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ASTRONOMICAL INTERFEROMETRY ON THE MOON*

Bernard F. Burke
Massachusetts Institute of Technology
Cambridge, Massachusetts 02139

Introduction

Optical interferometric arrays are particularly attractive candidates for a manned lunar base. The radio model already exists in the very large array (VLA) of the National Radio Astronomy Observatory, situated on the plains of St. Augustine near Socorro, New Mexico. A Y-shaped array of 27 antennas, each arm being 20 km long, operates as a coherent array, giving 0.1-arcsec resolution at 2-cm wavelength. An array of similar concept, but with optical elements, would therefore give angular resolution of nearly 1 μarcsec at optical wavelengths and would give an absolutely revolutionary new view of objects in the universe. It would not be built on the Earth's surface, because the atmosphere damages the phase coherence severely at optical wavelengths. It could be constructed in Earth orbit as an assemblage of stationkeeping free-flyers (proposals to do so have been put forward), but the technical problems are not simple (e.g., controlling element position and orientation to 10 nm at 20 km). If a permanent lunar base were available, an optical analog of the VLA would, in contrast, be a relatively straightforward project.

The Case for High Angular Resolution

Galileo's telescope was the first step in improving the angular resolving power of the human eye; this thrust in astronomy continues in our own time. The atmosphere of the Earth has posed a barrier at about 1 arcsec (perhaps one-third of an arcsecond at the best sites), but if optical instruments can be mounted in space, there seem to be few fundamental difficulties in extending to the microarcsecond range. Most of the problems are of a practical nature, centered on structural stability, satellite stationkeeping, instrument adjustment and control, and related technical questions. These problems are solvable in principle, but solutions may be costly if conventional orbital concepts are followed. Although the surface of the Moon has not been seriously considered in the past, it appears that a lunar location would be advantageous for astronomical instruments of great power. A permanently occupied lunar base could be a key factor in such a program.

Angular resolution can never be better than the diffraction limit λ/D, the wavelength divided by the aperture diameter, and at 500 nm, a 1-m aperture gives 0.1-arcsec resolution. Milliarcsecond and microarcsecond resolution will require interferometers of large size, but much wider classes of objects, all of great current interest, become accessible. These are illustrated in figure 1, which shows the approximate optical fluxes and angular sizes of a variety of stellar and extragalactic objects. Since the maximum flux and the largest angular size are indicated, objects in each class will generally fall along the locus indicated by the upward-sloping arrows. An object 10 times more distant than the closest member of its class lies at the tip of the arrow, for the given scale. The figure, therefore, gives the largest expected scale for each class of object.

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For the various classes of stars, Dupree et al. (ref. 1) have commented that measuring the size of a star is not enough. This conclusion is generally valid for nearly all astronomical objects. Most interesting objects tend to be complex, and understanding the physical processes requires some detailed knowledge of the phenomena. For most stars, at least a factor of 30 resolution beyond the gross size is certainly needed (i.e., about 100 pixels). Phenomena such as starspots, flares, and other analogs of solar processes will be interesting and, indeed, should be surprising. One must conclude that every class of stellar object (except for the closest red supergiants) will demand an angular resolution of a milliarcsecond or better.

The extragalactic phenomena are still more demanding. The complexity of the processes is not known, since we do not have close analogs (such as the Sun, for the stellar case) to guide us. The subject matter is of extraordinary interest, however. The physics of quasars, blacertids (extragalactic radio sources), and "ordinary" galactic nuclei are near (or perhaps extend beyond) the limits of fundamental principles. From both radio and x-ray observations of these objects, it is clear that enormous energies are generated, and the indications are very strong that the energy source must be gravitational.

"Black holes," though not yet demonstrated in nature, may be of fundamental importance in these energetic processes. The optical study of the accretion processes and instabilities near the cores of the active extragalactic objects, with high angular resolution, should be as astounding as it has been in the radio case, where milliarcsecond resolution reveals velocities that appear to surpass the speed of light. Figure 1 shows that only the broad-line regions at the nuclei of the closest Seyfert galaxies are accessible to an instrument of milliarcsecond resolution. The rest are smaller in angular size, and it is clear that an optical instrument having angular resolution in the 1- to 10-μarcsec range would have truly extraordinary impact. None of the objects is brighter than the 12th magnitude, and most are substantially fainter; an instrument having at least the collecting area of the Palomar 5-m telescope is indicated. This challenge of obtaining angular resolution in the milliarcsecond to microarcsecond range, with a net collecting area of at least 20 to 30 m^2, is fully justified by the scientific rewards that would surely be gained.

