International Lunar Network
Core Instruments Working Group

Final Report
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SUBMITTED BY
ILN Core Instruments Working Group

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1. Introduction

The International Lunar Network (ILN) Core Instruments Work Group (CIWG) was established by the ILN to identify core instruments for ILN nodes. The ILN encouraged each individual member country to provide two members of the CIWG. The ILN also appointed the first co-chairs of the CIWG. The inaugural meeting of the CIWG was held July 23, 2008 on the campus of the NASA Lunar Science Institute in Mountain View California. At the inaugural meeting it was decided that a "Core Instrument" would be identified by specified measurements to be obtained by that instrument.

According to the CIWG Terms of Reference, the CIWG was to undertake the following tasks:

a) Identify core science objectives that will substantially benefit from a lunar network;

b) Determine the measurement sets need to address the core science objectives;

c) Identify the classes of instruments (the core instruments) required to obtain the measurements; d) Establish performance goals for the instruments;

e) Establish links with other ILN Working Groups to inform them of their work as appropriate;

f) Report its findings in terms of an initial evaluation and comparison to the Plenary Group at the ILN meeting to be held in March 2009 timeframe.

g) Give priorities to the candidate core instruments

The composition of this core instrument list was debated over a series of teleconferences, email exchanges, and a follow-up face-to-face meeting in Yokohama, Japan, on March 12, 2009. This document gives the consensus recommendation of the CIWG for the ILN Core Instruments.

2. Core Instruments

The process by which the Core Instrument list was derived started by first collecting from the members a set of investigations, with associated measurements, that the various members might be interested in supporting as part of the ILN. These suggestions were collected in spreadsheet form, with information for each investigation on: The science goals and rationale; network, mission and measurement requirements; instrument requirements; and, in order to judge the realism of the investigation, an estimate of the resources (mass, power, data, etc.) required. This matrix is included as Appendix A.

Given that some of the ILN landers are likely to be relatively small and have limited capabilities, it is necessary to provide a Core Instrument list that is limited in scope. It was agreed that geophysical investigations of the lunar interior were most clearly enabled by a network mission. For example, seismology requires simultaneous measurements at multiple locations for its basic analysis techniques. Thus the following geophysical instruments were given highest priority.

The ILN Core Instruments recommended by the CIWG are:

1. Broadband Seismometer
2. Heat Flow Probe
3. Electromagnetic Sounder
4. Laser Retroreflector

These are each discussed in detail in the following sections.

It should be emphasized that the remaining investigations contained in Appendix A are each of high intrinsic value. Any of these instruments (or others that were not considered by this group) could well be considered for and included on any given landing mission to the Moon.

2.1 Seismometer

2.1.1 Seismometer Science Goals

The scientific goals of the ILN seismic investigation are to delineate the interior structure of the Moon to better understand its origin, evolution and current state. In particular, the volume and structure (large scale layering and regional variations in composition) of the crust, composition of the mantle (including radial variations) and size, composition and state of the core have important implications for the initial composition of the Moon, the details of its differentiation, the processes involved in magma ocean cooling and fractionation, and its thermal history. This in turn will help our understanding of the origin of the Earth and planets, and planetary processes in general.

2.1.2 Seismometer Measurement Goals

The goals of the ILN seismic investigation are to improve our knowledge of the structure of the crust, mantle and core, and to understand the distribution and causes of seismic activity. These goals can be described as follows:

1. Crust – Determine the mean crustal thickness and any large-scale compositional layering. To the extent possible, characterize local differences in velocity structure that can be related to lateral variations in crustal composition.

2. Mantle – Determine the vertical velocity structure of the mantle as a constraint on composition, particularly below 600 km, where the Apollo data provide little information. Characterize any global-scale layering and discontinuities due to chemical stratification or phase transitions.

3. Core – Determine the radius of the core and constrain its composition and state (liquid or solid). To the extent possible, determine the existence or absence of a solid inner core.

4. Seismicity – Characterize deep moonquake "nests", especially on the far side, and determine their source mechanisms and their relationships to tidal forces and other internal stresses. Determine the locations and causes of shallow moonquakes and their relationship, if any, to lunar tectonics. Characterize the lunar seismic background and determine the contributing sources such as meteoroid impact rate as a function of size, transient thermal stresses, etc.

2.1.3 Seismometer Measurement Requirements

Seismology provides knowledge about a planet and its processes from the measurement and analysis of seismic signals due to ground motion from the passage of elastic waves. The strength of this technique derives from the richness of information that is contained in theses signals, information about the origin of the elastic waves and the physical properties and spatial variations of the medium through which they travel.

The measurement of seismic waves on the Moon, particularly the identification of body wave, arrivals is complicated by attenuation (particularly at high frequencies), strong scattering within the crust, and the exceedingly small size of most moonquakes. These challenges can be overcome by extremely sensitive, three-axis broad-band measurements, which enable the utilization of sophisticated digital signal processing techniques that have been developed for terrestrial seismology over the past five decades.

Almost all useful information from the Apollo seismometers was derived from body-wave measurements between 0.1 to 5 Hz. At lower frequencies, however, there is potentially much additional information contained in surface waves and normal modes. The spectral analysis of these waves provides a direct measure of the elastic properties and density at various depths. In the case of surface waves, this information, derived from the velocity dispersion, is specific to the wave's path from its source to the receiver, providing localized information. For normal modes, the globally averaged structure determines the frequencies of the resonance peaks. Thus it is important to extend seismic measurements to lower frequencies to search for surface waves (~0.05 – 0.01 Hz) and normal modes (~0.01 – 0.001 Hz). These signals are likely to be rare, as they are only generated by relatively large events and can be damped (particularly the surface waves) by crustal scattering.

To make progress in these areas, it is desirable to significantly improve the seismometer performance over that of Apollo.

