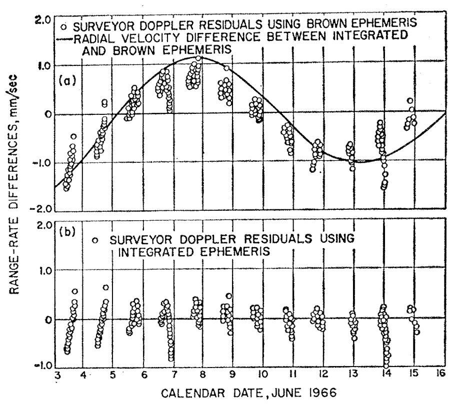

Fig. 2. Doppler residuals from Surveyor I on the lunar surface.

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

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

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 the radar site to Moon's center—the so-called subradar point. Such estimates are easily compared with the lunar-ephemeris predictions. Two different techniques were utilized for deduction of these Doppler values:

1) The radar antenna was directed toward the subradar point, and a delay-Doppler map (*3*) was constructed from the echoes. If the echo were free from noise and Moon were a perfect sphere, the average of the extreme (largest and smallest) frequencies contained in the spectrum of the return from each delay "ring" would be identical with the frequency of the echo from the subradar point. Since neither condition holds exactly, this frequency was approximated by the average of the frequency estimates deduced from each delay ring, the rings being separated by 10 μsec. Between ten and 15 delay rings were analyzed for each reported Doppler shift, and several different empirical methods were used for the selection of the extreme frequencies contained in the spectrum of each ring. The almost invariable good agreement between results from the different methods and the different rings makes us confident that the true error in each measurement is probably less than the assigned value of 0.15 hz.

2) The radar beam, whose angular extent is a small fraction of Moon's, is directed at regions removed from the subradar point. The delay-Doppler map of each such region exhibits features that can be readily identified with their optically visible counterparts (*4*). By this correspondence, the delay-Doppler coordinates can be identified with selenographic coordinates, and the Doppler shift associated with the subradar point can be inferred. The estimated probable errors in these determinations varied from 0.05 to 0.15 hz, depending on the region that was mapped. Often both types of data were obtained with separations of only a few minutes; the results from both generally agreed within the errors assigned (Fig. 1).

What physical effects could possibly contribute significantly to the differences between the measured and calculated Doppler shifts? Before attempting an answer we must describe the basis of the calculated values. The Brown lunar ephemeris, as corrected by Eckert (*5*), was used with the recommended constants to provide the geocentric values of the position and the velocity of the center of Moon as a function of ephemeris time. (Two different interpolation techniques were applied to the tabular values to guard against small errors.) The radius of Moon near the subradar point was taken to be 1738 km; the geocentric site coordinates of the Haystack radar were obtained from a standard land survey, with a modern value for Earth's flattening (see Table 1); and the relations between WWV time (used at Haystack), universal time, and ephemeris time were obtained from bulletins provided routinely by the U.S. Naval Observatory. We then calculated the Doppler shift for each observation,

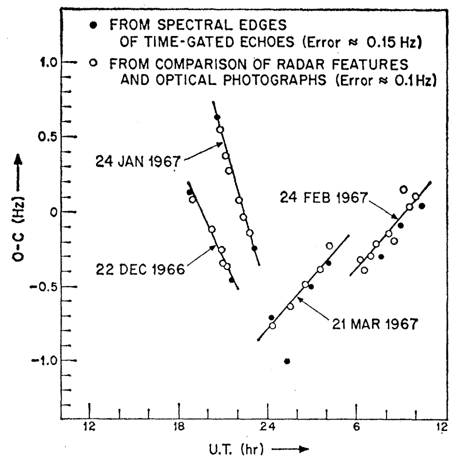

Fig. 1. Comparison of theoretical predictions with observed Doppler shifts accompanying radar echoes from Moon. The straight lines have no known theoretical significance; only slightly more than half of varying nearly linearly. *U.T.*, universal time.

Table 1. Sample of Doppler data from lunar radar echoes. Geocentric coordinates obtained for the Haystack site are: *r*, 6368.5504 km; latitude, 42.43157°N; longitude, 71.48869°W. The transmitter frequency was 7840 Mhz.

