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ORBIT DECAY ANALYSIS OF STS UPPER STAGE BOOSTERS

FINAL REPORT
Contract NAS9-15444
Exhibit "D"

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ANALYTICAL AND COMPUTATIONAL MATHEMATICS, INC.

ORBIT DECAY ANALYSIS OF
STS UPPER STAGE BOOSTERS

BY

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CONTENTS

Section

ORBIT DECAY ANALYSIS OF STS UPPER STAGE BOOSTERS

by

Otis F. Graf, Jr. and Alan C. Mueller

1.0 BACKGROUND AND INTRODUCTION

During the next decade, the Space Transportation System (STS) will launch many missions to geosynchronous orbit. Expendable upper stages will be used to boost the payloads out of near earth orbit and into the geosynchronous transfer orbit. After the mission is completed, these boosters remain in the transfer orbit. It is of some concern that over the years, these upper stage boosters could pose a hazard to future space missions. Thus, the purpose of this task was to study the lifetimes of the geosynchronous transfer orbits and to analyze the orbit decay.

This task (Exhibit "D", Contract NAS9-15444) is a follow-on to a previous study under Contract NAS9-15444.† That study showed that the geosynchronous transfer orbits can experience large variation in perigee altitude. It was also shown that the orbitswill rapidly decay for some initial conditions. However, the previous studies were based on a trajectory program (DSTROB) that did not include the effects of atmospheric drag. Thus, actual orbit decay studies were not carried out in the previous study.

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† This study is reported in ACM Technical Report TR-115 "A Study of the Lifetimes of Geosynchronous Transfer Orbits".

The next section contains a summary of the work that was carried out under Exhibit "D". Appendix A contains the slides that made up the Final Presentation of the work to the Johnson Space Center. These slides include details on the launch window studies. Appendix B is a copy of a paper that was presented at the 1979 AAS/AIAA Astrodynamics Specialists Conference.

2.0 SUMMARY

Atmospheric drag effects were added to the DSTROB† trajectory program. The perturbation models are described in Appendix B. The program was optimized for fast execution in a demand (interactive) environment. A twenty year time history of a geosynchronous transfer orbit can be computed in about 5 seconds. The accuracy of the DSTROB algorithm was checked against precision numerical integration methods.

Orbit lifetimes of the transfer orbit were studied for several planned STS geosynchronous missions. Included in the study were the SUSS-A and SUSS-D boosters on STS-6, the IUS booster on STS-7, and the SUSS-A booster on STS-8. Time history plots of perigee altitude were generated, using the DSTROB program. These plots are included in Appendices A and B.

Because of the fast execution time of DSTROB , it can be effectively used for parametric studies and scans. A driver routine for DSTROB was developed, that allowed orbit lifetime plots to be generated as a function of the initial longitude of the ascending node. This driver routine will generate trajectories on 10° increments of ascending node, and store the lifetime values on a mass storage file. The data can then be submitted to a plot routine for automatic output of figures. It was found that the initial ascending node and epoch are important parameters in determining orbit lifetime.

The study also included development of launch windows, such that the transfer orbit will decay within two years. Launch windows were given as a function of either initial

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† This is prototype program that was developed under Exhibits "C" and "D" of Contract NAS9-15444. DSTROB resides on the JSC Univac 1108/8 system.

ascending node or launch time. Example launch windows are included in Appendix A. These launch window figures were drawn by hand, using data that was generated by DSTROB, and a calculator program to compute launch time. However, the process could be automated so that a computer program would produce a hard-copy launch window figure.

APPENDIX A

ORBIT DECAY ANALYSIS OF STS UPPER STAGE BOOSTERS

FINAL REVIEW MEETING
CONTRACT NAS9-15444
EXHIBIT "D"

PRESENTED TO THE NASA JOHNSON SPACE CENTER
MISSION PLANNING AND ANALYSIS DIVISION

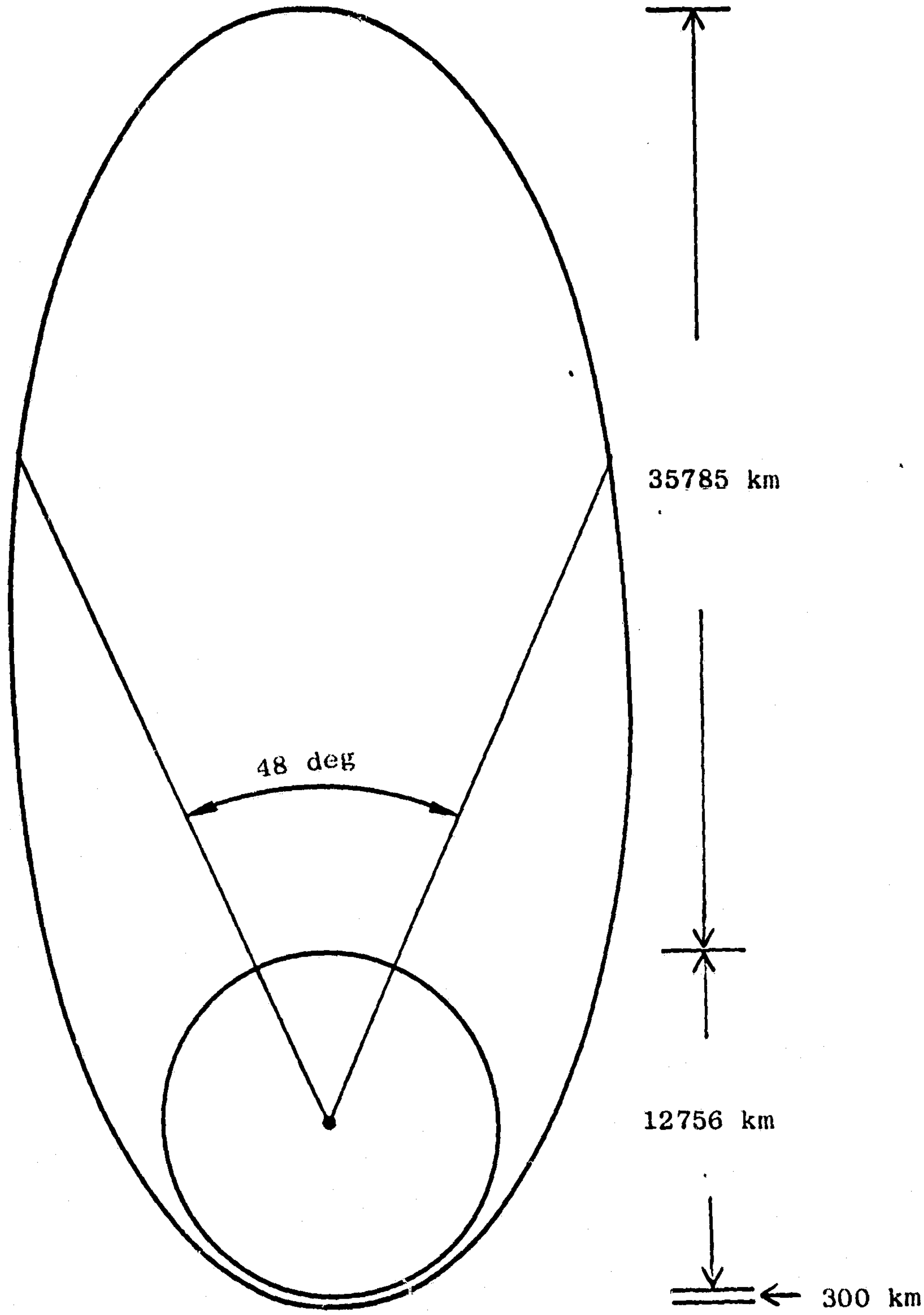
OCTOBER 5, 1979

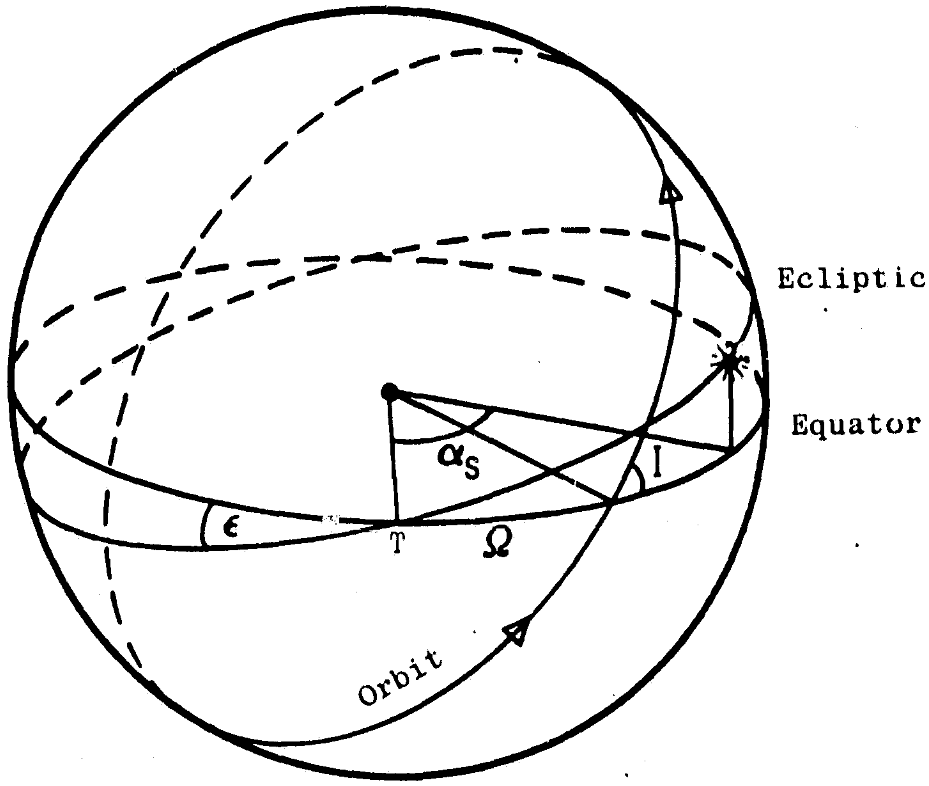
Analytical and
Computational
Mathematics, Inc.

CONTENTS OF PRESENTATION

- OVERVIEW OF THE DSTROB ALGORITHM
- DISCUSSION OF THE ATMOSPHERIC DRAG MODEL AND COMPARISON RESULTS
- ORBIT LIFETIMES OF STS-6 AND STS-7 PAYLOADS
- SOME ANALYTICAL RESULTS
- LAUNCH WINDOWS DERIVED FROM ORBIT DECAY STUDIES
- SUMMARY AND CONCLUSIONS

ORBIT SCALE





ORBIT GEOMETRY

SUMMARY OF THE STROBOSCOPIC METHOD

- DEFINE

$$\Delta\vec{a}_n = \vec{a}_{n+1} - \vec{a}_n$$

WHERE $\vec{a}_n$ IS THE VECTOR OF ELEMENTS AT THE n-TH PERIGEE.

- $\Delta\vec{a}_n$ IS GIVEN BY AN ANALYTICAL EXPRESSION:

$$\Delta\vec{a}_n = \vec{f}(\vec{a}_n, t_n)$$

SUMMARY OF THE STROBOSCOPIC METHOD
(CONCLUDED)

- COMPUTATIONAL ALGORITHM

  $\vec{a}_o$ = INITIAL ELEMENTS AT PERIGEE

(1) EVALUATE $\Delta \vec{a}_n = \vec{f}(\vec{a}_n, t)$

(2) $\vec{a}_{n+1} = \vec{a}_n + \Delta \vec{a}_n$

(3) $n + 1 \rightarrow n$

(4) GO TO (1)

AERODYNAMIC MODEL IN DSTROB

- CONSTANT BALLISTIC NUMBER VALUES USED IN CURRENT SIMULATION:

  $C_d = 2.2$

IUS

MASS = 2200 lbs. (998 kg.)

AVERAGE AREA = 84 ft^2 (7.8 m^2)

SUSS-A

MASS = 700 lbs. (316 kg.)

AVERAGE AREA = 42.2 ft^2 (3.92 m^2)

SUSS-D

MASS = 515 lbs. (234 kg.)

AVERAGE AREA = 27.4 ft^2 (2.55 m^2)

AERODYNAMIC MODEL IN DSTROB
(CONCLUDED)

- DENSITY MODEL

$$\rho = \rho_p \exp\left(\frac{h-h_p}{h_s}\right)$$

ρ_p : DENSITY AT PERIGEE

h_p : PERIGEE ALTITUDE

h_s : SCALE HEIGHT

h : CURRENT ALTITUDE

COMMENTS:

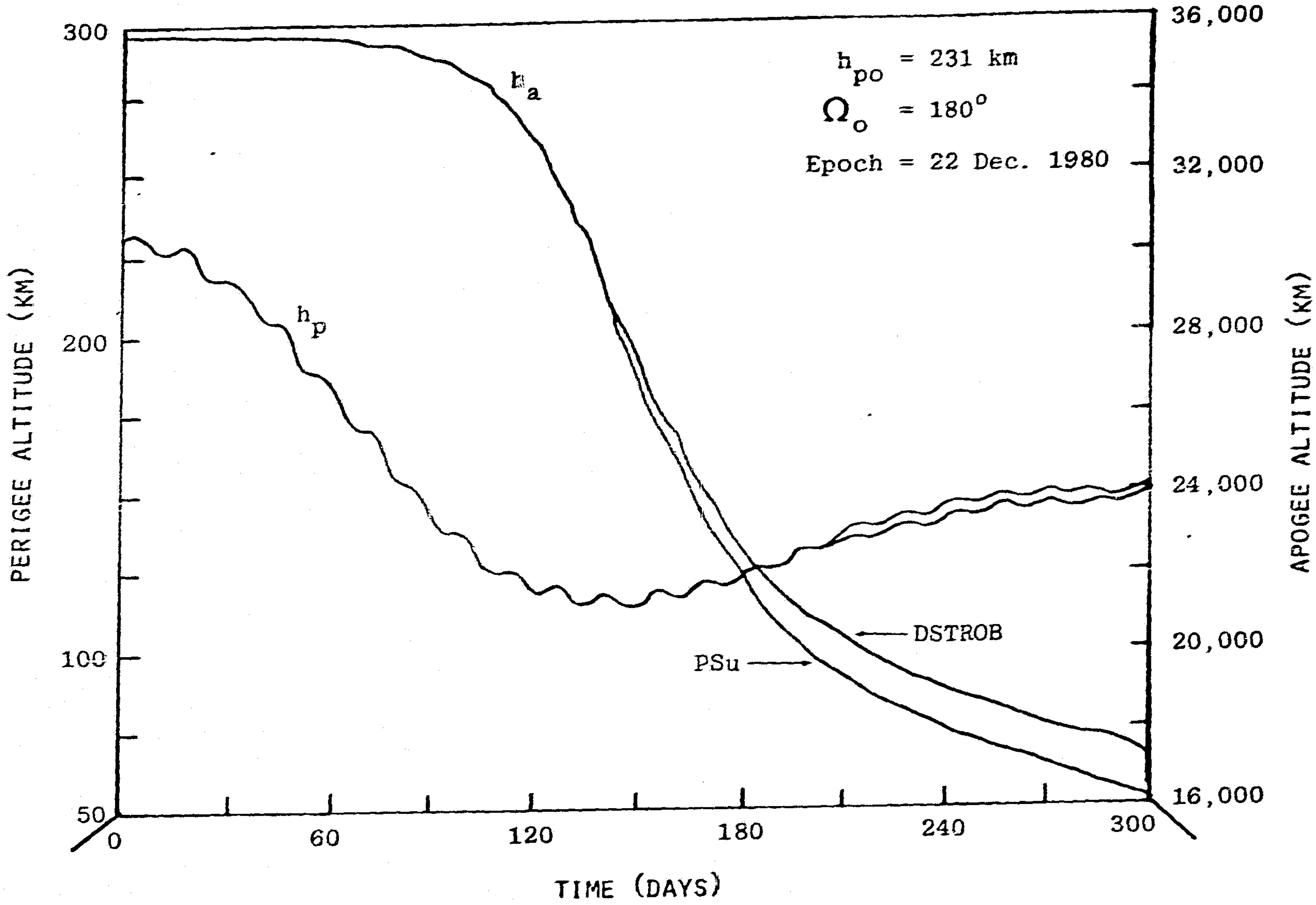
(1) ρ_p AND h_s ARE COMPUTED BY USING THE JACCHIA 71/LINEBERRY DENSITY MODEL.

(2) ρ_p IS THE DENSITY AT THE "GEOMETRIC" PERIGEE.

(3) ρ_p AND h_s ARE RECOMPUTED AT EACH STROBOSCOPIC STEP.

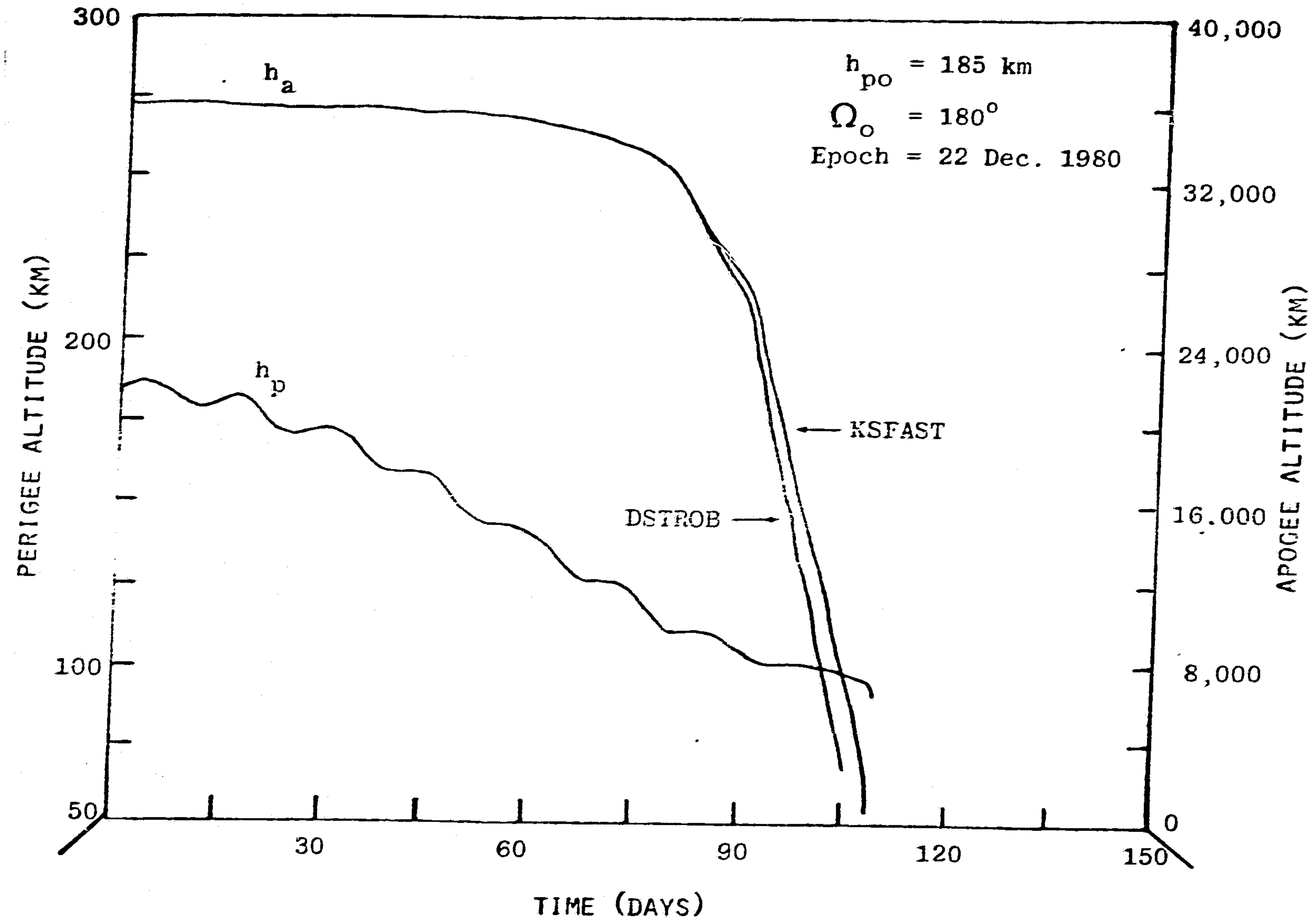
VERIFICATION AND CHECKOUT OF DSTROB

(A) PSU vs. DSTROB



VERIFICATION AND CHECKOUT OF DSTROB (CONCL.)