Aperture Synthesis

Radio astronomers have, for the past several decades, circumvented the problem of obtaining high angular resolution by using interferometry, culminating in the concept that is called aperture synthesis. The methods of aperture synthesis were, ironically, developed by Michelson (ref. 2) for measuring the diameters of stars at optical wavelengths, but the Earth's atmosphere hindered their quantitative use. The radio version of Michelson's stellar interferometer is illustrated in figure 2, which shows a pair of radio telescopes simultaneously receiving radiation from a distant source. There is a difference in arrival time, the geometrical time delay $\Delta\tau_g$, determined by the orientation of the source direction relative to the interferometer baseline. There is obviously no chance of interference if $\Delta\tau_g$ is larger than the coherence time t_c of the radiation, so a time delay must be inserted to compensate for this difference. Then, if the antennas are fixed and the source drifts through the reception pattern, the product of the received signal amplitudes varies sinusoidally as the signals interfere, alternately constructively and destructively. The primary reception pattern of half-width θ_B, the fringe spacing ϕ_F, and the delay beam ϕ_D are important characteristic angular scales. The analysis is most straightforward if the antennas track the source, when the source is small compared to the primary beam width θ_B. The fringe spacing is determined by the projected baseline D', which is the projection normal to the incoming radiation.

For the interferometer description, there is a third angle, the delay beam ϕ_D, which is determined by the receiving bandwidth or, equivalently, by the coherence time. If the time delay is set to match $\Delta\tau_g$ perfectly, the central fringe will have full amplitude, but as the time delay error grows, the interference conditions will be different at the upper and lower ends of the band. The interference effects cancel, and the fringe amplitude diminishes over an angle $\phi_D \sim 1/B\tau_B$, where B is the bandwidth and τ_B is the baseline length measured in light travel time. The number of fringes observed as a consequence is on the order of the inverse of the fractional bandwidth, an effect that has strong consequences for optical interferometry.

Given a two-element Michelson interferometer as illustrated in figure 2, the output is well specified if the following conditions are met: the source under study must be small compared to both the primary resolution θ_B and the delay beam ϕ_D, and the delay compensation must approximate $\Delta\tau_g$ with an accuracy corresponding to a fraction of the fringe angle ϕ_F, or at least the error must be calibrated to that accuracy. The interferometer output is the convolution of its sinusoidal fringe pattern with the source brightness $B(x,y)$, where x,y are angular coordinates on the sky. Therefore, the interferometer output is equal to the Fourier transform $B(u,v)$ of the brightness distribution. The conjugate coordinates (u,v) are defined by the baseline and the source location as shown in figure 2. On a plane normal to the source direction, coordinates (u,v) are defined (north and east, for example) and the interferometer baseline D, measured in wave numbers $(2 \times D/\lambda)$, is projected onto that plane with the reference antenna (which can be chosen arbitrarily) at the coordinate origin. The plane is called the u-v plane, and the projected vector $D'(u,v)$ defines the conjugate coordinates at which the Fourier transform $B(u,v)$ is defined by the fringe amplitude and phase. If all interferometer baseline lengths and orientations are taken, the complete Fourier transform is determined, and performing Fourier inversion gives a true map $B(x,y)$ of the source. In practice, of course, noise is introduced by the apparatus, the coverage of the u-v plane is not complete, and due caution and knowledge must be exercised.

