

PREPRINT

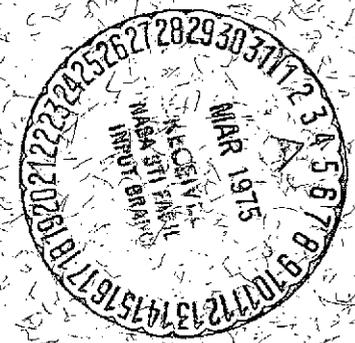
NASA-TM-X-70823

# ORBITAL FLUX INTEGRATIONS: PARAMETER VALUES FOR EFFECTIVE COMPUTER TIME REDUCTIONS

(NASA-TM-X-70823)	ORBITAL FLUX	N75-17982
INTEGRATIONS:	PARAMETER VALUES FOR	
EFFECTIVE COMPUTER TIME REDUCTIONS	(NASA)	
69 p HC \$4.25	CSCL 09B	Unclas
		10786
		G3/61

## E. G. STASSINOPOULOS

NOVEMBER 1974



————— **GODDARD SPACE FLIGHT CENTER** —————  
**GREENBELT, MARYLAND**

For information concerning availability  
of this document contact:

Technical Information Division, Code 250  
Goddard Space Flight Center  
Greenbelt, Maryland 20771

(Telephone 301-982-4488)

"This paper presents the views of the author(s), and does not necessarily  
reflect the views of the Goddard Space Flight Center, or NASA."

ORBITAL FLUX INTEGRATIONS:

Parameter Values for Effective  
Computer Time Reduction

E. G. Stassinopoulos

NASA-Goddard Space Flight Center  
Sciences Directorate  
National Space Science Data Center

November 1974

Goddard Space Flight Center  
Greenbelt, Maryland 20771

## Foreword

In order to improve computer utilization and reduce the cost of orbital flux integrations, the effects of integration parameters "duration" (T) and "stepsize" ( $\Delta t$ ) on integration results were investigated. Over given ranges of T and  $\Delta t$ , and within specified acceptable accuracy restraints, optimal values of these parameters were established for circular subsynchronous trajectories, in terms of the variables altitude (h) and inclination(i).

It is shown that above a certain statistically important value, duration is independent of both h and i; that is, the integration results are virtually unaffected by increases in T at any h or i, for any given  $\Delta t$ .

It is also shown that stepsize has a "relative" altitude dependence; that is, at any given altitude, regardless of duration or inclination, the integration results remain nearly constant for a substantial range of  $\Delta t$ , but they will vary appreciably whenever  $\Delta t$  is increased beyond some specific value, characteristic for that altitude level. Stepsize, however, is not a function of inclination, because the fluxes obtained with different  $\Delta t$ 's at each tested inclination did not vary significantly, regardless of altitude or duration.

Finally, the substantial savings in computer time, realized by minimizing T and maximizing  $\Delta t$  over their respective investigated ranges and for the specified accuracy restraints, are presented and the possibilities

are discussed to achieve still greater savings by further relaxing accuracy restrictions while not exceeding the minimum model-associated uncertainty factors of the environments.

Contents

	<u>Page</u>
Introduction. . . . .	1
Apparent Orbit Precession . . . . .	4
Duration and Step size . . . . .	6
Computer Time . . . . .	12
Summary . . . . .	17
Acknowledgements. . . . .	18
References. . . . .	19

Appendix

Attachments: Tables and Figures

**PRECEDING PAGE BLANK NOT FILMED**

## List of Tables

### Tables

- 1 Orbit Parameters and Integration Variables
- 2 Number of Samplings in Trajectories
- 3 Stepsizes and Durations per Altitude
- 4 Duration Dependence of Simple Deviations

## List of Figures

### Figures

- 1 Apparent Orbit Precession as a Function of Altitude
- 2 World Map of Flux Iso-intensity Contours:  $h=300$  km, electrons ( $E > .5\text{Mev}$ )
- 3 World Map of Flux Iso-intensity Contours:  $h=1000$  km, electrons ( $E > .5\text{Mev}$ )
- 4 Electrons:  $|D|$ % vs.  $h$  (over  $\Delta t$ 's per duration)
- 5 Protons:  $|D|$ % vs.  $h$  (over  $\Delta t$ 's per duration)
- 6 Electrons:  $|D^*|$ % vs.  $h$  (over  $\Delta t$ 's and T's)
- 7 Protons:  $|D^*|$ % vs.  $h$  (over  $\Delta t$ 's and T's)
- 8 Comparison of  $D^*$  to minimum model-uncertainty factor
- 9 Comparison of  $D$  to minimum model-uncertainty factor for polar and equatorial trajectories
- 10 Optimal  $\Delta t$ 's vs. Altitude
- 11 Dependence of Orbit Integrated Fluxes on Duration,  $h=2200$  km
- 12 Dependence of Orbit Integrated Fluxes on Duration,  $h=4000$  km
- 13 Dependence of Orbit Integrated Fluxes on Duration,  $h=16000$  km

14	Dependence of Orbit Integrated Fluxes on Duration, $h=30000$ km
15	Electrons: $\left D_T^*\right $ vs. comparison ranges
16	Protons : $\left D_T^*\right $ vs. comparison ranges
17-20	Electrons: $\left D_T^*\right $ vs. $i$ (over T's per minimum $\Delta t$ )
21-23	Protons : $\left D_T^*\right $ vs. $i$ (over T's per minimum $\Delta t$ )
24	Ratios of Transverse: Running Times vs. Trajectory Positions
25	Inclination-Averaged Running Times
26	Mean Running Times

## Definitions:

### Introduction

$T$  = duration, length of flight time interval considered in an orbital flux integration (hours)

$\Delta t$  = stepsize, time increment of integration (minutes)

$h$  = orbit altitude above sea level (km)

$i$  = orbit inclination (prograde) (degrees)

---

### Precession

$P$  = precession of orbit plane (degrees)

$\tau$  = orbit period (hours)

$k$  = proportionality constant = rotational speed of earth (degrees/hour)

$c$  = conversion factor (seconds/hour)

$r_e$  = equatorial radius of earth (km)

$\mu$  = gravitational constant ( $\text{km}^3/\text{sec}^2$ )

---

### Duration and Stepsize

$D$  = simple flux deviations over  $\Delta t$ ; based on a comparison of results obtained with  $\Delta t_{\max}$  and  $\Delta t_{\min}$  for a constant  $h, i$ , and  $T$ .

$D^*$  = transverse flux deviations over  $\Delta t$  and  $T$ ; based on a comparison of results obtained with the highest density ( $T_{\max}, \Delta t_{\min}$ ) and the lowest density ( $T_{\min}, \Delta t_{\max}$ ) of points available for a constant  $h$  and  $i$ .

$D_T^*$  = correlated flux deviations over  $T$ ; based on a comparison of results obtained with the highest density ( $T_{\max}, \Delta t_{\min}$ ) and lower densities ( $T_{\text{other}}, \Delta t_{\min}$ ) of points available for a constant  $h, i$ , and  $\Delta t$ .

---

$N(T, \Delta t)$  = number of actually evaluated flight path positions (trajectory points)

$\bar{E}_I(h;T, \Delta t)$  = actual computer running time averaged over inclination: combined CPU and I/O values of the execution step.

$R_p$  = ratio of  $N(T, \Delta t)$ 's of transverse comparisons

$\bar{R}_{t_I}$  = ratio of  $\bar{E}_I(T, \Delta t)$ 's of transverse comparisons

$d$  = conversion factor (min/hour)

## INTRODUCTION

Near-Earth space missions are routinely exposed to hazards deriving from various types of space radiation, as for example: galactic cosmic rays, energetic solar protons, Van Allen belt particles, etc. It is often important for effective mission planning purposes to have available advance information as to the severity of the expected radiation hazard, especially in order to calculate shielding requirements for man and equipment (weight problem), and in order to establish lifetimes and degradation of experiments, satellite components, power supply, etc.

Predictions of vehicle encountered trapped particle fluxes are usually obtained from Orbital Flux Integration (o.f.i.) processes, frequently performed over arbitrary lengths of flight-time intervals  $T$  and with arbitrary time increments  $\Delta t$ . However, both quantities affect not only precious computer time but also determine the precision of the calculated data. Thus, very short  $T$ 's and/or very large  $\Delta t$ 's may introduce substantial errors into the flux predictions while long  $T$ 's and/or very small  $\Delta t$ 's can be excessive and wasteful on computer time. Conceivably, an optimization of the variables " $T$ " and " $\Delta t$ " in terms of orbit altitude and inclinations may produce considerable savings in computer time while still insuring the accuracy of the results.

This report describes the procedure and presents the conclusions of an effort to approximate, within a given range of  $T$  and  $\Delta t$ , optimal values of these parameters in regards to computer time, with the stipulation that the results obtained for a fixed inclination and altitude

with the smallest number of points may not vary by more than 20% from the results obtained at the same  $i$  and  $h$  with the largest number of points. That is, within the range of interest, only those combinations of  $T$  and  $\Delta t$  values will be considered optimal, that minimize the number of points for which the error in the orbit integrated fluxes does not exceed 20%. The error limit was determined by taking one fifth of the minimum model-associated uncertainty factor of the environments, which is generally a factor of two or greater for both species of particles.

In the evaluation of the two parameters  $T$  and  $\Delta t$ , only circular trajectories were considered. Elliptical flight paths require special treatment and will be discussed in a separate report at a later date.

Orbital flux integrations were performed with the "UNIFLUX" system (Stassinopoulos and Gregory, 1974), described briefly in the Appendix, at six altitude levels and for four inclinations each, with three different stepsizes in every case, and for durations extending to 96 hours for the highest altitudes. Table 1 lists the values of some relevant parameters and variables. Table 2 indicates the number of samplings contained in trajectories with duration  $T$  and stepsize  $\Delta t$  for selected values of these variables.

Although the parameter evaluation presented in this analysis is based exclusively on integral proton and electron fluxes of energies  $E > 5. \text{Mev}$  and  $E > .5 \text{Mev}$  respectively, the calculations and the comparisons were actually performed for several energies. It was found that the comparison results were about the same and that the conclusions were valid for all investigated energies of both particle species. That is, no special considerations are necessary for different energy thresholds.

It should be noted that no B-L calculations are performed in the UNIFLUX system.

The environment models used in the flux calculations are the AE5 for inner zone electrons (Teague and Vette, 1972), the AE4 for outer zone electrons (Singley and Vette, 1972) and the AP6 for high energy protons (Lavine and Vette, 1969).

Data, discussions, and conclusions apply only to space missions in circular orbits and of long durations ( >15 revolutions); they are not valid for short sorties, parking orbits, transfer ellipses, or eccentric trajectories. Neither are they valid for L-band\* accumulations\*\*. L-band accumulations have not been considered in this work because of the very small interest in them and because of their limited usefulness.

---

\*L is McIlwain's (1961) magnetic shell parameter, which is used to label field lines, to order trapped particles, and to construct environment models; it is defined as the geocentric distance to the point where a line of force intersects the geomagnetic equator.

\*\*L-band accumulations are the summations of time related fluxes obtained, for a given L-range, in discrete L intervals or bands.

## APPARENT ORBIT PRECESSION

In the context of this paper, "longitudinal orbit precession" is the apparent westward drift of the orbit plane in reference to the rotating geoid. The precession  $P$  in degrees is proportional to the orbit period  $\tau$  in hours.

$$P = k\tau \quad (\text{degrees}) \quad (1)$$

where the proportionality factor  $k$  is the rotational speed of the Earth in degrees per hour. Since  $\tau$  is a function of trajectory altitude  $h$ , equation (1) can be written equivalently as

$$P = \frac{2k\pi}{c} \sqrt{\frac{(h+r_e)^3}{\mu}} \quad (2)$$

where the conversion factor  $c = 3600$  sec/hr, the equatorial Earth radius  $r_e = 6378.165$  km, and the constant  $\mu = 3.986032 \times 10^5$  km<sup>3</sup>/sec<sup>2</sup>. Values of  $P$  versus  $h$  are given in Figure 1.

With the exception of very short-term missions (flight duration  $T$  less than half a day), precession should have no effect on mission integrated fluxes and, as will be shown in a subsequent section, a flight duration of one day ( $T = 24$  hours) is fully sufficient to insure good integration results for most subsynchronous altitudes up to about 32,000 kilometers. Synchronous trajectories will be discussed in a special paper.

The old belief that at low altitudes precession may cause the trajectory to miss (skip, not sample) important parts of the trapped particle radiation belts, particularly the highest intensity regions of the South Atlantic Anomaly, shown in Figures 2 and 3 as the "10<sup>5</sup>" contours

for electrons with energies  $E > .5$  MeV at the 300 and 1000 km altitude levels, is unfounded because in the critical low altitude domain (300 - 1000 km) these intensity areas increase more rapidly in size when height is raised than does precession. This holds true for all energies. Incidentally, protons follow the same pattern.

At higher altitudes, where the multipole nature of the non-centered geomagnetic field and its anomalies rapidly disappear and the field approaches dipolar symmetry, precession is of no consequence because the particle gradients with L are much smaller.

## DURATION AND STEPSIZE

The data used in this analysis were obtained from a total of 168 orbital flux integration runs.

The smallest unit of duration investigated was one day, the largest four days. Shorter time intervals were of no concern to this study. The possibility, however, that T's of less than 24 hours could produce acceptable results for some particular orbits, cannot be ruled out.

As indicated in Table 3, several durations were used at all but the very low altitude levels, for all inclinations. In every case three stepsizes were tried.

Figures 4 and 5 depict, for electrons and protons respectively, absolute percentage-flux-deviations ( $|D|$ %) versus altitude for the four selected inclinations and the indicated durations, where the fluxes obtained with the smallest stepsize are compared to those of the largest. The stepsizes and durations are given in Table 3. According to the stipulated accuracy requirement, the apparent improvements in some of the results for the longer durations, are completely insignificant and meaningless; ranging from a small fraction of one percent to a maximum of 5%, these improvements lie totally in the "noise" area of the flux data, which it will be remembered, are no better than a factor of 2, to begin with. A comprehensive comparison of minimum model-uncertainty-factors to duration and stepsize deviations appears in a subsequent section.

Interestingly, the largest deviations of the T = 24 hour runs for the electrons and protons at h = 400 and h = 1000 km, due

entirely to the stepsize variation, shrink with increasing altitude and with greater stepsize variations. One might have expected the opposite to happen, since duration remained constant. A possible reason for the larger D's at the low altitudes, for both species of particles, may be the high intensity gradients of the inner trapping boundaries (more relevant comments on page 8).

The 24-hour curves further indicate that above 4000 km and up to almost synchronous altitudes, the deviations lie well within the acceptable error limit. Therefore, it is safe to use this smallest of the tested durations in the entire investigated h domain. As for the electrons, the data presented amply supports this proposal. Since energetic protons do not extend to synchronous altitudes, longer durations are of no concern. In regards to the protons, some related questions are discussed in a following paragraph.

Transverse flux deviations  $D^*$  obtained for a given orbit (fixed altitude and inclination) from a comparison of fluxes calculated with the smallest number of points,  $F(T=\min, \Delta t=\max)$ , to fluxes calculated with the largest number of points,  $F(T=\max, \Delta t=\min)$ , per altitude level per inclination, are shown in Figures 6 and 7, for electrons and protons respectively. For this comparison, data obtained with the durations and stepsizes indicated in Table 3 by circles around the  $\Delta t$  values were selected. The maximum cross-correlated deviation for electrons occurs at  $h = 30,000$  km when the  $F_e(T=96, \Delta t=3)$  is compared to the  $F_e(T=24, \Delta t=9)$  for all inclinations ( $0^\circ = 8.6\%$ ,  $30^\circ = 13.6\%$ ,  $60^\circ = 12.8\%$ ,  $90^\circ = 14.8\%$ ). The worst case for protons occurs at  $h = 16,000$  km but with additional occurrences at  $h = 400$  km for the case  $i = 0^\circ$ , and  $h = 4000$  km for all inclinations.

Particularly interesting is the equatorial proton curve at 16,000 km, jumping to the highest deviation (8.4%) encountered for these particles in the tests. When the respective data is checked in detail, it becomes apparent that this unusual rise in deviation: (1) is not related to a change in  $\Delta t$  (the individual results are totally insensitive to stepsize variation), and (2) appears in all three sets of runs (one set for each  $\Delta t$ ) where stepsize was kept constant but duration was varied from 24 to 96 hours. Evidently, this rise is not experienced by the inclined orbits. The reason for this phenomenon may be that the equatorial trajectory is skimming the very edge of the 5 MeV proton trapping region, which extends slightly past 16,000 km, and as duration is increased, a better statistical average is obtained. If altitude is further raised, no more 5 MeV protons will be encountered. This very special case is the only exception to the rule about duration. It will not be taken into account.

In this regard, it has been argued that at or near the proton trapping boundary larger durations and/or smaller stepsizes would improve o.f.i. results. This may be true but it is of marginal importance because at the trapping boundary the particle intensities are insignificantly small and, in most practical cases, do not contribute at all to the four significant figures with which the fluxes of a standard o.f.i. calculation are given. Furthermore, the location of this boundary, on or off the geomagnetic equator, is a function of the particle energy, among other things; on the equator it lies at about  $L=3.6$  Earth radii for the  $E > 5$  MeV protons and at about  $L=2.5$  Earth radii for  $E > 100$  MeV protons.

To take these details into account and to design programs around them, capable of handling all kinds of circular and elliptical trajectories, would be inefficient and expensive in comparison to the effected improvement in the results; the same can be said for the equivalently wasteful approach of varying duration and stepsize in such a way as to achieve a longer and denser environment sampling.

In either case, a very small fractional gain in accuracy is really trivial in view of the size of the minimum model-associated uncertainty factor of the environments.

The same argument applies also to the inner (low altitude) boundary, only that there the intensity gradient is much steeper and the energy dependent boundary locations lie much closer together. These enhanced conditions may affect the o.f.i. results of very low altitude (400 km) circular missions (elliptical trajectories with very low perigee fall into the category discussed in the previous paragraph).

Anyhow, the altitude regime below 400 km is of small interest and importance to this study because, with very few exceptions, it is not frequented by circular missions due to the rapidly increasing atmospheric drag effect experienced by spacecraft at these heights.

At this time, it is important to remember that except the one special case for protons and the 30,000 km altitude for electrons, all these so-called "maximum deviations" are less than 5% while the uncertainties inherent in the environment models used in the calculations are at least a factor of two. In this perspective, the deviations obtained in the tests are truly insignificant, even the exceptional ones. See Figure 8 for a proportional presentation of maximum deviations

versus model-uncertainty factor. This would of course allow the use of still larger increments or shorter intervals, further decreasing the number of points processed and further reducing computer time. However, it is suggested not to increase stepsizes or reduce duration beyond values which would produce deviations of 30% or greater.

The trends in the curves on Figures 6 and 7 between 4000 and 16000 km imply some altitude dependence of the  $0^\circ$ ,  $60^\circ$ , and  $90^\circ$  inclinations for the electrons, a very strong altitude dependence of the  $i = 0^\circ$  curve for the protons (on the same curve also observed at 400 km; reason explained in a preceding paragraph), and a rather weak dependence of the  $i = 60^\circ$  proton curve. Above 16000 km (electrons only), curves of all inclinations display a sharp rise with altitude.

In regards to an old argument, that polar orbits supposedly need smaller stepsizes than equatorial orbits in order to yield equally good results, it seems to have been resolved by the present study; no evidence was found in the data to support that contention. On the contrary, of the fourteen polar cases tested, each with three different stepsizes for a total of 42 runs, none indicated any abnormal, excessive, or plainly significant deviation in the integrated fluxes, not even when the  $\Delta t$  was tripled or quintupled. Over all, no one particular inclination tested did stand out in any way by producing consistently either better or worse results, for any stepsize. Figure 9 shows the stepsize deviation of polar and equatorial orbits in comparison to the minimum model-uncertainty-factor of 2.

