A Deep Field Infrared Observatory Near the Lunar Pole

Phase I FINAL REPORT

SUMMARY

A study has been made of the feasibility and scientific potential of a 20 – 100 m aperture astronomical telescope at the lunar pole, with its primary mirror made of spinning liquid at < 100K. Such a telescope, equipped with imaging and multiplexed spectroscopic instruments for a deep infrared survey, would be revolutionary in its power to study the distant universe, including the formation of the first stars and their assembly into galaxies.

Our study, made as a collaboration of investigators in Arizona, Texas and Canada, explored the scientific opportunities, key technologies and optimum location of such a Lunar Liquid Mirror Telescope (LLMT). An optical design for a 20 m telescope with diffraction limited imaging over a 15-arcminute field has been developed. It would be used to follow up of discoveries made with the 6 m James Webb Space Telescope (JWST), with more detailed images and spectroscopic studies, as well as to detect objects 100 times fainter, such as the first, high redshift star in the early universe. A model was made of a liquid mirror spinning on a superconducting bearing, as will be needed for the cryogenic, vacuum environment of the LLMT. Reflective silver coatings have been deposited for the first time on a liquid surface, needed to make infrared mirrors at ~ 80K. Issues relating to polar locations have been explored. Dust on the optics or in a thin atmosphere, though unlikely to be problematic at the poles, should be investigated in-situ. Locations at or within a few km of a pole are preferred for deep sky cover, and allow for long integrations by simple instrument rotation. We find that stars of the Large Magellanic cloud should not cause much difficulty for a South Pole location. The North Pole is more accessible for construction, and from very recent winter images, kindly made available from the new European SMART-1 lunar probe, we believe it to be competitive or better site than the South. It has peaks within ~ 20 km that could provide continuous solar power even in winter.

This revolutionary mission concept could provide a scientific focus to NASA's planned exploration of the Moon, just as currently HST stands as a major achievement of its Shuttle program

1. THE INVESTIGATION TEAM.

The studies reported here have been made by an international team of investigators. The US investigators have used the funds made available by NIAC for this study, but we have been joined (at no cost) by Canadian investigators Professor Ermanno Borra of Laval University, who pioneered the development of liquid mirrors for astronomical telescopes, and by Professor Paul Hickson, of the University of British Columbia, who built the largest liquid mirror telescope in operation, 6 m in diameter. Their practical experience and diligent pursuit of this new challenge have been invaluable. We would like to acknowledge the kind cooperation of Dr Bernard Foing and Jean-Luc Josset of ESA, whose Smart 1 spacecraft just arrived at the moon, for sharing with us their unique images of the lunar North Pole in winter.

The effort has been led at the University by PI Roger Angel, Profs Pete Worden, Dan Eisenstein (science) and graduate student Suresh Sivanandam. Prof Ki Ma of the University of Houston has led the superconducting bearing and model work.

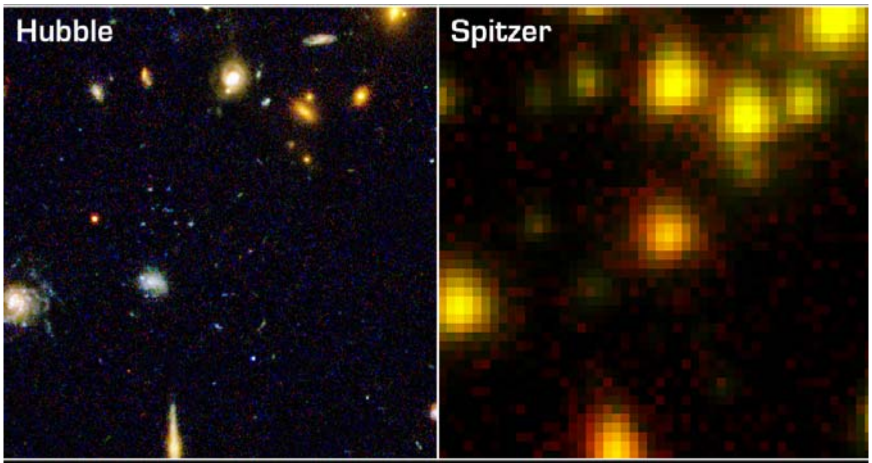

Figure 1. When he 0.8 m Spitzer telescope, the most powerful infrared telescope yet orbited, views the same deep field as the Hubble, it sees high redshift distant galaxies but is limited in resolution because of diffraction. The 20 m infrared telescope we propose will have the same resolution as Hubble, and see far deeper than even the Webb telescope.

2. RATIONALE FOR A LUNAR LIQUID MIRROR TELESCOPE

The telescope concept is aimed at furthering our understanding of the early universe. This has recently been revolutionized by deep optical fields imaged first with the Hubble Space Telescope (HST), and followed up by observations by other telescopes across the electromagnetic spectrum, including the Spitzer infrared telescope, and by spectroscopic analysis with 6-10 m ground-based telescopes. In the next 10-20 years Hubble's successor, the 6 m Webb infrared space telescope will work in tandem with 20-30 m class ground telescopes now being planned, such as the TMT and GMT. However, for high redshift studies of the early universe, it will no longer be possible to use larger ground apertures to follow up the very high redshifted faint objects found by the JWST, because of high atmospheric and thermal background in the infrared. To learn more about much deeper fields, a very cold space telescope such as the one we propose will be required, with aperture of 20-100 meters diameter and capable of integrations of days to years with Hubble quality imaging. (Figure 1).

The Moon is potentially an ideal location for such ultra-deep observations over the full electromagnetic spectrum, completely free from atmospheric absorption and distortion. Ultradeep fields can be chosen anywhere in the sky that is not compromised by dust in our own solar system or galaxy. From the Moon it is convenient to observe fields at or near the ecliptic poles, because the spin axis of the moon points always close to this direction. This allows a great simplification, in that telescopes do not have to be controlled to track stars around the sky. We can take advantage of the Moon as a stable platform to keep a telescope pointed constantly out along the Moon's spin axis. The field will slowly move (because of the Moon's 18.6 year precession) around the ecliptic pole in a circular path of 3º diameter, at 0.5º per year.

