spacecraft to the surface of the orbiting body. The distance is determined by precisely measuring the round-trip light time of a laser pulse from the instrument to the surface and back to the instrument. The most important limitations of these measurements are the spacecraft position and attitude knowledge, and the so-called range walk due to signal strength variations and the spread of the laser pulse waveform by surface variations within the laser beam footprint.

A laser altimeter can also be used for measuring distance between Earth and a spacecraft or between Earth and a corner cube on a spacecraft or on the surface of a planetary object. The precision of this measurement is related to the frequency stability of the onboard clock or ground station USO.

In Satellite Laser Ranging (SLR), arrays of retroreflector corner cubes on spacecraft serve as transponders (Degnan 1993), providing sub-cm accuracy and precision range measurements. With return signal declining as the fourth power of distance, the limitations of such passive transponders beyond Earth orbit are clearly apparent. Active interplanetary transponder experiments using laser altimeters in cruise were first proposed in 1992 after the September launch of the Mars Observer spacecraft, carrying the Mars Orbiter Laser Altimeter (MOLA) as part of its instrument suite. The goal was to test the MOLA laser by firing at Earth and attempting to detect its signal, and to fire a ground laser at MOLA. The request never received serious consideration and the spacecraft was lost before attaining Mars orbit. The Mars Global Surveyor project did approve such an experiment with the reflight of MOLA in 1997, but it was canceled due to a spacecraft anomaly. An attempt by the NEAR-Shoemaker spacecraft to range to Earth prior to a flyby in 1999 was unsuccessful owing to poor visibility over several days at the one ground station equipped to receive 1064 nm (very near infrared) signals. Eventually, in 2005, a one-way link was achieved to the Mars Global Surveyor (MGS) spacecraft at a distance of 80 million km from Earth, with a precision of 2 milliseconds. Improved precision could have been achieved if the clock element of MOLA had not already failed (Abshire et al. 2006).

Two-way interplanetary ranging was eventually demonstrated successfully in 2005 (Smith et al. 2006) with the Mercury Laser Altimeter (MLA) on board the MESSENGER spacecraft. The ranging precision was limited somewhat by the ~ 6 ns MLA pulse width and the weak signal received by the instrument on the spacecraft, just at the detection limit. This two-way asynchronous transponder experiment (Degnan 2002) achieved a few dozen downlink and uplink data that corresponded to the receive times predicted for a range of nearly 24 million kilometers. Solutions for the range and range rate as well as clock offset were obtained with a precision of 20 cm, 15 cm/s, and 0.7 ns respectively from the 104 data points acquired. The experiment succeeded in part due to the precision of the onboard USO that provided timing signals and was also monitored from the ground, but by the time the experiment could be repeated four days later, the clock had drifted by several microseconds so that a longer-baseline solution could not be obtained.

Building on this success, the Lunar Reconnaissance Orbiter (LRO) incorporated a one-way Laser Ranging (LR) experiment (Zuber et al. 2010), providing operational laser tracking for the first time of a satellite beyond Earth orbit. The Lunar Orbiter Laser Altimeter (LOLA) instrument had a ranging precision of 10 cm. To attain the stringent 50-m total position orbit requirement, a receiver telescope was articulated with the LRO high gain antenna (HGA) and coupled to the LOLA timing system to allow an Earth laser station to range to LRO in a one-way transponder mode whenever in view. LRO-LR operation was conducted for a total of $> 4{,}000$ hours by 11 ground stations in 5 years, from 30 June 2009 to 30 September 2014. LR data achieves a 5–10 cm precision after conversion into 5 s normal points (Mao et al. 2012, 2017). The spacecraft clock is a commercial ovenized crystal oscillator (Symmetricom 9500B) similar to the USOs flown routinely on other spacecraft with a short-term stability of $< 2 \times 10^{-13}$ Allan deviation (Bauer et al. 2016, 2017). For the two-hour duration of a lunar orbit, random walk errors are $\sim$ 1–2 ns. The one-way experiment relied upon the precision of both the spacecraft clock and multiple instances of ground station clocks, often with unpredictable offsets that introduced many additional parameters into the orbit estimation.

The GGAO (Goddard Geophysical and Astronomical Observatory) ground station relied at first on a GPS-steered clock for observation epoch time; this proved inadequate and was eventually replaced by a co-located H-maser. Other stations used masers during part of the experiment, or relied on Cs and Rb atomic clocks with variable stabilities and drift rates.

The LR observables for orbit determination are the matched transmit and receive times, corrected for system and atmospheric delay, formed into 5 s centered averages or “normal points”. Modeling the observable time difference requires a fully relativistic treatment of both clocks as well as the clock offsets and rates. Additional care to model the spacecraft clock required estimation of its intrinsic drift and aging, as well as its residual thermal response and its unpredictable or random walk noise. Several teams, using different software systems have utilized portions of the LR data to study orbit determination: the JPL navigation software package MONTE (Buccino et al. 2016), the software developed jointly at Delft and DLR using the Tudat software (Bauer et al. 2016, 2017), and the GEODYN2 software at GSFC (Mao et al. 2017). All three efforts obtained tracking residuals in the range of 10–30 cm, and found that performance on a par with 2-way radiometric tracking could be obtained over relatively short (1–2 day) arcs, for which the random walk of the USO was not severe. Some results have been obtained with longer (5–7 day) arcs, but the number of extra parameters to model the clock thus introduced limits the strength of one-way ranging. In combination with radiometric ranging and Doppler tracking, the incorporation of laser ranging data improved the LRO orbits, with the improvement correlated with the amount of tracking data and modeling sophistication.

The Moon is, however, a special example because the most important factor in orbit determination has been the use of high-degree gravity potential models derived from the GRAIL mission (Mazarico et al. 2013), and the best results obtained for LR likewise rely on the best resolution of gravity, particularly on the far-side where tracking from Earth is unavailable.

For well-determined orbits, the LR simultaneous data passes (up to four stations at a time) can be used to affect a time transfer between stations within the field of view of the LR telescope (about 12,000 km). The GGAO maser and the nearby US Naval Observatory master clocks can be correlated at well within 1 ns using data collected from GPS receivers, given that ionospheric sources of error are common to both stations and therefore largely cancel, resulting in residual differences over 20 months of < 10 ns after removing long-wavelength trends. Thus, strong bounds may be placed on ground station clock errors; the main issues reside in the behavior of the spacecraft clock.

Due to the very similar required systems, there is great synergy between laser ranging and laser communications (Hemmati et al. 2009). The LADEE (Lunar Atmosphere and Dust Environment Explorer) spacecraft was the first to apply such a communications system beyond Earth orbit (Elphic and Russell 2015), using the Lunar Laser Communication Demonstration (LLCD) (Boroson et al. 2014). From the communications data, range data with a precision at the several cm level was obtained.