When the data were ordered so as to determine the dependence of  $|D|$  % on T, Figures 11 - 14, it became apparent that longer durations

do not necessarily produce better results. Specifically, in all cases listed in Table 4 the simple deviations did not improve when T was increased.

Another approach to evaluate the T dependence of the o.f.i. results is by defining the quantity  $D_T^*$  (correlated deviation) for constant inclination and altitude:

$$D_T^* = \frac{F(T, \Delta t) - F(T_{\text{other}}, \Delta t)}{F(T, \Delta t)} \quad (3)$$

This permits a data comparison based on duration alone. It is assumed that in the limit as T approaches infinity and  $\Delta t$  approaches zero, the  $F(T, \Delta t)$  would have the greatest possible accuracy and that  $D_T^*$  would become smaller as values of  $T_{\text{other}}$  would approach T. The available closest approximation to this formula was used in the evaluation that follows:

$$D_T^* = \frac{F(T_{\text{max}}, \Delta t_{\text{min}}) - F(T_{\text{other}}, \Delta t_{\text{min}})}{F(T_{\text{max}}, \Delta t_{\text{min}})} \quad (4)$$

The results are discussed in the subsequent paragraphs. Again it should be remembered when talking about differences between  $D_T^*$ 's, that most deviations are really insignificantly small and that none exceed the specified error limit.

Figure 15 shows the absolute "correlated deviations" for electrons with energies  $E > .5$  Mev and Figure 16 for protons with  $E > 5$ . Mev, plotted versus comparison range, where range number 1 always pertains to a comparison of  $T_{\text{max}}$  to  $T_{\text{min}}$ . In this comparison, the latter quantity has always the same value of 24 hours at all altitude levels, all inclinations, in contrast to  $T_{\text{max}}$ , which has different values at different

altitude levels; however, at any given height,  $T_{\max}$  is the same for all inclinations, as indicated in Table 3. Range number 2, if available, is a comparison of the maximum-duration result to the result obtained from the  $T_{\min} + 24$  (hours) run; similarly, range number 3 compares the  $T_{\max}$  to the  $T_{\min} + 48$  (hours) results.

On both figures, the deviations of the  $i=90^\circ$  results at 4000 km increased, contrary to expectations, when  $T_{\text{other}}$  was extended from 24 to 48 hours, that is, going from range 1 to range 2. At the same altitude, the results for  $i=60^\circ$  remained almost constant while for  $i=30^\circ$  and  $i=0^\circ$  the  $D_T^*$ 's improved markedly.

A more complex situation exists at the 16000 km altitude level, where three ranges are available for comparison. The electrons at this height showed substantial improvement for the two high inclinations ( $i=60^\circ, 90^\circ$ ), especially going from range 2 to range 3, but indicate no significant improvement for the two low inclinations ( $i=0^\circ, 30^\circ$ ) at these ranges. The protons display a perplexing reversal at  $i=60^\circ$  and  $i=90^\circ$ : whereas almost no improvement is evident when comparing range #1 to range #3, the deviations in range #2 drop by about two orders of magnitude. No explanation can be given for this inversion. It appears as if a cyclic phase-effect were associated with duration, having a half-cycle of about 48 hours.

At 30000 km (electrons only) no range #2 data is available. In the comparison of range #1 to range #3, all inclinations show some small improvements.

The  $D_T^*$ 's of a fixed range are also plotted as functions of inclination in Figures 17-20 for the electrons and in Figures 21-23 for the protons,

each Figure corresponding to one of the investigated altitude levels.

Some general observations on these plots:

- a) the dependence of  $D_T^*$  on inclination is a function of particle species, range number, and altitude;
- b) deviations of a higher range will usually have a smaller value than those of a lower range; and
- c) polar orbits have as a rule higher deviations than equatorial orbits.

There are of course exceptions to items (b) and (c). For (b) these imply that longer durations do not necessarily always produce better results.

Since in no instance did the deviations exceed the specified error limit, even for the transverse comparisons presented in Figures 6 and 7, it is suggested that for the purpose of orbital flux integrations, the smallest tested time interval ( $T=24$  hours) be adopted as a uniform, standard flightpath duration for all circular subsynchronous trajectories.

In conclusion, a range of optimum  $\Delta t$ 's per altitude is presented in Figure 10, where the lower value produces an average deviation of less than 10%, and the higher value an average deviation of less than 20%.

A diagonal line in the graph expresses the functional relationship of a continuous optimum stepsize in altitude

$$\Delta t = m \log h + d \quad (5)$$

where  $m = \frac{\partial(\Delta t)}{\partial(\log h)} = 3.4767, \quad d = -6.0 \quad (6)$

This is then used to determine altitude intervals over which a mean, discrete  $\Delta t$  would be valid. For the purpose of simplicity and practicality, we now propose the stepsizes indicated at the top of the shaded areas as standard  $\Delta t$ 's for the altitude interval covered by these areas.

## COMPUTER TIME

It is obvious that by minimizing duration and by maximizing stepsize one also minimizes computer time. For the combination of parameters and variables considered in the transverse comparisons, the ratio  $R_p$  of actually evaluated flight-path positions  $N$  (i.e., the number of integration steps or trajectory points) is defined as

$$R_p = \frac{N(T_{\max}, \Delta t_1)}{N(T_{\min}, \Delta t_3)} \quad (7)$$

and is plotted in Figure 24 as a function of the ratio  $\bar{R}_{t_I}$  of the

mean running times  $\bar{t}_I$

$$\bar{R}_{t_I} = \frac{\bar{t}_I(h; T_{\max}, \Delta t_1)}{\bar{t}_I(h; T_{\min}, \Delta t_3)} \quad (8)$$

where the  $\bar{t}_I$ 's represent the combined CPU and I/O values of the execution step, averaged over inclination\*, for simultaneous calculations of electron and proton fluxes.

The graph indicates that on the average a decrease in points by a factor of 10 reduces computer time by about a factor of 2.4. The straight line is an attempt to eliminate the scatter in the data and linearize the  $R_p$  to  $\bar{R}_{t_I}$  relationship, which can be expressed as

$$\bar{R}_{t_I} = 0.1R_p + 1.4 \quad (9)$$

---

\*All times relate to an IBM 360/91 operating system.

Equation (9) should hold for other operating systems on computers with similar CPU and I/O algorithms, regardless of trajectory or models, as long as the orbital flux integration programs are similar in structure and complexity to the UNIFLUX system (see Appendix), used in the present calculations.

It should be pointed out, that statistically the  $R_p$  to  $\bar{R}_{t_I}$  relationship is independent of altitude and inclination because as indicated above, the running times were first averaged over inclination at each altitude level, for the duration and stepsize of interest, and then the per altitude values were folded into the final curve. On the case by case basis, there are of course differences; for example, it was observed that at altitudes of  $h \leq 16000$  km, polar and/or equatorial orbits required consistently less time than the other two intermediate inclinations; this apparent differentiation occurred at most durations and stepsizes. No explanation can readily be given for this peculiarity in timing, especially not in view of the fact that the total number of points treated per fixed  $h$ ,  $T$ , and  $\Delta t$  were equal for all four inclinations. These variations may have to do with search and B/L-interpolation requirements in the environment models (TRARA1, TRARA2) and with the decay bypass feature in UNIFLUX.

Table 2 lists the total number of positions  $N$  (i.e. integration steps) that are contained in a trajectory of given duration and stepsize, for sets of values of  $T$  and  $\Delta t$ , where:

$$N = \frac{d \times T}{\Delta t} \quad (10)$$

$T$  is in hours,  $\Delta t$  in minutes, and the conversion constant  $d$  in minutes per hour.

Flux calculations are performed at these points. For any T then, the size of  $\Delta t$  determines the density with which the environment of a spacecraft is sampled.

An interesting picture emerges when the averaged-over-inclination running times of all investigated altitudes, durations, and stepsizes are coded by symbols according to number of points treated per run, and are then plotted as  $\bar{t}_I(h;T, \Delta t)$  versus h; if in this process every  $\bar{t}_I$  is also subscripted by its  $\Delta t$ , the plotted data is unambiguously identified as to its origin through equation (10). Figure 16 shows some of these inclination-averaged running times.

Two striking patterns are immediately apparent from Figure 16. First, that runs for high and very low altitudes require less time for the same number of points to be processed than runs at intermediate altitudes, with a maximum time consumption occurring at about 2000 kilometers; and second, that with increasing stepsize, progressively more time was consumed by runs which in essence processed the same number of points.

No adequate explanation can be provided for the differentiation of the running times over h; maybe the trajectories at lower and higher altitudes require on the average fewer actual flux calculations because larger segments of their orbits lie outside the trapping regions of the models. The larger running times mentioned in the second observation can be attributed, partially at least, to the skipping mechanism in UNIFLUX, which is activated whenever the inputted stepsize is greater than an integer multiple of the constant orbit-tape time increment. Since all trajectories used in this study were generated with  $\Delta t=1$  minute, this process may account for some of the additional time expended with larger  $\Delta t$ 's.

If all trajectories of equal N value are grouped together and their running times t are averaged over altitude, inclination, duration, and stepsize, then the maximum variation from the mean, observed in the group, is less than 27%; it occurs only in large groups with 16 - 36 members and there only once, in one member. The average variation of the combined CPU-I/O time for all other members and groups is less than 10%. The mean running time for each group is plotted in Figure 17, which gives a good measure of program efficiency and optimization potential. Also plotted are the mean running times per point of the larger groups. The solid and dashed curves approximate a best fit to the means.

The non-linearity of the mean running times may be partially due to an initial element of time required by the computer to activate functions, to set up storage, to allocate core, to clear registers, etc. For extensive runs with a large number of positions, this initial time expenditure is then distributed over many points, thus minimizing the "penalty" per point, whereas for short runs with a small number of points, each point is charged with a correspondingly larger amount of initialization time.

Similar conditions should affect orbital flux integration runs on any computer. Of course, a difference in these conditions may alter the shape, slope, or amplitude of the curves in Figure 17.

In conclusion, it was determined that a perfectly reliable and useful orbital flux integration, if performed with the proposed optimal (for the investigated ranges of T and  $\Delta t$ ) values of duration and stepsize, would on the average require only from about .1 to .3

minutes of computer CPU-I/O time, depending on the altitude. All the test calculations were performed on an IBM 360/91 multiprocessor system with the new UNIFLUX program (Stassinopoulos and Gregory, 1974). It is to be expected that other codes on other machines may produce different absolute running times or flux results. However, the respective optimization effects should be analogous and the relative  $R_p$  and  $\bar{R}_{\tau I}$  ratios should be similar for equivalent runs.

## SUMMARY

It has been shown, that within the limit of accuracy and ranges of parameters, a duration of 24 hours is sufficient to insure an adequate sampling of spacecraft environments in circular subsynchronous orbits, and that an increase in T, while raising the number of points to be treated and expending more computer time, does not meaningfully improve the integration results.

It has also been established that stepsize in general is a function of altitude alone and does not depend on inclination or duration. A functional relationship was developed to yield an optimal  $\Delta t$  for any given h between 200 and 32000 kilometers.

### Acknowledgements

The author wishes to thank Dr. James I. Vette for many helpful suggestions and for reviewing the manuscript. Thanks are also due to Mr. Joel Hebert for his very valuable programming assistance.

## References

Stassinopoulos, E. G., and C. Z. Gregory, "UNIFLUX: A Unified Orbital Flux Integration and Analysis System"; to be published in 1975.

Singley, G. W., and J. I. Vette, "A Model Environment for Outer Zone Electrons," NSSDC 72-13, National Space Science Data Center, Greenbelt, Maryland, July, 1972.

Teague, M. J., and J. I. Vette, "The Inner Zone Electron Model AE-5", NSSDC 72-10, National Space Science Data Center, Greenbelt, Maryland, September, 1972.

Lavine, J. P., and J. I. Vette, Models of the Trapped Radiation Environment, Volume V: Inner Belt Protons, NASA SP-3024, 1969.

McIlwain, C. E., "Coordinates for Mapping the Distribution of Magnetically Trapped Particles", J. Geophysical Research, 66, 3681, 1961.

## APPENDIX

### UNIFLUX: A Unified Orbital Flux Integration and Analysis System

The system, developed by E. G. Stassinopoulos & C. Z. Gregory (1974) at Goddard Space Flight Center, combines into one compact program package several previously separate or independent functions and operations. It affords the user great flexibility as to selections of particle species, of threshold energies, of types of orbits, etc., and it permits the treatment of special cases, previously excluded from consideration. It offers more choices as to type, form, and format of output; it has greatly expanded capabilities for the presentation of results, providing additional information obtained through programmed data analysis. Most importantly, however, the system requires less core storage and is significantly faster than comparable computer programs presently in use.

UNIFLUX incorporates the currently valid proton and electron environment models in matrix storage form (the new Kluge-Lenhardt mode). It is capable of decaying artificial Starfish electrons, still contained in the latest solar-max electron models, down to approximately natural background levels. Included in the program is also a solar proton model and a method to calculate the exposure of a spacecraft to energetic solar protons for energies from 10 to 100 Mev.

Special Features of UNIFLUX are:

- a) unrestricted multiple orbit capability (in one execution step)

- b) liberalized plot selection (increased freedom of choice)
- c) optional accumulative B/L-bin account (output can be suppressed)
- d) selective integration stepsize (independent of trajectory time-increment)
- e) analytical differentiation of orbit integrated spectra
- f) multiple output-table production capability (to print set of tables any specified number of times)
- g) simultaneous (combined) processing of all electron and proton models during a single execution and I/O step (one run for all models, all species).

The program is available upon request from the National Space Science Data Center, Code 601, Goddard Space Flight Center, Greenbelt, Maryland, 20771.

TABLE 1

Evaluation of Duration and Step Size Requirements of Orbital Flux Integrations

Orbit Parameters and Integrations Variables

h Altitude (km)	Period (hrs)	P/ $\tau$ Orbital Precession (degr/hr)	Daily Advance (degr/day)	T Tested Durations (hrs)	$\Delta t$ Tested Integration Step sizes (mins)
400	1.5427	23.14	6.64	24	1,2,3
1000	1.752	26.28	4.52	24	1,2,3
2200	2.196	32.94	1.07	24,48	1,2,3
4000	2.923	43.85	11.85	24,48,72	1,3,5
16000	9.254	138.81	6.10	24,48,72,96	2,4,6
30000	19.999	299.99	60.01	24,72,96	3,6,9

Note: At all specified altitudes, four inclinations were considered in the tests:

$i = 0^\circ, 30^\circ, 60^\circ, 90^\circ$ .

TABLE 2

Number of samplings in trajectories with duration T  
and Stepsize  $\Delta t$

<u>T</u> \ <u><math>\Delta t</math></u>	<u>1</u>	<u>2</u>	<u>3</u>	<u>4</u>	<u>5</u>	<u>6</u>	<u>9</u>	<u>10</u>
24	<u>1440</u>	<u>720</u>	<u>480</u>	<u>360</u>	<u>288</u>	<u>240</u>	<u>160</u>	144
48	<u>2880</u>	<u>1440</u>	<u>960</u>	<u>720</u>	<u>576</u>	<u>480</u>	320	288
72	<u>4320</u>	<u>2160</u>	<u>1440</u>	<u>1080</u>	<u>864</u>	<u>720</u>	<u>480</u>	432
96	5760	<u>2880</u>	<u>1920</u>	<u>1440</u>	1152	<u>960</u>	<u>640</u>	576

Note: Values underlined were used in one or more of the calculations.

TABLE 3

Orbital Flux Integration Parameters:

Stepsizes and Durations per Altitude

(Circular Orbits)

<u>h</u> (km)	<u>i</u> (degr)	<u>T</u> (hrs)	<u><math>\Delta t</math></u> (min)
400	0, 30, 60, 90	24	① 2 ③
1000	0, 30, 60, 90	24	① 2 ③
2200	0, 30, 60, 90	24 48	1 2 ③ ① 2 3
4000	0, 30, 60, 90	24 48 72	1 3 ⑤ 1 3 5 ① 3 5
16000	0, 30, 60, 90	24 48 72 96	2 4 ⑥ 2 4 6 2 4 6 ② 4 6
30000	0, 30, 60, 90	24 72 96	3 6 ⑨ 3 6 9 ③ 6 9

○: circles, at the corresponding duration levels, indicate the stepsizes with which the data, used in the transverse comparison, were obtained.

Table 4

Duration Dependence of Simple Deviations<sup>+</sup>

Case showing no improvement with increase of duration

h(km)	Stepsize(mins)		Species	i(degr)	Simple Deviations  D  % for T(hrs)			
	$\Delta t_1$	$\Delta t_3$			24	48	72	96
2200	1	3	e	30	0	.84		
				60	.09	.32		
				90	.05	.27		
4000	1	5	e	0	0	.10		
				60	.14	.19	*	
			90	*	.06	.17		
			p	60	*	.03	.10	
				90	*	0	.08	
			16000	2	6	e	0	← no change →
30	.02	.02					0	0
90	*	.05					.05	.05
p	0	*				0	.07	.07
	30	.07				.07	.07	*
30000	3	9				e	0	.18
			90	*			.24	.25