An advantage of the ecliptic poles is that they are the two regions on the sky where the infrared sky background from zodiacal dust is minimized, and are thus preferred in any case for deep infrared observations. The lunar telescope one would likely choose to build first would be to survey primarily the infrared in the wavelength range 1 – 10 μm, for the following reasons:

1) It is a spectral region of very high scientific interest, particularly for the study of the early universe. The radiation of the first stars emitted primarily at rest wavelengths from 0.1 – 1 micron is redshifted by around a factor 10 to this region.

2) The zodiacal sky background is lowest in the 2-5 μm spectral region, allowing for extremely deep images. The 6-m James Webb Space Telescope (JWST), the successor to HST, is focused on the same spectral region for the above reasons. JWST will obtain the first really deep images of the high redshift universe.

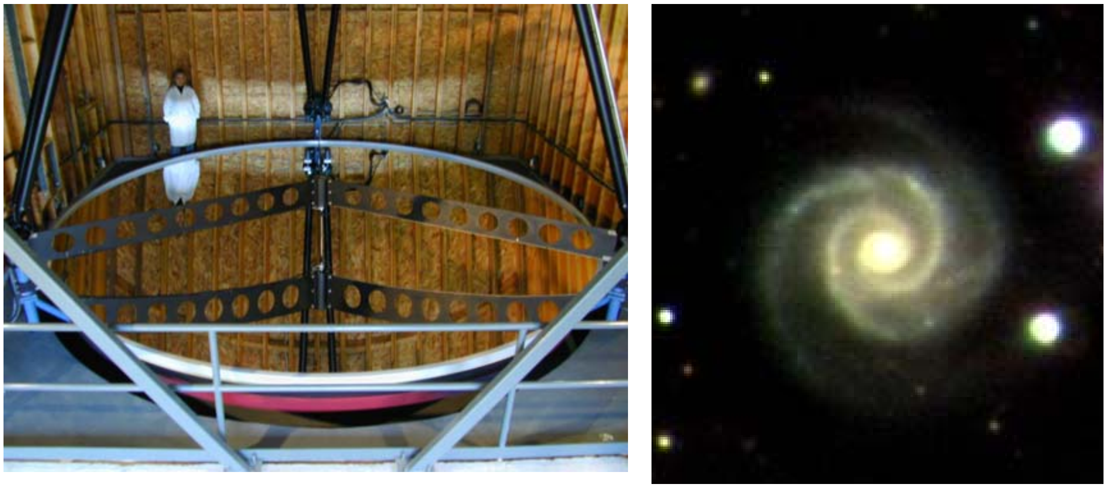

Figure 2. (a) The 6 m diameter mercury liquid mirror of the LZT. (b) galaxy image from this telescope. (courtesy P. Hickson)

We should be clear that while a fixed axis lunar telescope would be exceptional for early universe studies, because there is an abundance of high redshift targets is any direction, it is not useful for rare targets (such as nearby extrasolar planets) where we need access the whole sky. For the latter the best location might well be a gravity-free environment far from the warm Earth, such as L2. But the assembly and maintenance of a diffraction- limited 20-100 m diameter cryogenic telescope at L2, a million miles from earth, may well remain beyond reach. But the same aperture dedicated to a deep survey may well be feasible on one of the Moon's poles, by taking advantage of a trick to make a very high quality liquid mirror with the aid of gravity.

Primary mirrors made as a spinning dish of liquid in a gravity field represent completely different technology, with the potential to achieve very large size and high optical quality for an affordable. Liquid mirrors take on a smooth and precise surface automatically, and when rotating in a gravitational field takes the paraboloidal figure needed for a telescope primary. Mercury has been used to make such inexpensive mirrors with excellent surface quality. The technology is young but its performance is well documented by laboratory tests (Girard & Borra 1997, Tremblay & Borra 2000) as well as by observations (Sica et al. 1995, Hickson & Mulrooney 1998; Cabanac, Borra, & Beauchemin 1998). Zenith-pointing telescope mirrors of liquid mercury have been made at very low cost up to 6-m diameter, spinning at a few revolutions per minute in the 1-g gravity field of Earth (www.astro.ubc.ca/lmt/lzt, see also Cabanac, Hickson and de Lapparent, 2002).

Mercury is not suitable for a lunar survey telescope to operate in the infrared. The reflecting surface must be much colder than the freezing point of mercury, or it will produce a background thermal radiation much brighter than the very dark natural sky background. The Spitzer telescope shows the extremely deep views that can be reached when this background, set by zodiacal dust, is reached with very cold optics. A key requirement is thus to identify such a very old liquid, about the temperature of liquid nitrogen, that can be made reflective. The lunar poles are the ideal location, because when shielded from the sun, which is always near the horizon, very low temperatures are reached simply by radiative cooling. The Spitzer and Webb observatories similarly operate in direct sunlight, with their very cold telescopes protected by a radiative shield.

The Moon provides a highly favorable environment for cold liquid mirror telescopes, with gravity but unlike Earth with no atmosphere or wind and very little seismic disturbance.

The features of a 20-100 m survey telescope, operated at a temperature of ~ 80K at a lunar polar location, are illustrated by the artist's impression (Figure 3). The dish of reflecting liquid we envisage to be suspended from a superconducting levitation bearing. The secondary mirror (shown schematically as a 5 m

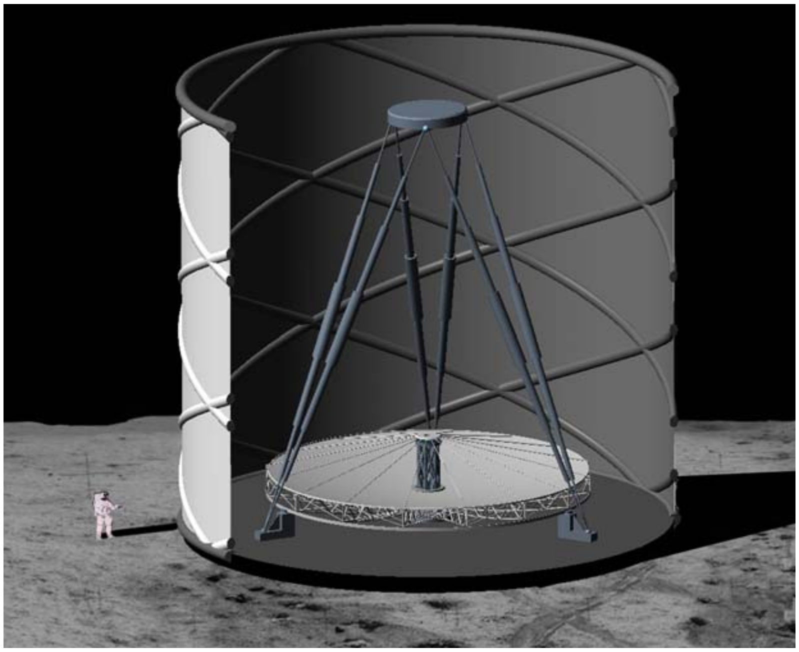

Figure 3. Artist's impression of the 20 m telescope. The secondary mirror is erected by extending the six telescoping legs, and the sunshield by inflation. The scientific instruments are below the bearing pier, shielded by lunar soil. (drawn by Tom Connors)