1.3 Accuracies/Stabilities of Clocks/USOs Currently Available for Space Science

As mentioned already, no clock is used onboard spacecraft for planetary science except for USOs with 10^{-13} stability used for one-way links. To reach this stability, the onboard USO must be thermally controlled. To make use of the Doppler effect for navigation and radioscience in a one-way link, it is necessary to know the frequency of the radio signal transmitted from the spacecraft at that level. Then the received frequency can be analyzed to calculate the line-of-sight speed of the spacecraft. Many interplanetary spacecraft carry a USO for this purpose, ensuring thermal stabilization to keep its output frequency stable. The long-term stability of a USO might be a problem if not calibrated against the stability of an Earth-based maser, which can be done using a model for the frequency changes over time.

The present-day precision of the radioscience measurements is limited by the noise arising on the signal from other sources, such as the errors due to solar plasma, ionosphere, troposphere, and non-gravitational forces such as maneuvers and angular momentum desaturations.

The precision of planetary laser ranging is limited by the pulse width, which is typically 10–100 ps (single-shot precision of 3–30 mm). The influence of clock noise for two-way ranging is limited, as discussed in Sect. 3.3. Measurement processing accuracy is limited to the several mm level by uncertainties in tropospheric corrections, ground station position uncertainties, and uncalibrated system instabilities.

2 Survey of Applications of Accurate Clocks and Transponders in Planetary Science

2.1 Global Static Gravitational Field Determined from a Spacecraft

When a spacecraft is orbiting a planet, it is perturbed by the gravity field of the central body. If the planet is homogeneous and spherical, the gravitational field is equivalent to that of a point mass, and the orbital motion of the spacecraft due to this gravity field would follow a Keplerian motion. However, planets, such as Earth, Mars, Venus, or Mercury, are not spherical and their masses inside are not uniformly distributed. For an oblate planet, one of the most important variations in the orbit corresponds to the precession in the longitude of the node of the orbit and is proportional to J_2 (the form factor of the planet), i.e. the coefficient of the first even zonal harmonics of the external gravitational potential. It provides information on the mass distribution inside the planet since J_2 is proportional to the difference between the polar moment of inertia (C) and the equatorial moment of inertia (A), representing the dynamical flattening of the planet. For a rapidly rotating planet like Mars or the

Earth, the contribution of the higher degree harmonics to the orbital drift is significantly lower than the J_2 contribution, because of the ellipsoidal distribution of the gravity field. *The limitations here are not arising from the clock but well from the other forces entering into the determination of the gravitational field, i.e., effects of angular momentum desaturation, maneuvers, atmospheric drag, solar radiation pressure effects on the spacecraft, as well as solar plasma and Earth ionospheric/tropospheric effects on the signal.* However, as mentioned previously, if a clock is available onboard the spacecraft, it is possible to add one-way communication between the Earth and the spacecraft, allowing to use passive telescopes on the surface of the Earth. The one-way links add data, which is important for a global computation of the gravity field. Moreover, assuming the clock noise could be reduced to provide comparable data noise as a two-way link, the one-way link would provide about a factor of $\sim \sqrt{2}$ improvement since the error due to media are cut in half.

2.2 Time Variation of the Gravitational Field as Determined from a Spacecraft

For a planet with an atmosphere, changes in the mass distribution and wind effects in the atmosphere may induce changes in the solid planet angular momentum and changes in the gravity coefficients. For Mars, about one fourth of the atmosphere of Mars is participating in the sublimation and condensation process of the CO_2 in the atmosphere and ice caps. The CO_2 seasonal cycle of Mars atmosphere induces mass exchange between the pole caps and the atmosphere, which in turn induces seasonal variations of the gravitational potential as well as of the rotation rate of the planet. The expected contributions to the gravity zonal harmonics variations of degree 2 to 5 are on the order of a few hundredths of percent of their static values as observed and expected from Global Circulation Model (GCM) of Mars' atmosphere. In turn, this small amplitude of the zonal harmonics variations generates small orbital perturbations, which needs an accurate reconstruction of the orbiter motion to be detected. *Again, the limitations are not arising from the clocks but from the non-gravitational corrections of the spacecraft acceleration.*

2.3 Time Variation of the Gravitational Field Induced by the Tides as Determined from a Spacecraft

Tides are interesting phenomena as they can be used for the determination of core properties such as the core density and size. The tides depend on the interior structure, e.g. there are larger tidal displacements for a body with a fluid core or a global subsurface ocean. If the tides are observed, it may be possible to determine the interior structure since the driving forces are usually known precisely. For Venus (Konopliv and Yoder 1996) and Mars (e.g. Konopliv et al. 2011), the tidal k_2 Love numbers have been observed and the physical properties of the core have been determined. At first, the core density/dimension can be determined, which are as well a tread off with respect to the mantle density profile. Equivalently, the tides of the icy moons are as well interesting to observe as they reveal the existence or not of a subsurface ocean. In this case as well, the ocean density can be determined in a tread-off approach with respect to the ice rigidity and the crustal thickness (e.g. see Baland et al. 2014; Mitri et al. 2014, for Titan; see Wu et al. 2001; Wahr et al. 2006, for Europa; and Moore and Schubert 2003, for Ganymede and Callisto). *Again, here the limitations are not arising from the clocks but from the non-understood non-gravitational corrections of the spacecraft acceleration.*

2.4 Time Variation of a Lander Position for Rotation and Tide Determination

The observables are Doppler and ranging in X-band or Ka-band or in both using the radio links between landers at the surface of Mars and the Earth surface tracking stations. From these observables, it is possible to determine Mars' rotation and orientation in space as well as the lander position as a function of time. These observations are further used to determine properties of Mars (or equivalently the Moon) interior, such as the core density, the fraction of core mass due to the presence of a light element (sulfur with the remaining mass assumed to be iron), the radius of the core etc. Similarly, rotational changes, such as changes in the length-of-day of Mars, may be determined by tracking the motion of a lander position in space, which enable to provide information on the atmosphere of Mars.

In addition to the determination of precession and nutation for Mars (i.e. variations of the orientation of Mars in space due to gravitational torque that the Sun exerts on the planet), the technique can be used for the determination of physical libration, (i.e. physical oscillatory response of a moon or planet in spin-orbit resonance to the gravitational torque exerted by the mother planet or the Sun, respectively) if one would have a lander on the surface of Mercury for instance, or on the surface of on icy moon of Jupiter.

Tidal effects do not only affect the dynamics of a spacecraft but as well of a lander. Periodic time variations of the lander position with respect to the planet or moon are induced either by the tides or by seasonal loading effects, which can be determined thus from radioscience with lander.

Here, again, the limitations are not arising from the clocks but from the non-gravitational corrections of the measurements.

3 Future Applications

3.1 Clocks on Spacecraft and Applications

Before we can really benefit from high-precision onboard clock, further advancements must be first made on the modeling and determination of non-gravitational forces acting on a satellite. These non-gravitational forces could be evaluated with the help of precise onboard accelerometers. In the case that all the forces acting on the satellite are well understood, with the exception of the gravitational forces (both static and time-varying), high-precision clock can be of interest.

Having an accurate clock onboard will allow one-way link with improved noise (i.e., a factor of $\sim \sqrt{2}$ since only one leg of radio path would be affected by the media error) than the two-way link. A gain of one order of magnitude on the onboard clock stability (i.e., 10^{-14}) would immediately translate into improvements in Doppler and ranging precision. However, since the Doppler data noise are limited by the media effects (e.g., solar plasma, ionospheric and tropospheric errors), use of a better clock is only meaningful if these errors can also be improved.

