Lunar Outgassing, Transient Phenomena and The Return to The Moon
III: Observational and Experimental Techniques

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ABSTRACT

In Paper I of this series, we show that transient lunar phenomena (TLPs) correlate with lunar outgassing, geographically, based on surface radon release episodes versus the visual record of telescopic observers (the later prone to major systematic biases of unspecified nature, which we were able to constrain in Paper I). In Paper II we calculate some of the basic predictions that this insight implies, in terms of outgassing/regolith interactions. In this paper we propose a path forward, in which current and forthcoming technology provide a more controlled and sensitive probe of lunar outgassing. Many of these techniques are currently being realized for the first time.

Given the optical transient/outgassing connection, progress can be made by Earth-based remote sensing, and we suggest several programs of imaging, spectroscopy and combinations thereof. However, as found in Paper II, many aspects of lunar outgassing seem likely to be covert in nature. TLPs betray some outgassing, but not all outgassing produces TLPs. Some outgassing may never appear at the surface, but remain trapped in the regolith.

As well as passive remote sensing, we also suggest more intrusive techniques, from radar mapping to in-situ probes. Understanding these volatiles seems promising in terms of their exploitation as a resource for human presence on the Moon and beyond, and offers an interesting scientific goal in its own right.

This paper reads, therefore, as a series of proposed techniques, some in practice, some which might be soon, and some requiring significant future investment (some of which may prove unwise pending results from predecessor investigations). These point towards enhancement of our knowledge of lunar outgassing, its relation to other lunar processes, and an increase in our understanding of how volatiles are involved in the evolution of the Moon. We are compelled to emphasize certain ground-based observations in time for the flight of *SELENE, LRO* and other robotic missions, and others before extensive

human exploration. We discuss how study of the lunar atmosphere in its pristine state is pertinent to understanding the role of anthropogenic volatiles, at times a significant confusing signal.

1. Introduction

Transient lunar phenomena are defined for the purposes of this investigation as localized (smaller than a few hundred km across), transient (up to a few hours duration, and probably longer than typical impact events - less than 1s to a few seconds), and presumably confined to processes near the lunar surface. How such events are manifest is summarized by Cameron (1972). In Paper I we study the systematic behavior (especially the spatial distribution) of TLP observations - particularly their significant correlations with tracers of lunar surface outgassing, and in Paper II some simple, theoretical predictions of other, not-so-obvious aspects that might be associated with TLPs and outgassing events. In this paper we suggest several ways that more information might be gleaned to determine the true nature of these events. At several points we emphasize the importance of timely implementation of these approaches.

TLPs are infrequent and short-lived, and this is the overwhelming fact of their study that must be surmounted. It is our goal to design a nested system of observations which overcomes the problems that this fact has produced, a largely anecdotal and bias-ridden data set, and replace it with another data set with *a priori* explicit, calculable selection effects. This might seem a daunting task, since the data set we used in Paper I was essentially the recorded visual observations of the entire human race since the invention of the telescope, and even somewhat before. With modern imaging and computer technology, however, we can overcome this.

Another problem that becomes clear in Paper II is the many, complex means by which outgassing can interact with the regolith. In the case of slow seepage, gases may take a long time to work their way through the regolith. If the gases are volcanic, there may be interactions along the way, and if water vapor is involved, it and perhaps others of these gases may remain trapped in the regolith. These factors must be remembered in designing our future investigations.

We can make significant headway, however. The various factors which complicate our task due to the paucity of information about TLPs also leave open avenues that modern technology can exploit. The many methods detailed in this paper are summarized in Table 1. There has been no areal-encompassing, digital image monitoring of the near side with

appreciable time coverage using modern software techniques to isolate transients. There are no published panspectral maps at high spectral/spatial resolution of the near side surface, beyond what is usually called multispectral imaging. (To some degree this will be achieved by the Moon Mineralogy Mapper onboard *Chandrayaan-1*, but not before other relevant missions such as *SELENE* have passed). There are numerous particle detection methods that are of use. The relevant experiments on Apollo were of limited duration, either of a week or less, or 5-8 years in the case of ALSEP. Furthermore the *Clementine* and *Lunar Prospector* missions were also of relatively short duration. All of these limitations serve as background to the following discussions.

2. Optical/Infrared Remote Sensing

2.1. Earth-Based Imaging

By necessity the monitoring of optical transients from the vicinity of Earth must be limited to the near side. As detailed in Paper I, however, all physical correlations tied to TLPs likewise strongly favor the near side e.g., ^{222}Rn outgassing (4 of 4 episodes being nearside, as well as nearly all ^{222}Rn residual (seen as ^{210}Po) and mare edges ($\sim$85% nearside, somewhat depending on one's definition, even more so if low-contrast albedo features such as Aitken basin are not included).

Remote sensing in the optical/IR is limited in spatial resolution either by the diffraction limit of the telescope or by atmospheric seeing. One arcsecond, a typical value for optical imaging seeing FWHM, corresponds to 1.8-2.0 km on the lunar surface, and is the diffraction limit of a 12 cm diameter telescope at $\lambda = 600$ nm.

The best, consistent imaging resolution will come from the *Hubble Space Telescope* with $0.07 - 0.1$ arcsec FWHM, and indeed images of the Moon have been obtained with the *HST*/Advanced Camera for Surveys combination (Garvin et al. 2005). *HST* observations of the Moon turn out to be relatively expensive in terms of spacecraft time due to setup time complicated by the relative motions of the target and spacecraft, and inefficiency due to exposure setup times of $\sim$80s for each exposure of typically 1s. Altogether $\sim$ 0.5-1 h of spacecraft time is needed to successfully image a small region in one filter band (due in part to several overlapping exposures needed for complete coverage avoiding masks and other obstructions on the HRC detector, as well as to reject cosmic ray signals). At least until the *Hubble* Servicing Mission 4, the guiding of *HST* and the state of ACS will allow no further such observations.

A competing method for producing high-resolution imaging is the "Lucky Exposures" (LE, also "Lucky Imaging") technique which exploits occasionally superlative imaging quality among a series of rapid exposures, then sums the best of these with a simple shift-and-add algorithm (Fried 1978, Tubbs 2003). The technique requires a high-speed, linear-response imager, and can be accomplished only with great difficulty using a more conventional astronomical CCD system. Nonetheless, many amateur setups have achieved excellent results with this technique, and the Cambridge group (Law, Mackay & Baldwin 2006) have achieved diffraction-limited imaging on a 2.5-meter telescope, very close to HST angular resolution. In practice, only about 1-10% of exposures, hence less than 1% of observing time, survive image quality selection, but for the Moon this amounts to a small investment of telescope time (a few minutes). We have attempted this ourselves and encountered some minor problems: image quality must be selected in terms of a fourier decomposition of the image rather than inspection of the point-spread function of a reference star, and shift-and-add parameters must be similarly defined, by image cross-correlation rather than by centroiding a bright star. We will present results from these efforts when they succeed more usefully.

Unlike adaptive optics approaches, LE does not depend on a bright reference star to define the incoming wavefront, but LE improvements are still limited to an angular area of the isoplanatic patch determined by atmospheric turbulence, $\sim$1000 arcsec^2. Covering the entire nearside Moon would be challenging ($\sim$3000 fields needed - at least 20 nights on a moderate-sized telescope). Likewise, the ACS HRC on HST, covering 750 arcsec^2 at a time, cannot be used practically to map the entire near side. The greater flexibility of an LE program, in terms of choice of epoch and wavelength coverage, provides many advantages; ACS HRC, on the other hand, would provide consistent-quality results, albeit at great expense.

High resolution imaging can be used to monitor small, specific areas over time, or in a one-shot application comparing a few exposures to imaging from another source. Currently, the best full-surface comparison map in the optical is the $Clementine$ UVVIS CCD map (Eliason et al. 1999), 5 bands at 415-1000 nm, with typically 200m resolution, a good match to LE and HST resolutions. Unfortunately, neither $Clementine$ UVVIS, or infrared cameras NIR (1100-2800 nm) or LWIR (8000-9500 nm) cover some of the more interesting bands for our purposes (for example, the regolith hydration bands at 2.9 and 3.4 μm). In the future, we will be able to make comparisons to the extensive map of the Moon Mineralogy Mapper (Pieters et al. 2005) on Chandrayaan-1, with 140 m and 20 nm FWHM spatial and wavelength resolution, respectively, over 0.4-3.0 μm.

