More precise lunar and Martian ranging will enable unprecedented tests of Einstein’s theory of General Relativity and well as lunar and planetary science. NASA is currently planning several missions to return to the Moon, and it is natural to consider if precision laser ranging instruments should be included. New advanced retroreflector arrays at carefully chosen landing sites would have an immediate positive impact on lunar and gravitational studies. Laser transponders are currently being developed that may offer an advantage over passive ranging, and could be adapted for use on Mars and other distant objects. Precision ranging capability can also be combined with optical communications for an extremely versatile instrument. In this paper we discuss the science that can be gained by improved lunar and Martian ranging along with several technologies that can be used for this purpose.

Keywords: Lunar Ranging, General Relativity, Moon, Mars

1. Introduction

Over the past 35 years, lunar laser ranging (LLR) from a variety of observatories to retroreflector arrays placed on the lunar surface by the Apollo astronauts and the Soviet Luna missions have dramatically increased our understanding of gravitational physics along with Earth and Moon geophysics, geodesy, and dynamics. During the past few years, only the McDonald Observatory (MLRS) in Texas and the Observatoire de la Cte d’Azur (OCA) in France have routinely made lunar range measurements. A new instrument, APOLLO, at the Apache Point facility in New Mexico is expected to become operational within the next year with somewhat increased precision over previous measurements.

Setting up retroreflectors were a key part of the Apollo missions so it is natural to ask if future lunar missions should include them as well. The Apollo retroreflectors are still being used today, and the 35 years of ranging data has been invaluable for scientific as well as other studies such as orbital dynamics. However, the available retroreflectors all lie within 26 degrees latitude of the equator, and the most useful ones within 24 degrees longitude of the sub-earth meridian as shown in Fig. 1. This clustering weakens their geometrical strength. New retroreflectors placed at
locations other than the Apollo sites would enable more detailed studies, particularly those that rely on the measurement of lunar librations. In addition, more advanced retroreflectors are now available that will reduce some of the systematic errors associated with using the Apollo arrays.

In this paper we discuss the possibility of putting advanced retroreflectors at new locations on the lunar surface. In addition, we discuss several active lunar laser ranging instruments that have the potential for greater precision and can be adapted for use on Mars. These additional options include laser transponders and laser communication terminals.

Fig. 1. Location of the lunar retroreflector arrays. The three Apollo arrays are labeled AP and the two Luna arrays are labeled LUN. ORI and SHK show the potential locations of two additional sites that would aid in strengthening the geometric coverage.

2. Gravitational Science From Lunar Ranging

Gravity is the force that holds the universe together, yet a theory that unifies it with other areas of physics still eludes us. Testing the very foundation of gravitational theories, like Einstein’s theory of General Relativity, is critical in understanding the nature of gravity and how it relates to the rest of the physical world.

The Equivalence Principle, which states the equality of gravitational and inertial mass, is central to the theory of General Relativity. However, nearly all alternative theories of gravity predict a violation of the Equivalence Principle. Probing the validity of the Equivalence Principle is often considered the most powerful way to search for new physics beyond the standard model[2] A violation of the Equivalence Principle would cause the Earth and Moon to fall at different rates toward the Sun resulting in a polarization of the lunar orbit. This polarization shows up in LLR as a displacement along the Earth-Sun line with a 29.53 d synodic period. The current limit on the Equivalence Principle is given by LLR: $\Delta((M_G/M_I)_{EP} = (-1.0 \pm 1.4) \times 10^{-13}$[3]
General Relativity predicts that a gyroscope moving through curved spacetime will precess with respect to the rest frame. This is referred to as geodetic or de Sitter precession. The Earth-Moon system behaves as a gyroscope with a predicted geodetic precession of 19.2 m sec/year. This is observed using LLR by measuring the lunar perigee precession. The current limit on the deviation of the geodetic precession is: $K_{gp} = (-1.9 \pm 6.4) \times 10^{-3}$. This measurement can also be used to set a limit on a possible cosmological constant: $\Gamma < 10^{-26}$ k m$^{-2}$

It is also useful to look at violations of General Relativity in the context of metric theories of gravity. Post-Newtonian Parameterization (PPN) provides a convenient way to describe simple deviations from General Relativity. The PPN parameters are usually denoted as $\gamma$ and $\beta$; $\gamma$ indicates how much spacetime curvature is produced per unit mass, while $\beta$ indicates how nonlinear gravity is (self-interaction). $\gamma$ and $\beta$ are identically one in General Relativity. Limits on $\gamma$ can be set from geodetic precession measurements, but the best limits come from measurements of the gravitational time delay of light, often referred to as the Shapiro effect. Ranging measurements to the Cassini spacecraft set the current limit on $\gamma$: $(\gamma - 1) = (2.1 \pm 2.3) \times 10^{-5}$ which combined with LLR data provides the best limit on $\beta$: $(\beta - 1) = (1.2 \pm 1.1) \times 10^{-4}$.

