ever, the line lies several thousand kilometers west of the edge of the visible rise as defined by bathymetry.

If one measures from the crest of the rise, the Clipperton, Clarion, and Molokai zones branch at a distance of 4600 to 4900 km. The crest is concealed under North America east of the Murray and Mendocino zones, but the position may be estimated as the center of Tertiary uplift of the western United States (*7*). Branching of these two fracture zones occurs 4500 to 4600 km west of this crest.

It may be significant that great lines of volcanoes commonly occur in the central region of branching fracture zones, where rotation of crustal blocks and tension faults would be expected. Volcanoes occur throughout the Pacific, but very large ones are mostly west of the line of branching. The southern Hawaiian Islands clearly are affected by faulting along the Molokai fracture zone because vulcanism is localized along east-west trends (*8*). A similar effect occurs on the west side of the central Hawaiian and Line islands, where narrow volcanic ridges follow fracture-zone trends. However neither the Hawaiian Island ridge nor the Molokai fracture zone is offset at their intersection (*9*). The lines of central-Pacific volcanoes apparently were superimposed on the fracture zones, which generally are buried where they intersect archipelagic aprons and volcanic ridges.

The origin and history of these great fracture zones are not becoming more obvious as additional facts accumulate. Indeed it has become necessary to distinguish them as "great" because a different system of shorter, more closely spaced, seismically active fracture zones with various trends exists in the same region along the crest of the East Pacific Rise. The probability that the great fracture zones are genetically related to the East Pacific Rise seems stronger when one considers the new evidence that branching occurs at a relatively uniform distance from the crest. However, there are at least two other possibilities: Perhaps the fracture zones of the central Pacific are a different system which intersects the northeastern-Pacific system to form what are here interpreted as branches. Perhaps the zones are part of an intermittently rejuvenated global fracture pattern of great antiquity. The extraordinary Clipperton fracture zone, which follows a great circle for a quarter of Earth's circumference, is especially extraordinary if it was produced by a nonglobal deformation.

A great fracture zone is not difficult to trace by special survey, provided a location and trend are known. Echo sounders, magnetometers, and subbottom profilers all can be used for the purpose at or near cruising speeds. Present concepts of large-scale tectonics might be more firmly based if the known fracture zones of the Pacific, Atlantic, and Indian oceans were traced to their terminations—apparently a valid purpose for the continuing Upper Mantle Project.

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Lunar Orbiter Ranging Data: Initial Results

Abstract. *Data from two Lunar Orbiter spacecraft have been used to test the significance of corrections to the lunar ephemeris. Range residuals of up to 1700 meters were reduced by an order of magnitude by application of the corrections, with most of the residuals reduced to less than 100 meters. Removal of gross errors in the ephemeris reveals residual patterns that may indicate errors in location of observing stations, as well as the expected effects of Lunar nonsphericity.*

One of the experimental missions of the Lunar Orbiter spacecraft is the providing of range data with an accuracy of 10 m, the highest accuracy yet achieved at such a great distance from Earth. These data have been used to confirm the validity of corrections now being made to the Lunar ephemeris (*1*). This confirmation consists of the order-of-magnitude reduction of the residuals (observed − computed) in range when the corrections are introduced. If the old ephemeris is used, the root mean square (r.m.s.) residual is about 800 m, with a maximum near 1700. After the corrections are applied, the r.m.s. residual is reduced to about 110 m, which is well within the uncertainties expected due to other factors. With the residuals thus reduced, the variations produced by errors due to station location and by the harmonics in the Lunar gravitational potential can be expected to exhibit a dominating influence. This, in turn, will facilitate the use of the range data for the better determination of the figure of the Moon and for the location of tracking stations.

Orbit determination of range data from Lunar Orbiter I and II gave nonrandom residuals which often far exceeded those expected from known effects. These analyses were performed with the standard Jet Propulsion Laboratory ephemeris tapes (*2*), in which the Lunar ephemeris is based on the improved Brown lunar theory [Eckert, Jones, and Clark (*3*)]. Such an ephemeris is subject to several corrections, and one of us (Mulholland) has been directing the effort to calculate and apply these corrections to the JPL ephemeris, in an effort to improve its adequacy. The simultaneous availability of the Lunar Orbiter data and the computations of the ephemeris corrections presented us with the means to test the significance of the corrections and, at the same time, to remove much of the model error for further data analysis.