Combining several frequencies would help decreasing the Doppler data noise, similar to what was done on GPS and Galileo. The use of at least two frequencies (e.g. X-band and Ka-band) is also a potential approach for calibrating the errors due to solar plasma and Earth ionosphere. However, we will also need to calibrate the tropospheric effect at the comparable level. This applies to both the Earth atmosphere as well as the planet atmosphere if the spacecraft signal passes through the planet atmosphere. The Earth tropospheric effect can be calibrated using complementary data such as Advanced Water Vapor Radiometer (AWVR) and/or GNSS.

Thus, one way of taking the advantage of accurate clocks in space is using it for one-way radio link, which could increase the number of measurements and provide better geometric coverage. Also, high-precision timing, together with the usage of several frequencies and AWVR, would allow improving the precision of the Doppler and ranging measurements.

3.2 Same Beam Interferometry (SBI)

Recently a new method has been proposed for gaining an order of magnitude precision improvement in the determination of differenced one-way or two-way measurement, i.e., Same Beam Interferometry (SBI). SBI entails the simultaneous tracking of two or more landers from a single ground station in a coherent, two-way mode (Bender 1994; Fermi et al. 2008; Iess et al. 2008; Gregnanin et al. 2012, 2014). The signals received back from the landers are recorded and combined in an interferometric mode to form a differential phase proportional to the difference in distance between the landers and the ground station. The interference fringes retain information only about rotation and tides, while common noise sources such as interplanetary plasma, the Earth troposphere and ionosphere cancel out. The relative motion of the Earth and Mars is also rejected when the differential phase is formed. The noise cancellation is limited only by the different path delays in the Martian atmosphere and ionosphere (to a much lesser extent), and the small gradients of the interplanetary plasma density across the two line-of-sights.

The availability of a network of landers on a planet, a moon, or even an asteroid would enable this new and powerful method for estimating the target's tidal and rotational states. The availability of two landers simultaneously viewed from Earth (from a single ground station) allows their simultaneous tracking in a coherent two-way mode as explained above. The crucial requirement of the interferometer is an excellent coherence between the transponders. Thanks to the common mode rejection, the main sources of measurement errors affecting single link (mostly propagation noises and clock drifts) are effectively suppressed in a differential (interferometric) configuration. This method requires the stability of the Earth ground station clocks and again do not need further improvement in clock in space.

Application of this technique has been foreseen/proposed in the frame of a network on the Moon and on Mars. In the present framework, we consider direct-to-Earth links using transponders on the landers for radioscience (and partly telecommunication) and examine different options for future configurations. All links need to be two-way coherent, with the signal transmitted from a single ground station. No ultra-stable oscillator (USO) is necessary on the landers. Indeed, one-way links would destroy the phase coherency required by SBI, and would seriously degrade even the performances of conventional Doppler and range measurements. This might be relaxed if very precise clocks would be available. However, this would add unnecessary weight on the payload, if one considers the present-day weight of atomic clocks for space. If miniaturization of the atomic clock were available, radioscience would benefit from it. This advance would go in pair with using several frequencies in space, as explained before, a little bit like the improvement of Galileo for positioning. In addition, all the applications foreseen with Galileo could be envisaged with the new system. For the Galileo satellites, the onboard passive hydrogen maser clocks' precision is four times better than the onboard rubidium atomic clocks of the previous GPS generation and is estimated at 1 second per 3 million years (a timing error of a nanosecond per day), which translates into a sub-millimeter positional error on Earth's surface. For such a probe and clock around a planet, the error on the distance would be at the level of ~ 10 centimeters.

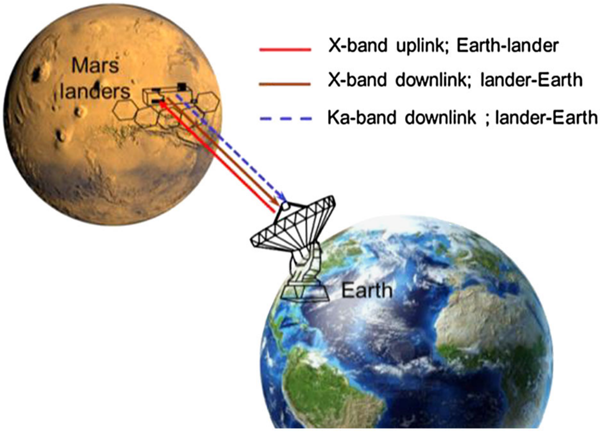

Fig. 3 Radio links for geodesy. "Up" means that the frequency is the one sent from Earth to space (which is for the X-band for instance near 7.15 GHz), and "down" means that the frequency is the one sent from space to Earth (which is for the X-band for instance near 8.4 GHz)

This is the level achievable by present-day two-way Ka-band Doppler. However, the position determined from Doppler measurements benefiting from such clock precision would be at the sub-centimeter level.

Several radio link configurations may be envisaged:

In the first option [Option 1], the links are enabled by conventional X-band transponder such as Mars Express, Venus Express, Rosetta, BepiColombo (without the Ka-band channel), and the LaRa (Lander Radioscience) onboard the surface platform of ExoMars 2020 or RISE (Rotation and Interior Structure Experiment) on the 2018 InSIGHT (Interior exploration using Seismic Investigations, Geodesy, and Heat Transport). This is the simplest instrumentation, but not the top performer, while it would already help the present-day precision of the measurements.

In Option 2, the transponder enables a dual frequency downlink at X- and Ka-band (see Fig. 3 for a lander-Earth case), both coherent with the X-band uplink. This configuration enables the removal of dispersive path delays due to charged particles in the downlink. The extent to which the downlink information can be used to assess the uplink contributions depends on the correlations between the two terms and must be safely assumed as unknown. Option 2 would therefore reduce the plasma noise by a factor 1.4 (approx.).

In Option 3, the transponder enables two separate two-way Ka-band links. This solution appears much satisfactory in terms of plasma noise level and very simple, but Ka-band transponders are technically much more complicated by the necessity of using waveguide in the transponder. The power consumption is also higher than an X-band transponder. One may consider the selection of the uplink frequency according to operational requirements and the availability of other nodes provided by different agencies.

It must be noted that Option 2 offers limited benefits over a pure X-band radio link, both for standard radiometric measurements (Doppler and range) and SBI. Option 3 offers a very effective suppression of plasma noise under most operational conditions (except for Sun-Earth-probe angles smaller than 15 degrees). Plasma noise is the dominant error source in X-band tracking systems.

