# THE DECLINE AND FALL OF IMP 3: SECOND REPORT

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February 1968

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Greenbelt, Maryland

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## ABSTRACT

This report discusses the reentry of the IMP 3 satellite (Explorer 28). It is predicted that the satellite will reenter on July 5, shortly before 5 a.m. local time, over the Indian Ocean between the Maldive Islands and Ceylon.

This report supersedes a GSFC document X-643-67-494, entitled "The Decline and Fall of IMP 3: A Preliminary Report". Further investigation has made possible a lowering of the error bounds of the reentry prediction. The time is estimated to be accurate within 10 minutes, and the latitude and longitude of the reentry track within 2 1/2°. The data has been rechecked and particularly bad points were found to be due to copying errors in all cases. Additional background information has been included to make the report more useful.

# CONTENTS



# LIST OF ILLUSTRATIONS

# THE DECLINE AND FALL OF IMP 3: A SECOND REPORT

## INTRODUCTION

The IMP series of satellites are launched into highly eccentric orbits, with large semimajor axes. ($e \sim 0.95$, $a \sim 20.$ earth radii). Currently, 4 satellites in this series have been put into orbit (not including A-IMP's); of these, it seems certain that IMP 1 and 2 are no longer in orbit (Ref. 1). IMP 4 went into orbit relatively recently - in May 1967. IMP 3, which this paper is concerned with, was launched on May 25, 1965 and will terminate its lifetime due to the combined action of solar and lunar gravitational forces in July of 1968.

The IMP 3 satellite presents an unusual opportunity to predict the re-entry time and position with sufficient accuracy to enable positioning observers with equipment in advance of the occurrence. There are two factors which make this satellite especially opportune for re-entry observations:

1) The lifetime is dominated by a very intense lunar perturbation which keeps the satellite above the earth's atmosphere until the final re-entry trajectory. The gravitational forces acting on the orbit are predictable quantities, while the density of the earth's atmosphere is a function of the solar activity, which cannot be predicted accurately. The next-to-last orbit of the satellite is hundreds of kilometers above the earth's surface where the atmospheric drag on the satellite is negligible. During the final orbit, the satellite's perigee is lowered over 1000 kilometers by the moon, bringing the perigee well below the ground. This results in a steep re-entry trajectory, much like a meteor's.

2) There are 2 years of tracking data on this satellite, covering 120 orbits in all. Because 2/3 of its total lifetime is spanned with data, it is possible to extrapolate ahead to the fall time. In particular, an initial value of the semimajor axis may be found which will allow the time of perigee passage to match the data over the 2 year period. When this data is matched with good accuracy, it is reasonable to expect that the predicted decay time will not deviate greatly from the actual fall time.

Because of these two factors, it is possible to give a prediction of the sub-satellite point of the decay with some accuracy. This is a rare opportunity; the satellite is reasonably heavy - 128.45 lbs - and the prediction is made months in advance.

While it is difficult to estimate the error in an extrapolated quantity, it is felt that the predicted decay time is not worse than 10 minutes in error. This represents a reduction of the error in the earlier prediction in GSFC X-643-67-494. This refinement is due to further study of the orbit.

ORBITAL HISTORY

The satellite's initial orbital elements are

$$a = 21^\circ.727138$$

$$e = 0^\circ.95251083$$

$$i = 33^\circ.828446$$

$$w = 135^\circ.72696$$

$$\Omega = -138^\circ.45267$$

$$M = 0^\circ.023663$$

Epoch time in May 29, 1965 at 12:07 hours U.T. (a = semimajor axis, e= eccentricity, i = inclination, w = argument of perigee, $\Omega$ = right ascension of ascending node, M = mean anomaly. The angular elements are taken with respect to the earth's equator.) The initial value of perigee is about 200 km above the equator, and the apogee is about 240,000 km. The orbital period is about 140 hours, or 5.8 days.

The lunar and solar gravitational fields strongly perturb the orbital elements, and, to a lesser extent, so does the oblateness. Solar radiation pressure exerts a slight perturbation. The atmospheric drag force exerts a negligible effect on the elements, except a very small perturbation as the satellite moves away from perigee following launch. It will not be considered in this paper and none of the perturbations described below are the result of atmospheric action.