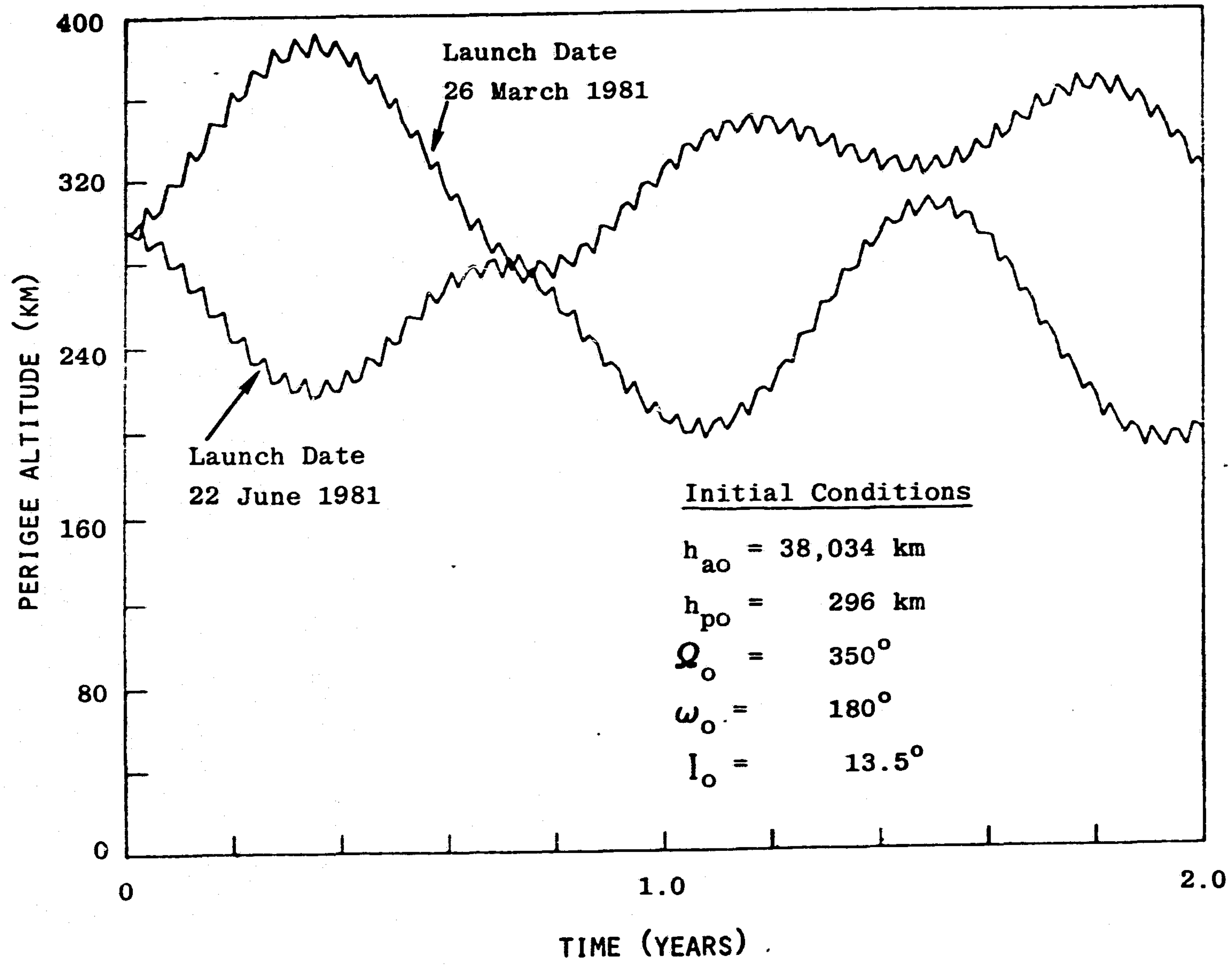
(B) KSFAST vs. DSTROB



EVOLUTION OF PERIGEE ALTITUDE GOES-E/SUSS-A

EFFECT OF LAUNCH DATE

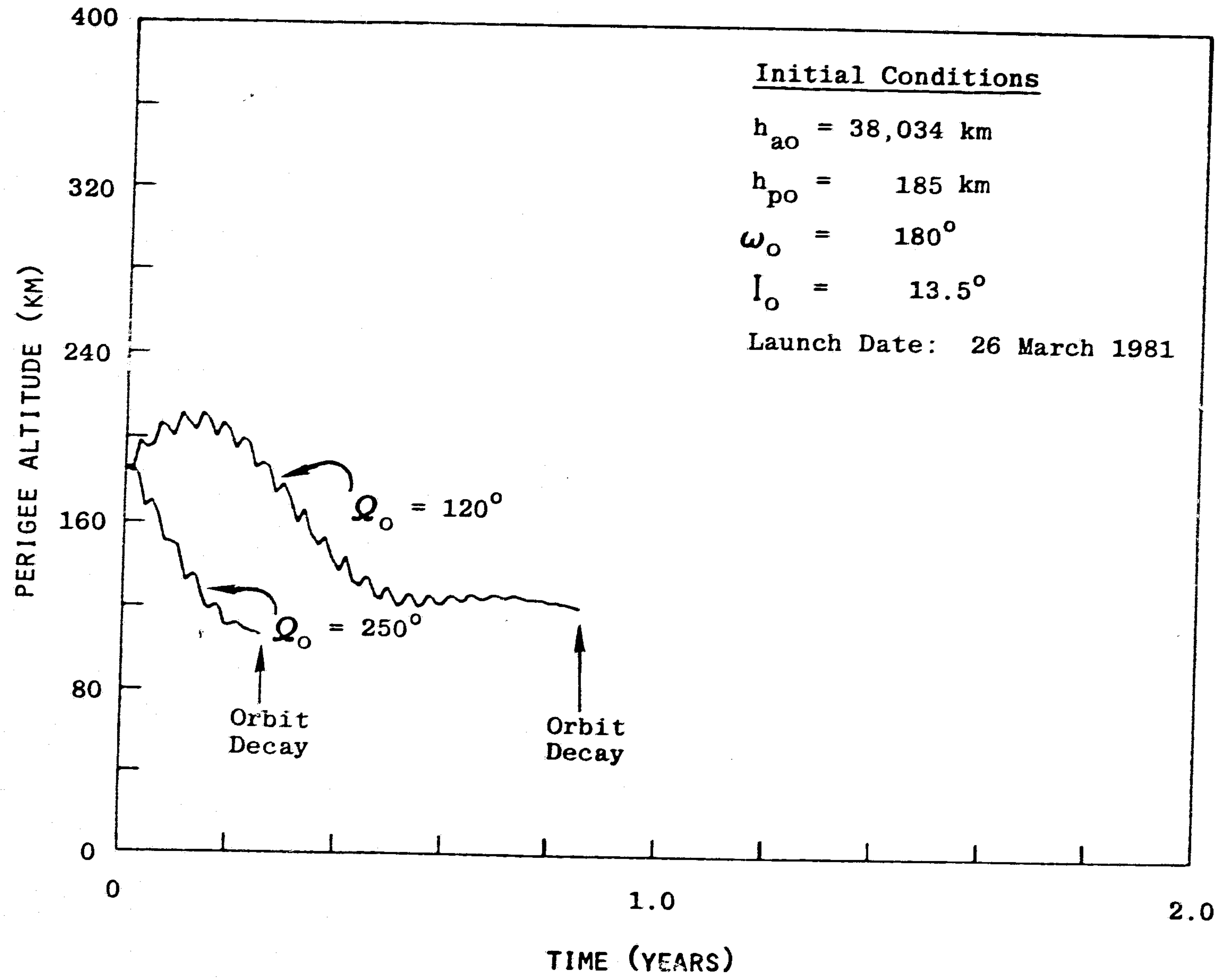
h_{po} = 296 KM



EVOLUTION OF PERIGEE ALTITUDE GOES-E/SUSS-A

EFFECT OF ORBIT PLANE PLACEMENT

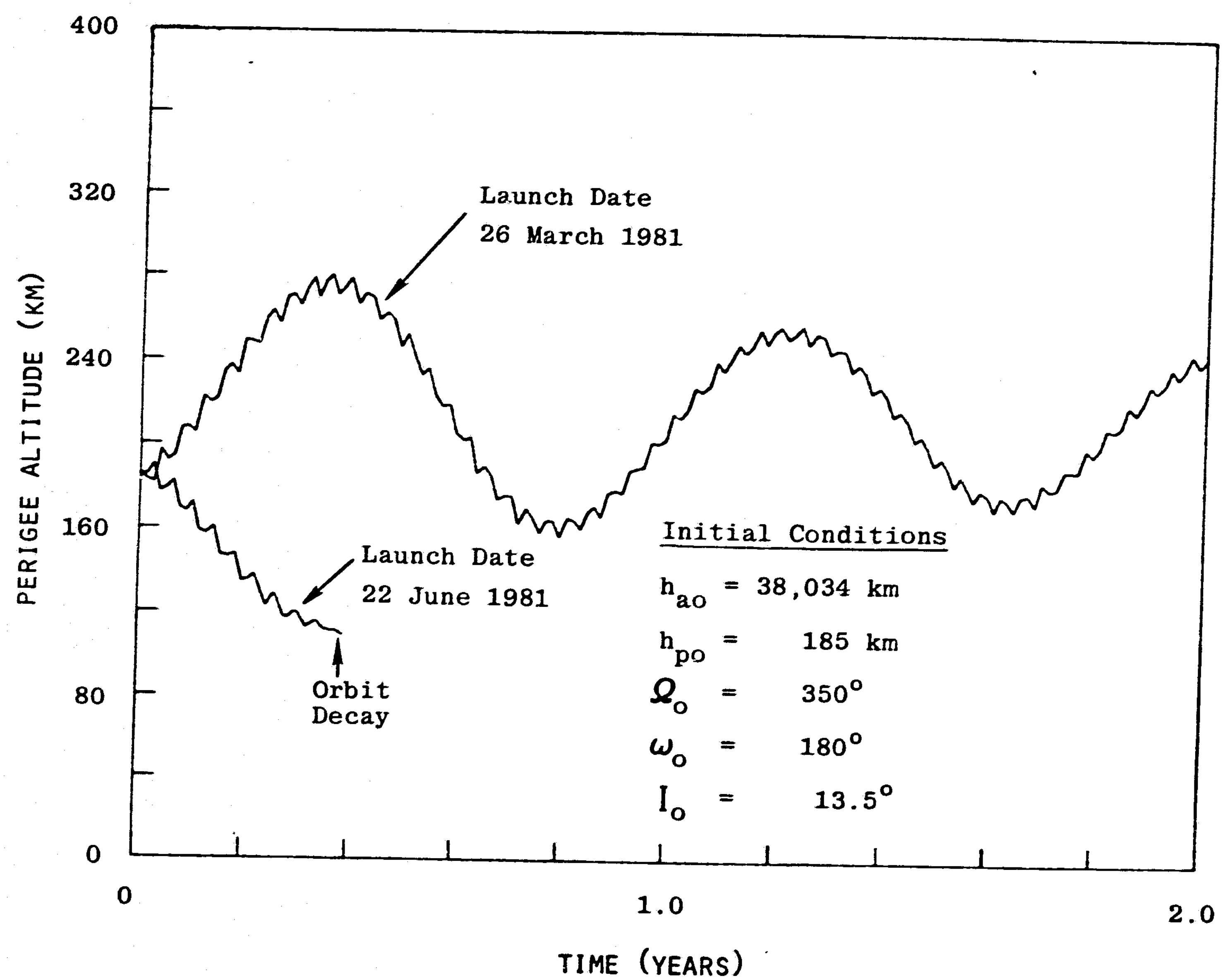
h_{po} = 185 KM



EVOLUTION OF PERIGEE ALTITUDE GOES-E/SUSS-A

EFFECT OF LAUNCH DATE

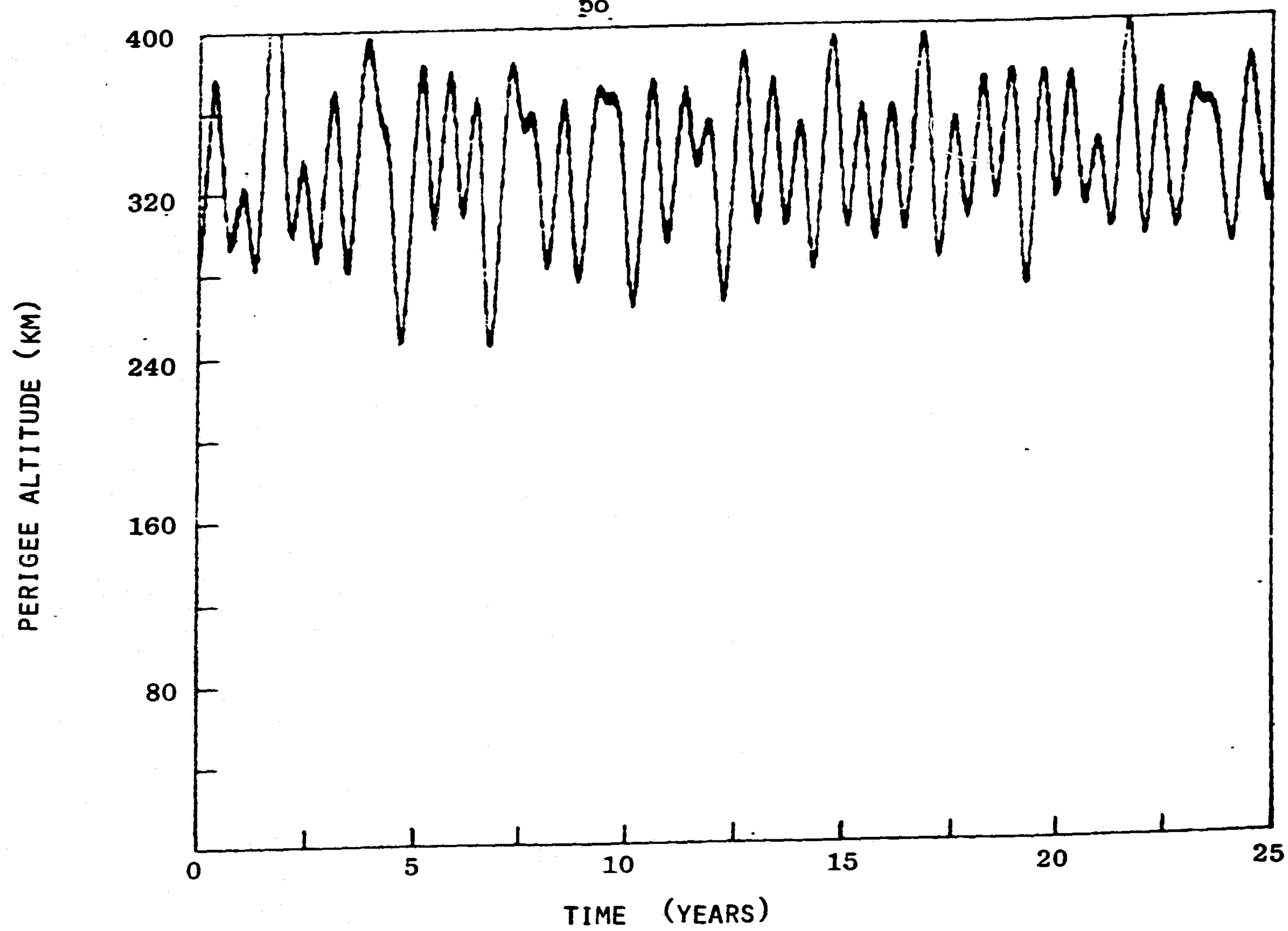
$h_{po} = 185$ KM



STS-6 SBS/SUSS-D

(A) PERIGEE TIME HISTORY

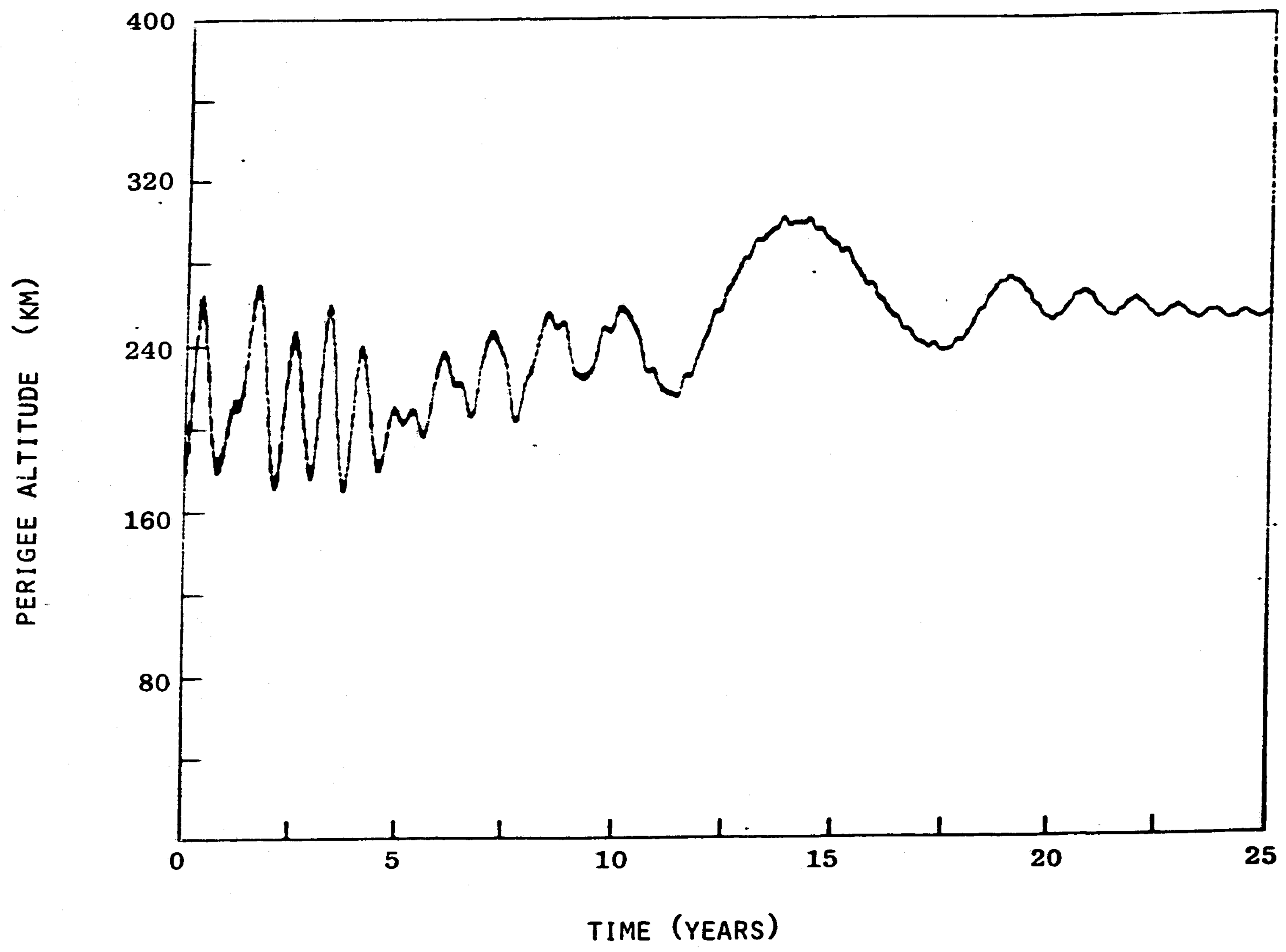
h_{po} = 296 km



STS-6 SBS/SUSS-D

(B) PERIGEE TIME HISTORY

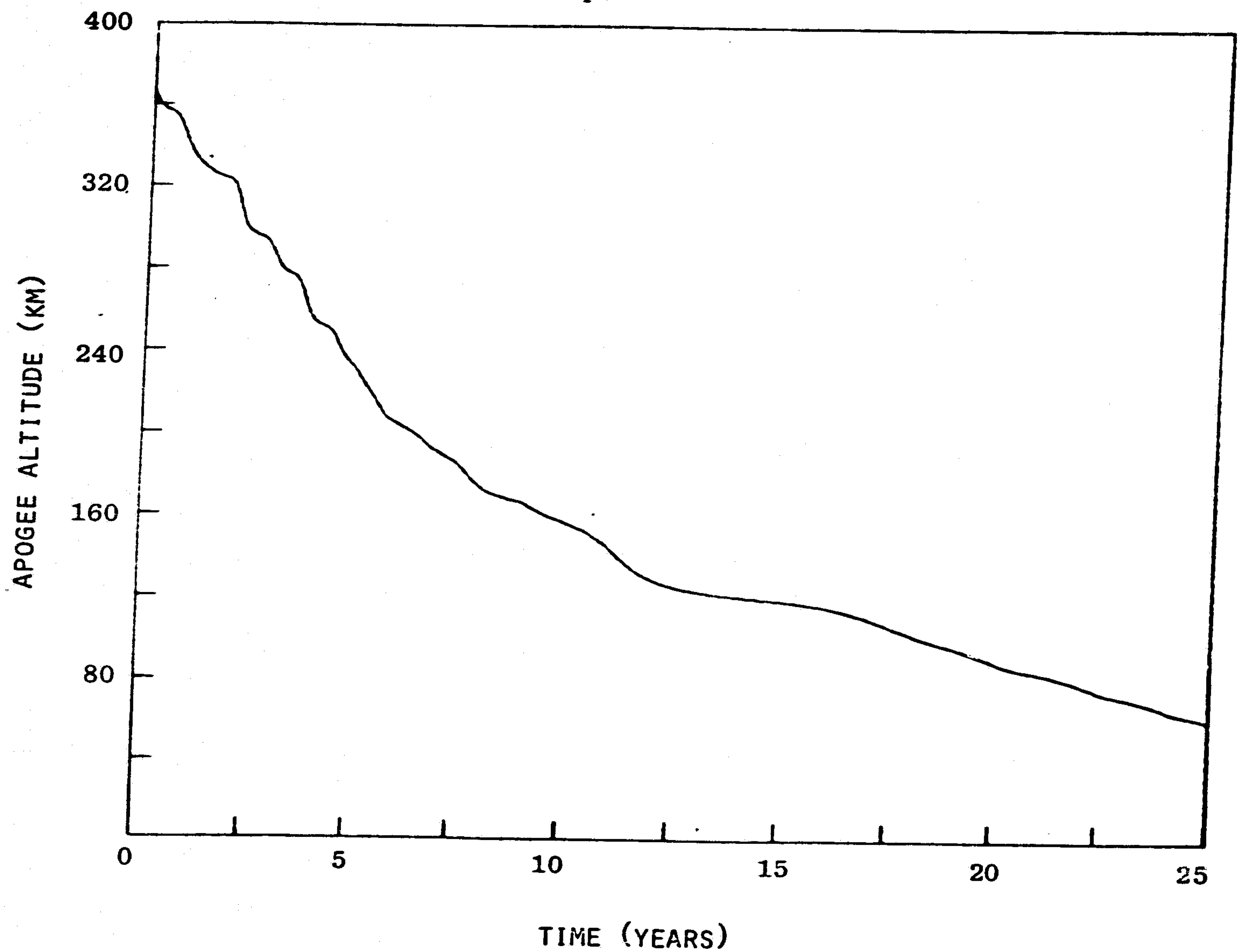
h_{po} = 185 km



STS-6 SBS/SUSS-D

(c) APOGEE TIME HISTORY

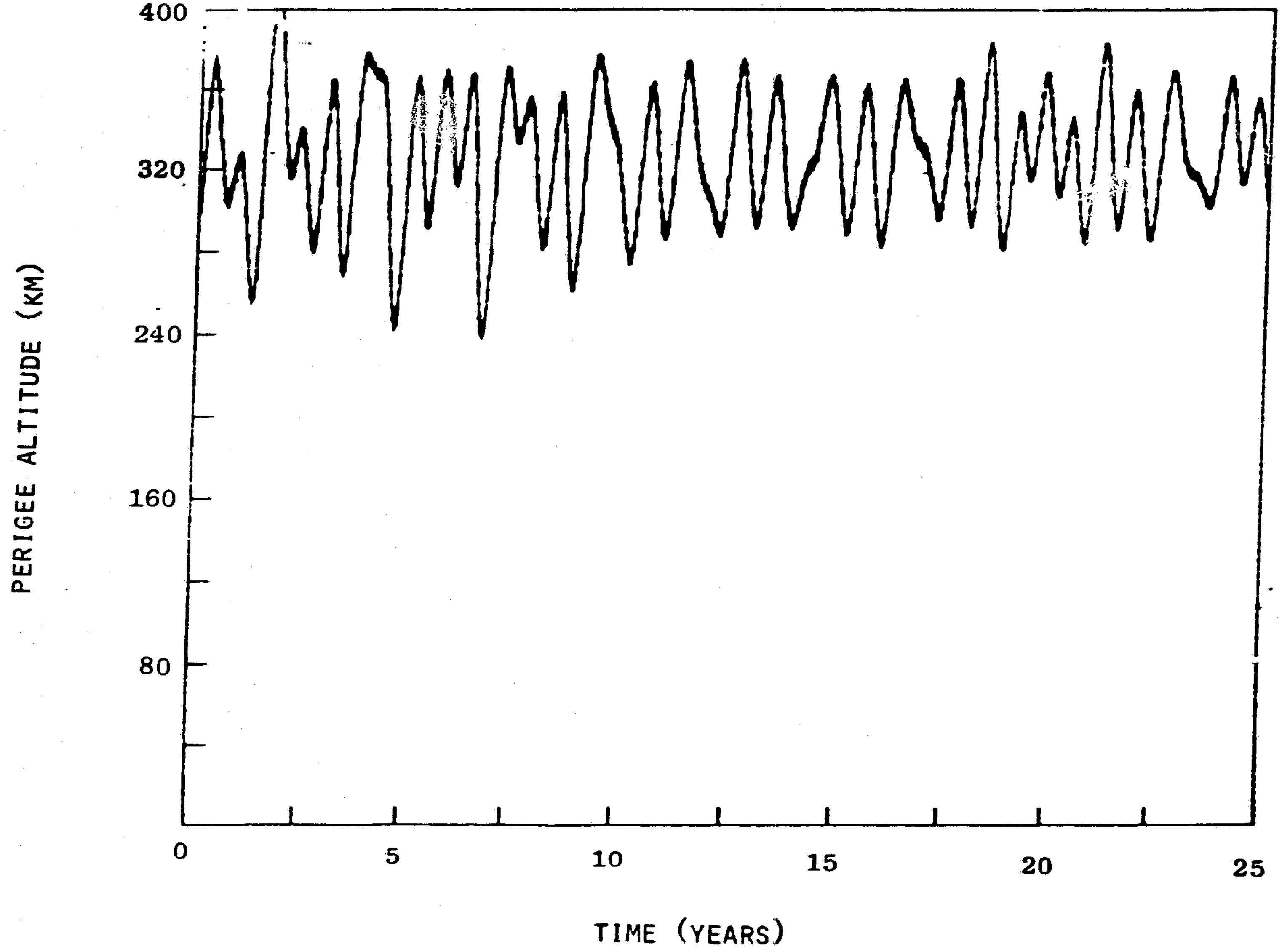
h_{po} = 185 km



STS-6 INTELSAT/SUSS-A

(A) PERIGEE TIME HISTORY

$h_{po} = 296$ km



STS-6 INTELSAT/SUSS-A

(B) PERIGEE ALTITUDE TIME HISTORY

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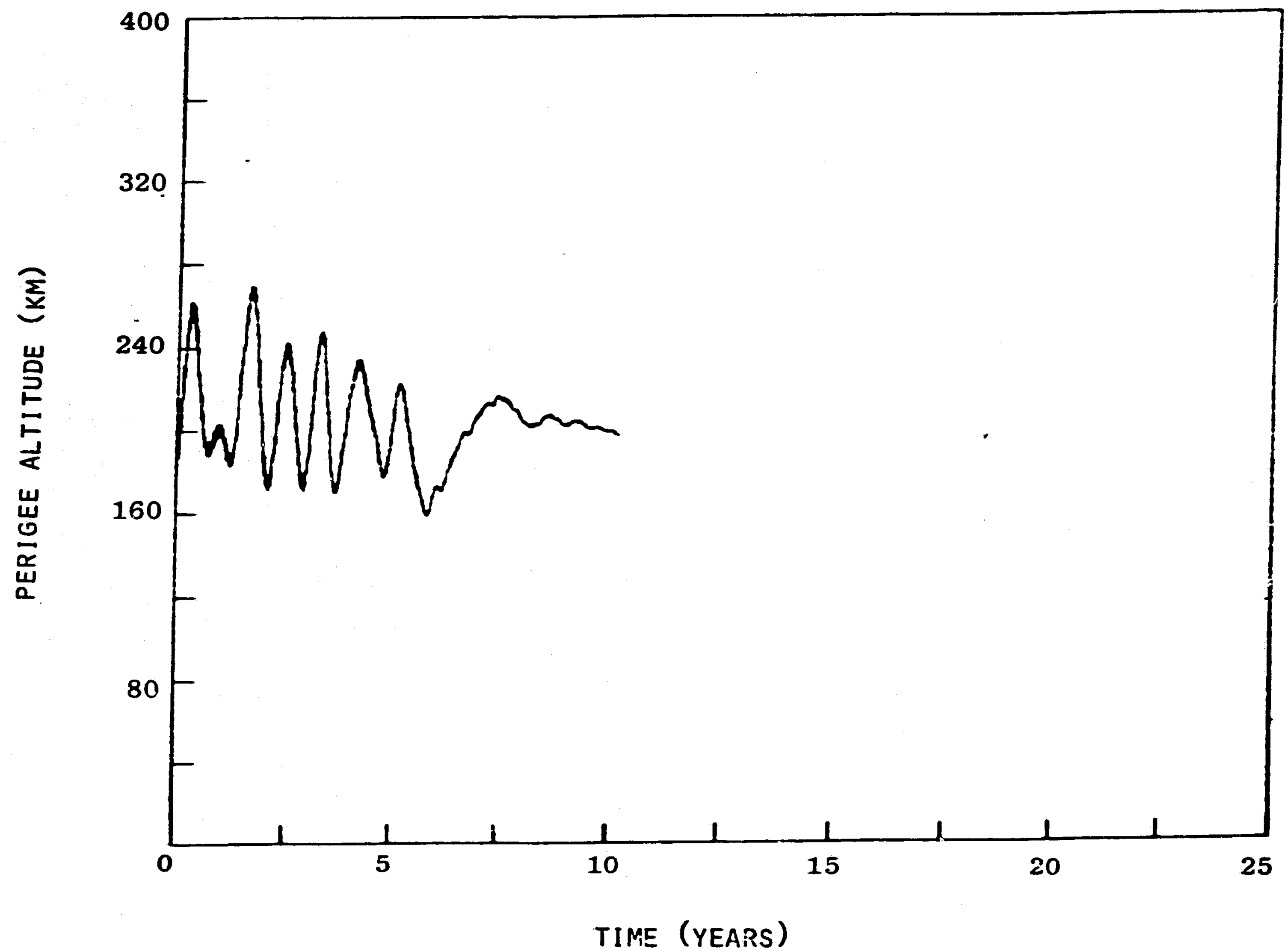
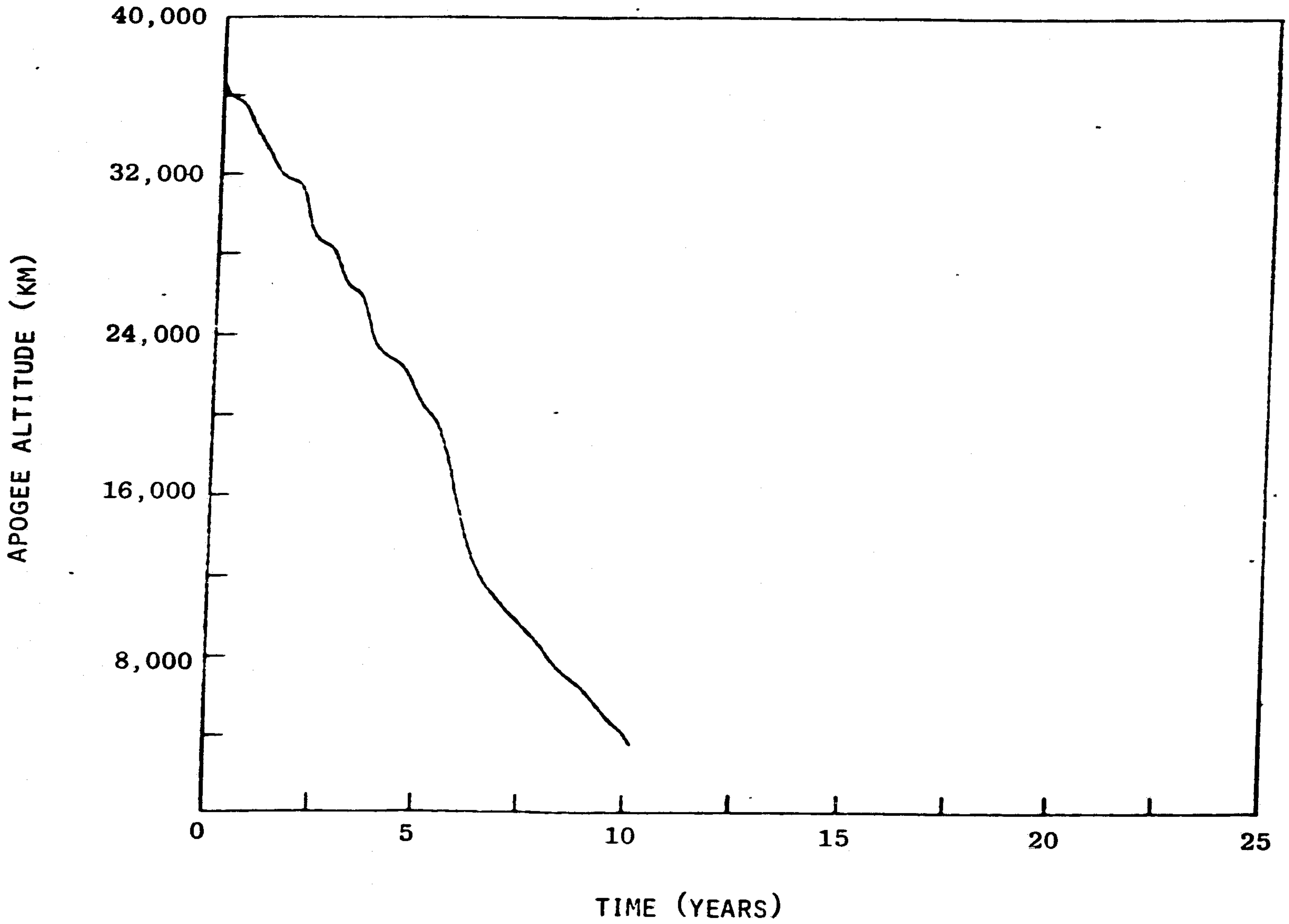


STS-6 INTELSAT/SUSS-A

(c) APOGEE ALTITUDE TIME HISTORY

h_{po} = 185 km