The strength of gravity is given by Newton’s gravitational constant $G$. Some scalar-tensor theories of gravity predict some level of time variation in $G$. This will lead to an evolving scale of the solar system and a change in the mass of compact bodies due to a variable gravitational binding energy. This variation will also show up on larger scales, such as changes in the angular power spectrum of the cosmic microwave background. The current limit on the time variation of $G$ is given by LLR: $\dot{G}/G = (4 \pm 9) \times 10^{-13}$/year.

The above effects are the leading gravitational limits that have been set by LLR, but many more effects can be studied using LLR data at various levels. These include gravitomagnetism (frame-dragging), $1/r^2$ force law, and even tests of Newton’s third law.

### 3. Lunar Science From Lunar Ranging

Several areas of lunar science are aided by LLR. First, the orientation of the Moon can be used for geodetic mapping. The current IAU rotation model, with respect to which images and altimetry are registered, has errors at the level of several hundred meters. A more precise model, DE403, is being considered that is based on LLR and dynamical integration, but will require updating since it uses data only through 1994. Errors in this model are believed to be several meters. Further tracking will quantify the reliability of this and future models for lunar exploration.

Second, LLR helps provide the ephemeris of the Moon and solar system bodies. The position of the lunar center-of-mass is perturbed by planetary bodies, particularly Venus and Jupiter, at the level of 100’s of meters to more than 1 km. LLR is an essential constraint on the development of planetary ephemerides and navigation of spacecraft.
LLR can also be used to study the internal structure of the Moon, such as the possible detection of a solid inner core. The second-degree tidal lunar Love numbers are detected by LLR, as well as their phase shifts. From these measurements, a fluid core of 20% the Moon’s radius is suggested. A lunar tidal dissipation of \( Q = 30 \pm 4 \) has been reported to have a weak dependence on tidal frequency. Evidence for the oblateness of the lunar fluid-core/solid-mantle boundary may be reflected in a century-scale polar wobble frequency. The lunar vertical and horizontal elastic tidal displacement Love numbers \( h_2 \) and \( l_2 \) are known to no better than 25% of their values, and the lunar dissipation factor \( Q \) and the gravitational potential tidal Love number \( k_2 \) no better than 11%. These values have been inverted jointly for structure and density of the core, implying a semi-liquid core and regions of partial melt in the lunar mantle, but such inversions require stochastic sampling and yield probabilistic outcomes.

4. Rationale for Additional Lunar Ranging Sites

While a single Earth ranging station may in principle range to any of the four usable retroreflectors on the near side from any longitude during the course of an observing day, these observations are nearly the same in latitude with respect to the Earth-Moon line, weakening the geometric strength of the observations. Additional observatories improve the situation somewhat, but of stations capable of ranging to the Moon, only Mt. Stromlo in Australia is not situated at similar northern latitudes. The frequency and quality of observations varies greatly with the facility and power of the laser employed. Moreover, the reflector cross sections differ substantially. The largest reflector, Apollo 15, has 300 cubes and returns only a few photons per minute to MLRS. The other reflectors have 100 cubes or less, and proportionately smaller rates. Stations and reflectors are unevenly represented, so that in recent years, most ranging has occurred between one ground station and one reflector. Over the past six years, 85% of LLR data has been taken from MLRS and 15% from OCA. 81% of these were from the Apollo 15 reflector, 10% from Apollo 11, 8% from Apollo 14, and about 1% from Luna 2. The solar noise background and thermal distortion makes ranging to some reflectors possible only around the quarter-moon phase. The APOLLO instrument should be capable of ranging during all lunar phases.

