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# A LUNAR OPTICAL VERY LARGE INTERFEROMETER (LOVLI) WITH SIMPLIFIED OPTICS

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## ABSTRACT

A long-baseline Fizeau-type interferometer for lunar operation is presented. It consists in 20 to 27 off-axis paraboloidal segments carried by robotic hexapodes which move during the observation run. The segments are 50 cm in diameter and actively deformed by 12 bending actuators to match the giant virtual mirror. This instrument has high-resolution imaging capabilities, and scientific objectives are briefly reviewed. Solar objects imaging, exo-planets, gravitationnal lenses and gravitationnal waves detection are considered. A conceptual description of the instrument is given. A comparison between the orbital (TRIO) and the lunar (LOVLI) versions closes the paper. 

## INTRODUCTION

The idea of an optical interferometric array on the Moon has been debated for more than a decade, and been the subject of conferences organized by NASA at Albuquerque (1990) and Annapolis (1990), and by ESA at Beaulieu (1992). At least one /1,2/ of the array principles and designs currently developped for Earth-based interferometry appears suitable for lunar operation, because it involves autonomous mobile telescopes equipped with robotic legs. A single Ariane V launch can deliver on the Moon 800 kg, enough to install a complete interferometer system with perhaps two dozen such telescopes for high imaging capabilities, if their size is less than 50 or 30 cm, together with the beam recombination package, the auxiliary systems and a solar power system. The system can deploy itself automatically and begin operating, with baseline sizes from a few tens to a few hundred meters. If the concept proves fruitful, second-generation instrument may utilize larger elements and baseline sizes reaching 10 kilometers.

Unlike previous concepts, the simplified instrument described here involves light collectors which are not telescopes but deformable segments of a virtual, and steerable, giant paraboloidal mirror. This simplifies the optical train and increases the observing field enough to allow observing reference stars together with the main object.

## SCIENTIFIC OBJECTIVES

The scientific objectives for a Moon-based optical array capable of producing high-resolution images, down to 0.1 or 0.01 milli-arc-second, at ultraviolet, visible, and near infrared wavelengths cover a broad range of topics, many of which have been discussed in previous reports. Among the targets mentioned in "Mission to the Moon" (ESA report SP1150) are: 1- the astrometry of single and multiple stars, providing tests of general relativity; 2- imaging of the surface and envelopes of stars; 3- imaging of accretion phenomena around single objects; 4- imaging of interacting binaries; 5- imaging of active galaxies and quasars; 6- imaging of gravitational lensing. Additional targets are: the imaging of solar system objects, the direct detection of exoplanets, the detection of dark bodies through the diffractive effects of gravitational lensing, and the detection of gravitational waves.

Imaging of solar system objects

Interest in small solar system bodies has grown tremendously of late, since the first images of asteroid surfaces were obtained, trans-Neptunian objects were discovered, as well as Earth-crossing asteroids and hybrid asteroidal-cometary objects like 2060 Chiron. A sub-milli-arc-second imaging facility could resolve a 10 km object at 10 a.u. (a Halley-like comet nucleus crossing the orbit of Saturn), or a 100 km at 100 a.u., in a image of 10x10 pixels or 100x100 pixels. Therefore, imaging of far asteroids, or cometary nuclei before they develop their obscuring bright coma, becomes possible and could study the possible relationship between asteroids and comets.

Detection of exoplanets

N=27 sub-apertures with active phasing provide good possibilities for the direct detection and imaging of planets associated to stars within a few parsecs of the solar system. A special technique utilizing slight adjustments of the wavefront phases at the sub-apertures can darken the speckles in the feet of the star's image. Within the phasing tolerance of $\pm 90°$ specified by Rayleigh for obtaining a central peak with nearly maximal brightness, the phases from each subaperture can indeed be slightly re-adjusted dynamically to obtain a dark speckle wherever desired in the speckled "feet" of the star image, where planets may be present /3/. Using such speckle-darkening techniques, the peripheral zone surrounding the bright central part of the star image may therefore be scanned for searching planets. The central bright peak of the spread function is little affected by the phasing re-adjustment, and remains N times brighter than the average of the surrounding speckles. Although it contains a small percentage of the image energy, the peak also appearing in the planet's image therefore improves N times the average planet contrast with respect to the image given by a single sub-aperture.

