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AN OPTICAL VLA ON THE MOON

Bernard F. Burke

Department of Physics 26-335
Massachusetts Institute of Technology
Cambridge, MA 02139

The Moon as an Observing Site

Optical observations on the Earth must cope with the refractive disturbances of the atmosphere, perturbations by the day-to-night thermal cycle, vibrations induced by the wind, and the bending of the telescope by gravity. These all conspire to limit telescope performance. In particular, in trying to improve angular resolution, there seems to be a practical limit of the order of a few tenths of an arc-second for the realizable angular resolution of single-aperture telescopes, largely imposed by the atmosphere, although other structural limitations would appear as limits at one-tenth of an arc-second or so.

Radio astronomers have demonstrated that interferometric aperture-synthesis methods supplant single-aperture methods completely when high angular resolution is desired. The same analysis applies to the optical problem, although the signal-to-noise ratio (SNR) considerations for the radio and optical domains differ. A variety of optical interferometer concepts were discussed at the Cargèse Symposium in 1984 (ESA 1985), and Burke (1985) proposed that a lunar location might be attractive. A more extended treatment of the radio-optical congruence was presented shortly thereafter (Burke 1987). At the Washington Symposium on Science from a Lunar Base (Mendell, 1985; Burke 1985), it was pointed out that the Moon appeared to be a preferred location for optical interferometry in the microarc-second ranges. Shortly thereafter, Johnson examined the engineering questions independently and gave a detailed summary of publications to 1988 on the broader aspects of a lunar observatory (Johnson 1985, 1988). The principal limitation is the cost of establishing an astronomical optical array on the Moon, which could be large if the construction has to be carried out remotely. The concept becomes more realistic if a human-tended lunar base should be established on broader policy grounds by the USA or by the USSR, separately or cooperatively. The construction of a large interferometric optical array then becomes a natural focus of scientific activity at such a base.

The concerns that had been voiced about the lunar environment were treated by Burke (1985a), where it was shown that the apparent problems were unlikely to be substantive. The concerns about lunar dust are largely answered by examining figure 1, which shows the deployment of the lunar laser reflector by the astronauts of Apollo 15. The footprints in the foreground are crisp, showing the cohesiveness of the lunar soil; the laser reflector being deployed in the background has shown no noticeable deterioration over the past 20 years. When the lunar surface is disturbed, dust particles can be kicked up; these travel in ballistic trajectories and generally stick to what they hit. The natural disturbance rate is low, but it is clearly important to avoid needless human activities in the vicinity of lunar-based optical instruments. The seismometer deployed by the Apollo astronauts has given another useful datum: the lunar seismicity is less than 10^{-7} than that of the Earth, and moonquakes will present no problems. Background light from the Moon is less trouble than for a satellite-based system in low-Earth orbit (LEO), and the problem of shielding from sunlight is much easier on the Moon because of the ability to construct suitable, cost-effective shielding structures. Similarly, the thermal environment, with the proper shielding that can be provided on the Moon, is more benign on the Moon than elsewhere.

Constraints from the Scientific Goals

A recent study by the National Research Council National Academy of Sciences (1988) summarized a variety of scientific goals that might be attacked by interferometric means. The problems that might be attacked by optical aperture-synthesis arrays are summarized in figure 2, which shows the various regimes in a distance-linear size plot, in which constant angular resolution shows as a diagonal line. The most interesting problems demand angular resolution considerably better than a milliarc-second, a microarc-second is a marvelous goal, but 10 microarc-seconds would yield an instrument of revolutionary capability. Baselines much greater than 100 m in length (i.e., resolving power better than 1 mas) are not easy to achieve with structures in Earth orbit, but on the Moon, once a lunar base is established, it should be a straightforward project. A resolution of 10 μas would require a 10-km baseline, which would present no real difficulties. A goal of one mas, requiring a 100-km baseline, is feasible, but the technological problem of relaying the signals over the curved surfaces of the Moon would have to be addressed. One scientific area of great current interest, the study of galactic structure near the central cusp, has not been included in the plot, and is one major problem that could be attacked with a smaller instrument, in the 20-30 m size range.