NECESSARY CONDITIONS FOR IMMEDIATE DECREASE IN PERIGEE ALTITUDE

- PERIGEE ALTITUDE WILL DECREASE WHEN ECCENTRICITY INCREASES

- FOR AN APPROXIMATE FORMULA, NEGLECT THE FOLLOWING EFFECTS:
  - AIR DRAG
  - SIN I, SIN ϵ
  - ORBITAL MOTION OF THE MOON AND SATELLITE

- THE CHANGE IN ECCENTRICITY IS APPROXIMATELY†

$$\Delta e \cong \frac{15}{8} \frac{n_\odot^2 a^2 e^2 \sqrt{1-e^2}}{n(\dot{\lambda}_\odot - \dot{\Omega} - \dot{\omega})} \left\{ \cos\left[2(\lambda_\odot - \Omega - \omega)\right] - \cos\left[2(\lambda_\odot - \Omega - \omega)_0\right] \right\}$$

$\lambda_\odot$ = MEAN LONGITUDE OF THE SUN

$\dot{\Omega} \cong -.36$ DEG/DAY

$\dot{\omega} \cong .62$ DEG/DAY

†THIS FORMULA WAS SUPPLIED BY
PROFESSOR JOHN V. BREAKWELL
DEPARTMENT OF AERONAUTICS AND ASTRONAUTICS
STANFORD UNIVERSITY

NECESSARY CONDITIONS FOR IMMEDIATE DECREASE IN PERIGEE ALTITUDE (CONCL.)

- USING THE PREVIOUS FORMULA, IT CAN BE SHOWN THAT THE GREATEST INITIAL <u>INCREASE</u> IN e OCCURS WHEN

$$(\lambda_{\odot} - \Omega)_0 = \pm \pi/2$$

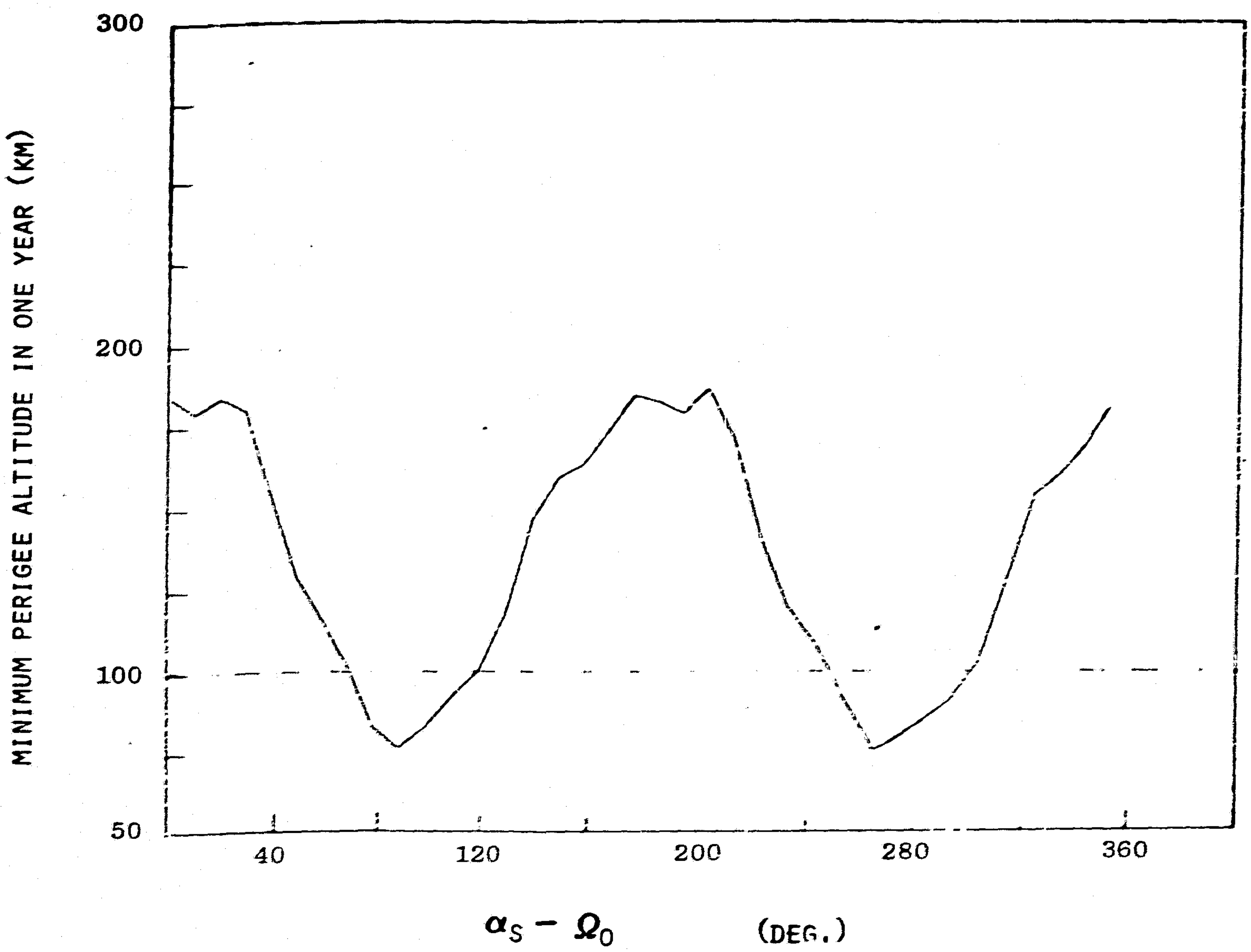
$$(\alpha_s - \Omega)_0 = \pm \pi/2$$

- THIS RESULT IS ILLUSTRATED IN THE NEXT SLIDE.