The 3 μm-reflectance hydration features in asteroidal regolith have been studied (Lebofsky et al. 1981, Rivkin et al. 1995, 2002, Volquardsen et al. 2004). There is little

written about the spectroscopic reaction of lunar regolith to hydration; however, it is apparent that the reflectance features near 3 μm do not appear immediately in lunar samples subjected to the terrestrial atmosphere (Akhmanova et al. 1972), but do after several years (Markov et al. 1980, Pieters et al. 2006). At least in the latter, samples lose this hydration reflectance effect within a few days of exposure to a dry environment. This issue could easily be studied with further lunar sample experiments.

The prime technique for detecting changes between different epochs in similar images will involve image subtraction. This technique is well-established in studying supernovae, microlensing and variable stars, and produces photon Poisson noise-limited performance (Tomaney & Crotts 1996). This technique is well matched to CCD or CMOS detectors, and at 1-2 arcsec FWHM resolution, these can cover the whole Moon with 10-20 Mpixels, as is available for conventional detectors. For proper image subtraction, one needs at least 2 pixels per FWHM diameter, or else non-Poisson residuals tend to dominate, driving up the variable source detection threshold.

To illustrate how image subtraction would work, we present data of the kind that might be produced by a monitor to detect TLPs. While the image shown in Figure 1 is taken on a 0.9-meter telescope with 24 μm pixels, the data are similar to that would be produced by a smaller, 1-arcsec diffraction-limited telescope with typical commercially-available digital-camera pixels e.g., 6 μm on a 20-cm telescope.

Image subtraction delivers nearly photon-noise level accuracy in the residual images taken in a ground-based time series, and this is demonstrated in Figures 2-4. We introduce an artificial "TLP" signal that is a 8% enhancement over the background in the peak pixel of an unresolved source - a signal at or below the threshold of a visual search. The TLP is detected convincingly even in a single image, once subtracted from a reference image e.g., the average of a time series. The subtraction gives a very flat residual subtracted image (except for the simulated TLP and a few "cosmic rays" of much smaller area and amplitude). The only exception is in the complex image region of the highlands near the global terminator.

More meaningful, perhaps, is the signal-to-noise ratio of residual sources, shown in Figure 3. This shows the TLP clearly and unambiguously, but there are some false detections in the highland local terminator region at the level of 10-20% of the TLP; we would like to improve on this. One alternative to reduce this noise is to consider applying an edge filter to supply a weighting function to suppress regions where the image structure is too complex. Figure 3 shows the result from processing the raw image with a Roberts edge enhancement filter ($G_{j,k} = |F_{j,k} - F_{j+1,k+1}| + |F_{j,k+1} - F_{j+1,k}|$, where $F_{j,k}$ is the raw count in the pixel (j,k) and G is the function shown in Figure 3). When the signal difference from

Figure 2 is divided by Figure 3, the result (Figure 4) uniquely and clearly shows the TLP. We would like to avoid this edge filter strategy if possible, relying completely on simple image subtraction, since it may be that some TLPs are associated with local terminators on the lunar surface.

Our group has automated a TLP monitor on the summit of Cerro Tololo that should be producing regular lunar imaging data as of mid-2007 (Crotts, Hickson & Pfrommer 2007). This will cover the entire Moon at 1 arcsec resolution, and we expect to be able to process the images at a rate of one per 10s. This is sufficient to time-sample nearly all reported TLPs (see Paper I). In addition we plan to add a second imaging channel on a video loop; this will retain a continuous record of imaging of sufficient duration so that an alert to a TLP event from the image subtraction processing pipeline will allow one to query the image cache of the video channel record and reconstruct the event at finer time resolution. The image subtraction channel will include a neutral-density filter to allow the exposure time to nearly equal the image cycle time, hence even short TLPs (or meteorite impacts) will be detected, albeit at a sensitivity reduced by a factor roughly proportional to the square-root of the event duration.

The presence of a lunar imaging monitor opens many possibilities for TLP studies. For the first time, this will produce an extensive, objective, digital record of changes in the appearance of the Moon, at a sensitivity level much finer than the capability of the human eye. While we will see the true frequency of TLPs soon enough, Paper I indicates that perhaps one TLP per month might be visible to a human observer observing at full duty cycle. An automated system should be able to distinguish changes in contrast at the level of 1% or slightly better, whereas this is perhaps 10% for a point source observed by the human eye (based on our tests). Even augmented human-eye surveys (such as Project Moon Blink or the Corralitos Observatory TLP survey - see Paper I) would be at least several times less sensitive than a purely digital survey. The resulting frequency of TLP detections at higher sensitivity depends on the event luminosity distribution function, poorly defined even at brighter limits and completely unknown at the level that will now be accessible. It might be reasonable to assume that a single monitor might detect several TLPs per month of observing time. Over several years, monitors at a range of terrestrial longitudes might detect of order 100 or more TLPs, providing a well-characterized sample that will avoid many of the selection problems of the anecdotal visual data base and approach similar sample sizes.

Our plan eventually is to run two or more such monitors independently. Not only does this increase the likely TLP detection rate, but allows us to perform simultaneous imaging in different bands, or in different polarization states. Dollfus (2000) details TLPs evident as polarimetric anomalies. The timescales involved are not tightly constrained, between 6 min

and 1 d. Other transient polarimetric events (Dzhapiashvili & Ksanfomaliti 1962, Lipsky & Pospergelis 1966) are even less constrained temporally; however, the fact that we can observe the same event with two monitors simultaneously (while observing the rest of the Moon), means that there is little systematic doubt concerning the degree of polarization due to variability of the source while the apparatus is switching polarizations. Presumably, since these are likely due to simple scattering effects on linear polarization, we should align the E-vector of one monitor's polarizer parallel to the Sun-Moon direction on the sky, and the second perpendicular to it. In the case of three or four monitors operating simultaneously, we can reconstruct Stokes parameters for linear polarization conventionally by orienting polarizer E-vectors every 60° or 45°, respectively. The total flux from two or more monitors can be obtained by summing in quadrature signals from the different polarizations.

A TLP imaging monitor will also open new potential as an alert system for other observing modes. A monitor detection can trigger LE imaging in a specific active area. A qualitatively unique possibility is using the monitor to initiate spectroscopic observations, which much better than imaging will provide information about non-thermal processes and perhaps betray the gas associated with the TLP.

2.2. Ground-Based Spectroscopy/Hyperspectral Observations

TLP spectroscopy has its challenges. In order to detect a change, we must make comparisons over a time series of spectroscopic observations. This is essentially a four-dimensional independent-variable problem, therefore: two spatial dimensions of the lunar surface, plus wavelength implying a data cube, plus time. Whereas "hyperspectral" imaging usually refers to a resolving power $R = \lambda/\Delta\lambda \approx 50 - 100$, where $\Delta\lambda$ is the FWHM wavelength resolution, the emission lines from TLPs might conceivably be many times more narrow than this, thereby diluted if higher resolution is not employed. It is not currently conceivable to monitor the whole near side in this way (at ~ 1 Gpixel s^{-1} for $R = 1000$ and an exposure every 10s), but this is unnecessary. A practical approach may be to set up the reduction pipeline of the TLP monitor to alert to an event during its duration e.g., in under 1000s, and then to bring a larger telescope with an optical or IR spectrograph to bear on the target, which our experience shows might be accomplished in $\sim$300s. We are working to implement this in 2007.

There are reasons to prepare an $R \approx 300$ data cube in advance of a TLP campaign for reasons beyond simply having a "before" image of the Moon prior to an event. For instance, in the IR there are regolith hydration bands near 2.9 and 3.4 μm, the latter with substructure on the scale of $\sim$20 nm, which will be degraded unless the instrumental

resolution is $R \gtrsim 300$. While there are fewer narrow features in the optical/near-IR, the surface Fe^{2+} feature at 950 nm of pyroxene (which requires only $R \approx 10$ to be resolved), shows compositional shifts in wavelength centroid and width on the scale of $\sim$10 nm (Hazen, Bell & Mao 1978), which requires $R \approx 100$ to be studied in full detail. Likewise, differentiating pyroxenes from iron-bearing glass (Farr et al. 1980) requires $R \approx 50$. This Fe^{2+} band (and the corresponding band near $1.9\mu m$) are useful for lunar surface age-determination since they involve surface states that are degraded by micrometeorites and solar wind in agglutinate formation (Adams 1974, Charette et al. 1976). It appears that overturn of fresh material can also be monitored with enhanced blue optical broadband reflectivity (Buratti et al. 2000).