disc) and the surface deposition equipment are supported near the prime focus some 25 m above the dish. The corrected field is relayed through a central hole in the bearing to an instrument module below, shielded from radiation by lunar soil. Three stations around the perimeter would house magnetic drive and stabilization units, and liquid filling apparatus. The telescope is surrounded by a cylindrical solar radiation shield. This would be of very lightweight multi-layer insulation, given the low gravity and absence of wind. The telescope would be built by some combination of astronauts and robots, taking advantage of capabilities developed as part of future lunar exploration.

3. STUDY RESULTS

3.1 Scientific Potential

We recognize from our study that an enormous investment would be needed to realize a large survey telescope on the moon, justifiable only if the scientific reward were commensurate. The scientific impact would have to be comparable to that of the Hubble telescope. It is also the case that without the strong support of the astronomical community, the necessary investment would unlikely to be sustained over the many years needed.

Our initial conclusion, here summarized by Dan Eisenstein, is that there is potentially a superb and unique scientific role in the study of the early universe, because of the potential on the moon cooled telescope to reach much deeper in the infrared than is possible from the ground, and to be built at a size that would likely be prohibitively expensive if built from precision panels in free space.

The infrared in the wavelength range between 1 and 10 microns is an extremely important region of spectrum because all of the optical and UV processes that dominate the light from galaxies are shifted into the infrared when one looks at galaxies in the early Universe. Notably one can study rest-frame optical and near-infrared (NIR) properties of galaxies at $1<z<6$ and study UV and optical properties of galaxies at $z>6$.

Modern computer simulations suggest that the first stars form around $z=20$. These stars are supermassive, very hot, and short-lived; they dramatically alter their environment by their ionization fronts and supernovae. Typically one believes that the stars completely disrupt the initial gas cloud in which they form. After this epoch, the IGM is likely heated sufficiently that only significantly more massive objects can overcome the thermal pressure and create an environment for gas cooling, collapse, and star formation. These are the first proto-galaxies. The energetic feedback and heavy element production from these early generations of stars provide a crucial boundary condition for the formation of the later generations.

JWST will likely see early galaxies, but it will not see the first stars and it may not be able to see the early proto-galaxies. The additional sensitivity of a much larger lunar telescope is needed. The objects are small such that its additional angular resolution above JWST would also be valuable.

The first stars radiate near the Eddington luminosity and emit predominantly in the UV. A 100 solar mass star at z=25 would have a continuum luminosity at 3 microns of roughly 15 picoJanskies. Yet more energy is actually emitted in the Lyman alpha and HeII 1640A lines; some kind of spectroscopy might be more efficient. Whether or not the Lyman alpha emission can actually escape the IGM is not presently known, but the HeII 1640A lines would and might reach about 200 picoJanskies (R=1000). Further in the IR, one could look for Balmer lines. These are realistic goals for the 20 m telescope.

One could look for globular clusters forming at high redshift and study this process in relation to the formation of proto-galaxies. Given that these objects are physically small (proto-galaxies at z=10-15 are expected to be marginally resolved by JWST), the additional angular resolution available to a larger telescope would give an increase in sensitivity above the simple increase in light collection.

At 50 m aperture, the diffraction limit at 2 microns is roughly 10 mas, which corresponds to a spatial resolution of no worse than 70 pc. This means that one can study rest-frame optical properties of galaxies at z=3 with resolution equivalent to a ground-based telescope looking at galaxies in the Virgo cluster. Integral-field spectroscopy could open detailed dynamical and stellar population studies of high-redshift galaxies.

High spatial resolution would also be advantageous for investigating supermassive black holes at high redshift. One would separate the nucleus from the stars at resolutions considerably above that of HST. Integral-field spectroscopy would permit spatially resolved line diagnostics. One can see black holes of 100,000 solar masses radiating at their Eddington luminosity out to z=30, thereby tracking the growth of black holes along with the growth of galaxies.

Of course, the benefits of an IR-optimized observatory have long been recognized, and the James Webb Space Telescope will provide a superb 6m-class facility. One must consider how a large lunar telescope could improve upon JWST. A key aspect is that a telescope that cannot point cannot take advantage of the closest/brightest examples of a class of local objects. In other words, for topics involving nearby galaxies, star formation, or planets, JWST will usually be able to find a much closer example than those found in a small field of view and thereby make up for its smaller size. However, for galaxy evolution, one is interested in distant galaxies as a class, and for high redshifts, even modest survey areas can include a large and representative volume. Hence, the focus on high redshift galaxies as the science driver. The one exception to this guideline is that from the south lunar pole the LMC is in the field of view, in which case one could image the closest example of a particular class of galaxy.

Strong gravitational lensing provides a way for a telescope such as JWST to achieve the effective spatial resolution and light collection of a larger telescope. This may be acceptable for some applications, but the amount of cosmological volume that one can probe with such techniques is very small, many orders of magnitude less than for the zenith pointed telescope.

3.2 Range of designs

Diameter (m)	2 m	20 m	100 m
Mirror area (m2)	3	300	7600
Mirror density	15 kg/m2	3.3 kg/m2	
Primary mass (tons)		1	50
Total mass (tons)	0.5	3	100
Field	3.1° annulus	15’	3’
Diffraction limit @ 1μm	0.1 “	0.01”	0.002”
Pixels @ 2μm (Nyquist)	18,000/°	45,000	45,000

We considered a series of designs beginning with a 2-m precursor telescope, scaling up to 20 m and 100m. The scaling parameters are in the table.