ORBIT LIFETIME PARAMETER SCANS

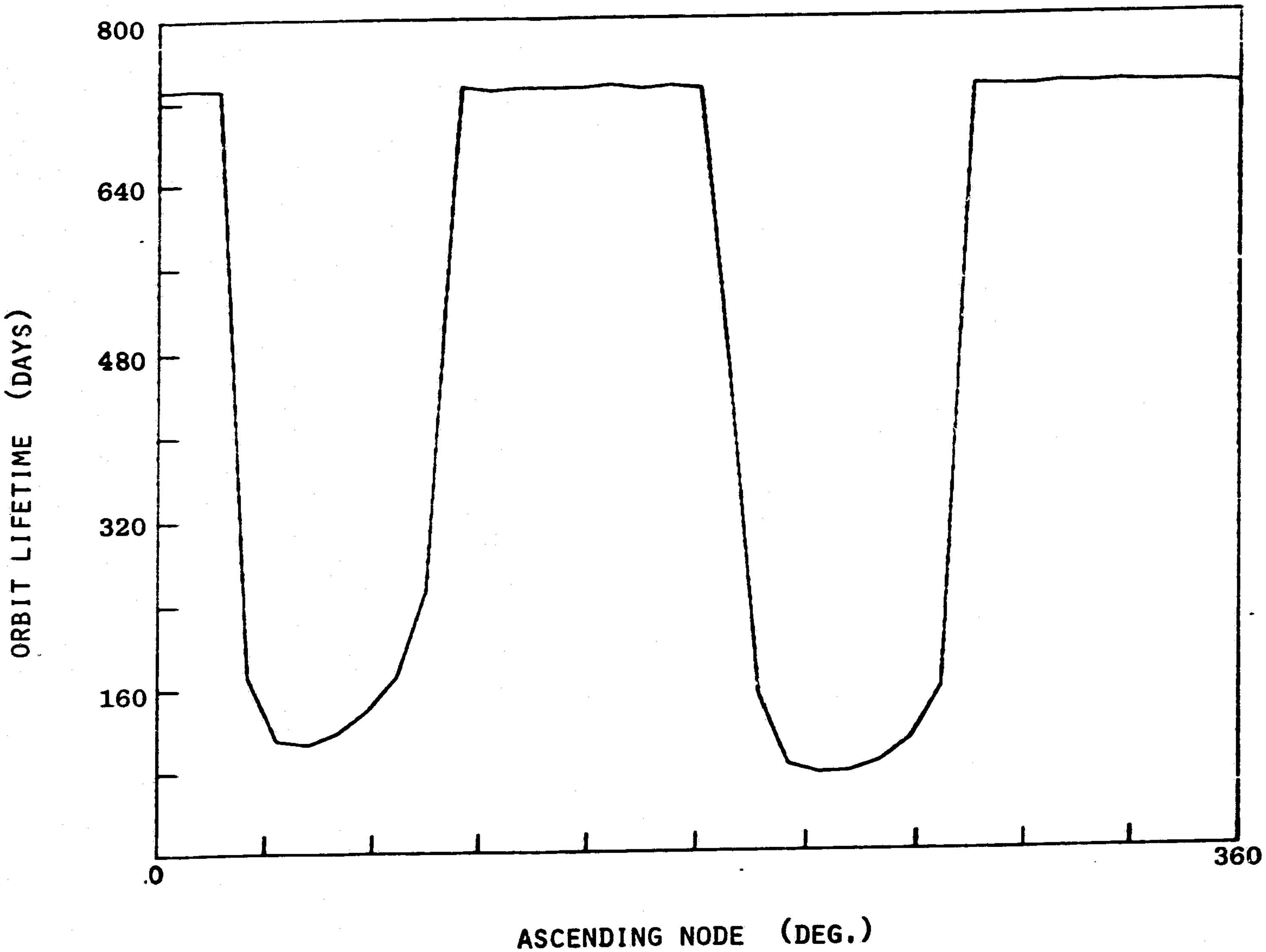
TIME OF YEAR OF LAUNCH

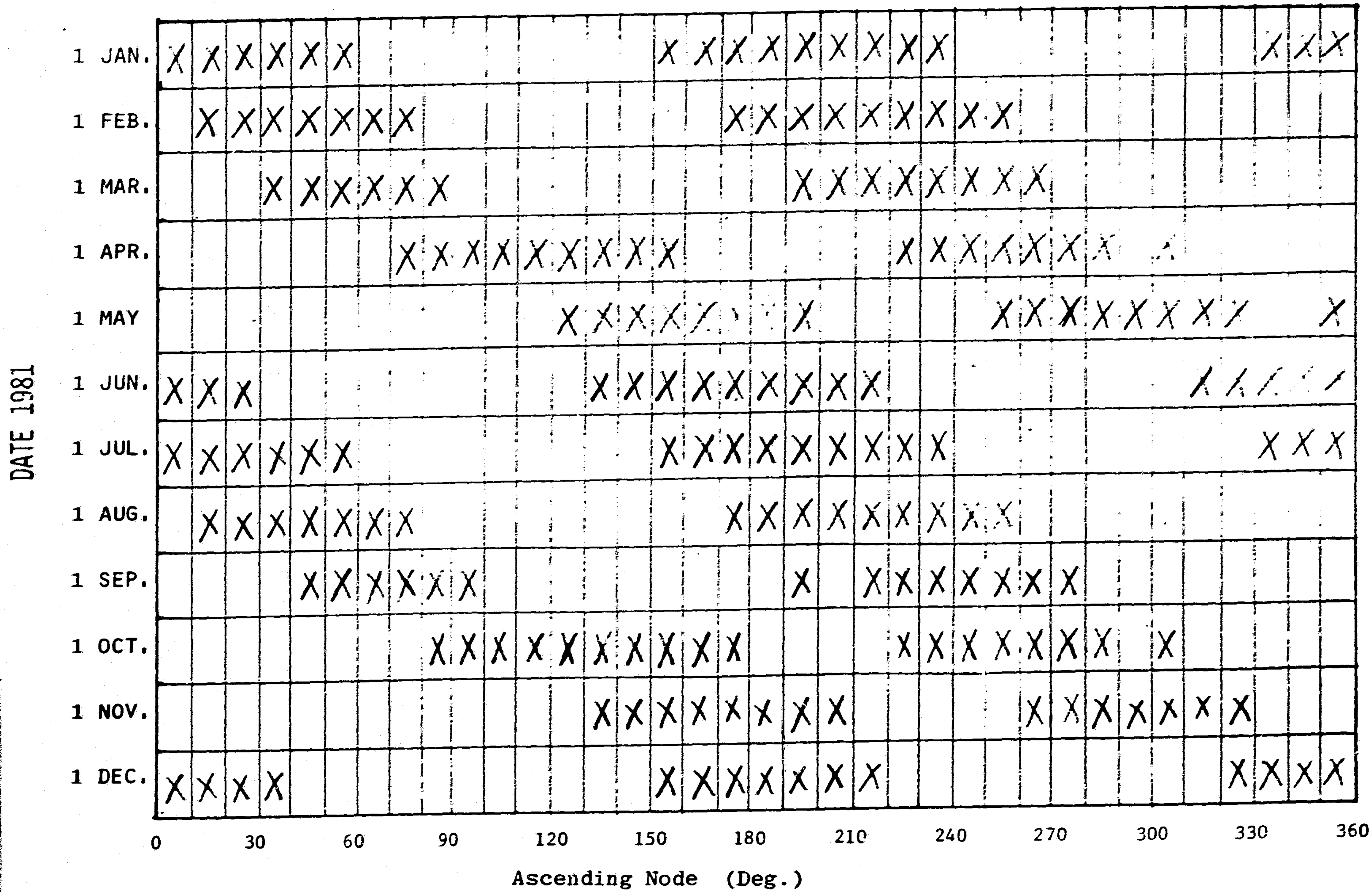
(b) $h_{po} = 185$ km , $I_o = 28.6^\circ$, $\Omega_0 = 0$



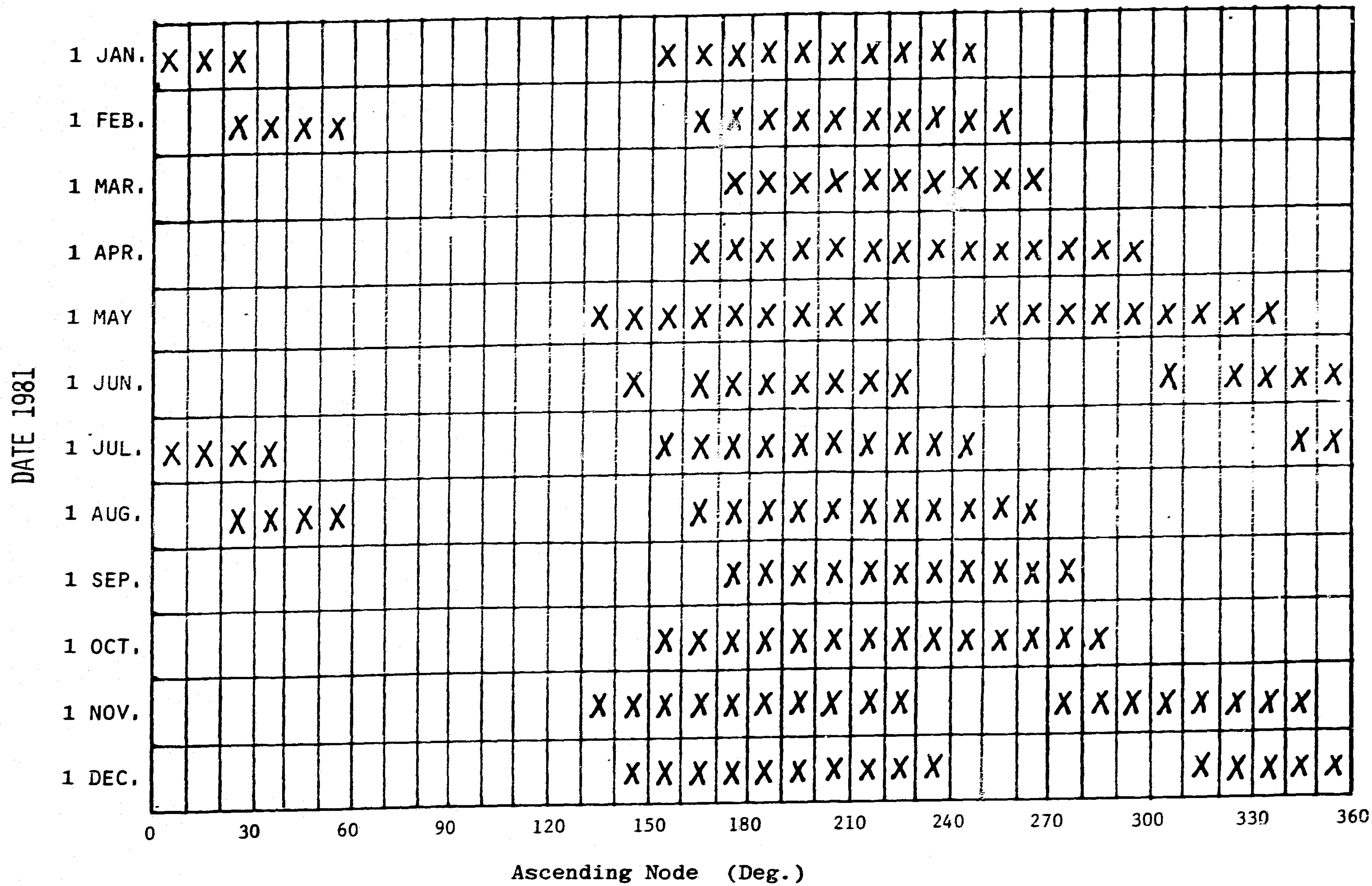
GOES-D LIFETIME SCAN

27 August 1980 h_p = 185 km

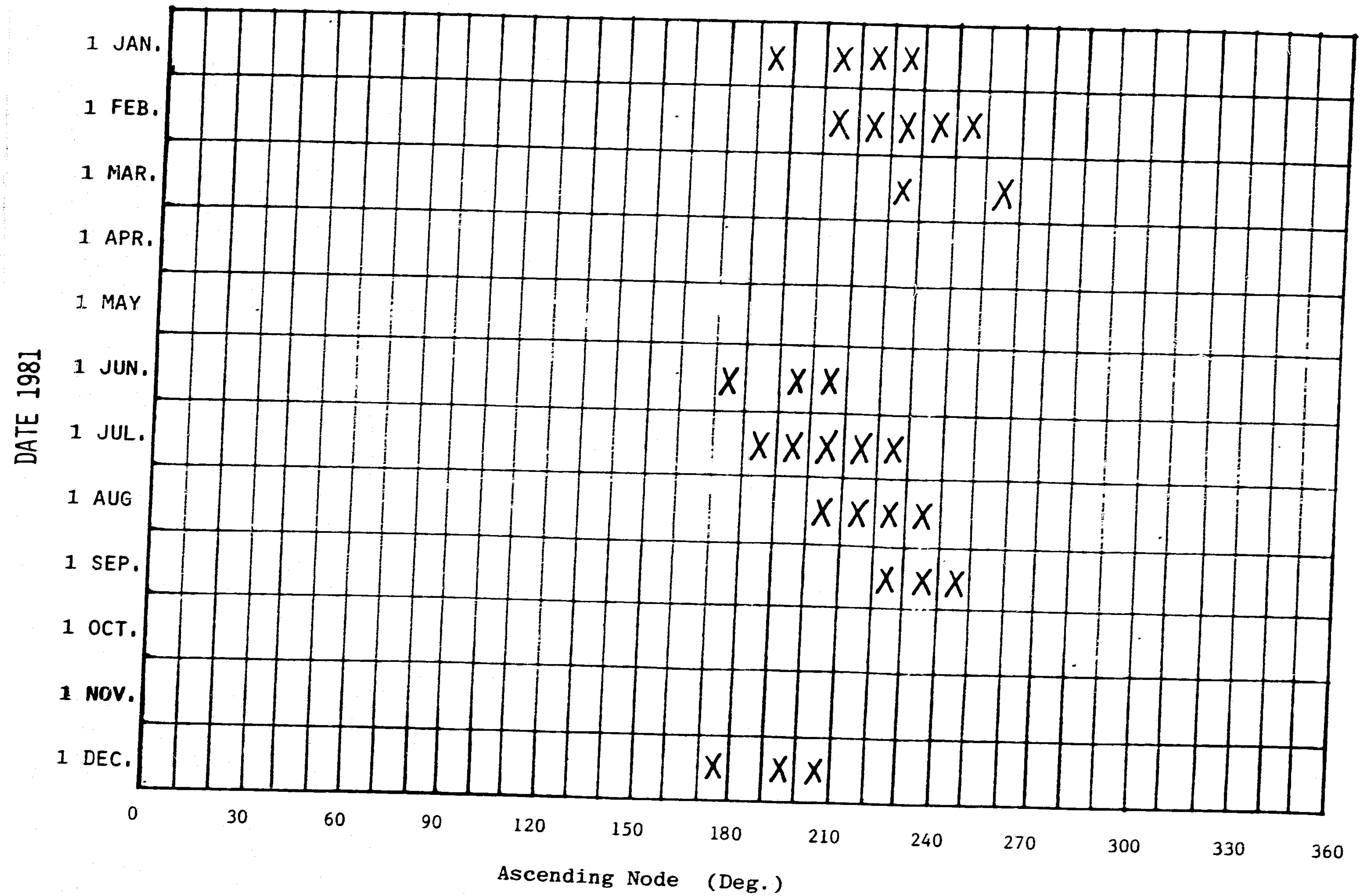




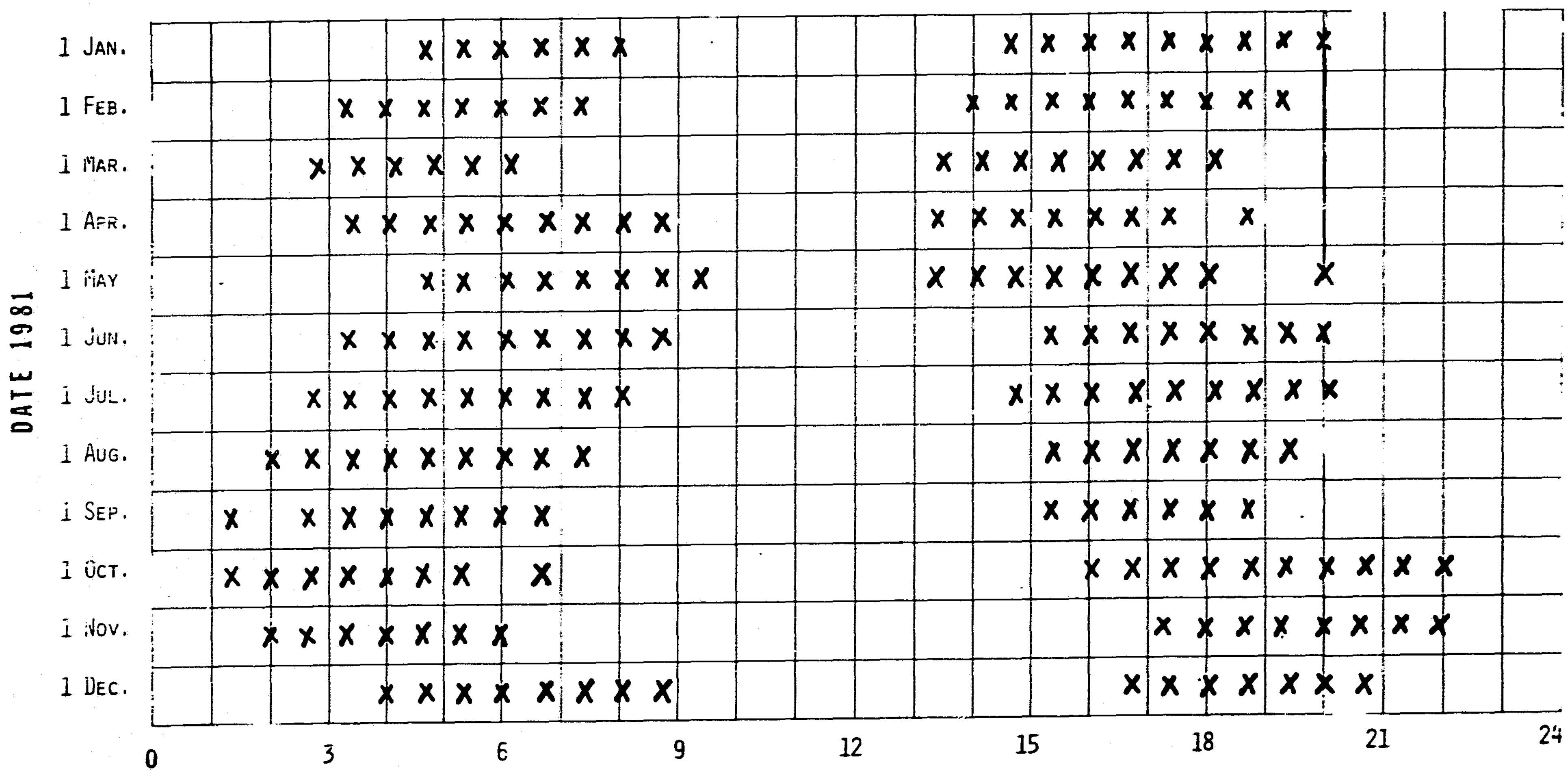
Launch Window STS-8 GOES-E/SUSS-A $h_{po} = 185$ km