To achieve the outlined science goals, at least four network nodes need to operate simultaneously over an extended period of time. The nodes must observe and localize a sufficient number of strong, shallow moonquakes to understand their locations and mechanisms. Such events are infrequent (~4 per year were recorded by the Apollo network, with ~1 per year having a body wave magnitude of ≥5), so the longer the observation period, the better the chance of detecting rare large events. The occurrence characteristics of the moonquakes from individual hypocenters are correlated with lunar tidal phases, including the moon's rotation period and orbit around the earth (~1 month); the coincidence of lunar anomalistic and synodic phases (when a new moon coincides with lunar apogee, or a full moon with perigee, ~7 months); the moon's period of libration (~6 years), and the precessional period of the lunar orbit (~18 years). At least two years of operation is required to observe enough events to provide sufficient science value; a minimum of six years is desired to provide a better sampling of events and to capture the 6-year lunar tidal period.

2.1.4 Seismometer Instrument Requirements

The ideal ILN seismometers would provide vector measurement (i.e., measure displacement on three orthogonal axes) covering a dynamic range of ~24 bits (Apollo was limited to 10 bits) in order to characterize the lunar background as well as seismic events. The seismometer effective sensitivity requirements are stated in terms of the acceleration power spectral density (PSD, units of $m/sec^2/Hz^{1/2}$) of the instrument noise in three frequency bands, f:

a. $f > 1.0$ Hz: The sensitivity should be about the same as or slightly better than the Apollo SP, with a high-frequency cutoff no lower than 20 Hz. This corresponds approximately to PSD ≈ $10^{-9} f^2$.

b. $0.1 < f < 1.0$ Hz: The sensitivity should be at least an order of magnitude better than the Apollo LP (peaked mode). This corresponds approximately to PSD ≈ $10^{-10} f$.

c. $0.001 < f < 0.1$ Hz: The sensitivity again should be at least an order of magnitude better than the Apollo LP (peaked mode). This corresponds approximately to PSD ≈ $2 \times 10^{-11.5}/f^{1/2}$. In order to satisfy the objectives of detecting surface waves and normal modes, it is strongly desired that the low-frequency performance should attain a PSD ≤ 10^{-11} across the entire band.

Whereas the ideal instrument would satisfy all three specifications, useful data for investigating the interior of the Moon can be acquired in any of these frequency bands. Thus an ILN seismometer should meet or exceed the specifications in at least one of the bands (a, b, or c) above.

Because of the high sensitivity requirements of the seismometer, the instrument deployment should maximize its thermal and mechanical stability.

The host mission is responsible for isolating the seismometer from the vibrational and thermal interference of the spacecraft in the frequency range of interest (e.g., 0.001-20 Hz).

Because interpretation of the seismic signals depends on the time the signals are received at the different stations, the host mission should have the ability to time-tag the seismic data with an accuracy of no worse that 50 msec (reconstructed).

2.1.5 Seismometer Siting Requirements

For seismology, the specific location of the individual landing sites is less important than the overall geometric distribution. For a network of 3 nodes, they should form an approximate triangle, ~2000 km on a side. This provides for a superior geometry compared to the Apollo network, and allows better resolution in locating seismic sources, a prerequisite for body wave travel time analysis. It is also highly important that at some point a number of nodes be located on the lunar farside, using a communications orbiter to relay data. In the event that farside communications cannot be established, nodes near the lunar limb can provide some of coverage for searching out as-yet unobserved farside seismic activity.

2.2 Heat Flow

2.2.1 Heat Flow Science Goals

The lunar heat flow provides key information about the thermal state of the interior and the workings of the planetary heat engine. Determining the heat flow in multiple locations over the surface of the Moon will also permit the characterization of radial and lateral variations in the distribution of radiogenic elements, as well as constrain the bulk abundance of these elements for comparison with the Earth and the rest of the solar system.

2.2.2 Heat Flow Measurement Goals

The scientific goals of the ILN heat flow investigation are to establish the global average heat flow of the Moon, and determine the relative contribution of the major geologic provinces (e.g., Procellarum KREEP Terrane [PKT], Feldspathic Highlands Terrane [FHT], farside/nearside, mare basins).

2.2.3 Heat Flow Measurement Requirements

Planetary heat flow at the surface is dependent on the thermal properties of the regolith and how temperature changes with depth. Thus, determination of the lunar heat flow requires independent measurement of thermal conductivity and thermal gradient.

The thermal gradient is determined by measuring temperature at multiple depths within the near-surface. Experience with Apollo has shown that the upper 1-1.5 m is strongly affected by propagation of the diurnal and annual thermal waves. The propagation of these waves can be used to determine the thermal conductivity of the upper layer of the regolith. Thus necessitating measurement of temperatures below this depth range, in order to constrain accurately the thermal gradient due to heat flow from the interior. In addition, the thermal gradient near the surface is likely of order 1 K m^{-1}, so to characterize precisely the gradient requires measurement over depth spans of at least 1 m. These factors determine an experiment depth requirement of 3 m. Similarly because the thermal conductivity is known to vary with depth, it must also be measured at multiple depths along this 3-m length.

2.2.4 Heat Flow Instrument Requirements

Measuring the conductivity and thermal gradient each place constraints on the heat flow experiment. In the low conductivity regolith, the thermal gradient is of the order of 1 K m^{-1}. Assuming that this measurement can be made below the depth of penetration of the annual thermal wave (~1-1.5 m), the temperature must be measured with high precision (0.05-0.001 K), comparable to that of Apollo. Temperature sensors must be placed closely enough to allow for an accurate determination of the gradient. Ideally, the experiment lasts longer than 1 year to validate that the gradient is in fact being measured below the annual wave.

Heat flow measurement places constraints on lander operation and configuration. The presence of the lander creates a thermal disturbance that conducts into the interior, potentially interfering with the thermal gradient measurement. This effect can be mitigated by either deploying the heat flow experiment at approximately 1 lander diameter away from the lander or by deploying the heat flow experiment in a location such that the thermal effect of the lander can be readily modeled and removed. Deployment away from the lander is preferred since monitoring the propagation of the annual wave into the interior provides a complementary measurement of conductivity.

Placing any device into the subsurface will alter the thermal environment by compacting the regolith adjacent to the drill, penetrator, mole, etc. In addition, due to the extremely low conductivity of the lunar regolith, the instrument is going to have a higher conductivity than the regolith. This can pose a challenge to making representative conductivity and temperature measurements. Thus the calibration of the thermal environment for the heat flow instrument is essential.