A number of variants of these three basic options can be considered. The most important one entails the adoption of a Spread Spectrum (SS) signal structure. In this configuration the carrier, telemetry and telecommand are identified by a unique code, with a signal effectively occupying the entire allocated bandwidth. The carrier phase (the main observable in SBI and radiometric measurements) is reconstructed from the code. In 3G and 4G terrestrial

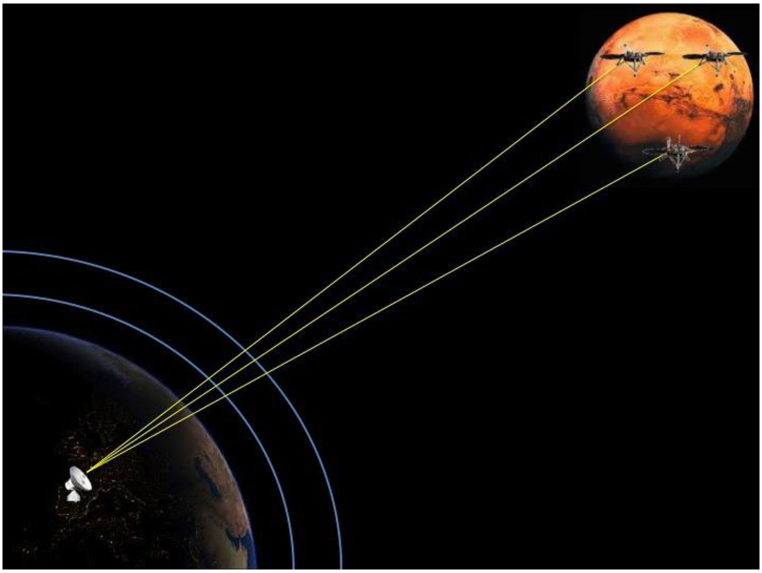

Fig. 4 The configuration of the Mars microwave interferometer. Two or three landers are simultaneously tracked from the same ground antenna. All signals use the same frequency, with the carrier phase reconstructed through a unique code for each lander. The differential phase retains only the effect of rotation and tides, while all noise contributions common to the links are cancelled out

cellular networks, the scheme is also known as Code Division Multiple Access (CDMA). SS communications are widely used in military space communications. European industry has a vast experience in this field.

For a network of landers, there are both operational and scientific motivations for adopting such an SBI scheme. Operationally, the entire network can be tracked and controlled from a single ground antenna, with considerable saving of antenna time. Orbiters can also be tracked simultaneously with landers. Science benefits are important for SBI as this configuration guarantees the maximum commonality between the radio links, as it will be explained later.

In summary, we have three options of SBI corresponding to the different options presented above: (1) X-band up-link from Earth to lander and X-band downlinks from lander to Earth; (2) X-band up-link from Earth to lander and X- and Ka-bands downlinks from lander to Earth; and (3) Ka-band up-link from Earth to lander and Ka-band downlinks from lander to Earth. Only the second option will allow studying the ionosphere of Mars in addition to the objectives of studying the global atmosphere and the interior of Mars from geodesy.

Thanks to the common mode rejection, the main sources of measurement errors affecting single links (mostly propagation noises and clock drifts) are effectively suppressed in a differential (interferometric) configuration. Interferometric observables can therefore provide an excellent determination of Mars' rotational parameters and tides. The concept of a microwave interferometer entails two or more transponders on Mars, simultaneously illuminated by a single radio antenna on the ground. Each transponder coherently retransmits a unique signal to ground, where each phase is measured and the phase differences are formed (see Fig. 4).

The measurement goal is to reach an accuracy of 1 mm (corresponding to 1/10 of the Ka-band wavelength) in each differential range, with integration times of 100–600 seconds.

The daily observation time can be limited to 1 hour in order to attain a suitable data set for geophysical interpretation. If the nodes are, say, 1,000 km apart, a 1 mm accuracy in the differential range corresponds to an accuracy of about 10^{-9} radians in the orientation of Mars. Differently from the case of a lunar interferometer, Mars' fast rotation allows an easy separation between tides and orientation changes with the use of just two landers. A particularly favorable positioning on the surface entails one transponder on the equator and another one shifted in latitude and longitude by 60 degrees. Other configurations are also possible and an efficient distribution can be studied.

3.3 Future Applications of Laser Ranging

Using experience with past transponder laser ranging experiments (see Sect. 1.2), in particular the one-way laser ranging data obtained operationally with the LRO spacecraft, laser ranging capabilities could be expanded to interplanetary distance (Degnan 2002). The very small (19 mm diameter) telescope aperture used on LRO was dictated by accommodation on an existing gimbaled antenna, whereas the LADEE spacecraft carried a purpose-built optical communication instrument with ~ 100 mm aperture and dedicated pointing. Neither system required more than 1 Watt of output laser power. Obviously, the technological development of a deep space system would require a larger power-aperture product. The LLCD space terminal required only modest clock stability ($\sim 8 \times 10^{-11}$) over the 2.5 s roundtrip time to meet its 200 ps requirement. Laser ranging in planetary missions would complement the tracking data with highly accurate range measurements (on the order of mm). Such tracking data would be especially attractive for the determination of solar system ephemerides, rotational variations, relativistic effects and other long-periodic effects that are encoded in the tracking data (Turyshev et al. 2010; Oberst et al. 2012; Dirkx 2015). The extraction of shorter-period effects, such as gravity field characteristics, will, in most cases, be more accurate using existing (two-way) radio Doppler techniques.

As with radio tracking, laser ranging can be performed in a one- or two-way mode (see Sect. 1.2). In the two-way mode, the contribution of clock noise to the error budget of the measurements is limited. An integrated timing error of 1–10 ps over 1–100 s typically below the noise level of two-way transponder laser ranging (Dirkx et al. 2015), is leading to a clock stability requirement of 10^{-10}–10^{-12} (at 1 s) and 10^{-12}–10^{-14} (at 100 s). Such requirements are not trivial, but are well within the capabilities of state-of-the-art systems. For one-way laser ranging, however, clock noise is the dominant source of measurement uncertainty, and poses a significant challenge during orbit determination, as discussed above for the case of LRO and shown in numerical simulations by Dirkx et al. (2015).

Using highly accurate space-based clocks would significantly reduce the number of clock parameters that need to be estimated during orbit determination from one-way data, thereby allowing these data to be used for the retrieval of a broader class of parameters. Since the science case for planetary laser ranging is especially strong for retrieving long-periodic signals, the system's long-period stability is crucial. For the case of one-way laser ranging to LRO (Buccino et al. 2016; Bauer et al. 2016, 2017; Mao et al. 2017), clock noise over longer integration times makes it difficult to achieve such stability, indicating that improvements in clock stability is highly desirable for future one-way systems. Additionally, it is shown by Dirkx et al. (2016) that the proper-to-coordinate time conversion must be updated (iteratively or concurrently) during the estimation process to fully utilize future laser ranging data sets, due to the large discrepancy between a priori state uncertainty and measurement noise level.

However, with two-way, two-frequency radio range measurements promising an attainable accuracy of 20 cm (Iess et al. 2014), it will be difficult for a one-way laser ranging system to be competitive. Dirkx (2015) have performed a comparative analysis of Doppler and range measurements for the retrieval of periodic signals from the tracking data, and conclude that a 20 cm range measurement becomes competitive with Doppler measurements (0.002 mm/s quality at 1,000 s integration time) only for signals with periods $>$ 200 hours. For one-way laser ranging systems, outperforming radio range measurements would require 10^{-15} fractional stability for signals with a characteristics period of 200 hours and 2.10^{-17} stability for 1 year periods.