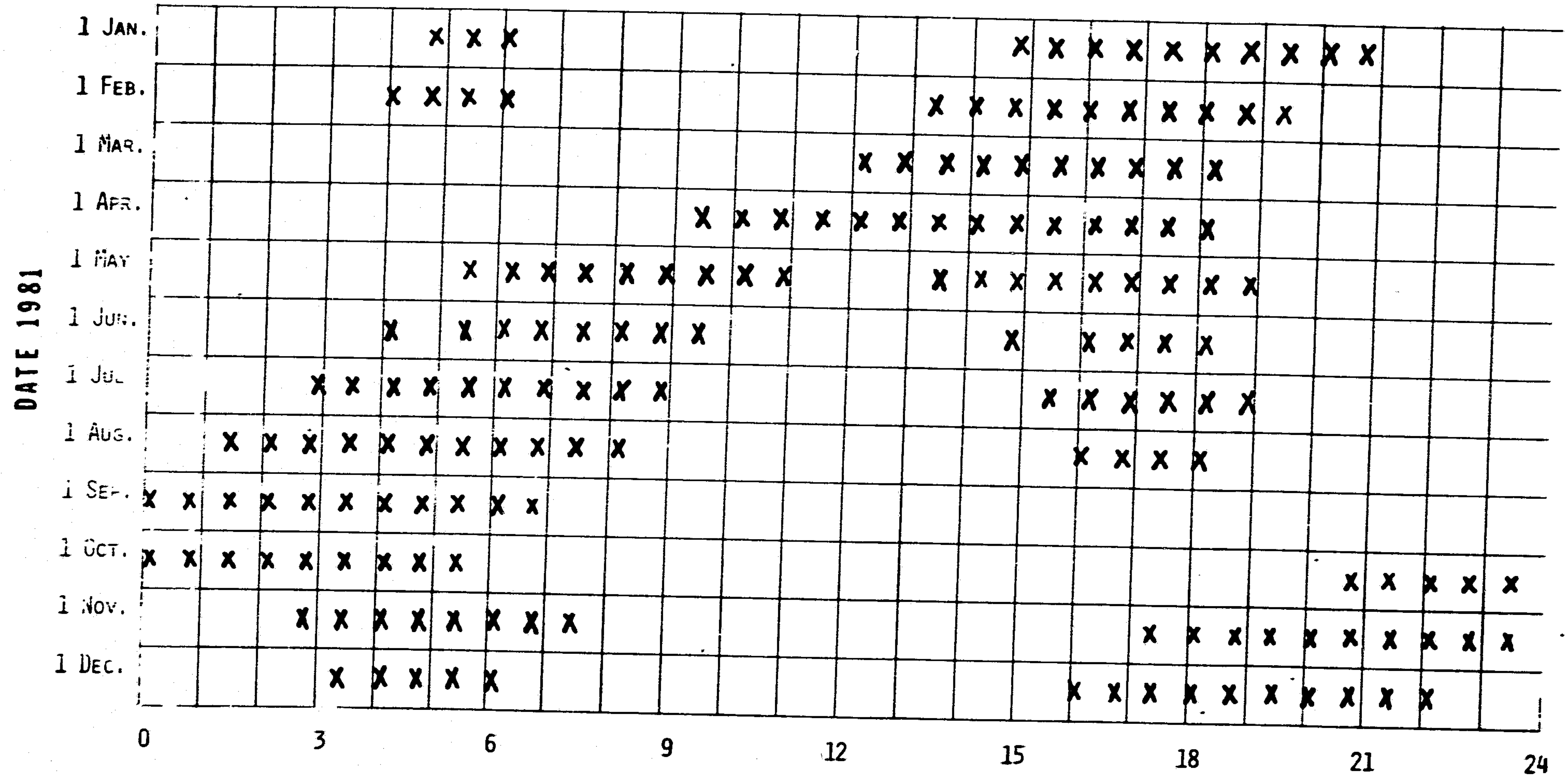
Launch Window STS-7 TDRS/IUS h_{po} = 185 km



Launch Window STS-7 TDRS/IUS h_{po} = 232 km



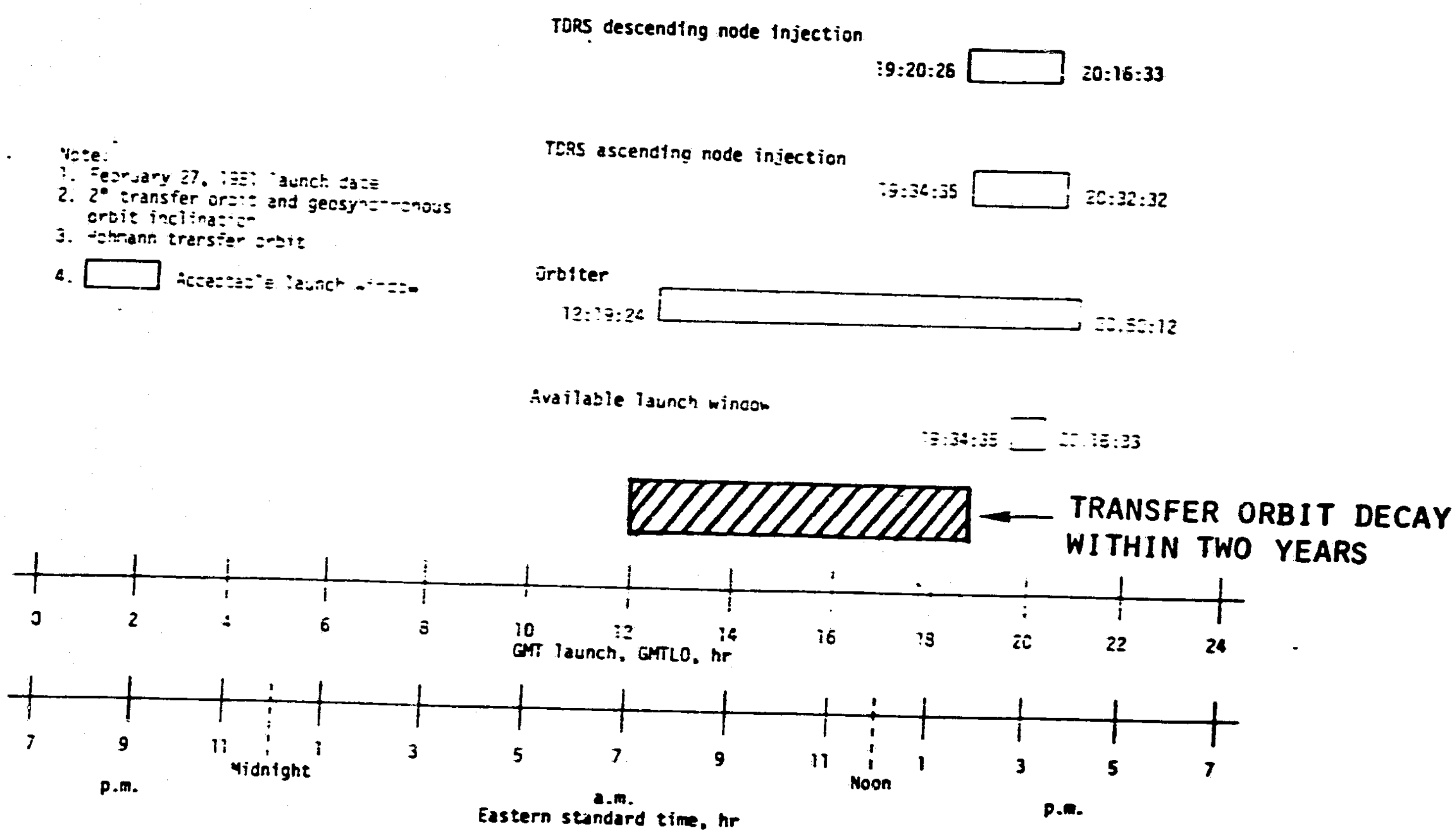
GOES-E Launch Window $h_{po} = 185$ km



Time of Lift-off (Hours, GMT)

TDRS Launch Window $h_{po} = 185$ km

STS-7 LAUNCH WINDOW COMPOSITE



CONCLUSIONS AND RECOMMENDATIONS

- THE MOST RAPID ORBIT DECAY OCCURS WHEN THE SUN'S RIGHT ASCENSION IS 90° AHEAD OR BEHIND THE ASCENDING NODE OF THE TRANSFER ORBIT.

- THE TRANSFER ORBIT SHOULD BE DESIGNED SO THAT THE INITIAL PERIGEE ALTITUDE IS LESS THAN 232 KM (125NM).
  - ALLOWS ADEQUATE STAY-TIME IN TRANSFER ELLIPSE.
  - ALLOWS POSSIBILITY OF FUTURE ORBIT DECAY.

- TRANSFER ORBIT DECAY LAUNCH WINDOWS CAN BE GENERATED FOR EACH MISSION AND INTEGRATED INTO THE COMPOSITE LAUNCH WINDOW.

SUMMARY OF THE WORK

- A SEMI-ANALYTICAL TRAJECTORY GENERATION METHOD (DSTROB) HAS BEEN DEVELOPED AND TESTED. IT IS APPLICABLE TO GEOSYNCHRONOUS TRANSFER ORBITS.
- ORBIT DECAY PREDICTIONS WERE COMPARED TO AIR FORCE TRACKING DATA. GOOD AGREEMENT WAS OBTAINED.
- A STUDY WAS MADE ON THE ORBIT DECAY DYNAMICS OF GEOSYNCHRONOUS TRANSFER ORBITS.
- UPPER STAGE ORBIT DECAY WAS STUDIED FOR CERTAIN PLANNED STS MISSIONS.

SUMMARY OF THE WORK (CONCL.)

- A PROTOTYPE COMPUTER PROGRAM WAS DEVELOPED TO PROVIDE ORBIT DECAY PARAMETER SCANS AND LAUNCH WINDOW DATA.
- A TECHNIQUE WAS DEVELOPED FOR DETERMINING ORBIT DECAY LAUNCH WINDOWS FOR STS UPPER STAGE MISSIONS.
- UPPER STAGE ORBIT DECAY LAUNCH WINDOWS WERE GENERATED FOR CERTAIN STS MISSIONS.

APPENDIX B

PAPER 79-105

A STUDY OF THE LIFETIMES OF GEOSYNCHRONOUS TRANSFER ORBITS

By

Otis F. Graf, Jr.
Alan C. Mueller

Analytical and Computational Mathematics, Inc.
Houston, Texas

AAS/AIAA Astrodynamics Specialist Conference

PROVINCETOWN, MASS/JUNE 25-27, 1979

A STUDY OF THE LIFETIMES OF

GEOSYNCHRONOUS TRANSFER ORBITS*

Otis F. Graf, Jr. and Alan C. Mueller†

The study concerns the orbit lifetimes of spent upper stages that are used to boost NASA Space Transportation System payloads into geosynchronous transfer orbits. A semi-analytical method of trajectory computation was developed and applied to these particular orbits. This method allowed very fast computation of orbit lifetimes. It was found that gravitational perturbations of the sun, moon and oblate earth cause large changes in the perigee altitude. Lifetimes may vary from a few months to many years. The following parameters have a strong influence on orbit lifetimes: Time of year of launch; Inertial orientation of orbital plane; Inclination of orbital plane. The transfer orbits can be designed to decay within one year if the initial perigee altitude is less than 231 km. However, there are restrictions on orbit plane placement and time of year of launch. The time of year restriction does not apply if initial perigee is lowered to 185 km.

INTRODUCTION

Statement of the Problem

The NASA Space Transportation System (STS) offers new economies for placing payloads into earth orbit. There will be new opportunities to organizations for operating their devices in space. Thus, there will be a much wider utilization of space as a resource for applications.

At the same time, however, the increasing number of satellites will increase the possibilities of collision in space. In the past, most

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* Presented at the AAS/AIAA Astrodynamics Specialist Conference, Provincetown, Massachusetts, June 25-27, 1979.

† Analytical and Computational Mathematics, Inc. Houston, Texas.

satellites were in near earth orbit, where air drag eventually forced them to fall back to earth. Now, however, many satellites will be put into geosynchronous orbit, using the Interim Upper Stage (IUS) or the Spinning Solid Upper Stage (SSUS).

For each satellite launched into geosynchronous orbit, one or more upper stages will be left in the transfer orbit. These orbits have a low perigee and will intersect the orbit of the Shuttle. Also, these orbits can have a very long lifetime. During the ten year period 1980-1990, there are 164 planned geosynchronous missions using the STS Space Shuttle (Ref. 1).

The purpose of this study was to investigate the orbit lifetimes of the spent upper stages that are used to boost STS payloads into geosynchronous transfer orbits. The upper stage vehicles remain in the transfer orbit.

It is assumed that the transfer orbit has an initial perigee altitude of 300 km and an apogee altitude of about 35,785 km. The scale of the orbit is shown in Fig. 1. It can be seen that the perigee altitude has a relatively small scale. Thus, a small change in the size or shape of the orbit can drastically raise or lower perigee.

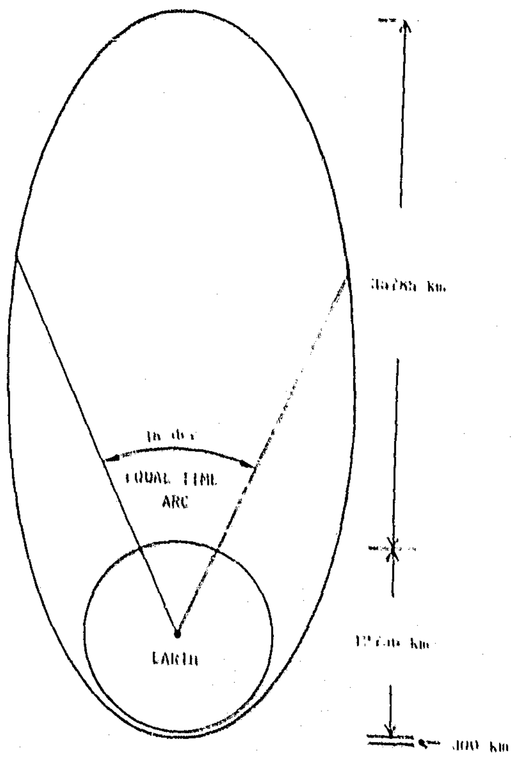

Fig. 1 Scale of Geosynchronous Transfer Orbit

The orbit geometry is shown in Fig. 2. Define the following symbols:

- ϵ Angle between the ecliptic plane and the equatorial plane (23.5°).
- Υ Direction of the vernal equinox.
- Ω Angle of the ascending node of the satellite orbit on the equator, measured from the equinox.
- I Inclination of the geosynchronous transfer orbit relative to the equator.
- α_s Right ascension of the sun.

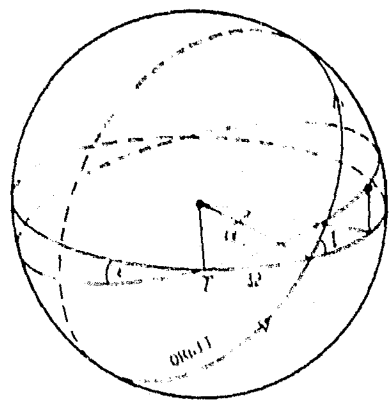

Fig. 2 Orbit Geometry

Since the geosynchronous orbits are placed at zero inclination, it is assumed in this study that the transfer orbit inclination will be less than the Shuttle parking orbit inclination. That is, I will be equal to or less than about 28 degrees.

<u>Summary of Results</u>

It was found that the gravitational perturbations of the sun, moon and oblate earth can make large changes in the perigee altitude of the geosynchronous transfer orbits. Some transfer orbits may have a lifetime of only a few months. In other cases, the perigee altitude is raised so that the orbit will have an extremely long lifetime.

The important results are listed below:

1. The following parameters have a strong influence on orbit lifetimes:
   - Time of year of launch.
   - Inertial orientation of orbital plane.
   - Inclination of orbital plane.

2. The most severe decay in perigee altitude occurs when the initial longitude of ascending node is near 180 degrees.

3. If the initial perigee altitude is less than 231 km (125NM), the transfer orbit can be designed to decay within one year.

4. Geosynchronous transfer trajectories may have lifetimes of many years for some cases.

EFFECTS OF THE DIFFERENT ORBIT PERTURBATIONS

The geosynchronous transfer orbits are strongly perturbed by the following forces: Gravitation of the oblate earth (J_2), Gravitation of the moon (point mass), Gravitation of the sun (point mass), Atmospheric drag.

All four of the above perturbations are of equal importance. There is at present, no analytical solution to the motion of a satellite in a geosynchronous transfer orbit (Refs. 2 and 3). Since all perturbations are of about the same magnitude, a linear perturbation method does not yield an accurate solution. Therefore, trajectory generation must be done with numerical or semi-analytical methods. This aspect of the problem is discussed in the next section.

The effects of the different gravitational perturbations on perigee altitude are shown in Fig. 3. The small oscillations are caused by the monthly revolution of the moon in its orbit. It can be seen in Fig. 3 that the magnitudes of the perturbations are all about the same.

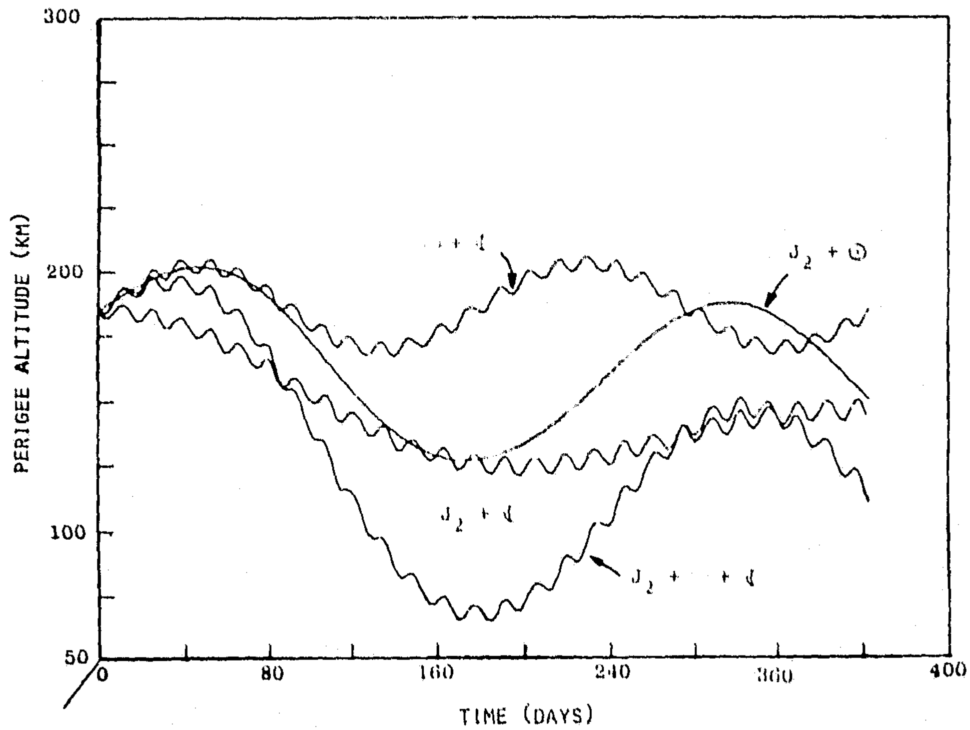

Fig. 3 Effect of the Different Gravitational Perturbations on Perigee Altitude

It was found that atmospheric drag does not have an important effect on orbit decay when perigee altitude is above 150 km. The effects of air drag on orbit decay are shown in Fig. 4. The drag model was based on the burn-out weight and average cross-sectional area of the Spinning Solid Upper Stage (SSUS). As the gravitational perturbations bring perigee down, air drag causes the apogee to drop. As the apogee comes down, the sun and moon perturbations on perigee are less severe. Therefore, perigee drops less rapidly for the drag-perturbed case than for the case where drag is neglected.