Such datasets are straightforward to collect, as are their reduction (although requiring of some explanation). Observations involve scanning across the face of the Moon with a long slit spectrograph, which greatly improves the contrast of an emission-line source relative to the background (Figure 5, showing recent data from the MDM Observatory 2.4-meter/CCD Spectrograph). Since the spectral reflectance function of the lunar surface is largely homogenized by impact mixing of the regolith, more than 99% of the light in such a spectrum can be simply "subtracted away" by imposing this average spectrum and looking for deviations from it (Figure 6). If a TLP radiates primarily in line emission, this factor along with our ability to reject photons outside the line profile yields a contrast as high as 10,000 times better than the human eye observing the Moon through a telescope. This could also be done farther into the infrared, for instance we are preparing to observe the L-band (2.9-4.3 μm) using SpeX on the NASA Infrared Telescope Facility in single-order mode, which can deliver $R \lesssim 2000$.

In general observations of this kind might be useful in the infrared for wider band emission, which is repeatable based primarily on temperature (versus ionizing excitation as in Paper II, Appendix 1). Using the HITRAN database to compute vibrational/rotational states for different molecules, one can see these starting in the infrared (or smaller wavenumbers for H_2O, NH_3, CO and CH_4), and extending into the optical for H_2O but at least to K-band for NH_3 (and intermediate bands for CO_2, CO and CH_4). At least for these molecules, the band patterns are strong and highly distinct.

To be clear, this latter idea requires having an IR spectrograph available at several minutes notice to follow up on an alert of a TLP (probably found in imaging). On a longer timescale, IR spectroscopy might also be useful for the L-band hydration test outlined above, especially on some of the narrower spectral features near 3.4 μm that imaging might overlook, even through narrow-band filters.

The data cube described above can be sliced in any wavelength to construct a map of

lunar features in narrow or broad bands. Figure 7 shows that specific surface features can be reconstructed in good detail and fidelity.

2.3. Imaging from High Orbit

Given the constraints on imaging from the vicinity of Earth, it is interesting to consider the limits and potentials of imaging monitors closer to the Moon. In general, we will not be proposing special-purpose missions in space-based remote sensing, and indeed will only mention dedicated missions related to in-situ exploration of areas affected by volatiles, where special-purpose investment seems unavoidable. With in-situ cases, we would perform a more extensive study, so will largely postpone these discussions to later work concentrating on close-range science. Here we propose experiments and detectors which might ride on other platforms, either preceding or in concert with human exploration, and which will accommodate the same orbits and other mission parameters which might be chosen for other purposes. Some of these purposes are not designated priorities for planned missions, but might prove useful and probably should be considered in the future. In some cases, we will give rough estimates of project costs based on our prior experience with similar spacecraft. These are for discussion only and would need to be re-estimated in detail to be taken with greater credibility.

An instance of such joint use: does exploration of the Moon imply establishment of a communications network with line-of-sight visibility from essentially all points on the lunar surface (excepting those within deep craters, etc.)? If so, these platforms might also serve as suitable locations for comprehensive imaging monitoring. A minimal example of such a network might have a tetrahedral configuration (with each point typically 60000 km above the surface) with a single platform at Earth-Moon Lagrange point L1, covering most of the nearside Moon, and three points in wide halo orbits around L2, each covering their respective portion of the far side plus a portion of the limb as seen from Earth. No single satellite will be capable of covering the entire far side, especially if operation of farside radio telescopes there require a policy of solely high-frequency communications e.g., via optical lasers. A single L2 satellite will cover at most 97% of the far side (subtending 176°.8, selenocentrically); full coverage (not to mention some communications system redundancy) will require three satellites, plus some means of covering the near side. With this configuration, the farthest points from each satellite will be typically 71° (in selenocentric angle), hence forshortened due to proximity to the limb by ~ 3 times. Extensive discussion is underway of using a facility at L1 to aid in transfer orbits throughout the solar system (Lo 2004, Ross 2006); in that case we should also consider placing an imaging monitor at L1.

An imaging monitor to improve significantly on Earth-vicinity capabilities might need to be an ambitious undertaking. For instance, to acheive 100m FWHM resolution at the sub-satellite point on the face of the Moon requires an imager of about 4 Gpixels, an aperture $\gtrsim 0.5$ m, and a field-of-view of 3°.3. Each such monitor, separate from power, downlink, attitude control and other infrastructure requirements will cost perhaps $100M. A stand-alone facility might cost several times more, at each of the several stations. Perhaps the system could be cut to a single farside monitor, in a narrow halo orbit extending beyond the Moon's Earth-shadow, plus some nearside monitoring, which together could still cover perhaps 95% of the lunar surface, albeit with some extreme limb foreshortening. We also need to ask ourselves at some point if the essential research and resource exploitation might be confined to the near side. This is an expensive undertaking, and one that must probably be combined with other reasons to establish platforms near L1 and L2. In the meantime, we should accomplish what is possible from the ground.

If the goal is to discover the source of volatiles for the sake of further scientific exploration or resource exploitation, however, an investment in remote sensing, in terms of spatial resolution (or spectral resolution to discover the substances involved, or temporal resolution to define the behavoir of the source) makes in-situ reconnaissance and exploration much less problematic. A human mission, or a sophisticated robotic mission, could conceivably cost $1B, and remote sensing could inform this effort as to where to look in detail, when dangerous eruptions might occur, and what is the material goal. Without such information, these investigation is likely to be more time-consuming, problematic, and perhaps more hazardous. We concentrate further on remote sensing, even if the proposed expense might be significant.

2.4. Surface and Subsurface Radar

As explained in Paper II, an expectation of water vapor seepage from the lunar interior should be an ice layer within the regolith about 15m below the lunar surface. A remote means of studying this feature would be ground-penetrating radar, either from the ground or spacecraft platforms.

One should realize that there is significant heritage and as well as plans involving lunar radar. The Lunar Sounder Experiment (LSE) on *Apollo 17* (Brown 1972, Porcello 1974) operated in both a high-frequency and penetrating radar mode (5, 16 and 260 MHz). Also planned are the Lunar Radar Sounder (LRE) aboard SELENE (Ono & Oya 2000: at 5 MHz (with an option at 1 MHz and 15 MHz), and Mini-RF on the Lunar Reconnaissance Orbiter, operating at 3 GHz and ~10 GHz. Finally, of note for comparison's sake in the

martian case is MARSIS ("Mars Advanced Radar for Subsurface and Ionosphere Sounding" at 1.8, 3.0, 4.0, and 5.0 MHz: Porcello et al. 2005).

At 5 MHz ($\lambda = 60$m) the depth of penetration is many kilometers below the lunar surface, but the spatial resolution is necessarily coarse. To study the regolith and shallow bedrock, we should choose a frequency closer to 100-300 MHz. The Apollo LSE operated for only a few orbits and only close to the equator. The SELENE LRE runs at lower frequency. A higher frequency mode is desirable.

The ground-based alternative is useful; lunar radar maps have been made at 40 MHz, 430 MHz, and 8 GHz (Thompson & Campbell 2005), also 2.3 GHz (Stacy 1993, Campbell et al. 2006a, b). At 8 GHz we are only studying structure of several centimeters within a meter of the surface. For 430 MHz we see perhaps ~ 10 m inside, and at 40 MHz, 100 m towards the interior (with attenuation lengths of roughly 10-30 wavelengths). In practice, better angular resolution at higher frequencies is possible e.g., 20 m (Campbell et al. 2006a, b). Of course from Earth only the nearside is accessible, and larger angles of incidence e.g., $\sim 60°$, imply echoes dominated by diffuse scattering in a way which cannot be modulated.

