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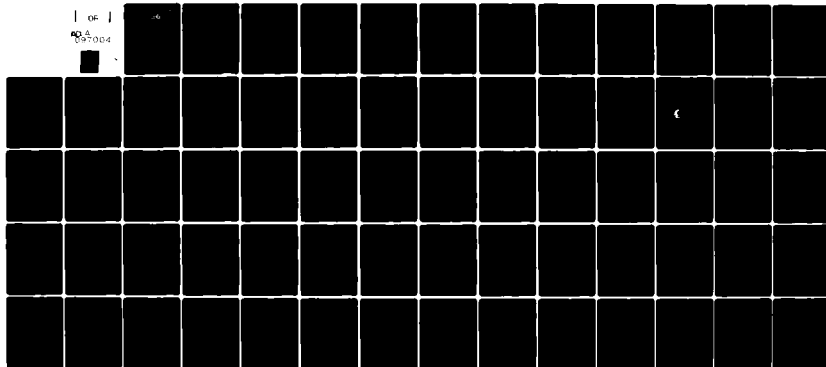
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Collision Hazard in Space

V. A. CHOBOTOV
Guidance and Control Division
The Aerospace Corporation
El Segundo, CA 90245

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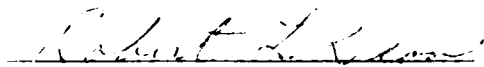
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This report has been reviewed by the Public Affairs Office (SD/PAS) and is releasable to the National Technical Information Service (NTIS). At NTIS, it will be available to the general public, including foreign nations.

This technical report has been reviewed and is approved for publication. Publication of this report does not constitute Air Force approval of the report's findings or conclusions. It is published only for the exchange and stimulation of ideas.


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The statistical data on the known orbiting population of objects is presented and analyzed. Several methods for determining the probability of collision in orbit are described. Collision probabilities for low and geosynchronous orbits are evaluated. Potential operational and design policies for reducing the collision hazard and minimizing the proliferation of debris in space are examined.			

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PREFACE

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I. INTRODUCTION

Since 1957 the continuous use of space has resulted in the buildup of a large number of space objects such as active and spent payloads, rocket bodies, and miscellaneous debris, including numerous explosion fragments. A catalog of an estimated radar-trackable population of some 5000 satellites is maintained by the North American Air Defense Command (NORAD) and other agencies. These objects are a subset of an unknown but larger population of objects including those that are too small to be tracked by radar, but large enough to cause damage to another spacecraft by collision.

In view of this, much interest and concern have been expressed recently by several government agencies and international organizations regarding the orbiting debris problem and the associated collision hazard. Questions on the subject have been posed by the United Nations, NASA and the USAF/SD which have resulted in some assessments of the collision hazard at present and in the near future. Also, work is currently underway to revise the USAF/SD Regulation 550-11 to establish Space Division guidelines and responsibilities for program directors and offices involved in the management of geosynchronous satellites.

The purpose of the present study is to update the existing data on the orbiting population (Ref. 1), and to reexamine the collision hazard issues as currently perceived. Probabilities of collision at low altitudes and in the geosynchronous corridor will be estimated using approximate methods developed in the study. Potential operational and design approaches that can aid in reducing the space debris population growth rates will be outlined. It is hoped that these efforts will contribute towards a better understanding and awareness of the collision hazard so that appropriate action can be taken to maintain a relatively low risk environment for current and future satellite systems.

II. SPACE OBJECT POPULATION

A. GROWTH RATE

On the basis of a worldwide network of sensors, NORAD tracks and maintains a catalog of most of the manmade orbiting objects in space. Although NORAD is the primary source of orbit elements for these objects, other sources are NASA Satellite Situation Reports, RAE tables of earth satellites, TRW Space Log and various military and civilian agencies including those of the United Nations.

The orbiting population of objects consists of operational and decayed payloads, miscellaneous mission-related debris such as rocket bodies, clamps, shrouds, etc., and a multitude of explosion fragments. The latter constitute more than 60% of the trackable population (Ref. 2). For example, the number and type of objects listed in the NORAD catalog for 27 April 1980 are given in Table 1 (Ref. 3). It should be noted, however, that the cataloged population includes only those objects which can be tracked by radar (greater than 0.01 m^2 in area) up to 5000 km in altitude or optically. The currently estimated total population (down to 1 cm^2 in size) is believed to be on the order of 10,000 to 15,000 objects. In the geosynchronous corridor, the total population down to 1 cm^2 is probably as much as an order of magnitude greater than that which is cataloged. More detail on the synchronous satellite catalog is provided in the Appendix.