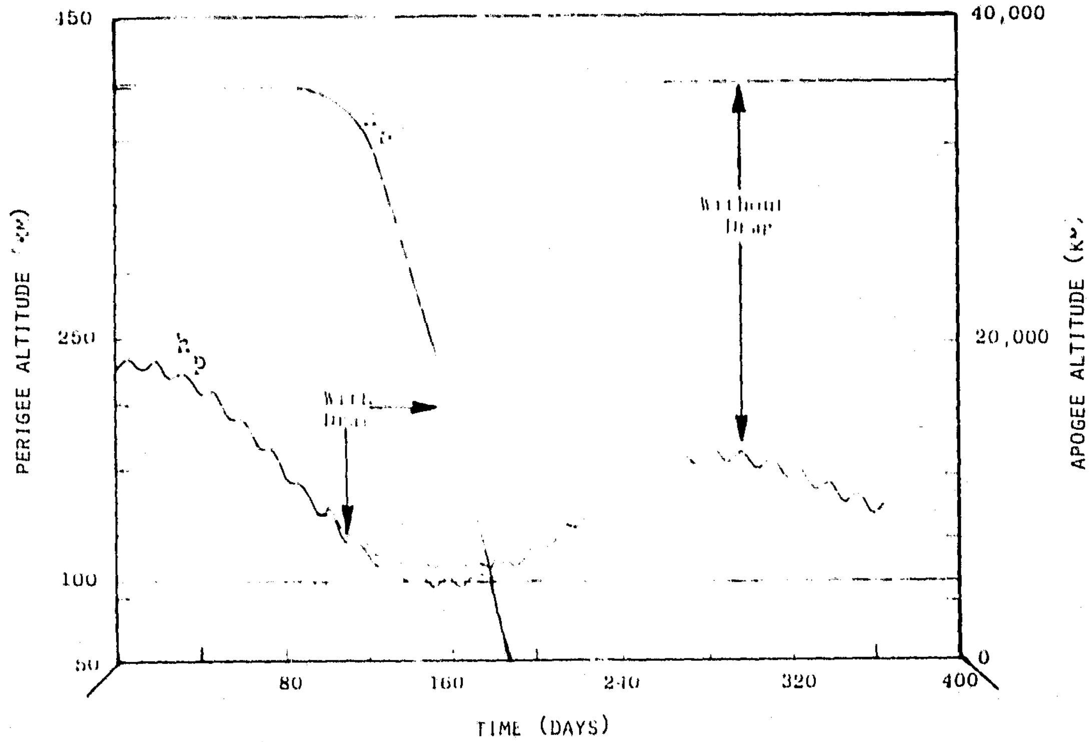

Fig. 4 Effects of Drag on Orbit Decay

For this study it was important to determine a *threshold perigee altitude*, defined as the maximum perigee altitude for which the satellite will deorbit within 90 days. That is, at any perigee altitude below the threshold, atmospheric drag will be certain to deorbit the satellite within 90 days.

The determination of the threshold perigee altitude h_{pt} was done by taking a case where the gravitational perturbations had the strongest effect on raising perigee. Several trajectories were simulated using the KSFAST program on the UNIVAC 1110 computer (Ref. 4). Each trajectory was initialized at a different perigee altitude h_{po}. The evolution of perigee altitude h_p for several cases is shown in Fig. 5. It was found that orbit lifetime was extremely sensitive to h_{po} at altitudes near 100 km. For $h_{po} \leq 101.5$, the orbit lifetime was less than 90 days. Therefore, h_{pt} was chosen to be 100 km. This value is in agreement with the remarks made in Section 5.1 of Ref. 3.

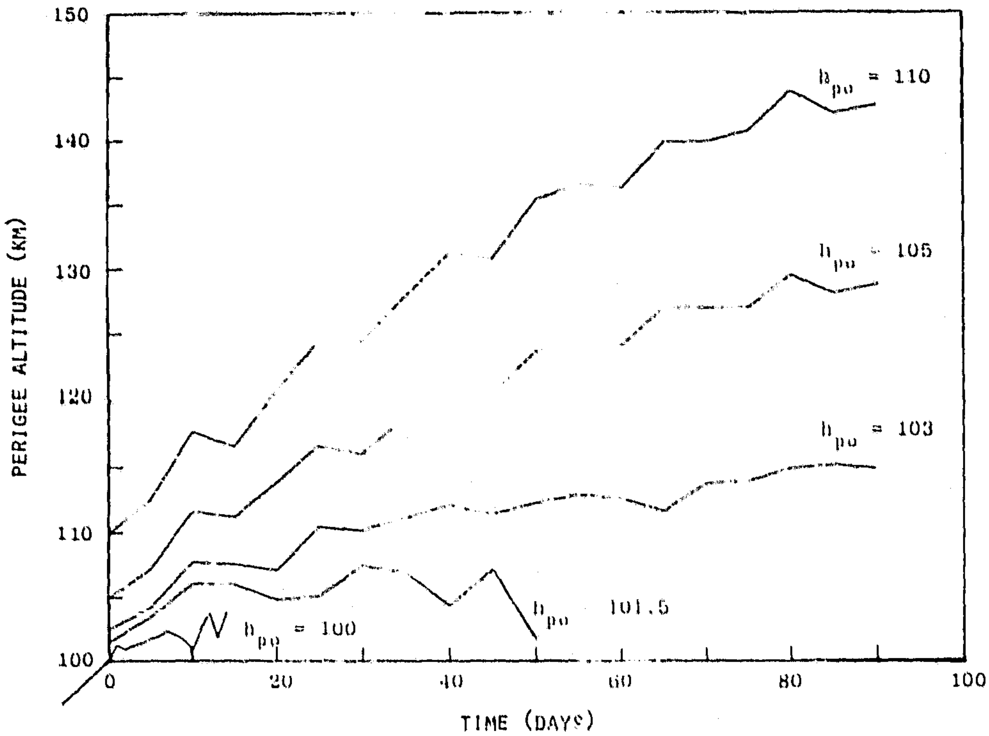

Fig. 5 Effects of Drag on Low Perigee Orbits

In the remaining discussion, it is assumed that when the perigee altitude drops to 100 km, the orbit will rapidly decay. This threshold altitude will be important in the discussion of orbit lifetime parameter scans.

A SEMI-ANALYTICAL TRAJECTORY GENERATION METHOD

Trade-Off Studies with Existing Routines

In order to get a global picture of the stability of the geosynchronous transfer class of orbits, their lifetimes must be determined as a function of the problem variables. This will require that many hundreds or thousands of trajectories be generated on a set of initialization parameters. These orbit lifetime parameter scans will give a general picture of how orbit decay is affected by a variety of control variables, such as time of launch, initial orbit placement, etc.

The complete set of trajectory programs available at the Johnson Space Center (JSC), Mission Planning and Analysis Division (MPAD), were investigated for their application to this problem. Existing analytical programs do not have an accurate representation of the perturbing forces. Therefore, numerical step-by-step programs were investigated. The required execution times (per revolution) of most numerical programs eliminated their application to this problem. Two MPAD programs found to be nearly applicable were KSFAST (Ref. 4) and STEPR (Ref. 5). Both programs are available on the UNIVAC 1110 computer system.

The execution times of STEPR and KSFAST are shown in Table 1. The test case was a two year trajectory generation of a geosynchronous transfer satellite. STEPR was found to be much faster than KSFAST.

Table 1

COMPUTER EXECUTION TIMES FOR A TWO YEAR TRAJECTORY

STEPR	100 sec.	UNIVAC 1110
KSFAST	800 sec.	UNIVAC 1110
DSTROB	1.5 sec.	UNIVAC 1108

A typical scan over the 360 degrees range of an angular variable would require 36 trajectories, if the scan interval was 10 degrees. The initial longitude of the ascending node Ω_o is a typical angular variable for this problem. Computer execution times for such a scan are shown in Table 2. Each trajectory in the scan was propagated for two years.

Table 2

COMPUTER EXECUTION TIMES FOR A 360 DEGREE SCAN
(36 points)

STEPR	60 min.	UNIVAC 1110
KSFAST	480 min.	UNIVAC 1110
DSTROB	.9 min.	UNIVAC 1108

The data in Table 2 demonstrates that both STEPR and KSFAST would be unsuitable for parameter scans. Therefore, no available JSC program could be used for an important part of this study. For this reason, ACM implemented and used the semi-analytical algorithm described below.

The DSTROB Algorithm

The semi-analytical algorithm in DSTROB is based on the stroboscopic method of orbit generation. This method has been extensively developed by Roth (Refs. 6, 7 and 8). The stroboscopic method is particularly suited to high eccentricity orbits. Roth has applied the method to launch window studies for orbits with eccentricites near 0.95 (Ref. 7). Janin discusses the decay of such orbits (Ref. 9).

The DSTROB algorithm makes use of Delaunay-Similar (DS) elements (Ref. 10) and the first order stroboscopic method described in Refs. 6 and 7. (Hence the name DS-STROB, or DSTROB). The perturbing forces include: Earth's oblateness (J_2), Sun point mass, Moon point mass, and Atmospheric drag. The sun and moon gravity models include only the first term in the distance ratio expansion. Also, the sun and moon are held fixed over one revolution of the satellite. The drag model is taken from King-Hele (Ref. 11) where the scale height and the density at perigee are found from a atmosphere model which includes the solar and seasonal variations in density (Ref. 12).

Comparisons between DSTROB and two numerical methods are shown in Figs. 6(a) and 6(b). Case 1 (Fig. 6(a)) is a comparison with a method that integrates numerically the Poincare-Similar elements (PSu). For Case 2 (Fig. 6(b)), the perigee curves for KSFAST and DSTROB are so similar that they appear as one curve. The deviation in perigee altitudes in Case 1 occurs because DSTROB does not account for the long period or second order perturbations in the eccentricity due to the zonal harmonics. This slight deviation in perigee over an extended period of time results in the differences in h_a predicted by the two methods.

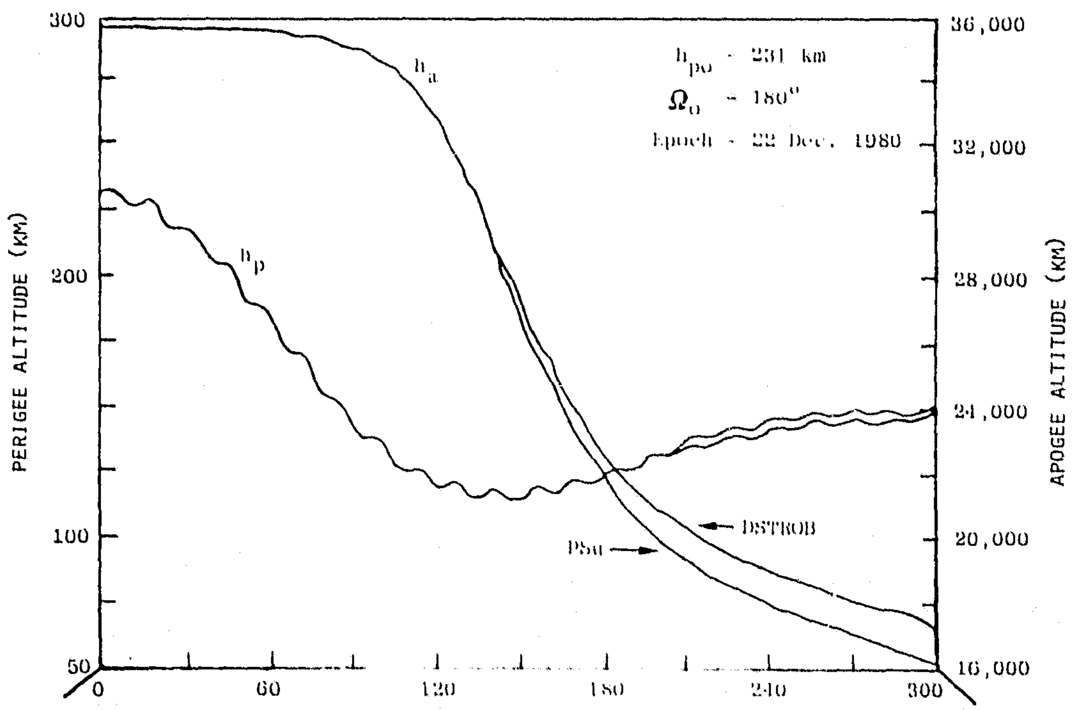

Fig. 6 Verification and Check-out of DSTROB

(a) PSu vs DSTROB

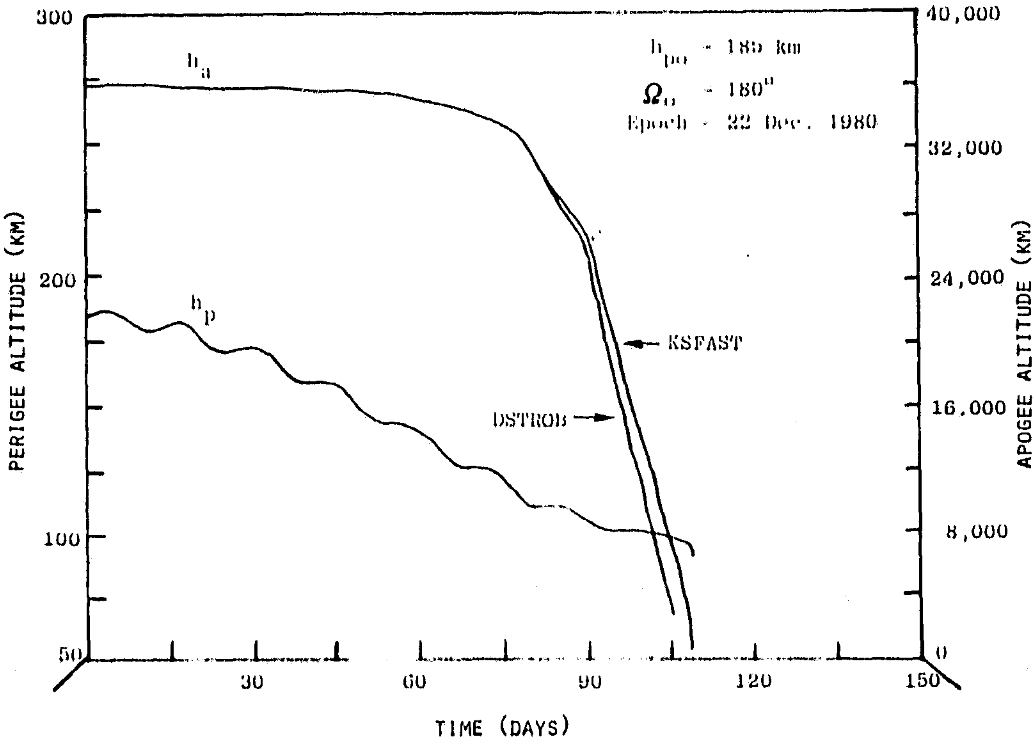

Fig. 6 Verification and Check-out of DSTROB

(b) KSFAST vs DSTROB

Tests such as those shown in Fig. 6 indicate that DSTROB gives good accuracy for orbit predictions of about two years. Computer execution times for DSTROB are shown in Tables 1 and 2. It is seen that DSTROB is much faster than the other two programs. An additional feature of DSTROB is that it can be executed in the demand (interactive) mode on the NASA/JSC UNIVAC 1108 Computer system. This greatly facilitated the data generation and analysis part of the study.

EVOLUTION OF PERIGEE ALTITUDE

This section will illustrate some cases of the long term variation in perigee altitude. As discussed in the previous sections, the gravitational perturbations can have a significant effect on perigee altitude. Thus, perigee can be either raised or lowered, depending on the orbital initial conditions.

Examples of the evolution in perigee altitude over two years are shown in Figs. 7 and 8. These cases were taken from the GOES-E mission that is planned to be launched from Space Transportation System (STS) Flight 8. The upper stage booster will be a SUSS-A in the following transfer orbit:

Apogee Altitude (h_a)	38,034 km
Perigee Altitude (h_p)	296 km
Right Ascension of Ascending Node (Ω)	350^0
Argument of Perigee (ω)	180^0
Launch Date	26 March 1981

For the drag model, it is assumed that the SUSS-A burn-out weight is 316 kg, with an average (tumbling) cross-sectional area of 3.92 square meters. The coefficient of drag C_d is assumed to be 2.2.

Two different launch dates are considered in Figs. 7. In Figs. 8, different values of the initial ascending node are considered. For each of these comparisons, three initial perigee altitudes are investigated: 296 km, 231 km and 185 km. The different perigee altitudes were included since NASA is giving some consideration to launching the satellites into transfer orbits with lower perigee altitudes than currently planned.

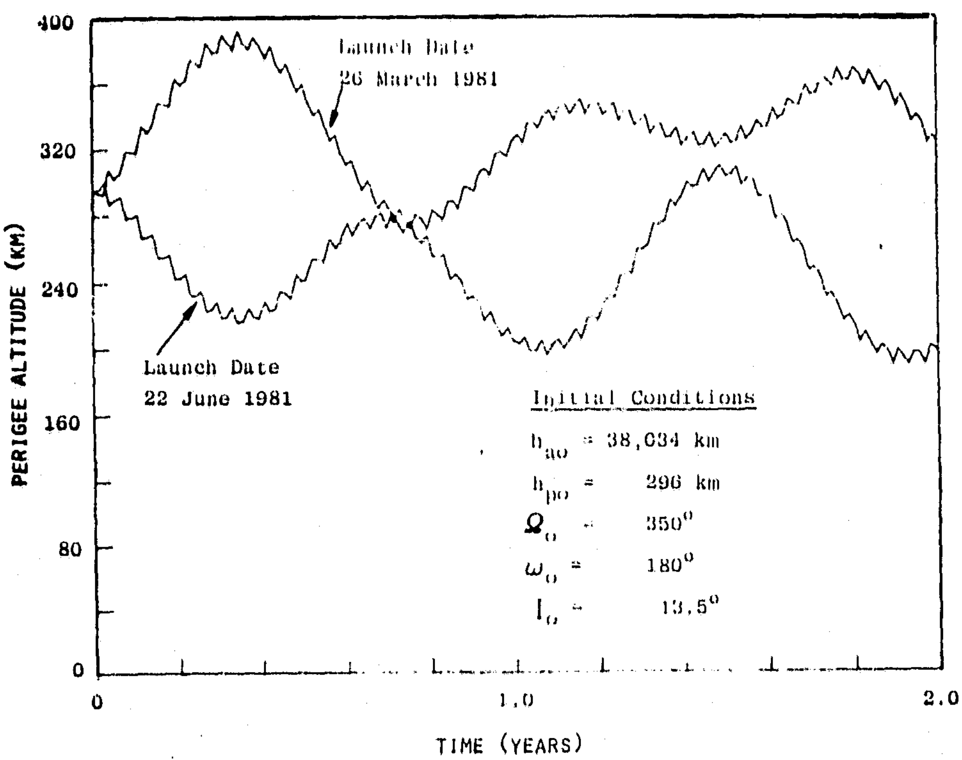

Fig. 7 Evolution of Perigee Altitude
(Effect of Launch Date)