\* not applicable for this comparison

<sup>+</sup>

$$D = \frac{F(T; \Delta t_1) - F(T; \Delta t_3)}{F(T; \Delta t_1)}$$

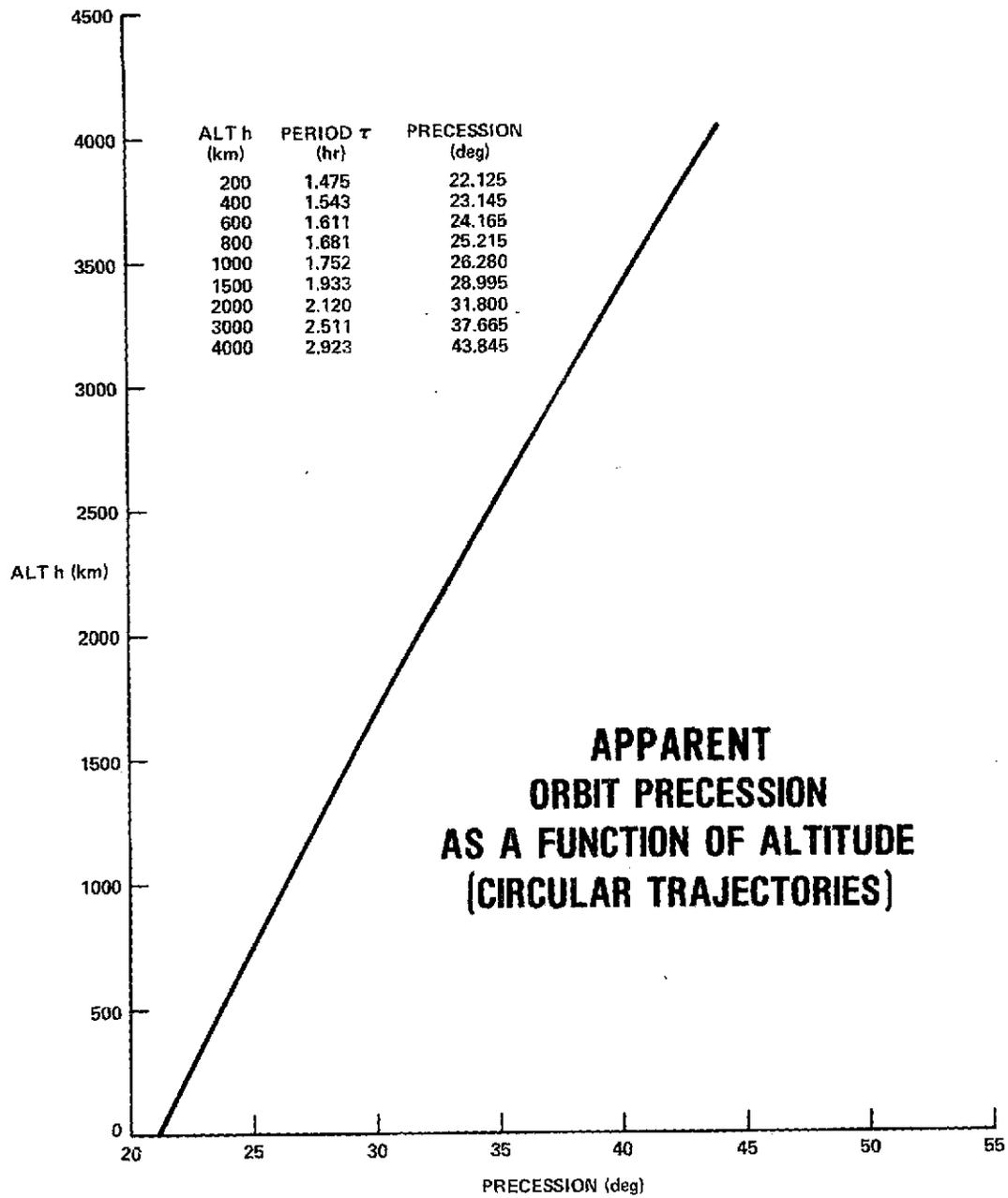
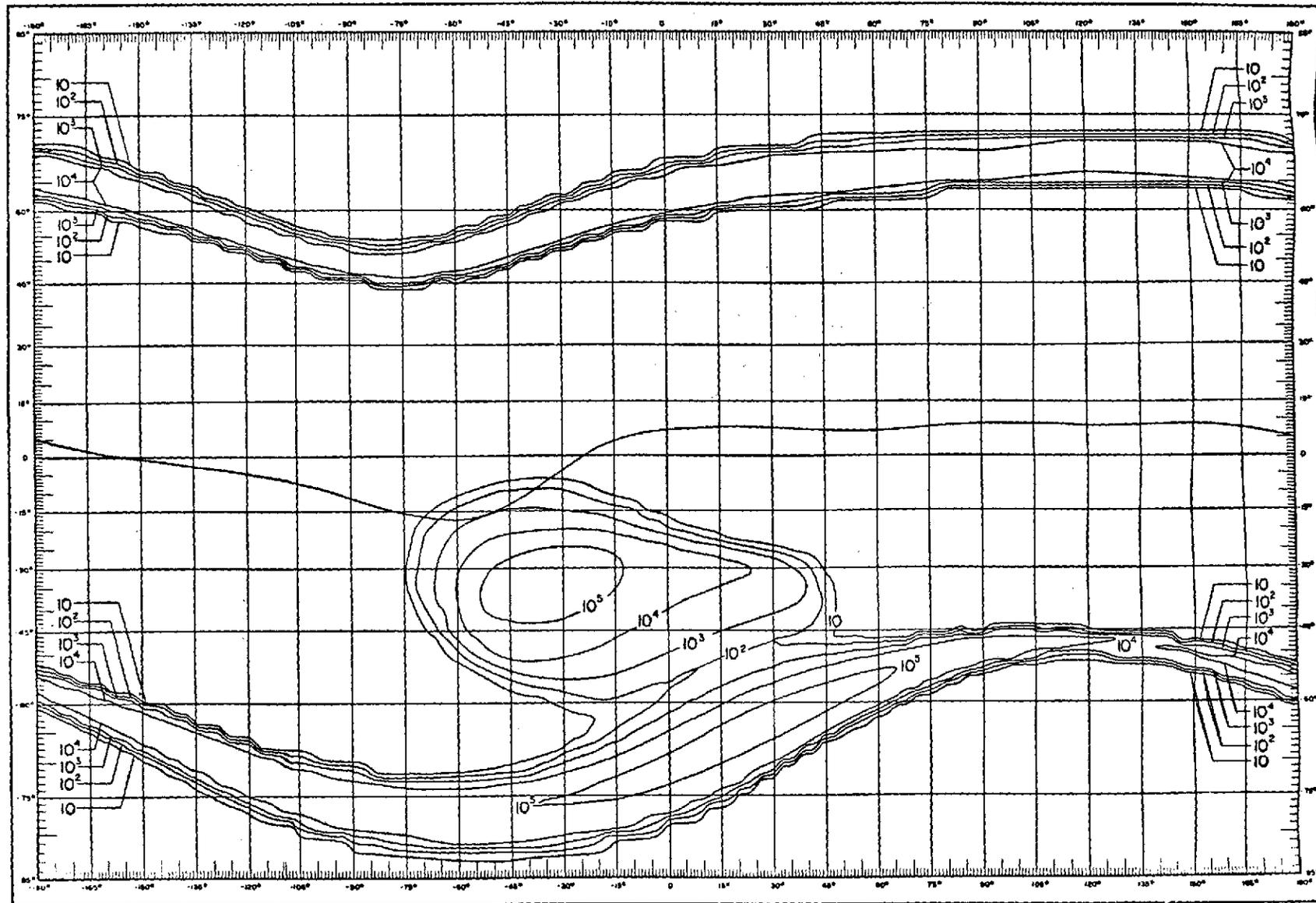