The approximate growth rate of the cataloged population is exhibited in Fig. 1. The observed rate of increase (on the basis of the smoothed data of Fig. 1) is between 9 and 13% per year depending on the time period of interest. An instructive computer illustration of the space objects which could be seen by an observer in a 300 nmi circular orbit for a period of 10 seconds is displayed in Fig. 2 where the apparent size of the object (circle radius) denotes relative distance from the observer.

Table 1. NORAD Catalog of All Objects for 27 April 80

Earth Orbit Payloads	1055	
Earth Orbit Debris	3384	
Deep Space Payloads	61	
Deep Space Debris	<u>52</u>	
Current Objects	4552	4552
Decayed Payloads	1399	
Decayed Debris	<u>5831</u>	
Decayed Objects	7230	<u>7230</u>
Total Objects		11782

Synchronous Population - 28 April 80

Satellites

DOD(SCF)/NATO	23	
NASA	17	
COMSAT CORP	13	
LINCOLN LABS, RCA, W.U., ESA	10	
USSR	16	
UK, CAN, JAP, FR, IT, INDONESIA	<u>18</u>	
	97	97

Rocket Bodies and Old Satellites

With Current Tracking	47	
No Recent Tracking	<u>56</u>	
	103	<u>103</u>
Total Synchronous		200