(a) h_{po} = 296 km

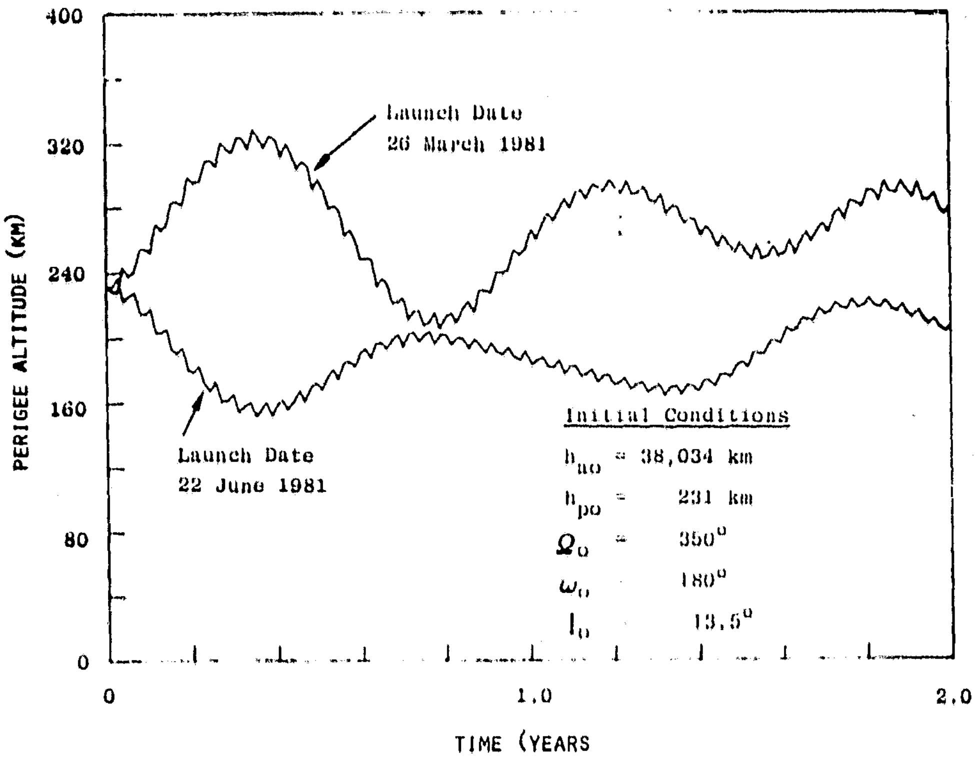

Fig. 7 Evolution of Perigee Altitude
(Effect of Launch Date)
(b) h_{po} = 231 km

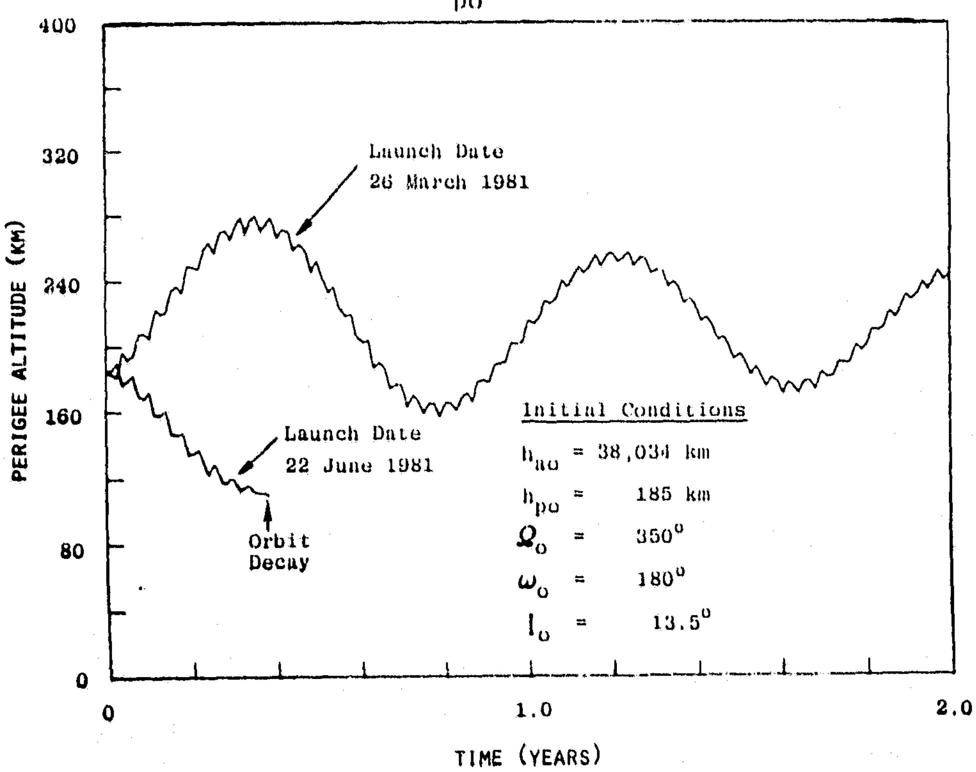

Fig. 7 Evolution of Perigee Altitude
(Effect of Launch Date)
(c) h_{po} = 185 km

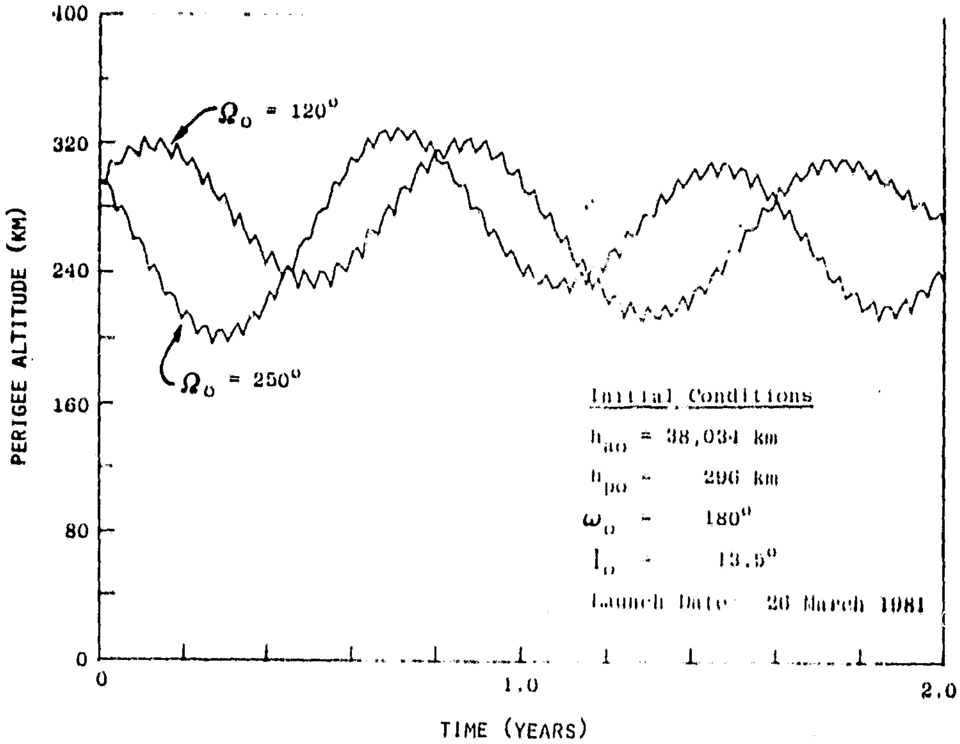

Fig. 8 Evolution of Perigee Altitude
(Effect of Orbit Plane Placement)
(a) h_{po} = 296 km.

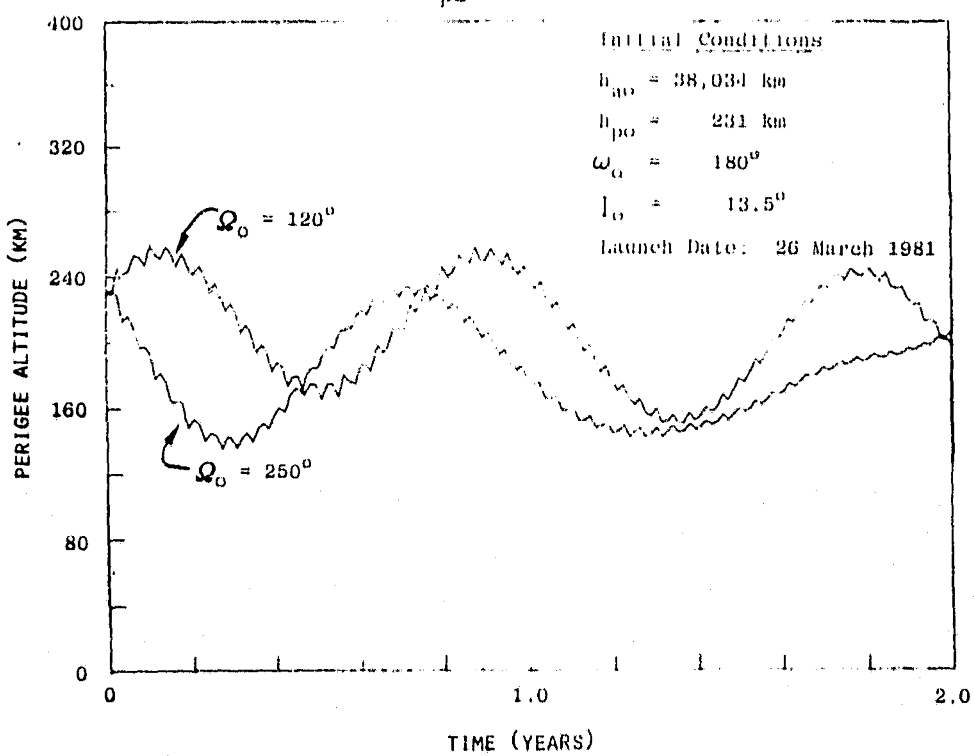

Fig. 8 Evolution of Perigee Altitude
(Effect of Orbit Plane Placement)
(b) h_{po} = 231 km

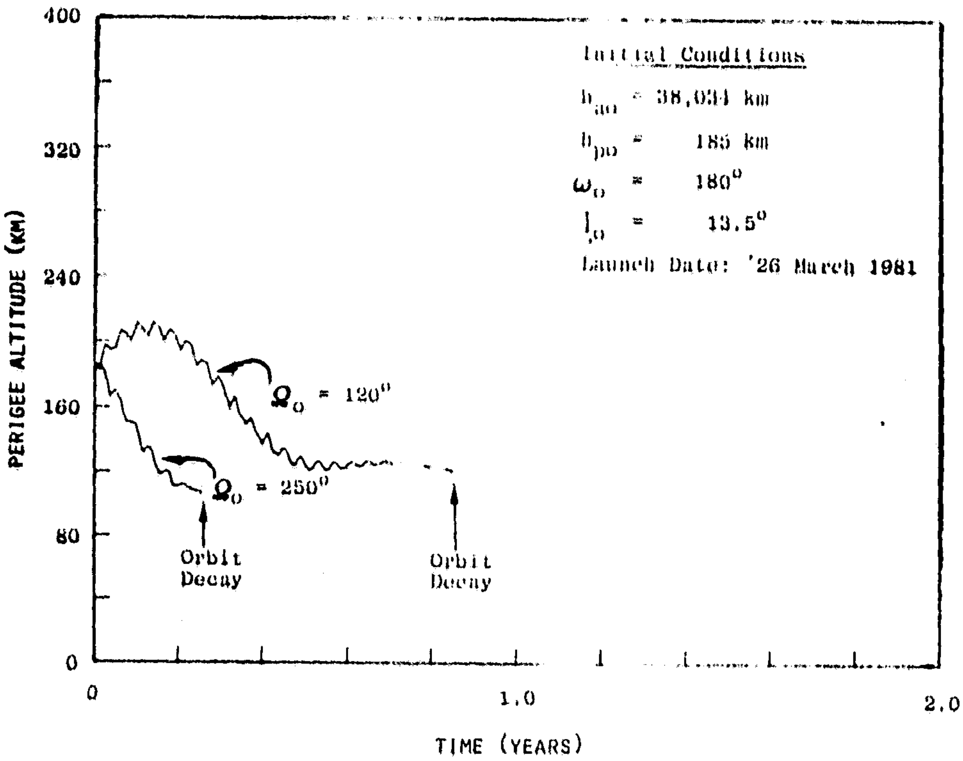

Fig. 8 Evolution of Perigee Altitude
(Effect of Orbit Plane Placement)
(c) h_{po} = 185 km

It is seen that launch date and ascending node have a significant effect on evolution of h_p, and hence orbit lifetime. (This is further illustrated by the parameter scans in a later section.) However, with the nominal initial perigee altitude (h_{po} = 296 km) none of the orbits in this study were found to decay within two years. Only by going to lower altitudes ($h_{po} \leq 231$ km), did the transfer orbits decay for certain initial conditions.

The following are some additional observations on Figs. 7 and 8:

1. As the apogee comes down, the perturbation of the moon is less severe and the small oscillations begin to smooth out. (Figs. 8(b) and 8(c))

2. With h_{po} = 185 km, there are several launch window opportunities such that the transfer orbit decays within a few months.

3. The DSTROB routine did not simulate the satellite's destruction, but only carried the trajectory to the point where reentry would occur within a few revolutions.

4. For the planned launch conditions of GEOS-E/SUSS-A, the transfer orbit will not decay within two years, even if perigee is initialized at 185 km (Figs. 7(a), 7(b) and 7(c)).

EXAMPLES OF ORBIT DECAY FROM AIR FORCE TRACKING DATA

The previous section presented computer simulations that depicted large fluctuations in perigee altitude. The question arises as to whether these simulations agree with the observed decay of satellites in geosynchronous transfer orbit. In this section the computer simulation (the DSTROB program) is compared to satellites that were tracked by the U.S. Air Force.

Trajectory data on all observed satellites are contained in a periodical called CLASSY (Ref. 13), published by the North American Air Defense Command (ADCOM). The satellite orbit data presented in this section were taken from these documents. Each of the four satellites presented here had orbits that were similar in apogee, eccentricity and period to that of a geosynchronous transfer orbit.

Comparisons of DSTROB with Air Force tracking data are shown in Figs. 9(a) - 9(d). The solid line in each figure is the output from DSTROB. The triangles represent data that were taken from precise orbital elements, obtained via private communications with ADCOM. These precise elements were used as inputs to DSTROB. When two triangles appear in a figure, only one was used to obtain the input vector to DSTROB.

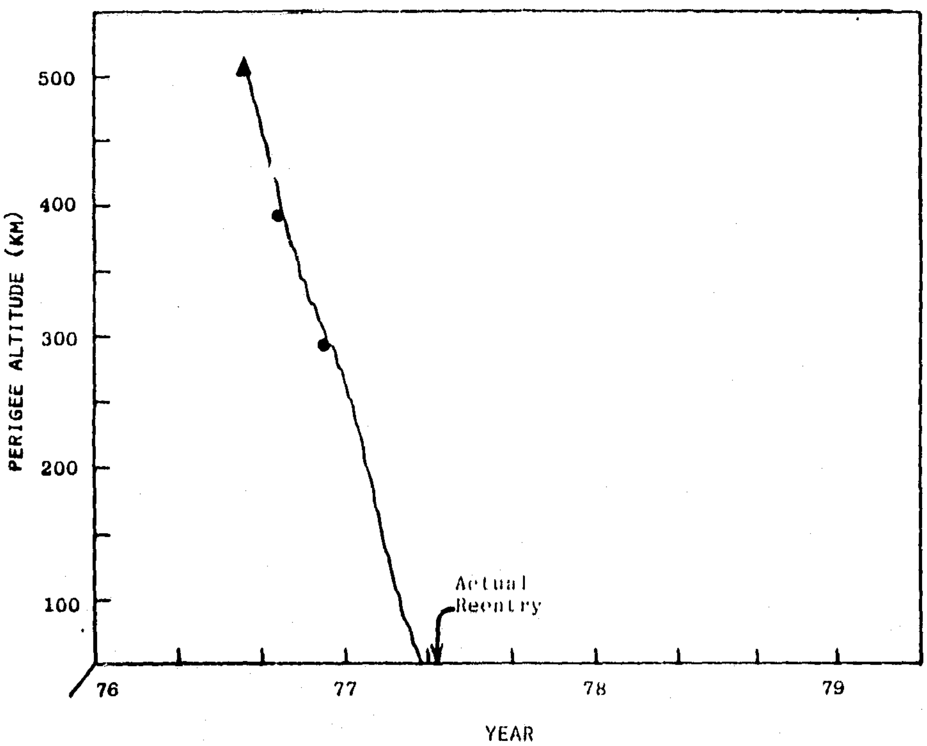

Fig. 9 Comparison of DSTROB with Air Force Tracking Data
(a) Satellite No. 5713, $I_0 = 65.1^0$

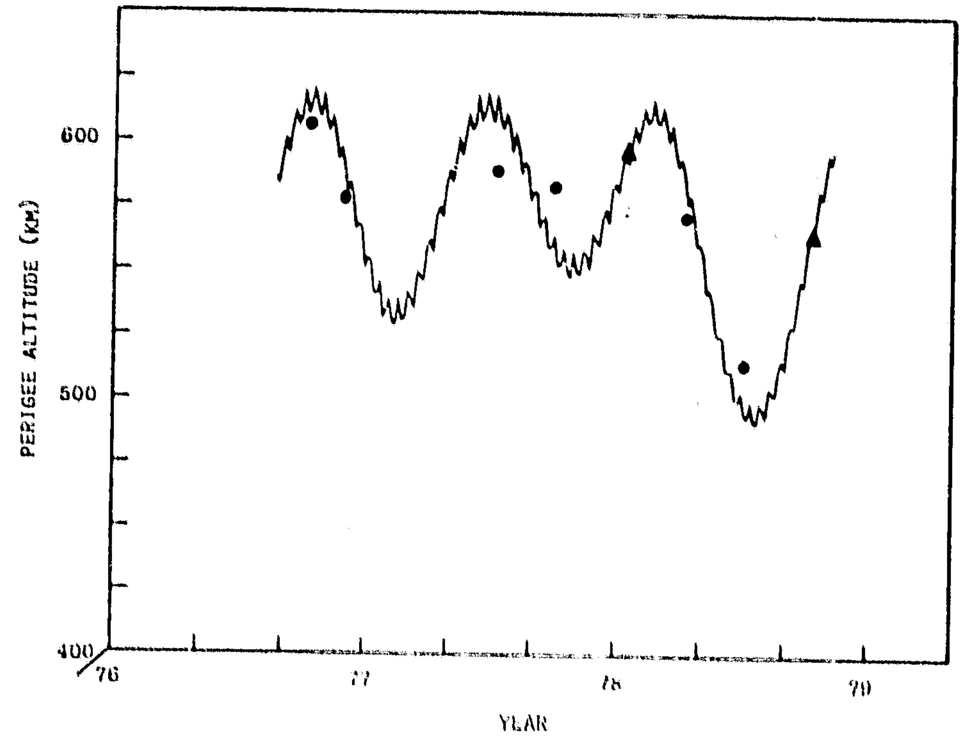

Fig. 9 Comparison of DSTROB With Air Force Tracking Data
(b) Satellite No. 9329, i_0 = 21.8°

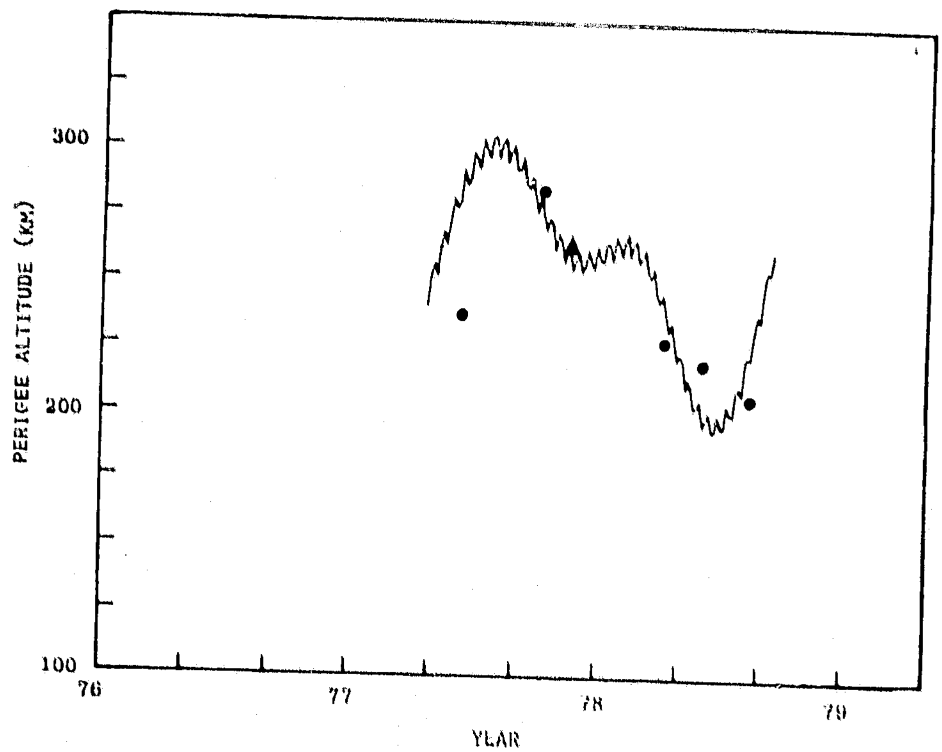

Fig. 9 Comparison of DSTROB With Air Force Tracking Data
(c) Satellite No. 9864, i_0 = 24.3°