Although this could point to the need for highly accurate space-based clocks in planetary missions, the attainable range accuracy can (at present) be reached with a much smaller hardware suite using a two-way laser ranging system (which will also be about 2 orders of magnitude more accurate). Nevertheless, future advances in miniaturizing highly accurate clocks would allow one-way systems to become competitive with existing tracking systems. An additional application for one-way systems is in missions where the Earth-pointing requirement of the space-based laser system is impossible to meet, or where stray light would be excessive (as for missions to the outer solar system).

3.4 New JPL Facility to Explore Deep Lunar Interior

LLR presently is conducted using pulsed lasers with very high peak power ($\sim$ GW) and sub-nanosecond pulses. However, despite the very high peak power, the average power is quite modest (2 W). For instance, APOLLO uses a laser with 150 mJ pulses at a rate of 20 Hz, multi-photon detection (3–5 photons per pulse), and a good astronomy site to get to $\sim$ 8 mm lunar range precision in single shot (Murphy et al. 2008). The primary limiting factor to the LLR accuracy today is the Earth's atmosphere, which imposes a lower limit of 5 mm for the current LLR operations. In addition, the accuracy of LLR is limited by the CCR (Corner Cube Retro-reflector) arrays currently on the Moon and their distribution on the lunar surface (Williams et al. 2009), and by the LLR model (Williams et al. 2004).

To further advance lunar research, JPL is building a new LLR facility at the Table Mountain Observatory (TMO) in California, with the objective of bringing major advances in the precision of LLR measurements. Equipped with a high-power ($\sim$ 1.1 kW) continuous wave (CW) laser, TMO will not only receive a much large flux of returned photons ($\sim$ 103 photons/sec is expected) and thereby obtain a concomitant higher signal-to-noise ratio than other facilities, it will also enter a new photon-rich regime in which differential LLR is feasible.

In a photon-rich regime, such as what we propose to enable for TMO, simultaneous ranging to two or three arrays is possible. With high photon flux (as above mentioned), the fundamental limitation to LLR accuracy is then no longer $\sqrt{N}$ where N is the number of photons, but the lack in knowledge of the atmospheric delay. The delay from Earth's atmosphere ($\sim$ 2.3 m at zenith) produces an uncertainty for single CCR ranging of $\sim$ 8 mm after correction using the temperature, pressure, and humidity data. However, the differenced delay error from one telescope to two or three sets of lunar CCRs can be as little as $\sim$ 30 μm. Also, in this regime, the station-specific errors are common mode. This will allow us to measure lunar librations with an accuracy of $\sim$ 10 microarcsecond as referred to the lunar rotation angle. The new LLR facility will dramatically improve our knowledge of the lunar interior, beyond the contributions from the GRAIL mission and current LLR data (Williams et al. 2014).

Differencing ranges to different CCRs would reduce substantially atmospheric perturbations, one of the dominant terms in the current LLR error budget. This can be done by switching between two (or several) lunar targets. To demonstrate this, we estimate the LLR differential delay error due to the atmosphere relying on the extensive data collected by adaptive optics systems over the past few decades. The isoplanatic angle is defined as the angular separation over which the wavefront from two stars will differ by 1 radian RMS. The isoplanatic angle in the visible (0.6 µm) is ~ 10 µrad (2 arcsecond); thus, two objects separated by this angle will have atmospheric delay contributions that differ on average by ~ 100 nm. At 0.5 degree separation (the angular width of the Moon), this differential path error grows to ~ 31 µm (using the Kolmogorov turbulence scaling law). This 31 µm error should decrease as $\sqrt{T/t_0}$, where t_0 is time it takes the wind to move the air across the two beams at the top of the troposphere ($\sim$ 5–10 sec). For an infrared laser (say, at 2.2 µm), the differential path difference over the lunar width would be ~ 30.8 µm.

At any given time, the new facility at TMO will monitor the return photon fluxes between OCTL (Optical Communications Telescope Laboratory) and a single lunar CCR array. Unlike classic LLR, which measures the round-trip light-time from Earth to the Moon and back, the advanced LLR will track the phase of the returned amplitude-modulated microwave signal to determine the lunar range. At TMO, we plan to difference any of the two consecutive range determinations to form a new LLR observable, differenced lunar range, previously not available. The advantage of the new scheme is in the fact that it allows reaching the differenced range precision at 30 µm, which is the Earth atmospheric limit. The time-multiplexing between two sets of CCR's results in a factor of $\sqrt{2}$ increase in error; also, subtracting two ranges causes another factor of $\sqrt{2}$ increase in error for the differenced range measurement. Thus, the differenced range photon noise is ~ 4 mm in 1 sec, reducing to 460 µm in 1 minute. Integrating this signal for 2 hours would get us down to 42 µm. The period of the libration signal is much longer than 2 hours, allowing for a precise determination of the relevant science parameters via the differenced LLR technique. With such a performance, we can reach quantitative goals even in the worst-case scenario of full Moon and small CCR arrays.

The combination of the new CCR on the Moon (Turyshev et al. 2013) and the new JPL facility would dramatically enhance our knowledge of the lunar interior, beyond the contributions from the GRAIL mission and current LLR measurements. The new differenced range data accurate to 30 µm-level would allow for an expansive study of the deep lunar interior including the core-mantle boundary shape, core rotation, and boundary-layer turbulence, inner solid core detection, deep mantle tidal rigidity and dissipation in a region of suspected partial melting, asymmetrical tidal response (Zhong et al. 2012), rheology-caused frequency-dependent tidal Love numbers (Efroimsky 2012; Nimmo et al. 2012; Williams and Boggs 2015), and stimulation of free librations (Rambaux and Williams 2011). Differenced LLR measurements would build on and enhance the results from the GRAIL mission (e.g., deep interior: study of the fluid core, detection of inner solid core, etc.).

3.5 The Special Case of the Moon

The Moon and instrumentation on its surface constitutes a special case as colocation of high-precision techniques and clocks would enable better reference frame realization. In the Apollo era, the use of passive laser reflectors on the lunar surface has been the most efficient measurement technique. However, the laser link margin is very small, permitting only very few ground stations to obtain valid measurements. Therefore, the next generation of the Lunar Laser Ranging (LLR) technique should aim for substantial improvement. Dehant et al. (2012b) proposed a one-way ranging concept involving laser transponders, which involves the use of a very stable frequency. This allows many more Satellite Laser Ranging (SLR) stations from the existing network on Earth to obtain measurements from the Moon. In addition, Dehant et al. (2012b) proposed to deploy and operate a microwave receiver/transmitter with precisely known mechanical local ties to the laser beacon/receiver, which will permit observations of the tangential position of the Moon with respect to the celestial frame. The ultimate objectives are threefold, the improvement of the reference frames for the Earth, a better understanding of the Moon's interior, and a better determination of the parameters of General Relativity, as described in that paper.

The interior objective is reached through the observation of the Moon libration, of which the amplitude is sensitive to the liquid core. A fluid core for instance does not necessarily share the rotation axis of the solid mantle because the oblateness of the core-mantle boundary is expected to be small and the viscosity has a negligible effect. While the equator of the solid Moon is subjected to a precession, a fluid core can only weakly mimic this motion.