2.2.5 Heat Flow Siting Requirements

Site selection is an essential consideration for the heat flow experiment. Ideally, a heat flow measurement would be obtained in the centers of each unique lunar terrane. The thermal gradient (and hence heat flow) can be perturbed by greater than 5% within ~200 km of the boundary between regions with disparate thermal properties. Thus, the sites should be located farther than 200 km from terrane boundaries (the Apollo 15 and 17 heat flow measurements did not meet this requirement, and thus there is continuing ambiguity on how representative these measurements are. Additionally, the sites should be in regions that are topographically smooth so that shadowing does not influence surface temperature.

In order to estimate the global average heat flow and the contribution of various major terranes, at least one measurement should be made in each of the following regions: PKT, FHT (nearside), FHT (farside), South-Pole Aitken Basin, and a representative nearside mare basin.

2.3. Electromagnetic Sounding

2.3.1 Electromagnetic Science Goals

The overall objective of electromagnetic (EM) sounding on the Moon is to infer internal temperature and composition, complementing seismology and heat flow in pursuit of the general goal of understanding the interior structure and thermal evolution of the Moon. An EM experiment also enables other investigations beyond the immediate scope of the ILN, involving solar wind and magnetosphere science.

2.3.2 Electromagnetic Measurement Goals

The primary measurement goal of the ILN should be to determine the electrical conductivity structure of the outermost 500 km of the Moon, and its spatial variability. This region was poorly resolved in Apollo-era measurements. Secondary goals of an EM investigation should be to improve the Apollo-era knowledge of the conductivity and composition of the lower mantle of the moon (~500-1400 km depth) and to assess the size and state of the core.

2.3.3 Electromagnetic Measurement Requirements

EM sounding using frequencies up to ~10 Hz would resolve the vertical and horizontal variations of in the upper 500 km. At these frequencies the transfer-function approach used with Apollo is problematic, requiring a second spacecraft with a magnetometer in low lunar orbit. Without the support of an orbiter carrying a magnetometer, the transfer-function approach is not viable.

A complete EM sounding can be performed from an individual surface station by measuring orthogonal horizontal components of the time-varying magnetic and electric fields, i.e., by the magnetotelluric (MT) method. MT naturally provides spatially independent measurements with horizontal resolution comparable to the EM skin depth. Improved knowledge of the conductivity of the lower mantle (~500-1400 km depth) does not require additional bandwidth and associated changes in measurement techniques, but rather improved signal-to-noise ratio (SNR). By comparing results from different parts of the lunar orbit around the Earth and by acquiring data over many such orbits, it should be possible to understand systematic differences evident in Apollo-era data and to determine the conductivity to within a half decade.

The EM sounding experiment has implications for other investigations. The DC magnetic-field strength and direction is important for constraining downward continuation of orbital data, ultimately to understand whether magnetic anomalies have an impact or a crustal origin, and plasma-surface interactions can be studied at more strongly magnetized regions.

2.3.4 Electromagnetic Instrument Requirements

The EM measurements will require a 3-component magnetometer with sensitivity above 10 $pT/Hz^{1/2}$. A second magnetometer may be required to allow the elimination of spacecraft magnetic effects. In addition, a two-component electrometer with a sensitivity above 100 $\mu V/m/Hz^{1/2}$ is required to complete the MT measurement. Voltage-probe separations of no more than a few meters should be sufficient to measure the relevant electric fields.

On the Moon the active plasma environment could affect local electric fields differently from magnetic fields and therefore bias the impedances. Standard characterization of the plasma environment will be important to identify any electrostatic plasma effects. This can be done, for example, with a vertically oriented Langmuir probe (500 K, 10 e/cm^3).

Good resistivity discrimination in the upper 500 km is established above 100 MHz. Measurements up to 100 Hz might be useful in detecting signatures of the crust, although strong, well-documented, EM fields at the Moon are restricted to ≤ 10 Hz.

2.3.5 Electromagnetic Siting Requirements

Because the objectives of EM sounding are aligned with seismology and heat flow, there are no additional constraints other than co-location with these experiments. As the number of ILN nodes increases, crustal magnetism and plasma interaction studies would benefit from measurements at sites of strong crustal magnetization (such as Reiner-gamma) and albedo anomalies.

2.4. Precision Ranging for Lunar Geodesy - Laser Retroreflector

2.4.1 Precision Ranging Science Goals

The scientific goals of the precision ranging investigation are to improve the determination of a number of globally-averaged lunar interior parameters involving the depths, densities, and deformational properties of the major interior divisions (crust, mantle, inner/outer core). This will provide a better understanding of the fluid core/solid mantle boundary conditions and the presence/absence of a solid inner core. It will also address several fundamental physics questions (see Section 3.3).

2.4.2 Precision Ranging Measurement Goals

The measurement goals of an advanced precision ranging experiment for the Moon involve measuring its orbital and rotational variations to extremely high precision, The science goals stated above can be addressed by several technical approaches to these measurements, including retroreflectors for Lunar Laser Ranging (LLR), laser transponder ranging, several Very Long Baseline Interferometry (VLBI) techniques, including Same Beam Interferometry (SBI), and precision astrometry. Because of its high level of development and its ease of integration into a spacecraft payload, we have concentrated on LLR as a core instrument, although other forms of ranging with similar performance could be substituted.

2.4.3 Precision Ranging Measurement Requirements

Current position determinations of existing LLR arrays have a precision of about 2 cm. New LLR measurements should be made with a precision better than current abilities. Such capabilities at a more geographically distributed set of sites will serve to address important scientific questions. Beyond that, there are a number of additional topics that can be addressed with measurements with mm-class observations, although this will require an improvement in the existing modeling and analysis software.