Figure 1

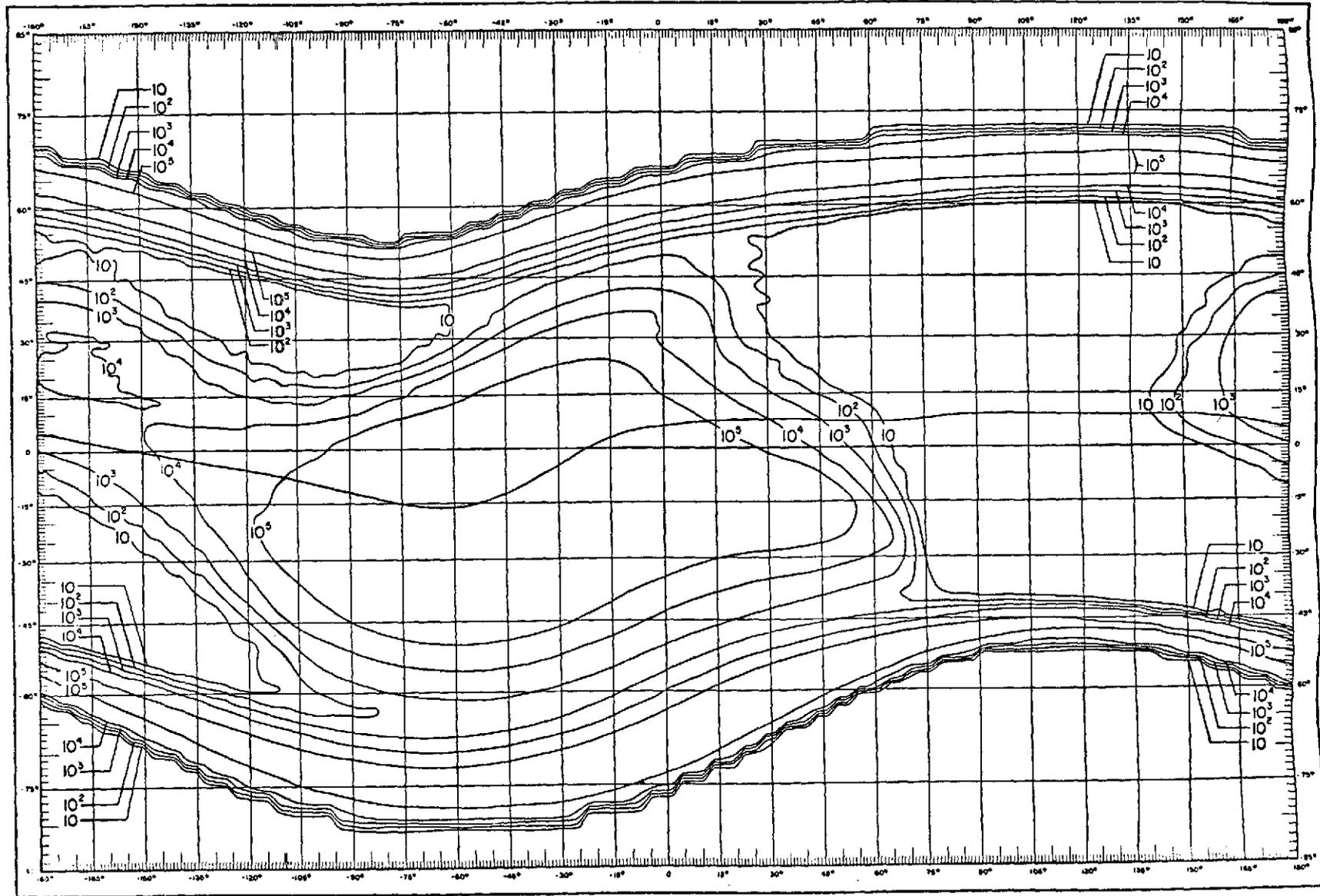
# ELECTRON FLUX CONTOURS— $E > 0.5$ MeV



ALTITUDE = 300 KM

Figure 2

# ELECTRON FLUX CONTOURS— $E > 0.5$ MeV



ALTITUDE = 1000 KM

Figure 3

# ELECTRONS (E > 0.5 MeV)

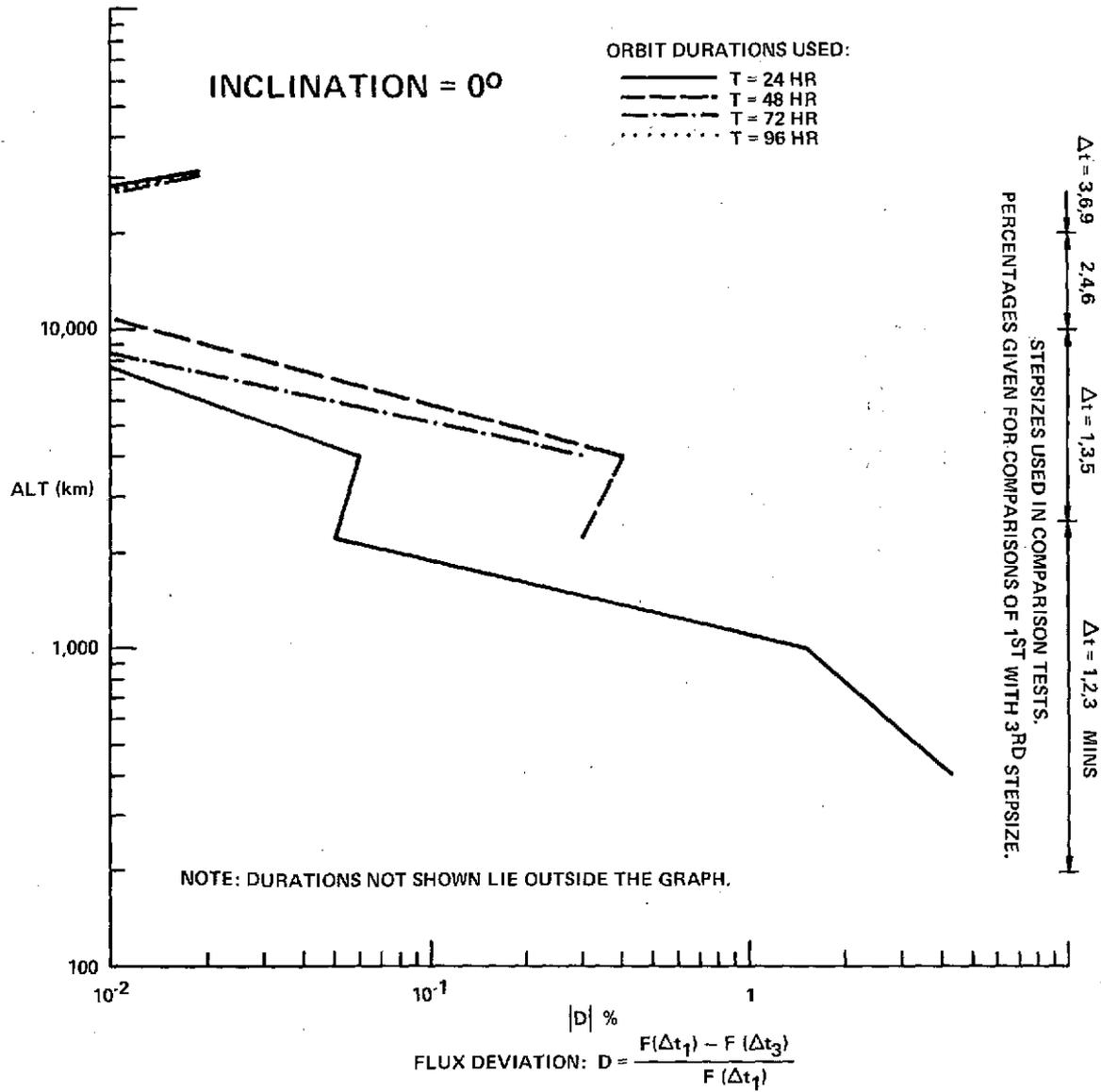


Figure 4a

# ELECTRONS (E > 0.5 MeV)

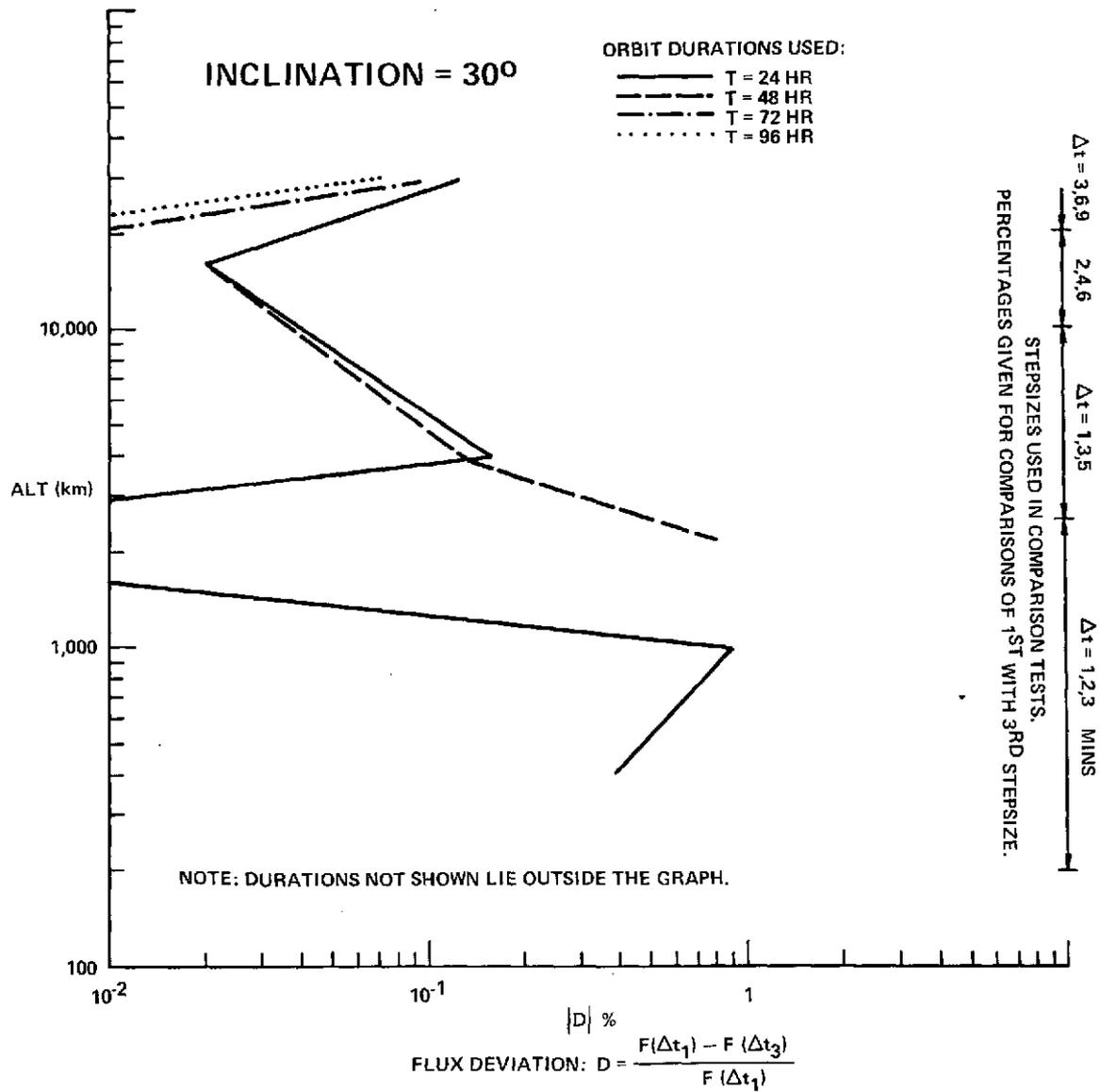


Figure 4b

# ELECTRONS (E > 0.5 MeV)

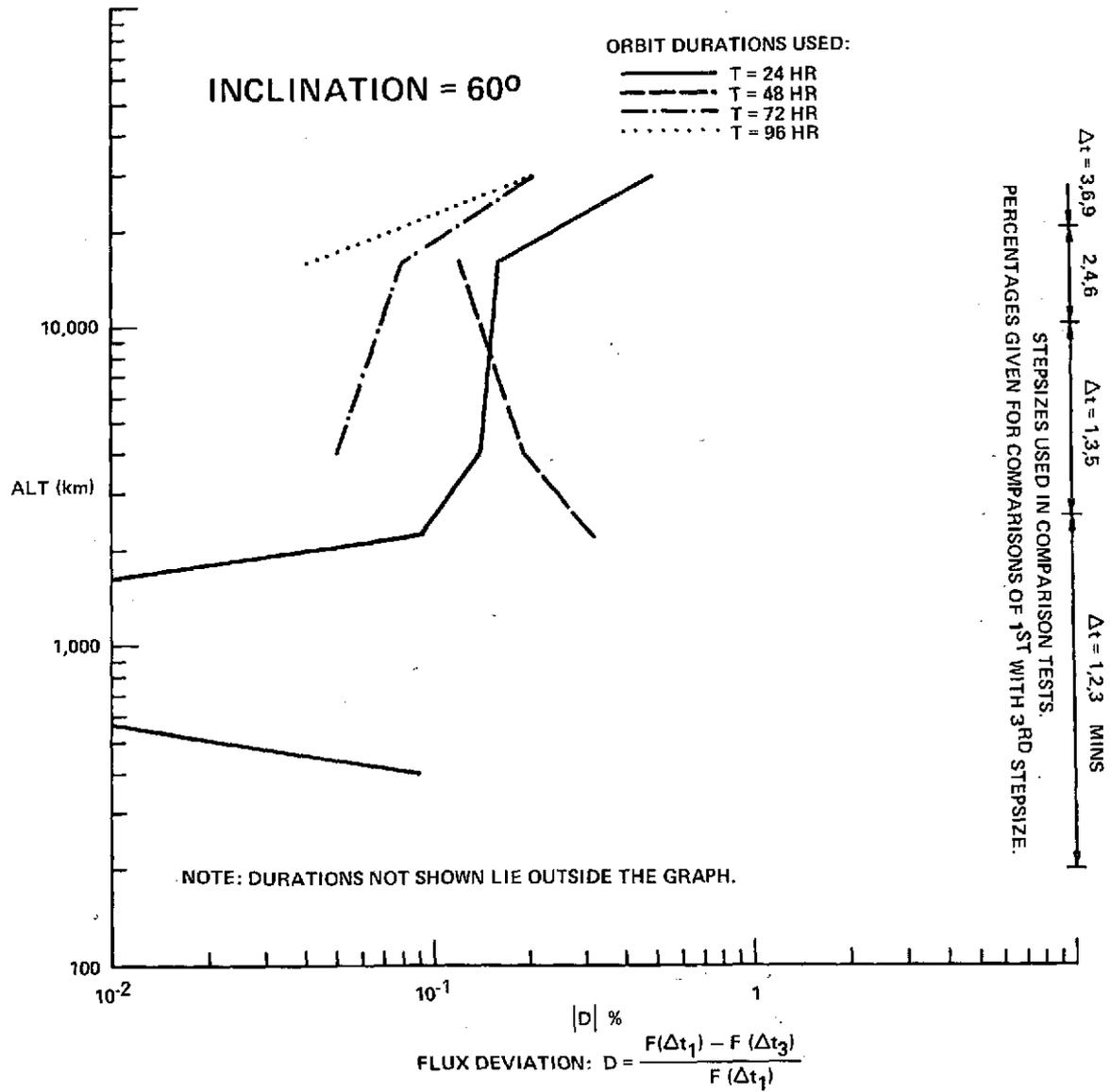


Figure 4c

# ELECTRONS (E > 0.5 MeV)

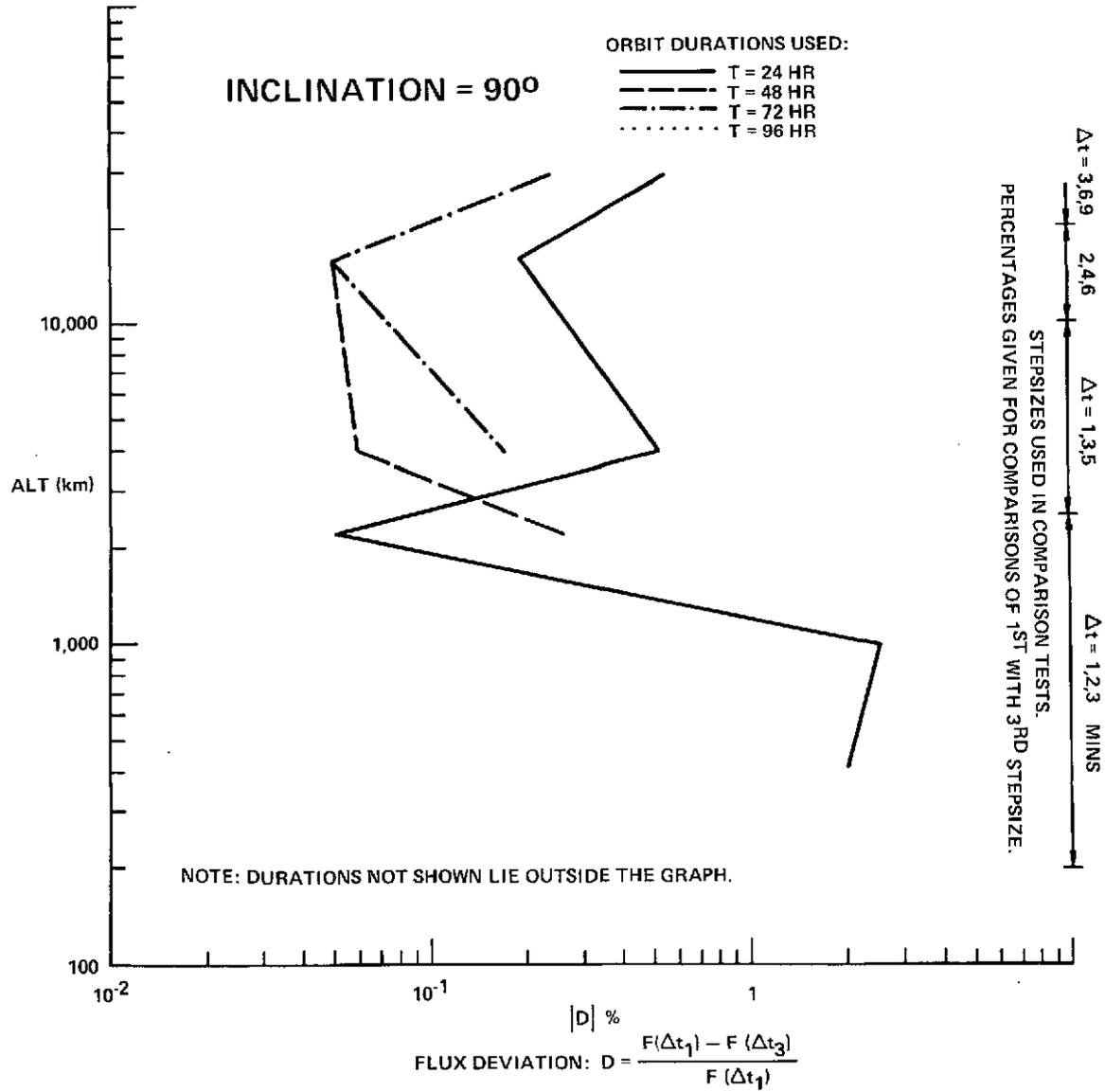


Figure 4d