The first LLR measurements had a precision of about 20 cm. Over the past 35 years, the precision has increased only by a factor of 10. The new APOLLO instrument has the potential to gain another factor of 10, achieving mm level precision, but this capability has not yet been demonstrated. Poor detection rates are a major limiting factor in past LLR. Not every laser pulse sent to the Moon results in a detected return photon, leading to poor measurement statistics. MLRS typically collects less than 100 photons per range measurement with a scatter of about 2 cm. The large collecting area of the Apache Point telescope and the efficient avalanche photodiode arrays used in the APOLLO instrument should result in thousands of detections (even multiple detections per pulse) leading to a potential statistical un-
certainty of about 1 mm. Going beyond this level of precision will likely require new lunar retroreflectors or laser transponders that are more thermally stable and are designed to reduce the error associated with the changing orientation of the array with respect to the Earth due to lunar librations.

Several tests of General Relativity and aspects of our understanding of the lunar interior are currently limited by present LLR capabilities. Simply increasing the precision of the LLR measurement, either through ground station improvement or through the use of laser transponders, will translate into improvements in these areas.

Additional ranging sites will also help improve the science gained through LLR. The structure and composition of the interior require dynamic measurements of the lunar librations, while tests of General Relativity require the position of the lunar center of mass. In all, six degrees of freedom are required to constrain the geometry of the Earth-Moon system (in addition to Earth orientation). A single ranging station and reflector is insufficient to accurately determine all six, even given the rotation of the Earth with respect to the Moon.

To illustrate the importance of adding high-cross-section reflectors (or transponders) near the lunar limb, we performed an error analysis based on the locations of two observing stations that are currently operating and the frequency with which normal points have been generated over the last 10 years. While data quality has improved over the years, it has reached a plateau for the last 15 years or so. The presently operating stations are comparable in quality, and we assume an average of 2.5 cm for all observations. The normal point accumulation is heavily weighted toward Apollo 15, and a negligible number of returns are obtained from Lunakhod 2. We anticipate that ranging to a reflector with 4x higher cross section than Apollo 15 would approach 1 cm quality, simply by the increased return rate.

The model assumes a fixed Earth-Moon geometry to calculate the sensitivity of the position determination jointly with lunar rotation along three axes parallel to Earth’s X-Y-Z coordinate frame at a moment in time when the Moon lies directly along the positive X axis. The Z axis points North and Y completes the right-hand system. Partial derivatives of range are calculated with respect to perturbations in position and orientation, where orientation is scaled from radians to meters by an equatorial radius of 1738 km. The analysis makes no prior assumptions regarding the dynamical state of the Moon.

The normal equations are weighted by the frequency of observations at each pair of ground stations and reflectors over the last ten years. We then replace some of the observations with ranges to one or more new reflectors. The results are given in Table. 1.

The addition of one or more reflectors would improve the geometrical precision of a normal point by a factor of 1.5 to nearly 4 at the same level of ranging precision. Such improvements directly scale to improvements in measurement of ephemeris and physical librations. The uncertainty in Moon-Earth distance (X) is highly correlated with uncertainty in position relative to the Ecliptic (Z) when all
Table 1. Additional ranging sites and stations increase the precision of the normal points for the same measurement precision due to better geometrical coverage. The precision in meters on the six degrees of freedom of a typical normal point is shown for several possible ranging scenarios.

| X    | Y    | Z    | RotX | RotY | RotZ | Station Details                  |
|------|------|------|------|------|------|----------------------------------|
| 0.265| 6.271| 23.294| 15.958| 0.179| 0.225| MLRS and OCA                    |
| 0.263| 3.077| 23.305| 7.611 | 0.174| 0.140| 25% of observations to ORI       |
| 0.259| 2.840| 23.271| 4.692 | 0.114| 0.198| 25% of observations to SHK       |
| 0.259| 2.969| 23.291| 4.850 | 0.116| 0.086| both ORI and SHK                 |
| 0.030| 2.501| 2.902 | 2.244 | 0.050| 0.078| both ORI and SHK with 25%         |
|      |      |      |       |      |      | additional observations from     |
|      |      |      |       |      |      | Mt. Stromlo                      |

stations lie at similar latitudes. An advanced reflector with high cross section would enable southern hemisphere ground stations such as Mt. Stromlo to make more frequent and precise observations. The geometric sensitivity to position is dramatically improved by incorporating such a ground station, as shown in the last row of Table 1.

