ALSEP – Quasar Differential VLBI

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A program of Apollo Lunar Surface Experiments Package (ALSEP)–Quasar Very Long Baseline Interferometry (VLBI) is being carried out at the Jet Propulsion Laboratory. These observations primarily employ a "4-antenna" technique, whereby simultaneous observations with two antennas at each end of an intercontinental baseline are used to derive the differential interferometric phase between a compact extragalactic radio source (usually a quasar) and a number of ALSEP transmitters on the lunar surface. A continuous ALSEP–quasar differential phase history over a few-hour period can lead to extremely high angular accuracy ($\lesssim 10^{-3}$ arcsecond) in measuring the lunar position against the quasar reference frame. Development of this application of the "4-antenna" technique has been underway at JPL for more than a year and is now producing high-quality data utilizing Deep Space Network (DSN) stations in Australia, Spain, and Goldstone, California, as well as the Spaceflight Tracking and Data Network (STDN) "Apollo" station at Goldstone. These high accuracy observations are of value to tie the lunar ephemeris to a nearly inertial extragalactic reference frame, to test gravitational theories, and to measure the Earth–moon tidal friction interaction.

I. Introduction

The development of a high-precision, nearly inertial, celestial reference frame defined by the positions of extragalactic radio sources (principally quasars) will offer many unique opportunities to perform both astronomical and geophysical studies at previously unrealizable levels of accuracy. These positions will be derived from analysis of extremely accurate VLBI observations. The internal consistency of the new reference frame should be two orders of magnitude better than that of the present "optical star" celestial reference frame (~0.1 arcsecond). In addition, the great distances associated with the extragalactic sources will eliminate the optical star catalog problems arising from stellar proper motions. As part of a program of making accurate measurements of universal time and polar motion, a group at JPL is engaged in an extensive effort to build such a quasar reference frame (Preston *et al.*, 1975). A similar effort is also being undertaken by a group at the Massachusetts Institute of Technology (MIT) and the Goddard Space Flight Center, again primarily for geophysical studies (see Robertson, 1975; Counselman, 1976).

The ALSEP–quasar VLBI program represents the first systematic use of the new quasar reference frame for performing high accuracy solar system studies.[1] Essentially, the ALSEP transmitters on the lunar surface are being tracked against the quasar background as one might follow a planet's motion across an optical star field. These angular observations, in combination with range observations obtained by laser pulse time-of-flight (Bender *et al.*, 1973), will be used for refining the parameters of the Earth–moon system and for extremely precise tests of gravitational theories. When more radio beacons are placed in orbit about or landed on other planets, such observational programs are certain to become more numerous.[2]

The authors are presently conducting an intensive survey of the ecliptic region of the sky to identify extragalactic sources which are suitable for the quasar reference frame. The principal requirement that must be satisfied for intercontinental baselines is that the source have compact components on a size scale of no more than a few thousandths of an arcsecond in angular extent. The structure of the source should be simple, preferably a point source. Figure 1 shows the results of this survey. To this point, 43 sources with sufficient strength for ALSEP–quasar observations ($>$0.5 jansky) have been found within 10 degrees of the ecliptic. To truly form a high-precision reference frame, the relative positions of these objects should be accurately determined. Although accurate source positions are not yet available, it is important to note that the finite lifetime of the ALSEP transmitters demands that the ALSEP–quasar data be obtained now. Interpretation of observations after the reference frame is developed is no less valuable. Some scientific goals also can be achieved by tracking the moon's motion as it makes successive passes of the same quasars without precise absolute positions being known.

The VLBI technique involves the passive reception of radio signals from celestial radio sources at two widely spaced antennas, each with extremely precise but independent clocks and frequency systems. The radio signals may be from a natural source (quasars, radio galaxies) or a man-made source such as the ALSEP transmitters. By digitally recording the received signals on magnetic tape at both antennas, the tapes can be brought to a common location for cross-correlation to produce the VLBI observable, fringe phase. Differential VLBI (ΔVLBI) refers to the application of this technique to simultaneous observations of objects located close together in the sky. If the fringe phase data from two closely spaced sources are differenced, common error sources tend to cancel, and the resultant differential fringe phase data provide a precise measure of the angular separation of the two sources. Specifically, significant reductions occur in the sensitivity to antenna site location, UT1, polar motion, troposphere, ionosphere, and certain instrumental effects such as clock offset errors and frequency drifts (see Counselman *et al.*, 1972, and Preston, 1974). Differential VLBI has been intensively used for ALSEP–ALSEP observations by a group at MIT (King, 1975).

The ALSEP–quasar observations employ a "4-antenna" technique in which the differential phase is obtained with no integer cycle ambiguities by continuous observations of both the extragalactic source and a number of ALSEP transmitters on the lunar surface. A continuous ALSEP–quasar differential phase history over a few-hour period can lead to extremely high angular accuracy ($\lesssim 10^{-3}$ arcsecond) in measuring the lunar position relative to the quasar reference frame if systematic error sources can be sufficiently reduced. These error sources include: (1) source structure effects, (2) propagation media effects, and (3) instrumental phase effects. Careful selection of sources and various calibration techniques promise to allow the observations to be utilized at nearly their potential accuracy.

II. Technique Development

After some feasibility studies for ALSEP–quasar VLBI (Slade *et al.*, 1972), the ΔVLBI technique was first tried in a January, 1972, "2-antenna" experiment involving Mariner 9 and several quasars (Slade *et al.*, 1974). The "2-antenna" approach to ΔVLBI requires that single antennas at each end of the baseline move back and forth in unison between the two celestial sources. Hence the resultant phase history on each of the sources is not continuous, and unambiguous "phase connection" must be performed during the periods off source (i.e., no integer cycle mistakes). The results were not of high accuracy ($\sim$0.1 arcsecond) due to the small amount of data and the inability to connect phase, but seemed promising enough to perform a trial "2-antenna" ALSEP–quasar experiment on October 20, 1973, with DSN antennas in Spain and South Africa moving between ALSEP 14 and quasar

[1] In 1972, an attempt was made to use the Mariner 9 spacecraft in Mars orbit to make a single tie of the planet's orbit to the quasar reference frame. See text.

[2] Such experiments are planned during the Viking Mission to Mars with I. I. Shapiro, MIT, as principal investigator (Michael *et al.*, 1972).