Planet detection is probably also feasible from the ground /4/, using adaptive optics to correct "seeing" as much as possible. Residual "seeing" brightens appreciably the feet of the Airy disk, but a passive variant of the dark speckle technique can in principle extract the information /3/. In space, baselines reaching 10 km can in principle resolve some detail on the planets.

Diffraction patterns from gravitational lenses

Calculations /5/ indicate that invisible planet-like bodies which may be present within parsecs in the interstellar darkness may become detectable through the diffraction associated to their lensing effect. If sufficiently spherical, they project on the Earth and on the Moon images of stars, from background galaxies, which resemble an Airy pattern with peak size of the order of 3 to 300 m. As they drift across a telescope or array, these peaks cause characteristic light pulses lasting a few milliseconds. These signals can provide information on the invisible body, and also images of the background sources. Once a dark body has been detected in this way by a wide-field telescope observing a nearby galaxy, recurrent diffraction events may be expected at its position, as stars from the galaxy happen to cross the line-of-sight. Optical arrays in space may be inefficient for discovering the bodies, owing to their narrow field, but they are uniquely adapted to observe the recurrent events caused by a previously detected body

Detection of gravitational waves

Calculations /6/ suggest that gravitational waves emitted by fast binary stars, pulsars, etc... may become visible in the form of modulated or expanding arcs surrounding these sources, when background stars are present near the line of sight. Since the apparent size of the Einstein ring for a one-solar-mass star located at 10 parsecs is a few arc milliseconds, a comparable angular resolution is needed to detect this effect. The "seeing" noise caused on Earth by the atmosphere obviously favors observational attempts in space.

## CONCEPTUAL DESCRIPTION

### Overview

Because it involves Fizeau-type optics the LOVLI system considered here (figure 1) differs markedly from the ground-based Optical Very Large Array under construction /1,2/ and from the Moon-based versions previously described /7,8/. It is a self-deployable array of moderate-size telescopes (0.3 to 1.5 m). Telescopes as small as 30 cm can meet much of the scientific objectives if there are enough of them. The optimal trade-off between the number N of telescopes and their size, for a given delivery capacity on the Moon, deserves to be evaluated