For a precision of LLR ranging at cm-level, effects of general relativity are seen in the data. Parameters of relativity theory such as the famous post-Newtonian (PPN) β and γ parameters and the geodetic precession can be estimated (Williams et al. 1996 and 2004). For variation of the gravitational constant to be discernible, the precision on this determination must be better than at the present level of precision of the measurements, i.e. at the $1/c^2$ order of the gravitational gradient accelerations of Earth and Moon due to the Sun.

4 Direction of Future Clocks for Planetary Science

4.1 Advancements in Clocks Need to be Made for Space Science Instruments

For a clock to be onboard a spacecraft and to be beneficial for space science, its size and power-usage must be reduced as well as able to support launch, impacts, radiation, and large differences in temperature.

4.2 Limiting Factors of Advanced Clocks in Space Science

The limitation factor for the data using new clocks are related to other perturbations that are not yet sufficiently modeled and that contaminate the measurements, such as the plasma and atmosphere effects or the spacecraft motion. New methods have been discussed above that enable to circumvent these errors, either by using interferometric methods or using combination of different frequencies.

4.3 Known/Key Behavior for Clocks that Are Critical for Space Science

For future of clocks for space science, understanding the effect of thermal variation would be the enabling technology. Additionally, in any laser application, beam stability is primarily affected by point-to-point relative motion changes. This motion can be caused by many different sources of vibration and even acoustic sources. Analyses of the measured vibration-transfer functions can show resonance peaks generated by local vibration modes. The vibration modes may thus also be a challenging problem. They can re-introduce frequency noise with deleterious effects on the laser coherence that had been so carefully realized.

Concerning the stability, both the short-term and long-term stabilities are needed. For instance, the Allan variance of 10^{-13} at short term (@ 60 seconds) is necessary for the Doppler, and obtaining this with a miniaturized clock would already help the one-way link, assuming thermal and vibrational challenges are addressed. Long-term stability is necessary as well in order to be able to interpret long-term variations in the Doppler and ranging related to geophysics.

5 Conclusion

The planetary radioscience have addressed numerous important scientific objectives, such as the study of the gravity field for orbiting spacecraft or the demonstration of the presence of a liquid core inside a planet inferred from its rotation for a lander. Except for the atmospheric occultation science, the classical two-way radio links in X-band or Ka-band (or both) have shown to be sufficient as it relies on the frequency stability of the clocks of stations on Earth.

Currently, the precision of very good ultra-stable oscillator is at the level of 10^{-13}. Using such clocks in space would enable one-way links at the same precision as two-way links and reduces the geometric constraints of the observations, as well as improvement in the data noise since only one leg of radio path would be affected by the media error. Increasing the precision of the clock (better than 10^{-13}–10^{-14} stability) would immediately map into the precision of the measurements. However, at this level of precision, other error sources must be reduced as well in order to take the full benefit of clock's intrinsic accuracy. In orbiting or navigating spacecraft, non-gravitational accelerations acting on the spacecraft and contaminating the determination of the gravity field can be further estimated/corrected from precise accelerometer measurements. Additionally, the Earth media effects and plasma perturbations on the signal must be reduced to the level comparable to the accuracy of the new clock system. One way for calibrating radio links from media effects (and plasma effects if radio signal) is to consider interferometric methods like SBI or the new JPL laser facility. In that case, the large differential phase delay from the Earth's troposphere (and ionosphere and plasma for radio link) is a common mode bias, due to the small view angle of the transponders/laser beams as seen from the ground antenna ($\sim 2 \times 10^{-5}$ rad). It is therefore completely cancelled out. The interferometer setup does not allow the same cancellation for the other intervening media, namely the target planet or moon atmosphere and ionosphere if they exist. Another approach for media calibration is to use multi-frequency radio links, which can be used to almost completely remove the media errors.

Acknowledgements Part of the research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

References

J.B. Abshire, X. Sun, G. Neumann, J. McGarry, T. Zagwodzki, P. Jester, H. Riris, M. Zuber, D.E. Smith, Laser pulses from Earth detected at Mars, in *Conference on Lasers and Electro-Optics/Quantum Electronics and Laser Science Conference and Photonic Applications Systems Technologies, Technical Digest (CD)* (Optical Society of America, Washington, 2006), paper CThT6

S.W. Asmar, J.W. Armstrong, L. Iess, P. Tortora, Spacecraft Doppler tracking: noise budget and achievable accuracy in precision radio science observations. Radio Sci. **40**, RS2001 (2005). doi:10.1029/2004RS003101

R.-M. Baland, G. Tobie, A. Lefevre, T. Van Hoolst, Titan's internal structure inferred from its gravity field, shape, and rotation state. Icarus **237**, 29–41 (2014). doi:10.1016/j.icarus.2014.04.007

S. Bauer, H. Hussmann, J. Oberst, D. Dirkx, D. Mao, G.A. Neumann, E. Mazarico, M.H. Torrence, J.F. McGarry, D.E. Smith, M.T. Zuber, Demonstration of orbit determination for the Lunar Reconnaissance Orbiter using one-way laser ranging data. Planet. Space Sci. **129**, 32–46 (2016). doi:10.1016/j.pss.2016.06.005

S. Bauer, H. Hussmann, J. Oberst, D. Dirkx, D. Mao, G.A. Neumann, E. Mazarico, M.H. Torrence, J.F. McGarry, D.E. Smith, M.T. Zuber, Analysis of one-way laser ranging data to LRO, time transfer and clock characterization. Icarus **283**, 38–54 (2017). doi:10.1016/j.icarus.2016.09.026

P. Bender, Proposed microwave transponders for early lunar robotic landers. Adv. Space Res. **14**(6), 233–242 (1994). doi:10.1016/0273-1177(94)90033-7

D.M. Boroson, B.S. Robinson, D.V. Murphy et al., Overview and results of the lunar laser communication demonstration. Proc. SPIE **8971**, 1–11 (2014)

D. Buccino, J.A. Seubert, S.W. Asmar, R.S. Park, Optical ranging measurement with a lunar orbiter: limitations and potential. J. Spacecr. Rockets **53**(3), 457–463 (2016). doi:10.2514/1.A33415

J.J. Degnan, Millimeter accuracy satellite laser ranging: a review, in *Contributions of Space Geodesy to Geodynamics: Technology*. Monograph Geodynamics Series (AGU, Washington, 1993), pp. 133–162

J.M. Degnan, Asynchronous laser transponders for precise interplanetary ranging and time transfer. J. Geodyn. **34**, 551–594 (2002)

V. Dehant, W. Folkner, E. Renotte, D. Orban, S. Asmar, G. Balmino, J.P. Barriot, J. Benoist, R. Biancale, J. Biele, F. Budnik, S. Burger, O. de Viron, B. Häusler, Ö. Karatekin, S. Le Maistre, P. Lognonné, M. Menvielle, M. Mitrovic, M. Pätzold, A. Rivoldini, P. Rosenblatt, G. Schubert, T. Spohn, P. Tortora, T. Van Hoolst, O. Witasse, M. Yseboodt, Lander radioscience for obtaining the rotation and orientation of Mars. Planet. Space Sci. **57**, 1050–1067 (2009). doi:10.1016/j.pss.2008.08.009