2.4.4 Precision Ranging Instrument Requirements

Current LLR science requires single photon detection due to r^4 signal loss ($\sim 10^{-21}$ photons lost over the 2 x 385,000 km round trip). For retroreflectors, even single photon returns require large (hundreds of cm^2) arrays pointed within a few degrees of the Earth. New LLR devices should be designed to reduce the scatter of the individual photons used to make a normal point. A small thermo-mechanical source of distortion in the position of current arrays is due to thermal deformation of their support structures, so one solution may be to thermally and mechanically anchor the arrays to the isothermal regolith at a depth of 1 meter, or actively control array temperature, or use new materials such as beryllium, which experiences smaller thermal distortions. The primary range error is due to the librations of the Moon: the orientation of the Moon changes with respect to the line of sight from the Earth station to the moon by up to ten degrees over the course of a month. For existing arrays this can contribute over 50 mm to the range uncertainty per photon. It is by far the leading source of range uncertainty, and thousands of photons must be collected to average down to the millimeter level. New designs such as a single-cube large reflector should be utilized to minimize this uncertainty.

Besides retroreflector arrays, laser transponders are also a possibility. Transponders would give much brighter and more coherent signals that would be receivable by Earth-based assets over a broad geographic area, but they require power and pointing capability.

2.4.5 Precision Ranging Siting Requirements

For LLR we would like a broad spread of locations on the near side of the Moon. Define the x-axis from the lunar center of mass toward the mean Earth direction and z along the mean rotation axis. Much of the LLR lunar science information comes from physical librations, the three-axis response of orientation to torques. For a retroreflector array, the sensitivity of range to physical librations in longitude depends most strongly on the Y coordinate while the sensitivity to the latitude librations depends most strongly on the Z coordinate. The sensitivity of LLR to physical librations can be increased by placing new retroreflectors at larger north-south and east-west separations than the existing sites. A retroreflector in the southern hemisphere would be very useful, since we have nothing south of -4 degrees. Any site that expands the existing pattern would be welcome, though sites near the limb (7-10 degrees) will not always be visible and are consequently less favorable for LLR.

LLR can measure tidal displacements and get Love numbers. Tides are nonlinear functions of the X, Y, and Z coordinates. Consideration shows that a spread of X values between retroreflectors helps separate tides from physical librations and other phenomena. The spread of X values with the Apollo retroreflectors is 98 km or 0.06 radii. The Lunokhod 2 retroreflector triples the X spread, but that target gives a weak signal and consequently less than 3% of our data is from that site.

Finally, lunar geodesy would also benefit from a wide spread of accurate positions. What is said above for laser ranging sensitivities is also appropriate for radio ranging or phase sensitivities.

2.4.5.1 Existing LLR Sites

The distribution of LLR sites on the Moon is important to the scientific results. The Table gives the coordinates of the four retroreflector arrays derived with the DE421 ephemeris (Williams et al., 2008) and the Figure shows their locations. A fifth array on the Lunokhod 1 vehicle is lost to use, probably due to an uncertain position (Williams and Dickey, 2003; Stooke, 2005).

Table. Lunar Laser retroreflector array coordinates as determined with DE421 using the mean Earth/mean rotation axis frame. Axis x is from the lunar center of mass toward the mean Earth direction and z is toward the mean rotation axis.

Array	X	Y	Z	R	E Longitude	Latitude
	Meters	Meters	Meters	Meters	Degrees	Degrees
Apollo 11	1591747.845	691222.345	20397.830	1735472.732	23.4730729	0.6734398
Apollo 14	1652818.934	-520454.721	-110361.346	1736336.135	-17.4786483	-3.6441703
Apollo 15	1554937.875	98605.140	764412.735	1735477.340	3.6285073	26.1333959
Lunokhod 2	1339388.500	802310.872	755849.325	1734639.009	30.9221489	25.8323070

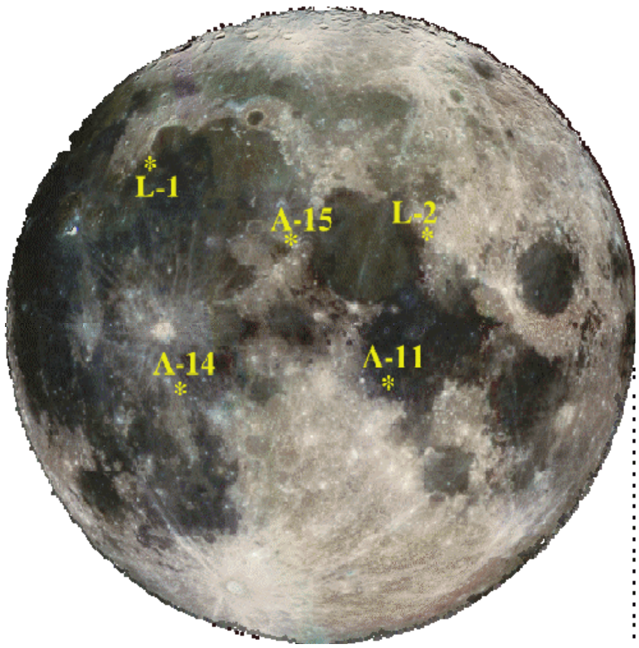

Figure. Lunar laser retroreflector arrays at the Apollo and Lunokhod sites.

The Apollo 11, 14, 15 and Lunokhod 2 sites span a limited region on the Moon. The spread of LLR Y values in the Table is 38% of the lunar diameter and the spread of Z values is 25% of the diameter. The X value spread is only 18% of the radius. 77.5% of the ranges for 1970-2008 are to Apollo 15, the largest array. Lunokhod 2, the smallest and most thermally sensitive array, gets 2.8% of the ranges. Apollo 11 and 14, near the equator, make up 9.9% and 9.7% of the total data set, respectively. Since 80% of the existing ranges are from 26° north of the lunar equator, recovery of center-of-mass motion requires very good latitude librations.

2.4.5.1 The Lunar analog of the ITRF

Space navigation and geodesy in Earth orbits is governed by the International Terrestrial Reference Frame (ITRF), maintained by the IERS, the International Earth rotation and Reference system Service (see http://www.iers.org/). The ITRF relies on a global network of co-located sites with combinations of space geodesy techniques: SLR/LLR, VLBI, GNSS, DORIS, etc. The next logical step needed to build an extended Earth-Moon positioning metrology system is the establishment of a network of similar geodetic sites on the surface of the Moon equipped with retroreflectors and radio transponders. This would be the future "International Moon Reference System" (the IMRF), referenced to the ITRF with LLR and VLBI/SBI. The ILN we propose to build in this decade will be the first realization of the IMRF, which will be needed for the long-term lunar exploration and settlement. In the future, IMRF stations will also provide an absolute altitude reference for orbiters equipped with laser altimeters or laser-communication satellites. The far side IMRF, instead, will be referenced to the ITRF by relay satellites.

