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"VLBI OBSERVATIONS OF ALSEP TRANSMITTERS"

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Under this grant we have observed the Apollo Lunar Surface Experiment Package (ALSEP) S-band radio transmitters by very-long-baseline-interferometry (VLBI). The data obtained from these observations have been analyzed under a separate grant (NSG 7010) from the Lunar Programs Office, to make improved determinations of the positions of the ALSEPs and of the parameters governing the motion of the moon about its center of mass. Results of this analysis, as well as detailed descriptions of both the observational and the analytical procedures employed, have been presented in the following reports:

1. King, R. W., Precision selenodesy via differential very-long-baseline interferometry, Ph.D. thesis, Mass. Inst. of Technol., Cambridge, 1975.
2. King, R. W., C. C. Counselman III, and I. I. Shapiro, Lunar Dynamics and Selenodesy: Results from Analysis of VLBI and Laser Data, J. Geophys. Res., vol. 81, pp. 6251-6256, 1976.
3. Snow, W. R., Atmospheric Refraction Errors in DLBI Observations at Low Elevation Angles, M.S. thesis, Mass. Inst. of Technol., Cambridge, 1977.

On the following four pages, abstracts of these three reports are reproduced.

PRECISION SELENODESY VIA DIFFERENTIAL VERY-LONG-BASELINE INTERFEROMETRY

by

Robert W. King, Jr.

Submitted to the Department of Aeronautics and Astronautics on May 12, 1975, in partial fulfillment of the requirements for the degree of Doctor of Philosophy

ABSTRACT

The technique of differential very-long-baseline interferometry (VLBI) has been used to measure the relative positions of the ALSEP transmitters at the Apollo 12, 14, 15, 16, and 17 lunar landing sites with uncertainties less than 0".005 of geocentric arc. These measurements have yielded improved determinations of the selenodetic coordinates of the Apollo landing sites, and of the physical libration of the moon.

By means of a new device, the Differential Doppler Receiver (DDR), instrumental errors were reduced to less than the equivalent of 0".001. DDRs were installed in six stations of the NASA Spaceflight Tracking and Data Network (STDN) and used in an extensive program of observations beginning in March 1973. Data obtained over a 16-month period were used simultaneously with lunar laser ranging data in least-squares solutions for the 6 elements of the lunar orbit, the mass of the earth-moon system, the 2 lunar moment-of-inertia ratios $\beta[\equiv(C-A)/B]$ and $\gamma[\equiv(B-A)/C]$, 7 third-degree harmonic coefficients of the moon's gravitational potential, 6 initial conditions of the physical libration, and 3 coordinates each of the observing stations, ALSEP transmitters, and laser ranging retroreflectors. The uncertainties in the relative coordinates of the 5 ALSEP transmitters, estimated from the consistency between solutions with independent sets of VLBI data and from the consistency between VLBI and laser ranging results, are 30 m in the radial coordinates and 10 m in the two transverse coordinates. Values determined for the libration parameters

β, C_{31}, and C_{33} have uncertainties smaller than the uncertainties obtained when laser ranging data alone is used in the solution. The rms of the postfit residuals for the VLBI observations is 16° of phase (at 2.3 GHz), about 2 times larger than the random noise level. The systematic components in the residuals may result from unmodeled propagation-medium effects.

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Lunar Dynamics and Selenodesy: Results From Analysis of VLBI and Laser Data

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Very long base line interferometry (VLBI) observations of lunar radio transmitters have been combined with data from laser ranging to lunar retroreflectors to estimate simultaneously (1) parameters in models of the lunar orbit and libration and (2) the selenodetic coordinates of the radio transmitters and retroreflectors. For the ratio of the mass of the sun to that of the earth plus moon we obtain 328,900.50 ± 0.03. For the lunar moment-of-inertia ratios we find $\beta\,[\equiv (C - A)/B] = (631.27 \pm 0.03) \times 10^{-6}$ and $\gamma\,[\equiv (B - A)/C] = (227.7 \pm 0.7) \times 10^{-6}$. The value implied for C/MR^2 is 0.392 ± 0.003, the uncertainty being dominated by that of the coefficient J_2 of the second zonal gravity harmonic, obtained by Gapcynski et al. from analysis of Explorer spacecraft orbital data. The values and most of the uncertainties that we obtain for the third-degree harmonics of the moon's gravity field are comparable to those which have been obtained by others from observations of lunar orbiting spacecraft. However, our determination of β appears to be the best available, and our results for the two third-degree gravity coefficients $C_{31} = (26 \pm 4) \times 10^{-6}$ and $C_{33} = (2 \pm 2) \times 10^{-6}$ have much less uncertainty than determinations based on laser data alone. For the relative position vectors of the lunar radio transmitters and the retroreflectors our estimates have uncertainties of about 30 m along the earth-moon direction and about 10 m in each of the two transverse coordinates.