Use of circular polarization return measurements can be used to test for water ice (Nozette 1996, 2001) but have been questioned (Simpson 1998, Campbell et al. 2006). We will not review this debate here, but application of the idea to subsurface ice is problematic. It is unclear that this could be accomplished at frequencies of hundreds of MHz required to penetrate to depths of $\sim$15m, and the more standard technique (at 13 cm) only performs to depths $\lesssim$1m, where ice sublimation and diffusion rates are almost certainly prohibitive of accumulation.

Finding subsurface ice has its challenges. For instance, the dielectric constant $K \approx 3$ for both regolith and water ice (which is slightly higher), as it is for many relevant mineral powders of comparable specific gravity e.g., anorthosite and various basalts. Ice and these substances have similar attenuation lengths, as well. On the strength of net radar return signal alone, it will be difficult to distinguish ice from any usual regolith by their mineral properties. However, in terrestrial situations massive ice bodies reflect little internally e.g., Moorman, Robinson & Burgess (2003). One might expect ice-bearing regions to be relatively dark in radar images, if lunar ice-infused volumes homogenize or "anneal" in this way, either by forming a uniform slab or by binding together regolith into a single, uniform K bulk.

On the other hand, hydrated regolith samples have K values much higher than unhydrated ones (by up to an order of magnitude), as well as attenuation lengths even more than an order of magnitude shorter (Chung 1972). This hydration effect is largest at lower frequencies, even below 100 MHz. One might suspect that significant water ice

might perturb the chemistry of the regolith significantly, which might even increase charge mobility as in a solution, which appears to invariably drive up K, and conductivity even more, increasing the loss tangent: conductivity divided by K (and the frequency). One should expect a reflection passing into this high-K zone, but this depends strongly on the details of the suddenness of the transition interface.

Of particular interest is the radar map at 430 MHz (Ghent et al. 2004) of the Aristarchus region, site of roughly 50% of TLP and radon reports. The 43-km diameter crater is surrounded by a low radar-reflectivity zone some 150 km across, particularly in directions downhill from the Aristarchus plateau onto Oceanus Procellarum. In general the whole plateau is relatively dark in radar, occasionally interrupted by bright crater pock-marks and Vallis Schröteri. In contrast the dark radar halo centered on Aristarchus itself is uniquely smooth, indicating that it was probably formed or modified by the impact itself, a few hundred million years ago. This darkness might be interpreted as higher loss tangent, consistent with the discussion in the previous paragraphs, or simply fewer scatterers (Ghent et al. 2004) i.e., rocks of approximately meter size; it is undemonstrated why the latter would be true in the ejecta blanket of a massive impact especially given the bright radar halo within 70 km of the Aristarchus center. Ghent et al. (2005) show that other craters, some comparable in size to Aristarchus, have dark radar haloes, but none so extended. The region around Aristarchus has characteristics that might be expected from subsurface ice redistributed by impact melt: dark, smooth radar-return, spreading downhill but otherwise centered on the impact; this should be expected to be confused, at least, with the dark halo effect seen around some other impacts. It seems well-motivated to search for similar dark radar areas around other likely outgassing sites, particularly ones not associated with recent impacts; unfortunately, the foremost candidate for such a signature is competing with such an impact, Aristarchus, which can be expected to produce its own confusing effect.

We would propose that radar at frequencies near hundreds of MHz be considered for future missions, in a search for subsurface ice. This is a complex possibility that we will not detail here, that must be weighed against the potential of future ground-based programs. In particular, the near side has been mapped at about 1 km resolution for 70 cm wavelength (Campbell et al. 2007), this could be improved with an even more intensive ground-based program, or from lunar orbit. Orbital missions can be configured to combine with higher frequencies and different reception schemes to provide better spatial resolution, deal with ground clutter, and varying viewing angles. A lunar orbiter radar map would be less susceptible to interference speckle noise, which will likely require long series of pointings to be reduced from the ground. In combination with an optical monitor, a GHz-frequency radar might produce detailed maps in which changes due to TLPs might be sought, and

might be then correlated with few-hundred MHz maps to aid in interpretation in terms of volatiles.

At shorter wavelengths one should consider mapping possible changes in surface features due to explosive outgassing, which Paper II hints might occur frequently on scales excavated over tens of meters, and expelled over hundreds or thousands of meters. Again, earth-based observations suffer from speckle, but planned observations by the *Lunar Reconnaissance Orbiter (LRO)* Mini-RF (Mini Radio-Frequency Technology Demonstration - Chin et al. 2007) at 4 and 13 cm might easily make valuable observations of this kind. Both modes scan in a swath ∼5 km wide, which would make comprehensive mapping difficult, but would mesh well with the event resolution from a ground-based optical monitor. A "before" and "after" radar sequence meshed with an optical monitoring program would likely be instructive as to how outgassing and optical transients actually interact with the regolith.

2.5.   Monitoring from Low Lunar Orbit

2.5.1.   Planned Optical Imaging

Several upcoming missions will carry high-resolution optical imagers, each of which will be capable of mapping nearly the entire lunar surface e.g., *Chang'e-1* CCD imager (Yue et al. 2007), *SELENE* Spectrometer/Multiband Imager (LISM/MI) (Ohtake et al. 2007), *LRO* Camera (LROC) (Robinson et al. 2005), and *Chandrayaan-1* Moon Mineralogy Mapper (MMM) (Pieters et al. 2006), typically at tens to hundreds of meters resolution. In particular the MI/SP will usefully observe at 20m resolution the pyroxene near-IR band that can indicate the exposure of fresh surface, as can the MMM (albeit at 280m resolution). All of these are sensitive at blue wavelengths which can also indicate surface age. The LROC and MMM will repeatedly map each point on the Moon, not in any way sufficient to be considered realtime monitoring of transients, but sufficient to allow frequent sampling on timescales of a lunation. This allows an interesting synergy with ground-based monitors since they can highlight sites of activity for special analysis. Furthermore, LROC has a high resolution pointed mode which might provide sub-meter information in areas where TLPs have been recently detected, hence excellent sampling on the scales that we suspect will be permanently effected, perhaps in a "before" and "after" sequence. At any given time, any these four spacecraft have a roughly 10% chance of at least one of them being in view of a particular site above its horizon; it would be fascinating (but perhaps too logistically difficult) if a program could be implemented wherein spacecraft could be alerted to image at high resolution a TLP site in real time during an event.

2.5.2. Alpha-Particle Spectrometry

In order to study outgassing directly, we need instruments at or near the lunar surface. In the case of ^{222}Rn, the thermal velocity is typically $v \approx 150$ m s^{-1}, so typical ballistic free flight occurs over $d = v^2/g = 7$ km. Over its half-life of 3.8 d, a ^{222}Rn atom travels typically 50000 km in a random walk that wanders from the source only a few hundred km before decaying (or sticking to a cold surface). Thus the alpha particles must be detected in much less than a day after outgassing, or the ^{222}Rn signal disperses by an amount that makes superfluous placing the detector less than a few hundred km above the lunar surface, except for r^{-2} sensitivity considerations.

Three alpha-particle spectrometers have observed the surface of the Moon, but for relatively brief periods of time. The latitude coverage was severely limited on *Apollo 15* (| *Lat* |$\lesssim$ 26° for 145 hours) and *Apollo 16* (| *Lat* |$\lesssim$ 5°, 128 h). *Lunar Prospector's* Alpha Particle Spectrometer covered the entire Moon, over 229 days spanning 16 months, but was partially damaged (one of five detectors) upon launch and suffered a sensitivity drop due solar activity (Binder 1998). *Apollo 15* observed two outgassing events (from Aristarchus and Grimaldi), *Apollo 16* none, and *Lunar Prospector* two sources (Aristarchus and Kepler), although the signals from these last sources were integrated over the mission duration. In addition, Apollo and *Lunar Prospector* instruments detected an enhancement at mare/highlands boundaries from daughter product ^{210}Po, indicating ^{222}Rn leakage over approximately the previous century.

