X-550-69-312
PREPRINT

NASA TM X- 63652

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JAMES P. MURPHY
JOSEPH W. SIRY

JULY 1969

GSFC — GODDARD SPACE FLIGHT CENTER
GREENBELT, MARYLAND

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James P. Murphy
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ABSTRACT

Apollo VIII tracking data have been analyzed to obtain new evidence for a mascon in the neighborhood of Sinus Aestuum. Data from elliptical and nearly circular lunar orbits of Apollo VIII can be interpreted in terms of a mascon in this region at a depth of approximately 100 kilometers which has a mass on the order of 5×10^{-6} lunar masses and gives rise to a gravitational anomaly at the lunar surface of roughly 250 milligals.

LUNAR MASCON EVIDENCE FROM APOLLO ORBITS

Analyses of the gravitational field of the moon in terms of spherical harmonic expansions of its potential have been presented by several investigators.[1-4] Certain features of the effect of the moon's gravitational field upon the motions of spacecraft in the Lunar Orbiter series have been interpreted by Muller and Sjogren in terms of lunar mass concentrations, or mascons.[5] They identified six mascons associated with major ringed maria and also found evidence for at least one and possibly two additional mascons in the region between Sinus Aestuum and Sinus Medii. They assumed that this represented a feature which was once similar to a ringed sea and has since been obscured by impact debris. They noted that data from a key orbit which might have shed further light on this interesting region were, unfortunately, missing.

Apollo VIII completed ten orbital revolutions of the moon at Christmastime in 1968. During the first two lunar revolutions the perilune height was 110 kilometers, the apolune height was 310 kilometers, and the period was 129 minutes. A coplanar circularizing maneuver carried out between the second and third lunar revolutions put Apollo VIII into a nearly circular orbit having a perilune height of 110 kilometers, an apolune height of 113 kilometers and a period of 119 minutes.[6] In the case of both the elliptical and the nearly circular orbits, the inclination was 12° retrograde and the orientation of the orbit was such that the spacecraft passed over the region between Sinus Aestuum and Sinus Medii which is located at the center of the lunar disc. During the first two lunar revolutions the spacecraft travelled over this area at altitudes of approximately 310 kilometers, while during the last eight lunar revolutions it passed over nearly the same area at altitudes close to 112 kilometers. (Cf. Fig. 1.)

The Apollo spacecraft are tracked by means of the Unified S-band Tracking System which was developed by the Goddard Space Flight Center especially for use in the Apollo program. This system reflects experience gained through the use of earlier Doppler and ranging systems for tracking which were developed and operated by the Jet Propulsion Laboratory and the Goddard Space Flight Center. The Unified S-band Tracking System operates at a frequency of about 2300 MHz. It is deployed in the NASA Manned Space Flight Network which is operated by Goddard. Typical tracking data sampling intervals are one minute, and six seconds.

The tracking data obtained during the lunar orbit phase of the Apollo VIII mission occurred in ten sets separated by the periods when the spacecraft passed behind the moon during each revolution. Studies of the lunar gravitational field are being conducted on the basis of these data with the aim of improving the capability for determining and predicting Apollo orbits in later missions. These efforts are being reported upon elsewhere.[7]

The present analysis is based upon a set of orbits each of which was determined using tracking data for a single revolution and a gravitational model which included a triaxial lunar field and effects due to the earth and the sun. The values used for the unnormalized lunar harmonic coefficients were $J_2 = 2.072 \times 10^{-4}$ and $C_{22} = 0.202 \times 10^{-4}$.

The residuals of the range rate tracking data with respect to the lunar orbits clearly revealed marked positive derivatives in the neighborhood of the meridian at longitude -8° which passes through the Sinus Aestuum region. This can be seen from Figs. 1 through 3. Typical residuals of Doppler data obtained from orbits determined for the first and seventh lunar orbit revolutions of Apollo VIII are plotted vs time in Figs. 2 and 3, respectively. Subsets of these two sets of residuals obtained in the neighborhood of Sinus Aestuum which were taken from the same differential corrections are plotted vs position along the retrograde orbit in the upper and lower portions of Fig. 1. Spacecraft positions in the two revolutions are indicated by surface tracks which are correspondingly marked in the central portion of Fig. 1. The Apollo lunar landing sites are also shown there. Apollo VIII crossed the meridian at longitude -8° in the first and seventh revolutions at 11 hours, 11 minutes, U. T., and 23 hours, 16 minutes, U. T., respectively, on December 24, 1968. The altitudes of the spacecraft above the lunar surface at these times were approximately 310 kilometers and 112 kilometers, respectively.