INTRODUCTION

The placement of optical retroreflectors and radio transmitters on the lunar surface (Figure 1) has stimulated significant advancement in the fields of lunar dynamics and selenodesy. The retroreflectors at the Apollo 11, 14, and 15 sites are being observed from the McDonald Observatory telescope in Texas by the Lunar Ranging Experiment (Lure) team. These observations, entailing measurements by laser of the round trip flight time of light signals traveling between telescope and retroreflector, have been described by *Bender et al.* [1973] and will not be discussed here in detail. Our group, on the other hand, is observing the radio signals being transmitted from the nuclear-powered Apollo lunar surface experiments packages, or 'Alsep's.' These observations, which yield angular position, are made at a radio frequency of 2.3 GHz via the technique of very long base line interferometry (VLBI). Before discussing the simultaneous analysis that we have made of the laser and VLBI data we describe the characteristics of the radio observations in more detail.

Each Alsep has a transmitter with a crystal oscillator which provides strong signals suitable for angular position measurements by VLBI. The existence of more than one Alsep transmitter permits the use of the technique of differential interferometry [*Counselman et al.*, 1972], in which the difference between the phases of the signals received from two Alsep's at one ground station is subtracted from the corresponding difference for another station. The resulting doubly differenced observable is sensitive to the differences between the right ascensions and the declinations of the two Alsep transmitters and, through the time variations of these quantities, to the moon's physical libration. The differential VLBI observable is relatively insensitive to the moon's orbital position, observing site coordinates, receiver instabilities, and propagation delays introduced by the earth's atmosphere and ionosphere, all of which tend to affect the observations of both transmitters equally.

In the following sections we describe the span of the VLBI and laser observations and then our simultaneous analysis of these data to estimate the parameters of the moon's physical libration and the selenocentric coordinates of the laser retroreflectors and the Alsep's. The data and our mathematical models are described briefly, and the postfit residuals are examined for evidence of systematic errors. Results are given for various physical constants, including the lunar moment-of-inertia ratios β and γ, the third-degree harmonic coefficients of the moon's gravitational potential, and the selenocentric coordinates of the Alsep's and the retroreflectors.

OBSERVATIONS

VLBI observations of the five Alsep transmitters have been carried out by stations of the NASA Spacecraft Tracking and Data Network (STDN) under our direction since March 1973 [*Counselman et al.*, 1973*a*, *b*]. The VLBI data analyzed thus far consist of observations on 97 separate days during the 16-month period ending in June 1974. Because of their relative insensitivity to the moon's orbital motion these data were always analyzed in combination with laser ranging data. The laser data consisted of 1194 'normal points' constructed at the University of Texas by using range measurements made between McDonald and the three Apollo lunar ranging retroreflectors (LRRR's) from January 1970 through June 1974 [*Abbot et al.*, 1973; *Shelus et al.*, 1975; *Mulholland et al.*, 1975; P. J. Shelus, personal communication, 1975].

MATHEMATICAL MODEL

The Massachusetts Institute of Technology Planetary Ephemeris Program [*Ash*, 1972] was used to obtain a weighted least squares estimate of parameters in mathematical models for the lunar orbit, for the rotations of the earth and the moon about their centers of mass, and for the locations of the observing stations, the Alsep's, and the retroreflectors. The moon's orbital motion was numerically integrated by using equations developed by *Ash* [1965] and *Slade* [1971]. The rotation of the earth was calculated from conventional expressions for precession and nutation, but three parameters to represent rotations about three orthogonal axes were added to the formulation to account for a possible error in the relative

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ATMOSPHERIC REFRACTION ERRORS IN DLBI OBSERVATIONS AT LOW ELEVATION ANGLES

by

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Submitted to the Department of Aeronautics and Astronautics on August 26, 1977, in partial fulfillment of the requirements for the degree of Master of Science.

ABSTRACT

Differential very-long-baseline interferometry (DLBI) observations of the ALSEP S-Band radio transmitters at the Apollo 12, 14, 15, 16, and 17 lunar landing sites have been analyzed to estimate the accuracies of Saastamoinen's, Berman's, and Chao's models for calculating the radio propagation delay of the neutral atmosphere at the zenith, and Chao's tables for mapping from the zenith to low elevation angles. The DLBI observations considered here were made at five stations of the NASA Spacecraft Tracking and Data Network on 7 days between March, 1973 and January, 1974. Effects of the neutral atmosphere were easily distinguished in these observations since the elevation angle of the moon at one station varied between relatively high (>30°) and very low (between 0.4° and 4°) values during each observation period. The observed values of differential interferometric phase were compared with theoretical values calculated from each of the models under consideration, with emphasis on the observations made at the lower elevation angles. The behavior of the differences (observed minus computed) found was correlated with data from meteorological observations made near the tracking stations. The Chao method of mapping the zenith delay to lower elevation angles was found to be inaccurate below about 4° elevation, due partly to changes in the weather down range from the station. The model calculations of the dry component of the zenith delay based on the local measurements of barometric pressure, and the mapping of this component, were judged to be relatively accurate down to 4° elevation. However, the wet component of zenith delay, calculated from the surface measurements of temperature and humidity, was inferred from the observations between 10° and 4° elevation to be as much as 50% in error. Typical errors were inferred to be between 15% and 20% of the computed zenith delay. The zenith delay model which yielded the smallest RMS difference between theory and observation was Saastamoinen's.

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