The expected detection rate for a single alpha-particle spectrometer in a polar orbit and without instantaneous sensitivity problems, might be grossly estimated from these data. The *Apollo 16* instrument covered a sufficiently small fraction ($\sim 12\%$) of the lunar surface so that we will not consider it, whereas *Apollo 15* covered about 37%. These missions were in orbit $\sim$6 d apiece, and considering the ^{222}Rn lifetime thereby were sensitive to events (at >10% full sensitivity) for $\sim$ 18 d. *Lunar Prospector* covered the entire lunar surface every 14 d, hence caught events typically at 28% instantaneous full strength (minimum 8%), however, by averaging over the mission diluted this by an factor $\sim$20-30. These data are consistent with a picture in which Aristarchus produces an outgassing event 1-2 times per month at the level detectable by *Apollo 15*, and by *Lunar Prospector* when integrated over the mission. Apparently other sites such as Grimaldi and Kepler collectively are about equally active as Aristarchus, together all sites might produce 2-4 events per month at the sensitivity level of *Apollo 15*. This level of activity is consistent with the statistics of TLPs constrained in Paper I.

A new orbiting alpha-particle spectrometer with a lifetime of a year or more and an instantaneous sensitivity equal to that of *Apollo 15*'s detector would likely produce a

relatively detailed map of where outgassing occurs on the lunar surface, separate from any optical manifestation. This is likely an important test for many of the procedures mentioned above, which are critically dependent on the outgassing/optical correlation. This must be examined in further detail, because there are many ways in which one might imagine that gas issues from the interior, thereby producing radon, without a visible manifestation, either due on one extreme to such rapid outgassing that previous events have cleared the area of regolith that might interact with gas on its way to the vacuum, or due to seepage sufficiently slow to trap water (and perhaps other gasses by reaction) in the regolith, and too slow to perturb dust at the surface. Radon, an inert gas that will not freeze or react on its way to the surface, is more likely to escape the regolith to be detected, regardless.

The Alpha-ray Detector (ARD) onboard *SELENE* (Nishimura et al. 2006) promises to be ~ 25 times more sensitive than the Apollo Alpha Particle Spectrometers, with a mission lifetime of one year or more, in a polar orbit. This, in conjunction with an aggressive optical monitoring program (as in Section 2.1), holds the prospect of extending the TLP/^{222}Rn-outgassing correlation test from Paper I to a dataset of order 10 times larger. This would likely serve as a significant advance in understanding their connection, but it is probably best to consider what a following generation alpha-particle spectrometer study might entail.

To insure better sensitivity coverage two such detectors in complementary orbits would cover the lunar surface every 1.8 half-lives of ^{222}Rn. This may nearly double the detected sample. Unless the alpha-particle detectors are constructed with a veto for solar wind particles, it is best to avoid active solar intervals. We will exit the solar minimum probably by year 2008, with the next starting by about 2016. On the other hand, some of the lack of sensitivity to lunar alpha particles and elevated solar particle background count on *Lunar Prospector* was due in part to it being spin-stabilized. If detectors on a future mission were kept oriented towards the lunar surface and shielded from solar wind to the extent possible, the Apollo results indicate that prompt ^{222}Rn outburst detection at good sensitivity is possible. Beyond this, extending the mission(s), of course, will help, and the best approach might be to develop a small alpha-spectrometer package that might easily fly on any extended low-orbital mission.

2.5.3. On-Orbit Mass Spectrometry

The radioactive decay delay in alpha-particle detection insures that a reasonable number of orbiting detectors can have near unit efficiency. This is not the case for prompt detection of outgassing e.g., by mass spectrometers. An instantaneous outburst seen 100 km

away will undergo a dispersion of only a few tens of seconds in arrival time. The detectors must either be very sensitive or densely spaced, and prepared to measure and analyze what they can in these short time intervals. This is a problem for Apollo-era instruments e.g., the *Apollo 15* Orbital Mass Spectrometer Experiment (OMSE - Hoffman & Hodges 1972) required 62s to scan through a factor of 2.3 in mass (12 to 28, or 28 to 66 AMU).

Total amount of outgassing is in the range of many tons per year, and with perhaps tens of outbursts per year, the mass fluence of particles from a single outburst seen at a distance of 1000 km is approaching 10^{12} cm^{-2} AMU. While a burst on the opposite side of the Moon will not be detected and/or properly interpreted, one that can be seen by a few detectors would be very well constrained.

The specific operational strategies of these detectors is paramount. For example consider an event at 1000 km distance, which will spread over ~ 500s in event duration. A simple gas pressure gauge will not be overwhelmingly sensitive, in that even with an ambient atmosphere that is not unusual e.g., number density $n \approx 10^4 - 10^5$ cm^{-3} (varying day/night e.g., Hodges, Hoffman & Johnson 2000), the background rate of collisions over 500 s amounts to an order of magnitude or more than the particle fluence than for a typical outgassing outburst, assuming ~ 20 AMU particles in the outburst. Since interplanetary solar proton densities can change by amount of order unity in an hour or less (e.g., McGuire 2006), pressure alone is not likely to be a useful event tracer.

A true mass spectrometer is useful in part by subdividing the incoming flux, in mass, obviously, but also in direction, thus decreasing the effective background rate. The disadvantage of this approach in the past has been that it cannot cover the entire parameter range of this subdivision at once, so must scan in atomic mass or direction, or must always accept a significantly limited range. For a short burst, this means that mass components may not be examined during the event, or that events might be missed due to detectors pointing in the wrong direction. For Apollo-era detectors, these problems, particularly the former, were significant. We would prefer to operate a mass spectrometer operating continuously over a significant mass range, with ballistic trajectory reconstruction over a large incoming acceptance solid angle. We will return to this concept below.

First, let us discuss low-orbit platforms. We will not propose special purpose probes of the atmosphere alone, but there are other reasons for dense constellations of lunar satellites, most prominently a lunar global positioning system (GPS). Terrestrial systems in operation (GPS) and planned (Galileo, Beidou and GLONASS: GLObal NAvigation Satellite System) are typically 25-30 satellites at orbital radii $\sim$25000 km. Around the Moon this could be much lower, ~ 8000 km, and with fewer satellites, $\sim$12, which would put satellites within $\sim$7000 km of a surface outburst. This is compared to ~ 100 km for Apollo. Scaling the

sensitivity of the *Apollo 15* OMSE (Hodges et al. 1973), a detector on a GPS would be sensitive (at the 5σ level) to an instantaneous outburst of about 50000 kg (and more depending on the details of non-r^{-2} propagation effects). This is insufficient sensitivity to detect outgassing events. One needs a lower orbit (or much more sensitive detectors, by three orders of magnitude).

It is unclear if a lower-orbit GPS system, while more favorable for an add-on mass spectrometer array, would serve its navagational purpose. A GPS/mass spectrometer constellation only 1000 km above the lunar surface could likely be made sufficiently sensitive for gas outburst monitoring, nearly continuously. Such a low orbit makes GPS more difficult, require several more satellites, and increasing the effects of mascons on their orbit. This requires further modelling.

Nonetheless, we should consider other science instrumentation on a lunar GPS. High-resolution imaging from ~ 8000 km radius could be $10\times$ finer (~ 10 m) than platforms at L1 or near L2. Covering the Moon at this resolution would require $\sim 10^{12}$ pixels, which might allow mapping occasionally, but only crude monitoring temporally. Still, if one-third of lunar GPS platforms were equipped with a prompt, high-resolution imager, any portion of the lunar surface could be imaged during the course of a surface event. If an event is observed from the ground or from L1/L2, it could be detailed at 10 m or even higher resolution. This imager network should establish an atlas of global maps (at various illumination conditions) to serve as a "before" image in this comparison (as well as allowing a wealth of other studies). By allowing transient events to be studied at $\lesssim 10$ m resolution, this sets the stage for activity to be isolated at a sufficiently fine scale for in-situ investigations that would thereby be targetted and efficient in localization.

Returning to mass spectrometry, it is clear that there are two separate modes for gas propagation above the lunar surface, neutral and ionized, and that a significant amounts are seen in both (Vondrak, Freeman & Lindeman 1974, Hodges et al. 1972), at a rate of one to hundreds of tonne y^{-1} for each process. There is some possibility that a large portion of the ionized fraction might be molecular in nature (Vondrak et al. 1974).