The lunar and solar perturbations on perigee height are the key factor in the length of the lifetime. There is long term perturbation by the sun and moon which determines the average change of perigee height which depends on the orientation of the satellite's orbital plane relative to the disturbing planes. The long period effect may be seen in Figure 1, which shows perigee distance (measured from the center of the earth) during the entire lifetime of the satellite. For 1 1/2 years, the perigee distance increases steadily, until it reaches a maximum of 41,000 miles. Thereafter, it declines until the perigee intersects the earth. This graph is constructed from a numerical integration employing a starting vector without further orbit determination. The observed perigee distance, obtained from radio tracking during the first two years, produces points which fall exactly on the curve, within the accuracy of this graph.

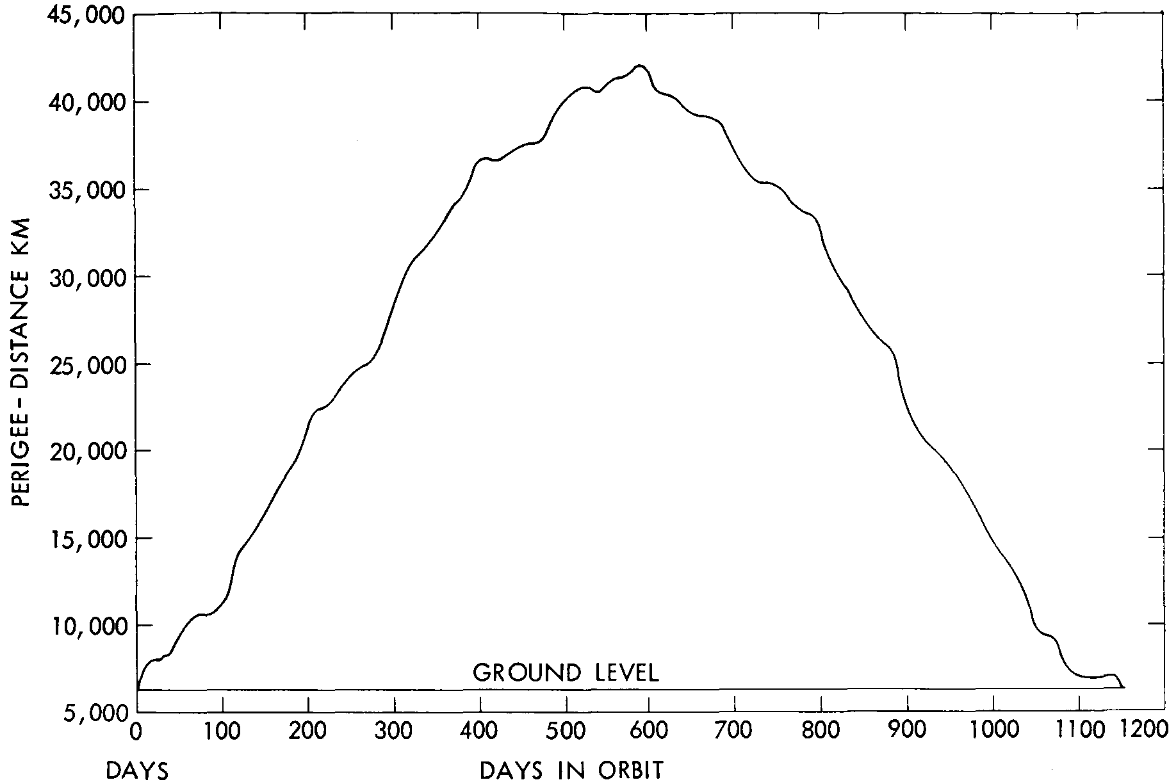


Figure 1. Perigee During Satellite Lifetime

There is further a strong short period lunar perturbation which depends on the orientation of the satellite's line of apsides with respect to the moon's longitude as the satellite is passing through apogee. This short period lunar effect is of importance during the early and late portions of the satellite's lifetime. Figure 2 shows the height of perigee in the first weeks of the satellite's lifetime. The perigee at launch, termed the 0th perigee passage, is 200 km. On the first return to perigee, almost 6 days later, the perigee height has risen to 600 km, well above the regions where the atmospheric drag force can exert a perceptible effect on a dense satellite such as IMP 3. The rise continues in an irregular manner, depending on the position of the moon as the satellite passes through perigee.

This behavior is both predicted by computation and observed in practice. The difference between the computation and the observation is too small to be discernible on this scale. The actual residuals will be discussed later.

The effect of the short period lunar perturbation on the perigee height during the last weeks of the lifetime is shown in Figure 3.