# PROTONS (E > 5.0 MeV)

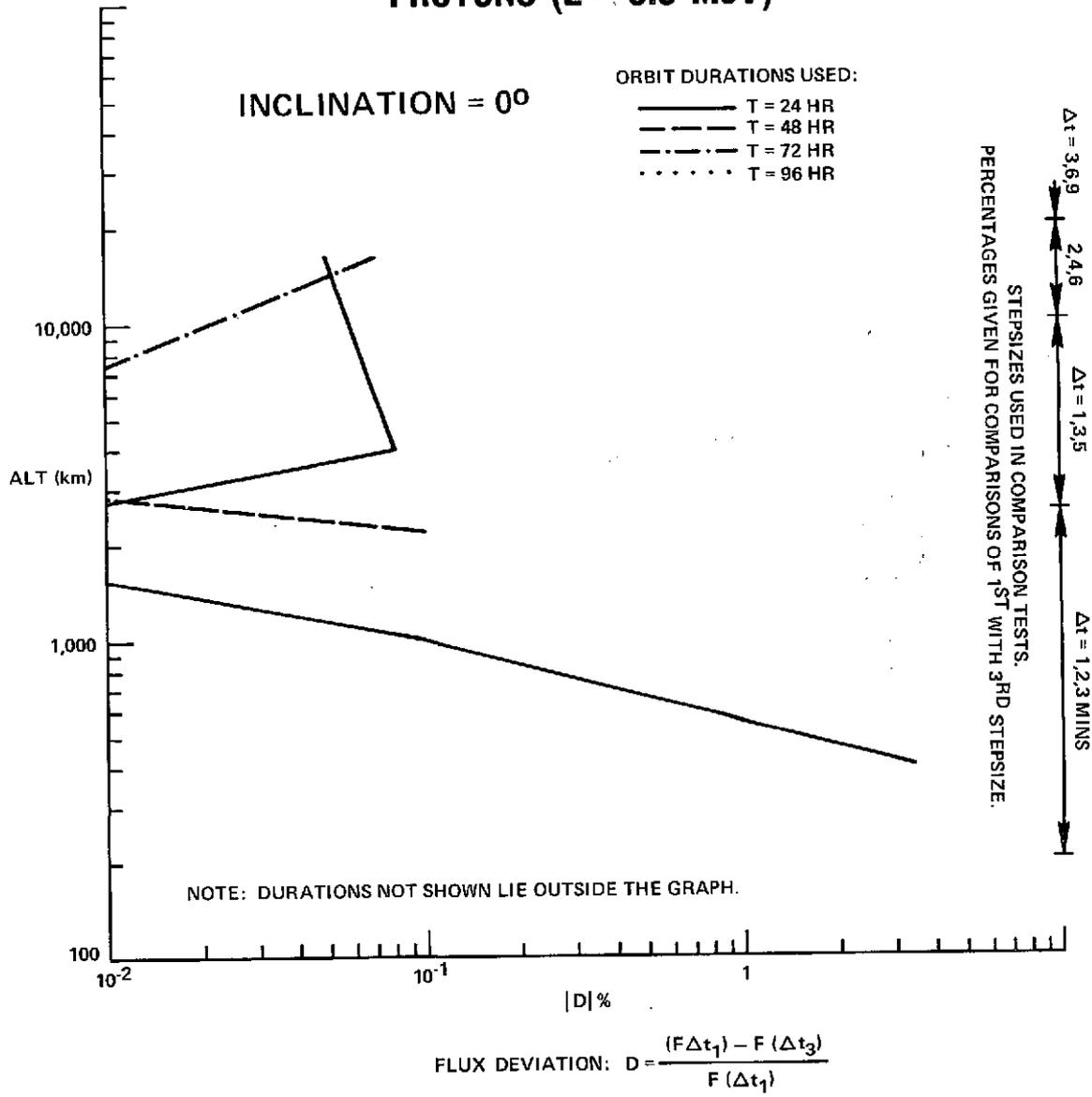


Figure 5a

# PROTONS (E > 5.0 MeV)

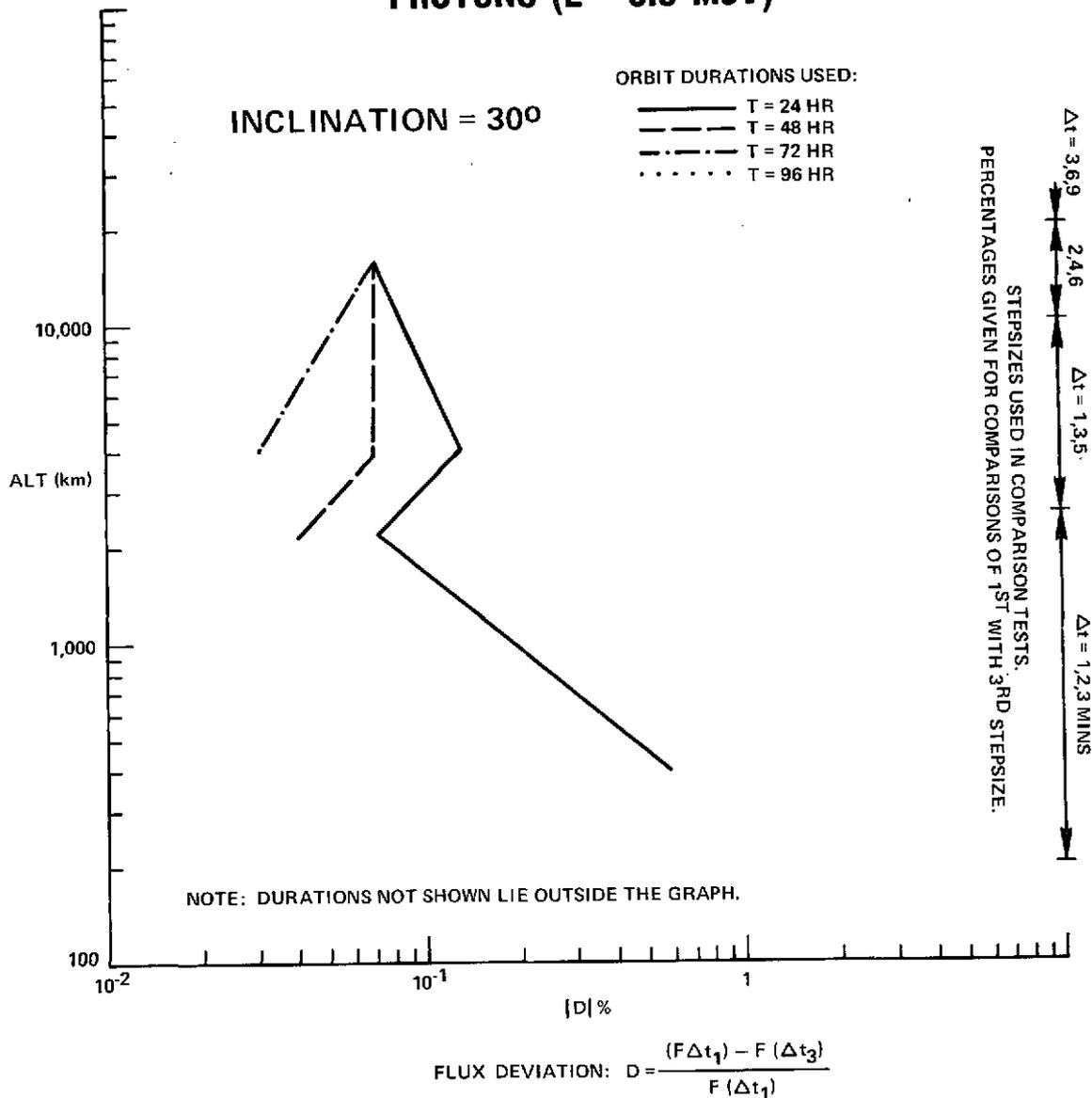


Figure 5b

# PROTONS (E > 5.0 MeV)

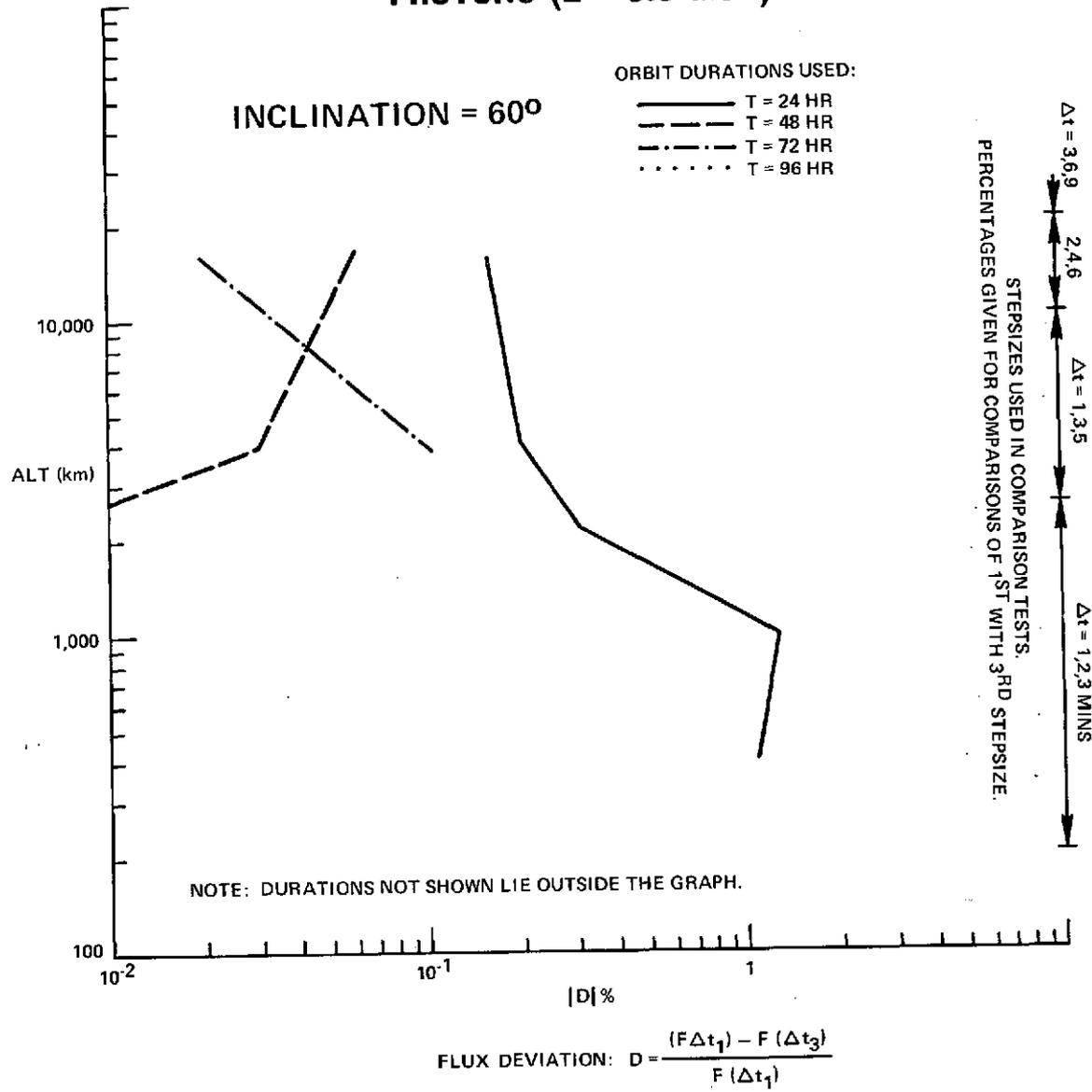


Figure 5c

# PROTONS (E > 5.0 MeV)

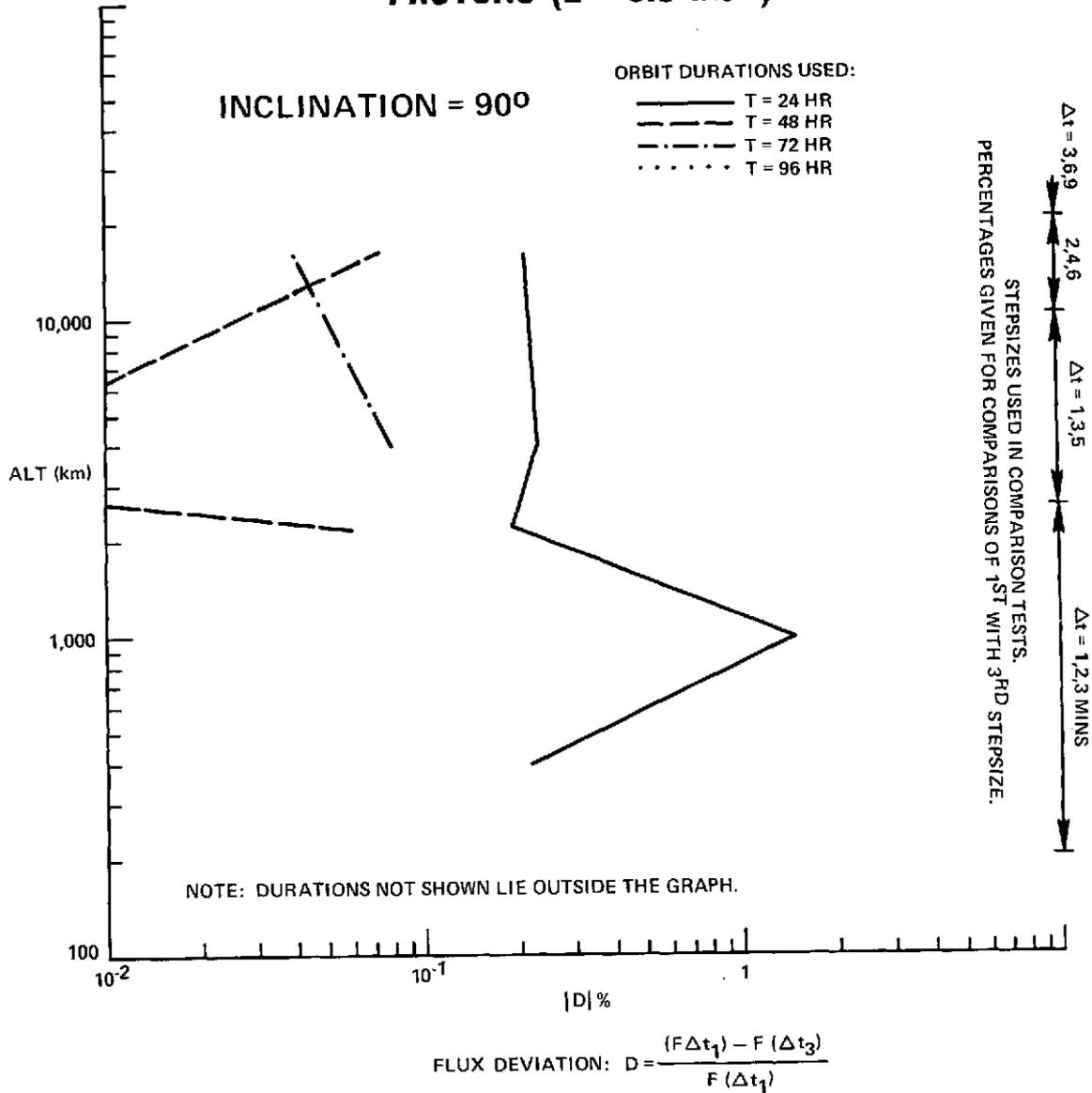


Figure 5d

# ELECTRONS (E > 0.5 MeV)

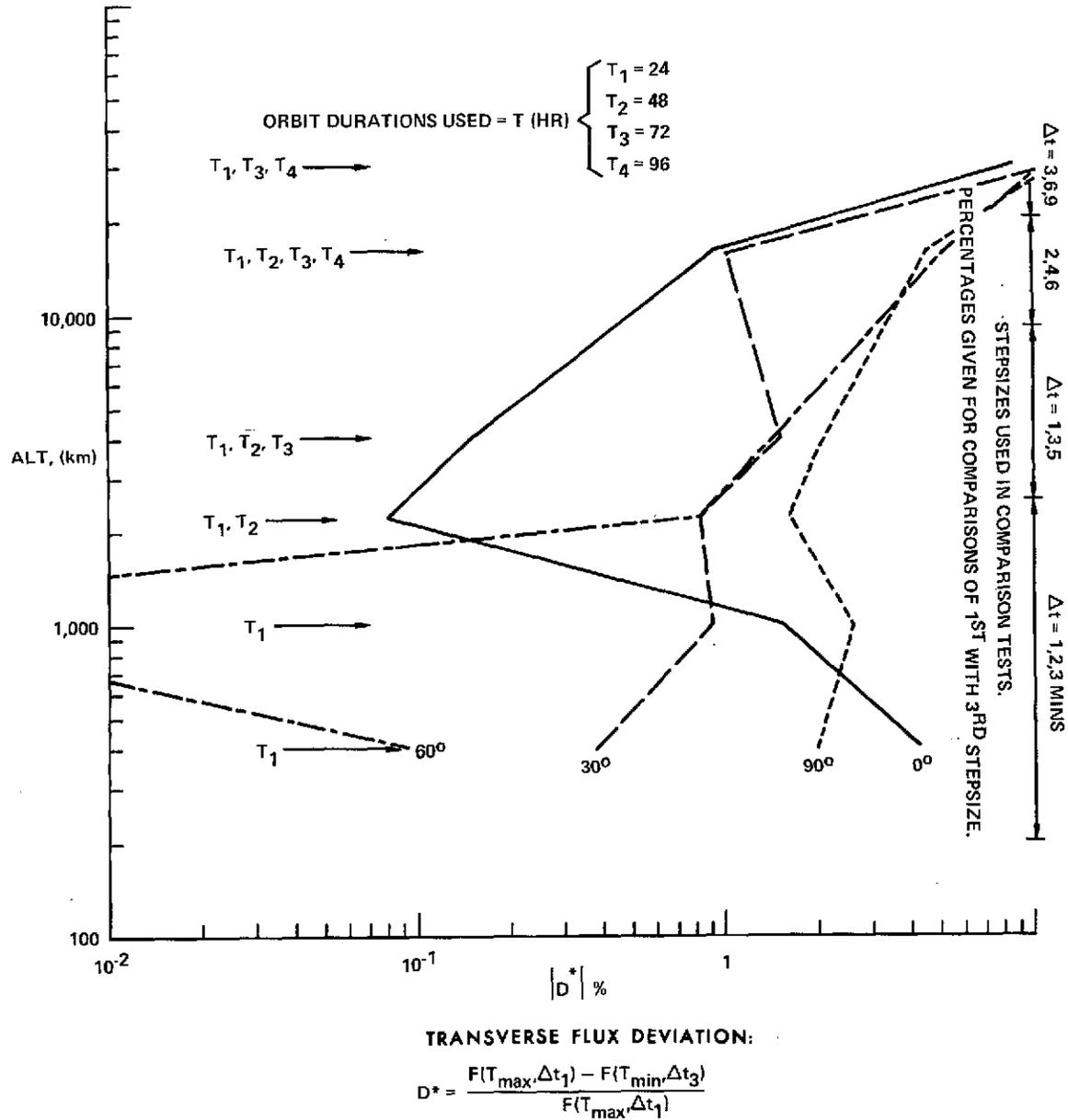


Figure 6

# PROTONS (E > 5.0 MeV)

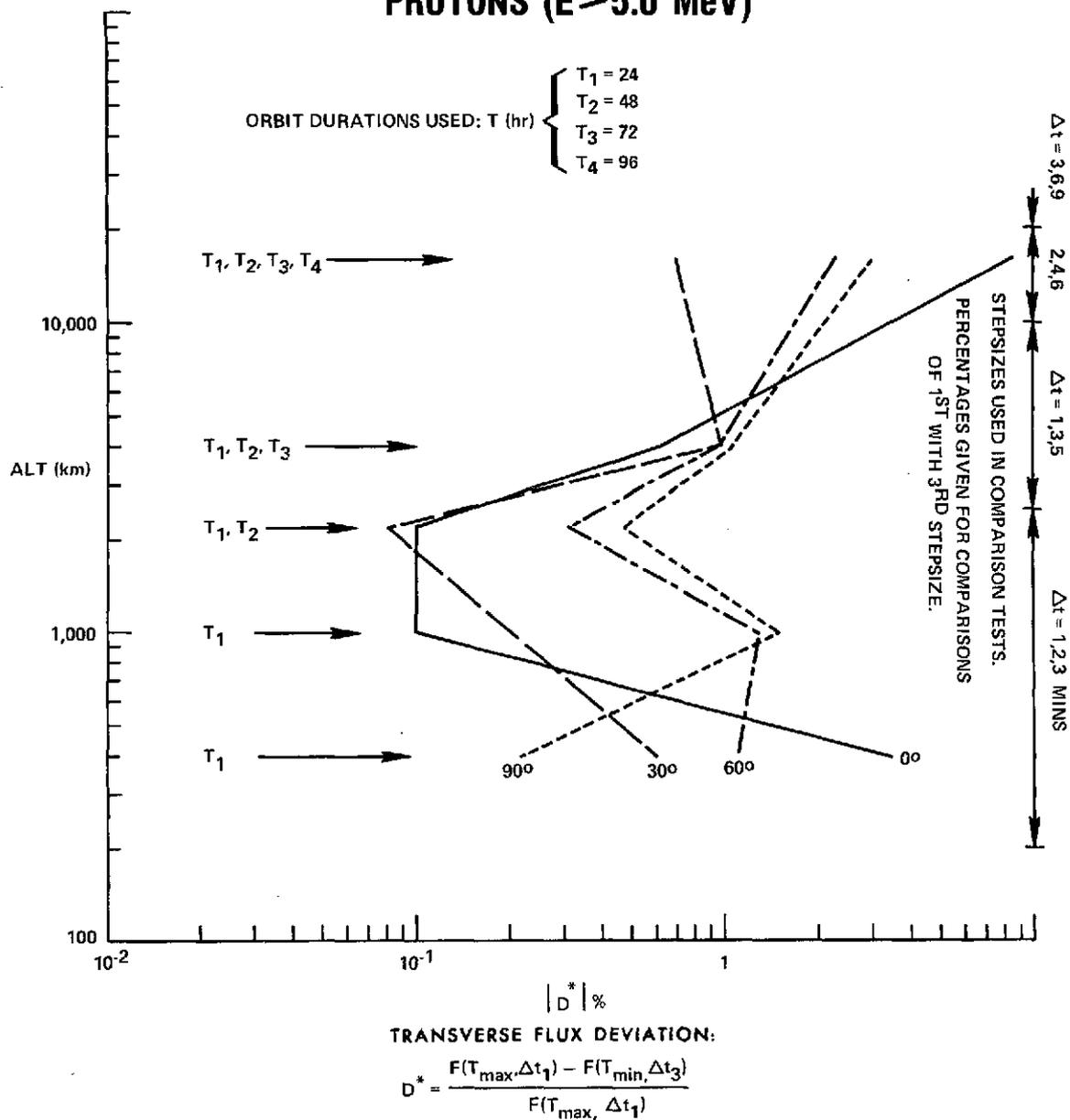


Figure 7

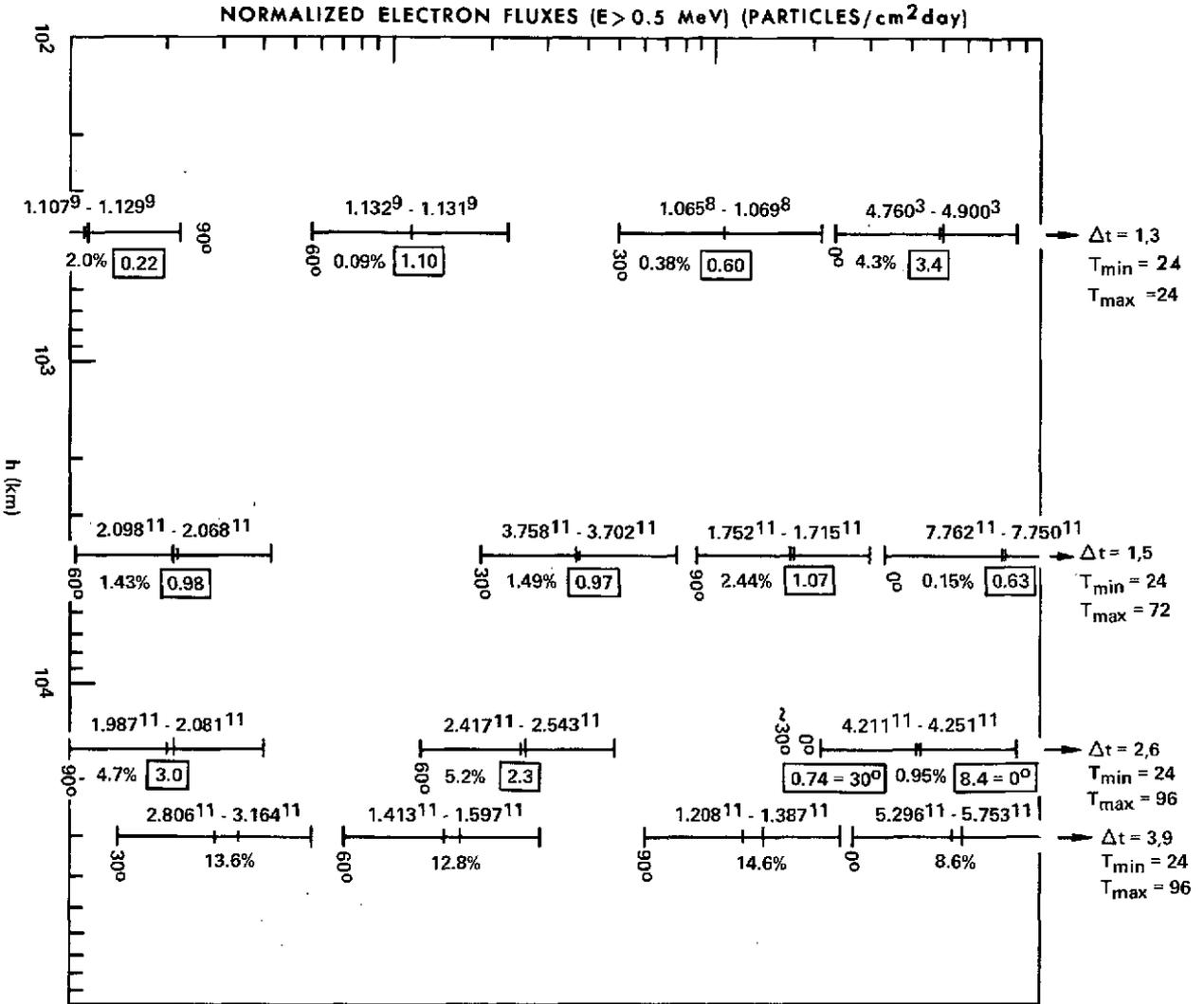