OJ287. The observations were made using a narrow-bandwidth (24-kilohertz) recording system, which had a relatively low signal-to-noise performance. This recording system demanded observing the relatively strong quasar OJ287 ($\sim$2 jansky), even though this choice of natural source was not ideal because the separation between the moon and quasar was fairly large ($\sim$7 degrees). The phase history for both sources in this experiment is shown in Fig. 2a. Least-square fitting of linear and quadratic terms to the differential phase, after correcting a cycle error at 06:00 hours, produced the residual differential phase shown in Fig. 2b. The rms fluctuation in phase about the mean is 0.175 cycles. Fitting the differential phase with a constant and diurnal sine and cosine amplitudes gave the corrections to differential right ascension and declination. The former errors on these quantities when the data are weighted to give a χ^2 of 1 are 3.0×10^{-3} and 4.5×10^{-3} arcsecond, respectively. Systematic errors will degrade these estimates by about a factor of 2.

Despite the moderate success of the above ALSEP–quasar experiment, the "2-antenna" switching approach to differential VLBI has several inherent difficulties. Most importantly, the probability of mistakenly moving at wrong times to the wrong position is quite high. Because antenna moving at high drive rates is not programmed, a fallible human operator must command the operations. Also severe propagation media or frequency system fluctuations may make phase connection difficult through the "planned" gaps even if the antenna pointing is done flawlessly at both ends. Finally, the accuracy of the differential phase data obtained with the "2-antenna" technique is degraded due to the non-simultaneity of the fringe phase determinations on the two sources. These reasons motivated the investigation of the continuous tracking of both signals by "4-antenna" experiments, a technique first employed with natural sources for relativity experiments (Counselman *et al.*, 1974). (The "2-antenna" experiments would, of course, still be performed if the special antennas required as described below were not available for a particular time-critical experiment.)

In ALSEP–quasar "4-antenna ΔVLBI," a large antenna (26-meter) at each end of the VLBI baseline observes an extragalactic source, while smaller "acquisition aid" antennas that are attached to the large dishes are observing the stronger ALSEP transmissions. Even though the principal axes of the smaller antennas and their associated parent dishes are aligned, the wider beamwidth of the smaller antennas allows them to view the moon at the same time the narrow-beamwidth larger dishes are pointed at an extragalactic source a few degrees from the moon (see Figs. 3 and 4). The ALSEP signals are so strong that, even with the small acquisition aid antennas, the signal-to-noise ratio (SNR) for the ALSEP signals is much greater than the SNR obtained with the 26-meter antennas on a strong natural source ($\sim$2–3 jansky).

The ALSEP–quasar observations mainly utilize Deep Space Network 26-meter antennas in Australia, Spain, and California, where the associated acquisition aid antennas have 3-decibel beamwidths of 16 degrees. In addition, the 26-meter STDN "Apollo" antenna at Goldstone, California with an acquisition aid beamwidth of 8 degrees is also occasionally used.

A schematic diagram of the instrumental configuration for ALSEP–quasar ΔVLBI is shown in Fig. 5. An important feature of this configuration is that the local oscillator signals that are used in the downward frequency conversion of the S-band ALSEP and quasar signals are all derived from a common rubidium frequency standard, thereby allowing any frequency drifts of the frequency standard to cancel when the ΔVLBI observable is formed. Data are recorded by a Mark II VLBI recording system (Clark, 1973) developed by the National Radio Astronomy Observatory (NRAO). The Mark II system records a 2-megahertz bandwidth of data by placing (two-level) digital samples on a video tape at a rate of 4 megabits per second. ALSEP and quasar signals are recorded on alternate seconds and thus are practically (but not truly) continuous. The 2-megahertz bandwidth allows signals from up to three ALSEPs to be simultaneously recorded. In order to maximize the signal-to-noise ratio for the ALSEP signals, which are each only a few kilohertz wide, a specifically designed series of bandpass filters is inserted into the 2-megahertz baseband to filter out much of the noise when ALSEP signals are being recorded. The phase characteristics of these filters were carefully designed to introduce no additional instrumental phase effects.

From January to August 1974, this particular "4-antenna" technique was debugged through engineering tests of the acquisition aid antennas, deployment and testing in Australia of a Mark II recording terminal, and software development in connection with use of the NRAO correlator. An acquisition aid antenna was installed on Deep Space Station (DSS) 62 near Madrid, Spain. The installation of an acquisition aid antenna was requested for DSS 11 at Goldstone.

Until the acquisition aid at DSS 11 was installed, the use of the acquisition aid-equipped Apollo station at Goldstone was arranged with the cooperation of the

STDN. On September 18, 1974, a "4-antenna" experiment between the Apollo Station and DSS 42 in Australia was conducted. The continuous phase track for ALSEP 15 during part of this experiment is shown in Fig. 6. The quasar OP-192 tracked during this experiment was somewhat weaker than expected. On a subsequent experiment between Apollo and Australia on January 1, 1975, the quasar observed (3C446) also appeared weaker than anticipated. Engineering tests during subsequent months revealed instrumental difficulties with the ALSEP filter box in Australia.

By June 1975, the Goldstone DSN acquisition aid became operational at DSS 11 and a Mark II terminal had been deployed to Spain. On June 19, 1975 a "4-antenna" experiment with Australia was performed. On July 31, 1975, an experiment was performed between the Apollo STDN station and Spain. Further experiments were performed between DSS 11 and DSS 62 on November 23, 1975, and between DSS 11 and DSS 42 on December 27, 1975. Experiments using DSS 11 have yielded amplitudes on the natural source as anticipated from theoretical signal-to-noise calculations.

III. Data Processing Techniques

The cross-correlation of the data tapes from these experiments has been done at NRAO in Charlottesville, Virginia on a special hardware–software correlator. (A similar correlator is now being built by JPL and Caltech and should be ready for use by mid-1976.)

The computer software at the NRAO correlator was designed for the processing of natural source data. The rapid motion of the moon requires special provisions to account for the different time variation of the interferometric phase for the various ALSEP transmitters. The so-called "fringe phase" from the NRAO correlator (Clark *et al.*, 1972) for wide-band noise sources can be represented by

$$\phi_{cor} = \phi_B - \phi_A + \phi_I + \phi_V$$

where ϕ_B results from offsetting in delay and multiplying together of the two bit-streams

$$\phi_B = (\omega_2 - \omega_1)t + \omega_2\tilde{\tau}_M + \omega_0(\tau - \tilde{\tau}_M)$$

and ϕ_A results from the modeled phase stopping of the lobe rotator

$$\phi_A = (\omega_2' - \omega_1')t + \omega_2' \tau_M - \Delta\omega_{LO}\, t$$

In these expressions

t = time from midnight on day of experiment from Station 1 recorder, UTC.