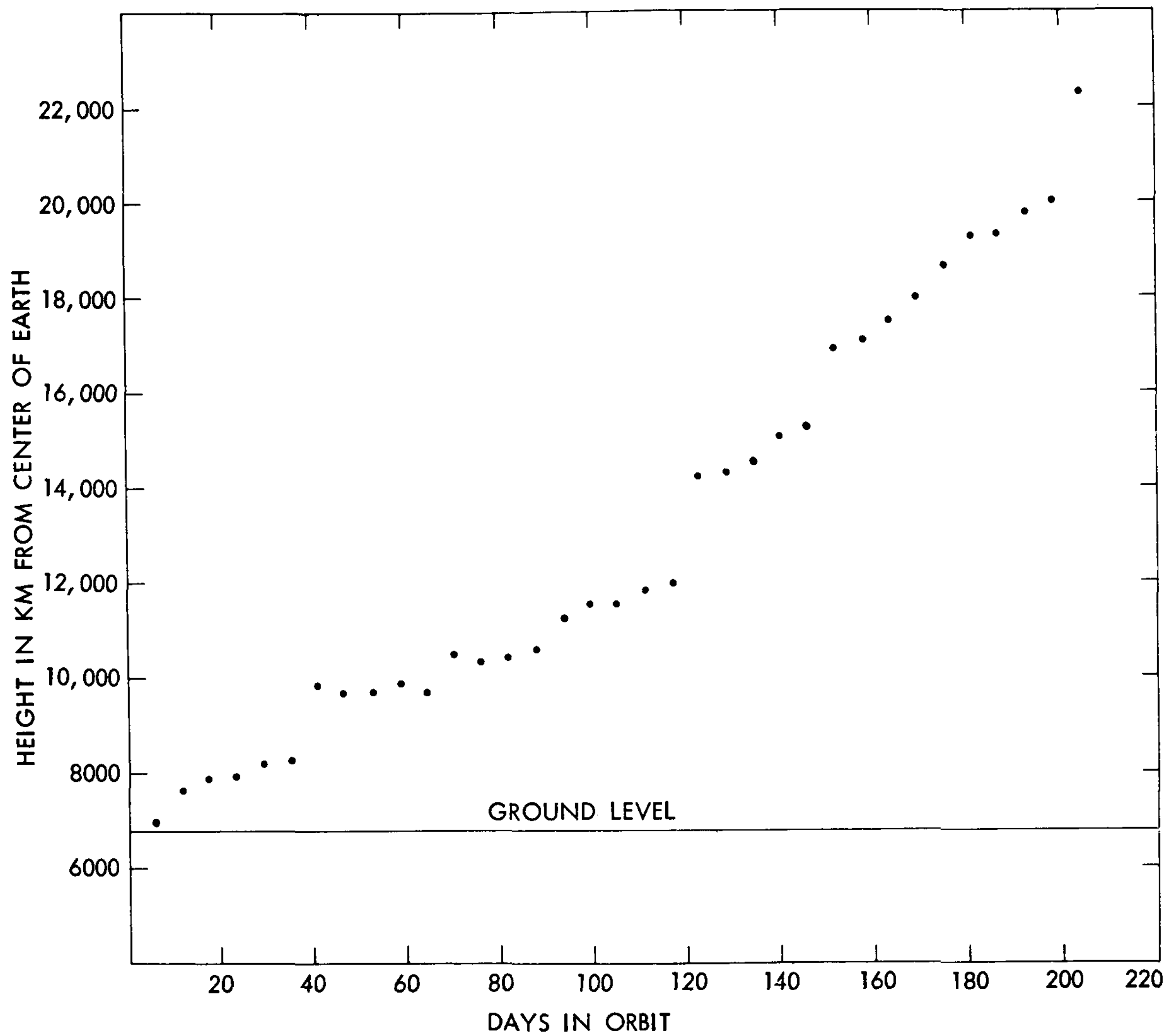


Figure 2. Perigee Distance During Early Lifetime

When the moon is aligned with the line of apsides in such a way as to produce the maximum perigee perturbation, sharp drops will occur. The change in perigee height during one orbital revolution may be as large as 2200 km or as little as 10 km. During the final orbit, the perigee height drops 1100 km. Because of this, the closest the satellite comes to earth on the next-to-last, or 193rd orbit, is 600 km; on the final approach, or 194th perigee, the projected value of perigee is 500 km below the ground. This sharp decrease is an important factor in having the ability to predict the re-entry time and location. On the 193rd passage, the satellite is far above the regions of the earth's atmosphere where the drag force has an effect of any consequence on the orbital elements. During