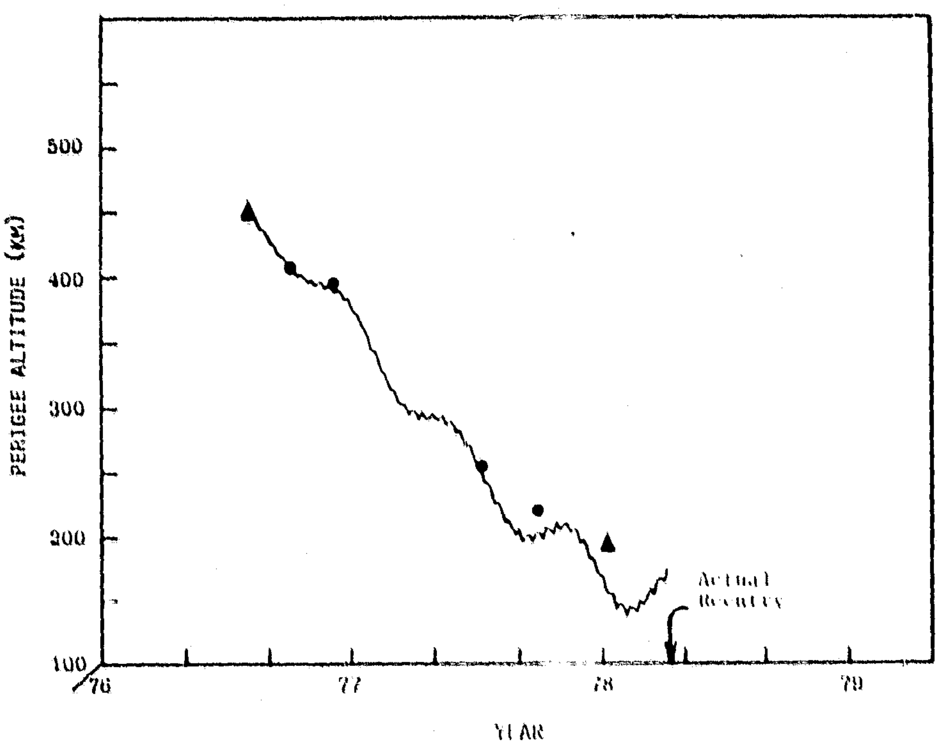

Fig. 9 Comparison of DSTROB With Air Force Tracking Data
(d) Satellite No. 8792, $I_0 = 63.0°$

The dots in Figs. 9(a) - 9(d) represent data taken from the orbital elements published in the CLASSY documents. The epoch for a set of CLASSY elements is known to be within a three month interval of time. We attempted to refine the epoch by starting from the precise elements and using an average value of the mean motion. Therefore, the time coordinates for the dots can have an error of 1-3 months. Drag model data was not available on the four satellites. Therefore, atmospheric drag effects could not be simulated. Even so, the DSTROB program gives quite good agreement with the Air Force data. Satellites No. 5713 and No. 8792 decay rapidly due to gravitational perturbations. Their orbits are unstable because of the large inclinations. Fig. 9(d) is another example where the perigee altitude decays less rapidly (for awhile) when drag becomes significant.

ORBIT LIFETIME PARAMETER SCANS

The remaining part of this study is to determine orbit lifetime as a function of the free parameters of the problem. The parameters of interest are the set of initial orbital elements, defined as follows:

a = semi-major axis,

e = eccentricity

I = inclination

ω = argument of perigee,

Ω = longitude of the ascending node (Fig. 2),

T_e = epoch.

initial values for a and e are specified by the mission objectives. It will also be required that perigee be near the equator and that the inclination be near 28.6°. Therefore, ω and i are not suitable scan parameters.

The remaining parameters of interest are:

Ω_o = initial longitude of the ascending node.

T_d = date of launch.

The time of day of launch can be related to Ω_o. Therefore, T_d should signify the day of year of launch. A physical parameter might be more useful. Thus, the right ascension of the sun α_s (see Fig. 2) was used for the time of year parameter.

In practice, STS geosynchronous missions involve a variety of launch constraints. These constraints depend, in part, on the mission and payload. It was, therefore, outside the scope of this study to include mission constraints on geosynchronous transfer orbit lifetime.

The parameter scans were done by computing 36 one year trajectories of a geosynchronous transfer satellite. It was assumed that the launch occurred during 1980. For each trajectory, the minimum perigee in one year was determined. The angular parameter was incremented by 10 degrees over the 360 degree range.

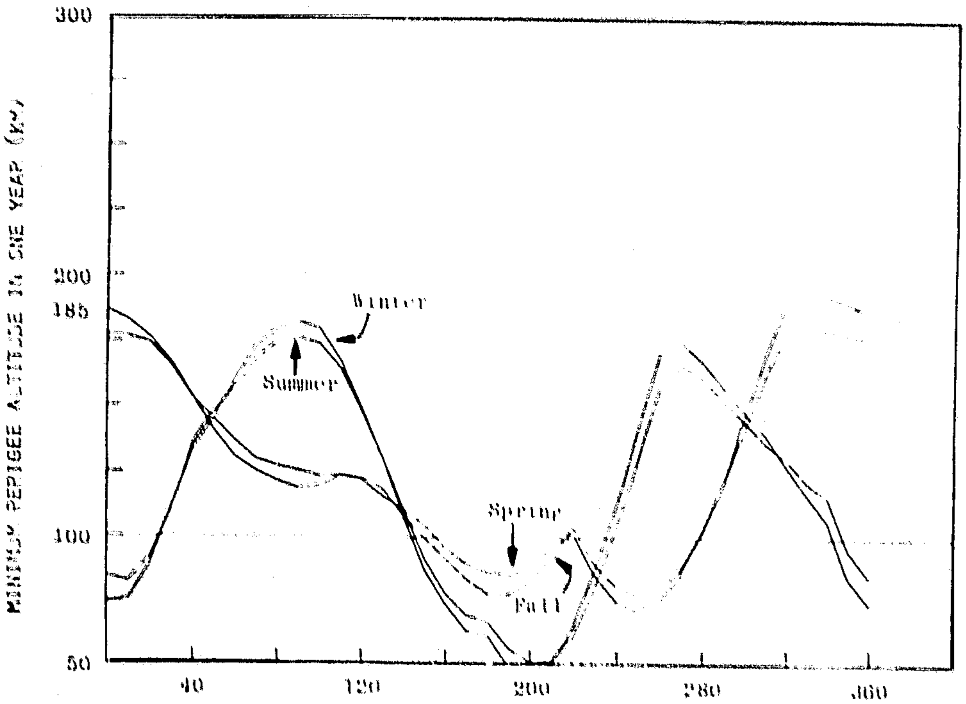

Fig. 10 Orbit Lifetime Parameter Scans
Inertial Placement of Orbital Plane
(a) h_{po} = 185 km, i_o = 28.6°

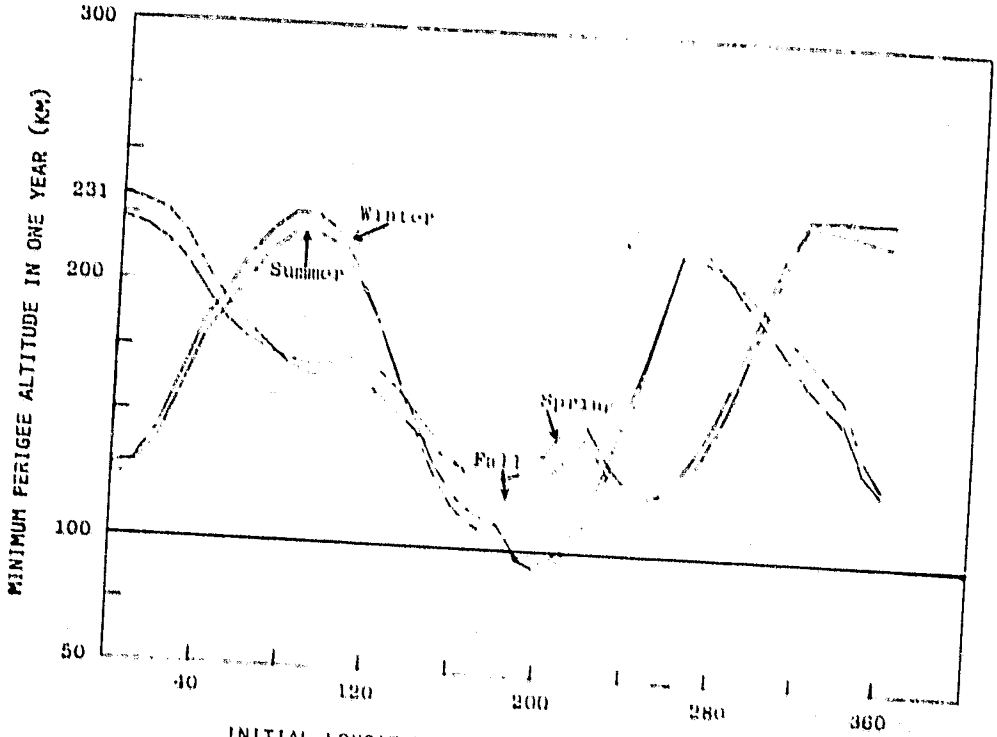

Fig. 10 Orbit Lifetime Parameter Scans
Inertial Placement of Orbital Plane
(b) h_{po} = 231 km, I_o = 28.6°

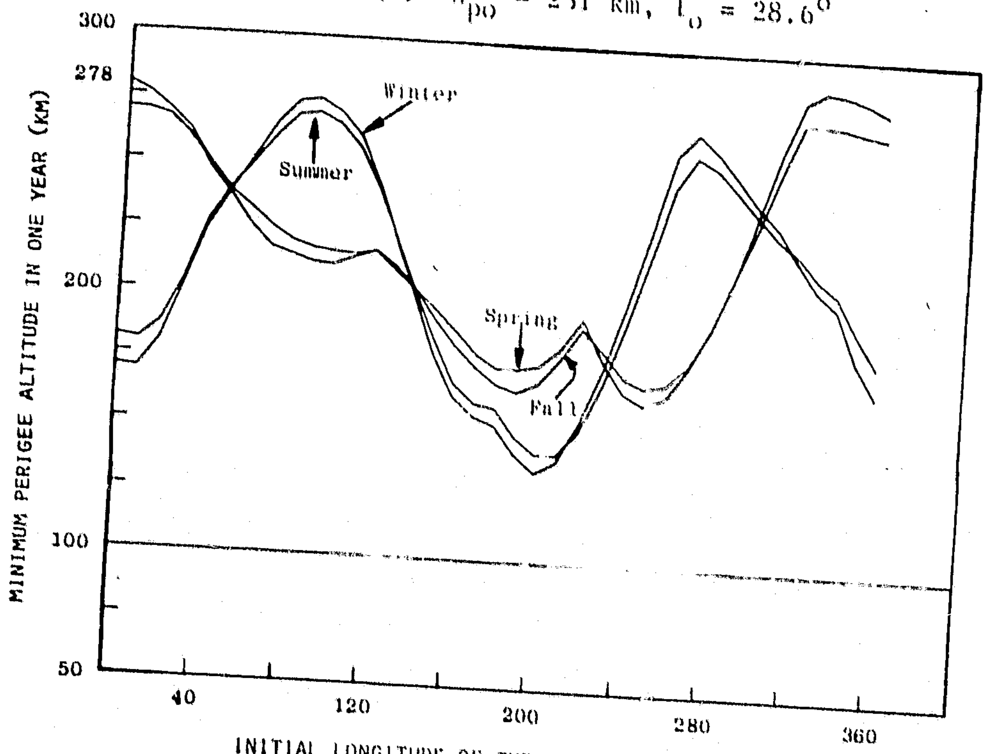

Fig. 10 Orbit Lifetime Parameter Scans
Inertial Placement of Orbital Plane
(c) h_{po} = 278 km, I_o = 28.6°

Scans on the Ascending Node

The parameter of interest in this case was the initial longitude of the ascending node Ω_o, which describes the inertial placement of the orbital plane relative to the planes of the sun, moon and equator. This parameter has an important effect on orbit evolution.

Plots of minimum perigee as a function of Ω_o are shown in Figs. 10(a) - 10(c). Three different initial perigee altitudes were investigated: h_{po} = 185 km, 231 km, 278 km. For each case, trajectories were initialized for summer (June), winter (December), spring (March) and fall (September). The epoch was 1980.

The lowest perigee altitudes always occur near $\Omega_o = 200^o$. Trajectories that are initialized in summer and winter allow lower perigee altitudes.

Scans on the Launch Date

The time of year paramter was taken to be the difference between the sun's right ascension at launch and the initial longitude of the ascending node, i.e., $\alpha_s - \Omega_o$. Both angles are defined in Fig. 2. This parameter was chosen because it describes the position of the sun in its orbit relative to the satellite orbital plane.

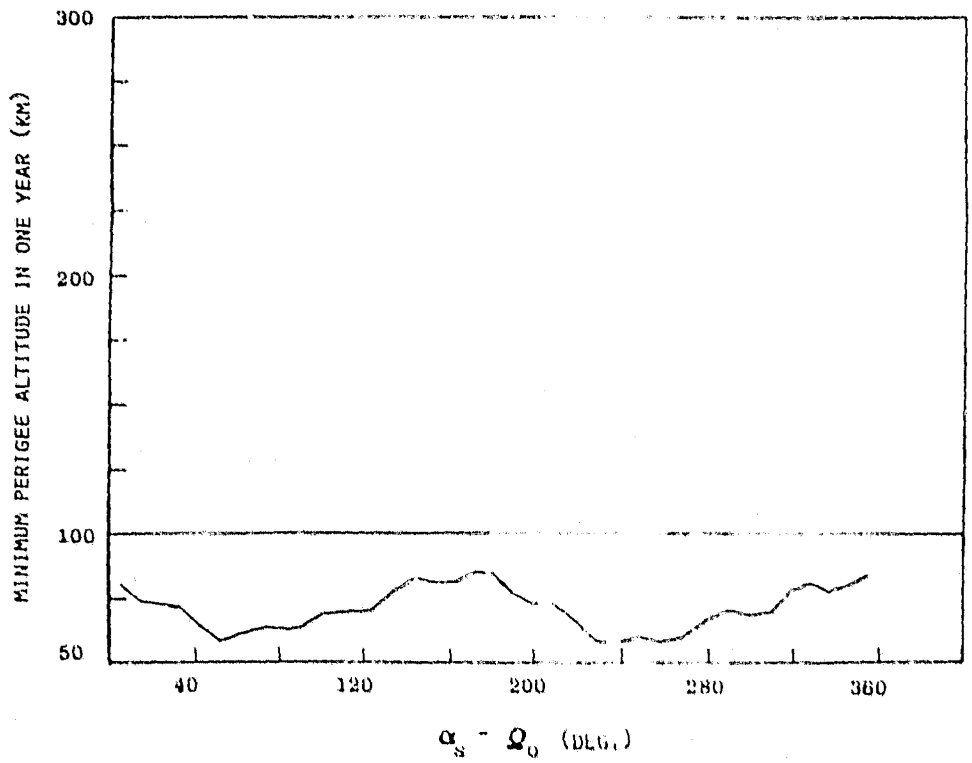

Fig. 11 Orbit Lifetime Parameter Scans
Time of Year of Launch
(a) h_{po} = 185 km, $i_o = 28.6^o$, $\Omega = 180^o$

Parameter scans are shown in Figs. 11(a) and 11(b) for an initial perigee altitude of 185 km, for the two cases $\Omega_o = 180^o$ and $\Omega_o = 0$. As would be expected from the results of Fig. 10, the case $\Omega_o = 180^o$ gives a consistently low minimum perigee, regardless of the time of year.

For other values of Ω_o, the perigee is lowest when the sun begins 90^o (or 270^o) ahead of the ascending node.

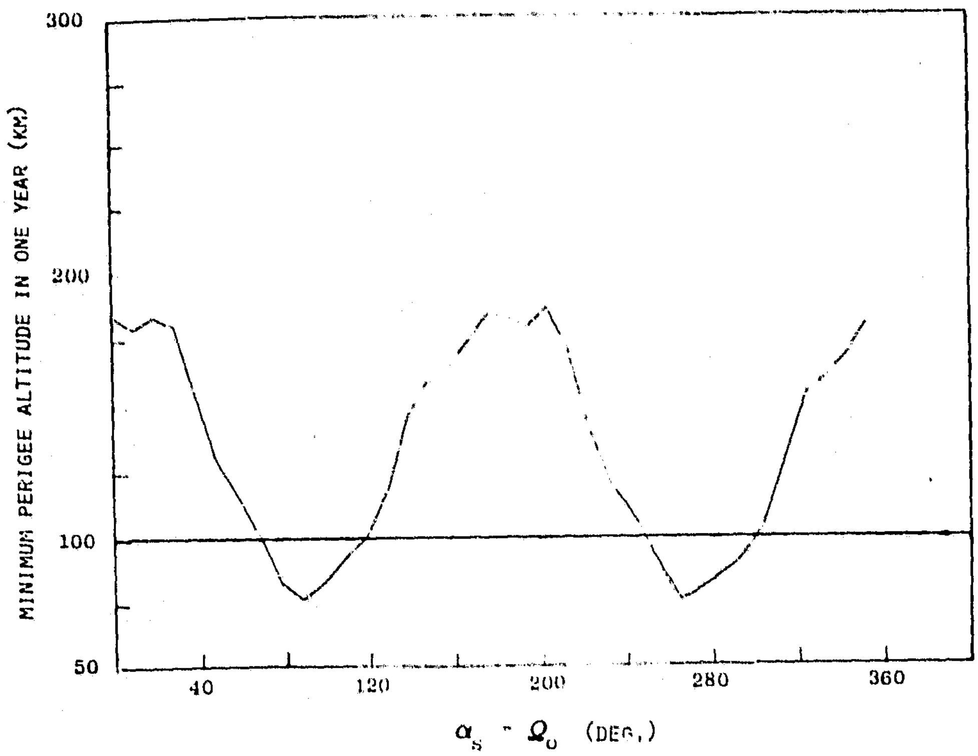

Fig. 11 Orbit Lifetime Parameter Scans
Time of Year of Launch
(b) $h_{po} = 185$ km, $I_o = 28.6^o$, $\Omega_o = 0$

Discussion of Results

1. In Figs. 10 and 11, the threshold perigee altitude is drawn as a solid line at 100 km. It can be assumed that when the minimum perigee altitude falls below this line, the orbit will decay within one year.

2. The parameter scans shown in this section are for $I_o = 28.6^o$. We found that the results were similar for inclinations less than 28^o. However, these figures should be used with caution if I_o is much different from 28^o. We intend in the future to publish a catalog of parameter scans for various epochs and inclinations.

3. If h_{po} = 185 km, there will be launch opportunities throughout the year such that the transfer orbit will decay within one year (Figs. 10(a) and 11 (a)). For h_{po} = 231 km, good chances for orbit decay occur only for summer and winter launches (Fig. 10(b)).

4. If h_{po} = 278 km (150 N.M.) there is little possibility of rapid decay of the transfer orbit.

ACKNOWLEDGMENT

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