τ = actual group delay including propagation media and instrumental effects

τ_M = model group delay

$\tilde{\tau}_M$ = model group delay (bit-quantized)

ω_i = total effective mixing frequency at station i

ω_i' = estimate of ω_i used in processing

ω_0 = effective bandpass center

$\Delta\omega_{LO}$ = analytic offset (to avoid zero frequency)

ϕ_I = instrumental phase shift

ϕ_V = visibility phase due to source angular structure

For an ALSEP transmitter, ω_0 becomes ω_a, the center frequency of the ALSEP line.

The model delay τ_M to be quantized and used in cross-correlation is computed by a simple model:

$$\tau_M = A + B\cos(\omega_E[t - t_0]) + T$$

where A, B, t_0 are functions of the baseline, its orientation in space, and the source position, ω_E is the sidereal rotation rate of Earth, and T is an adjustable clock offset to allow for the different clock initialization at different stations.

The model delay for the ALSEP transmitters cannot be adequately modeled by this simple formula for any significant length of time. The approach we have followed to obtain stopped fringe phase is to match $(\omega_2' \tau_M - \Delta\omega_{LO}\, t)$ to a good model $\omega_2' \tau_{ALSEP}$ and its first three time derivatives at a given time t by adjusting the parameters A, B, t_0, and $\Delta\omega_{LO}$ every 10 minutes.

The phase as a function of time is recovered from the correlation functions $\rho\,(\tau_i, t_n)$ measured at $i = 1 \rightarrow N$ delays at times t_n. The correlation functions are complex:

$$\rho\,(\tau_i, t_n) = \rho_c\,(\tau_i, t_n) + j\rho_s(\tau_i, t_n)$$

where ρ_c is the output of the so-called "cosine" channel and ρ_s is the sine channel output of the hardware correlator.

The estimates of the cross-power spectrum $S_{12}(\omega_k, t_n)$ at frequency ω_k time t_n (equispaced at Δt) are computed from the cross-correlation function by a discrete Fourier transform in the lag domain (see Moran, 1974):

$$S_{12}(\omega_k, t_n) = \sum_i [\rho(\tau_i, t_n)]\, W(\tau_i) \exp[j\omega_k(\tau_i + \Delta\tau_n)]$$

where

$$\omega_k = 2\pi\,(k-1)\,B_0/N'$$

$$\Delta\tau_n = \tau_M(t_n) - \tilde{\tau}_M(t_n)$$

The frequency range of the spectrum from 0 to B_0 is governed by the bandpass filter of the Mark II recorders and is 1.8×10^6 hertz in our application. The spectral weighting function is $W(\tau_i)$. N' can be larger than N for interpolation purposes. The term $\Delta\tau_n$ is necessary to correct for the discrete delay tracking of the correlator.

The phase of an individual ALSEP is then extracted from $S_A(t_n) = S_{12}(\omega_A, t_n)$ at the value ω_A of ω_k closest to the ALSEP center frequency. $S_A(t_n)$ is fitted by a function $A_K \exp j\left[\phi_0^K + \dot{\phi}^K t_n + \frac{1}{2}\ddot{\phi}^K t_n^2\right]$ for t_n ($n = n_0$ to n_f) over a specified time interval of length L, where $L = (n_f - n_0)\Delta t$. The epoch of the estimated amplitude A_K, phase ϕ_0^K, fringe rate $\dot{\phi}^K$, and, if necessary, rate of fringe rate $\ddot{\phi}^K$ for interval K is $t_{n_0} + L/2$ because the center of the interval yields the smallest correlation between the estimated parameters and the smallest phase uncertainty (rigorously for a 3-parameter fit).

IV. Expected Performance

The "4-antenna" technique allows the differential interferometric fringe phase to be observed for each source without 2π ambiguity for the length of the experiment, with the differential phase between the two sources providing a precise measure of their angular separation. The inherent angular precision available from the ΔVLBI observable can be represented as being a small fraction of the interferometer fringe spacing in the sky (neglecting geometric effects for simplicity at the moment):

$$\sigma_{\Delta\theta} = \left(\frac{\sigma_{\Delta\phi}}{2\pi}\right)\left(\frac{\lambda}{D}\right)$$

where

$\sigma_{\Delta\theta}$ = uncertainty in angular separation, $\Delta\theta$ (radians)

$\sigma_{\Delta\phi}$ = uncertainty in measuring differential phase, $\Delta\phi$ (radians)

λ = the S-band wavelength (0.13 meters)

D = the baseline length (meters)

and

λ/D = the interferometer fringe spacing.

For our experiments, $\sigma_{\Delta\phi} \approx 30$ degrees of phase and $D \gtrsim 8 \times 10^3$ kilometers, which yields

$$\sigma_{\Delta\theta} \approx 1.4 \times 10^{-9} \text{ radians or } 2.8 \times 10^{-4} \text{ arcseconds}$$

However, this inherent precision is degraded by factors due to the position in the sky of the two objects, the baseline orientation, the limited mutual visibility of the two objects from both ends of the baseline, and systematic errors.

In order to show the effects of the corrupting geometric factors, computer error analyses were performed. The results of this study are presented in Fig. 7 for a typical lunar–quasar geometry: a source separation of 2 degrees and a mean source declination of 15 degrees. This study assumed that a differential fringe phase data point was obtained every 5 minutes and that the rms noise associated with each data point was 0.1 S-band cycles. The solve-for parameters were the differential right ascension, differential declination, and a constant offset in phase between sources. Notice that geometric degradation factors play an important role for about 2 hours into an experiment, at which point the resultant angular precision tends to level out at a magnitude approximately equivalent to the previously calculated value for the inherent precision of a single observation. As the experiment length and number of observations increases, the expected angular precision continues to slowly improve. On a Goldstone–Australia baseline, mutual visibility limits an experiment to about 4 hours for any source position. On a Goldstone–Spain baseline, mutual visibility ranges from 0 to 6 hours, depending on the declination of the sources.

The expected angular precision of these observations may not translate directly into angular accuracy due to the corrupting effects of systematic error sources. Three systematic error sources could be important: (1) differential instrumental phase drifts, (2) differential propagation media effects, and (3) differential phase variations due to small-scale structure in the extragalactic radio sources. These error sources will be discussed in some detail below.

The primary origin for the first of these possible errors is due to the separate receiver chains (maser amplifiers, mixers, etc.) used at each station for the signals from the main antenna and the acquisition aid antenna. Initial testing indicates that the differential phase variations due to the receiver chains, excluding masers, do not exceed 0.1 S-band cycles. Additional tests, including masers, are planned. In order to calibrate out slow differential phase drifts during actual experiments, the receiver phases are calibrated in one or both of the following ways:

(1) The signal paths are interchanged periodically ($\sim$30-minute intervals) by means of a waveguide switch preceding the masers.

