Very Long Baseline Interferometry (VLBI) Possibilities for Lunar Study

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The availability of several channels of transmissions from the lunar surface and lunar orbiting vehicles presents opportunities for demonstrating the utility of radio interferometric tracking. The expected accuracy of such very long baseline interferometry (VLBI) tracking is expected to be equivalent to 50 cm (transverse to the line of sight) at the moon's distance, affording significant opportunities for studies of lunar dynamics and selenodesy. In addition to direct applicability to lunar study, VLBI tracking of these several lunar-based signals provides an opportunity to evaluate simultaneous multiprobe tracking techniques which could significantly enhance the Viking 1975 and Pioneer Venus 1977 missions, where multiprobe tracking is imperative.

I. Introduction

As part of the development of new methods of spacecraft tracking and navigation for the Deep Space Network, the utility of very long baseline interferometry has been explored using S-band transmissions from the Apollo lunar surface experiment packages (ALSEP) and from the Mariner 9 orbiter. The experimental results from Mariner 9 will be outlined in a future article. This article describes results obtained using the ALSEPs as the radio source and the very interesting opportunities in selenodesy and lunar dynamics afforded by this technique.

II. Applications

Briefly, these opportunities include the application of VLBI for measurement of the following:

(1) Differential angular separation of the lunar-fixed ALSEP S-band radio signals equivalent to 50 cm or better, transverse to the line of sight, for selenodetic control.

(2) Relative angular displacement of a lunar orbiting vehicle (e.g., Apollo 17 Command and Service Module equivalent to 50-cm displacement and 0.05 mm/s velocity with respect to the lunar-fixed ALSEPs.

(3) Angular relationship of the moon relative to the inertial frame of extragalactic radio sources to an accuracy of 0.1 to 0.01 arc second.

(4) Lunar physical librations equivalent to 0.1 arc second (selenocentric).

These experimental opportunities should be exploited as soon as possible because of the finite lifetime of the ALSEP S-band radio transmission.

III. Procedure

The fundamental observational procedure for these measurements is the use of explicit differencing of observations from different sources so as to allow cancellation of mutual error sources. The differencing mode of observations takes on several forms:

(1) Interferometry differences between the various available ALSEPs themselves; (e.g., ALSEP 12, 14, 15, 16, and 17) in order to establish angular selenodetic control and the measurement of lunar libration.

(2) Difference between the radio transmissions from the lunar orbiting phase of the Apollo 17 Command and Service Module (CSM) relative to the lunar fixed ALSEPs (12, 14, 15, 16, and 17) in order to constrain the CSM position for the metric photography experiments.

(3) The interferometer difference between the ALSEP signals and a nearby extragalactic radio source, so as to measure the center of mass motion of the moon relative to an inertial frame of angular reference.

Figure 1 illustrates the overall VLBI technique. The technique is inherently passive, requiring only that two independently operated stations receive the same time series of electrical signals. These radio signals may be from either a natural source (e.g., a quasar), or a man-made source, such as an ALSEP or a spacecraft. Since this technique operates by receiving S-band (13-cm) radio signals, it is an all-weather method. The theoretical foundations of this technique are given in Refs. 1 and 2.

An interferometer composed of 26-m-diameter tracking antennas is well suited to simultaneous reception of all the ALSEPs since a 26-m-diameter antenna has a 3-dB beam width of 0.33 deg and the ALSEPs are very strong in the radio source sense (approximately 50,000 flux units, compared with 5 flux units for a strong quasar).

Several DSN baselines would be useful for lunar observations—specifically, Goldstone/Madrid, Goldstone/Australia, Australia/South Africa, and South Africa/Madrid. All these baselines will offer considerable flexibility for measurements of the moon, since the moon has a wide excursion in declination during the month; e.g., with the moon at positive declination, the Goldstone/Madrid, Madrid/Johannesburg, and Goldstone/Australia baselines will be most advantageous. However, with the moon at negative declination, the Madrid/South Africa, Goldstone/Australia, and Australia/South Africa baselines will be most advantageous. This occurs because the moon must obviously be mutually visible to the two stations composing the interferometer; thus, at negative declinations greater than 20 deg, there is no arc of mutual visibility on a Goldstone/Madrid baseline.