The problems that might be addressed in the infrared part of the spectrum have not been summarized as fully in the literature, but can be summarized as the study of stellar formation, the production of circumstellar discs, and protoplanetary systems. In general, the problems do not require as high an angular resolution. Nominally, the range of resolution is from 1 mas to 1 arcsec. At $\lambda 10\mu m$, the work will probably be done best from ground-based facilities, but at wavelengths from $\lambda 2\mu m$ to $\lambda 10\mu m$, the space environment is probably superior. This implies interferometer dimensions of the order of 10 m to one km. Although the optical and infrared interferometric arrays may have some degree of mutual compatibility, it is probable that different arrays will be needed.

The prospect has been raised that planetary systems belonging to nearby stars can be imaged directly by optical interferometric arrays (Burke 1986). There are special requirements on the optical quality of the system that go far beyond the requirements of the two general scientific areas discussed above. On the other hand, a maximum baseline of 20 to 30 m is entirely adequate, and there are special demands on optical quality that are more vigorous than for a general purpose array. The likely outcome, therefore, is that a planetary interferometric array would be a separate project, relying upon the same facilities and personnel of a lunar base, but physically distinct.

Elements of the Project

Assume that a lunar base has been established, that a freighter system exists to carry supplies and equipment to the Moon, and that among the residents of the lunar base there will be personnel to assemble, adjust, and deploy equipment. The scientific objectives suggested by figure 2 and by the discussion of the previous section should be addressed in an impressive way by an array with mapping capability in the range of 10 mas to 10 μas. The general specifications of the array are set by these scientific objectives.

The sensitivity of the array should be sufficient to allow the study of 20th magnitude objects; this means that detection alone is not enough, since maps with many resolution elements would be the output in most cases. The point-source sensitivity of an N-element interferometer, in the absence of extraneous noise, is independent of the number of elements provided that the total area remains fixed (Burke 1987). The desired point-noise source sensitivity, therefore, is determined by the magnitude limit, and the total area of the array is set. The number of elements can then be specified by the interferometric aperture-synthesis requirements, combined with practical economic considerations.

If a 20th-magnitude object, composed of a thousand elements at maximum resolution, is to be mapped, this means that the equivalent point-source sensitivity should be 28th magnitude. An object of 28th magnitude yields a total photon flux of the order of 1.5 photons/m^2/sec, and an integration lasting 1 hour would yield 5400 photons to be processed by the correlators for all baselines, for a device of complete efficiency. At fractional bandwidth of 10 percent is probably the best one could hope for, and a throughput of 10 percent is also a reasonable assumption, given the many reflections needed in the optical train. Thus, the detected photon flux for a real system might be of the order of 50 photons/m^2/hr.

The SNR (or S/N) of each interferometric pair, for n_{phot} total detected photons detected by an N-element array, will be:

$$(S/N) = (2n_{phot} / N(N+1))^{1/2} / \sqrt{2} \qquad (1)$$

Two photons are required, at a minimum, to estimate fringe amplitude and phase, and during the integration period the instrument itself must be phase-stable. Assuming that the stability condition has been met, an N-element array having a total area $A=NA_o$ (A_o=area per element) will yield S/N equal to

$$(S/N) = (S\,At / (N+1))^{1/2} = (S\,A_o t)^{1/2} \qquad (2)$$

for a detected photon flux S and integration time t. Hence, a collecting area (per element) of 1 m^2 will give two photons in an hour per element if there are approximately 27 elements in all. It should be remembered that this is an extreme example: a 1-sigma fringe estimation per pair, with $N = 27$, gives 5-sigma detection of a 28th-magnitude object in an hour, when the individual fringe estimates are coherently added. The scale of the instrument, then, could be on the order of 27 1.6 m telescopes; there are reasons to be conservative in the specifications. The total collecting area would be about 50 m^2 in this example.

The wavelength range could be anywhere from 0.1 μm to an infrared wavelength of perhaps 3 μm. There is reason to limit the long-wavelength limit if optical relaying of the image to the central processor is used. Diffraction spreads the light in the relay process, and delay lines, especially, become large. An infrared instrument, beyond this range, probably requires different design considerations. Within these general assumptions, one can outline the general specifications of a real system, indicate the alternative choices, and assess the state of the relevant technology.