5. Retroreflectors

Five retroreflector arrays were placed on the Moon in the period 1969 - 1973. Three were placed by US astronauts during the Apollo missions (11, 14, and 15), and two were sent on Russian Lunokhod landers. The Apollo 11 and 14 arrays consist of 100 fused silica “circular opening” cubes (diameter 3.8 cm each) with a total estimated lidar cross section of 0.5 billion square meters. Apollo 15 has 300 of these cubes and therefore about 3 times the lidar cross section and is the lunar array with the highest response. Because the velocity aberration at the Moon is small, the cube’s reflective face angles were not intentionally spoiled (deviate from 90 degrees).

The two Lunokhod arrays consist of 14 triangular shaped cubes, each side 11cm. Shortly after landing, the Lunokhod 1 array ceased to be a viable target - no ground stations have since been able to get returns from it. It is also very difficult to get returns from Lunokhod 2 during the day. The larger size of the Lunokhod cubes makes them less thermally stable which dramatically reduces the optical performance when sunlit.

Since 1969, multiple stations successfully ranged to the lunar retroreflectors. Some of these stations are listed in Table 2 along with their system characteristics. However, there have only been two stations continuously ranging to the Moon since the early 1970s: OCA in Grasse, France, and MLRS in Texas. The vast majority of their lunar data comes from the array with the highest lidar cross section - Apollo 15.

The difficulty in getting LLR data is due to the distance to the Moon coupled with the $1/r^4$ losses in the signal, and the technology available at the ground stations. MLRS achieves an expected return rate from Apollo 15 of about one return per minute. Increasing the lidar cross section of the lunar arrays by a factor of 10...
would correspond to a factor of 10 increase in the return data rate. This can be achieved by making arrays with 10 times more cubes than Apollo 15 or by changing the design of the cubes. One possibility is increasing the cube size. The lidar cross section of a cube with a diameter twice that of an Apollo cube would be 16 times larger. However, simply making solid cubes larger increases their weight by the ratio of the diameter cubed. Additional size also adds to thermal distortions and decreases the cube’s divergence: a very narrow divergence will cause the return spot to completely miss the station due to velocity aberration. Spoiling can compensate for the velocity aberration but reduces the effective lidar cross section. Changing the design of the cubes, such as making them hollow, may be a better alternative. For example, 300 unspoiled 5 cm beryllium hollow cubes would have a total mass less than that of Apollo 15 but would have 3x higher lidar cross section.

An option being investigated at Goddard is to replace solid glass cubes with hollow cubes which weigh much less than their solid counterparts. Thermal distortions are less, especially in hollow cubes made of beryllium, so the cubes can be made larger without sacrificing optical performance. Hollow cubes (built by PLX) flew on the Japanese ADEOS satellite and on the Air Force Relay Mirror Experiment, but are generally not used on satellites for laser ranging. This is due in part to the lack of optical performance test data on these cubes under expected thermal conditions, but also because of early investigations which showed that hollow cubes were unstable at high temperatures. Advances in adhesives and other techniques for bonding hollow cubes make it worthwhile to reinvestigate them. Testing that was done for Goddard by ProSystems showed that hollow cubes (with faces attached via a method that is being patented by ProSystems) can survive thermal cycles from room temperature to 150 degrees Celsius. Testing has not yet been done at cold temperatures. Preliminary mechanical analysis indicate that the optical performance of
hollow Beryllium cubes would be more than sufficient for laser ranging.

6. Satellite Laser Ranging Stations

Satellite Laser Ranging began in 1964 at NASA’s Goddard Space Flight Center. Since then it has grown into a global effort, represented by the International Laser Ranging Service (ILRS) of which NASA is a participant. The ILRS includes ranging to Earth orbiting artificial satellites, ranging to the lunar reflectors, and is actively working toward supporting asynchronous planetary transponder ranging.

The ILRS lunar retroreflector capable stations have event timers with precisions of better than 50 picoseconds, and can tie their clocks to UTC to better than 100 nanoseconds. Most have arc-second tracking capabilities and large aperture telescopes (> 1 meter). Their lasers have very narrow pulse widths (< 200 psec) and most have high energy per pulse (> 50 mJ). All have the ability to narrow their transmit beam divergence to less than 50 rad. The detectors have a relatively high quantum efficiency (> 15%). All current LLR systems range at 532nm.

Clearly there is more than one way to increase the laser return rate from the Moon. One is to deploy higher response retroreflector arrays or transponders on the Moon. Another is to increase the capability of the ground stations. A third is to add more lunar capable ground stations. A combination of all these options would have the biggest impact.