IV. Experience to Date

Actual interferometric reception of ALSEP signals has been acquired using the Goldstone 64-m-diameter and Madrid 26-m-diameter stations in September 1971. A JPL hydrogen maser frequency system was used in California, and a Smithsonian Astrophysical Observatory hydrogen maser was used in Spain for deriving the radio system local oscillator signals. A sample of the results obtained with the Goldstone/Madrid baseline is shown in Fig. 2. This figure is the result of differencing the observed, minus the computed (including a constant linear phase rate) interferometer phase.

Since the ALSEPs move very rapidly with respect to the fixed extragalactic radio sources typically used in VLBI, it was necessary to adapt existing lunar ephemeris programs to accomplish cross correlation signal detection. As seen in Fig. 2, a phase noise of 0.02 cycles RMS has been achieved over a 10-min time span. The difference between the 0.008 cycle individual point (12 s of integration) precision and the 0.02 cycle 10-min precision is probably due to systematic errors introduced by a combination of frequency system instability and the differential transmission media variations. These data were acquired by using frequency synthesizers to generate the first local oscillator signals, and thus their instabilities were multiplied by a factor of 96. As shown in the Radio System Configuration Section, any further experiments would use fixed frequency multipliers, limiting this error source to less than 10^{-3} cycles.[1]

V. Estimated Performance

Observing several ALSEPs simultaneously could afford a significant canceling of frequency system and transmission media variations over a time scale of several seconds and longer. In addition, platform parameter errors of station location uncertainties and the effects of polar motion and universal time are self-canceling. Thus, the relevant interferometer phase statistic is approximately 0.008 cycles. For the Goldstone/Madrid baseline (8,500 km), at these S-band wavelengths (13 cm), each cycle corresponds to an angular change of 0.003 arc second. Therefore, 0.008 cycles phase measurement precision affords a 24 micro-arc-second angular precision equivalent to 5 cm transverse displacement at the moon's distance.

However, systematic error sources prevent exploitation of this 5-cm angular equivalent measurement precision. Because all the ALSEPs' signals do not traverse precisely the same atmospheric paths to the receiving stations, the differencing does not entirely remove the atmospheric effects. The expected uncertainties remaining after calibration for the troposphere and the ionosphere combine to be equivalent to 50 cm of displacement at the moon's distance. Such calibrations are felt to be valid for elevation angles greater than 10 deg. There appears some hope for atmospheric parameter estimations from the data themselves, thereby allowing for some improvement in the differential angular measurement accuracy.

To summarize, the instrument measuring *precision* gives 5 cm, or better, but systematic Earth atmospheric effects degrade these measurements, so that only 50-cm accuracy will be realized initially.

VI. Radio System Configuration

Figure 4 illustrates a possible receiving station configuration for VLBI ALSEP experiments using the DSN. The dotted boxes denote experiment-particular modules. These modules are of relatively simple nature, being made up of mostly commercially available components. The 24-kHz bandwidth digital recording model shown is one which has been used extensively in VLBI Earth physics and DSN development experiments. The results shown in Fig. 2 were derived with this 24-kHz data-taking mode and a modified version of the data reduction software.

VII. Summary

The possibilities for lunar studies made available by the existence of the ALSEP S-band transmissions are essentially unique and should be undertaken as soon as possible because of the finite lifetime of the ALSEP signals themselves. This opportunity to develop multiprobe tracking techniques should also be of considerable interest to the Viking 1975 and Pioneer Venus 1977 missions. In the Viking mission, there will be two orbiters and two Mars landers to be tracked. During the Pioneer Venus mission, five vehicles will enter the Venusian atmosphere, requiring simultaneous tracking to determine relative probe positions. Such tracking may also provide the major measurement of the transverse winds.

[1]Figure 3 illustrates the switching mode which would be used in the proposed experiments. The switching time would be reduced to 6 s instead of 240 s, allowing the phase to be accurately connected.

References

1. Thomas, J. B., "An Analysis of Long Baseline Radio Interferometry," in *The Deep Space Network Progress Report*, Vol. VII, pp. 37–50, Jet Propulsion Laboratory, Pasadena, Calif., Feb. 15, 1972.
2. Thomas, J. B., "An Analysis of Long Baseline Radio Interferometry, Part II," in *The Deep Space Network Progress Report*, Vol. VIII, pp. 29–38, Jet Propulsion Laboratory, Pasadena, Calif., Apr. 15, 1972.