The process by which the Fourier transform is developed is known as aperture synthesis, and substantial literature has been developed for the radio case. The first complete description, in which the rotation of the Earth was used to move the interferometer baseline, was conceived by Ryle and Hewish (ref. 3). An authoritative summary of the two-element interferometer has been given by Rogers (ref. 4). The most powerful aperture-synthesis instrument, the radio array known as the VLA (the very large array, operated by the National Radio Astronomy Observatory), is described by Napier et al. (ref. 5). The VLA probably provides the best model for a desirable optical instrument. Its 27 elements give 351 simultaneous baselines; therefore, "snapshots" of fairly complex objects are nevertheless faithful representations if the target is not excessively complex, or if a dynamic range of a few hundred to one is sufficient. At the same time, for large fields of view and complex targets, its variable configuration and capability to use the rotation of the Earth to obtain more complete u-v plane coverage is vital. The size of the array, 20 km per arm of 35 km equivalent overall size, was set by the original operating requirement that it should equal conventional optical telescope resolution (1″ at 20 cm, 0.3″ at 6 cm). The same considerations will apply to an equivalent optical instrument. The discussion in the beginning of this paper, illustrated by figure 1, indicates that a mapping capability of 10 μarcsec would give a rich scientific return. At this angular scale, significant changes can be expected for both stars and active extragalactic objects within brief timespans. The system must therefore have a large number of elements, as in the case of the VLA, which gives two further advantages: a large number of objects can be studied in a short time because of the "snapshot" capability, and the more complete u-v plane coverage can yield maps of high dynamic range. If the optical array contains 27 elements, each element would have to have a diameter of at least 1 m to give a total collecting area comparable to the Palomar 5-m telescope. The instrument should cover the wavelength range 121.6 nm (Lyman-alpha) to 5 μm; thus, for the mean wavelength of 500 nm, an optical aperture-synthesis array should have a diameter of about 10 km.

One of the major considerations of any concept has to be the phase stability of the system. Incoherent and semicoherent interferometers (the Brown-Twiss interferometer is a brilliant example) have the disadvantages of low signal-to-noise ratio and loss of phase information and so must be rejected. For the complex objects of greatest interest, phase information is essential. This requirement exacts a price; control (or measurement) of the optical paths to $\lambda/20$ means that 25-nm precision is needed at λ = 500 nm, and proportionally tighter specifications are required as one goes to shorter wavelengths. The radio astronomers, in developing very-long-baseline interferometry (VLBI), have formulated a powerful algorithm for phase and amplitude closure that eases the problem if there are enough receiving apertures. The technique has been applied to VLBI mapping problems with great success (ref. 6). If one has three elements, and hence three baselines, the instrumental phase shifts to total zero. Similarly, if there are four elements in any array, the instrumental perturbations to the amplitudes cancel. As the number of elements increases, the quality of information recovered increases. For N antennas, a fraction $(N - 2)/N$ of the phase information and $(N - 3)/N - 1$ of the amplitude information can be recovered. If N is 10 or more, the procedure appears to be thoroughly reliable. Because the phases must remain stable over the integration period, the precision requirement on the optical paths must be held, but the time for which it is held is reduced. The desired sensitivity and the total collecting area therefore set the final stability specifications.

Two general classes of optical space interferometers have been proposed: stationkeeping, independently orbiting interferometers and structurally mounted arrays. Examples of the first class are SAMSI (ref. 7), in which pairs of telescopes are placed in near-Earth orbit, and TRIO (ref. 8), in which a set of telescopes is maneuvered about the fifth Lagrangian point (L5) in the Earth-Moon system. Among the structural arrays that have been proposed are COSMIC (ref. 9), OASIS, a concept proposed by Noordam, Atherton, and Greenaway (unpublished data), and a variety of follow-on concepts to the Hubble Space Telescope being examined by Bunner (unpublished data). All of these concepts hold promise for giving useful results in the milliarcsecond class, but when the number of elements grows to the order of 27 (or more) and when the spacings extend to 10 km (or even 100 km for 1-μarcsec resolution at λ = 500 nm), the solutions may prove to be expensive, perhaps prohibitively so.

A third class of optical array becomes feasible, however, if there is a permanently occupied lunar base. The Moon is a most attractive possible location for an optical equivalent of the VLA, capable of microarcsecond resolution.

A Lunar VLA

Assuming that a lunar base has been established, the general outlines of a large optical array following the pattern of the VLA can be visualized with some confidence. A schematic form is shown in figure 3; a set of telescopes, suitably shielded, is deployed at fixed stations along a Y, each arm being 6 km long, for a maximum baseline length of 10 km. There is a fixed station that monitors the telescope location by means of laser interferometers. The telescopes must be movable, but whether they are self-propelled (as shown in fig. 3) or are moved by special transporters (as in the case of the VLA) is a technical detail. The received light signals also are transmitted to the central correlation station, but time delays (not shown in fig. 3) must be inserted to equalize the geometrical time delays ($\Delta\tau_g$) illustrated in figure 2. A number of configurations are possible, probably in the form of laser-monitored moving mirrors.