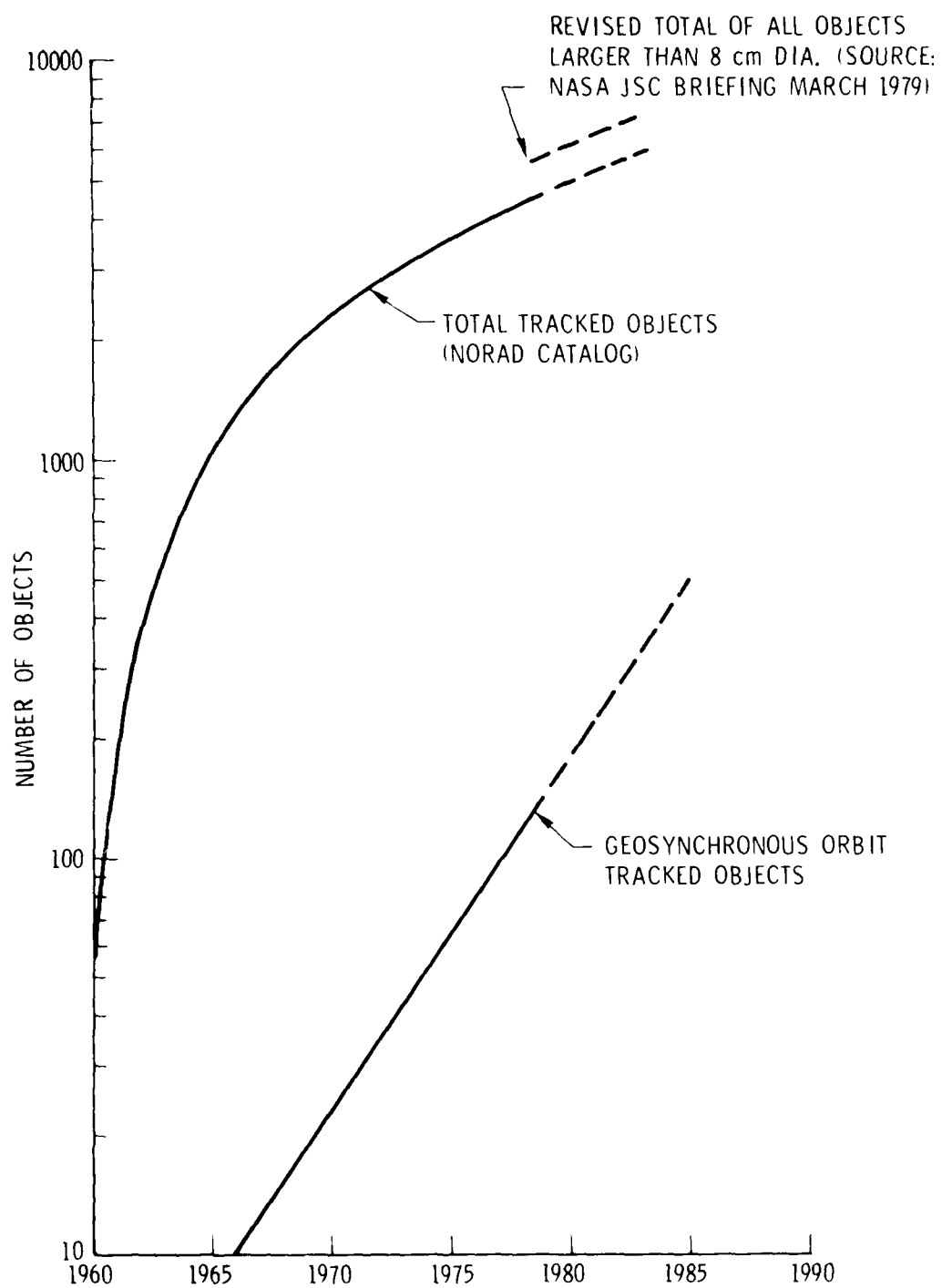


Fig. 1. Cataloged Objects Population History

OBSERVER LATITUDE = 34.6°N , LONGITUDE = 239°E , ALTITUDE = 300 nmi
 AIMPOINT ABOVE LATITUDE = 21.4°N , LONGITUDE = 201.7°E
 10.0 deg ABOVE HORIZON
 MOTION IS FOR 10 sec

NOTE: APPARENT SIZE INDICATES RELATIVE DISTANCE FROM OBSERVER.
 FIELD-OF-VIEW IS $30^{\circ} \times 55^{\circ}$.