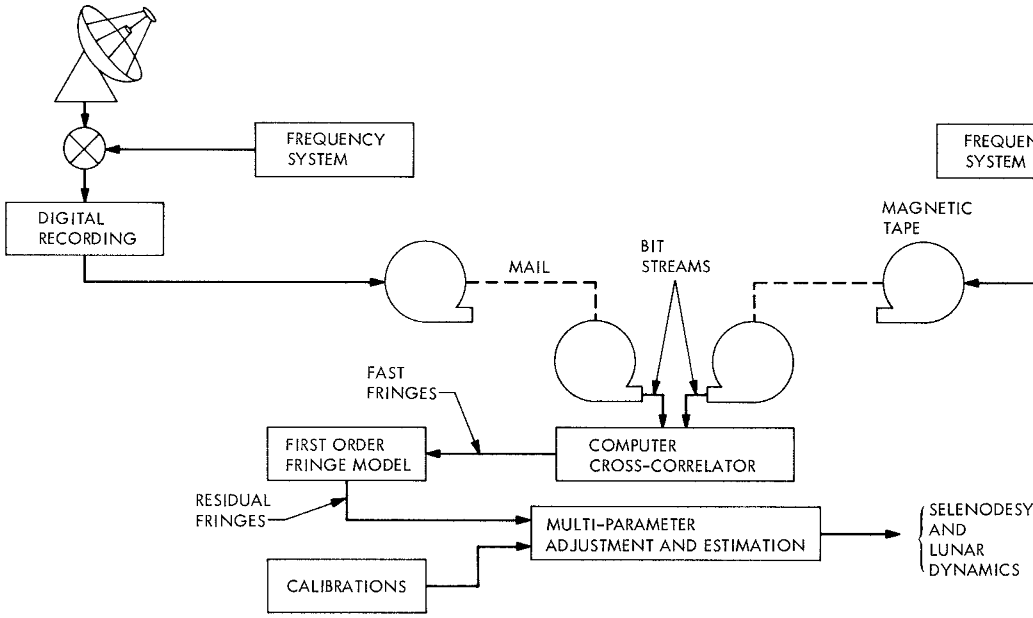

Fig. 1. The VLBI technique

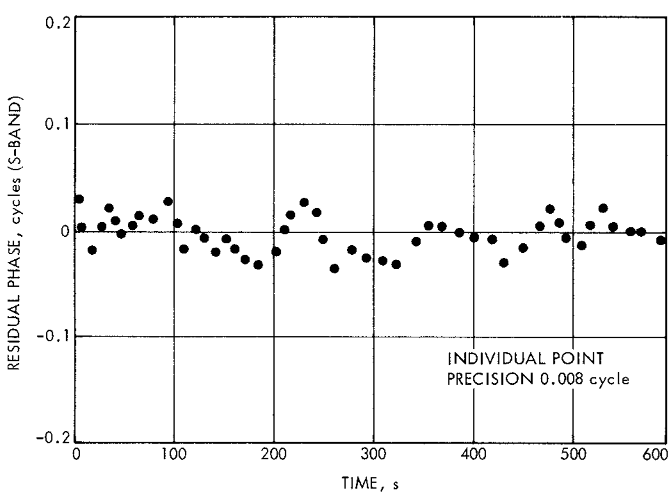

Fig. 2. Goldstone/Madrid VLBI observation of Apollo 15 ALSEP (Sept. 7, 1971)

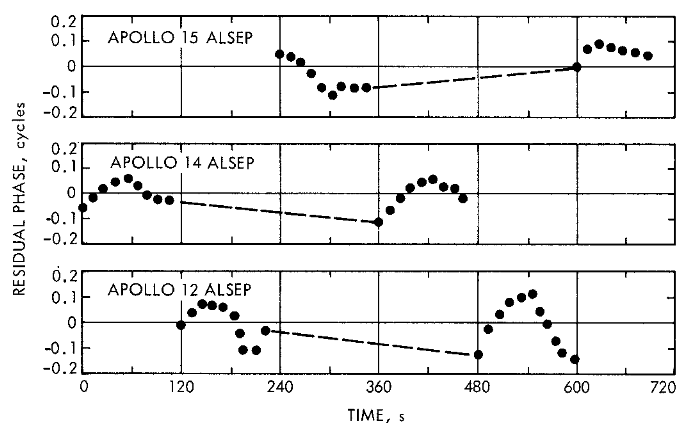

Fig. 3. An example of the switching-type mode to be used in proposed experiments (Goldstone/Madrid VLBI observations made on Sept. 7, 1971)