The individual telescopes might well be approximately 1 m in diameter. The telescopes could be transported in disassembled form; hence, they need not be extremely expensive since launch stress would not be a problem. A simple conceptual design indicates that each telescope might have a mass of 250 kg or less. Then, the total telescope mass for 27 telescopes plus a spare would be about 7 tonnes. The packing volume could be relatively small, since the parts would nest efficiently. The sketch in figure 3 shows each telescope being self-propelled, but if mass transportation to the Moon is a key consideration, one or two special-purpose transporters seem much more likely. Each might have a mass of about 200 kg.

The shielding of the telescopes is an interesting design problem. The simplest scheme would be to adopt the systems used on past space telescopes such as the International Ultraviolet Explorer (IUE), but the construction possibilities on the lunar surface may allow concepts that give dramatic improvements. Instead of being mounted on the telescopes, the shields could be constructed as independent structures that sit on the lunar surface, free of the telescope. The shields might be very simple, low-tolerance, foil and foam baffles, keeping the telescope forever in the shade, radiatively cooled to a very low temperature, or perhaps kept at the average 200-K temperature of the lunar subsurface. It would appear that the thermal stresses might be kept very low by adapting the design to the lunar surface conditions.

Transmission of the received light from the telescopes to the central correlation station must proceed through a set of variable time delays as indicated earlier, and here there is a need for technical studies. For the 10-km maximum baselines proposed here, the maximum time delay rate would be 2.6 cm/sec, which is not excessively high. The requirement of $\lambda/20$ phase stability is challenging; the motion should not have an instability much greater than 10 nm/sec rms, so a smoothness of something better than a part per million is needed. This is not an easy goal, but it is not beyond reason. The curvature of the lunar surface has to be considered unless a convenient crater having a suitably shaped floor can be found. The height of the lunar bulge along a 6-km chord is 2.6 m and, hence, is not a serious obstacle. For the larger concept (60-km baseline, microarcsecond resolution at $\lambda = 500$ nm), the intervening rise of 260 m would be more serious, and suitable refraction wedges or equivalent devices would have to be arrayed along the optical path. The transmitted signal probably should be a quasi-plane wave; this form translates to the requirement that the receiving aperture at the central correlator station still should be in the near field of the transmitting aperture of the most distant telescope. Therefore, the diameter of the transmitted beam must be greater than 10 cm at $\lambda = 500$ nm, and 30 cm for a wavelength of 5 μm. If there were a desire to perform aperture synthesis at $\lambda = 50$ μm (which there might well be), the transmitted beam would have to be at least 1 m in diameter, a requirement that would still be easy to meet since the tolerances would be relaxed.

The characteristics of the central correlator will depend on the results of detailed studies. Two general classes of optical systems can be projected: the "image plane" correlation geometry developed by Labeyrie et al. (ref. 8) for TRIO (a continuation of the traditional technique of Michelson), and the "pupil plane" correlation scheme generally used by radio astronomers, but realized in the optical regime by the astrometric interferometer of Shao et al. (ref. 10).

One interesting advantage generally characteristic of optical interferometry as compared to radio interferometry is the ease with which multibanding circumvents the "delay beam" problem described earlier. Labeyrie (ref. 11) has devised an ingenious dispersive system that efficiently eliminates the problem for most cases. The fringes are displayed in delay space and frequency space, but modern two-dimensional detectors such as charge-coupled devices (CCD's) handle the increased data rate easily.

The data rates are not excessive, being completely comparable to the data rates now handled by the VLA. The 351 cross correlations needed for a 27-element system (or 1404 if all Stokes parameters are derived) requires an average data rate of about 100 kilobauds for a 10-sec integration period; future systems always require larger data rates, but even a projection of an order-of-magnitude increase does not seem to present formidable data transmission problems.

Finally, a word is in order concerning the use of heterodyne systems to convert the optical signals to lower frequencies. The technique is in general use in the radio spectrum, extending to wavelengths as short as 1 mm. Unfortunately, the laws of physics offer no hope for astronomical use of heterodyne techniques at optical and ultraviolet frequencies. Every amplifier produces quantum noise, and the laws of quantum mechanics are inexorable; approximately one spurious photon per second per hertz of bandwidth is produced by every amplifier. At radiofrequencies, the quantum noise is swamped by the incoming signals since there is so little energy per quantum. Optical systems, with bandwidths of 10^{13} or 10^{14} Hz, can afford no such luxury. The crossover in technology occurs at radiation frequency between 100v and 10v. As infrared detectors improve, the shortest wavelength at which heterodyne detectors are practicable will be perhaps 50 μm.