Preliminary estimates indicate that the range rate residual derivatives observed near Sinus Aestuum during the first two lunar revolutions of Apollo VIII had maxima whose average value was about 0.15 mm/sec^2. Similarly, an estimate of about 0.56 mm/sec^2, or 56 milligals, was obtained for the mean of the maximum values of range rate residual derivatives obtained near this region during the last four lunar revolutions of Apollo VIII. These two mean values were based upon two-way Doppler data. The probable error of the arithmetic mean in the former case was about one milligal and in the latter case about three-quarters of a milligal. Here the probable error of the arithmetic mean was taken to be the ratio $Q/\sqrt{n}$ in which the quantity, Q, given by the expression

$$k \left\{ \left[\sum_{m=1}^{n} r_m^2 \right] / (n - 1) \right\}^{1/2} , \qquad (1)$$

denotes the probable error of a single measure when k has the familiar value 0.67449, n denotes the number of measures in the set under consideration which, here, is the set of maximum values of the range rate residual derivatives, and the r_m denote the residuals of these measures relative to the mean of this set. These formulas, due to Bessel, apply to Gaussian distributions.

They may not reflect the true state of affairs, however, if the force model or the tracking system description is inappropriate. In the presence of bias-like effects, for example, the error associated with the mean may not tend toward zero as the number of measures increases indefinitely. It is possible, theoretically, to calculate probable errors in these cases, too, although, in practice, it is not always a simple matter actually to carry through the process. In a number of instances of this type, however, a useful characterization or estimate of the uncertainty of the mean is provided by the quantity obtained through the evaluation of the expression (1) for the case in which k = 0.67449 or, alternatively, for the case in which k has another value such as unity. Evaluation of the expression (1) for the former case yields uncertainty estimates of about one and a half milligals for each of the two mean values given above.

The locations associated with these mean values were within a couple of degrees or so of the meridian at longitude -8°. The spacecraft orbits traversed this meridian within about a degree of latitude 10°. In this portion of the orbit the direction from the tracking station toward the spacecraft was close to the nadir direction from the spacecraft toward the lunar center, hence positive derivatives of the range rate residuals can be identified with acceleration increments in directions toward the moon's center or its surface, and maximum values of range rate residual derivatives and means of these maxima can be viewed as estimates of acceleration increment maxima.

The estimates of the acceleration increment maxima obtained from the elliptical and nearly circular lunar orbits of Apollo VIII can be interpreted in terms of a mascon located beneath the lunar surface within a couple of degrees or so of the meridian at longitude -8°. If the mascon is assumed to be equally close to latitude 10°, its depth, d, can be found by means of the relation:

$$\frac{a_1}{a_2} = \frac{(d + h_2)^2}{(d + h_1)^2} \qquad (2)$$

on the basis of the acceleration increment maxima a_1, and a_2, associated with the heights h_1, and h_2, respectively, which were cited above. The depth estimated on this basis turns out to be about a hundred kilometers. The uncertainties estimated earlier for the acceleration increment maxima through the evaluation of expression (1) are reflected in a corresponding uncertainty of the order of twenty-five kilometers in the depth. The mascon mass, estimated on the basis of Newton's laws, is about 3.8 x 10^{20} grams, or five millionths of the lunar mass. Such a mass concentration of five "micromoons" gives rise to a gravitational anomaly at the nominal lunar surface of about a quarter of a gal. The uncertainties just indicated imply uncertainties on the order of twenty-five percent in the mascon mass and the associated gravitational anomaly.

Sets of residuals of three-way Doppler data also were obtained from Apollo VIII using additional tracking sites. These data were more numerous than the two-way Doppler data, however, they exhibited greater scatter. They were generally consistent with the results derived from the two-way Doppler data.