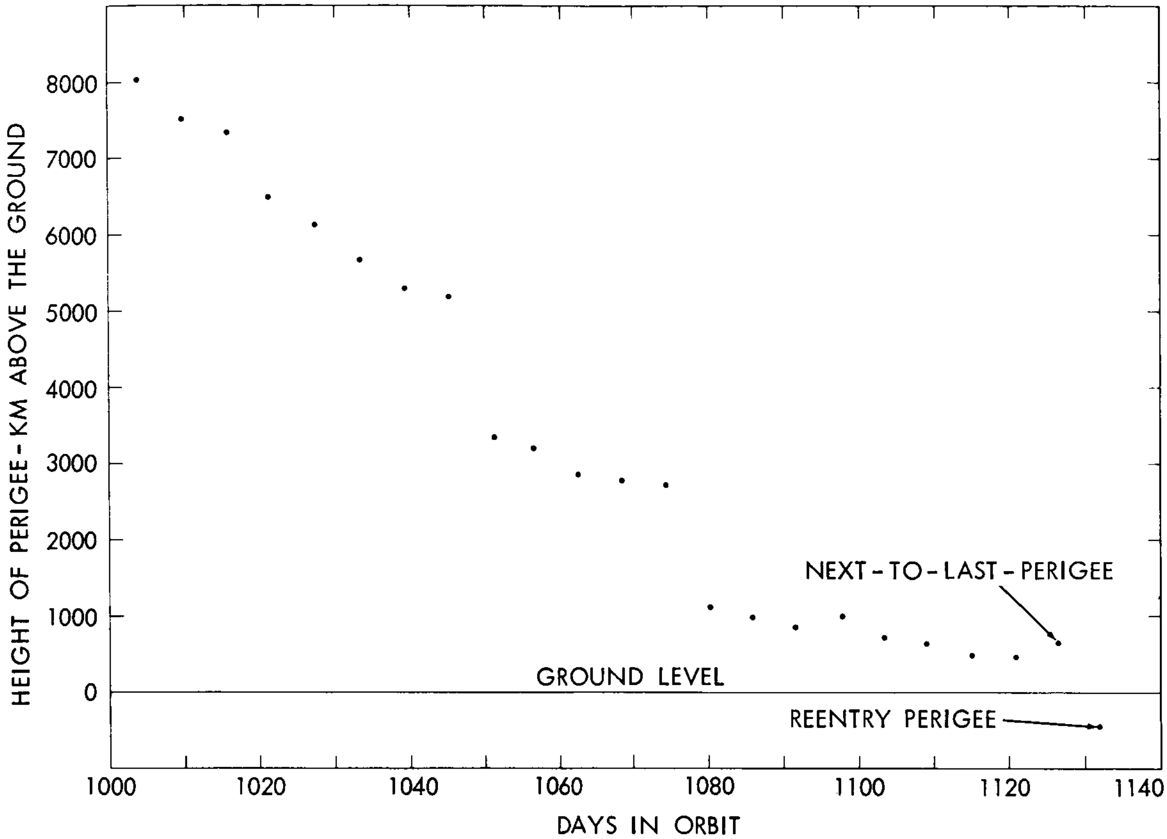


Figure 3. Perigee Height at Last of Lifetime

the re-entry orbit, or 194th "passage", the perigee is far below the earth's surface, thus precluding any chance that, owing to uncertainties in the prediction of perigee height, the satellite will just skim the atmosphere and reenter on a later orbit. That the expected uncertainties in perigee height are indeed much smaller than 500 km will shown later in this paper. Therefore, the moon's short period effect is of great importance in establishing the orbit during which the reentry will occur.

Although the perigee height perturbation is crucial to the determination of the lifetime, all of the orbital elements are strongly perturbed. The inclination is initially 33°, attains a maximum value of 50° and declines to less than 30° during the last orbits. (The reference plane is the earth's equator.) Even the semimajor axis fluctuates within wide limits.

Due to the moon's short period perturbation and to short period oblateness effect, the osculating value of the semimajor axis will be between 21.3 and 21.8 earth radii. The change in the latitude of the subsatellite point at perigee passage is shown in Figure 4. During the orbits soon after launch, the satellite passes closest to earth at a latitude of 20°; however, the perigee latitude drifts steadily southward until it is at -15° during the last orbits before decay.