Except for these quantum limitations, the concepts developed for radio techniques carry over to the optical domain. The signal-to-noise analysis differs somewhat. The noise limits are determined by the Rayleigh noise of the system in the radio case, whereas the quantum shot noise of the signal determines the signal-to-noise ratio in an optical system. Otherwise, the extensive software armory developed for radio synthesis systems should be directly applicable to optical interferometers.

Are There Serious Obstacles?

Relatively little thought appears to have been given thus far to the advantages of the Moon as a base for astronomical instruments. There are a number of current misconceptions that seem to hold little substance.

1. Does lunar gravity cause problems? On the whole, the effects of lunar gravity appear to be beneficial. The relatively small (1/6g) acceleration helps to seat bearings and locate contact points, and it generally should provide a reference vector for mechanical systems. The lunar gravity keeps dust settled and thus keeps the density of light-scattering particles low.

Gravitational deflection for telescopes in the 1-m size range is completely negligible. Gravitational deflection does not depend on the weight of a structure; elementary physics shows that the structural deflection s of a structure depends on the length l of the beam, on Young's modulus Y, on the density ρ, on the gravitational acceleration g_m, and on a dimensionless geometrical factor γ that decreases as the depth of the beam increases.

$$s \approx \gamma \left(\frac{\rho}{Y}\right) g_m l^2 \qquad (1)$$

On Earth, 4- and 5-m telescopes have been built with mirror support systems that limit mirror deflection to a fraction of a wavelength of light under full gravity. A 1-m mirror, located on the Moon but otherwise similar, would be stiffer than a terrestrial 4-m mirror by a factor of about 100!

Deflection of the telescope structure can be controlled to high tolerances. Not only are superior materials like carbon-epoxy now available, but improved design methods exist such as the concept of homologous design (introduced by von Hoerner in 1978), in which a structure always deforms to a similar shape. In summary, gravitational deflection poses no problem.

2. What about the thermal environment? The Moon is an approximately 200-K blackbody subtending 2π sr on the underside of a lunar-based instrument. For a conventional satellite in low Earth orbit (LEO), the Earth is an approximately 300-K blackbody subtending nearly 2π sr beneath the spacecraft; however, if the spacecraft is tracking a celestial object, the aspect is changing rapidly – on the order of 4 deg/min. The telescope tracking a celestial source in the lunar environment is changing its aspect at about 0.01 deg/min. When one considers the additional advantage of the natural lunar terrain for better thermal shielding initially and the ability to upgrade its quality at a permanent base, the lunar environment is almost certainly more favorable than LEO from the point of view of thermal stresses. The L5 case is different, since the elements would always be exposed to direct solar radiation.

3. Is scattered light a problem? Again, equipment in LEO has the Earth subtending nearly a hemisphere, but the Earth has high albedo and the Moon has low albedo. The lunar environment is strongly favored, and, as in the thermal case, superior light shielding on the Moon should be achievable.

4. Is direct sunlight a problem? The Sun shines only half the time, and its direction changes slowly. Given the superior light baffling of the lunar-based telescopes, the lunar environment probably will be far superior to either LEO or L5, but thermal studies of real designs should be made.

5. What about lunar dust? The lunar laser retroreflectors have been in service for more than a decade with little performance degradation reported. Dust seems to be no problem, probably because the Moon's gravity settles it rapidly. A very rare meteorite impact nearby might take one or two telescopes out of service, and the choice would have to be made to clean or to replace the instruments.

6. Is seismic activity a problem? The Moon is far quieter than the Earth, with a low background noise. At good seismic stations on the Earth, the seismic noise is less than 0.1 nm rms; the poor locations have high noise because of the effects of wind and surf. Lunar seismic activity is not a concern.

7. Do the solid-body tides of the Moon move the baselines excessively? Earth tides are routinely accommodated by geodesy groups conducting VLBI studies on Earth, where the motions amount to several wavelengths every 12 hours. Although lunar tides are larger in amplitude, they proceed slowly enough that they can be compensated for. The 10-km maximum baseline of a lunar VLA is a smaller fraction of the lunar diameter than the 10 000-km VLB baselines are of the Earth's diameter; therefore, the amplitude of baseline motion is diminished. The net tidal motion of the maximum baseline vector should be on the order of a few tenths of a millimeter. This motion is not negligible, measured in wavelengths of light, but the slow lunar rotation leads to a manageable correction rate on the order of a few wavelengths per hour. The usual interferometric calibration routines should keep this error source under control.