In succeeding sections, the nature of the telescope elements, the possible array configurations, the possible types of delay lines, the correlator requirements, shipping and deployment, and operational considerations will be discussed.

Weight and cost estimates are highly uncertain at this time, but reasonable projections are not entirely impossible. One factor seems to be especially pressing: the equipment should not be space-rated in the usual way. The reason for placing the facility at a lunar base is to take advantage of human presence to assemble, deploy, and service the equipment. In this respect, there is a fundamental difference between the proposed lunar optical interferometer and an automated space facility of the usual type. Today's space facilities must operate for years without direct human intervention or, if there is human servicing, it is clumsy, expensive, and ad hoc. Lunar gravity may turn out to be an unexpected ally in this respect: it will fix the equipment and give the astronauts firm ground to stand on.

The Telescope Elements

Design and construction of a lunar-based telescope is far easier than on Earth. These stem from two fundamental mechanical restraints, gravitational deflection and columnar failure. These put constraints on the accuracy and sturdiness of a structure, and depend upon Young's modules, Y, density p, the moment of the cross-section I, and the local acceleration of gravity as follows:

Deflection of a beam: $\varsigma = \gamma (p / Y) g L^2$ (3)

Length of Euler buckling: $L_E = I (Y / (gM))^{1/2}$ (4)

The net deflection of a real truss can be much less than the ς given in equation 3 (γ is a geometrical factor, and is essentially the square of the length-to-depth ratio of the beam). The homology principle, originated by von Hoerner, recognized that gravitational deflection must occur, but since real 3-D structures are generally redundant, a fixed set of points can continue to lie on a given quadratic surface except for translation and rotation, despite the internal deformations. There are more degrees of freedom than constraints, and physically real homologous solutions usually can be found for real structures. Of course, no real structure is perfect, and for a reduced γ, the above equations will still represent the order of magnitude of the net deflection.

The buckling criterion affects the weight of the supporting structure. In practice, buckling occurs for a smaller length than L_E, but the above accurately represents the dependence upon g for a fixed mass M. The net effect is that a sufficiently robust structure on the Moon will have considerably lighter elements than an Earth-bound telescope. In particular, a daring (but still practical) design for an Earth-bound telescope becomes over-designed when it works under lunar gravity.

It seems prudent, therefore, to design telescope elements that could be tested on Earth, but which are light and compact enough to be assembled by lunar-base personnel. To meet the total area requirements with a reasonable number of telescopes, the reflector diameter would be greater than 1 m, but a diameter of more than 2 m would seem to be cumbersome for easy handling at a lunar base. In this example, a diameter of 1.6 m will be assumed, as a reasonable compromise.

The telescope could be mounted equatorially or in an alt-azimuth configuration; the latter is probably to be preferred, even though field rotation would be needed. The optical design should have a wide field of view, to allow nearby stellar objects to be used as phase references for the system.

The mass of the telescope, the telescope mounting, and the base (which might easily carry the shielding cabin as well) can be scaled to the lunar environment, using the above considerations, from Earth-based experience, although the design of radio telescopes may be more relevant than conventional optical design. Earth-based optical telescopes are massive because they must withstand stresses such as vibration and wind torques that are not present in the lunar environment. Recent developments in mirror design have reduced the mass of optical mirrors dramatically, and this then allows lighter supporting structures. A 1.6 m mirror, made for lunar use, should have a mass of no more than 160 kg (and should, with proper attention to scaling laws, be even less massive). This reflects into the following mass budget, using modern high-strength composites: The mass seems small

Mirror	160 kg
Telescope	160 kg
Alidade	160 kg
Auxiliary Equipment	100kg/total
	580 kg

compared to Earth-based optical telescopes, but if it were to be tested under Earth gravity but free of air currents, vibration, and thermal gradients, the instrument should have good optical performance. This would become even more favorable under the reduced lunar gravity.