For neutral atoms more massive than H or He, their thermal escape lifetime is sufficiently long that they have ample time to migrate across the lunar surface until they stick in a shadowed cold-trap. Furthermore, the ionized component will predominently follow the electric field embedded in the solar wind, which tends to be oriented perpendicular to the Sun-Moon vector and hence frequently pointing from the sunrise terminator into space. For these two reasons the best location to monitor outgassing is a point above the sunrise terminator, presumably on a low-orbit platform. Note that there is some degeneracy between the timing information recorded by a particle detector on such a satellite between

the episodic behavior of particle outgassing versus the motion of the spacecraft at ~ 1.6 km s^{-1}. The ideal situation would be to triangulate such signals with more than one platform. Such an experiment is not trivial, but there are alternatives, explored below.

For a low lunar orbit to be "low maintenance" i.e., require few corrections due to mascon perturbations, it should be at one of several special "frozen orbit" inclination angles $i = 27°$, $50°$, $76°$ or $86°$ (e.g., Ramanan & Adimurthy 2005). However, we want to maintain a position over the terminator, using a sun-synchronous orbit, which requires a precession rate $\omega_p = 0.99°d^{-1} = 2 \times 10^{-7}$ rad s^{-1}. Natural precession due to lunar oblateness is determined by the gravitational coefficient $J_2 = (2.034 \pm 0.001) \times 10^{-4}$ (Konopliv et al. 1998) according to $\omega_p = -(3a^2 J_2 \omega cos\ i)/(2r^2) = -(3a^2 J_2 sqrtGM cos\ i)/(2r^{7/2})$, where a is the lunar radius, ω the orbital angular speed, M the lunar mass and r the orbital radius. (The precession caused by Earth is 1000 times smaller, and 60000 times smaller for the Sun.) One cannot effectively institute both conditions, however, since the maximum inclination orbit with $\omega_p = 2 \times 10^{-7}$ s^{-1} occurs at $47°$ (or else the orbit is below the surface). While an orbit at $i = 27°$ is stable (at $r = 1876$ km, 138 km above the surface) and has the correct precession rate, it spends most of its time away from the terminator.

In contrast, at $i = 87°$, $\omega_p = 1.5 \times 10^{-8}$ s^{-1}, and the spacecraft needs to accelerate continuously only $a = 0.3$ mm s^{-2} to place it into sun-synchronous precession. This is nearly the same as the thrust provided by the Hall-effect ion engine on *SMART-1* (and corresponds to an area per mass of 330 cm^2 g^{-1} under the influence of solar radiation pressure.) While it is not apparent that an ion engine would be the best choice for a platform with mass and ion spectrometers, this illustrates the small amount of impulse need to maintain this favorable orbit, comparable to station-keeping in many non-frozen orbits. In truth, the most efficient location to apply this acceleration is only near the poles, so a slightly more powerful thruster might be needed. Since, time-averaged, this perturbed orbit still lands in a frozen-orbit zone, it should still be relatively stable in terms of radius. We would propose that a instrumented platform in this driven, sun-synchronous polar orbit would be ideal for studying outgassing signals near the terminators.

There is an interesting synergy between this outgassing monitor platform and another useful investigation from a similar satellite(s), although not necessarily simultaneously. An outstanding problem is gravitational potential structure of the Moon, particularly the far side (where satellite orbits cannot be monitored from Earth). With the inclusion of the the 562-day *Lunar Prospector* data set (Konopliv et al. 2001) the error is typically 80 milligals on the far side (corresponding to surface height errors of about 25 m) versus 10 milligals in the near-side potential. Also the limiting harmonic is of order 110 approximately on the near side, and only order 60 on the far side (≈ 200 km resolution).

In contrast, the GRACE (Gravity Recovery and Climate Experiment) can define the geodesy of Earth at much better field and spatial resolution, a few milligals at about order 200 (Tapley et al. 2005 - one year of data), using a double satellite at $\sim$500 km above the Earth in polar orbit, with the separation ($\sim$200 km) between the two components carefully monitored (by laser interferometer for the proposed GRACE follow-on mission - Watkins et al. 2006, or in the microwave K-band for GRACE itself). Such a satellite pair in lunar orbit would improve our knowledge of the farside field by orders of magnitude, determined independent of Earth-based tracking measurements, and in general make the accuracy and detail of lunar potential mapping much closer in quality to mineralogical mapping already in hand. One interesting question this might address is whether mascons extend to much smaller scales than currently known. While this mapping is underway, one could use outgassing monitors on board to look for outbursts, and when the geodetic mission is complete, drive the satellites into a polar, sun-synchronous orbit above the terminator. Depending on the type of monitors imployed, forcing sun-synchronous precession by chemical, ion or even solar-sail propulsion may or may not interfere; neutral-gas spectrometers may be compatible with ion drives while charged species trajectories might be perturbed, for instance.

Maintaining $a = 0.3$ mm s^{-1} for a 100 kg spacecraft requires 20 kg month^{-1} of chemical propellant (exhaust velocity of 4000 m s^{-1}) versus 2.5 kg month^{-1} of ion propellant (30000 m s^{-1}). For a 100 kg spacecraft a solar sail about 30m in radius would be required. None of these solutions are so easy that they do not inspire a search for alternatives, and their non-gravitational acceleration would mean that they could take place only after (or before) any geodesic mission phase. Furthermore, ion propulsion and probably chemical propulsion would tend to interfere with mass spectrometry. These should be traded against other possibilites e.g., several small probes on various orbital planes at $i = 87°$, rather than one or two sun-synchronous platforms.

The fact that there would be an outgassing detectors on each platform would make temporal/spatial location of specific outbursts more unambiguous, aided by differences in timing and signal strength at the two moving platforms, at least for neutral species. The timing difference will give an indication of the distance difference to the sources, with the source confined to the hyperboloid $x^2/a^2 - y^2/(e^2 - a^2) = 1$ where x is the distance along the line connecting the two satellites, with the origin at the half-way point between them, and y is the distance perpendicular to this line. The distance between the two satellites is given by $2e$ and the difference in distance between the source and the first satellite versus the source and the second is $2a$. There is still a left/right ambiguity in event location to be resolved by detector directionality, and better directional sensitivity would add a helpful overconstraint on the measurement.

3. In-Situ and Near Surface Exploration

Our research group[1] is developing ways to efficiently transfer the insight gained from a program of remote sensing to a program of in-situ research involving the lunar surface. I would like to emphasize a few key points already becoming apparent.

The neutral fraction from lunar outgassing need not respect the correlation with lunar sunrise; a detector giving enough prompt information about outgassing might be invaluable. Neutral gas emitted on the day side is free to bounce ballistically until either sticking to a cold surface or escaping (either due to ionization or by reaching the high-velocity maxwellian tail). A highly desirable monitor of this activity would be a mass spectrometer capable of simultaneously accepting particles in a wide range of masses e.g., $\sim 10 - 100$ a.m.u., and reconstructing incoming particle trajectories and velocities to allow the locus of outgassing to be reconstructed (at least within hundreds or thousands of km).

In addition to tracking the sunrise terminator outgassing signal, such a mass spectrometer would be able to monitor wide areas of the Moon for prompt neutral outburst signals from point sources, and therefore the instrument should be placed in the vicinity of known outgassing sites to establish which species succeed in propagating to the regolith surface. The suggested ground-based approaches provides this rough localization, buttressed by the low-orbital outgassing detectors.

At some point the identification of a good tracer gas to act as a proxy for endogenous emission would be highly valuable in simplification of outgassing alert monitors not required to scan entire mass ranges. Now it is unclear what that gas should be. It is true that ^{222}Rn seems to be highly correlated with optical transients, but the relationship between radiogenic gas emission and that of volcanic emission is uncertain. Besides, while usefully radioactive, radon is a very minor constituent. Radiogenic ^{40}Ar is more abundant, and episodic, but its relation to volcanic gas is uncertain (as is its correlation to optical transients). The most reliable observed molecular atmospheric component is CH_4, but it is likely to derive in large part from cometary/meteoritic impacts and is somewhat unnatural to expect from the oxygen-rich interior. Water suffers from the situation described in Paper II in which a large fraction of any large, endogenous source might never propagate gas to the surface, making it an unreliable tracer. Even while endogenous water of nearly certain volcanic origin has been found in glasses likely derived for the deep interior (Saal et al. 2007), CO_2 is absent. The limits on CO are more unclear, as are those for oxides of nitrogen. The first mass spectrometer probes should be designed to clarify this situation.