3. Other Science Investigations

In addition to the core instruments described above, the committee identified a number of additional high-value investigations that would benefit from inclusion on ILN landers. These do not primarily address the goals of interior geophysics, but would add to our understanding of the Moon and/or other scientific areas.

3.1 Exploring Unsampled Lithologies

3.1.1 Lithology Science Goals

Determining the diversity of lunar crustal rock types was recognized as a high priority lunar science goal by the US National Research Council ("Scientific Context for Exploration of the Moon", 2007). It was ranked third out of the eight top-level science objectives. The only places on the Moon from which samples have been collected *in situ* are the six Apollo landing sites and the three Russian Luna sample return missions. No samples have been returned from high latitudes, the western nearside limb or the farside, greatly limiting our knowledge of lunar geological processes. Although, statistically, many of the 65+ lunar meteorites must be derived from these unsampled regions, the provenance, and thus geological context, of any given meteorite is unknown, which limits their value in interpreting lunar geology.

3.1.2 Lithology Measurement Goals

Although sample return missions to a number of currently unsampled regions would be the preferred means of furthering our knowledge of lunar geological diversity, this may not be practical in the short term. An alternative would be to make *in situ* geochemical measurements, similar to those obtained on Mars by the Pathfinder and Mars Exploration Rover (MER) missions. This will be the goal of the geochemistry package on the ILN nodes. In addition to providing local geological context for the ILN geophysical instruments, these measurements will also provide additional 'ground truth' calibration points for orbiting remote sensing instruments. The recent remote-sensing evidence for water and/or hydrated minerals at high lunar latitudes (in non-shadowed locations) could also be confirmed by suitable geochemical instruments on the ILN nodes.

3.1.3 Lithology Measurement Requirements

In the absence of mobility, the ILN geochemistry instruments will only be able to measure the composition of the surficial regolith at each landing site. However, the well-mixed nature of the regolith means that this will accurately reflect the composition of underlying bed-rock lithologies, and hence would be a valuable measurement for any as-yet unsampled locality. Suitable instruments for this task would be an Alpha Particle X-ray Spectrometer (APXS; for example, those implemented on Mars Pathfinder, the MERs and planned for Mars Science Laboratory), or a Laser-Induced Breakdown Spectrometer (LIBS; for example the ChemCam instrument being developed for MSL).

An APXS-type instrument will require a deployment mechanism able to place the sensor head in contact with the regolith. A deployment arm, such as those employed on the Surveyor landers, would have the added advantage of being able to measure several discrete patches of regolith around the lander, and any small rocks, which may serendipitously be within reach, but at the expense of extra mass and complexity. A remote LIBS instrument, such as ChemCam, would also be able to achieve this, and to a greater range, but again at the expense of added complexity on the lander. The ultimate geochemical sensitivity would be achieved by an on-board mass spectrometer (e.g. a Laser Ablation Mass Spectrometer (LA-MS), but it is doubtful that this could be implemented within the ILN concept.

3.1.4 Lithology Instrument Requirements

The geochemistry package should be able to measure the abundances of the major rock-forming elements (i.e. Na, Mg, Al, Si, P, K, Ca, Ti, Cr, Mn, Fe) to an accuracy of order 0.1 wt% [TBC]. Accurate determination of the Mg abundance is crucial as the Mg/Fe ratio is a key petrological indicator of the origin and evolutionary history of igneous rocks.

Additional measurements of key diagnostic minor and trace elements (e.g., Ni, Co, Sc, Sm, Sr, Ba, Zr, Th, U, etc) are desirable at the few ppm level, although this added requirement will have implications for the choice of instrument (i.e., it would point to LIBS-type instrument or an on-board mass spectrometer, rather than a relatively simple APXS implementation).

In order to confirm or refute remote sensing evidence for water and/or hydrated silicates at high lunar latitudes it is desirable to measure the concentration of H_20 and/or OH in the regolith at the ~10 ppm level [TBC]. Because the remotely sensed data refer to only the uppermost few mm, in order to determine the distribution of water as a function of depth, it is desirable to make these measurements with a vertical spatial resolution of a few mm [TBC] throughout a representative thickness (~1m [TBC]) of regolith. In order to release adsorbed or chemically bound water it may be necessary to step-heat the samples, with the released volatiles being fed into an onboard mass spectrometer (similar to the Gas Analysis Package implemented on Beagle2).

3.1.5 Lithology Siting requirements

There are no special siting requirements for the ILN geochemistry instruments. It is understood that geochemistry will not drive site selection for the ILN, which is primarily a geophysical network. Inclusion of a geochemistry package will be valuable on any ILN node sent to any previously unsampled locality on the lunar surface, where it will provide local geological context for the geophysical measurements, further elucidate or knowledge of lunar crustal diversity, and provide additional ground truth for orbiting remote sensing instruments. However, a search for water and/or hydrated minerals would require that one or more ILN nodes be targeted to locations (mostly ≥60 degrees latitude) where there is remote sensing evidence for these materials.

3.2 Astronomy from the Moon

3.2.1 Astronomy Science Goals

When Low-Frequency (LF) radio emissions from the Earth and the Sun are absent (e.g., at solar minimum or during the lunar night, and from the far-side or near-limb locations shielded from terrestrial radio sources by the Moon's topography), the lunar surface can provide the most radio-quiet observing position in the Earth's locale. Also, due to its tenuous ionosphere, it provides access to distant LF radio sources down to ~100 kHz, instead of ~10 MHz accessible from the surface of the Earth. The only noise that limits sensitivity is the steady galactic radio background, which peaks around 1 MHz and strongly decreases below ~500 kHz. The Moon has thus been recognized as a favorable platform for a LF radiotelescope in the range 0.1–30 MHz, and perhaps even 0.01–100 MHz. At these low frequencies, an interferometer setup is necessary to provide some angular resolution (seconds to degrees) to the observations. This approach can be adapted to a lunar network although much of what is discussed below may be beyond the capability of currently envisioned geophysical landers.