Despite initial fears that the thermal and radiation environment might be hostile, it has become clear that, with proper attention to shielding, the Moon is a relatively benign environment, especially when compared to the Earth-orbited environment. Free-flying telescopes must carry their own light and radiation shields, but there is much greater freedom in designing such structures on the Moon (although the shield still might be preferably mounted as part of the telescope). They can be light, delicate structures, since the wind never blows and they can be constructed *in situ* without having to withstand the stress of launching in the deployed form. Figure 3 shows a conceptual drawing that expresses the philosophy: the eventual shape and scale, of course, could be quite different. The mass of the shield should be no more than 100 kg, and with the telescope mass given above, the total mass of telescope plus shield comes to 680 kg.

Array Configuration

There is a strong scientific imperative to go to an optical array that would yield 1-mas resolution at λ5000, but this requires a maximum baseline of 100 km. This is not out of the question, but there is a real problem that would have to be surmounted: the curvature of the Moon's surface. The deviation in elevation from the tangent plane in meters is $R^2/3$, where R is the distance in kilometers, and thus a radius of 50 km from the central station involves a height change of 0.75 km. This is not an insurmountable problem, but if an array of one-tenth that size were planned for, the height difference shrinks to about 7.5 m, a far easier, almost trivial effect compared to the random relief that will be found. The basic assumption, therefore, will be that the most distant element will be 6 km from the central station. For a VLA-like Wye configuration, this gives a maximum UV spacing of about 11 km, and this can serve as a nominal parameter for the exercise.

There is an alternative configuration that may have advantages: The "Cornwell Array" or "Cornwell Circle." This configuration, derived from studies of the physics or crystals, represents an optimum solution to the problem of placing N antennas within a square of given size, using the entropy of the UV distribution as the figure of merit. The result is antenna placement on a circular locus, but unevenly spaced, with a transfer function that has a quasi-crystalline look in the UV plane. The details can be found in the report of Cornwell (1987).

The choice between the "VLA-Wye" and the "Cornwell Circle" will probably be determined by the balance between the need for several array configurations addressing angular-size ranges and the sufficiency of a single array configuration for most problems of interest. Any finite array is a spatial filter whose transfer function spans a range from the maximum array spacing to a minimum spacing (in angle, from the angle of maximum resolution to a maximum angle), and this implies in turn that angular structures requiring spatial frequencies lower than the minimum array spacing cannot be studied. This, of course, is why the VLA was made variable in extent: For extended objects, the most compact configuration is used; the largest possible array gives the high angular resolution needed for the most compact objects. Intermediate configurations are used for those cases where either a compromise is indicated, or when scaled arrays are desired at different wavelengths. Concentric Cornwell circles could be used, of course, but the Wye gives scaling most easily.

The antennas could be moved on rails (as they are for the VLA) or they could be transported by a wheeled carrier, which would then deposit them on hard points fixed in the lunar soil. The choice would have to depend on the results of a detailed engineering study; for the purposes of this exercise railroad tracks will be adopted as the baseline with the full realization that a wheeled transporter might ultimately be preferred. Tracks have the desirable property that they are kinematically well-defined, and will conduct the telescope to the hard points with a minimum of final adjustment. Because the lunar gravitational acceleration is only one-sixth that of the Earth, the weight on the rails is modest: the conservative mass estimate given earlier would predict a mass of less than 700 kg (i.e., a weight of 64 lb on each of four wheels). This would imply that the rails and ties could have a mass as small as 1.5 kg/m.

The hard points on which the telescope elements would be mounted need not be massive, deeply seated foundations in the lunar surface. The lunar soil is surprisingly resistive to penetration, based on the Apollo experiments and on the Lunakhod penetrator results. A cylinder 10 cm (or even less) in diameter driven 1 m or so into the lunar soil would almost certainly be an adequate post; three of these would easily support the telescope in a competent fashion. These would be placed beforehand at surveyed locations, and the competence of the lunar soil is such that no movement would be expected.

