Eckert (*7*) for the solar terms. The range residuals are somewhat worse than those in longitude and latitude. In terms of sine parallax, the maximum is 0.0047 second of arc and the standard deviation is 0.0018 second (roughly 525 and 200 m in range). The residuals in range rate are about 1 to 2 mm/sec.

As must be expected, the residuals show several very distinct periodicities, some of which are more pronounced in the rectangular coordinates and velocities than in the spherical coordinates of Fig. 1. We have not yet performed a spectral analysis of the residuals, but visual examination of the data leads us to conclude that periodicities appear closely resembling several planetary arguments, such as an Earth + Venus period (140 days) and the synodic periods of Venus (600 days) and Jupiter (400 days). In addition to these, of course, there are periodicities of about 1 month. If a spectral analysis reveals that most of the residuals can be correlated with physically significant periods, one may artificially construct terms causing the theory to represent gravitationally consistent motion more adequately.

Our result implies a problem in timekeeping. Ephemeris time, which was until recently the closest determinable approximation to Newtonian time, is determined in practice by comparison of observations with the theoretical longitude of Moon; it is assumed that the theoretical longitude is not contaminated by any error. If such errors exist, the practical foundation of ephemeris time is compromised. An error of 0.16 second of arc in the theoretical longitude produces an error of about 0.30 second of time in the determination of ephemeris time. It appears that, if ephemeris time is to have any validity on time scales below the 1-second level of precision, the planetary portion of the lunar theory must be recalculated.

If our work indicates defects of hundreds of meters in the ephemeris, one may ask why the residuals (*3*) were so small. By a fortunate coincidence the gravitational defects in the ephemeris were smaller than usual during the two periods of spacecraft data, especially that of November 1966, during which the range residuals (Fig. 1) never exceed 150 m and have a mean value near zero.

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References and Notes

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2. J. D. Mulholland and N. Block, *Tech. Mem. 33-346* (Jet Propulsion Laboratory, Pasadena, Calif., 1 August 1967).
3. J. D. Mulholland and W. L. Sjogren, *Science* **155**, 74 (1967).
4. Jet Propulsion Laboratory "Seminar on uncertainties in the lunar ephemeris," Pasadena, Calif., 20 July 1967.
5. G. M. Clemence, in *Proc. JPL Seminar on Uncertainties in the Lunar Ephemeris*, J. D. Mulholland, Ed. (Jet Propulsion Laboratory Tech. Rept. 32-1247, in press).
6. *Proc. General Assembly Intern. Astron. Union 12th Hamburg 1964* (Academic Press, New York, 1966), vol. 12B, p. 595.
7. W. J. Eckert, M. J. Walker, D. Eckert, *Astron. J.* **71**, 314 (1966).
8. The constants used in the integration were those of the I.A.U. System of Astronomical Constants, except for the following: astronomical unit, 149,597,900 km; Earth's gravitational constant, 398,601.3 km^3/sec^2; Earth-Moon mass ratio, 81.302; Earth's oblateness factor (J_2), 0.00111157; scale factor, 6378.1495 km. Apart from J_2, these are consistent with radar and radio tracking results.
9. Supported by NASA contract NAS 7-100. We thank G. M. Clemence for drawing our attention to this problem. Working independently, F. M. Sturms has found residuals similar in nature and magnitude. We have benefited from the cooperation of W. L. Sjogren and C. Cary who are studying the spacecraft data from Lunar Orbiter and Surveyor, respectively.

20 February 1968

Gravitational Inconsistency in the Lunar Theory: Confirmation by Radio Tracking

Abstract. *When range and Doppler observations of space probes near or on Moon are reduced by use of a lunar ephemeris calculated from the Brown lunar theory, residuals as large as 440 meters in position and 1.5 millimeters per second in velocity are observed. When the calculations are repeated with use of LE 5, the integrated lunar ephemeris described* (1), *the residuals are greatly reduced.*

The numerically integrated lunar ephemeris (LE 5) described (*1*) has been tested by reduction of spacecraft data. Range data from five Lunar Orbiters, as well as Doppler (range-rate) data from a Surveyor resting on the lunar surface, confirm the presence of systematic errors in the currently adopted Jet Propulsion Laboratory (JPL) lunar ephemeris (LE 4) and demonstrate the greater accuracy of LE 5.