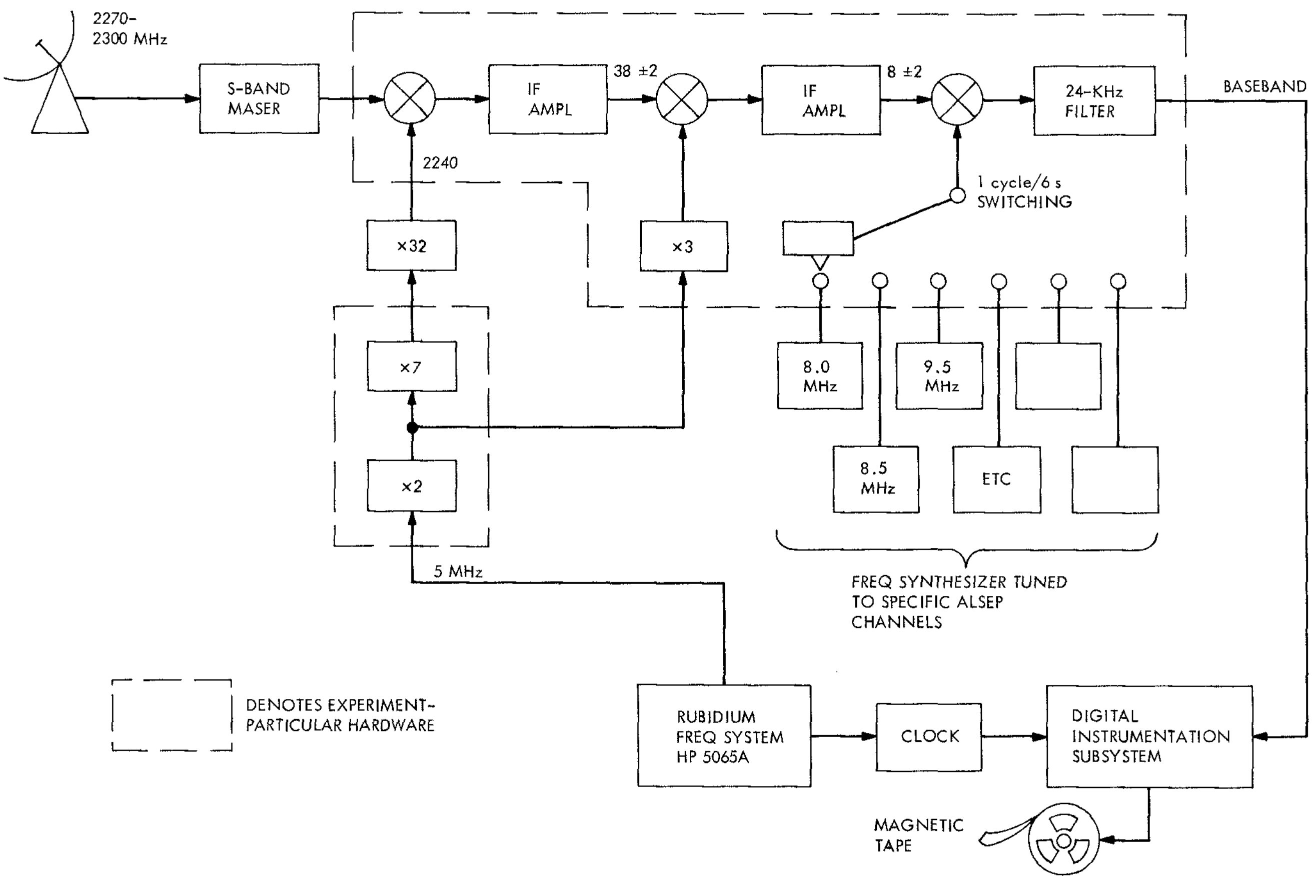

Fig. 4. Deep Space Station configuration for multichannel ALSEP radio science