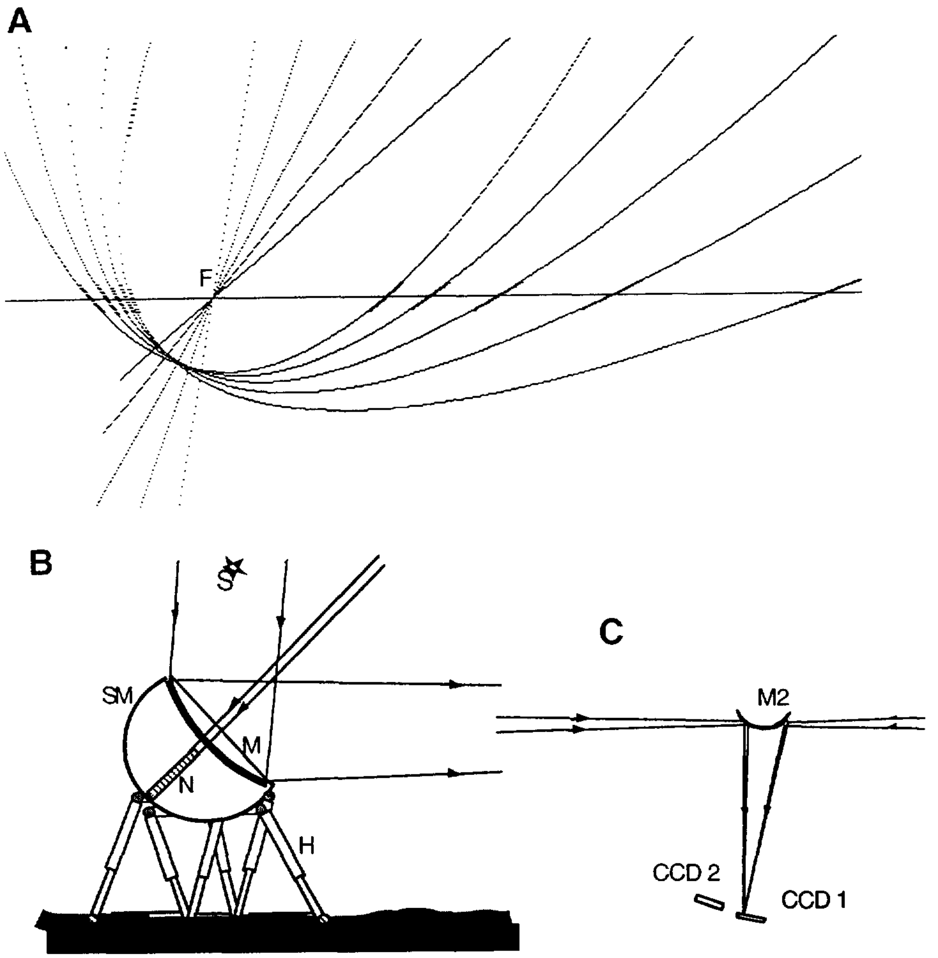


Fig. 1: The LOVLI concept: A - Principle of a planar Fizeau array. A giant paraboloidal "virtual mirror", here shown in cross section at different times as it rotates around its focus, can be matched by mirror segments (thick lines) if these are deformable and movable in the horizontal ground plane. **B** - Deformable mirror segment with its hexapod mount. The segment is nearly flat and has a central hole. Pointing first requires a coarse adjustment of the normal direction, achieved by a camera N, using field-recognition techniques to acquire the field expected to appear in the normal's direction. Fine pointing and active mirror shaping use signals from the focal camera. S - observed star. M - active mirror (curvature enlarged for clarity, actuators not shown). SM - spherical mount. H - hexapod carrier with micrometric capabilities. A small corner cube reflector, not represented, is also located at the center of the segment for laser metrology. C - Central recombining optics: M2 - Cassegrainian hyperboloidal secondary mirror, with axis coarsely aimed towards the observed star for minimal field aberrations. CCD1 - acquisition camera. CCD2 - camera for reference star. Auxiliary optics, not represented, may be added for multi-spectral imaging, spectrography, polarisation analysis, etc...

closely. Both the efficiency of image reconstruction and the system reliability benefit greatly from a large value of N, whereas very high limiting magnitudes, beyond perhaps $m_V$=25, would require telescopes larger than 50 cm, which may be considered for a second-generation system. Pending a more detailed study, the case of 20 to 27 telescopes, each 50 cm in size, is taken as an example in the following description. In the absence of human attendance, the desired reliability can thus be achieved with numerous small telescopes and occasional (every six years for example) deliveries of additional telescopes.

## Lunar site

It appears desirable to utilize a site located near one of the lunar poles, where the grazing illumination from the Sun and Earth leaves shadowed areas in the craters. The obvious disadvantage in terms of sky coverage is more than offset by the observing continuity achievable, the thermal stability, and the fact that the nearly continuous solar illumination received on the overlooking polar summits makes it unnecessary to utilize power systems containing dangerous radio-isotopes or high-capacity batteries.

## Optical design

Like the Optical Very Large Array, parts of which are under construction, the LOVLI has collecting elements arranged along an elliptical ring, which materializes the intersection of the ground plane with a giant paraboloidal "virtual mirror" aimed towards the observed object. In the LOVLI case however, the virtual mirror is generated somewhat more realistically since the collecting elements are mirror segments actually shaped to match exactly the shape of the virtual mirror. The virtual mirror has its focus located close to the ground plane, and rotates around it to track the star's motion. For a non-polar site, the intersection is therefore a deformable ellipse, and the mirror segments located along this ellipse must themselves be deformable. The array geometry thus obtained is hereafter referred to as a planar Fizeau array since the collector segments are in the same plane as the primary focus. At a lunar pole, the ellipse rotates around the central station without changing shape, and the segment shapes can also remain invariant during the observation.