A key consideration is the focal plane instrumentation. A 20 m LLMT telescope will be able to obtain usable infrared spectra at the same limiting magnitude that the JWST can just detect objects, and can detect objects 10x fainter. For a 15' field of view and focal plane array with 18µ pixels this would result in a ~1.6 m diameter montage of array detectors. With current technology limits of 2000x2000 arrays we might expect within the next decade that technology will improve to the point where individual arrays might have 4000 pixels on a side – requiring about 120 such chips for imaging. Spectroscopic instruments, which could have a primary mission of following up JWST discoveries would be considerably less demanding on detectors.

3.3 Optical Design

We have examined a number of design considerations for a LLMT. These results follow directly from the work of Hickson at the University of British Columbia whose 6 m liquid mirror telescope has demonstrated seeing-limited imaging performance.

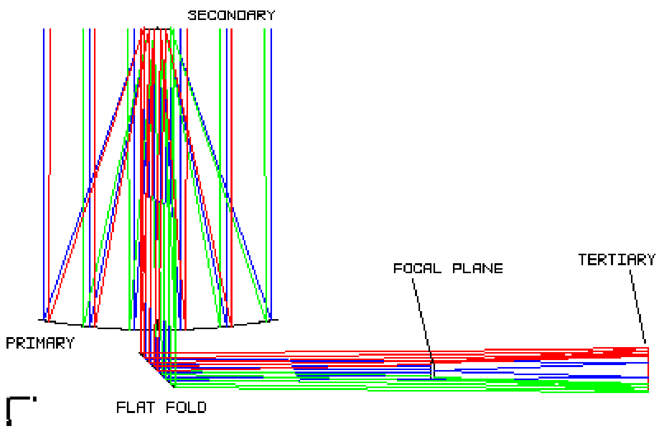

Figure 4. Three -mirror design by Dr Simon Thibault, contracted by Ermanno Borra

The lunar telescope is considerably more challenging because it must be diffraction limited. As part of the study, we have explored off-axis systems that would allow increased sky cover. These however generally suffer from field distortion, typically at the level of a percent or so. But once it exceeds the reciprocal of ten times the number of resolution elements across the field (~10^4), it results in unacceptable image degradation during long exposures. This precludes drift-scanning to accommodate star motion away from the zenith, or any kind of long exposures except for the special case when the telescope is located ***exactly*** at the Lunar pole or otherwise set to image only a set zenith position, so that a rotation about the symmetry axis of the primary mirror can be made to compensate for Lunar rotation. Designs to circumvent this problem exist but require complex optics and control systems. We conclude that *off-axis LLMT's are not practical*. A large LLMT should therefore have simple optics that view the zenith. Large reflecting or refracting elements are difficult to support and align. The prospect of accurately deploying, or assembling, a large complex corrector at the top of a ~ 30 m high structure on the Moon is daunting. For this reason a Cassegrain type system, with a single mirror deployed above the primary, would be preferred. An example of one such design, with three reflecting mirrors is shown in (figure 4).

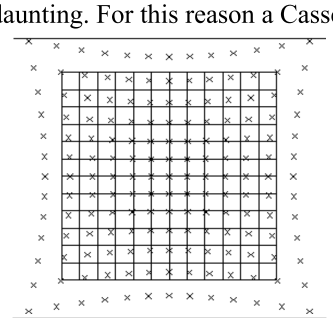

Figure 5 Image distortion for the 3 mirror telescope

This design achieves the goal of a 15-arcminute field with diffraction limited images $\lambda \geq 1$ µm wavelength. It is for an f/1.5 20 m parabolic liquid primary, has a 2.4 m Cassegrain secondary and a 4 m tertiary mirror. The final focus is at f/15, for a field diameter of 1.3 m. The imaging array would be a mosaic of 18 x 18 four-megapixel arrays, with each 18 micron pixel corresponding to 12.4 milliarcseconds. This provides Nyquist sampling of images down to 1.6 µm wavelength. This first optical concept has significant vignetting by the focal plane, and options to reduce this are being explored. This type of design is expandable to larger sizes – perhaps as large as 100m diameter.

The distortion in this design is shown for the 15 arcminute field in figure 5 exaggerated by a factor of 100. For a telescope located precisely at the pole, rotation of the star field about the optical system axis would be exactly compensated for long exposures by rotation of the detector. However, if the telescope were only 7 arcminutes (3.5 km) from the pole, the star field and the detector would rotate about one edge of the telescope field. The smear caused by distortion for the above design would be about 1 pixel/hour, about the limit we could accept.

3.4 Mechanical design

A LMMT provides many mechanical design challenges. One needs a lightweight structure that has high stiffness and good thermal stability. For the primary mirror dish, lightweight honeycomb sandwich panels of graphite-epoxy is probably best. This could be made in segments and assembled by astronauts or robots. A space-frame substructure would provide global rigidity and stability. A very important issue is the dynamic control of the primary mirror. Deformations of the primary mirror and support structure result in redistribution of the liquid on the surface, which changes the loading. If the gravitational potential energy released by the fluid exceeds the elastic energy of the deformation, the mirror will be unstable. The softest mode is usually a global tilt resulting from inadequate stiffness in the bearing and support structure. However, the stiffness required to maintain liquid mirror stability for a 20 m diameter system seems well within current technology for an actively controlled telescope.

3.5 Superconducting Bearings

A superconducting bearing for the spinning mirror is an ideal choice, because no lubricant is required and there is a large gap that avoids issues of dust contamination. Professor Ma conducted a series of experiments with “toy” magnetic suspension bearings. Figure 6 shows the experimental setup and the reflected image in the rotating liquid.

	Model	Simple scale up	Optimized design
Mirror diameter	0.2 m	20 m	
Mirror mass	0.18 kg	1000 kg	
Mirror weight	0.18 kgF	167 kgF	
YBCO diameter	25 mm	0.75 m	1 m
YBCO thickness	12 mm	0.36 m	0.025 m
Superconductor mass	0.055 kg	1.53 tons	0.2 tons
Total bearing mass	0.085 kg	2.4 tons	0.3 tons

The superconductor bearing was an inch in diameter and weighed 85 grams, as listed in table 1. The spinning dish of liquid weighed 180 g. The speed of rotation ranged from 40 RPM to 60 RPM to yield a mirror of focal ratio f/1.