8. Can the baseline reference system be well defined? The analogy with terrestrial VLBI is sufficiently close that the answer has to be affirmative. The errors can be controlled; the lunar soil is sufficiently competent to stably bear the load of a telescope; and, if necessary, hard points can be established to check on vertical motions. Interferometers are largely self-calibrating; there are enough quasi-stable reference points in the sky to enable control of instrumental constants by means of celestial observations.

Summary

A permanent lunar base can provide support for a variety of astronomical investigations. An optical interferometric array, perhaps of the general form of the VLA but designed for optical instead of radio wavelengths, would lead to a qualitative advance in our understanding of the universe. The Y configuration is well suited to expansion, and the capability of the VLA to make maps both rapidly (in its snapshot mode) and with high dynamic range (when multiple array configurations are used) has been demonstrated. Other configurations, such as maximum-entropy-derived circles, certainly should be examined.

A wide variety of scientific problems could be addressed by such an instrument. The stellar analogs of the solar cycle, the behavior of sunspots on other stars, the magnetic field configurations of other stars, and the behavior of dynamic plasma phenomena such as flares and winds are examples of star-related problems that ultimately would lead to both increased understanding of our own Sun and fundamental knowledge of the manner in which stars form and evolve. A wide variety of extragalactic problems could be studied, including the fundamental processes associated with black holes and massive condensed objects as they are manifest in quasars, galactic nuclei, and other optically violent variables. A number of dramatic surprises, in both stellar and extragalactic studies, could be expected, and the instrument certainly would be at the forefront of astronomy from the time of its first use.

No fundamental problems in building such an instrument are apparent. The total mass to be delivered to the lunar surface for the instrument would be 10 to 30 tonnes, which is roughly equivalent to one space station habitat module. The detailed system studies have not been made, but even a preliminary conceptual investigation indicates that the elements of the system are relatively straightforward. The presence of man is highly desirable for this particular instrument; this fact is in marked contrast to the free-flyer case in which the instruments are easily perturbed by human presence.

How long would it take to build the instrument? The answer depends on the time scale of development for a lunar base. Once a clear consensus exists to establish a base on the Moon, development of the components of a lunar VLA could be started and would be ready to be among the first large shipments of non-life-support systems to the Moon. Assembly and development time at the lunar base would depend on the details of the design and on the philosophy of lunar base operations.

Finally, it is clear that a large astronomical community would use the instrument. All the major astronomical facilities on Earth are heavily subscribed, and the VLA probably supports more users than any other astronomical instrument today. An interferometric array has many possible modes of operation: it can take brief snapshots, it can be broken into subarrays to serve multiple-user groups simultaneously for specialized projects, and it can interweave long observing sequences with short projects in an efficient fashion. The VLA supports the observing programs of more than 1000 scientists per year, and a lunar-based optical equivalent could be expected to do the same.

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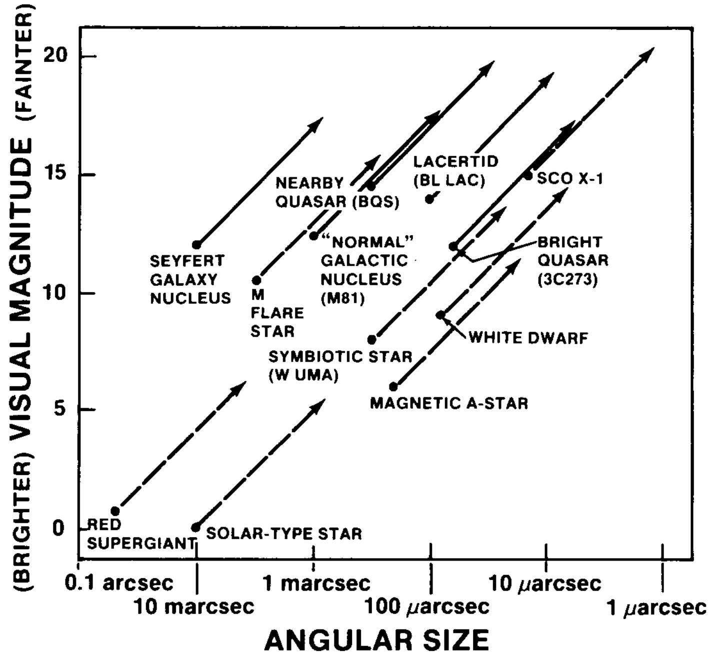