For a 260 m baseline, with the axis of the virtual mirror pointed at 60° from zenith, the most deformed mirror element is located at 17.4 m from the focus and deviates from flatness by 6.48 micron peak-to-valley in defocus and 25.32 micron peak-to-valley in astigmatism if its size is 50 cm. The higher order Zernike terms are negligible. In order to fit the giant paraboloid at varied pointing attitudes, such parabolic deformations can be achieved, and varied as a function of the zenith distance and segment position, with simple active optics /9/ in the form of a few actuators bending the flexible mirrors. The proposed active segment consists in a flat mirror, 12 mm thick, with an external radius of 300 mm and a clear aperture radius of 250 mm. It is well known that parabolic deformations can be provided by a continuous, peripheral, radial bending moment distribution /10/. Our simplified design involves only 12 discrete peripheral bending actuators. To avoid their strong print-through on the optical surface, they act along the external radius, at 50 mm from the optical clear aperture. Each actuator has a radial 2-point, 10 mm apart, contact on the rear mirror surface. It provides a couple of forces, one pushing, the second puling, figuring the bending moment. The figure 2 shows for the above example that a 51 nm peak-to-valley and 9 nm RMS fit of the off-axis parabolic segment can be achieved with this actuators configuration. Maximal forces are about 180 N, and the required precision is 0.1 N. The maximal internal tensile stress is about 1 MPa for a glass ceramic, well below the breaking limit. The residual errors represent less than the half of the Raleigh's criterion and are choosen as the maximun error tolerable on a segment. The shortest interferometric baselines can therefore be calculated: they range from 70 m for an object near zenith to 260 m for a zenith distance of 60°. Nevertheless, even shorter baselines, spanning a few meters, or larger zenith distances, can be obtained without causing undue curvature to the segments or high-speed segment displacements, by grouping the active mirrors close together along the elliptical ground track. Note that we considered here a segment without central hole. In the case of a central hole, the simple peripheral actuators configuration induces spherical aberration and is no longer consistent. Mirrors with an axi-symmetric variable thickness distribution should be considered.