Before the comparisons are examined, we will give a short explanation of how ranging data from a spacecraft in orbit around the Moon can provide an independent test of the lunar ephemeris, as well as a brief discussion of the causes from which the ephemeris corrections arise.

In the orbit determination program used for the Lunar Orbiter calculations, the selenocentric (that is, Moon-cen-

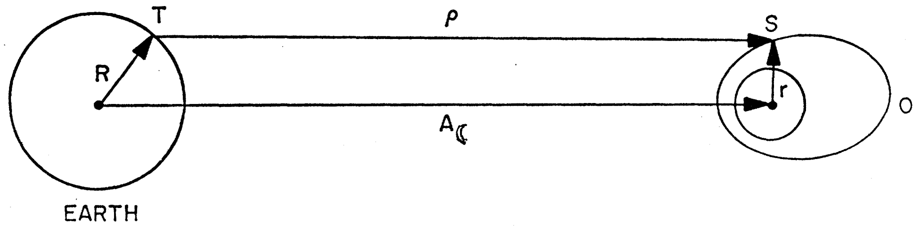

Fig. 1. Geometry of the Lunar Orbiter problem. The ellipse O is the spacecraft orbit, S the position of the spacecraft, T the location of the tracking station.

tered) orbit of the spacecraft is established solely from Doppler observations. These frequency shift data (range rate) are independent of the range data. A lower limit is placed on the accuracy of the orbit determined in this way, primarily because of the state of our knowledge of the Moon's gravitational potential field, the improvement of which is another goal of the Lunar Orbiter program. An estimate of the standard deviation, or uncertainty, in the selenocentric position of the spacecraft due to this cause is about $\sigma = \pm 100$ m. On the other hand, the application of the Doppler data to orbit determination is quite insensitive to errors in the position of the Moon; studies conducted by one of us (Sjogren) show that a bias of as much as 9 km (*4*) in the lunar ephemeris has no discernible effect on the selenocentric orbit elements of the spacecraft. Other errors independent of the ephemeris are those in the locations of observing stations ($\sigma = \pm 30$ m) and that inherent in the single-precision range computation ($\sigma = \pm 4$ m). If these standard deviations are meaningful, then residuals of several hundreds of meters in the topocentric range (that is, the range from a point of Earth's surface) must primarily reflect error of ephemeris. Indeed, the size of the residuals that were obtained virtually precluded their use for analyzing the lunar potential or the positions of observing stations.

The two corrections to the ephemeris that are of interest here arise from two quite divergent causes: (i) an improved value of the ratio of the mass of Earth to that of Moon and (ii) augmented accuracy in a coordinate transformation in the Brown lunar theory. The new value of the mass ratio, $\mu = 81.30$, is based on data from the Mariner II flight and was adopted by the International Astronomical Union at its 1964 meeting (*5*). Since this quantity appears in the gravitational potential of the Brown lunar theory, it is necessary to make corresponding modifications to the affected terms in the expressions for the lunar coordinates. On the other hand, Eckert, Walker, and Eckert (*6*) have noted that the published tables based on the lunar theory are less accurate than the theory itself, because of a coordinate transformation which was permitted to be of a lower precision than the rest of the analysis. They have derived the necessary corrections for rendering the tables as accurate as the theory, including terms which correspond to linear distances as small as 20 cm, although the accuracy of the resulting ephemeris is not that high. The effects of these two corrections combined can amount to radial displacements of up to 2 km.

We should note that the 1964 adoption of a new value for the astronomical unit in meters, the scaling factor for the solar system, does not affect our work directly, even though it gives rise to the largest correction (about 10 km) by far to the lunar ephemeris.