Figure 6. Model of spinning liquid mirror on a superconducting bearing by Professor Ma. (a) shows the bearing, with a nitrogen-cooled YBCO superconductor in the upper cup, and a neodymium magnet in the inverted cup below. The gap is ~ 3 mm. Hanging on 3 strings below is a 20 cm spinning dish of black soy sauce with ~ 8" focal length (b). The lettering is the reflection of a screen above.

The bearing needed to support a 1 ton mass lunar telescope (weighing 160 kg force can be crudely estimated by scaling this design. Since the load capacity increases as the superconductor area and we require a factor of 890 times, from 0.18 to 160 kgf, the superconductor diameter must be increased 30 times to 0.75 m. If the scaling is in all three dimensions, the total bearing mass will be 2.4 tons (see table). However, the efficiency of mass utilization can be dramatically improved with more sophisticated designs, as demonstrated in smaller versions described in papers given in the references. An optimized bearing with of 0.3 tons is shown in the third column of the table. . We conclude that a superconducting magnetic levitation bearing is ideal and feasible for a large LLMT telescope.

In the model we placed the bearing above the center of mass of the spinning dish, for basic passive stability. The drive torque was by eddy currents in the conducting aluminum mirror dish, induced by a rotating magnet below. In operation, we discovered that the period of rotation settled in to equal the pendulum period of the suspended mirror. The radius of curvature of the liquid surface was then equal to the pendulum length. This has the fortunate consequence that wobble of the mirror at the pendulum period did not upset the natural curvature of the surface, which remains fixed with respect to the dish. . Nature showed how to achieve a naturally stable mirror!

For a diffraction-limited telescope the optical requirements are severe, but by adopting this geometry with the bearing at the center of curvature, we would have a good start. For the spin axis to remain vertical to within ~ 1 milliarcsec, and the gap to be stable to ~ 1 micron, to avoid defocus, the required inherent axial stiffness of the bearing is ~ 40 N/mm and the tilt compliance ~0.02 sec of arc/mN*m. These tolerances would be achieved by active control. A telescope mounted on this bearing would have a resonant frequency of around 2.5 hz. Fortunately, this is considerably higher than the rotation speed of 0.03 hz. Still, as a vibration isolator, the bearing will not shield the telescope from vibrations below about 3 hz.

3.6 Mirror Liquids and Reflective Coatings

Fig 7 Mirror surface of silver on polypropelene glycol deposited by Prof. Borra.

For thermal emissivity less than the natural zodiacal sky background below 10 microns, the LLMT requires a mirror surface at < 100K. We need a material that is liquid at this temperature, with very low vapor pressure to prevent evaporation, and either intrinsically reflective or can be metallized to become so. Borra considered three main classes liquids that could be used: eutectics of alkali metals, which have the advantage of high intrinsic reflectivity; low-reflectivity liquids coated with a thin metallic coating produced by sputtering or evaporation; and low-reflectivity liquids coated with self-assembling nanoparticles. He concluded that the most promising approach was to apply metallic coatings to low temperature, low vapor pressure moderate viscosity liquids.

The reflectivities of the alkali metals are very high (> 98%) in the blue and the visible and increase monotonically with increasing wavelength. Thompson (1985) find emissivities of 0.015 for K and Na. Eutectic alloys of alkali metals have lower melting temperatures than their components. Supercooling, very common among liquid metals, should allow even lower temperature liquids. The two other techniques require a substrate liquid that has a low melting temperature, ideally 100 K or less, with a metallic coating. A search of chemical databases shows 1 butene as the most promising candidate, liquid at 90K with a vapor pressure of 10^{-7} torr.

Liquid could potentially be coated by vaporizing a reflective metal, borrowing from techniques used to coat solid mirrors on Earth. Professor Borra conducted a number of experiments to explore the parameter space in this important area, starting with liquids at room temperature. He reached rapidly an important milestone, namely the demonstration with two different techniques that it is possible to deposit, in vacuum, a metal on a liquid. This was done with a sampling of the parameter space using a variety of liquids at hand. He found it possible to coat only some liquids. Therefore, before identifying cryogenic liquids suitable for a lunar liquid mirror telescope, one must determine the physical characteristics needed for successful coating.

Borra's coating experiments have shown that boiling during vacuum coating was a major problem for most liquids tried. He began an exploration by studying the effect of viscosity because our experiments so far indicate it may play an important role. It appears that if viscosity is too small there is no coating; if viscosity is too high, the liquid outgases too slowly and boils during coating because of radiative heating from the hot electrodes. We successfully coated polypropelyne glycol with vacuum deposited tin and silver (Figure 7). With this success we believe that a suitably chosen eutectic liquid with a metallic coating is the most promising approach for a LLMT .

3.7 Is dust an issue?

The possibility has been raised of a "dust atmosphere" above the lunar surface that might increase sky brightness or contaminate telescope optics. Apollo missions have shown the lunar regolith to consist of fine-particulate dust. A literature survey suggests two properties of lunar dust we need to consider:

1. Photoelectric charging of lunar surface by the sun levitates and moves dust near the terminator;
2. A dust atmosphere extending to at least 100 km in altitude might exist.

We note these properties were derived from only a handful of observations, outlined below, where the existence of levitated dust was only inferred. There has yet to be a direct detection of levitated dust, and there is no knowledge of any levitated dust level at the poles. But the possibility of surface dust levitation to a high enough level to deposit on our optics, and a dust atmosphere could elevate the sky background reducing the sensitivity of our observations has to be considered.

Diverse data from the Apollo era suggest the existence of levitated dust near the terminator. Rennilson and Criswell (1973) modeled the horizon glow observed by Lunar Surveyor 7 lander a few hours after sunset to be forward-scattered light from a dust layer, consisting of 5-6 micron particles, levitated 10-30 cm in the vertical extent. They suggest the ground and dust are photo-electrically charged by high-energy solar photons creating potential differences between dark and bright regions as the terminator sweeps across the surface. Since the dust is charged, it is transported by electrostatic forces. A robust numerical model for this phenomenon is developed by Pelizzari and Criswell (1978). These models are a strong function of solar illumination and only predict low-level dust transport. But due the high obliquity of solar rays in the polar regions, it is possible this would be a negligible effect there. Indeed, a recent paper by Stubbs et al (2005) proposes that high altitude lunar dust, as discussed below, might be due to solar charging and interaction with the solar wind. However, these processes may not operate near the terminator – and particularly at the poles.