V. Dehant, S. Le Maistre, A. Rivoldini, M. Yseboodt, P. Rosenblatt, T. Van Hoolst, M. Mitrovic, Ö. Karatekin, J.C. Marty, A. Chicarro, Revealing Mars' deep interior: future geodesy missions using radio links between landers, orbiters, and the Earth. Planet. Space Sci. **57**, 1069–1081 (2010). doi:10.1016/j.pss.2010.03.014

V. Dehant, B. Banerdt, P. Lognonné, M. Grott, S. Asmar, J. Biele, D. Breuer, F. Forget, R. Jaumann, C. Johnson, M. Knapmeyer, M. Lefeuvre, D. Mimoun, A. Mocquet, P. Read, A. Rivoldini, O. Romberg, G. Schubert, S. Smrekar, T. Spohn, P. Tortora, S. Ulamec, S. Vennerstrøm, Future Mars geophysical observatories for understanding its internal structure, rotation, and evolution. Planet. Space Sci. **68**(1), 123–145 (2012a). doi:10.1016/j.pss.2011.10.016

V. Dehant, J. Oberst, R. Nadalini, U. Schreiber, N. Rambaux, Geodesy instrument package on the Moon for improving our knowledge of the Moon and the realization of reference frames. Planet. Space Sci. **68**(1), 94–104 (2012b). doi:10.1016/j.pss.2012.02.008

D. Dirkx, R. Noomen, P.N.A.M. Visser, S. Bauer, L.L.A. Vermeersen, Comparative analysis of one- and two-way planetary laser ranging concepts. Planet. Space Sci. **117**, 159–176 (2015)

D. Dirkx, Interplanetary laser ranging—analysis for implementation in planetary science mission. PhD thesis, Delft University of Technology (2015)

D. Dirkx, R. Noomen, P.N.A.M. Visser, L.I. Gurvits, L.L.A. Vermeersen, Space-time dynamics estimation from space mission tracking data. Astron. Astrophys. **587**, A156 (2016)

M. Efroimsky, Bodily tides near spin-orbit resonances. Celest. Mech. Dyn. Astron. **112**(3), 283–330 (2012). doi:10.1007/s10569-011-9397-4

R.C. Elphic, C. Russell, *The Lunar Atmosphere and Dust Environment Explorer Mission (LADEE)* (Springer, Cham, 2015)

M. Fermi, P. Bender, B. Bertotti, M. Chersich, M. Gregnanin, L. Iess, L. Simone, Investigation of the lunar interior with a microwave interferometer. 37th COSPAR Scientific Assembly, paper P162-TueWed B01-0062-08 (2008)

W.M. Folkner, C.F. Yoder, D.N. Yuan, E.M. Standish, R.A. Preston, Interior structure and seasonal mass redistribution of Mars from radio tracking of Mars Pathfinder. Science **278**(5344), 1749 (1997)

M. Gregnanin, B. Bertotti, M. Chersich, M. Fermi, L. Iess, L. Simone, P. Tortora, J.G. Williams, Same beam interferometry as a tool for the investigation of the lunar interior. Planet. Space Sci. **74**, 194–201 (2012). doi:10.1016/j.pss.2012.08.027

M. Gregnanin, M. Yseboodt, V. Dehant, L. Iess, T. Van Hoolst, Estimation of Mars geophysical information through Same Beam Interferometry, in *Proc. European Planetary Science Congress EPSC 2014*, Centro de Congressos do Estoril, Cascais, Portugal Austria, 7–12 September, 2014, vol. 9 (2014), EPSC2014-EPSC395

H. Hemmati, K.M. Birnbaum, W.H. Farr, S. Turyshev, A. Biswas, Combined laser communications and laser ranging transponder for Moon and Mars, in *Free-Space Laser Communication Technologies XXI*. SPIE Conference Series, vol. 7199 (2009), No. 71990N

L. Iess, M. Fermi, P. Bender, B. Bertotti, M. Gregnanin, L. Simon, A microwave interferometer for the investigation of the lunar interior. NASA NOI N9-ILN09-0016 for the International Lunar Network (2008)

L. Iess, M.D. Benedetto, N. James, M. Mercolino, L. Simone, P. Tortora, Astra: interdisciplinary study on enhancement of the end-to-end accuracy for spacecraft tracking techniques. Acta Astronaut. **94**(2), 699–707 (2014)

A.S. Konopliv, C.F. Yoder, Venusian k_2 tidal Love number from Magellan and PVO tracking data. Geophys. Res. Lett. **23**(14), 1857–1860 (1996). doi:10.1029/96GL01589

A.S. Konopliv, S.W. Asmar, W.M. Folkner, Ö. Karatekin, D.C. Nunes, S.E. Smrekar, C.F. Yoder, M.T. Zuber, Mars high resolution gravity fields from MRO, Mars seasonal gravity, and other dynamical parameters. Icarus **211**, 401–428 (2011). doi:10.1016/j.icarus.2010.10.004

P. Kuchynka, W.M. Folkner, A.S. Konopliv, R.S. Park, S. Le Maistre, V. Dehant, New constraints on Mars rotation determined from radiometric tracking of the Opportunity Mars Exploration Rover. Icarus **222**(1), 243–253 (2013). doi:10.1016/j.icarus.2012.11.003

P. Kuchynka, W.M. Folkner, A.S. Konopliv, R.S. Park, S. Le Maistre, V. Dehant, New constraints on Mars rotation determined from radiometric tracking of the Opportunity Mars Exploration Rover. Icarus **229**, 340–347 (2014). doi:10.1016/j.icarus.2013.11.015

S. Le Maistre, P. Rosenblatt, A. Rivoldini, V. Dehant, J.C. Marty, Ö. Karatekin, Lander Radio science experiment with a direct link between Mars and the Earth. Planet. Space Sci. **68**(1), 105–122 (2012). doi:10.1016/j.pss.2011.12.020

D. Mao, J. McGarry, M. Torrence, G. Neumann, E. Mazarico, M. Barker, X. Sun, D. Rowlands, J. Golder, T. Zagwodzki, J. Cavanaugh, M. Zuber, D. Smith, Laser ranging experiment on Lunar Reconnaissance Orbiter: timing determination and orbit constraints, in *Proceedings of ILRS Workshop*, Bad Kotzing, Germany, May 2012 (2012). http://cddis.gsfc.nasa.gov/lw17/docs/papers/session13/02-Mao_LRO-LR_Kotzting2011_paper_final.pdf

D. Mao, J.F. McGarry, E. Mazarico, G.A. Neumann, X. Sun, M.H. Torrence, T.W. Zagwodzki, D.D. Rowlands, E.D. Hoffman, J.E. Horvath, J.E. Golder, M.K. Barker, D.E. Smith, M.T. Zuber, The laser ranging experiment of the Lunar Reconnaissance Orbiter: five years of operations and data analysis. Icarus **283**, 55–69 (2017). doi:10.1016/j.icarus.2016.07.003