Universal time of echo reception (hr)	Observed Doppler shift (hz)
22 December 1966	
1840	19,321.31*
1855	19,311.60
2015	18,103.14
2045	17,166.02
2100	16,604.95
2115	15,985.18
2130	15,309.03*
21 March 1967	
0010	4677.06*
0020	4024.39
0115	454.23*
0125	−181.35
0230	−4096.01
0245	−4926.00*
0335	−7423.31
0355	−8288.80*
0410	−8881.78

* Obtained from an average of the positions of the spectral extremes of time-gated echoes near the subradar point; remaining data were obtained from comparison of mapped radar features and optical photographs.

assuming propagation to take place in a vacuum and using a formula, derived in accordance with special relativity, to express the shift in terms of the velocities of our site and Moon (*6*).

First we investigated the effects of the propagation medium. Because of the change in elevation angle of the radar beam during the course of an observation, Earth's atmosphere and ionosphere introduce systematic changes in the Doppler shift. Using a model ionosphere in which the integrated electron density in the zenith direction is $6 \times 10^{13}/\mathrm{cm}^2$, we found that, even for the lowest elevation angles at which measurements were made, the effect on the Doppler shift is always less than 10 percent of the estimated error and thus is negligible. Except for the relatively few observations made at elevation angles less than about 10 deg, the correction for the neutral atmosphere is substantially smaller than the quoted error. The possible influence of clouds passing rapidly through the radar beam was considered as well. If conditions were to change within 10 seconds from absolutely clear to cloudy, with a cloud thickness of 1 km, the concomitant effect on the Doppler shift would be about 0.15 hz; we conclude that the passage of clouds is unlikely to cause the observed discrepancies. Similar calculations of the effects of rapidly changing ionospheric conditions lead to the same conclusion.

Since Moon is ellipsoidal in shape, rather than spherical as was assumed, the time-delay rings are not circular and the Doppler shift inferred for the subradar point may therefore be in error. However, a simple calculation shows that Moon's surface at the apparent lunar equator would have to have an ellipticity as great as 0.003—about 15 times larger than is currently believed—to induce an error in Doppler shift of even 0.1 hz; hence this possible source of error also is negligible. Doppler shifts attributable to polar motions and variations in Earth's rate of rotation are lower by several orders of magnitude than the threshold of observability. To have an appreciable effect on the Doppler shift, an error in the estimate of the difference between universal and ephemeris times would have to exceed the published estimate of error by a factor greater than 10.

The remaining aspect of our theoretical model to be investigated is the assumed location of the radar site. Its geocentric rectangular coordinates, referred to the mean equinox and equator of 1950.0, compared well with the results of application of the corrections, required by the Smithsonian Standard Earth, to the coordinates obtained from the land survey (7). To check possible errors in surveying or modeling we investigated the effects of variation in these coordinates. Since, for the observations under discussion, the effect of change in the station altitude could be almost exactly duplicated by a suitable change in its latitude, only variations in latitude and longitude were considered. The making of a weighted-least-mean-square fit to the raw residuals, for estimation of corrections to the latitude and longitude, led to changes of a few seconds of arc in these coordinates. The root-mean-square values of the after-fit residuals, although of course reduced, were still essentially double the estimated errors. Thus we are left with discrepancies whose absolute values average about 0.3 hz, corresponding to unexplained average variations of nearly 0.6 cm/sec in the radial velocity between the Haystack site and the subradar point on Moon.

Most but by no means all of the sets of data have residuals that appear to vary nearly linearly with time. The implied discrepancies in radial acceleration vary from about 3×10^{-5} to 10^{-4} cm/sec^2. The sets of data are unfortunately too far apart for reliable inference of the periodicities in the residuals; presumably they are of the order of 1 day. Although seemingly very small, such residuals are larger by several orders of magnitude than lunar accelerations attributable to, say, the second harmonic of Earth's gravitational field, or the differential gravitational effect of Venus. Thus it is hard to believe that these residuals are attributable to shortcomings of the lunar ephemeris. Earth's rotation also appears to be known with more than sufficient accuracy for this application. Nonetheless, recent independent evidence from deep space probes (8) indicates that the site-Moon ephemeris has similar but substantially smaller errors.