The recent development of the Apache Point system, APOLLO, shows what a significant effect improving the ground station can make. Apache Point can theoretically achieve a thousand returns per minute from Apollo 15 versus the few per minute return rate from MLRS (see Table 2). Apache Point does this by using a very large aperture telescope, a somewhat higher laser output energy and fire rate, and a judicious geographical location (where the astronomical seeing is very good). Other areas that could also improve ground station performance are higher quantum efficiency single photon detectors (> 30% QE at 532nm), higher repetition rate lasers (kilohertz versus tens of hertz), and the use of adaptive optics to maintain tight beam control.

Table 2. Lunar retroreflector capable laser ranging stations and their expected return rate from the Apollo 15 lunar array. Link calculations use 1 billion meters squared for Apollo 15’s cross section, a mount elevation of 30 degrees, and a standard clear atmosphere (transmission = 0.7 at zenith) for all but Apache Point where transmission = 0.85 at zenith. The laser divergence was taken to be 40 rad for MLRS and 20 arcsec for the other systems. The detector quantum efficiency was assumed to be 30% for all systems.

| System          | Telescope aperture (m) | Pulse energy exiting system (J) | Laser fire rate (Hz) | System transmission | Apollo 15 photoelectrons/min link calculation |
|-----------------|------------------------|---------------------------------|----------------------|---------------------|---------------------------------------------|
| MLRS            | 0.76                   | 60                              | 10                   | 0.5                 | 4                                          |
| OCA (France)    | 1.54                   | 60                              | 10                   | 0.22                | 20                                         |
| Matera (Italy)  | 1.5                    | 22                              | 10                   | 0.87                | 60                                         |
| Apache Point    | 3.5                    | 115                             | 20                   | 0.25                | 1728                                        |
Higher cross section lunar retroreflectors may make it possible to use NASA’s next generation of satellite laser ranging stations (SLR2000) for LLR. The prototype SLR2000 system is currently capable of single photon asynchronous laser transponder ranging, and will participate in both a 2-way asynchronous transponder experiment in 2007 and the 1-way laser ranging to the Lunar Reconnaissance Orbiter (LRO) in 2008-2009. Approximately ten SLR2000 stations are expected to be built and deployed around the world in the coming decade. Adding ten lunar laser ranging stations to the existing few would dramatically increase the volume of data as well as giving the data a wide geographical distribution. The global distribution of the new SLR2000 stations would be very beneficial to data collection from an asynchronous transponder on the Moon.

7. Laser Transponder

Laser transponders are currently being developed for satellite ranging, but they can also be deployed on the lunar surface. Transponders are active devices that detect an incoming signal, respond with a known or predictable response signal, and are used to either determine the existence of the device or positioning parameters, such as range and/or time. For extraterrestrial applications, a wide range of electromagnetic radiation, such as radio frequency (RF), are used for this signal. To date, most spacecraft are tracked using RF signals, particularly in the S and X bands of the spectrum. NASA and several other organizations routinely track Earth orbiting satellites using optical satellite laser ranging (SLR). Laser transponders have approximately a $1/r^2$ link advantage over direct ranging loss of $1/r^4$, essentially because the signal is propagating in only one direction before being regenerated. In fact, it is generally considered that ranging beyond lunar distances is not practical using direct optical ranging to cube-corner reflectors. Laser transponders are in general more energy and mass efficient than RF transponders since they can work at single photon detection levels with much smaller apertures and beam divergences. A smaller beam divergence has the added benefit that there is less chance of interference with other missions, as well as making the link more secure should that be necessary. With the development and inclusion of laser communications for spaceflight missions, it is logical to include an optical transponder that uses the same opto-mechanical infrastructure such that it has minimal impact on the mission resources.

The simplest conceptual transponder is the synchronous or echo transponder. An echo transponder works by sending back a timing signal with a fixed delay from the receipt of the base-station signal. This device has the potential for the lowest complexity and autonomous operations with no RF or laser based communications channel. To enable this approach, an echo pulse must be created with a fixed offset delay that has less than 500 ps jitter from the arrival of the Earth station signal. This is very challenging given the current state-of-the-art in space-qualifiable lasers. Furthermore, several rugged and simple laser types would be excluded as candidates
due to the lack of precision control of the pulse generation. The synchronous/echo transponder has a total link probability that is the joint probability of each direction’s link probability (approximately the product of each).