Figure 8

# POLAR VS. EQUATORIAL ORBITS: EFFECT OF STEPSIZE ON O.I. FLUXES

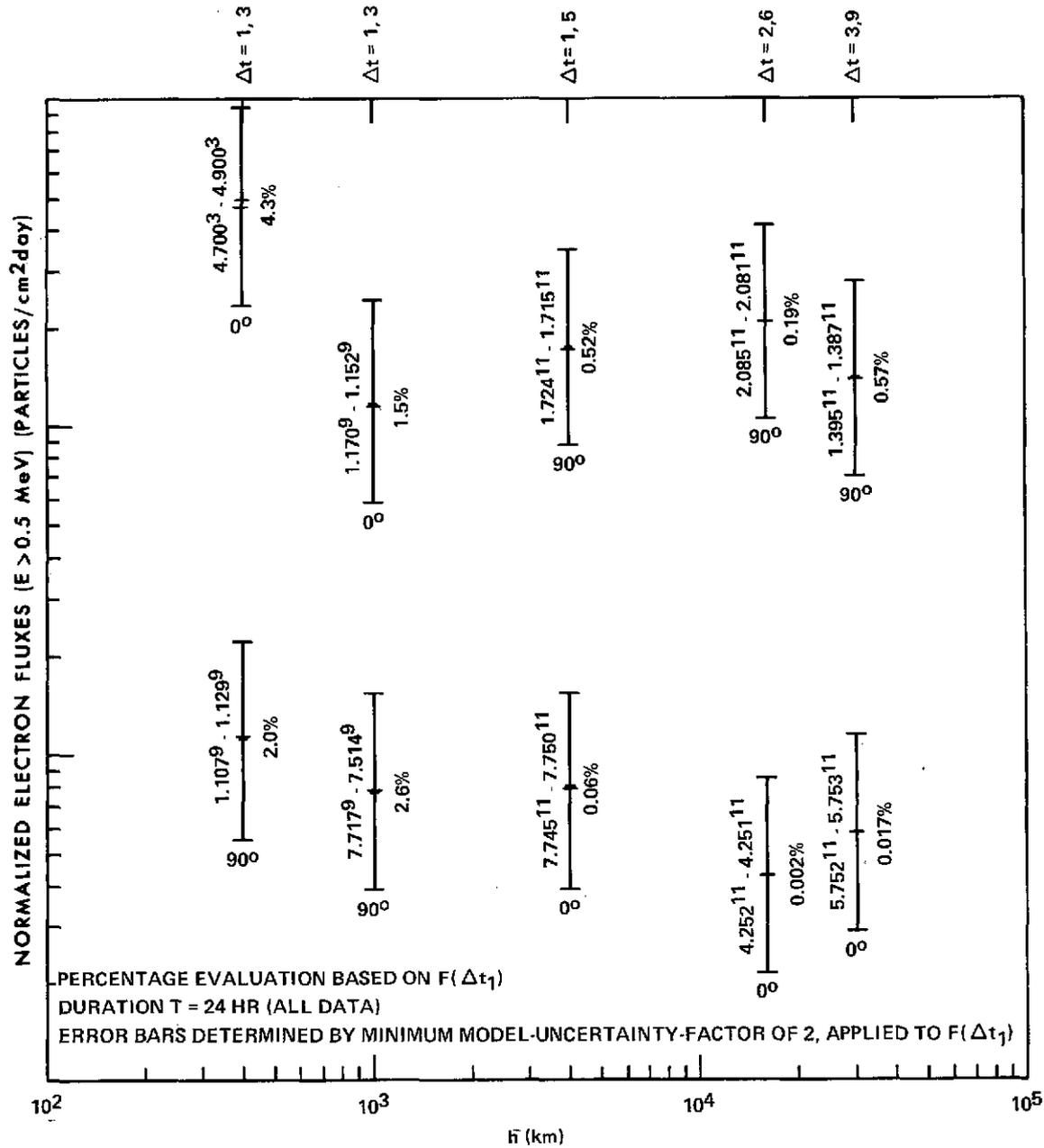


Figure 9

# OPTIMAL INTEGRATION CONDITIONS

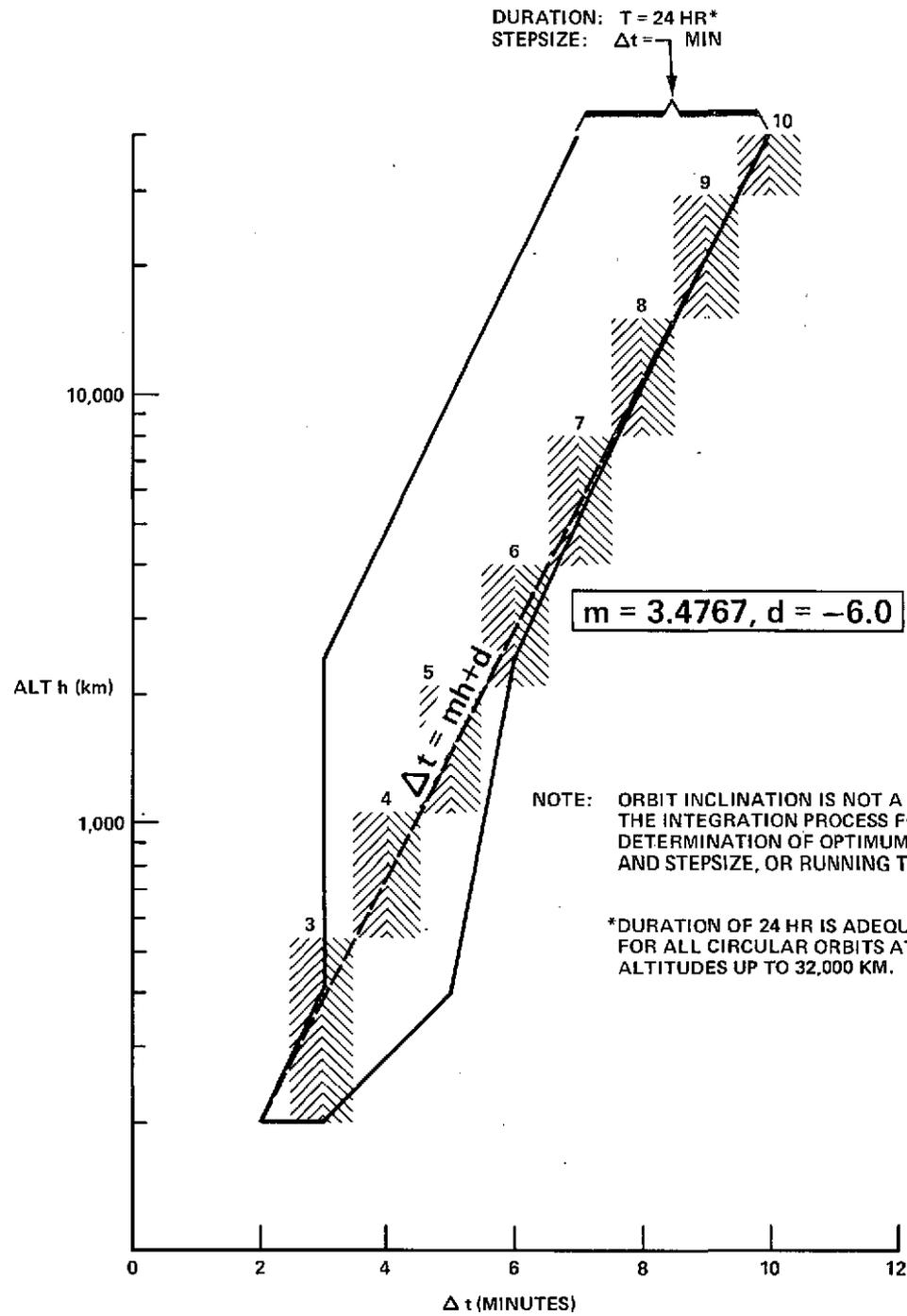


Figure 10

# DURATION DEPENDENCE

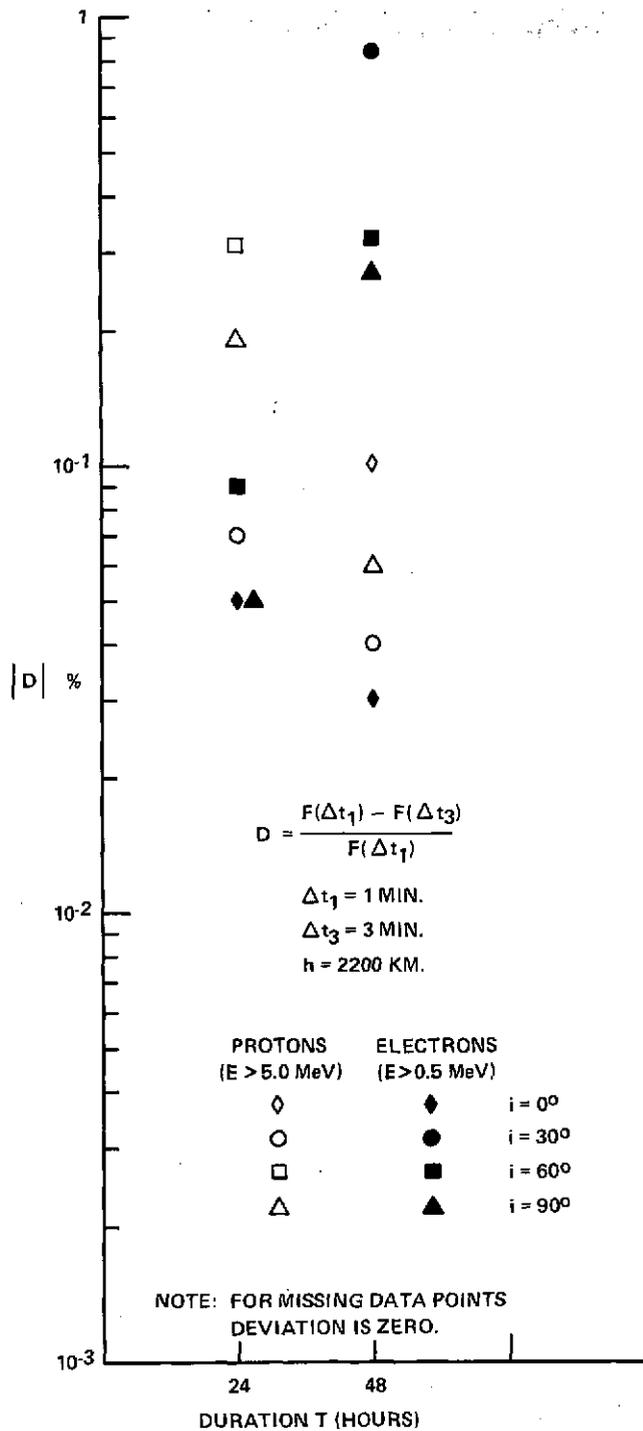


Figure 11

# DURATION DEPENDENCE

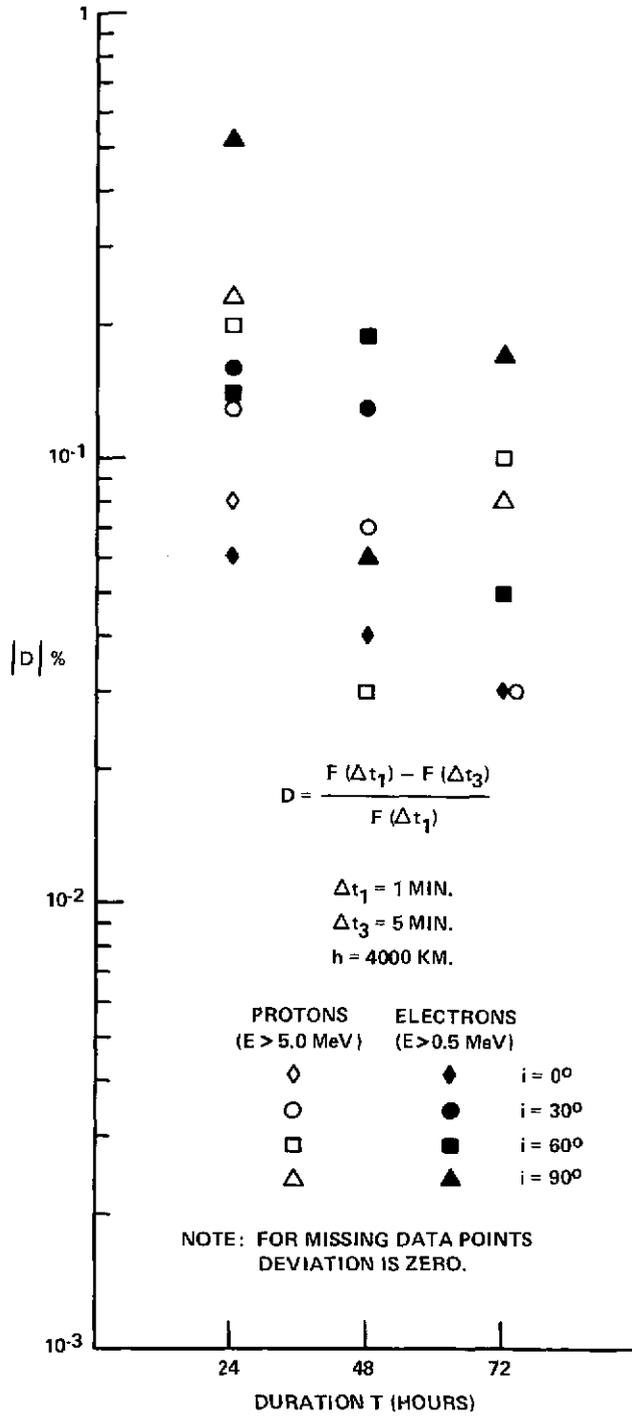


Figure 12

# DURATION DEPENDENCE

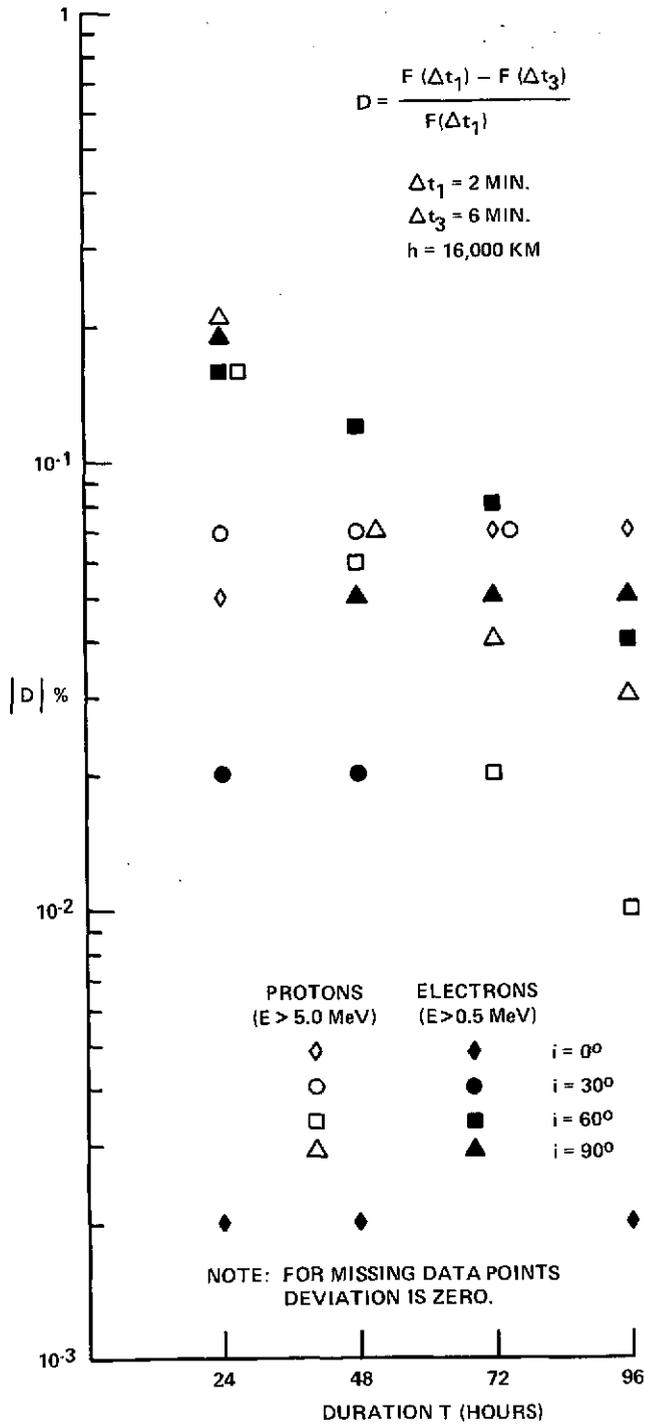


Figure 13

# DURATION DEPENDENCE

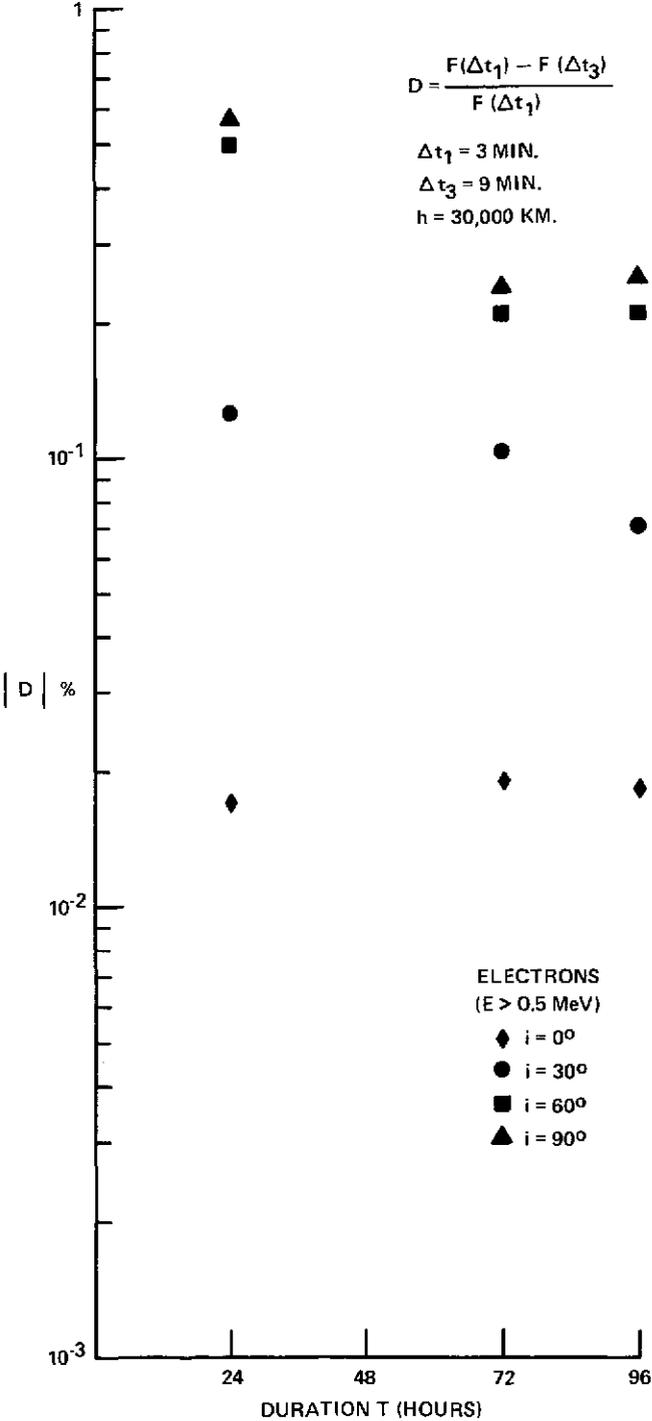


Figure 14