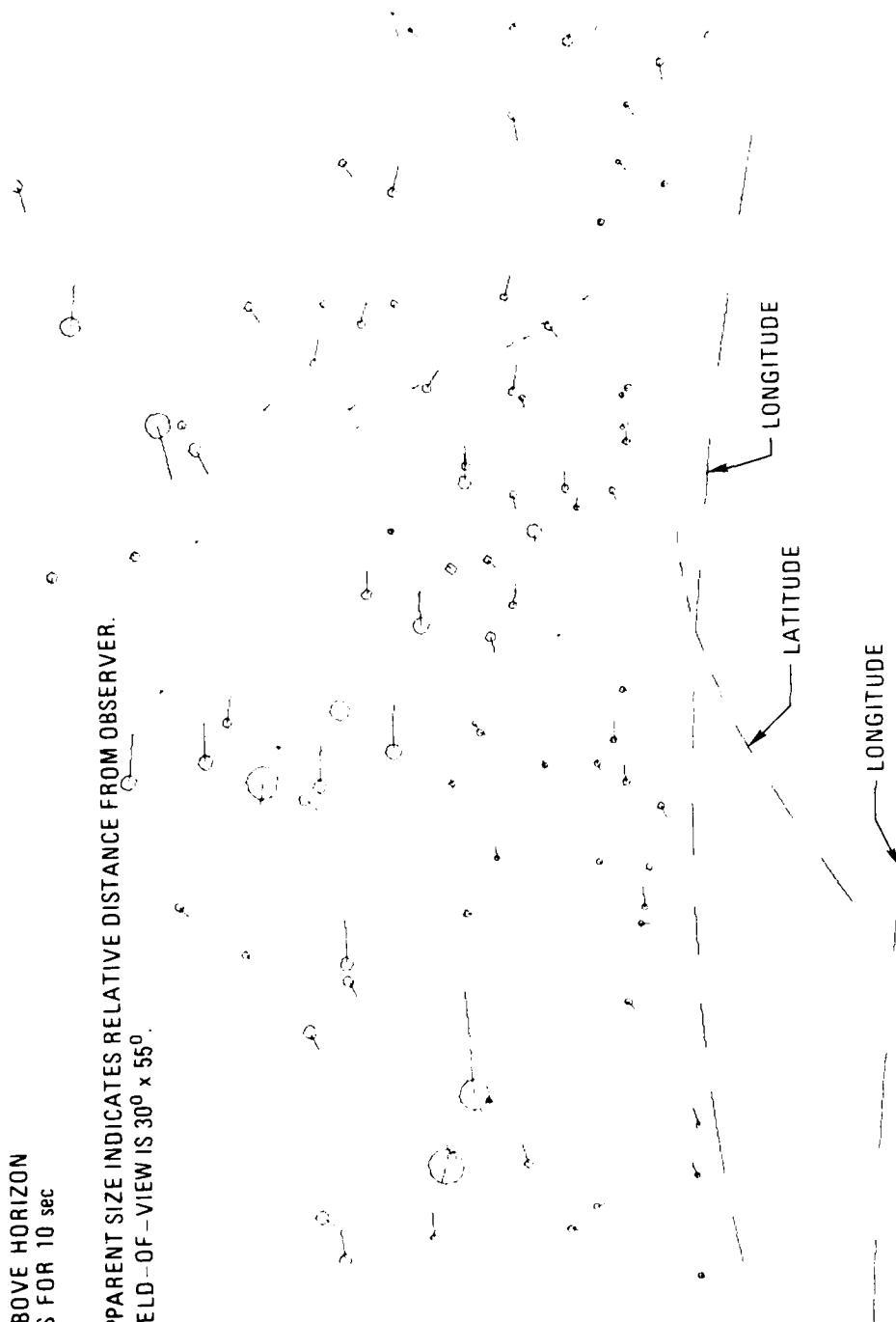


Fig. 2. Computer View of a Sample of Space Objects
 in a 300 nmi Circular Orbit

B. ORIGIN AND DISTRIBUTION

The principal sources of the orbiting population of objects to date have been the nearly 2000 launches by the U.S., the USSR, and several other countries. The history of known launches and payloads placed in orbit since 1975 is exhibited in Fig. 3. The principal U.S. launch vehicles are the Delta, Atlas/Agena, Centaur, Titan III and the Scout stages which have accounted for the estimated 33 U.S. launches in 1978. The total of 87 USSR launches in 1978 have resulted in a large number of the COSMOS series of satellites some of which were returned to earth or commanded into a destructive reentry into the atmosphere. By 1 January 1979 there were six launches by France, four by Japan, two by China and one by the U.K. From 1968 the yearly total number of launches varied between 106 and 128 for all countries (Ref. 4).

Payload and rocket body explosions in orbit are another source of space debris. It is known for example, that there have been over 50 such explosions as of 4 October 1978. A number of spacecraft explosions are known to have taken place in orbit related to antisatellite tests (ASATs) and/or attempts to inject payloads into geosynchronous orbit. A recent example of the latter was the apparent loss of the RCA Satcom 3 and the Japanese ECS 2 satellites which seem to have experienced anomalous burns of the apogee injection motors that resulted in a loss of telemetry before the completion of the insertion burn. Another example of such a malfunction is the SKYNET 1B launch on 19 August 1970 on a Thor-Delta vehicle which placed a communication payload into a 137×20099 nmi transfer orbit. On 22 August 1970, the apogee burn motor (ABM) was fired which should have placed the satellite into a nearly synchronous equatorial orbit. Approximately 14 seconds after the initiation of the apogee burn, all tracking and telemetry data were abruptly lost. Subsequent analyses of the data (Refs. 5 and 6) indicated that the ABM performed anomalously resulting in "regressive burning." An estimated $\Delta V = 4000$ fps out of the required $\Delta V = 5814$ fps appears to have been added at apogee. The resultant orbit for the assumed explosion fragments was estimated as approximately 5192×20088 nmi inclined 5.30° to the equator. The velocity at apogee relative to the geosynchronous velocity is about 1700 fps which may represent