There are other factors, as was indicated previously, which could also affect the values of parameters characterizing a mascon. These include possible perturbing effects of spacecraft control jets and venting systems, the choice of the reference model of the lunar gravitational field used in the primary orbit determinations, and the selection of the data spans employed in these orbital differential corrections. Information available concerning the operation of the spacecraft reaction control system, the water boiler venting, and the waste water dumps indicates that perturbations of the orbit associated with these activities did not affect the present results in a significant way. A limited amount of checking has been done using a spherically symmetric model of the lunar gravitational field. The indications obtained are, in general, qualitatively consistent with the results described above which were based upon a triaxial model for the lunar field. It is recognized, though, that this type of comparative analysis could yield larger variations than those which were found to occur. This was seen to be the case, for example, in recent work of Muller and Sjogren.[8]

The acceleration increment maxima observed during the flight of Apollo VIII occur within a couple of degrees or so of the acceleration peak of the Sinus Aestuum mascon feature which they found earlier.[5] This provides the basis for the above assumption concerning its latitude, and an indication of the consistency of the two estimates of this feature's meridian.

The present results include estimates of the depth and the mass of the Sinus Aestuum mascon feature as well as the magnitude of the surface gravity anomaly which is associated with it.

It is of interest to note that the estimate of the acceleration increment maximum given above for Apollo VIII in its nearly circular lunar orbit at 112 kilometers altitude is consistent with the acceleration value normalized to 100 kilometers altitude which they reported for this region, and that the value for the depth of the Sinus Aestuum mascon feature based upon the two types of Apollo VIII lunar orbits is consistent with the general range of depths which they and their colleagues reported on the basis of the analysis of distinct spacecraft.[9]

Their findings were based upon the tracking of Lunar Orbiter spacecraft by means of the NASA Deep Space Network operated by the Jet Propulsion Laboratory. As was noted above, the results reported here are based upon Apollo VIII tracking data obtained by means of the NASA Manned Space Flight Network's Unified S-band Tracking System. The results reported here thus include a direct confirmation of a mascon feature for which they found evidence. This confirmation is independent in the sense that it is based upon data obtained from a different tracking system operating in a different network. The present results were derived using computer programs and types of computers which are different from the ones employed in their analysis of the Lunar Orbiter data. The confirmation is thus independent in this sense also.

It is planned to refine these results and to continue the analysis in terms of representations involving spherical harmonics, mass points and mass concentrations of various shapes using tracking data obtained from Apollo, Lunar Orbiter and Anchored IMP spacecraft. Later Apollo flights involve not only the orbits of the command module of the type flown in the Apollo VIII mission but, in addition, a lunar module in an orbit which approaches to within about fifteen kilometers of the lunar surface before its rocket engine is fired. It is anticipated that Apollo missions of this type may afford opportunities to obtain improved resolution in the estimation of mascon depths and masses.

ACKNOWLEDGEMENTS

We thank James W. Ryan and his colleagues of Goddard's Manned Flight Support Directorate for their help relating to tracking data processing; J. P. Mayer, W. R. Lacy, A. J. Loyd, R. K. Osburn, R. M. Swalin and their associates at the NASA Manned Spacecraft Center for information concerning perturbing forces associated with the spacecraft; F. O. Vonbun for helpful discussions.

REFERENCES

1. to 4. J. Lorell, in Measure of the Moon, Z. Kopal, Ed. (Gordon and Breach, New York, 1967); Robert H. Tolson; and John P. Gapcynski, "An Analysis of the Lunar Gravitational Field as Obtained from Lunar Orbiter Tracking Data" presented at IQSY/COSPAR Assemblies (London, England), July 17-18, 1967; William H. Michael, Jr., "Physical Properties of the Moon as Obtained from Lunar Orbiter Data," presented at the Fourteenth General Assembly of the International Union of Geodesy and Geophysics Meeting, Lucerne, Switzerland, September 1967; W. Thomas Blackshear, "Progress on Lunar Gravitational Potential Determination by Analysis of Lunar Orbiter Tracking Data," Transactions of the American Geophysical Union, 50, 124 (1969).

5. P. M. Muller and W. L. Sjogren, "Mascons: Lunar Mass Concentrations," Science, 161, 680-684 (1968).

6. Data Evaluation Branch, Manned Flight Plans and Analysis Division, "MSFN Metric Tracking Performance Report AS-503, Report No. X-832-69-69" (Goddard Space Flight Center, Greenbelt, Maryland).

7. T. L. Felsentreger, J. P. Murphy, J. W. Ryan and L. M. Salter, "Lunar Gravity Field Determined from Apollo 8 Tracking Data" (in press).