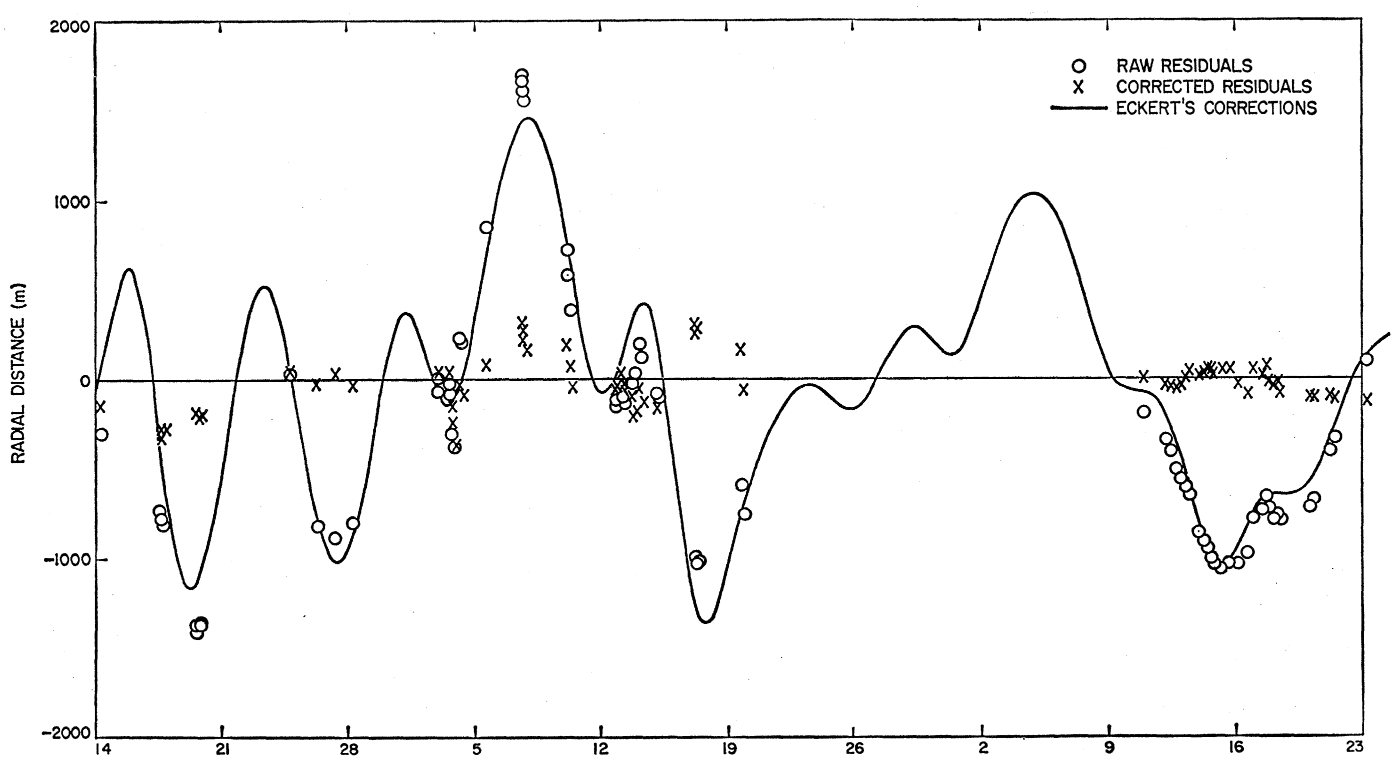

Fig. 2. Lunar Orbiter residuals and Eckert's transformation correction to the lunar radial distance. The interval 14 September to 20 October corresponds to Lunar Orbiter I, 11 to 23 November to Lunar Orbiter II.

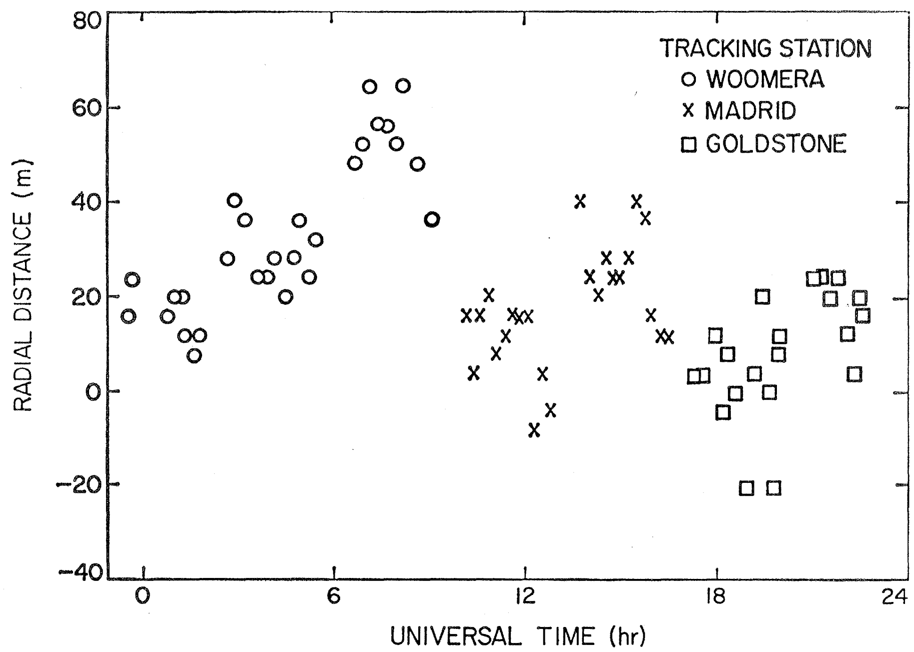

Fig. 3. Lunar Orbiter II ranging residuals for 14 November 1966, with the corrected ephemeris.