Observations of a Lunar Orbiter are used for detection of ephemeris errors in the following way: The spacecraft moves in an elliptical orbit about Moon. Range and Doppler measurements, which are independent of each other, are recorded at the tracking station. The Doppler data alone are used for determination of the spacecraft's orbit, from which its selenocentric position vector **r** can be calculated within 100 m. This computation is insensitive even to very large errors in the lunar ephemeris. From a priori information, **R**, the position vector of the tracking station, is known within 30 m. The geocentric position vector of Moon, $\mathbf{A}_☾$, is obtained from the ephemeris. The range to the spacecraft is calculated at

$$\rho = |\boldsymbol{\rho}| = |\mathbf{A}_☾ + \mathbf{r} - \mathbf{R}|$$

with an additional error of ± 4 m being introduced at this point by the finite size of the computer word. A

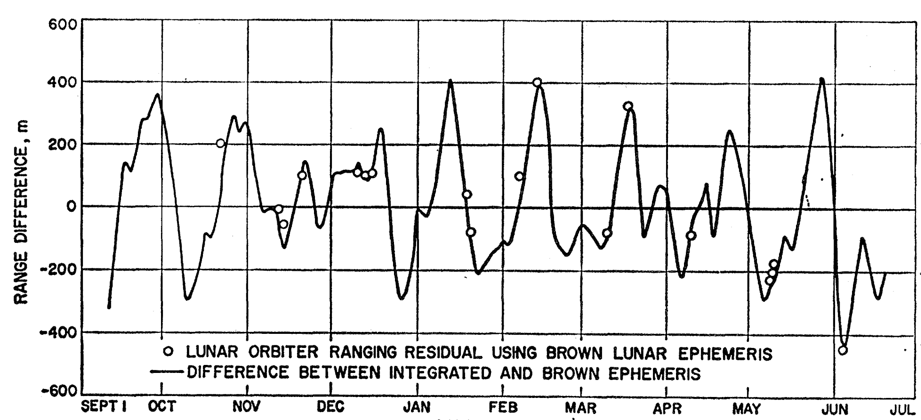

Fig. 1. Range residuals on the geocentric radial coordinate of Moon, 1966–67.

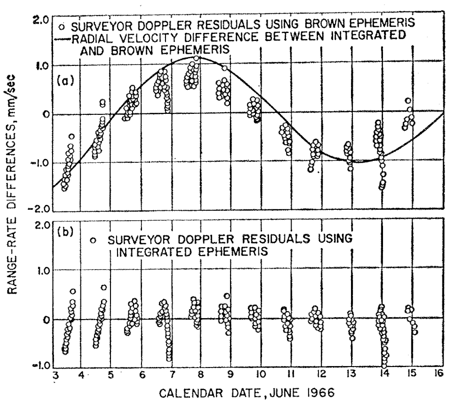

Fig. 2. Doppler residuals from Surveyor I on the lunar surface.

direct comparison is made between the calculated range values and the high-precision range measurements that were not used in the computation. Since **r** and **R** are well known, any large differences must be attributed to errors in $\mathbf{A}_☾$, which in this preliminary analysis was assumed to be parallel to $\boldsymbol{\rho}$. This assumption introduces an error of approximately 0.1 m, which is negligible.

The solid curve in Fig. 1 is a plot of the difference in radial distance to Moon between LE 5 and LE 4. The dots are Lunar Orbiter range residuals (observed minus computed), which were calculated with LE 4 used as the source of $\mathbf{A}_☾$ (*2*). The residuals are in excellent agreement with the curve (Fig. 1)—generally within 50 m; the improved accuracy of the integrated ephemeris is thus confirmed.

Another test is provided by data obtained from Surveyor I, which landed in the Ocean of Storms on 2 June 1966; it was tracked continuously for 2 weeks after landing and intermittently for the next 6 months until it apparently ceased to function; it did not include ranging equipment, so that only Doppler range-rate data were recorded. The geometry for this situation is the same as that for the Orbiters, except that the vectors $\boldsymbol{\rho}$ and **r** meet at the lunar surface. The vector **r** and its time derivative, which depend only upon the selenographic coordinates of the spacecraft, are calculated from the theory of lunar rotation (*3*). The spacecraft range rate, as observed at the tracking station, is calculated at

$$\dot{\rho} = \dot{\boldsymbol{\rho}} \cdot \mathbf{u} = (\dot{\mathbf{A}}_☾ + \dot{\mathbf{r}} - \dot{\mathbf{R}}) \cdot \mathbf{u}$$

where **u** is a unit vector in the direction of $\boldsymbol{\rho}$. This data type is sensitive to errors in the lunar velocity that project on **u**; because this is very nearly the direction of $\mathbf{A}_☾$, Doppler observations are most sensitive to errors in Moon's radial velocity.