Figure 1.- Visual magnitude as a function of angular size for a selection of stellar and extragalactic objects. The scales are chosen to reflect the largest expected value for each class of object. The length of each upward-sloping line corresponds to a factor of 10 in distance; thus, an object at the tip of an arrow would be 10 times more distant than the closest member of that class designated at the foot of the line.

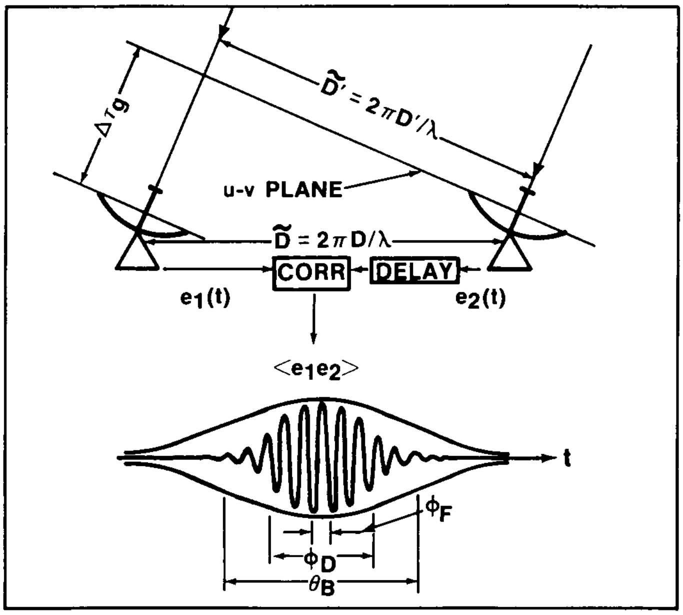

Figure 2.- Schematic diagram of the Michelson stellar interferometer in radio telescope form. The correlator (CORR) output, shown for fixed apertures as a function of time with the direct-current term removed, is equivalent to variation with angle off axis.

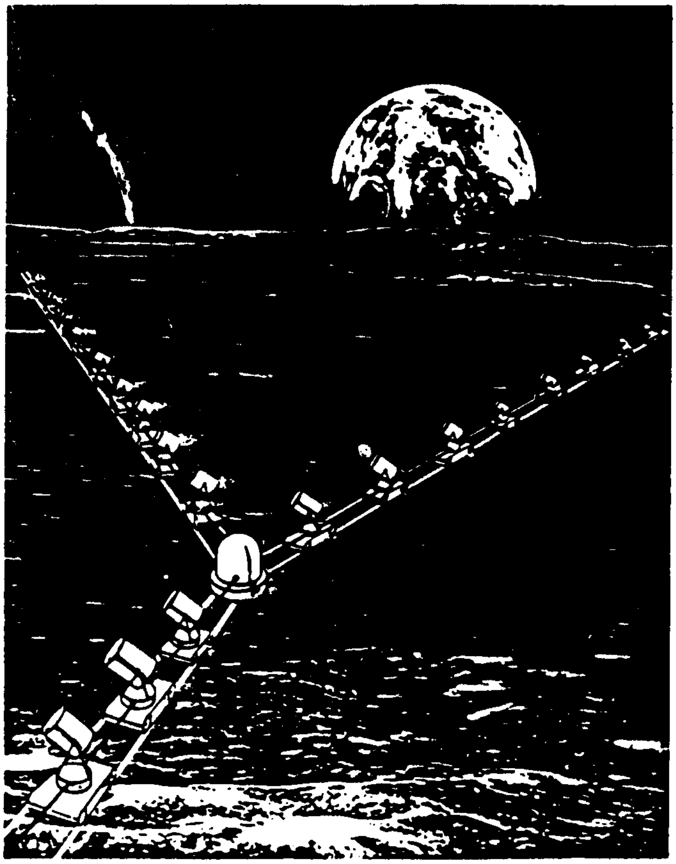

Figure 3.- Schematic view of an optical aperture-synthesis array on the Moon. The individual elements could assume forms very different from the versions shown.