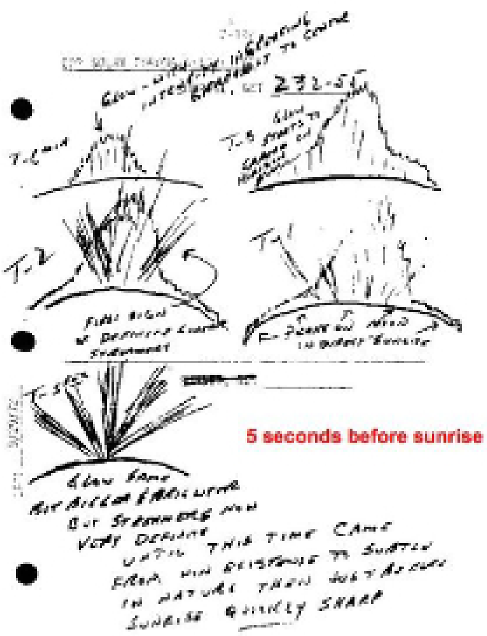

Figure 8. Sketch by Apollo 17 captain Cernan

In addition, Apollo 15 and Apollo 17 astronaut and Lunokhod-2 observations suggest a completely different phenomenon of a very high, thin dust atmosphere. Apollo 15 astronauts detected an excess of light while photographing the solar corona in orbit just after sunset. McCoy et. al (1975) claim this as evidence for a scattering source located a few kilometers above the lunar terminator. While in orbit, Apollo 17 astronauts observed streamers just before sunrise suggesting a scattering atmosphere extending beyond the 100 km altitude Apollo orbit (McCoy and Criswell 1974). Lastly, the Russian lander Lunokhod-2 detected unusually bright sky background with a dependence on the zenith angle of the sun, once again suggesting a scattering atmosphere (Severny et. al 1975). We contacted Apollo 17 astronaut Jack Schmidt, now at the University of Wisconsin, who suggested the following:

"The "streamers" we saw appeared to be related to the sun with the moon as an occulting disk of sorts. There is at least one paper on this. I do not believe that these extremely long streamers from the sun out into space were indicators of levitated lunar dust but rather of solar activity. There was some broad horizon glow just before sunrise that may have been caused by dust as seen through a very long path, however, in over 30 years, I understand from the Macdonald Observatory people the corner reflectors have shown no sign of dust accumulation on their cubes. Surveyor saw what some have interpreted as levitated dust at sunset and I think that is in their mission reports. Frankly, I don't think it will be a problem and if it is there may be an electrostatic countermeasure."

We conclude that the best way to resolve these issues is the mount a low-cost microsatellite lunar lander to resolve this issue.

3.8 Is star contamination by the Large Magellanic Cloud a problem for the South Pole?

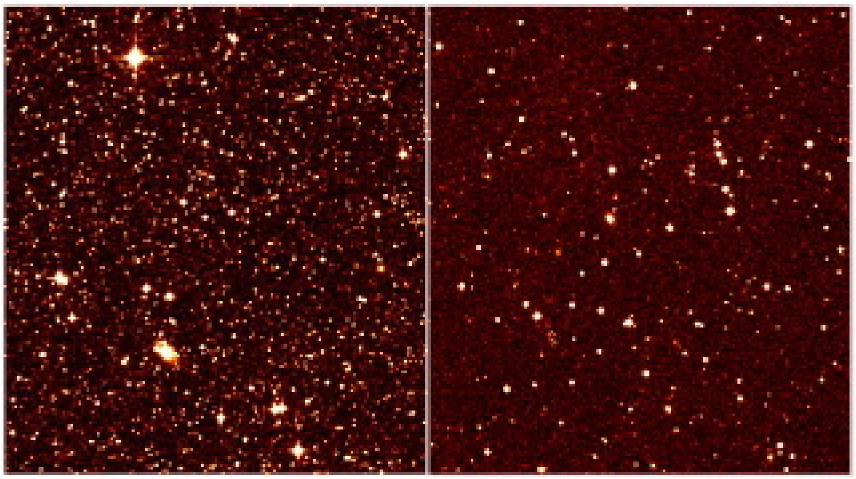

Figure 9: Comparison of N and S ecliptic poles. Schmidt survey photographic R-band images: Left – South Pole view; Right – North Pole view. R_{limit} = 21; FWHM = 2"; FOV = 12'×12'.

Our initial thoughts were that the South lunar pole might be ideal for a LLMT. However, courtesy of Bernard Foing and Jean-Luc Josset we were able to study the first ever winter images of the North lunar pole (see 2.2.9 below) Solar illumination near the pole shows it is a viable alternative. Suresh Sivanandam, astronomy graduate student funded by this Phase I study, studied the differences in scientific potential arising from different stellar field contamination.

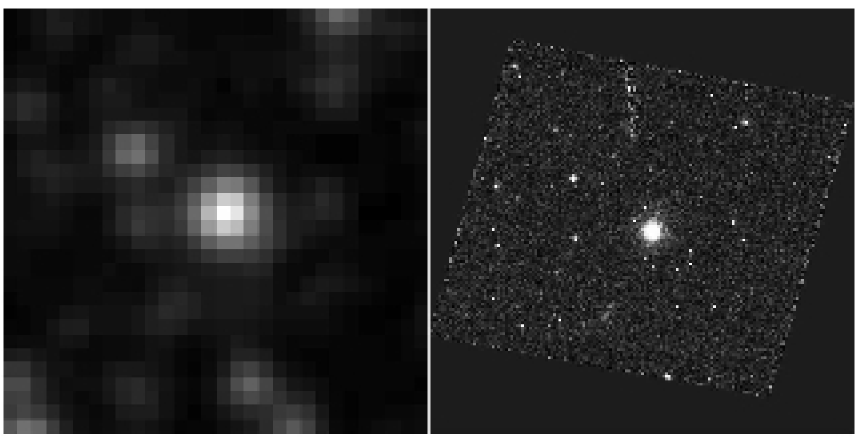

Figure 10. (a) Detail from the red Schmidt survey image of figure 9 shows a field (30"×30" in size) close to the South ecliptic pole. (b) HST red image of the same field at the same scale. HST's high resolution is able to resolve out all of the stars to V=26.