Optical Design

The conceptual design of an optical aperture-synthesis array is fundamentally the same as the radio counterpart. The design might follow the general outline of the VLA (Napier et al. 1983), applying the same general principles outlined in the monograph of Thompson et al. (1986). The physical realization would look quite differently; the optical interferometer described by Colavita (1985) and its extension, as outlined by Shao et al (1986) illustrates the main components. These are (1) the telescope, (2) the telescope guidance system, (3) the optical relay system, (4) the delay line system (and its associated equalization devices), (5) the beam splitters, (6) the correlator, and (7) the data reduction system, which averages the fringe amplitudes and phases. The system must include a fringe stabilization system, using either a field star for a phase reference (this is much easier to accomplish on the Moon because of freedom from atmospheric seeing trouble) or by monitoring the entire optical path with a battery of laser interferometers, as currently practiced by Shao et al. (1986). The major large component that would need the most serious engineering attention is probably the delay-line system, which equalizes the optical path. The optical signals would be relayed as a quasi-planar beam, spreading slightly because of Fresnel diffraction. For the array dimensions that are contemplated, this means that the beam would be about 10 cm in diameter. Each delay line, one per telescope, would have to give a delay equal to the distance from the central station to the most distant station if full delay compensation were to be desired. This means a "throw" of 3 km unless a multiple-pass system is used. Super-reflective optics allow a certain saving, and the throw of the delay line might be some integral submultiple of 3 km; the particular design of delay line would have to follow from an engineering study that is yet to be made. Even a 3-km throw is not beyond reason; a set of carriages mounted on their own tracks, compensated by lasers in the fashion described by Shao et al. could be made to work. It would probably be a multiple-stage affair, with gross stabilization of the main carriage, with a successive set of subcarriages to give the final adjustments.

The delay-line system is not shown in figure 3, because of the great uncertainty in how it should be designed, but one can envisage N tracks radiating from the central station, each with its own laser-controlled mirror. A more elegant solution is to hoped for, but is not yet in hand.

The Cost

A prefatory remark is in order. If an optical array on the Moon were to be built to conventional flight-test standards, including complete man-rating, it would be an extremely expensive undertaking. The intention, however, would be to send the components to the Moon by whatever freight carrier is used to supply a lunar base. The mirrors would be stacked like a set of dishes (with appropriate spacers to avoid scarring), the mounting and alidade would be shipped in pieces, packed to avoid the mechanical stresses that accompany launch, and the material for the shielding cabins would be packed in bulk. Assembly would be on the Moon by the skilled personnel already there. Individual components such as telescopes and delay lines could be "throwaway" designs. It might be far better to have cheap elements, with a number of spares, than to have complex, elegant, super-reliable elements costing ten or a hundred times more. A cost tradeoff study would determine the best compromise. The fundamental conclusion, however, is that a basic philosophical change from current practice in experiment design will be needed because of the availability of personnel to construct and adjust the equipment and because of the stabilizing influence of lunar gravity.

With this caveat, one can start from the weight budget: These estimates

	Mass	Cost ($ x 10^6)
Telescopes and shelters	680 kg	2
Delay-line element	800 kg	4
TOTAL	1480 kg x 27 = 40 tonnes	162
Track (270 km @1.5 kg/m)	400 tonnes	100
Correlator and housing	10	10
Instrumentation	10	100
TOTAL	460 tonnes	372 M

are extremely rough, but they illustrate a few key points. The telescopes themselves are a minor component in the budget. The delay lines are an extremely critical (and uncertain) element. The biggest contribution is mass to be transported is the track, although it is not a prohibitive element. Nevertheless, wheeled transporters might well be preferred (but they, too, might not be cheap). Bulk transport should be far less expensive than current practice.

A comment is in order concerning the number of elements. The assumed value of N was 27, as for the VLA, but if binary beams splitting is preferred, the number of telescopes would be $2^N + 1$. There would then be 9, 17, or 33 telescope elements, in all probability. If there were only nine elements, the synthesis coverage in the UV plane would be inferior. An array of 17 elements gives excellent coverage, but the 33-element array would give superb UV coverage, especially for snapshots, where full instantaneous sampling of the UV plane is called for. Given the budgetary estimate shown above, the 33-element array might well be preferred. The instantaneous number of interferometer pairs is $N(N + 1) / 2$, and 33 elements can give, therefore, 528 independent samples instantaneously if the array is nonredundant.