E. Mazarico, F.G. Lemoine, S. Goossens, T.J. Sabaka, J.B. Nicholas, D.D. Rowlands, G.A. Neumann, M.H. Torrence, D.E. Smith, M.T. Zuber, Improved precision orbit determination of lunar orbiters from the GRAIL-derived lunar gravity models. Adv. Astronaut. Sci. **148**, 1125–1141 (2013)

G. Mitri, R. Meriggiola, A. Hayes, A. Lefevre, G. Tobie, A. Genova, J.I. Lunine, H. Zebkerg, Shape, topography, gravity anomalies and tidal deformation of Titan. Icarus **236**, 169–177 (2014). doi:10.1016/j.icarus.2014.03.018

W.B. Moore, G. Schubert, The tidal response of Ganymede and Callisto with and without liquid water oceans. Icarus **166**, 223–226 (2003). doi:10.1016/j.icarus.2003.07.001

T.D. Moyer, *Formulation for Observed and Computed Values of Deep Space Network Data Types for Navigation*. Monograph 2 Deep Space Communications and Navigation Series (2000). 549 pp.

T.W. Murphy, E.G. Adelberger, J.B.R. Battat, L.N. Carey, C.D. Hoyle, P. Leblanc, E.L. Michelsen, K. Nordtvedt, A.E. Orin, J.D. Strasburg, C.W. Stubbs, H.E. Swanson, E. Williams, The Apache Point Observatory lunar laser-ranging operation: instrument description and first detections. Publ. Astron. Soc. Pac. **120**, 20 (2008). doi:10.1086/526428

F. Nimmo, U.H. Faul, E.J. Garnero, Dissipation at tidal and seismic frequencies in a melt-free Moon. J. Geophys. Res. **117**(E9), E09005 (2012). doi:10.1029/2012JE004160

J. Oberst, V. Lainey, C. Le Poncin-Latte, V. Dehant, P. Rosenblatt, S. Ulamec, J. Biele, J. Spurmann, R. Kahle, V. Klein, U. Schreiber, A. Schlicht, N. Rambaux, P. Laurent, B. Noyelles, B. Foulon, A. Zakharov, L. Gurvits, D. Uchaev, S. Murchie, C. Reed, S.G. Turyshev, J. Gil, M. Graziano, K. Willner, K. Wickhusen, A. Pasewaldt, M. Wahlisch, H. Hussmann, GETEMME—a mission to explore the Martian satellites and the fundamentals of solar system physics. Exp. Astron. **34**, 243–271 (2012)

R.S. Park, A.S. Konopliv, S.W. Asmar, B.G. Bills, R.W. Gaskell, C.A. Raymond, D.E. Smith, M.T. Zuber, Gravity field expansion in ellipsoidal harmonic and polyhedral internal representations applied to Vesta. Icarus **240**, 118–132 (2013)

R.S. Park, A.S. Konopliv, B.G. Bills, N. Rambaux, J.C. Castillo-Rogez, C.A. Raymond, A.T. Vaughan, A.I. Ermakov, M.T. Zuber, R.R. Fu, M.J. Toplis, C.T. Russell, A. Nathues, F. Preusker, A partially differentiated interior for Ceres deduced from its gravity field and shape. Nature **537**, 515–517 (2016)

N. Rambaux, J.G. Williams, The Moon's physical librations and determination of their free modes. Celest. Mech. Dyn. Astron. **109**(1), 85–100 (2011). doi:10.1007/s10569-010-9314-2

D.E. Smith, M.T. Zuber, X. Sun, G.A. Neumann, J.F. McGarry, T.W. Zagwodzki, Two-way laser link over interplanetary distance. Science **311**, 53 (2006)

S.G. Turyshev, W. Farr, W.M. Folkner, A.R. Girerd, H. Hemmati, T.W. Murphy, J.G. Williams, J.J. Degnan, Advancing tests of relativistic gravity via laser ranging to Phobos. Exp. Astron. **28**(2), 209–249 (2010)

S.G. Turyshev, J.G. Williams, W.M. Folkner, G.M. Gutt, R.T. Baran, R.C. Hein, R.P. Somawardhana, J.A. Lipa, S. Wang, Corner-cube retro-reflector instrument for advanced lunar laser ranging. Exp. Astron. **36**(1–2), 105–135 (2013). doi:10.1007/s10686-012-9324-z

J.M. Wahr, M.T. Zuber, D.E. Smith, J.I. Lunine, Tides on Europa, and the thickness of Europa's icy shell. J. Geophys. Res. **111**(E12), E12005 (2006). doi:10.1029/2006JE002729

J.G. Williams, X.X. Newhall, J.O. Dickey, Relativity parameters determined from lunar laser ranging. Phys. Rev. D **53**, 6730–6739 (1996)

J.G. Williams, S.G. Turyshev, T.W. Murphy, Improving LLR tests of gravitational theory. Int. J. Mod. Phys. D **13**(3), 567–582 (2004). doi:10.1142/S0218271804004682

J.G. Williams, S.G. Turyshev, D.H. Boggs, Lunar laser ranging tests of the equivalence principle with the Earth and Moon. Int. J. Mod. Phys. D **18**(07), 1129–1175 (2009). doi:10.1142/S021827180901500X

J.G. Williams, A.S. Konopliv, D.H. Boggs, R.S. Park, D.-N. Yuan, F.G. Lemoine, S. Goossens, E. Mazarico, F. Nimmo, R.C. Weber, S.W. Asmar, H.J. Melosh, G.A. Neumann, R.J. Phillips, D.E. Smith, S.C. Solomon, M.M. Watkins, M.A. Wieczorek, J.C. Andrews-Hanna, J.W. Head, W.S. Kiefer, I. Matsuyama, P.J. McGovern, G.J. Taylor, M.T. Zuber, Lunar interior properties from the GRAIL mission. J. Geophys. Res. **119**(7), 1546–1578 (2014). doi:10.1002/2013JE004559

J.G. Williams, D.H. Boggs, Tides on the Moon: theory and determination of dissipation. J. Geophys. Res. **120**(4), 689–724 (2015). doi:10.1002/2014JE004755

X. Wu, Y.E. Bar-Sever, W.M. Folkner, J.G. Williams, J.F. Zumberge, Probing Europa's hidden ocean from tidal effects on orbital dynamics. Geophys. Res. Lett. **28**(11), 2245–2248 (2001). doi:10.1029/2000GL012814

S. Zhong, C. Qin, A. Geruo, J.M. Wahr, Can tidal tomography be used to unravel the long-wavelength structure of the lunar interior? Geophys. Res. Lett. **39**(15), L15201 (2012). doi:10.1029/2012GL052362

M.T. Zuber, D.E. Smith, R.S. Zellar, G.A. Neumann, X. Sun, R.B. Katz, I. Kleyner, A. Matuszeski, J.F. McGarry, M.N. Ott, L.A. Ramos-Izquierdo, D.D. Rowlands, M.H. Torrence, T.W. Zagwodzki, The lunar reconnaissance orbiter laser ranging investigation. Space Sci. Rev. **150**(1–4), 63–80 (2010)