Since the LLMT is designed to carry out long integrations on a small field, a dense, nearby stellar population in the field-of-view can cause confusion problems and reduce the usable field-of-view of the telescope. A telescope located at the South Pole will inevitably see part of the Large Magellanic Cloud (LMC). A quick look at the Digital Sky Survey (DSS) R-band plates of the North and South Pole fields, shown in the figure below, clarifies the issue. At an R-band limiting magnitude of 21, there is significant stellar contamination in the South Pole field, though the angular resolution is only 2". At our sensitivity, we will reach an M-band limit of 26 mag with 0.1" resolution, comparable to Hubble's red-end resolution. This means we will see all of the Main Sequence (MS) stars of the LMC and reach about a magnitude fainter. This may not be an issue if our telescope has sufficiently high angular resolution to resolve out the stars at our sensitivities. The North Pole location, as shown by the contrast in stellar densities depicted below, does not experience this problem as it looks well away from the galactic plane.

To assess the South Pole site carefully, we need an estimate of the surface density of LMC stars to place constraints on the size of a usable field. We address this by modeling the LMC stellar population using STARFISH (Zaritsky et al), a code that generates a stellar population and associated photometric values for each star from a specified star formation history (SFH). Using a built-in SFH derived specifically for the LMC, STARFISH generates results that match the observations of a complete LMC stellar catalogue, which samples the bright and "giant"-end of the stellar distribution. We extend the model to the faint-end of the MS to get a crude idea of expected stellar surface densities at our sensitivity.

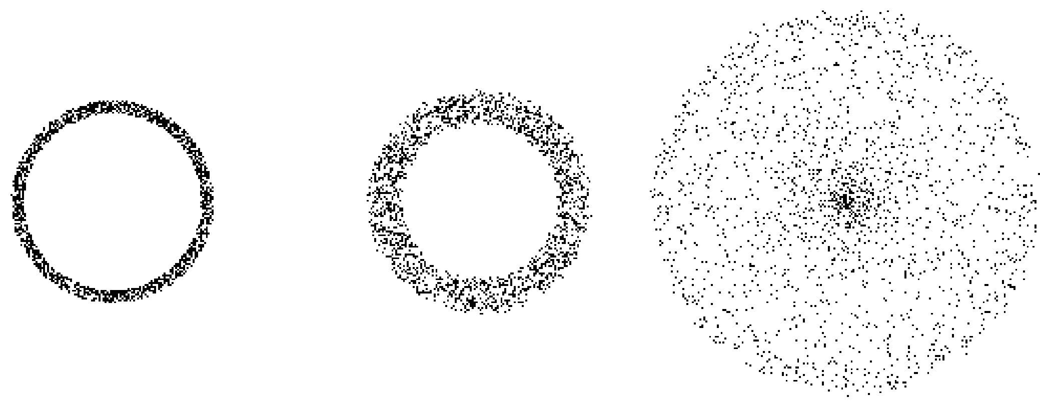

Figure 11 Effect of location on sky access for a zenith-pointed telescope with 0.2 degree field of view. The integrated exposure over 18 years is shown in each case. *Left* – at the pole, over 18.6 years the field sweeps out an annulus 3.1 degrees in diameter centered on the ecliptic pole, with contiuous integration of ~ 5 months on any one spot. *Center* – 0.2 degrees from the pole, the field sweeps out a half degree annulus each month, covering any one spot every month for a year *Right* – 1.55 degrees from the pole. Each month the field sweeps a 3.1 degree annulus, covering any spot for about 15 hours. The ecliptic pole is seen for this time every month, for a total integration time of 5 months over 18 years.

We use the catalogue stars within a 5' field of the SEP to be representative of the top end of the stellar population (V_{limit} = 22) and derive a stellar density of 0.005 stars/arcsec^2. We scale our simulation accordingly to obtain a predicted LMC stellar density of 0.3 stars/arcsec^2 down to a V_{limit} of 33 corresponding to the faintest MS stars in the LMC. At the M-band diffraction limit, we would expect about 99.9% of field to be usable.

To add credence to this analysis, we performed the same analysis using an archival Hubble ACS High-Resolution Camera (HRC) F606W image of a field close to the SEP, shown in the figure below. This exposure is deeper and is able to detect V=26 stars in the LMC at 4 sigma. Unlike the DSS observations, HST resolves all of the stars. Suresh's simulation predicts the number of stars observed in the HST image within a factor of 3. If we use the HST-derived surface density for our top-end calibration, we derive a predicted LLMT-observed surface density of 0.7 stars/arcsec^2. This translates to a 99.8% usable field in the M-band. The main sources of uncertainty in this analysis arise from the imprecise determination of the LMC SFH, and the luminosity distribution at the faint, low mass end. However, we would require 50 times as many sources as our predictions to decrease our usable field-of-view to 90%. Such a large discrepancy from our modeling seems unlikely, which leads to our conclusion that LMC stars will only be a minor interference to a South Pole telescope.

3.9 Sky cover versus distance from the pole for a zenith-pointing telescope

We consider the case of a zenith pointing telescope with 15-arcminute field. If it is placed the telescope directly at the pole, the observed field rotates around its center once per month, at a center 1.55 degree off the ecliptic pole. Over the course of the 18.6 year lunar precession cycle, the view will trace a circle around the ecliptic pole. The result would be to sweep out an annulus 9.7 degrees in circumference and 15' in width centered on the ecliptic pole, dwelling on individual objects continuously for about 6 months. If the telescope is off the pole, the view will sweep around in a circle once per month, and the center of the circle will slowly move around the ecliptic pole. In 18 years, 2 square degrees would be covered with integration time close to 6 months for all points. An alternate location of especial interest would be at 1.55 degrees latitude from the lunar pole. Here the telescope and detector suite would sweep out a 9.7 degree annulus once each lunar month centered on the lunar pole position, but passing through the ecliptic pole monthly for about 1 day a month . Over 18 years this would provide a 6 month total integration on a 15'