(2) Periodically, the main antennas are briefly pointed at the moon to allow the phase drift between receivers to be measured directly.

Another possible source of instrumental phase variation arises due to the motion of the moon in the beam pattern of the acquisition aid antennas as the main antenna tracks the extragalactic radio source. This variation is quite small for the angular separation in our experiments, however, and can be completely removed by calibration of the phase as a function of angle off-axis.

Another source of instrumental phase variation deserves brief mention. The crystal oscillators controlling the transmitted frequency of the ALSEPs are subject to drift due to environmental effects, especially when the lunar terminator passes the ALSEP. This variation requires monitoring of the received frequency of the ALSEP signals, and calculating the geometric doppler effect to derive the transmitter frequency as a function of time. The parameters of this calculation are known well enough to derive the frequency to the required accuracy (see King, 1975). In order to simplify the procedure to obtain this frequency, separate observations of ALSEP doppler have often been made with the cooperation of the STDN by MIT ΔVLBI experimenters. Of course, the Mark II video tapes of the experiments contain this information, but the procedures to obtain doppler signals from these tapes (e.g., autocorrelation) to the required accuracy of $\sim$5 hertz are not simple.

Significant systematic effects will exist in the differential phase due to propagation media (i.e., troposphere, ionosphere, space plasma). These effects can be calibrated (at some level) and/or modeled with solve-for parameters in the data analysis. We have estimated the magnitude of these systematic effects (also see King, 1975) by some simple models.

The systematic part of the tropospheric contribution to the differential phase $\Delta\phi_{trop}$ is estimated for the case of 30-degree elevation at one station and high elevation at the other, for a 3-degree separation in elevation at the former station, i.e., a worst-case geometry. If we take a typical value for the zenith contribution of 2 meters, we obtain at 30-degree elevation that $\Delta\phi_{trop} \simeq 1000$ degrees of phase. If surface conditions are measured, a calibration for the dry part of the troposphere to 2% (20 degrees or 0.05 cycle) of differential phase appears completely realistic (Berman, 1970; Chao, 1974). The wet part of the troposphere is highly variable, especially at some times of the year. The use of microwave radiometry sensing techniques (Schaper *et al.*, 1970, Moran and Rosen, 1975, Resch, 1975) appears to be able to calibrate the path-length variations due to water vapor content to the equivalent of 1–2 centimeters (0.08–0.15 S-band cycles). A radiometer is available at Goldstone, and will be used unless other higher priority experiments using the radiometer conflict. Radiometers at the overseas stations do not yet exist, but may be deployed on an experimental basis within a year.

For a night-time ionosphere with integrated total electron content of 10^{17} electrons/meter^2, and the geometry as in the tropospheric case above, we calculate that for elevations at the first station between 5 and 35 degrees, $\Delta\phi_{ion} \simeq 210$ degrees of phase. Therefore, a calibration of 10% appears adequate, which can be achieved with present calibration schemes. However, daytime ionospheric electron content is an order of magnitude greater than night. Better calibration of the ionosphere will soon be available, since all DSN complexes are now being equipped with automated 24-hour/day meteorological monitoring assemblies which include a new polarization tracking receiver. These receivers will monitor the ionospheric electron content between the DSN site and a synchronous satellite by measuring the Faraday rotation of a linearly polarized signal transmitted by the satellite. The accuracy of the measurements should be better than a 0.9-centimeter equivalent path length at S-band (Burnell *et al.*, 1975). Mapping errors from line-of-sight of the synchronous satellite to the experiment observation path will degrade this accuracy. However, for experiments with

Australia, the line-of-sight to ATS-5 from Australia will be at an elevation of ~15 degrees in the quadrant of the sky towards California. For experiments with Spain, observations of satellites over the Atlantic Ocean also may be able to reduce mapping errors. The satellite which initially will be observed is a West German "Symphonie" satellite station-keeping at 11°W longitude. Total accuracy of the actual *average* path length of 1–2 centimeters at S-band seems quite possible at this time.

Several other calibration schemes also are being pursued. Simultaneous observations of the extragalactic radio sources at X-band several times during an experiment is possible in principle. The Venus antenna at Goldstone, the Aries antenna, and all 64-meter stations will soon have X-band receivers, and thus S–X calibration for the ionosphere could be possible occasionally. When the UT1–polar motion wide-band switching equipment is available, we will obtain data on the extragalactic source at a 40-megahertz synthesized bandwidth to derive group delay measurements. A DRVID scheme (MacDoran, 1970) comparing phase and group delay effects from the ionosphere also may contribute significant ionospheric information. Modeling these effects in the data analysis with solve-for parameters is also a possibility.

Apart from the systematic effect discussed above, random variations in electron content about the mean also will occur. These variations in the experiment path length will not be related to the fluctuation along the line-of-sight of the Faraday rotation data. We can estimate the size of these variations by examining the scatter in a short baseline S-band VLBI experiment using very stable (hydrogen maser) frequency systems in which the lines-of-sight to the same source penetrate the ionosphere with angular separation equivalent to our differential angular separation between ALSEPs and natural source. The relevant baseline length is ~20 kilometers. In a 16-kilometer baseline experiment using hydrogen masers at each end, Thomas *et al.* (1976) found no variations within that experimental accuracy of 7 centimeters (~0.5 cycle). A theoretical estimate of the expected random variations can be made knowing the measured width of the spatial autocorrelation function of the ionosphere. An accepted average value for this width is ~400 kilometers (Mathur *et al.*, 1970, Dickinson *et al.*, 1970). Using this, one expects to find the random variations about the average differential path contribution to be well under 0.1 cycle, although direct experimental evidence for this may be several years away.

The interstellar medium through which the quasar signals travel also contributes a difference in differential path length. However, over the course of an experiment, the variation in this contribution will be negligible. The large constant part simply contributes to the overall constant in phase between extragalactic radio source phase and ALSEP signal phase.

The systematic errors introduced by source structure appear manageable, but are difficult to accurately assess at this time. Extensive observations exist for only a relatively small collection of sources (~10) which are selectively chosen for rapid variability. A realistic worst-case phase change over an ALSEP–quasar experiment seems likely to be ~0.5 cycles. Simple models of the structure could remove much of this variation for most sources, but may require a modest monitoring program to obtain the model parameters.