Because of uncertainties in the flight path, the precise location of the spacecraft on the lunar surface was not known a priori. An orbit-determination program was used to adjust the spacecraft coordinates (and those of the tracking station) so as to minimize the weighted sum of squares of Doppler residuals. When this was done with LE 4 used as the source of lunar positions and velocities, the residuals shown as dots in Fig. 2a (*4*) were obtained. Each group of dots represents several hundred Doppler observations made during a 12-hour tracking period. For comparison, differences between LE 5 and LE 4 in Moon's geocentric radial velocity are shown as a solid curve. The fact that the estimated location of the spacecraft lies nearly 6 km below the accepted lunar radius (*5*) is further evidence of the presence of systematic errors. When the computations were repeated with LE 5 used instead of LE 4 (*6*), the residuals in Fig. 2b were obtained, and the estimated location of the spacecraft moved to within 120 m of the accepted lunar radius.

The lack of long-term variations in the final set of residuals and the more reasonable estimate of the lunar radius clearly demonstrate the improved quality of LE 5. However, as shown in Fig. 2b, the use of LE 5 has not removed all the systematic trends: variations with a period of about 1 day are still evident. While these errors may be partly caused by deficiencies in other aspects of the physical model used in the JPL orbit-determination program, preliminary analysis indicates that use of an obsolete value of the oblateness of Earth, in the computation of LE 5, probably contributes to the errors (*7*); this discrepancy produces errors of approximately 0.2 second of arc (400 m) in Moon's latitude and longitude.

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References and Notes

1. J. D. Mulholland and C. J. Devine, *Science*, this issue. We assume that the reader has read descriptions of the JPL lunar ephemerides LE 4 and LE 5.
2. Nominally each point represents the average of 100 ranging measurements recorded over a 12-hour period. Many additional points have not yet been reduced.
3. D. H. Eckhardt, *Astron. J.* **70**, 466 (1965).
4. The residuals shown are for data recorded at the Canberra tracking station; residuals from other stations had a similar appearance.
5. "Accepted radius" refers to a value 2.5-km smaller than that shown on the lunar charts prepared by the Aeronautical Chart and Information Center. This adjustment is based on observed impact times of Rangers.
6. In these calculations, the corrections to all lunar position and velocity coordinates were taken into account.
7. J. D. Mulholland, personal communication, 20 October 1967.
8. Supported by NASA contract NAS 7-100.

20 February 1968

Discrepancies between Radar Data and the Lunar Ephemeris

Abstract. *Precise measurements of the Doppler shift of radar waves reflected from Moon disclose unexpectedly large discrepancies—averaging about 0.6 centimeter per second—between the radial velocities and the predictions based on the Eckert-Brown lunar ephemeris. These residuals have a rapidly changing component corresponding to a relatively large, variable, and unexplained discrepancy in radial acceleration of about 10^{-4} centimeter per second, per second, in magnitude and about 1 day in period.*

A series of radar observations of Moon, made between 25 July 1966 and 19 April 1967 (*1*), yielded Doppler shifts differing significantly from predictions based on the Eckert-Brown lunar ephemeris (*2*). Table 1 contains the data for a representative sample drawn from the total of more than 100 independent Doppler measurements, and Fig. 1 shows the residuals from four sets of these observations. The remainder of this report is devoted to (i) description of the methods used to take and reduce the data, (ii) analysis and elimination of factors—other than possible errors in the lunar ephemeris—that may have caused the observed disagreements between measurements and predictions, and (iii) an outline of a program that may lead to reconciliation between theory and observation.

Each measurement of Doppler shift was obtained by analysis of the lunar echo resulting from the transmission toward Moon of a series of coherent short pulses of X-band radiation. Before 1 October 1966 the carrier frequency employed was 7750 Mhz and the pulse duration was 10 μsec; thereafter, with a new transmitter system, the carrier frequency was increased to 7840 Mhz but the pulse length remained unchanged except for a few special runs.

The goal of the analysis was estimation of the Doppler shift associated with a wave reflected from the point on the lunar surface that lies on the line from