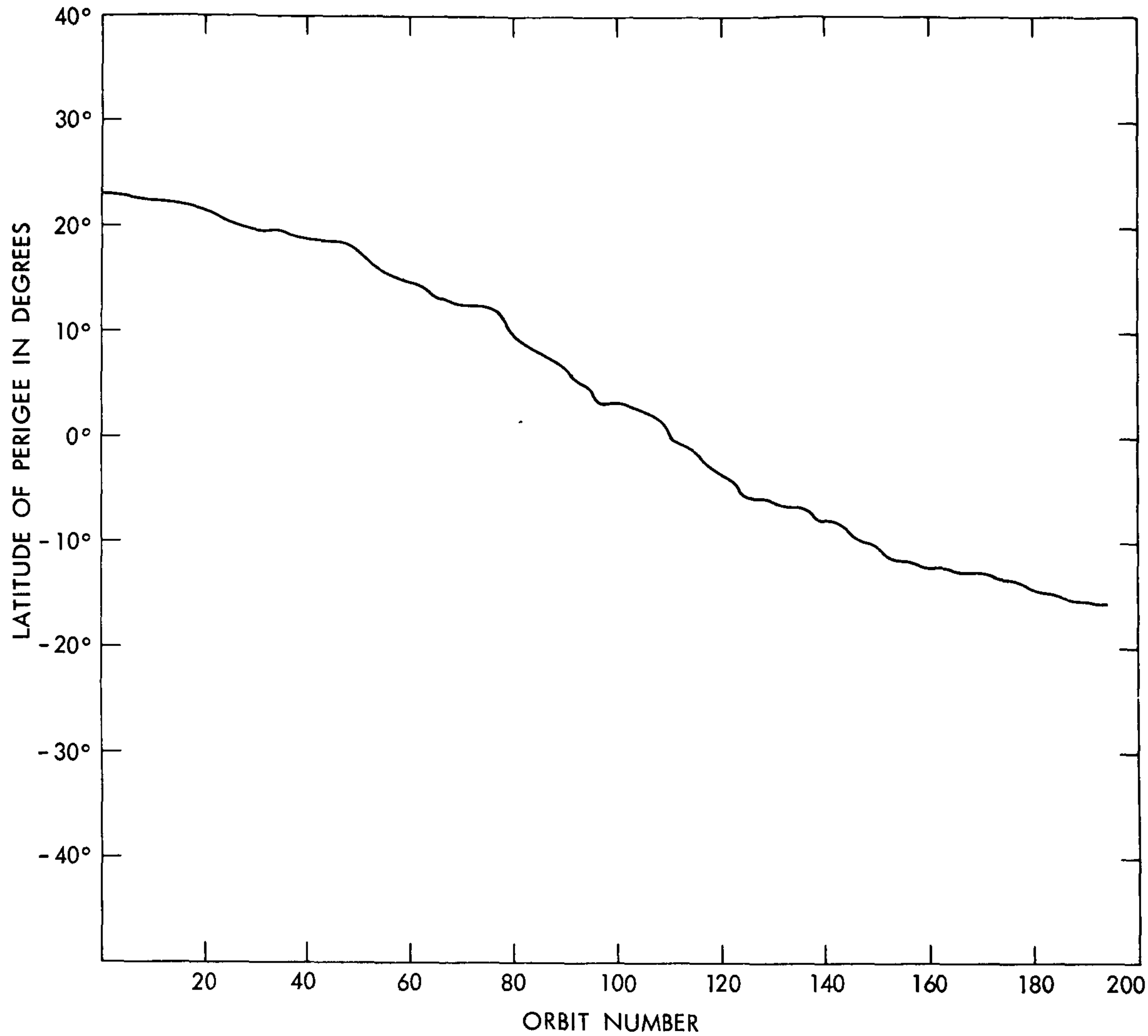


Figure 4. Latitude of Subsatellite Point at Perigee

## DISCUSSION OF DATA AND COMPUTATION

The data is obtained from the World Maps (Ref. 2), which list the subsatellite points at one minute intervals along the orbit. These maps are generated from the raw data as transmitted by the satellite system. The raw data is reduced over approximately month long arcs to provide the satellite ground track. The "data" referred to in this report is taken from the World Maps and therefore is not raw, or directly observed, data.