Depending on the number of elements deployed, such an LF radiotelescope will give access to:

- The early universe (primordial H at redshifts 50 to 1000)
- Long-wavelength all-sky survey and monitoring of 10^4 to 10^6 sources (radio galaxies and clusters, stars, planets, etc.)
- Solar system planetary magnetospheric radio emissions and their exoplanetary analogs
- Solar system planetary lightning
- Properties of the interstellar medium (ISM) at LF by study of propagation effects (dispersion, broadening) on intense pulsar emission (as well as pulsar spectrum turnover and polarization)

- The unknown “LF universe”

3.2.2 Astronomy Measurement Goals

For the early universe or surveys, the goal of the measurements is to make an all sky image of the LF radio sky and measure spatial fluctuations as well as small-scale/point source spectra, as well as their temporal variations as constrained by LF ISM propagation effects.

A modest number of network sites (1-10) would permit the monitoring and study of LF radio emissions from Jupiter, Saturn, Uranus and Neptune, addressing magnetospheric dynamics (via the variabilities/periodicities of radio emissions, from short pulses to planetary rotation period), solar wind/magnetosphere and satellite/magnetosphere couplings (substorms, satellite volcanism, etc.), possible presence of planetary magnetic field anomalies (and their secular variations), for example. For Uranus and Neptune radio emissions and the dynamics of their peculiar magnetospheres, this would be the first observations since Voyager 2 in the 1980s. LF lunar observations would be very complementary to in-situ spacecraft, HF ground-based, and multi-wavelength measurements.

Individually, a LF Lunar instrument could study fluxes of cosmic rays, grazing ultra-high energy neutrinos, micrometeorites and dust, as well as solar and magnetosphere/tail electromagnetic emissions (space weather) and the Moon’s wake, ionosphere and subsurface.

3.2.3 Astronomy Measurement Requirements

The basic element of a Lunar LF radio network is a set of antennas (2 or 3 crossed dipoles) connected to a receiver. Ideally, each element should be able to operate in standalone RS (radio spectrometer) mode and, in conjunction with the other nodes, as an interferometer in TDS (Time Domain Sampler) mode.

The RS would consist of a 2- or 3-channel receiver performing as a multi-channel receiver (via direct conversion) at the lowest frequencies (typically <1 MHz) and as a swept-frequency analyzer above that. An analog front-end can provide 80 to 120 dB dynamic range (using an AGC loop). After signal A/D conversion, wavelet-like transform and channel auto- and cross-correlations provide flux and polarization spectra. Direction of the dominant point source can also be derived with ≥2 co-located dipoles, allowing spatial separation of radio sources. RS can perform quasi-continuous spectrum monitoring.

The TDS would ensure broadband waveform capture at a sampling rate of 20–50 MHz with 12–14 bit resolution. Digitized waveform can be processed on board for event detection, synchronous de-dispersion, etc., and/or sent to a central correlator (also part of the ILN) to compute fringe visibility maps that can be processed into sky images. Data and synchronization signals could be sent to the central correlator by cables or by RF signal. It is possible to combine the TDS with the RS synthesizer in order to digitize a limited spectral band (e.g., 1 MHz) at reduced sampling rate. The duty cycle of the interferometer mode will be set by data processing and transmission limitations.

Note that coupling a transmitter to the RS permits Ground Penetrating Radar measurements that can be used to characterize the Lunar subsurface in terms of ground resistivity and permittivity. This could allow mapping of local subsurface through dielectric inversion, allowing the exploration of structural heterogeneities, regolith thickness and possibly thermal properties down to a few hundred meters depth. Adding a Langmuir probe would allow monitoring of the local plasma parameters and their variations, as well as the near-surface electric field.

3.2.4 Astronomy Instrument Requirements

Elementary antennas should be short dipoles under a few meters long ($L << \lambda$, i.e. << 10 m at 30 MHz) in order to have a broad reception pattern. The corresponding effective area is $A_{\rm eff} = \lambda^2/k$ with $k \sim 3$, thus ~300 m^2 at 10 MHz. There could be one to several antennas per ILN station (to increase sensitivity). A separation $D \sim 1$–1000 km between ILN stations would provide an angular resolution of the radio images λ/D = 1.6°– 6" (~1' for D=1000 km at 1 MHz). Achievable receiver sensitivity is ~10 nV/Hz$^{1/2}$. Although digital radio frequency interference (RFI) mitigation techniques can be implemented onboard, self-generated RFI should be kept to a minimum.

Receiver mass is ~1 kg for RS plus an additional ~1 kg for TDS, plus antennas (wires or booms), harness, clock and RF transmitter (a few kg per radio network element). Expected power consumption is ~10 W. Output data rate of an RS is a few kbps. Only a few RS output spectra need to be transferred to Earth for monitoring. For TDS operation, data transmission on the lunar surface (to the central correlator) will be of several 100 Mbps, resulting in a final data rate of the order of 10's kbps to Earth. This rate is scalable by adjusting the duty cycle of interferometric measurements. Availability of a high-rate burst mode would be useful.

3.2.5 Astronomy Siting Requirements

A Lunar LF radio instrument would take advantage of the quietness of the far-side or near-limb locations shielded from terrestrial radio sources by the Moon's topography (no terrestrial RFI), and of the lunar night (no solar RFI, more tenuous ionosphere).

3.3 General Relativity and New Fundamental Physics

3.3.1 Fundamental Physics Science Goals

Extremely precise tests of General Relativity and other explanations of dark energy (for example, Dvali's weak gravity theory) can be performed by accurately reconstructing the orbit of the Moon and thus precisely measuring the lunar orbit perigee precession (de Sitter effect), performing tests of the Equivalence Principle (strong and weak), placing limits on the time variation of the gravitational constant (G) and deviations from the $1/r^2$ force law. A search for strange quark nuggets (SQN), a theoretical (and as yet unobserved) form of condensed matter, can be done with seismometers on a very seismically quiet planet. Non-standard (i.e., non-baryon or non-meson) aggregate quark states have a major interest in fundamental physics. If they exist and are cosmological relics, they may also be a significant contributor to dark matter.