In summary, considering the expected angular precision of the measurements as well as the possible systematic error sources, the "4-antenna" observations should allow determinations of the angular separations of sources with an accuracy of better than 10^{-3} arcseconds.[3]

V. Scientific Goals

The direct goal of the ALSEP–quasar observations is to accurately tie the lunar orbit to the nearly inertial quasar reference frame. Currently NASA is planning to intercompare a number of techniques which might be used for future high-accuracy geodetic measurements. Two of these techniques are VLBI and Lunar Laser Ranging. A tie of the lunar orbit to the VLBI quasar reference frame could prove a valuable tool in any intercomparison of these two techniques.

By monitoring the angular motion of the moon with respect to this extragalactic radio source reference frame, several other valuable scientific results can be achieved. The effects to be observed can be divided naturally into two categories by the motions which give the principal sensitivity to the effects:

(1) Motion in the plane of the lunar orbit.

(2) Motion of the orbit plane.

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[3]It should be noted that an MIT group has found repeatability of ~10^{-3} arcsecond in measuring the differential separation of a pair of extragalactic sources (Wittels, 1975). These sources had a 1/2-degree separation, and the observations were made at a wavelength of 3.8 centimeters where the ionosphere is an order of magnitude less important than at S-band (13 centimeters).

The first category contains effects which cause the moon's mean longitude to depart quadratically with time from the predictions of Newtonian or general relativistic gravitational theory. These effects are a time variation of the gravitational constant ($\dot{G}$) and tidal friction. The tidal interaction has major implications for the origin and evolution of the Earth–moon system (see, e.g., Kaula and Harris, 1975). The lunar orbit has changed greatly over time under the influence of tidal dissipation. Knowing the magnitude of this effect would enable the time scale for the orbital changes to be determined. Time variation of the gravitational constant is a crucial prediction of many non-Einsteinian cosmologies (e.g., Hoyle, 1973, Brans and Dicke, 1961; Dirac, 1938).

These quadratic effects in mean longitude L are commonly characterized by the magnitude of the time derivative of the mean motion n, which itself is the time derivative of L. Empirical estimates of the total anomalous part of $\dot{n}$ range from the classical value of -22.44 ± 0.5 arcseconds/century^2 (Jones, 1939) to recent estimates of -65 ± 10 arcseconds/century^2 (Van Flandern, 1975) and -37 ± 6 arcseconds/century^2 (Muller and Stephenson, 1975). A nominal value for $\dot{n}_{total}$ of ~ 30 arcseconds/century^2 leads to a discrepancy in longitude ΔL over 3 years of

$$\Delta L = -14 \times 10^{-3} \text{ arcseconds}$$

The sensitivity of ALSEP–quasar VLBI to $\dot{n}_{total}$ can be greatly increased by combination with lunar laser ranging data. This added sensitivity occurs because the long time base and comparable accuracy of the laser ranging observations strongly constrain the 3 parameters necessary for a quadratic fit to the longitude discrepancy.

The effect on the lunar mean longitude of a slow time variation of G can easily be computed from its effect on the mean motion:

$$\frac{\dot{n}}{n} = \frac{2\dot{G}}{G}$$

If $\dot{G}/G$ had a value of 5×10^{-11} year^{-1}, then over three years the resultant longitude discrepancy would be

$$\Delta L \simeq 8 \times 10^{-3} \text{ arcseconds}$$

assuming L_0 and n are well known. Tidal friction also affects the mean longitude, with separability coming from large solar terms which also give sensitivity to $n_{\oplus}$, the mean motion of the Earth about the sun. $n_{\oplus}$ is only affected by $\dot{G}$, and thus the contribution from $\dot{G}$ alone can be separated, albeit slowly. The best present experimental limit of the present value of $\dot{G}$ comes from analysis of radar observations of the inner planets (Reasenberg and Shapiro, 1975):

$$\left(\left|\frac{\dot{G}}{G}\right|\right)_{present} < 1 \times 10^{-10} \text{ year}^{-1}$$

Combination of the above data types (laser ranging, VLBI, and planetary radar) in a joint solution would extract the optimum information concerning tidal friction and $\dot{G}$.

The second category above contains effects causing motion of the orbit plane, i.e., the longitude rate of the lunar node and perigee. The most important of these is a general relativistic precession of the lunar orbital angular momentum, first discussed by de Sitter (1916), but not yet detected with significant accuracy (see Weinberg, 1972, and Slade, 1971). This precession causes an advance of the longitude of the lunar node and perigee of $\sim 20 \times 10^{-3}$ arcseconds/year.

The detection of these effects can most effectively utilize the accuracy of ΔVLBI by many repeated observations of the same quasars. Source position uncertainty then becomes unimportant. The observation of several ALSEP transmitters during each experiment allows solution for the position of the center of mass of the moon, removing in large part any libration uncertainties. The libration ephemeris has been greatly improved using the laser ranging data (Williams *et al.*, 1973), and the uncertainties presently are no worse than 3×10^{-3} arcseconds geocentric. Analysis of observations of the differential ALSEP phases by the MIT group (Counselman *et al.*, 1972, 1973; King, 1975) give the relative ALSEP positions and greatly alleviate any remaining difficulty with the physical librations.

VI. Summary

JPL is presently developing a high-precision, nearly inertial, celestial reference frame composed of compact extragalactic sources (principally quasars) for use in both astronomical and geophysical studies. The ALSEP–quasar VLBI program will utilize this new quasar reference frame to perform dynamical investigations of the lunar orbit by monitoring the moon's motion relative to angularly nearby quasars. These high-accuracy measurements are of value to tie the lunar ephemeris to the quasar frame, to test gravitational theories, and to measure the Earth–moon tidal friction interaction.