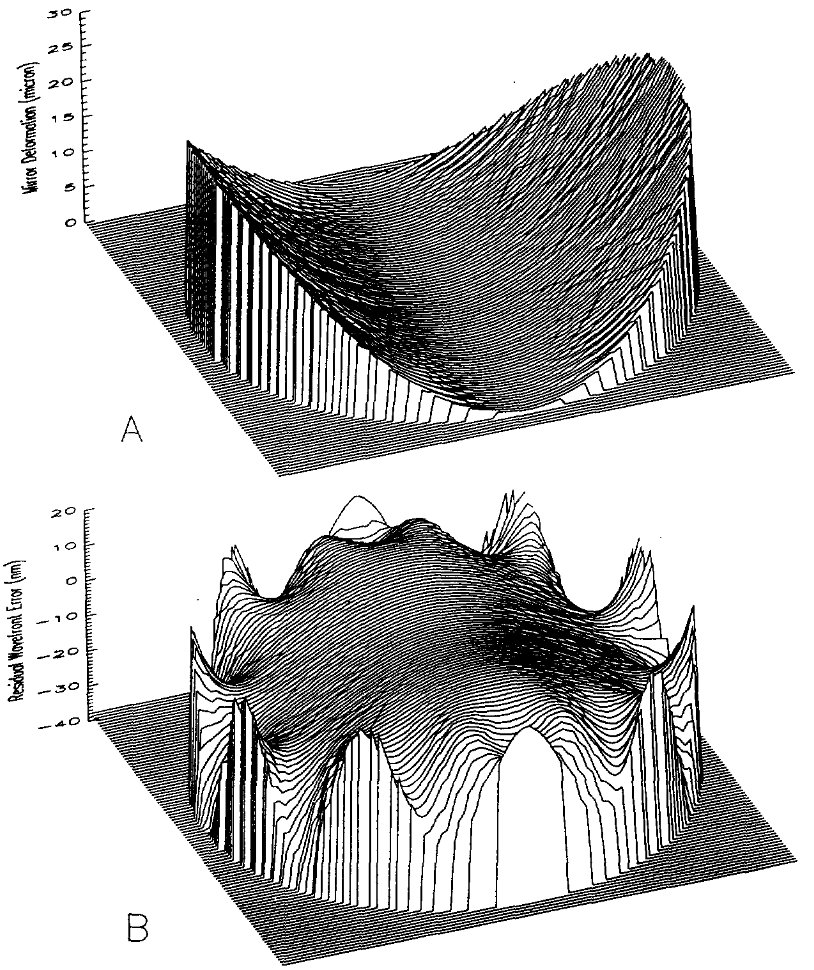


Fig. 2: **A** - The mirror segment the closest to the central station (17.4 m for a baseline of 260 m and a zenith distance of 60°) has to match this off-axis portion of the giant paraboloidal "virtual" mirror. Other segments are less deformed. **B** - Residual wavefront errors between the off-axis paraboloid and the deformed segment. Wavefront errors = 51 nm peak-to-valley, 9 nm RMS. The material considered is a glass ceramic, (Young's modulus = $9.1 \times 10^{10}$ Pa, Poisson's ratio = 0.24). Gravity effects raise a negligeable extra deflection since they are compensated by a ring of three passive levers having a triple contact point at an intermediate radius under the mirror.

The planar Fizeau optics, thus implemented as a close approximation to a giant Cassegrainian telescope built in mosaic form, provides a larger usable field than the OVLA and other Michelson designs. Even more field is achievable with an additional mirror following M2, achieving for example the equivalent of a Paul-Baker telescope. However, extra-axial aberrations are very strong with the f/0.25 aperture of the virtual primary mirror. Paraboloidal M1 and M2 mirrors provide zero coma and astigmatism, but only to the third order. Considerable coma appears when the primary aperture increases from f/1 to f/0.25. The latter value, ensuring the planar array, makes it unnecessary to carry M2 atop a tall mast, which would raise appreciable difficulties for deployment and operation. Suitable trade-offs have to be explored, using possibly highly aspherical correctors such as adopted by Ardeberg et al. /11/ for their proposed 25-meters four-mirror telescope with a f/0.9 primary. A non-planar 3-mirror solution, with a 1° field, has also been proposed for the GAIA (Global Astrometric Interferometer for Astrophysics) Fizeau interferometer project by Lindegren et al. /12/.

Optical path equalisation and phasing

Unlike Michelson's interferometer, the system is equivalent to a giant telescope carrying a multi-aperture mask, and therefore provides a fringed spread function which is invariant with field position, across the aberration-free field. As a result, a reference star appearing in the field at the same time as the observed object can provide the information needed to achieve blind phasing on faint or extended objects. A low-accuracy metrology system, using for example laser pulses rather than fringes, can provide a sufficiently accurate coarse knowledge of the system's geometry. Rather than the complex fringe-counting laser systems considered in previous proposals /13/, computer-controlled versions of commercial laser theodolites may suffice.

The coarse equalization of optical paths is achieved by moving the telescopes during the observation, instead of using optical delay lines which necessarily introduce extra reflexions. Each mirror segment is supported and translated by a hexapod mount walking on the natural ground. Wheeled rovers carrying a 1-axis fine translator and a 2-axis rotator may also be considered to move the segments. For a 400 m baseline and a star at 60° from zenith, a 1-meter translator allows 9 minutes of observation for the fastest mirror segment, lying at 746 m from the central station. The duration improves at smaller zenith distances. Signals from the laser theodolite provide coarse feed-back to the translators. The fine optical path equalisation and phasing is done by piezoelectric elements carrying the mirrors, using signals from the recombining camera: the Fourier tranform of the image for an unresolved reference star is the autocorrelation function of the pupil, where distinct peaks correspond to each pair of sub-apertures if the array is non-redundant. The phase which is measured in each peak provides the signal required for phasing the array. The phasing thus achieved on the reference star, which may be off-axis, can instead be applied to the faint object of interest, located on-axis. This requires a phase correction, calculated from the known aberration terms and the known separation. In the case of Michelson-type arrays such blind phasing capability requires a complex double-coudé system /7/, unlikely to be implemented in a first-generation instrument.

Pointing

The coarse pointing of each off-axis paraboloidal segment is achievable by first aiming its normal direction towards the stars which happen to be there. Knowing the position of a given segment, from the laser theodolite located in the central package, it is indeed possible to calculate its normal vector, and the track which it follows on the celestial sphere while the observed star is tracked. A small auxiliary telescope with CCD sensor, looking through the segment in its normal direction, acquires the field thus defined. Field-recognition software /14/ makes it unnecessary to have encoders. The segment's normal direction being thus oriented by the mount, with accuracy levels of arc-seconds to arc-minutes, one also needs to control the amplitude and azimuth of the predominantly astigmatic deformation which must be generated on the segment by the active optics actuators. This, together with the image stabilisation, is verified from the shape and position of the reference star's image in the recombined focal plane. The focal camera has fine pixels since it must capture the fine interference features, the size of which is smaller than the sub-aperture's Airy disk by the same ratio as the size of the subapertures compared to the baselines.