General relativity is well-established theory, but it is not the ultimate theory of gravity, in part because it is a non-quantum theory. It should be tested with greater and greater accuracy in order to find if it "breaks", requiring that it be replaced with a new theory. So General Relativity test are, in this sense, searches for new physics.

All of the investigations in this section are complementary to Core Instrument investigations (specifically "Seismology" and "Precision Ranging for Lunar Geodesy") in the sense that no additional hardware (e.g., spacecraft payload) is required.

3.3.2 Fundamental Physics Measurement Goals

Goals for fundamental physics measurements are similar to those for geodesy ranging (see section 2.4.2). The measurement goals of an advanced precision ranging experiment for the Moon involve measuring its orbital motion to extremely high precision, The science goals stated above can be addressed by several technical approaches to these measurements, including retroreflectors for Lunar Laser Ranging (LLR) and laser transponder ranging.

The search for SQN involves identifying their passage through the Moon. These events should result in seismic disturbances along the line of their passage, which have a different signature than endogenic seismic events.

3.3.3 Fundamental Physics Measurement Requirements

Requirements for fundamental physics ranging measurements are similar to those for geodesy ranging (see section 2.4.3). Current position determinations of existing LLR arrays have a precision of about 2 cm. New LLR measurements should be made with a precision better than current abilities. Such capabilities at a more geographically distributed set of sites will serve to address important scientific questions. Beyond that, there are a number of additional topics that can be addressed with measurements with mm-class observations, although this will require an improvement in the existing modeling and analysis software.

The identification of SQN passages requires the same types of measurements as the seismology experiment. However differentiating SQN events (line sources) from moonquakes (point sources) requires a minimum of five simultaneously operating stations.

3.3.4 Fundamental Physics Instrument Requirements

The instruments and their requirements for ranging and seismic detection for fundamental physics investigations are the same as for precision ranging for geodesy and seismology, respectively. See Sections 2.4.4 and 2.1.4 for discussions of these requirements.

3.3.5 Fundamental Physics Siting Requirements

The siting requirements for ranging and seismic detection for fundamental physics investigations are the same as for precision ranging for geodesy and seismology, respectively (except that SQN search requires at least five sites, whereas seismology has a minimum of four). See Sections 2.4.5 and 2.1.5 for discussions of these requirements.

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Appendix B. Core Instruments Matrix

Discipline or Science Question	Science Goal	Network Requirement	Science Rationale	Measurement Requirements	Mission Requirements	Instrument Requirements	Mass, Power, Thermal, Data
Seismology	Understand the current seismic state of the Moon, at multiple depths, to better resolve the stratigraphy of the lunar crust and determine the internal structure of the Moon. Constrain the impact flux rate.	Multiple, simultaneously operating sites about the Moon are required to understand lateral variations in the composition of the lunar crust, and interpret deep seismic events.	Seismic experiments enable a better understanding of lunar crustal stratigraphy. Seismic waves from lunar tectonic events can be used to determine the structure and composition of the crust, mantle and core. Nearside Earth-based impact flash observations may provide timing and locations for impact generated events.	Measure lunar seismicity using broadband seismometry at multiple, geographically dispersed, locations.	At least 4 sites simultaneously operating for 6 years. Inter-station timing accuracy: 5ms. Instrument attached to ground and vibrationally isolated from the spacecraft to reduce ground vibrations spacecraft vibrations for frequencies below 20 Hz. Possible micro-accelerometer on S/C to monitor S/C vibrations.	Three axis Very Broad Band (VBB) seismometers with: Dynamic Range >24 bits; High Frequency Cutoff ~ 20 Hz. Sensitivity: [1.0<f<20 Hz] PSD≤10-9f2 m/s2/Hz1/2; [0.1<f<1.0 Hz] PSD≤10-10f m/s2/Hz1/2; [0.001<f<0.1 Hz] PSD≤2×10-11.5/f1/2 m/s2/Hz1/2. Thermal stability +/_ 5deg with need to thermally blanket ground within 1m if surface deployed. Attitude knowledge.	Mass 6 kg: Power 2 W (peak), and 1 W (cont.), and 0.2 W (low power). May need additional power for instrument heating. (Is low power correct for broad-band seismometer operation). 100 Mbits per Earth day; no downlink drivers.
Heat Flow	Measure variations in lunar surface and interior heat flow to characterize the temperature structure of the subsurface and interior of the Moon.	The available evidence points to lateral variations in the heat flow. Representative sites of interest include the maria, the FHT the PKT the farside and the SPA Basin	Heat flow measurements constrain the local and bulk abundance of radiogenic elements in the lunar regolith, crust, and upper mantle. They are required to understand the thermal evolution of the Moon.	Determine the thermal conductivity by in situ heating at multiple depths. Determine the thermal diffusivity by measuring the amplitude of the diurnal temperature wave at multiple depths. Determine the thermal gradient via long-term monitoring at multiple depths at each location.		Each active thermal conductivity measurement records the heaters self-heating curve for more than 1 lunar day. Each sensor measures T every 6-12 hr. Temperature sensor precision: 0.05-0.001 K. A minimum of 9 thermal conductivity measurements and 9 temperature measurements. Sensors space 30 cm apart.	Temperature sensors = 10g each. 3 W in temperature measurement mode, 3 W in thermal conductivity measurement mode (during heating). Sensor deployment mass depends on implementation chosen. MOLE mass is 2 kg and peak power use is 10 W. Possible deployment mechanism weights ~2 kg. 10 Mbit total during the soil intrusion phase. A few tens of kbit/day during the monitoring phase.