To check the possibility of errors in our computer calculations, we requested independent computation of the Doppler shifts corresponding to a random selection of ten of our data points. The results (9) in most instances showed greater disparity when compared with the observed values. The differences between the corresponding theoretical results, varying from 0.05 to 0.2 hz, also remain unresolved.

A sustained series of closely spaced radar observations of Moon, under varying conditions of weather and lunar elevation above the horizon, may provide the clues to enable elimination of these perplexing differences between theory and observation.

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2. See, for example, J. D. Mulholland and N. Block, *Jet Propulsion Laboratory Tech. Mem. 33–346* (Aug. 1967).
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10. We thank M. E. Ash, K. Becker, A. Forni, W. Mason, and T. W. Thompson for their contributions in preparation and writing of the computer programs; J. Bauer kindly provided the models of the neutral atmosphere and ionosphere. Lincoln Laboratory is supported by the U.S. Air Force; a portion of this work was aided by NASA contract NSR 22-009-106.
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Denver Meteorite: A New Fall

Abstract. *A meteorite, a single stone weighing 230 grams, was discovered in the roof of a warehouse on 17 July 1967; evidently it fell during the preceding week. The warehouse is on the northeast edge of Denver, Colorado; coordinates, 39°46′57″N, 104°55′50″W. This is the first recovered fresh fall in the United States since the Bells (Texas) meteorite of 9 September 1961. The composition and structure are those of an olivine-hypersthene chondrite.*

Meteorite researchers in the United States have felt frustrated by the few recoveries of meteorites in recent years. Whereas statistics indicate that about ten meteorites probably fall within the United States annually, we now report the first recovery since the Bells (Texas) meteorite of 9 September 1961. A small meteorite penetrated the roof of a Denver, Colorado, warehouse (1) in July 1967. A search of the neighborhood for possible additional stones from the same fall was unproductive.

The meteorite was discovered on 17 July 1967 when water dripped through the ceiling. Inspection of the roof (flat galvanized-steel sheeting covered with tar and stone chips) revealed a small hole, with the meteorite, a 230-g stone, resting on the inner ceiling about 15 cm below. Heavy rain had fallen on 15 July; the meteorite presumably fell either during or before the rain, but after the preceding rain on 11 July. None of the usual visual and sound effects associated with the fall of a meteorite were observed, but the warehouse is close to the Denver airport and two military airfields, so that loud noises and bright flashes of light do not attract much attention.

The Colorado School of Mines Prospector Service reported that the stone was probably a meteorite and suggested that it be sent to the U.S. National Museum for confirmation. It was received as a rounded stone the size and shape of a small fist; a piece (2) had been removed from one end evidently by a diamond saw. The stone had the typical dull-black fusion crust and gray-white interior of a chondritic meteorite. The original weight of the stone was approximately 230 g; density, 3.58.

The mineralogic composition of the meteorite is (percentages by weight) olivine [$(Mg_{0.76}Fe_{0.24})_2SiO_4$], 45; hypersthene [$(Mg_{0.79}Fe_{0.21})SiO_3$], 25; plagioclase [$(Na,Ca)\ (Al,Si)_4O_8$, (9 mole percent $CaAl_2Si_2O_8$)], 11; nickel-iron, 8; troilite (FeS), 6; diopside [$Ca(Mg,Fe)Si_2O_6$], 5; chromite ($FeCr_2O_4$), 1; and merrillite [$Ca_3(PO_4)_2$], 1. Such composition is typical of olivine-hypersthene chondrites, the commonest class of meteorites, that comprise about 40 percent of observed falls.

Occasional chondrules as large as 2 cm in diameter are visible on the cut surface of the meteorite. The chondritic structure is not prominent in a thin section under the microscope; the margins of individual chondrules are diffuse and tend to merge with the crystalline groundmass. Interstitial plagioclase is unusually well developed but does not show the polysynthetic twinning characteristic of this mineral in terrestrial rocks. A large grain of merrillite was noted in the thin section. Composition and structure place this chondrite in the L6 type (3).

Chemical analysis gave the following percentages by weight: SiO_2, 40.57; TiO_2, 0.14; Al_2O_3, 2.48; Cr_2O_3, 0.47; FeO, 14.16; MnO, 0.33; MgO, 25.30;