The computations are made using a numerical integration program, ITEM (Ref. 3). This program utilizes a modified Encke method to integrate the Cartesian position and velocity coordinates of the spacecraft as a function of time. The computation is initiated using a starting vector which satisfactorily matches the data. No further adjustments or corrections are made in the computation. The forces accounted for in the numerical integration include the major harmonics of the earth, the gravitational field of the moon and the sun, and the solar radiation pressure perturbation. Not included is the atmospheric drag force since the satellite is well above the regions where the earth's atmospheric can affect the orbit except slightly during the trajectory immediately following launch and during the reentry orbit.

The ITEM program is a double precision program which allows computation to high accuracy. To ensure that the numerical integration was accurate, it was tested by halving the integration interval and comparing results. Differences between the time of perigee passage in the two computations were found to be no larger than 0.002 hours. Since this is much smaller than the differences between computation and data, the numerical integration is performing to sufficient accuracy.

The effect of possible model errors on the matching of the orbit has not been specifically investigated. Model errors may be of two types: omission of a necessary force or uncertainties in a physical constant. It would seem that all pertinent forces have been included.

## COMPARISON BETWEEN DATA AND COMPUTATION

The computation of the orbit must closely match the data in order that a reentry prediction be accurate. Comparison of two critical quantities is made here: the time of perigee passage and the height of perigee.

The computation of the time of perigee passage must agree well with the data because the computation is to be extrapolated forward one year when there is no data. In this time, a small inaccuracy in the orbital time will accumulate to render the reentry prediction useless. For example, if there is a deviation in the period of the orbit of one minute (out of 140 hours) between the computed orbit and the actual orbit, then the error in prediction of the time of perigee will grow by one minute every orbit. After one year, or about 60 orbits, the error will be one hour in the predicted time of perigee passage. This uncertainty might be tolerable in the case of a patient observer; but, in the meantime, the earth will have rotated 15° underneath the satellite orbit, with the possible result that the reentry would occur below the observer's horizon.

The comparison of the computation of the time of perigee passage with the reduced data is shown in Figure 5. The absence of a cumulative trend in the residuals indicates that the orbital period used in the computation is indeed closely matched to the actual orbital period. During the 120 orbits for which