8. P. M. Muller and W. L. Sjogren, "A New Reduction of Lunar Orbiter Radio Tracking Data in Describing the Lunar Near-Side Gravity Field," Transactions of the American Geophysical Union, 50, 124 (1969).

REFERENCES (Continued)

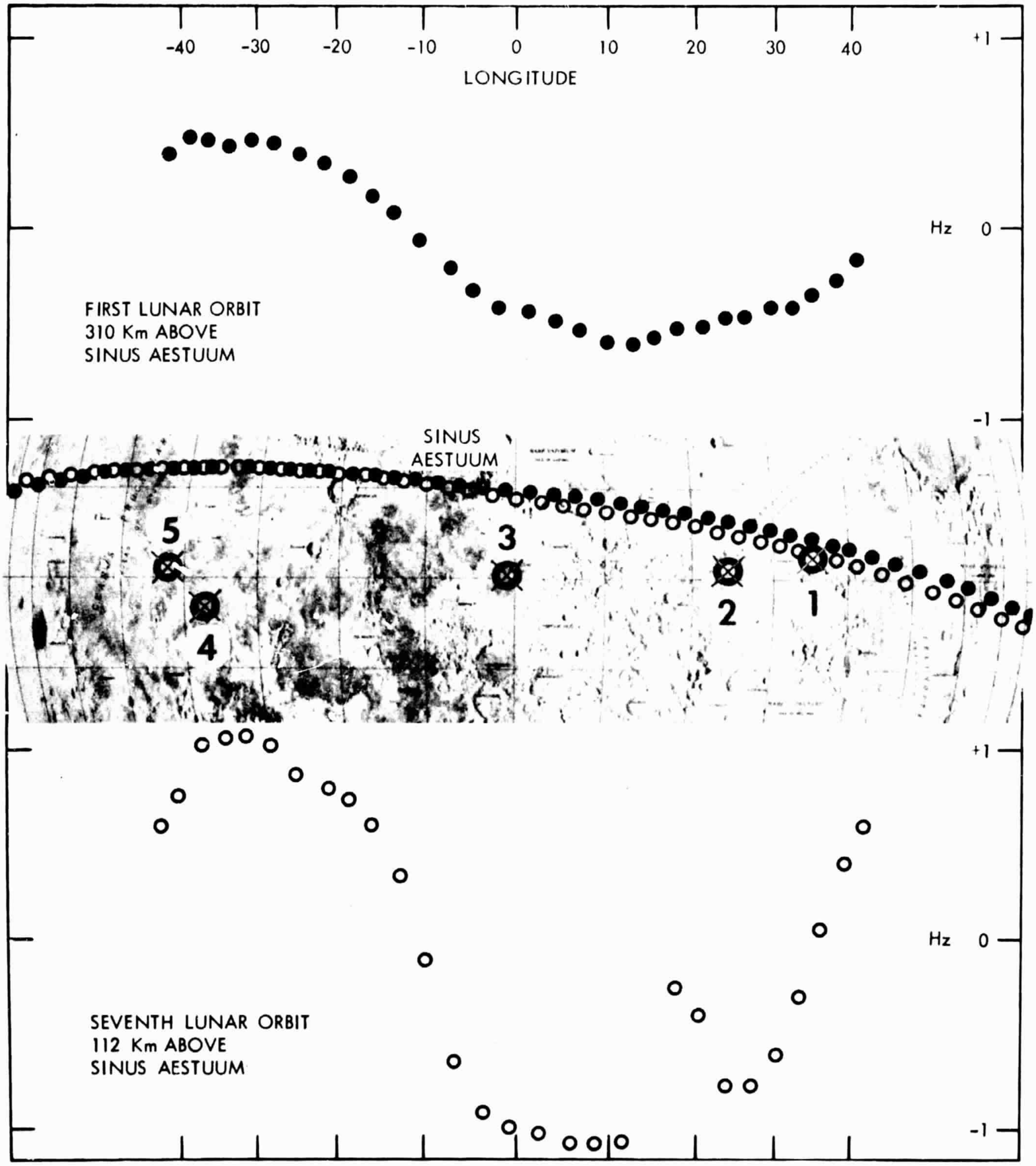
9. P. Gottlieb and P. Laing in "Mass Distributions Inferred from Lunar Orbiter Tracking Data," Transactions of the American Geophysical Union, 50, 124 (1969).