Discipline or Science Question	Science Goal	Network Requirement	Science Rationale	Measurement Requirements	Mission Requirements	Instrument Requirements	Mass, Power, Thermal, Data
Electromagnetic Sounding	Use electromagnetic sounding to measure the electrical conductivity of the lunar interior.	The available evidence points to lateral variations in the composition and thermal state.	Interior temperature and composition can be inferred from conductivity. Provide measurements of crustal magnetization at additional sites as well as measurements of the space-physics environment.	Measure ambient electric and magnetic fields as a function of frequency at each station. Quantify contribution to E&M measurement by the local plasma field.	Continuous operation for 1 year. No ground contact requirements. Both magnetometers and the electrometer must be 2 m from the spacecraft, and the arms of the electrometer deployed in orthogonal directions. Langmuir probe should be 0.5 m from the spacecraft.	Frequency range: DC - 100 Hz. 2 3-component magnetometers (10pT/rtHz). 1 2-component electrometer (100uV/m/rtHz). 1 Langmuir probe (500 K, 10 e/cm3) on a vertical mast. Temperature sensor (calibration). Altitude knowledge for deployed sensors.	Estimated mass is 2-5 kg for sensor, booms and avionics. Estimated continuous power is 6 W. 10-100 Mbits/day continuous.
Precision Ranging for Lunar Geodesy	Precise ranging to the lunar surface to improve our understanding of the deep lunar interior, particularly the core.	1) Extending current network of 3 Apollo and 1 Lunokhod sites, particularly at the limbs and at the poles, would improve the capabilities of lunar geodesy. 2) Further improvements will come from improved retro-reflector or laser transponder design (e.g. LSSO, LLRRA-21 developments). These improvements will range from a factor of a few to a factor of ten, with even greater accuracy possible as ground stations improve.	Laser ranging reveals small irregularities in the lunar rotation rate due to tidal changes of the Moon's shape and the effects on lunar shape, rotation, and other motions of the lunar core and mantle It also permits most accurate determination of PPN β parameter, equivalence principle, 1/r2 deviation.	Improve accuracy in measurements done from Earth (currently about 2 cm; few mm for APOLLO at Apache Peak) to 0.1 mm level. Retro-reflectors could also provide fiducial references for spacecraft orbiting the moon.	Reflector array oriented to provide direct Earth view. If/when multiple retroreflectors are deployed at the same landing site, their spacing must be such that Earth stations can separate their laser returns.	Minimum size of a core retroreflector array: 10 cm on a side.	Retroreflector about 1 kg; deployment hardware about 1 kg. No power required, no thermal control required. Must have stable mounting with respect to surface. No need for data transmission from the Core package. Lots of data from ground stations (APOLLO at Los Alamos, ASI-MLRO in Italy, etc).

Appendix C. Additional Instrument Matrix

Discipline or Science Question	Science Goal	Network Requirement	Science Rationale	Measurement Requirements	Mission Requirements	Instrument Requirements	Mass, Power, Thermal, Data
Exploring Unsampled Lithologies	Investigate in situ composition and lateral inhomogeneities in the lunar crust by in situ mineralogical and geochemical analysis of materials unsampled by Apollo but identified from orbit spectral measurements.	Post-Apollo work such as lunar meteorite studies and the results of the prospector and Clementine missions as well as earth based spectral observations indicate that at least many mare basalt types as well as South-Pole Aitken materials were not sampled during Apollo.	Further refinement of our current construct for the formation and evolution of the Moon requires sampling of South-Pole Aitken as a window into the mantle and Lunar farside as a window in the very early past at a minimum	Chemical composition, mineralogy and lithology as well as trace elements	First it requires predicted information from spectral global coverage flowed by geochemical and mineralogical landing site selection	In situ sampling instruments (Camera for sample identification and geological context of samples, spectrometers for sample selection) including a sample acquisition mechanism to detect the chemical composition (O, Si, Ca, Fe, Mg, Al, Na, K..) including Ar isotopes.	10 to 12 Kg and 12 W. 100 Mbits/day during sampling.
Astronomy from the Moon	Astronomical observations of un-available frequency ranges from the Earth and Earth orbit	Requires farside or near-limb placement.	Observations of red-shifted 21-cm lines signatures in absorption during early universe informs us of the emergence of early luminous objects and the initial evolution of the IGM.	Radio observations; 25-100 MHz.	Requires farside placement sufficiently far from the nearside as to prevent detection of radio sources from the Earth. Only one farside site required.	Dipole antenna and receiver.	Up to 10 kg; average power usage of 6W; average data rate 1 kbps.
General Relativity and New Fundamental Physics	(1) Precise ranging to the lunar surface to measure the geodetic precession (de Sitter effect), perform tests of the Equivalence principle (strong and weak), place limits on the time variation of the gravitational constant (G) and deviations from the $1/r^2$ force law. 2) Test additional proposed gravity theories beyond General Relativity (e.g., brane-world theory by Dvali et al). 3) Detection of new aggregate states of matter (e.g., strange quark nuggets)	1) and 2) Extending current network of 3 Apollo and 1 Lunokhod sites, particularly at the limbs and at the poles, would improve the capabilities of gravitational theory tests. Further improvements will come from improved retro-reflector or laser transponder design (e.g. LSSO, LLRRA-21 developments). 3) Multiple, simultaneously operating sites about the Moon are required to interpret seismic events.	1) and 2) Alternatives to GR have been advanced which may explain apparent acceleration of the universe without Dark Energy. Precision ranging permits the most accurate determination of the PPN β parameter, equivalence principle, and $1/r^2$ deviation 3) The existence of strange quark nuggets is an important prediction which could also provide a candidate for Dark Matter.	1) and 2) Retro-reflectors with ranging accuracy of 0.1 mm (cannot be performed with current arrays). 3) Measure lunar seismic events using broad-band seismometry at no fewer than 5 geographically dispersed locations.	1) and 2) Reflector array oriented to provide direct Earth view, provides ranging opportunities for many years. 3) Detection of strange quark nuggets via epilinear seismic source identification requires at least 5 sites simultaneously operating for as many years as possible.	1) and 2) Ranging accuracy requirement for gravity theory tests is 0.1 mm. 3) Same as for Seismology requirements.	1) and 2) Same as for Precision Ranging for Lunar Geodesy. 3) Same as for Seismology.