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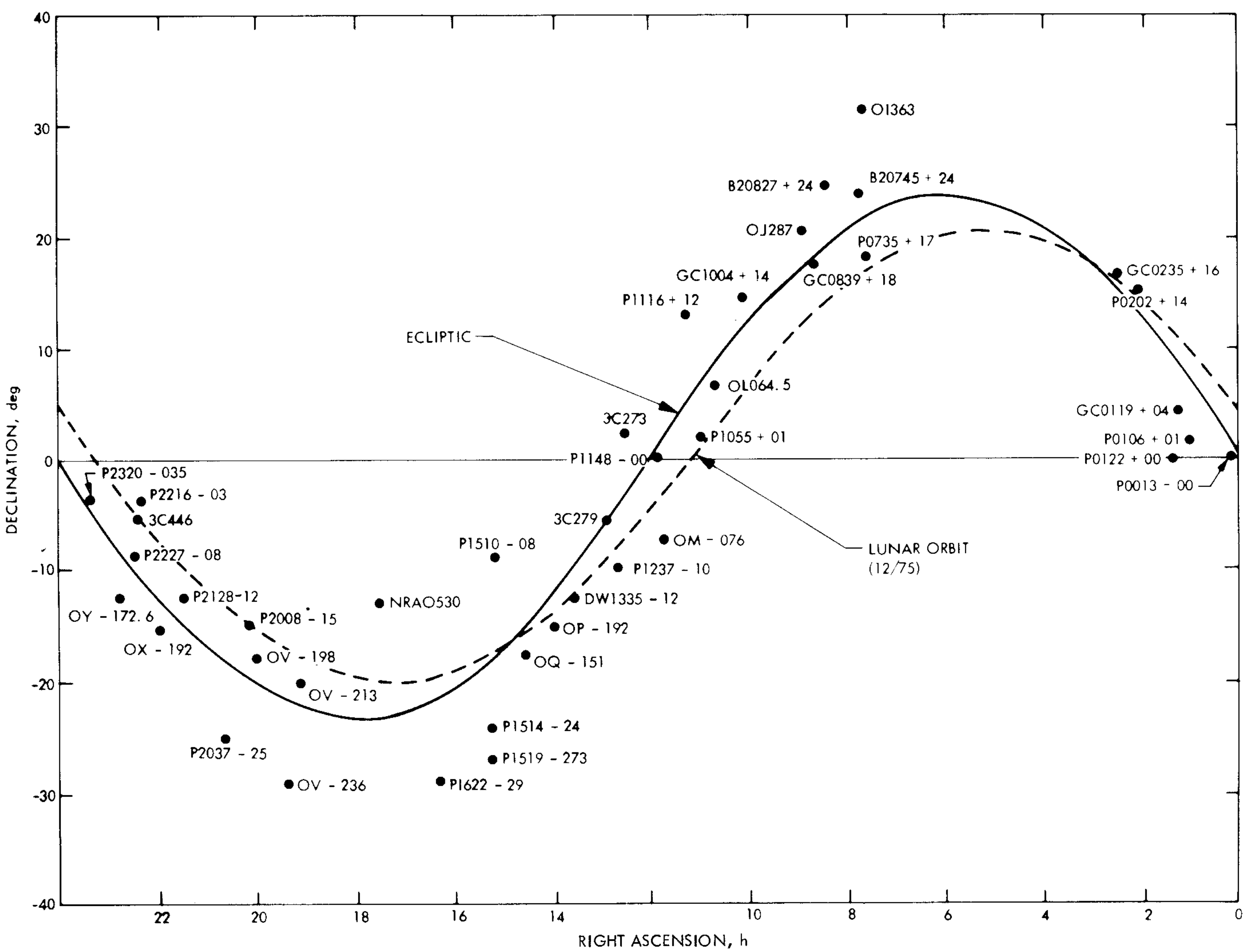


Fig. 1. Extragalactic VLBI sources within 10 deg of ecliptic (>0.5 jansky)

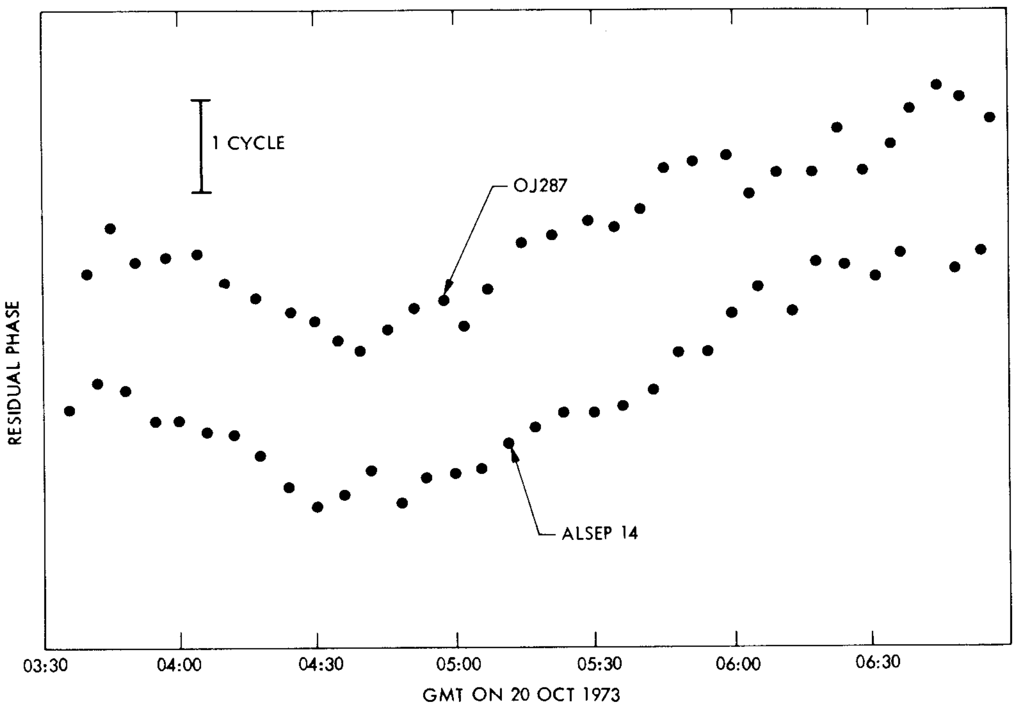


Fig. 2a. VLBI phase residuals on Oct. 20, 1973 "2-antenna" experiment. The points represent the mean values of data segments. The fluctuation about these means is typically 0.04 cycles for ALSEP 14 and 0.11 cycles for OJ287.

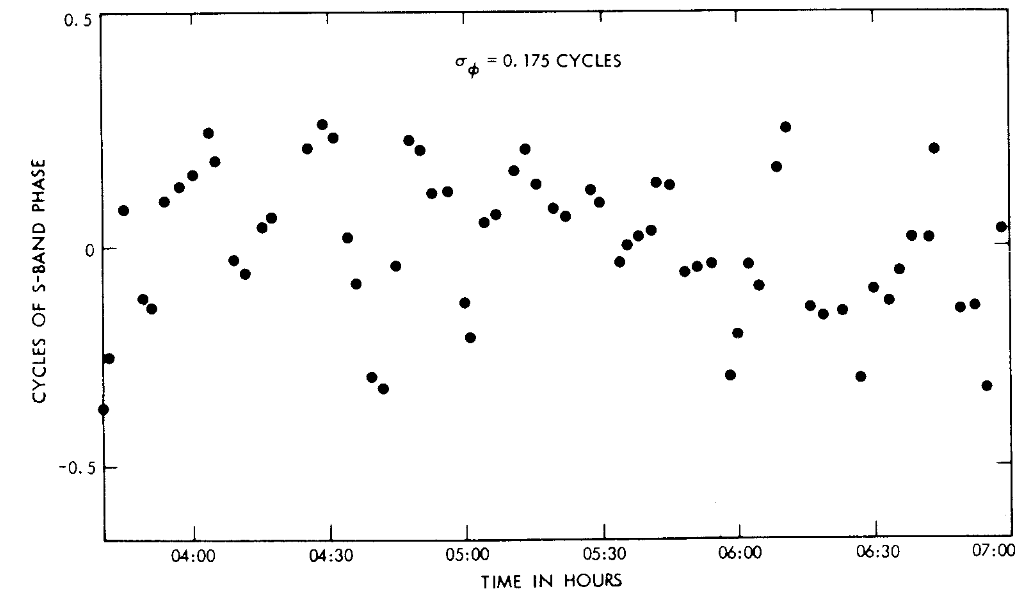


Fig. 2b. Differential phase of Fig. 2a. Fitted by quadratic polynomial in time. Note expanded scale on abscissa.