FIGURE CAPTIONS

Figure 1. Doppler residuals from Lunar Orbits of Apollo VIII on December 24, 1968. The upper and lower portions of the Fig. depict residuals obtained in the neighborhood of Sinus Aestuum during the first and seventh revolutions, respectively. The residuals are plotted vs. position along the retrograde orbit. The positions in the two revolutions are indicated by surface tracks which are correspondingly marked in the central portion of the Fig. The Apollo Lunar landing sites are also shown.

Figure 2. Apollo VIII First Lunar Orbit Dopper Residuals

Figure 3. Apollo VIII Seventh Lunar Orbit Doppler Residuals



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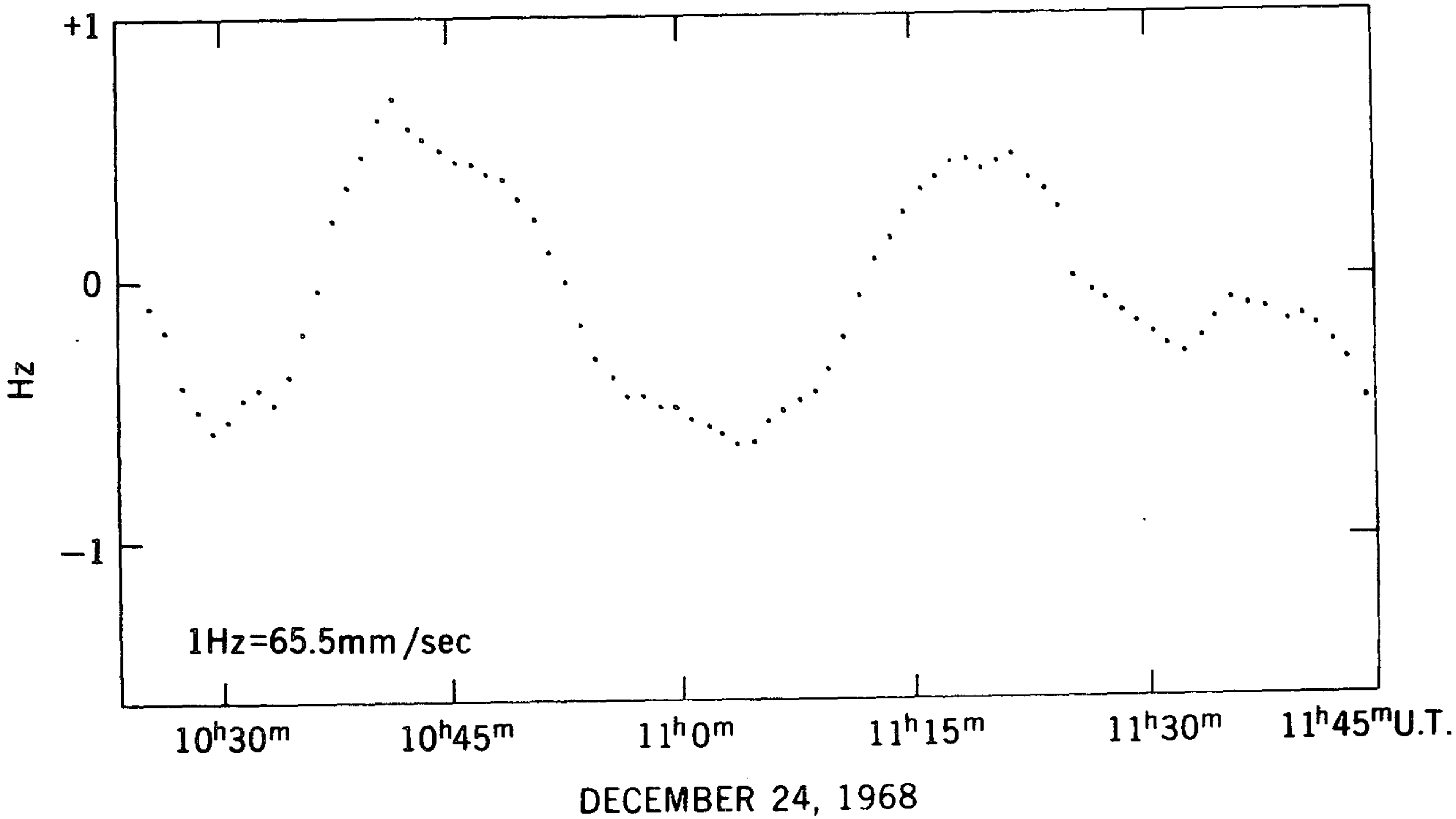