In summary, therefore, the cost of an aperture-synthesis optical array, having the ability to give many different configurations, is not an unreasonable project, in scale, to be a major scientific objective of a permanent lunar base. The problems are well defined, and enough research is already in hand to give one confidence in finding workable concepts, ready to go as soon as a lunar base has been established.

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Figure 1: Deployment of scientific instruments on the Moon. Note the crisp footprints.

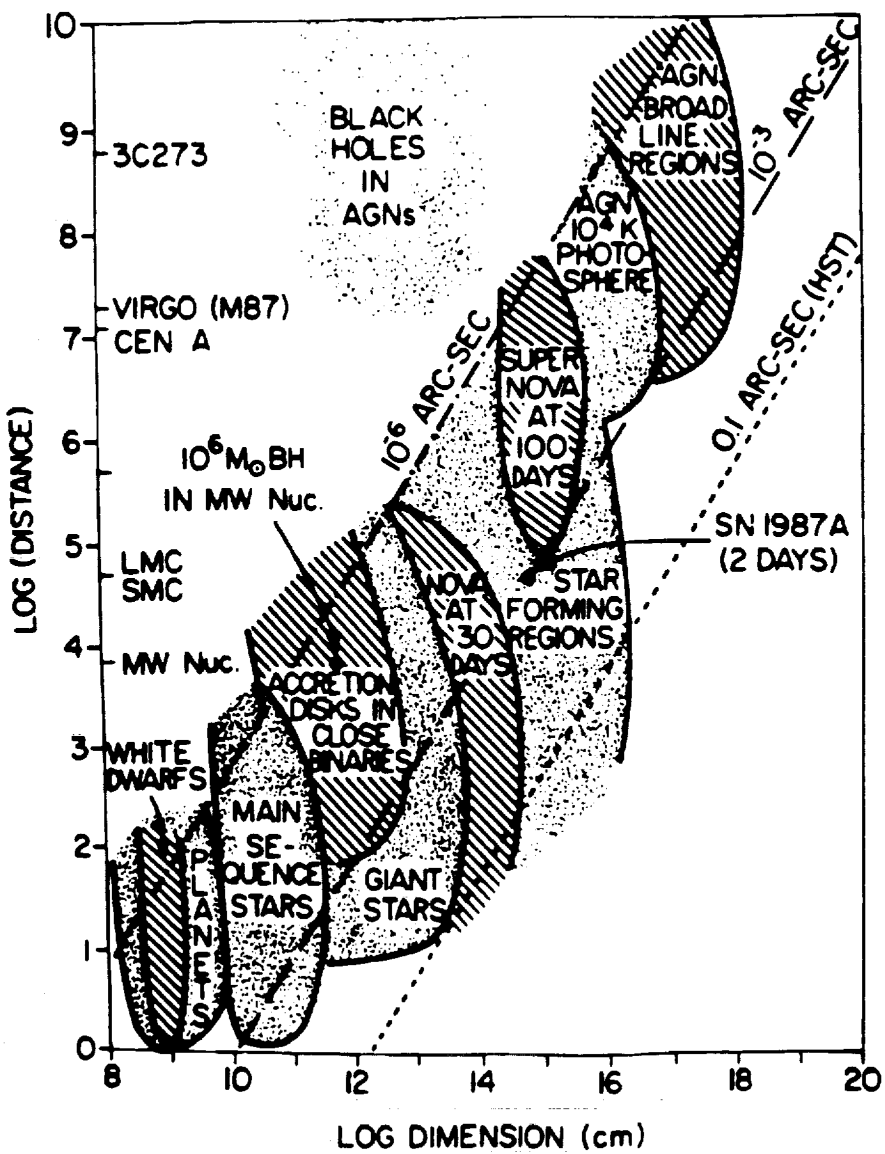

Figure 2: Scientific problems opened by angular resolution improvements. Distance is plotted against characteristic discussion of the object to be studied; constant angular size is given by the diagonal lines in the log-log plot.