# ELECTRONS ( $E > 0.5$ Mev)

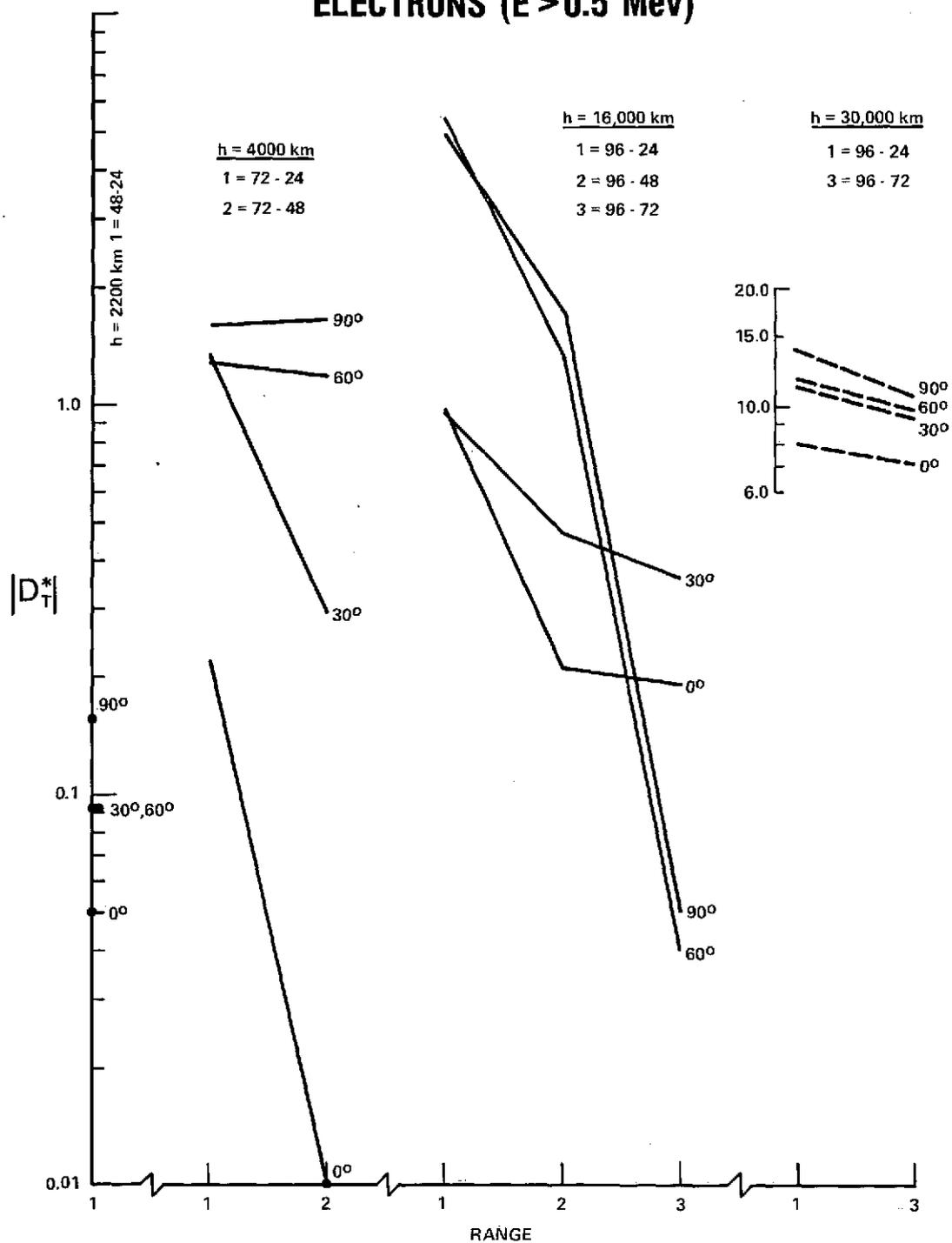


Figure 15

# PROTONS (E > 5.0 Mev)

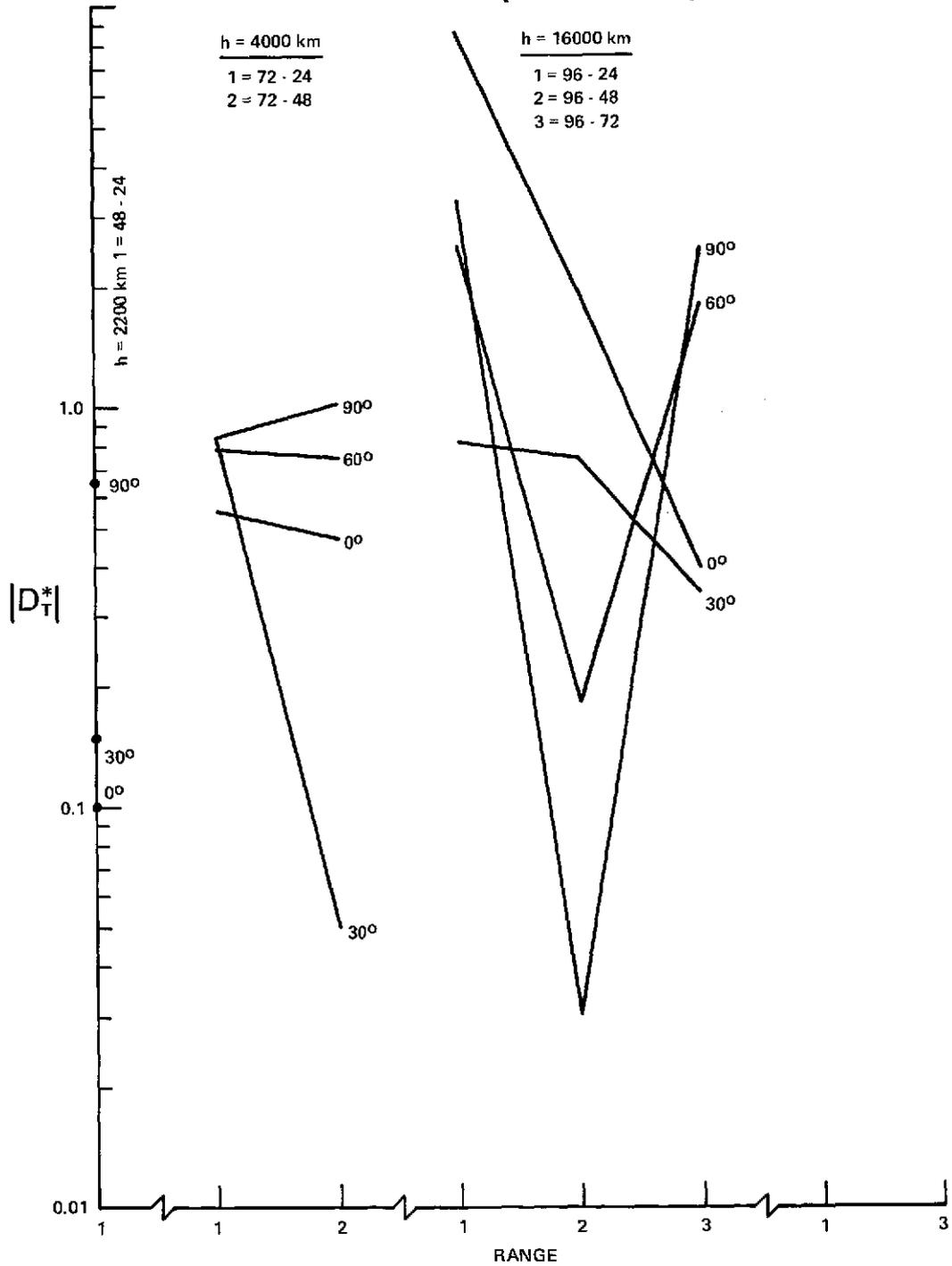


Figure 16

# ELECTRONS ( $E > 0.5$ Mev)

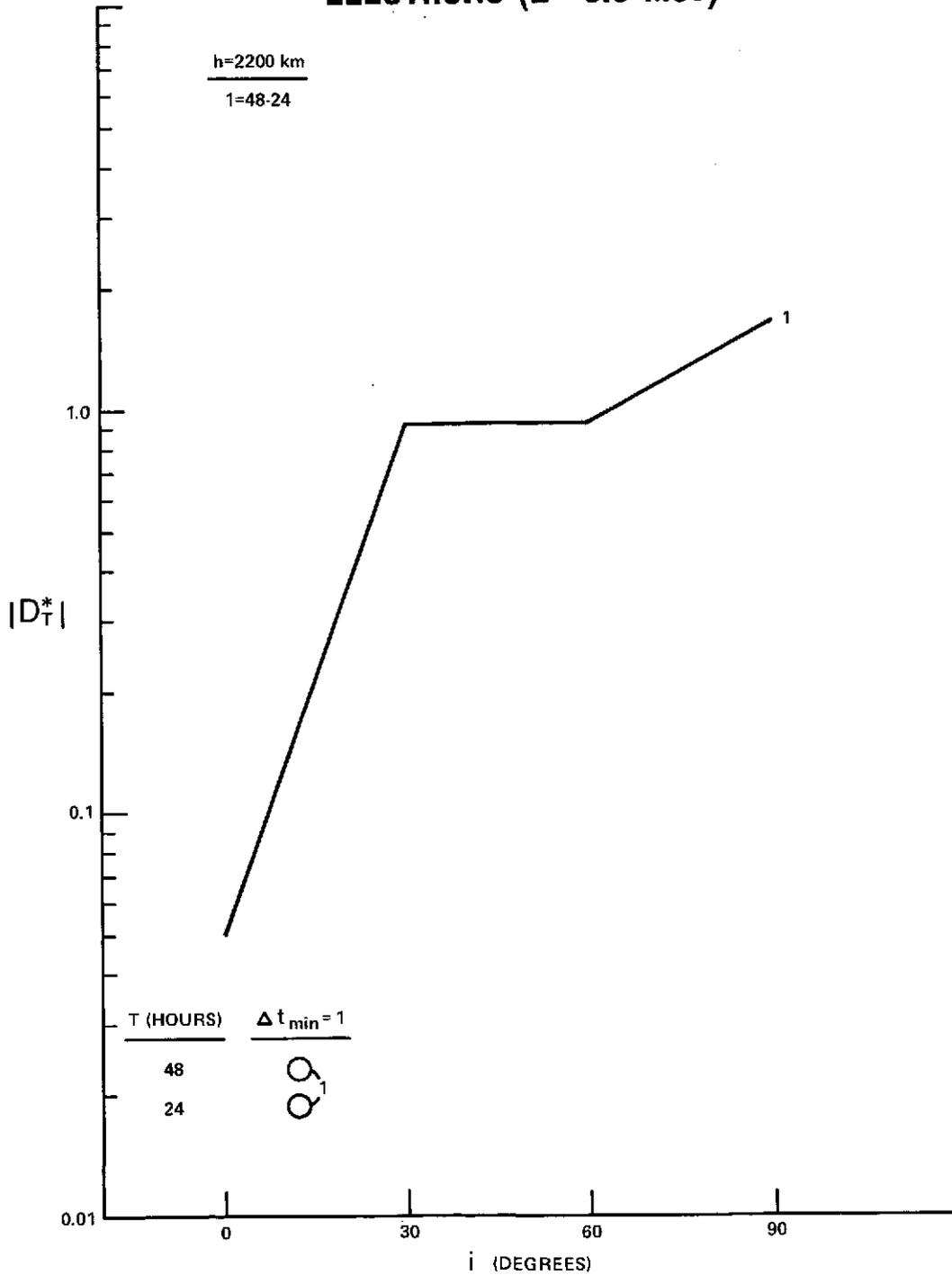


Figure 17

# ELECTRONS ( $E > 0.5$ Mev)

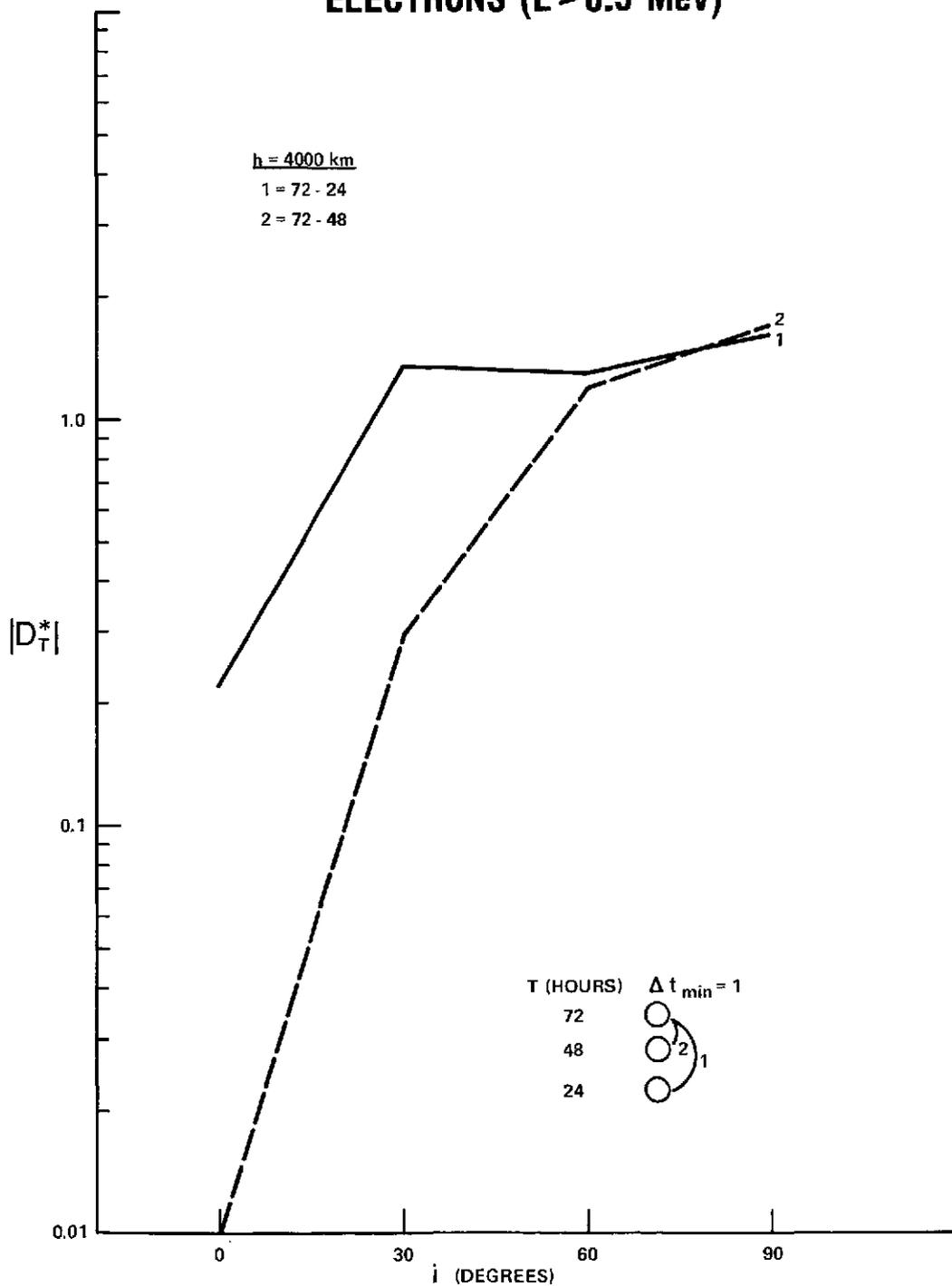


Figure 18

# ELECTRONS ( $E > 0.5$ Mev)

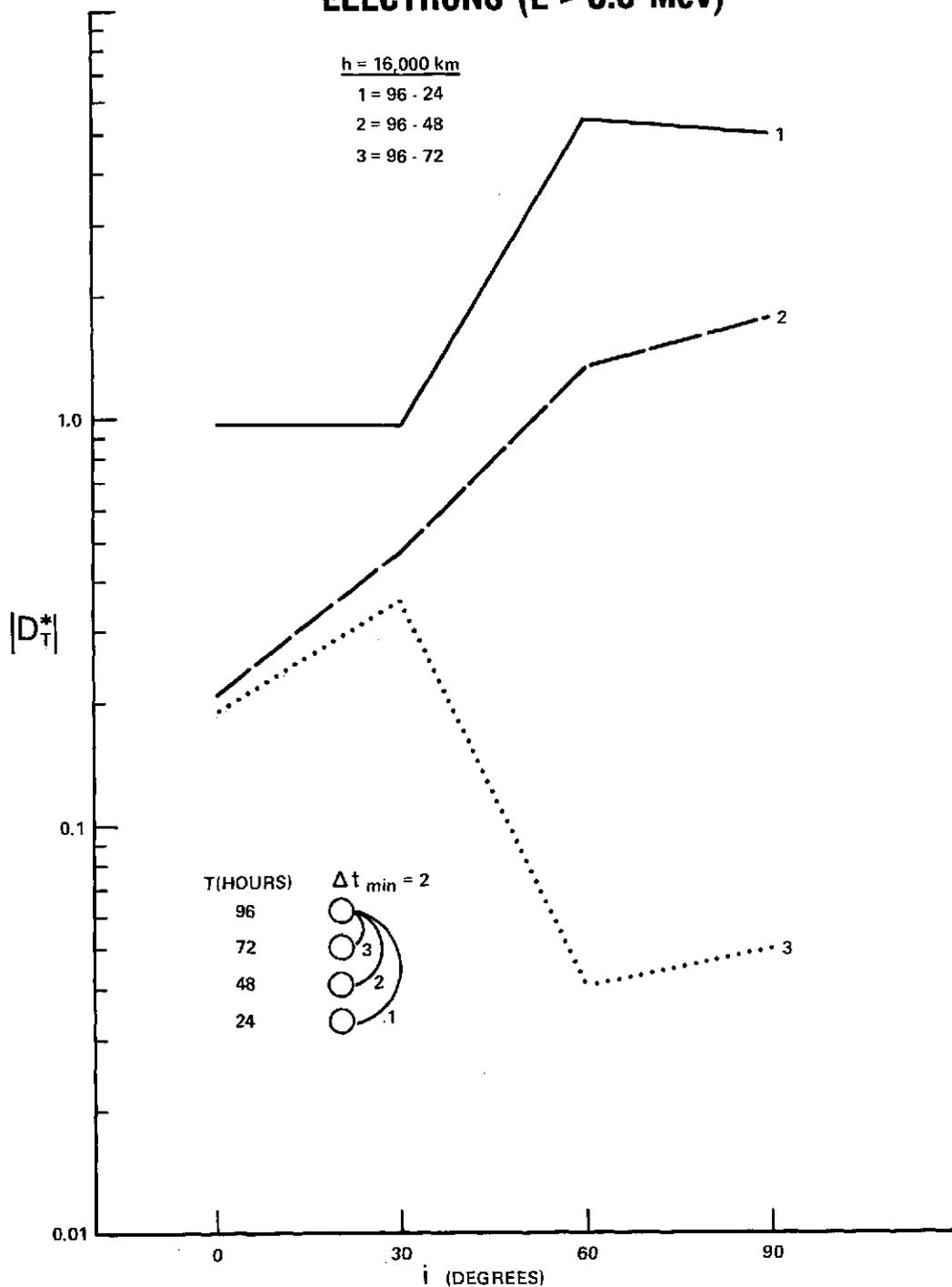


Figure 19

# ELECTRONS ( $E > 0.5$ Mev)

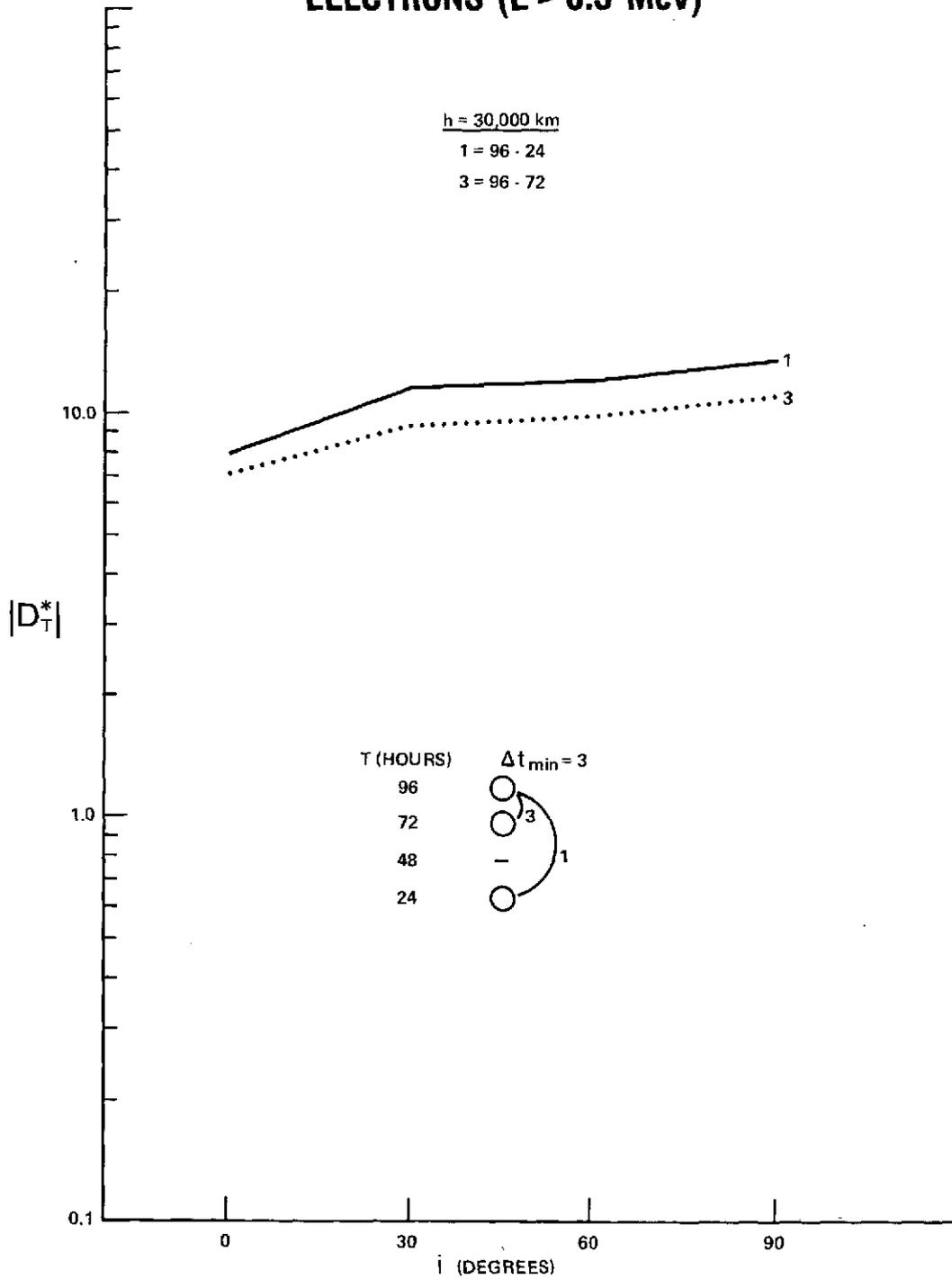


Figure 20