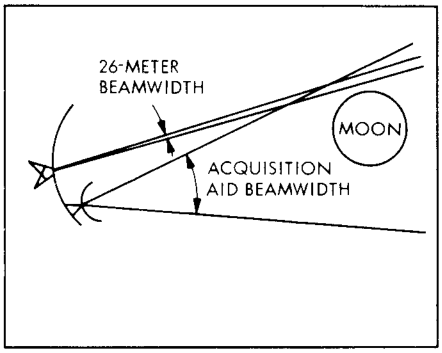


Fig. 3. Conceptual diagram of 26-m/acquisition aid antenna beam patterns

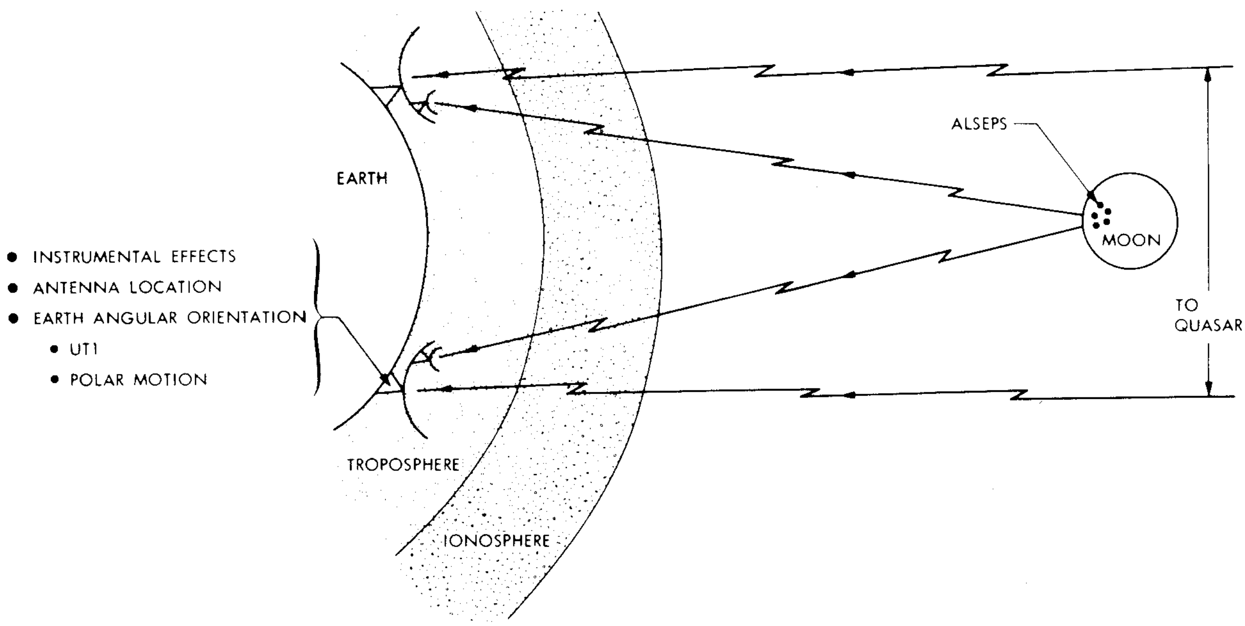
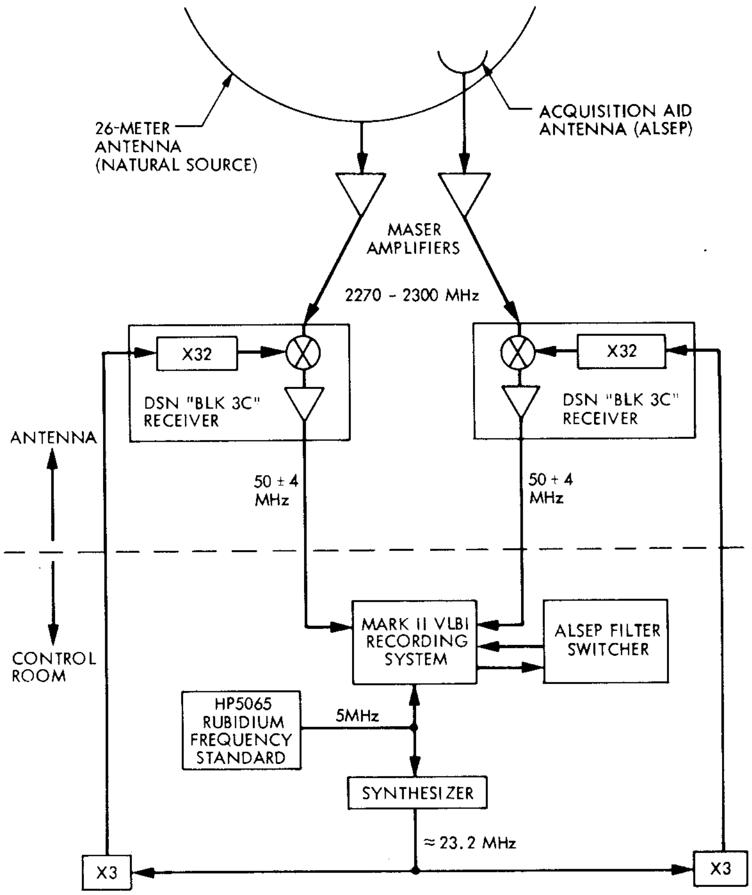


Fig. 4. Cancellation of common error sources with "4-antenna" ΔVLBI



NOTE: ABOVE CONFIGURATION APPLIES TO DSN 26 - METER STATIONS ONLY. CONFIGURATION OF THE STDN 26 - METER "APOLLO" STATION IS SIMILAR IN CONCEPT.