Asynchronous Laser Transponders (ALT) have been shown analytically\(^{14}\) and experimentally\(^{15}\) to provide the highest link probability since the total link is the root-sum-square of each one-way link probability. Furthermore, they allow the use of free-running lasers on the spacecraft that operate at their most efficient repetition rates, are simpler, and potentially more reliable. Fig. 3 shows a conceptual asynchronous laser transponder using an existing NASA SLR ground station that is already precisely located and calibrated in the solar reference frame, and a spacecraft transponder that receives green photons (532nm) and transmits near-infrared (NIR) photons (1064 nm). This diagram shows the spacecraft event times being down linked on the RF (S-band) channel but this could be done on the laser communication channel if one exists. This dual wavelength approach is being explored for reasons of technical advantage at the ground station, but may also be used to help remove atmospheric effects from the range data (due to its wavelength dependent index of refraction). Using the same wavelength for each direction is also possible. Expressions for recovering the range parameters from an asynchronous measurement can be found in reference\(^{14}\) and in the parameter retrieval programs developed by Gregory Neumann for the Earth-MLA asynchronous transponder experiments\(^{15}\).\(^{16}\)

An ALT will likely have systematic errors that will limit its long-term accuracy. A retroreflector array located near the ALT’s lunar site should allow the study and calibration of the ALT’s systematic errors. Performing this experiment on the Moon will be particularly important should this technology be adapted for Mars or other
bodies where retroreflector cannot be used.

Recently, two interplanetary laser transponder experiments were successfully demonstrated from the NASA Goddard Geophysical and Astronomical Observatory (GGAO) SLR facility. The first utilized the non-optimized Mercury Laser Altimeter (MLA) on the Messenger spacecraft and the second utilized the Mars Orbiting Laser Altimeter (MOLA) on the Mars Orbiter spacecraft. The Earth-MOLA experiment was a one-way link that set a new distance record of 80 M-km for detected signal photons. The Earth-MLA experiment was a two-way experiment that most closely resembles the proposed asynchronous laser transponder concept. This experiment demonstrated the retrieval of the clock offset, frequency drift, and range of 24 M-km using a small number of detected two-way events. These experiments have proven the concept of being able to point both transceivers, detect the photons, and retrieve useful parameters at low-link margins.

The Lunar Reconnaissance Orbiter (LRO) mission includes a GSFC developed laser ranger that will provide a one-way ranging capability. In this case the clock is assumed to be stable enough over one Lunar orbit. The result is a range profile that is extremely precise but far less accurate than what a two-way asynchronous transponder would provide with its full clock solution.

An ALT conceptual design was developed as part of the LRO laser ranger trade study. Link analyses performed on this design showed that it is possible to make more than 500 two-way range measurements per-second using a 20 mm aperture and a 10 micro-joule/pulse, 10-kHz laser at the Moon and the existing eye-safe SLR2000 telescope located at the GGAO. The ALT was not selected due to the need for a very high readiness design for LRO, but the analysis did show its feasibility. It was also shown that many of the international SLR systems could participate with nominal receiver and software upgrades thereby increasing the ranging coverage. The ALT increases the tracking/ranging availability of spacecraft since the link margins are higher than for direct ranging to reflector arrays.

8. Communication Terminal

A communications terminal conceptually represents the most capable kind of transponder ranging system and is at the other end of the spectrum in terms of complexity from the echo transponder. In general, a communications link of some kind is necessary to operate and recover data from a spacecraft or remote site. There are several potential benefits if the communications link can be made part of the ranging system, including savings in weight, cost, and complexity over implementations that use separate systems for each requirement.

As with other types of transponder systems, the active terminals for a full-duplex communications system mean that the loss budget for the ranging/communications link scales as $1/r^2$ instead of $1/r^4$, which is a substantial advantage. The communications link need not be symmetric in terms of data rate to achieve this benefit. Very often the uplink is relatively low bandwidth for command and control, and
the downlink is at a higher data rate for dumping data. The ground antenna can be made substantially larger than the remote antenna both to make the receiver more sensitive and as a way to reduce the mass and the pointing and tracking requirements for the spacecraft, since a smaller antenna has a larger beam.

Forward Error Correction (FEC) is a technique that can improve the link budget and hence the range of the system. FEC is a signal processing technique that adds additional bits to the communications data stream through an algorithm that generates enough redundancy to allow these bits to be used to detect errors. There are a wide variety of possible FEC algorithms that can be used, but it is possible to get link budget gains of the order of 8 dB at the cost of 7% overhead on the data rate even at data rates of several Gbits/sec. Gains of the order of 10 dB and higher are available at lower data rates, but at the cost of higher overhead. Generally the FEC algorithm may be optimized for the noise properties of the link if they are known.