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[1]AEOLUS: "Atmosphere seen from Earth, Orbit and the LUnar Surface" - see Crotts et al. 2007

To place these monitors on the surface, one may exploit human exploration sorties, which will be relatively infrequent and potentially concentrated in sites of just a very few bases. I reiterate that another concern is the contamination that each of the missions will produce, concentrated primarily near the landing site itself. It is evident that by the deployment of LACE on the final Apollo landing that the outgassing environment was contaminated by a large contribution of anthropogenic gas, and that these vehicles in a new epoch of human exploration will deliver many tens of tons per mission of gases to the lunar surface of composition relevent to species suspected from a potential endogenous volcanic component, a level of contamination comparable to the potential annual output of such gases from endogenous sources.

The Constellation spacecraft consist of Orion, carrying about 10 tonne of N_2O_4 (nitrogen teroxide) and $CH_3N_2H_3$ (monomethyl hydrazine) propellant, and LSAM, propelled by liquid oxygen and nitrogen. The Orion fuel mix produces N_2, CO_2 and H_2O and the LSAM exhausts water. Depending on the orientations and trajectories of the spacecraft when thrusting they will deposit about 20 tonnes of mostly water to the surface, where most will remain for days (up to about one lunation). During the course of the Return to The Moon, measurements of at least these three product molecules will be suspect, since in fact their signal will disappear completely over successive lunations.

In many respects the surface layer of regolith should be considered as a planet-sized sorption pump coupling the atmosphere, across which gases are free to propagate (and exit the system if they are ionized or low-mass), and the lower regolith, which is cold ($\sim 250K$) and relatively impermeable. Gas in the atmosphere can be delivered to the surface where, if it penetrates a few cm, enters a region in which particle mobility slows considerably and where it essentially becomes entrained in the time-averaged signal of endogenous gas (radiogenic or volcanic) that is leaking from greater depth. (Indeed, since the temperature increases inwards, gas reaching this colder zone preferential migrates to greater depths.) Furthermore, once gas from the interior reaches the outer few cm of regolith subject to large temperature swings, it is likely to escape into the vacuum.

There is a scientific premium, therefore, to delivering surface monitors to their site without delivery of many tons of anthropogenic gas, annd for this purpose one might consider small, parasitic landing rockets that deliver an experiment package from the Orion or LSAM human exploration vehicles to the vicinity of the surface, but transition to a low-contamination soft lander system such as an airbag. This is an established, low-cost technology with extensive heritage (from the Ranger Block 2 lunar probes to the highly successful Mars Exploration Rovers) and might easily be the landing technique of choice for small lunar surface packages. On small ($\lesssim$ tens of km) scales, robotic rovers are less prone to sowing contamination when delivering detector packages across the surface.

When human exploration turns towards study of lunar outgassing sites the primary challenge may be converting the lower spatial resolution information obtained at Earth or lunar orbit into meter or 10-meter scale intelligence regarding where to initiate in-situ exploration. The transitional technologies to bridge this gap consist of local networks of sensors that map area on the scale of a 1 km or 100 m to resolutions of 1-10 m using various techniques: local ground-penetrating radar, local seismic arrays, directional and ground-sniffing mass-spectrometers that work to localize, and another technique we propose to investigate: intensive laser grids that densely populate the space above the patch of surface in question with lines of sight sampling strong transitions of some predominant species e.g., an infrared vibrational/rotational transition if molecules are discovered in quantity.

The details of the ideas promulgated in this section are beyond the scope of the current paper and will be presented in a larger document currently in preparation.

If the reader will allow a personal statement, I am not easily swayed into writing research papers based on data of the uncertain quality of those seen in Papers I and II, but this is the nature of the field. It has been the purpose of this investigation not only to clarify the implications of existing data, which I think it has done, but also to understand the range of interesting possibilities of phenomena consistent with these data and ask how we should proceed to investigate them, cognizant that many of our actions have implications in terms of disturbing the environment that we care to assay. We need to access which interesting questions need to be addressed, given the state of our ignorance, and consider how to proceed. I hope and intend that these works have advanced the discussion significantly.

4. Discussion and Conclusions

The phenomena that we have been studying are subtle, and many important aspects may be highly covert. The above-surface signals of outgassing of radiogenic endogenous sources is fairly clear, but gas of more magmatic origin, while possibly present, needs further study to be absolutely confirmed. Activity associated with Apollo landings easily dominated with anthropogenic gas production the activity in molecular species that might trace residual lunar magnatism. Apollo-era and later data were insufficiently sensitive to establish the level of outgassing beyond ^{222}Rn, ^{20}Ne and isotopes of Ar, plus He, presumably, but did detect molecular gas, particularly CH_4, but of uncertain origin. It is important to assess how we can advance the Apollo-era understanding. Consistent with these molecular gas outflows, and perhaps traced by optical transients, there is a range of possible phenomena that have interesting possible scientific consequences and might easily

be useful in terms of resource exploitation for human exploration. While this amount of volatile production is inconsequential on the scale of the geology of the Moon as a whole, and is poorly constrained by any measurement of current or previous volatiles, even in returned surface samples, it is still capable of massively altering the environment locally in ways which should be investigated in a timely way. We could learn a great deal from the current production of volatiles and their accumulation over geologic timescales in an extraterrestrial environment so easily explored.

The salient facts from the above treatment is that for many years yet monitoring for optical transients will still be best done from the Earth's surface, even considering the important contributions that will be made by lunar spacecraft probes in the next several years. These spacecraft will be very useful in evaluating the nature of transient events in synergy with ground-based monitoring, however. Given the likely behavior of outgassing events, it is unclear that in-situ efforts alone will necessarily isolate their sources within significant winnowing of the field by remote sensing. Early placement of capable mass spactrometers of the lunar surface, however, might prove very useful in refining our knowledge of outgassing composition, in particular a dominant component that could be used as a tracer to monitor outgassing activity with more simple detectors. This must take place before significant pollution by large spacecraft, which will produce many candidate tracer gasses in their exhaust.

We do not know enough now to discuss the potential implications of this line of research in terms of resources for human exploration, or even in terms of prebiologic chemistry on the Moon and for tenuous endogenous outgassing and atmospheric interactions with the regolith on other bodies, but all of these are interesting, new avenues of such research. It is crucial that exploration of these issues progress while we have a pristine lunar surface as our laboratory.

5. Acknowledgements

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Table 1: Summary of Basic Experimental/Observational Techniques Detailed Here

All methods are Earth-based remote sensing unless specified otherwise.

Goal	Detection Method	Channel	Advantages	Difficulties
Map of TLP activity	Imaging monitor, entire nearside, ~2 km resol.	optical	schedulability comprehensive; more sensitive than human eye	nearside only, limited resol.
Polarimetric study of dust	Compare reflectivity in two monitors with perpendicular polarizers	optical	easy to schedule; further limits dust behavior	requires use two monitors
Changes in small, active areas	Adaptive optic imaging, ~100 m resolution	0.95 micron, etc.	"on demand" given good conditions	undemonstrated, depends on seeing; covers ~50 km dia. max
	"Lucky Imaging," ~200 m resolution	0.95 micron, etc.	on demand given good conditions	low duty cycle, depends on seeing
	Hubble Space Telescope, ~100 m resolution	0.95 micron, etc.	on demand given advance notice	currently unavailable; low efficiency
	Clementine/LRO/ Chandrayaan-1 imaging, ~100 m resolution	0.95 micron, etc.	existing or planned survey	limited epochs; low flexibility
	SELENE/Chang'e-1 imaging, higher resol.	0.95 micron, etc.	existing or planned survey	limited epochs; low flexibility