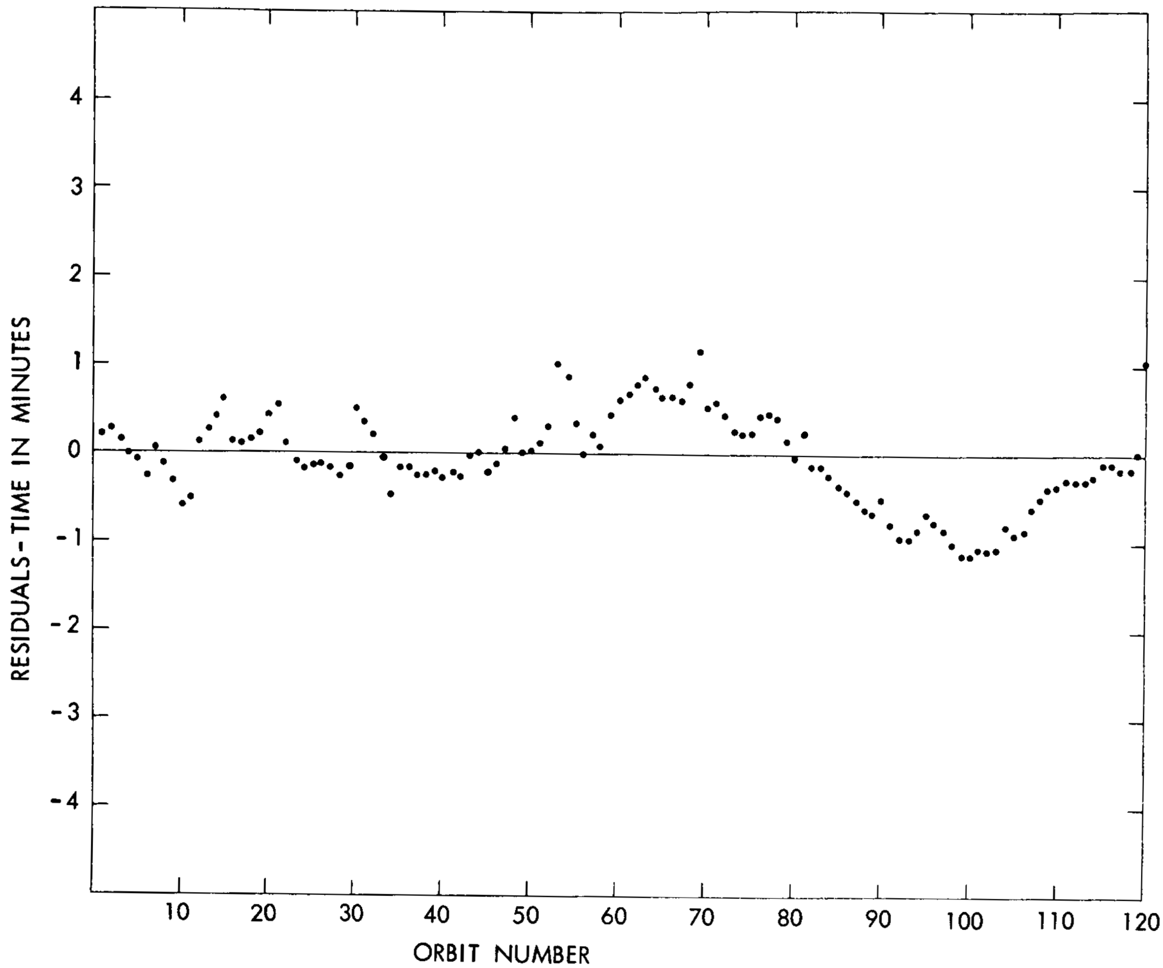


Figure 5. Residuals in Time of Perigee Passage

data is available, the residual is never larger than one minute and usually smaller. There is a nonsecular sinusoidal trend which is currently unexplained; however, there is no evidence of a cumulative error which would become very larger after extrapolating forward another 60 orbits. It would appear that the error in the extrapolation might be 3 minutes, or, at the outside, 10 minutes.

The height of perigee must also be reasonably accurate. The "final" - 194th-perigee is lower by 1100 km than the previous perigee and is 500 km below the surface of the earth. Therefore the computation must describe the perigee height accurately enough to ensure that this is indeed the orbit during which reentry occurs; i.e., the uncertainty in perigee height should be less than 500 km. The residuals in perigee height are shown in Figure 6. These residuals are at most 50 km, which confirms that the 194th perigee passage is the reentry orbit, even allowing that the error in perigee height might grow somewhat during the extrapolated year.