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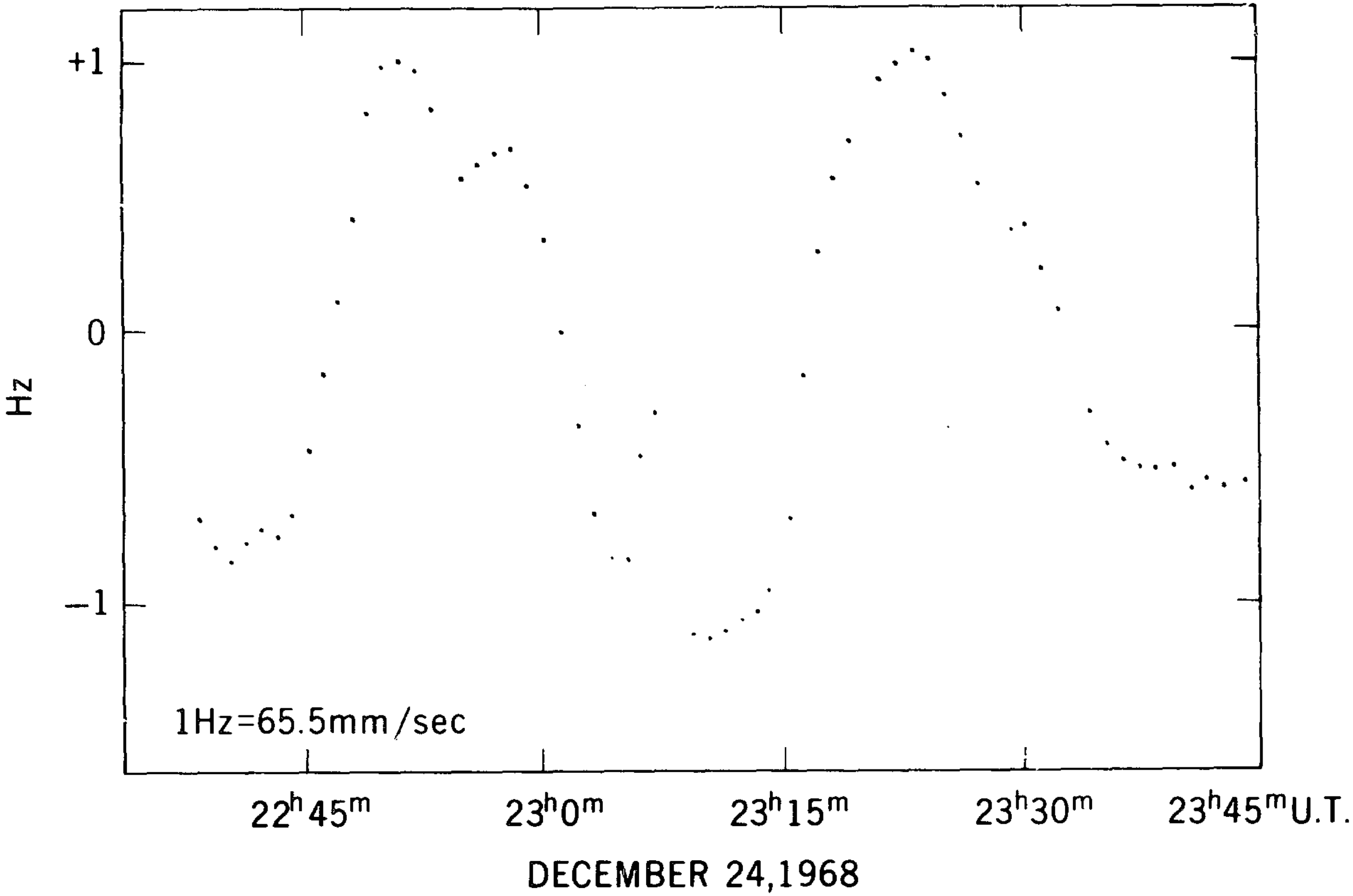

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