TLP spectrum	Scanning spectrometer map, then spectra taken during TLP event	NIR, optical	may be best method to find composition & TLP mechanism	requires alert from TLP image monitor; limit to long events
Regolith hydration measurement	NIR hydration bands seen before/after TLP in NIR imaging	2.9,3.4 micron	directly probe regolith/water chemistry; detect water	requires alert from monitor, flexible scheduling
	Scanning spectrometer map, then spectra taken soon after TLP	2.9,3.4 micron	directly probe regolith/water chemistry; detect water	requires alert from monitor, flexible scheduling
Relationship between TLPs & outgassing	Simultaneous monitoring for optical TLPs and by SELENE for Rn-222 alpha particles	Rn-222 alpha & optical	refute/confirm TLP/outgassing correlation; find gas loci	optical monitor only covers nearside; more monitors better
Subsurface water ice	Penetrating radar	~430MHz	directly find subsurface ice with existing technique	ice signal is easily confused with others
	Penetrating radar from lunar orbit	~300MHz	better resol.; can study sites of lower activity	ice signal is easily confused with others; more expensive
	Surface radar from lunar orbit	> 1GHz	better resol.; study TLP site surface change	redundant with high resol. imaging?
High resol. TLP activity map	Imagers at/near L1, L2 covering entire Moon, at 100 m resolution	optical	map TLPs with greater resol. & sensitivity, entire Moon	expensive, but could piggyback communications network

| Comprehensive Rn-222 alpha particle map | Two Rn-222 alpha detectors in polar orbits 90 degrees apart | Rn-222 alpha | map outgassing events at full sensitivity | expensive; even better response w/ 4 detectors |
| Comprehensive map of outgas components | Two mass spectrometers adjacent polar orbits | ions & neutral | map outgassing events & find composition | expensive; even better w/ more spectrometers |

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In situ, surface experiments: we refer the reader to work in preparation by
AEOLUS collaboration.


Abbreviations used:
dia. = diameter, max = maximum, NIR = near infrared, resol. = resolution

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6. FIGURES

FIGURES 5 AND 6 ARE LARGE FILES AND INCLUDED AS CAPTIONS ONLY (see http://www.astro.columbia.edu/ arlin/TLP/ for full Figures 5 and 6.)

FIGURE 5 - a) Left: spectrum of an 8-arcmin slit intersecting Aristarchus (bright streak just above center) and extending over Oceanus Procellarum, and covering wavelengths 5500-10500Å, taken by the MDM 2.4-meter telescope; **b)** Right: the residual spectrum once a model consisting of the outer product the one-dimensional average spectrum from Figure 3a times the one-dimensional albedo profile from Figure 3a. The different spectral reflectance of material around Aristarchus is apparent (at a level of about 7% of the initial signal), with r.m.s. deviations of about 0.5%, dominated by interference fringing in the reddest portion, which can be reduced.

FIGURE 6 - a) Left: a B-band image of the region around Aristarchus; b) Right: an image of Aristarchus in a 3Å-wide centered near 6000Å, constructed by taking a vertical slice through Figure 3a and other exposures from the same sequence of spectra scanning the surface. Any such band between 5500Å and 10500Å can be constructed in the same manner, with resolution of about 1km and 3Å.
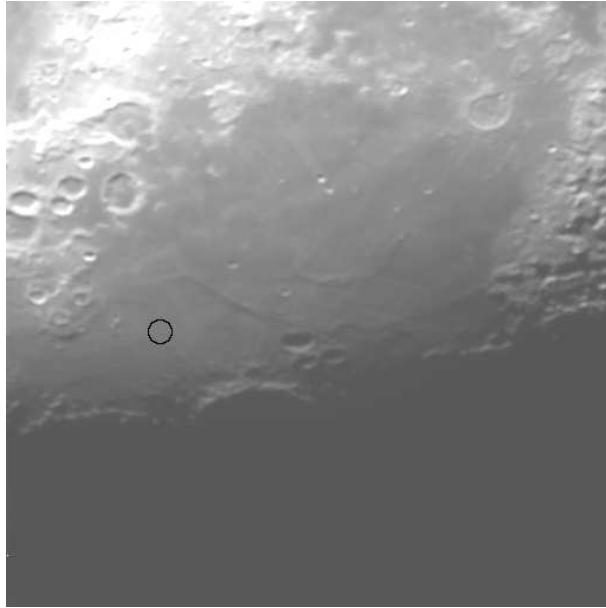
Fig. 1.— Raw image of a lunar surface subimage typical of what we expect to achieve with our CCD/telescope combination. A synthetic signal, corresponding to a TLP below the visual threshold, has been added at the position marked by the black circle.
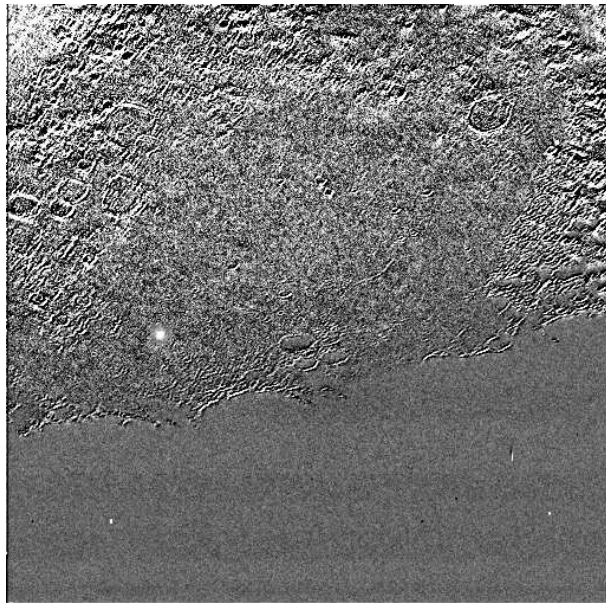

Fig. 2.— The difference in signal between the image in Figure 2 and similar one obtained five minutes later. The noise in the residual signal is at or near the photon limit. Only the TLP, a few small cosmic rays, and some low-level poor subtraction residuals in the most complex portion of the image (highland near global terminator) remain.
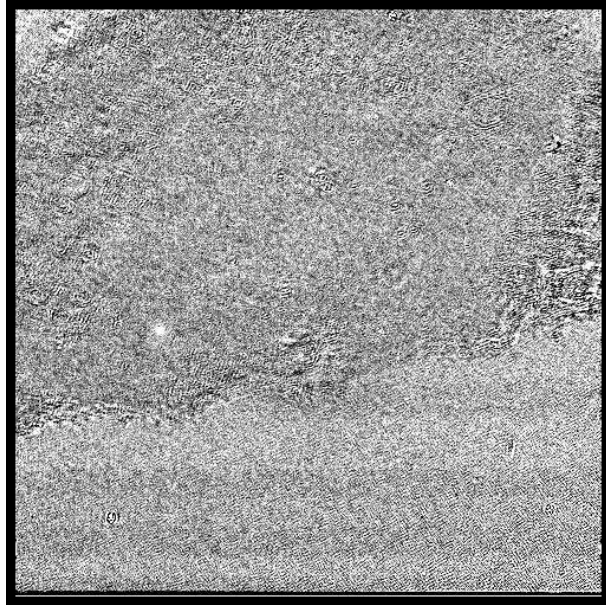
Fig. 3.— A "signal-to-noise plot" of residual signal seen in Figure 2 divided by the square root of the number of photoelectrons from the signal seen in Figure 1. Note that the "TLP" stands out above all other signals.
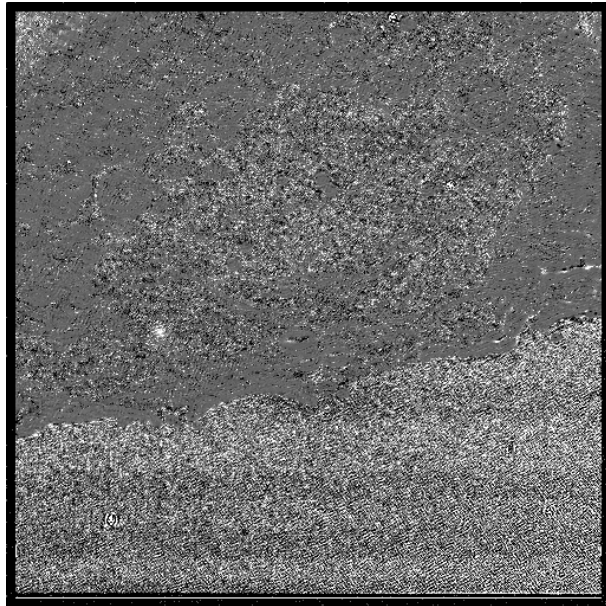

Fig. 4.— The result from applying a Roberts edge-enhancement filter to Figure 1's signal then dividing this into the data from Figure 2.