This is because the JPL (Jet Propulsion Laboratory) system has already taken the error in the astronomical unit into account.

The geometry of the problem is shown in Fig. 1. The selenocentric position vector **r** of the spacecraft is known to ± 100 m, independent of the range data. The geocentric position vector **R** of the tracking station is known to ± 30 m. The geocentric lunar position $\mathbf{A}_{\leftmoon}$ is obtained from the ephemeris. The calculation of the range estimate

$$\rho_c = |\bar{\rho}_c| = |\mathbf{A}_{\leftmoon} + \mathbf{r} - \mathbf{R}|$$

introduces another uncertainty of ± 4 m. The quantity ρ_c can be compared directly with the high-precision range data. For the initial analysis, we assumed that the corrections to sine parallax (the inverse geocentric distance of Moon) could be treated as acting along the topcentric vector $\bar{\rho}$ rather than along the geocentric vector $\mathbf{A}_{\leftmoon}$; the error is about 0.1 m, negligible for the present purpose. We also assumed the corrections that the other coordinates have negligible effect on these calculations in the first approximation. Figure 2 shows the residuals $\Delta\rho$ (observed − computed) for Lunar Orbiter I during the period 14 September to 20 October 1966 and for Lunar Obiter II over the interval 11 to 23 November 1966. The two sets of points correspond to the cases of (i) analysis with the uncorrected ephemeris, and (ii) these same data with both corrections applied to the residuals. Since it is evident that, at most time points in this period, the Eckert corrections dominate over the mass ratio corrections, we have, accordingly, also plotted the transformation corrections, in order to show the general trends that may be expected of the range data in the sparsely populated regions of the graph.

Some of the raw data have been analyzed with the use of a preliminary ephemeris tape in which the fully corrected lunar ephemeris was incorporated, as opposed to the more approximate calculations discussed above. Figure 3 shows the range residuals from this analysis for densely populated data over an interval of 1 day (approximately seven orbits), during which time the spacecraft was tracked continuously except during occultation periods. Three widely separated tracking stations (Goldstone, Woomera, and Madrid) of the Deep Space Network participated. With the major portion of the model error eliminated, three significant features are evident in these data: (i) high-frequency noise is discernible; (ii) each station is slightly biased with respect to the others, probably evidence of error due to station location; and (iii) the entire set of data has a slight positive bias which may be due to still further refinements required by the ephemeris (7).

The variations in the ranging residuals verify the unusual Doppler residuals that were obtained near pericenter passage during the Lunar Orbiter I mission. These occasioned much speculation concerning the validity of the Doppler data, with such items as multipath effects, temperature variations, and antenna vibration being suggested as possible explanations. Comparison of the integrated Doppler residuals with the range residuals obtained with the new ephemeris shows agreement to within the 4-m accuracy of the range computation. Thus, it appears that the peculiar Doppler residuals are real and that the spacecraft has an anomalous motion on the order of 60 m near pericenter. The Doppler data should prove very powerful for the determination of the lunar oblateness, which we regard as the most probable cause of these inequalities.

We emphasize that the corrected ephemeris tapes used in this work are still being tested and are not yet available for general distribution; indeed, they are not yet complete. When the new ephemeris is complete, thoroughly tested, and published, it will supersede that detailed in (2).

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8. The range calculations were based on inflight orbit determinations performed at JPL by the Boeing Company, under the direction of M. Grogan. We thank W. J. Eckert, IBM Watson Laboratory, for the release of the tabular data (6) prior to publication, and D. Dannenfeldt, IBM Federal Systems Division, who calculated the ephemeris corrections. J. D. Mulholland is a Member of the Technical Staff, W. L. Sjogren is a Senior Research Engineer. This paper presents the results of one phase of research carried out at the Jet Propulsion Laboratory, California Institute of Technology, under contract No. NAS 7-100, sponsored by the National Aeronautics and Space Administration.

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