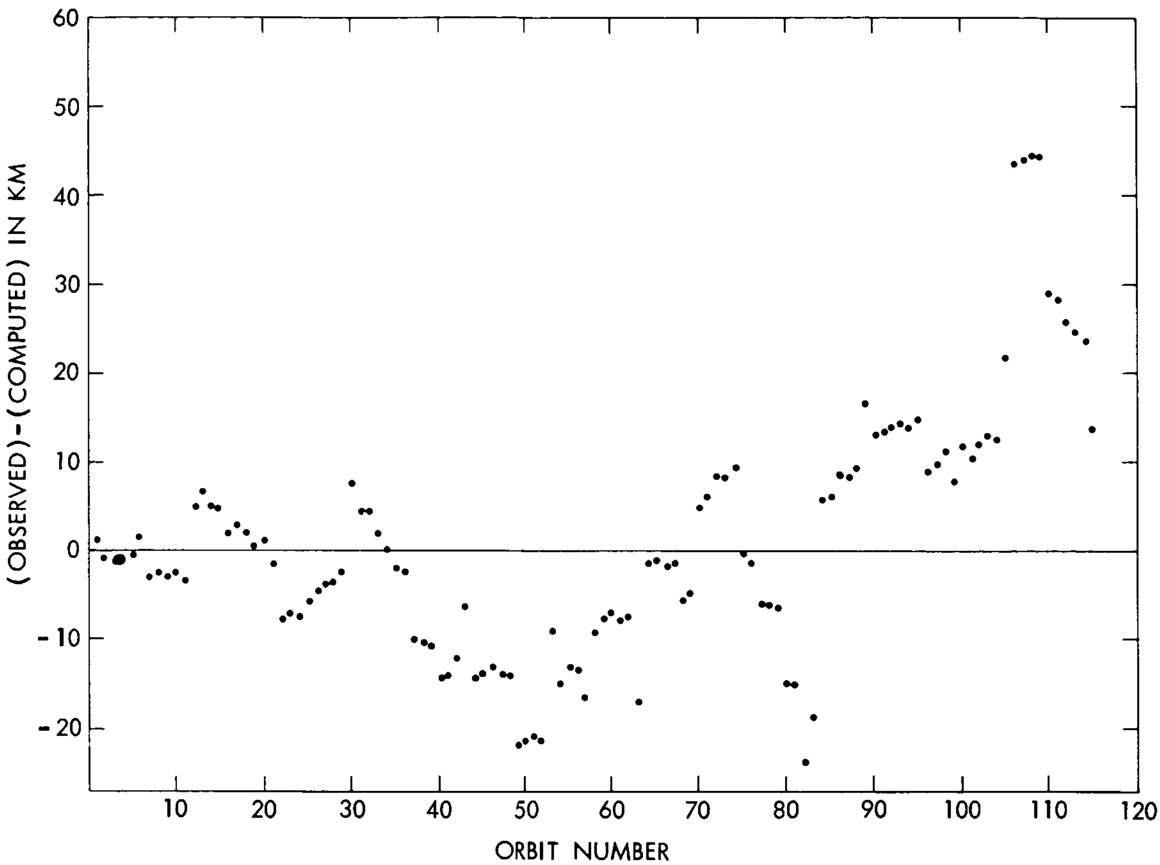


Figure 6. Residuals in Perigee Height

ACCURACY OF DATA

The comparison between the numerical integration and the data points allows some inferences to be made concerning the accuracy of the data. The data are taken from the World Maps (Ref data catalogue). These are from reductions of raw data over month-long intervals (4 or 5 orbits). It can be seen in Figure 5 that the deviation between the computed and observed time of pericenter is no larger than 1 minute in time. This should be taken as a maximum limit since the deviation shows a systematic trend, rather than a random pattern. It seems likely that the deviation is not due to the errors in the data but rather to a factor in the numerical integration that is unidentified at present. Therefore, the error in the data may actually be much less than the 1 minute in time of perigee.

The height of perigee shows large deviations. It is difficult to estimate how much of this deviation is due to the numerical computation and how much to the data, since it is more random in character. During a single arc, the data often shows the same amount of deviation from orbit to orbit; however, when the next arc begins, there will be a sharp change in the deviation. Further, in some cases, the same perigee passage will occur on two adjacent arcs, which overlap slightly. The difference between the perigee height for the same passage computed on two overlapping arcs is about 6 km early in the lifetime and as large as 20 km toward the end of the data; therefore, the data is at least that inaccurate.

## REENTRY CONDITIONS

The reentry position is determined by extrapolating the computation forward. The reentry occurs as the satellite approaches the 194th perigee passage. The location of the reentry is near the Maldive Islands in the Indian Ocean southwest of Ceylon (Fig. 1). The reentry trajectory is in an east-southeast directicn (120° measured clockwise from north). The angle of reentry with respect to the local horizon is 17°.

The time of reentry is July 4, 1968 at 23:36 U.T. This prediction is estimated to be accurate to with 10 minutes. The local time of reentry is 4:48 a.m., on July 5, where "local time" refers to the longitude of the subsatellite point. It will still be dark, as local civil twilight does not occur until 5:38, and sunrise is 6:01 a.m.

The uncertainty in the location of reentry is no larger than 2 1/2° in longitude and in latitude.

The earth-fixed velocity is 10.5 km/sec at reentry. The atmosphere was not included in computing the reentry trajectory so that the actual trajectory will not penetrate quite as far as southward as indicated.

## CONCLUSIONS

The reentry prediction given in GSFC document X-643-67-494 has been confirmed by further study. The estimated error in reentry time has been reduced to 10 minutes.

The sinusoidal trend in the residuals in the time of perigee passage has been reduced slightly, either because of the inclusion of the solar radiation pressure, or because improved initial conditions have been obtained. However, the sinusoidal trend persists and is currently unexplained. Rechecking the data and copying errors removed particularly large residuals. Interpolating the data to obtain closer values of the time of perigee passage removed the random scatter in the residuals and provided a smooth and systematic trend. Therefore, it is felt that this data is very accurate, and that the residuals are due to some problem in matching the computation to some problem in matching the computation to the data.

The height of perigee has been slightly improved due to the addition of solar radiation pressure. It is uncertain how much of the residuals is due to the error in the data, and how much due to the imperfection in the matching of the computation.


## ACKNOWLEDGMENTS

Skillful assistance has been obtained from Miss Ann Proffitt and Miss Susan Orth in preparing the data and preparing the computations.


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