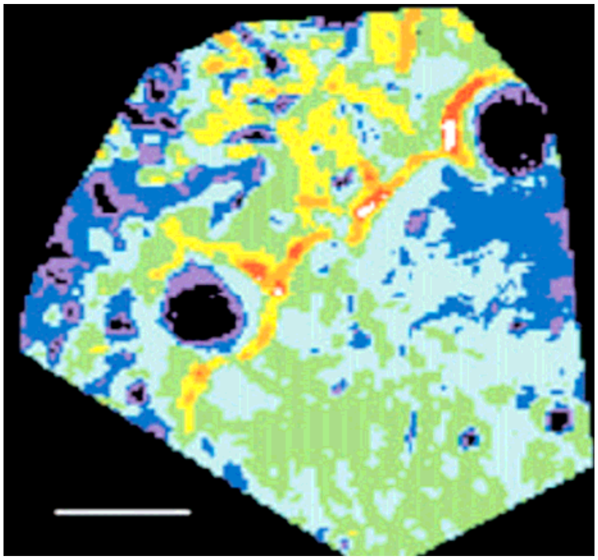

Figure 12: Summertime illumination map generated from Clementine data of the North Pole (marked by arrow). The scale bar on the left is 15 km in length. The crater located near the 90°E meridian is the encircled crater shown in the SMART-1

square image of the ecliptic pole, dropping off the typically 3 weeks over a 30 square degree area.

3.10 Telescope location, solar power considerations.

The precise location for a LLMT depends on many factors. Some locations are permanently shaded. For example, to place a telescope exactly at the South lunar pole would place it within the permanently shaded Shackleton Crater (see Bussey et al., 1999). This location could have the advantage of very low ambient temperature and minimal possibility for problems from solar levitated dust. However, this location would be difficult to access for construction and maintenance and would require large amounts of beamed power as well as complicated data relay systems as it is permanently out of the line of sight from the Earth. Moreover, this crater could become the scene of volatile extraction operations that could produce vibrations, dust and other interference with astronomical observations. Alternate locations for an LLMT would be in locations with near continuous solar illumination – so called "peaks of eternal light." One such site is the rim of the Shackleton Crater. These locations have the potential advantage of easy access to solar power during most of the lunar day-night cycle, benign thermal conditions and potential frequent direct access to the earth for communications.

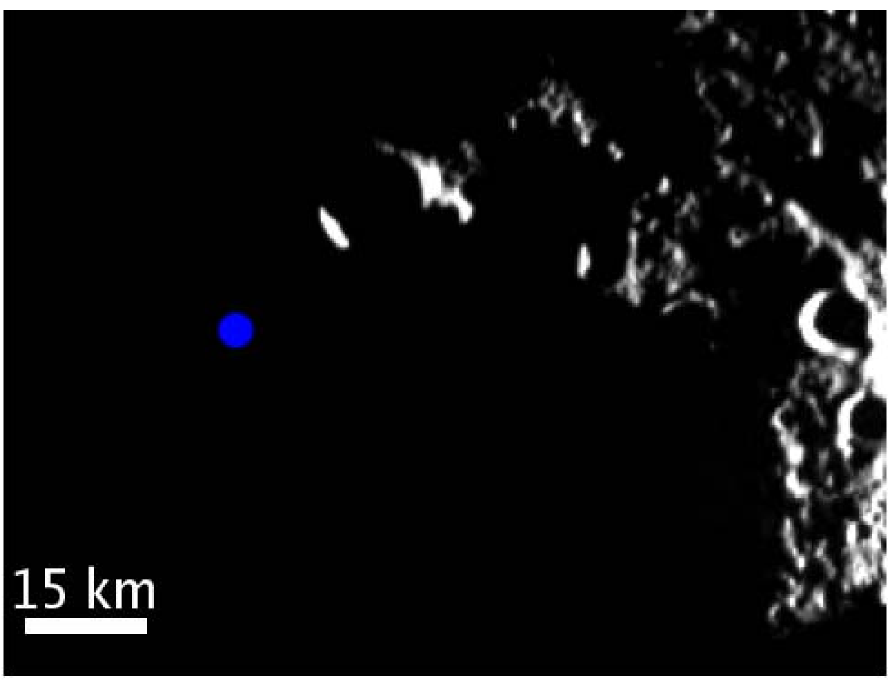

Figure 13 SMART-1 AMIE image of the North pole in mid-winter. The dark pole is marked in blue, and the nearest crater still showing illumination 15 km distant is the one top-right crater of figure 11, which has 100% summer illumination. Solar panels on this ridge would provide power for at least some of the winter months. (Credit: SMART-1 AMIE Team)

Based on our conclusion that the North lunar pole offers a deep view less contaminated by faint stars, we investigated its suitability for LLMT sites. A good study of lunar polar illumination was made from the 1994 Clementine data, which was orbiting at a time of winter at the South Pole and summer in the north. A recent Nature article by Bussey et al (2005) identifies permanently illuminated locations during summer at the North Pole. (Figure 12) The pole is marked at the end of a 3 km long east-west ridge of red (75-90% illumination). However, until now there have been no observations of the North Pole in winter.

Fortunately, the ESA SMART-1 probe arrived at the moon during our Phase I work. In a collaborative effort with ESA's lunar orbiter team, we obtained the first images of the North Pole in winter. SMART-1 arrived at the Moon in November 2004 and has since spiraled down to a polar orbit. During the commissioning period and between orbit modifications, the orbiter imaged strips of Moon with its 5°× 5° AMIE camera. We analyzed available images of the North Pole region (hereafter NPR) acquired during that period, which was close to the January 25th 2005 winter solstice. Our preliminary analysis shows ridges and crater rims within 0.5° of the North Pole are illuminated at least some sun angles during lunar winter. Figure 12 is a SMART-1 image of the NPR taken very close to mid-winter on January 19th 2005 from an altitude of 5500 km. The SMART-1 images indicate that solar power for a polar telescope could be obtained even in winter from locations within 15-20 km from the true pole.

4. CONCLUSION

Our phase I study resulted in preliminary LLMT designs for a 20m diameter system. We believe that such a system is feasible in the next 20 years, given appropriate robotic/human infrastructure on the Moon. We have also shown that the scientific potential of such a telescope is extremely high.

The revolutionary mission concept that will be developed could provide a scientific focus to NASA's planned exploration of the Moon, just as HST stands as a major achievement of its Shuttle program. The low cost, giant space mirror technology we are developing might also benefit other future major telescopes, by providing an affordable way to make end-to-end, full aperture optical tests. Such a test is badly needed for TPF-C, but one of adequate precision is currently discounted as being prohibitively expensive with conventional mirror technology.

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