Operational strategy for self-deployment

The pallet delivered by the lunar lander carries the telescopes, the central optics and the solar arrays mounted on small rovers. First, the rovers move, with their own batteries, to a high point receiving direct solar light, for example the central peak of the polar crater or its rim. Once there, they deploy their solar cells and start transmitting power to the system, in the form of laser beams. Each of the unit telescopes then begins walking, or roving, towards its assigned initial position. The central station may, or not, itself be carried some distance away from the lander.

The telescopes align themselves, and observation can begin on a bright star close to the celestial pole of the Moon, itself close to the local zenith if the site is nearly polar. Little or no telescope motion is required when observing such high-declination objects. Very short interferometric baselines are obtained by reducing the clear aperture of the segment to avoid unreachable deformations. Once fully adjusted and calibrated, the system may undertake routine observations, initially on bright stars with small baselines, and progressively in more difficult conditions once enough operating experience is gained.

## TECHNOLOGY STATUS AND REQUIREMENTS

### Phasing the array

The main difficulty of optical interferometry is the extremely tight requirements for optical phasing. An optical array may be viewed as a giant telescope, the optical quality of which has to meet Rayleigh's criterion of wavefront errors amounting to less than a quarter of wavelenght. This implies sub-micronic positioning tolerances on some critical elements, and low levels of vibrations. Each component telescope is pointed with 0.1 to 0.01" accuracy, and its position is adjusted within the correction range of the fine phasing mechanism. Instead of gyroscopes, gravity sensors and encoders, constellation recognition algorithms such as developped by Baldini et al. /14/ provide coarse and fine pointing. Neural architectures are considered.

The progress of adaptive optical techniques in the recent years shows that such extreme tolerances can be met provided that the observed object, or a reference star close to it, provides fringe signals usable to activate the servo loops. In space, unresolved stars as faint as $m_V$=20 to 25 may provide enough photons during the characteristic time of mechanical drift to meet this condition. In the Fizeau case, the availability of brighter reference stars in the field of view, with the stable isoplanaticity characteristics achievable above the atmosphere, makes the phasing easier (see previous section) and tends to relax the mechanical stability tolerances, as well as the accuracy required for the metrology system.

### Mechanical, optical and electronic systems

Another difficulty is the complexity of these systems. Many mechanical degrees of freedom have to be controlled with accurate servo systems. Ensuring a sufficient level of reliability requires a careful and proven design. Considerable experience has now been gathered on these aspects with ground based interferometers, but limited experience is available on mechanical performance in the lunar conditions. The low temperatures, expected to be of the order of 60 K in a permanently dark crater, are helpful in several respects (linear motors with supra-conductive windings may be considered for the hexapod robot) but they raise problems of friction and sticking for the mechanisms. The elastic properties of the mirror, made of a borosilicate glass or a glass ceramic, do not change dramatically at 60 K with respect to room temperature: the Young's modulus only increases by about 10% leading to slightly larger internal tensile stresses.

There are many ways of designing the system, as indicated by the diversity of the published projects for ground and space. All require complicated mechanisms for pointing and the correction of the optical path differences arising as the Moon rotates. The main technical challenge is to find simplified designs and correct choices of trade-offs. The ground-based experience gathered so far is invaluable in these respects.

### Launcher and orbit

A preliminary mission analysis performed at CNES by D. Moura shows that an Ariane V launcher can deliver up to 800 kg on the Moon. In addition to the usable surface equipment, the mission requires a landing device and a transfer spacecraft leading to injecting a mass of about 4 tons in the lunar transfer orbit.