A synchronous communications terminal must maintain a precise clock to be able to successfully recover the data. A remote terminal will recover the clock from the incoming data stream and phase-lock a local oscillator. All modern wide area terrestrial communications networks use synchronous techniques, so the techniques and electronics are well known and generally available. The advantage of having a stable reference clock that is synchronized to the ground terminal is that long times (and therefore long distances) may be measured with a precision comparable to that of the clock simply by counting bits in the data stream and carefully measuring the residual timing offset at the ground station. A maximal-length pseudorandom code can be used to generate a pattern with very simple cross-correlation properties that may be used to unambiguously determine the range, and the synchronous nature of the signal plus any framing or FEC structure imposed on the data stream mean that even long times may be measured with the same precision as the clock.

For optical communications terminals, it is almost as cost-effective to run at a high data rate as it is at a low data rate. The data rate might then reasonably be chosen for the timing precision instead of for the data downlink requirements. For example, a 10 Gbps data rate has a clock period of 100 picoseconds, which translates to a sub-millimeter distance precision with some modest averaging - just based on the clock. Specialized modulation formats such as phase-shift keying offer the possibility of optical phase-locking in addition to electrical phase-locking, which may allow further increases in precision.

Spacecraft or satellites may be used as repeaters or amplifiers much as they are in terrestrial telecom applications, further extending the reach. Multiple communications terminals distributed around an object, such as a planet, offer the ability to measure more complicated motion than just a range and a change in range. A high data rate terminal might also be used as part of a communications network in space. In addition to serving as a fixed point for high precision ranging, it could also provide various communications functions such as switching and routing.
9. Conclusions

LLR has made great advances in the past 35 years. However, the amount of light returned by the current retroreflectors is so little that only the largest ranging stations can be used for this purpose; poor detection statistics remains the leading source of error. Thermal and orientation effects will ultimately limit range measurement to the Apollo retroreflectors. Measurements of the lunar librations are also limited by the poor geometric arrangement of the visible retroreflectors.

More precise range measurements to retroreflectors placed at sites far from the existing arrays will greatly improve the gravitational and lunar science discussed above. A number of improvements (such as higher cross section) can be made to the retroreflector designs to realize these gains. This natural extension to the Apollo instruments is likely to produce a solid incremental improvement to these scientific studies for many years to come.

To make a much larger leap in ranging accuracy, a laser transponder or communication terminal will most likely be required. The robust link margins will enable the use of much smaller ground stations, which would provide for more complete time and geometric coverage as more ranging stations could be used. An active system will also not be susceptible to the libration induced orientation errors.

An active laser ranging system can be considered a pathfinder for a Mars instrument, as it is likely to be the only way to exceed the meter level accuracy of current ranging data to Mars. Laser ranging to Mars can be used to measure the gravitational time delay as Mars passes behind the Sun relative to the Earth. With 1 cm precision ranging, the PPN parameter \( \gamma \) can be measured to about \( 10^{-6} \), ten times better than the Cassini result.\(^\text{17} \) The Strong Equivalence Principle polarization effect is about 100 times larger for Earth-Mars orbits than for the lunar orbit. With 1 cm precision ranging, the Nordtvedt parameter, \( \eta = 4\beta - \gamma - 3 \), can be measured to between \( 6 \times 10^{-6} \) and \( 2 \times 10^{-6} \) for observations ranging between one and ten years.\(^\text{18} \) Combined with the time delay measurements this leads to a measurement of PPN parameter \( \beta \) to the \( 10^{-6} \) level. Mars ranging can also be used in combination with lunar ranging to get more accurate limits on the time variation of the gravitational constant.

The ephemeris of Mars itself is known to meters in plane, but hundreds of meters out-of-plane.\(^\text{19} \) Laser ranging would get an order of magnitude better estimate, significant for interplanetary navigation. Better measurements of Mars’ rotational dynamics could provide estimates of the core size.\(^\text{20} \) The elastic tidal Love number is predicted to be less than 10 cm, within reach of laser ranging. There is also an unexplained low value of \( Q \), inferred from the secular decay of Phobos’ orbit, that is a constraint to the present thermal state of the Mars interior.\(^\text{21} \) Laser ranging to Phobos would help solve this mystery.
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