Fig. 5. ALSEP–quasar VLBI instrumental configuration

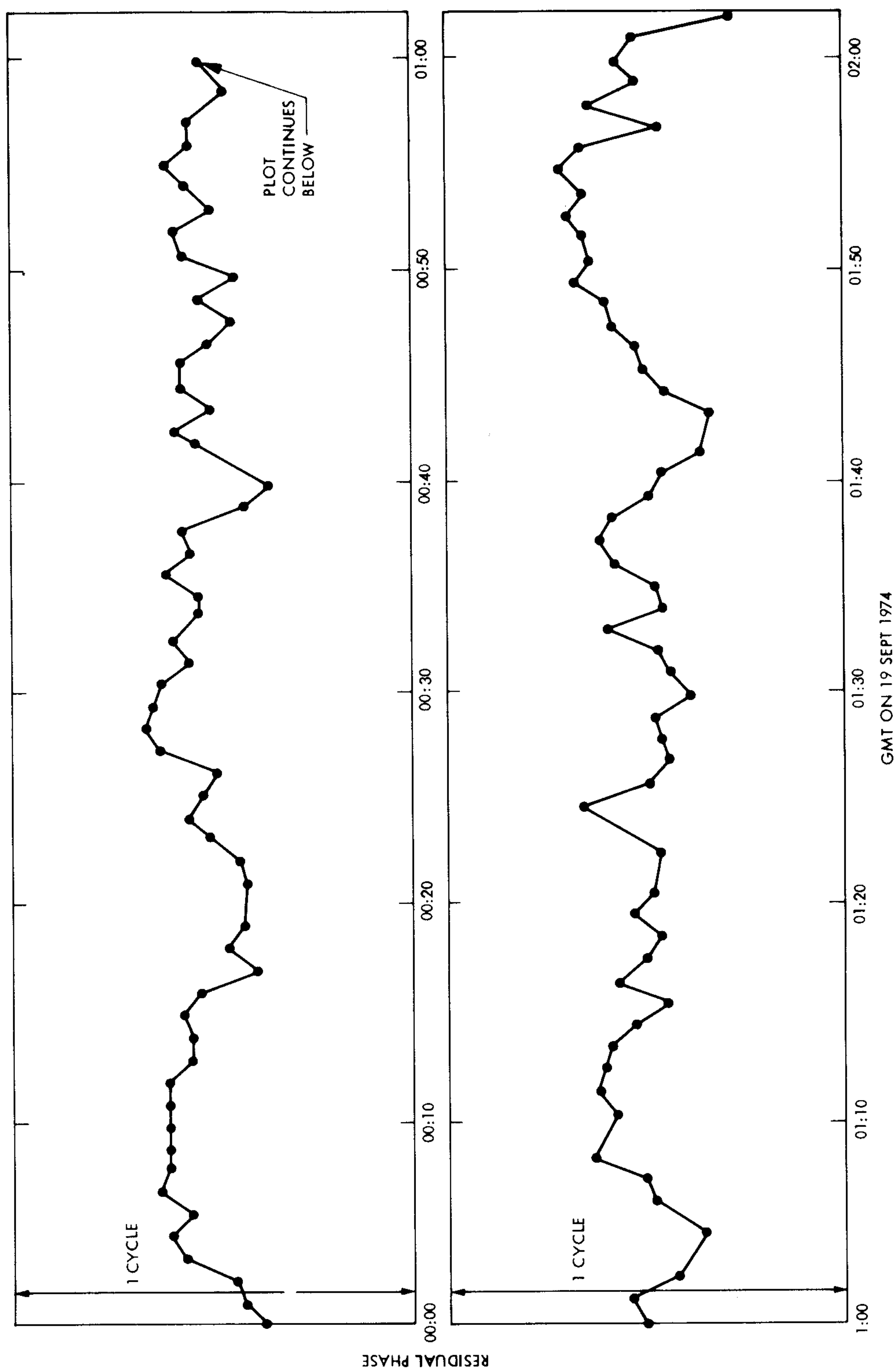


Fig. 6. VLBI phase residuals for ALSEP 15 on Sept. 19, 1974 "4-antenna" experiment. The lines joining points have no physical meaning. The instrumental noise is typically 0.03 cycles.

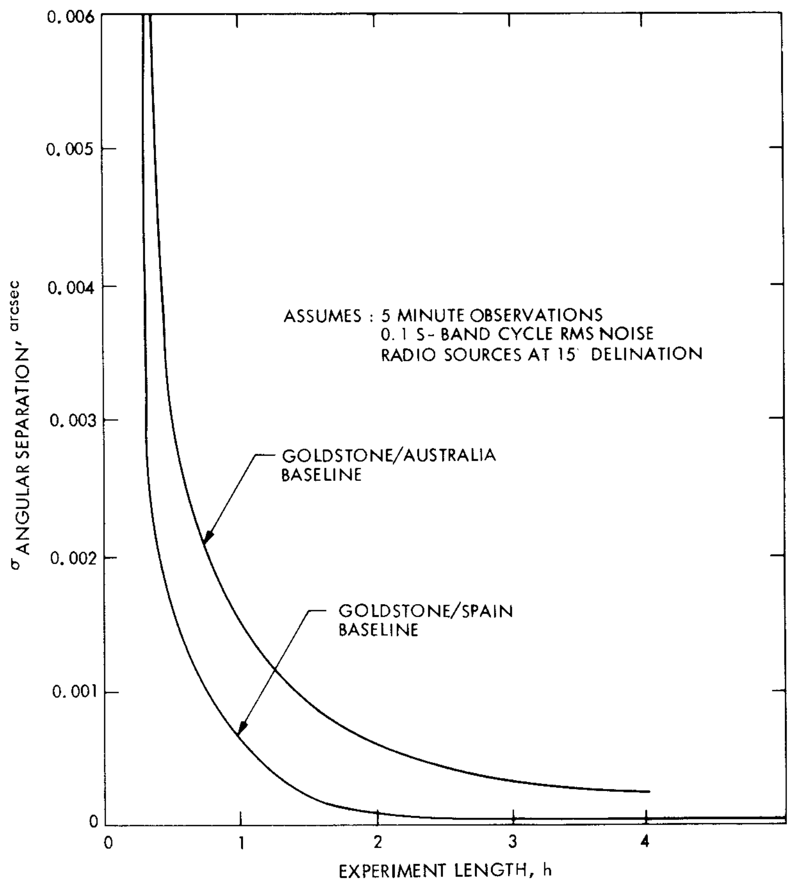


Fig. 7. ΔVLBI precision as function of experiment length