### Power

Favorable sites for a lunar interferometer are the dark craters located near the poles. Several among the possible craters have a central peak and rims which receive the grazing solar illumination most of the time. These local summits are possible sites for the few square meters of solar array, made of high-efficiency AsGa cells, needed to power the array, itself located in the lowland part of the crater. Because the telescopes are movable, a favored solution for transferring power from the solar array to the telescopes and central station involves beams of near infrared laser light, aimed from the array towards each of the receiving units. The efficiency of diode lasers reaches 20-30%, and new materials have increased their life expectancy. Several solar power stations should be installed on the various high points within eyesight from the observing site, so that a continuous supply of solar power be collected when some of the stations become shadowed. Each station has a few square meters of solar cells, aimed towards the horizon and possibly fixed. It also has a small emitting telescope in order to point the laser beam towards whatever interferometer element which may be in need of battery recharging. Battery-less operation can also be achieved, using multiple emitting telescopes, each feeding an interferometer element. Power cables can also be laid from the stations down to the instrument if some convenient battery recharging scheme is found. Such power systems are generally of interest for all instrument projects at the lunar poles.

Data rate

The camera outputs can be pre-processed on-board to a large extent, for reducing the transmission bandwidth. Some diagnostic data from the servo systems, etc... are desirable in certain circumstances, but most of the control is achievable by local processors. The data rates needed do not appear to exceed one megabit/s. As seen from the power stations, the Earth is close to the local horizon, and this may allow a direct-view optical or radio link to geostationary satellites. It is unclear yet whether nearly polar sites meeting this condition can be found.

Alternately, a radio link at such lunar latitudes can be implemented through a lunar orbiter. A circular polar orbit at 100 km altitude can provide a few minutes of data transmission every 2 hours, and is suitable for a latitude higher than 85 degrees. A higher polar orbit, at 1000 km altitude, can provide transmission during a few tens of minutes every 3.6 hours.

Lifetime and automated maintenance

In the absence of human attendance, the desired reliability appears achievable with numerous small telescopes for a design lifetime of the order of 5 to 10 years. Every 6 years for example, deliveries of additional telescopes could be sheduled. New telescopes would replace any which have failed, and the surplus ones would be added to the array for increasing N. Extra mobile segments can be inserted at any time without changing the central optics. These follow-up segments can be larger than the initial ones.

## COMPARISON WITH ORBITAL PROPOSALS

Among the proposals made for long-baseline interferometers in Earth orbit, the TRIO concept /15/ may serve for comparison since it has expandability characteristics comparable to the LOVLI. With its free-flying elements controlled by solar sails, it provides a global tilting of the array, thereby avoiding the internal geometry changes required for a planar Fizeau design constrained to remain on the lunar surface. TRIO moreover can be designed as a non-planar Fizeau array: therefore, the virtual primary mirror can have a focal ratio noticeably larger than 0.25., with the secondary mirror far above the flying array, to reduce the off-axis aberrations. LOVLI's delicate mechanical translators and rotators are absent in TRIO. The solar sails, considered as micrometric actuators, have useful properties of zero friction and hysteresis, and low power drain, but the solar radiation pressure, of the order of $10^{-5}$ $Nm^{-2}$, provides very low accelerations. To achieve kilometric baselines, this requires Lagrangian sites with low gravity gradients. Hours are needed for repointing an array across 90°, a problem which may be minimized by suitably arranging the observing lists. Types of ion engines now available (R. Laurance, private communication) may prove preferable. The low temperature of lunar sites can be of advantage, as well as the possibility of shielding the detectors from cosmic rays by burying them underground.

## CONCLUSION

Although optical arrays have been operated on Earth since 1974, Moon-based systems raise a number of unsolved problems. The reliable operation of the complex mechanisms is a challenge, even with the inherent redundancy provided by the numerous telescopes. The issue of whether or not optical delay lines are needed, and the selection of an optimal first-generation design requires more studies.

Judging from the experience gained with Earth-based multi-telescope interferometers, the critical items requiring more research and development for a lunar array are: 1- the robotic mechanisms, possibly incorporating piezo-electric linear or rotary motors, and their control softwares, which may require neural networks; 2- the limited adaptive optics required to cope with mirror deformations and the settling of the lunar soil under the "feet" of the translators; 3- the laser theodolite system; 4- the wireless transmission of power with laser beams towards moving targets; 5- linear motors with supra-conductive windings are also of interest for the robot legs, if the low polar temperatures allow their use with no active cooling, since they can apply force without power expanse when the robot stands idle or is in slow motion.

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