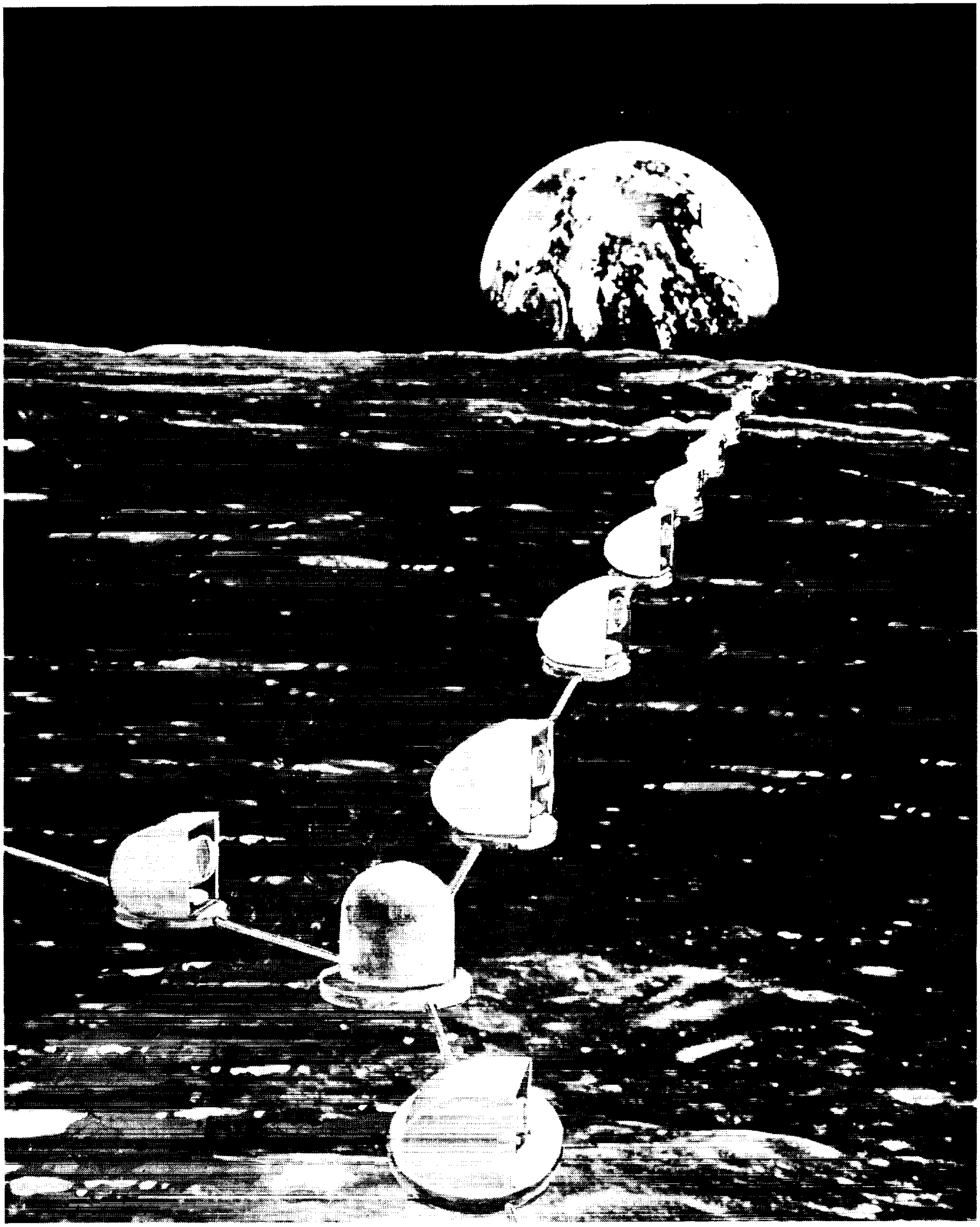

Figure 3: Conceptual rendition of an aperture-synthesis interferometer on the Moon. The delay-line system is not shown, but would consist of tracks radiating from the central processing station, in all likelihood.