# PROTONS (E > 5.0 Mev)

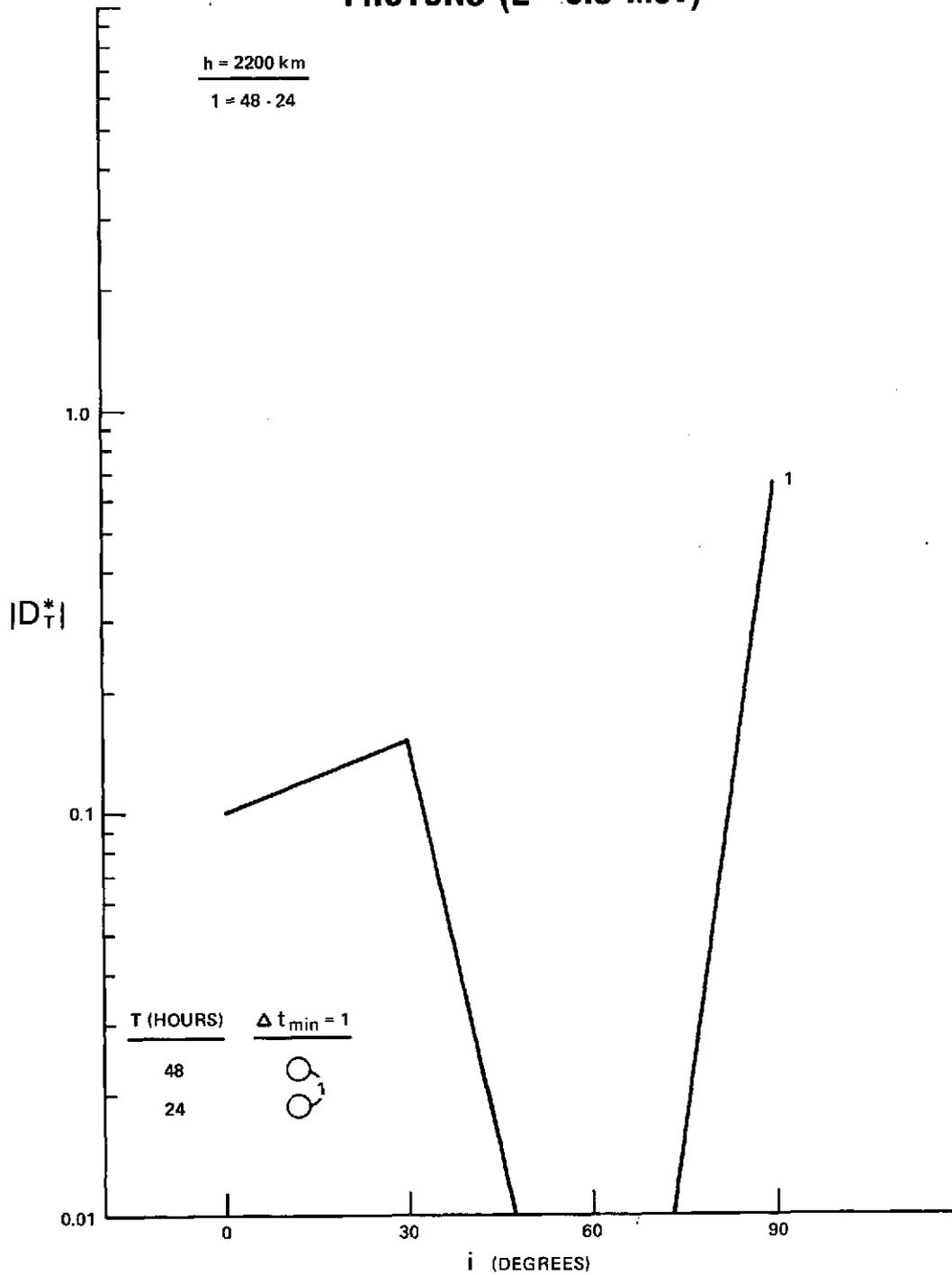


Figure 21

# PROTONS (E > 5.0 Mev)

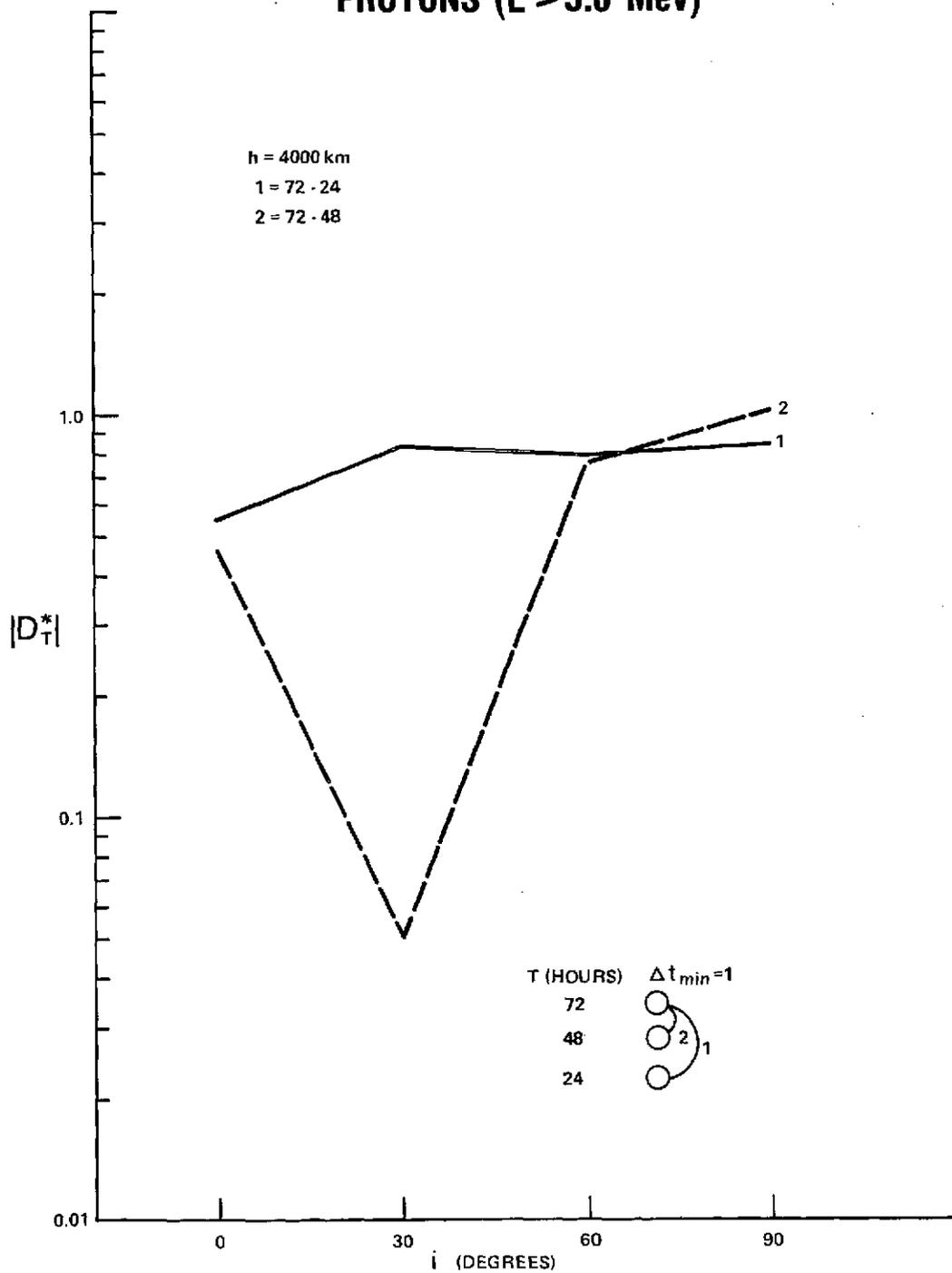


Figure 22

# PROTONS (E > 5.0 Mev)

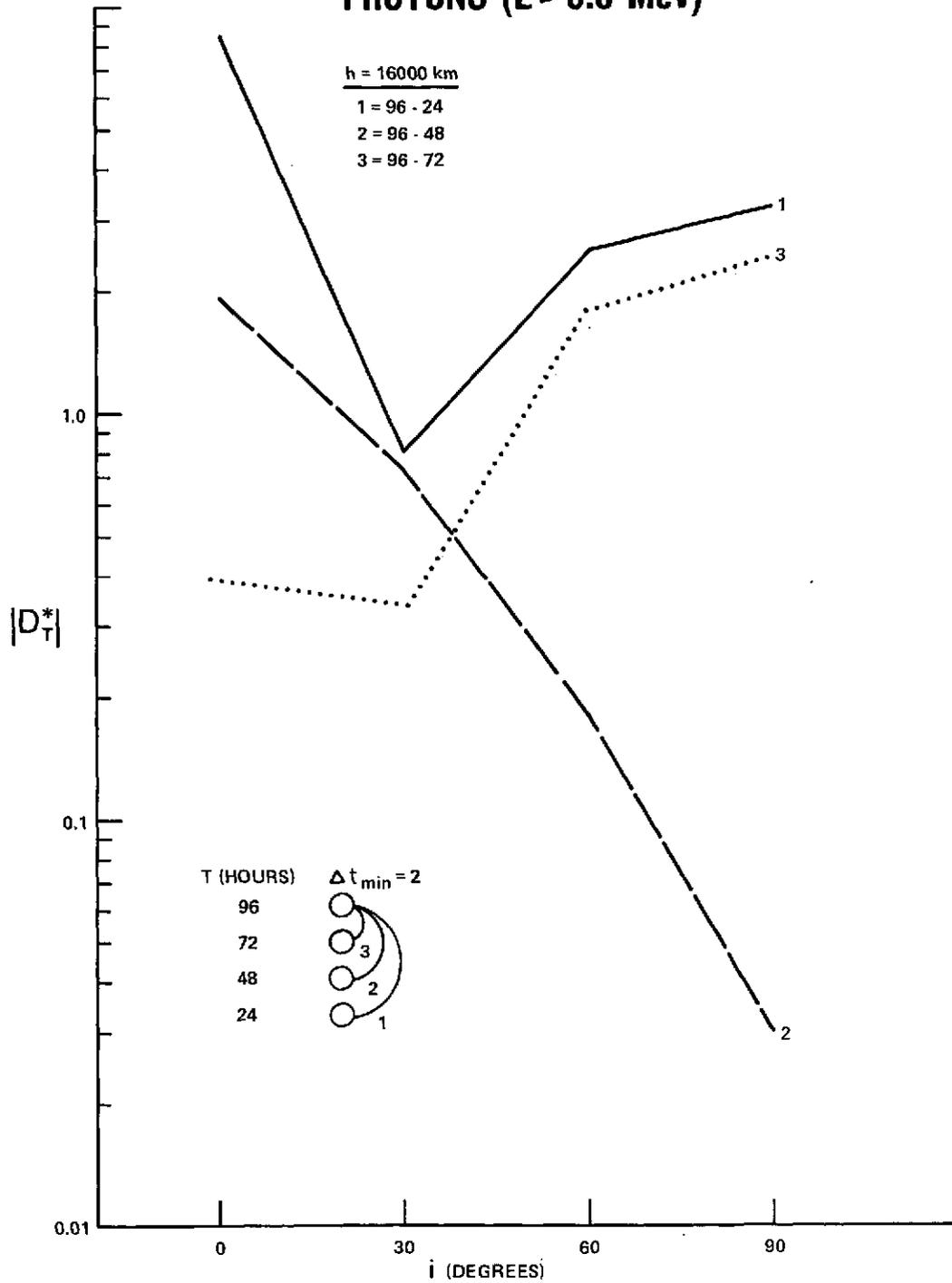


Figure 23

# DETERMINATION OF OPTIMAL INTEGRATION CONDITIONS: TEST RESULTS

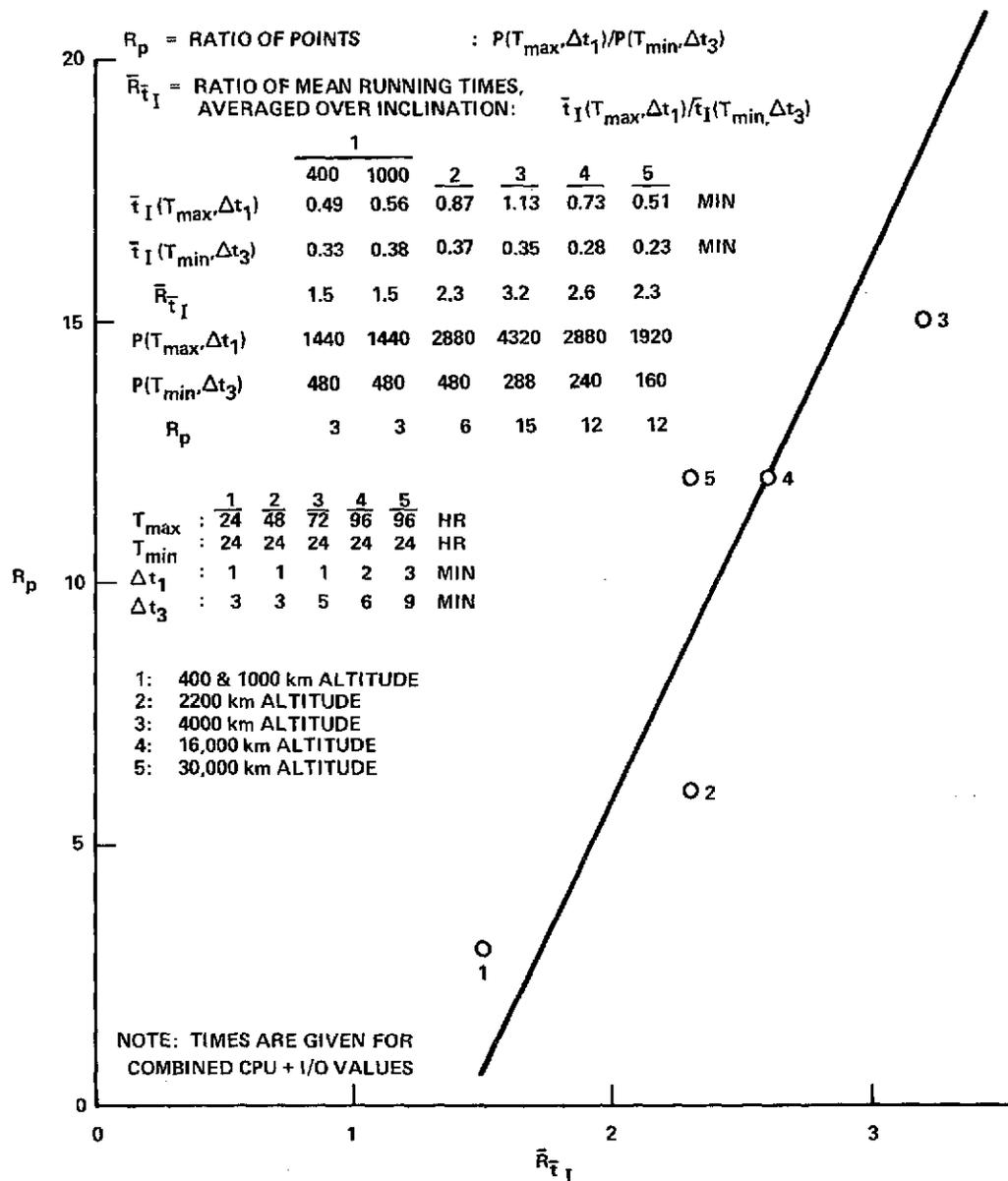


Figure 24

# INCLINATION AVERAGED RUNNING TIMES: COMBINED CPU & I/O OF EXECUTION STEP

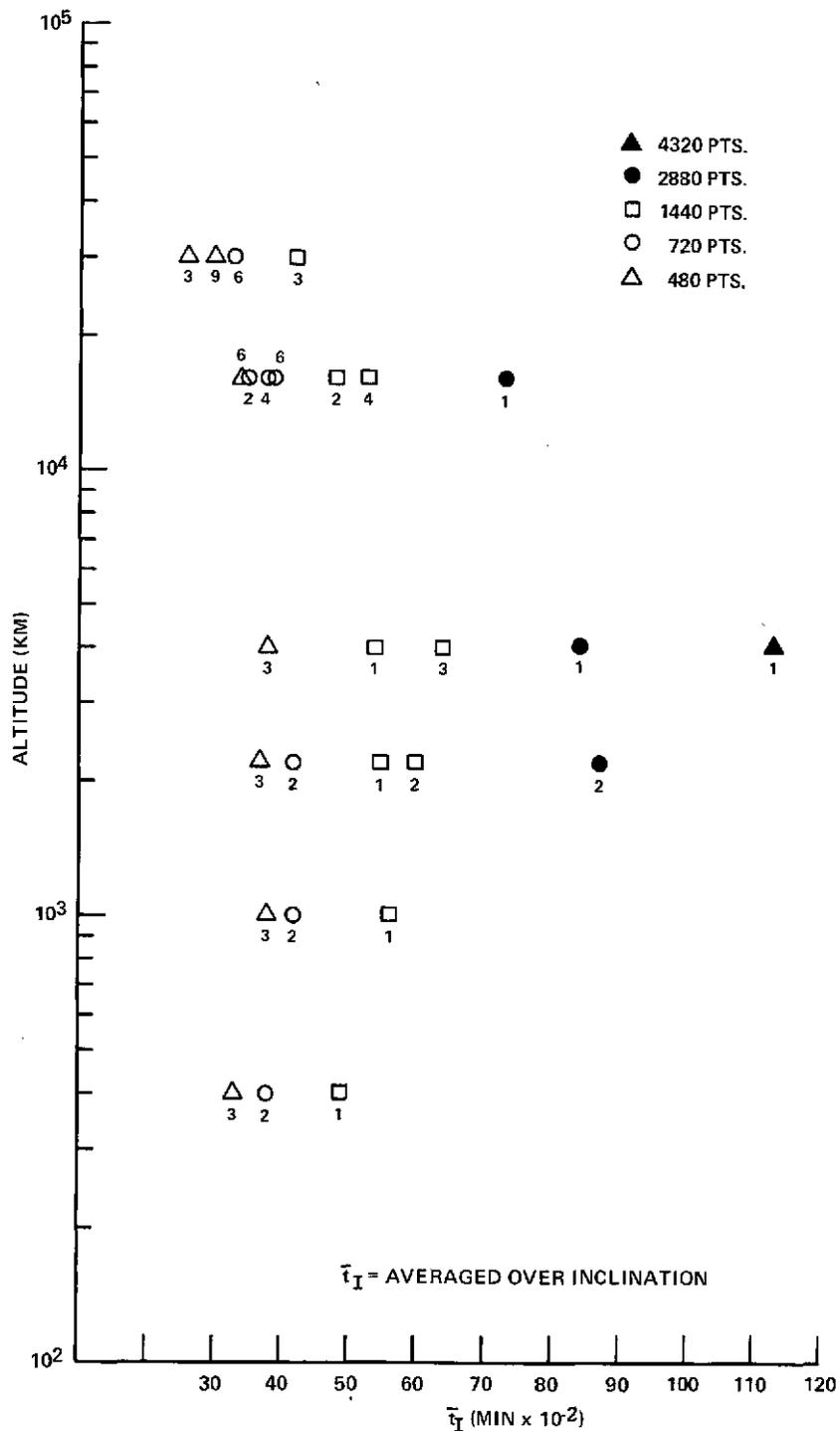


Figure 25

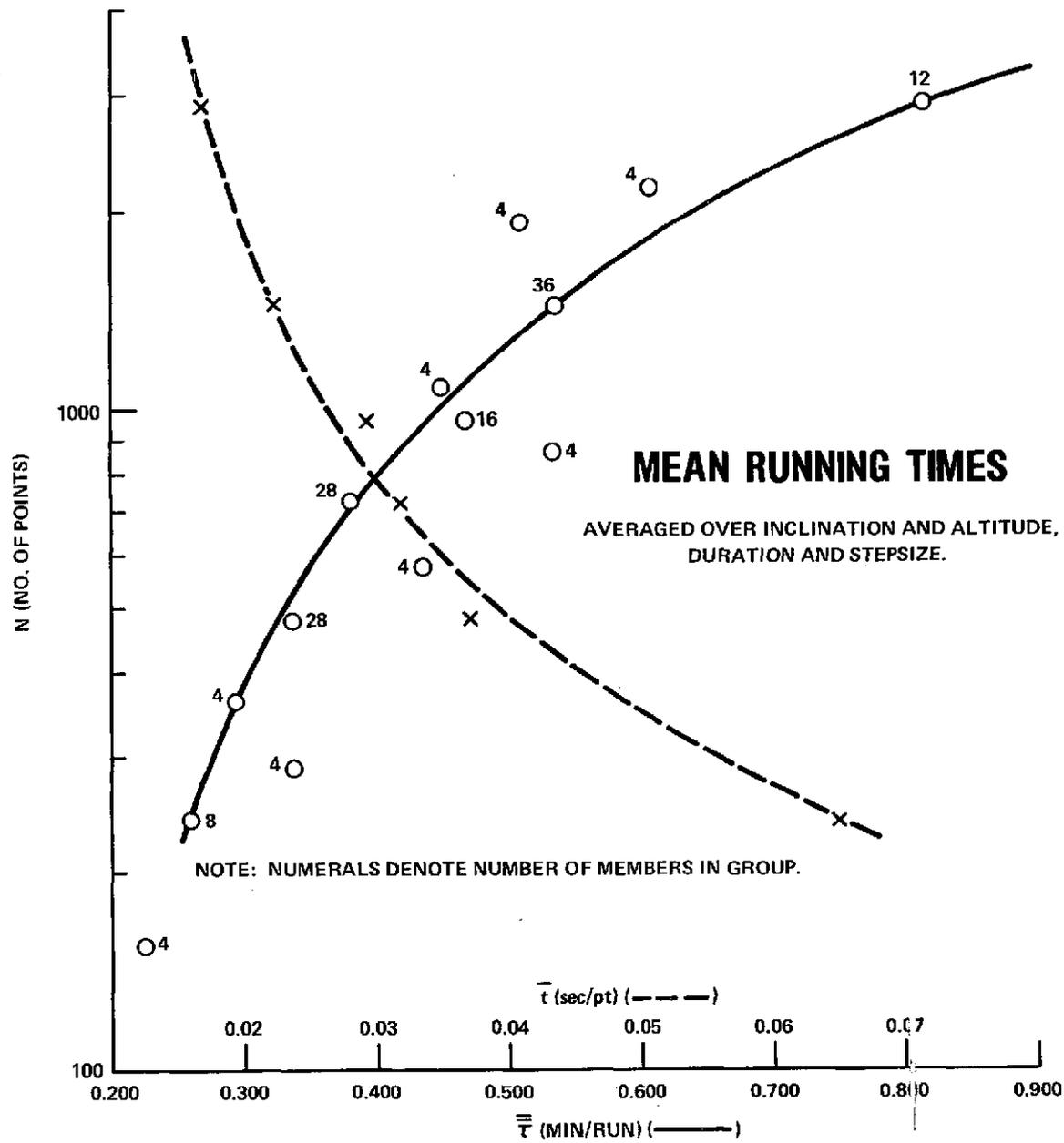


Figure 26