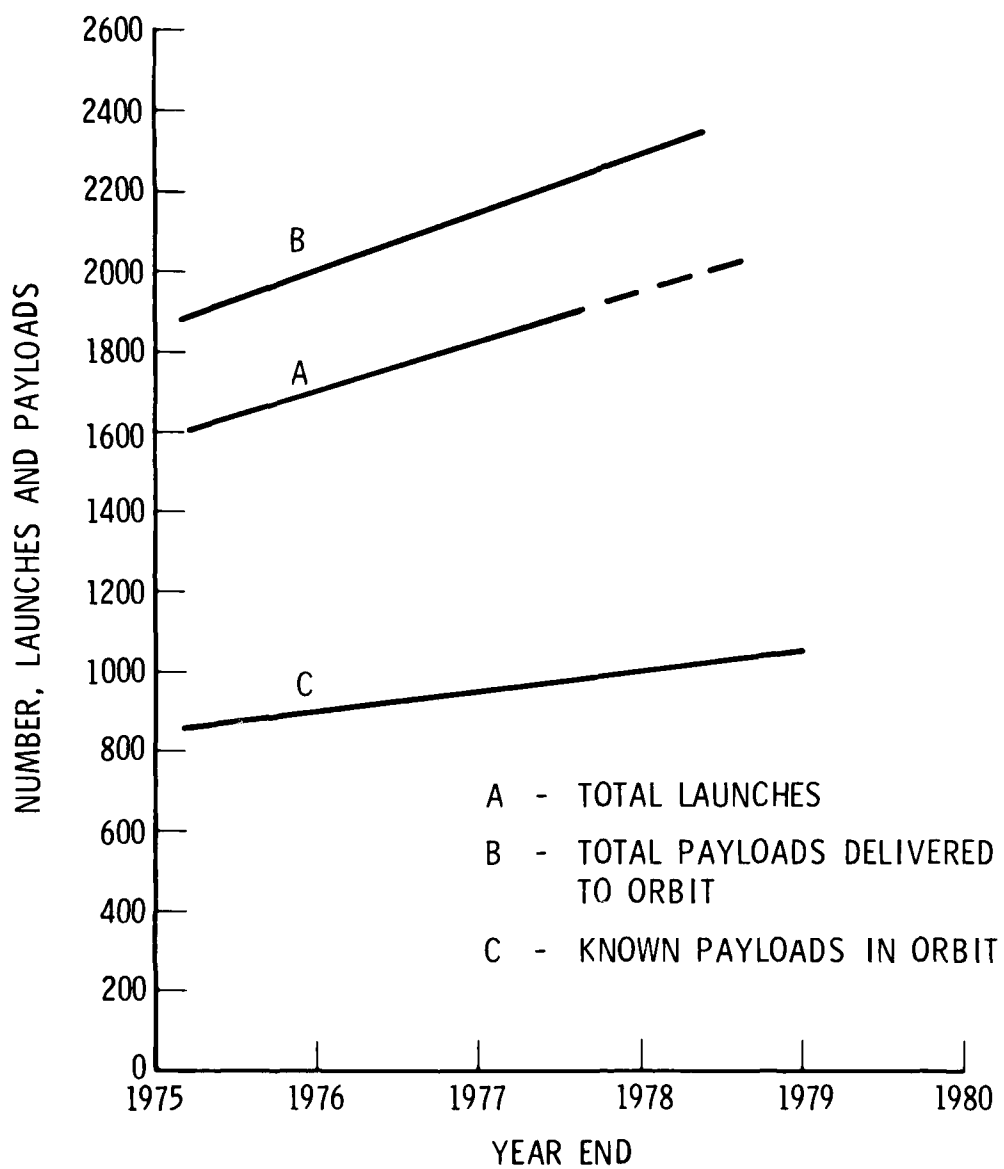


Fig. 3. Known Launches and Payload History

a significant collision hazard to any geosynchronous object in the vicinity of this orbit. The number and distribution of the explosion fragments, if an explosion in fact occurred, cannot be easily determined. However, the high perigee altitude of the final orbit precludes any significant reduction of the debris because of atmospheric or other perturbative effects. Figure 4 exhibits the orbit geometry for this event.

Other potential sources of space debris are collisions between debris objects and spacecraft or other debris objects. It is considered likely, for example, that the solar panel malfunction on the geosynchronous GEOS-2 spacecraft is a result of a collision with a small object (Ref. 7). Also, the breakup of PAGEOS balloon in July, 1975 after 9 years in orbit appears to have resulted from a similar cause. The low orbit COSMOS 954 was similarly reported to have suffered a sudden depressurization thought to be caused by a collision with debris (Ref. 2). Air Force satellite programs in synchronous orbit have reported, on two separate occasions, sudden small changes in spacecraft angular momentum. These unexplained changes may have been caused by impacts with natural or manmade objects.

The possibility of a self-perpetuating debris belt caused by intercollisions between objects in space also exists. This process would parallel certain theories concerning the growth of the asteroid belt. The debris flux in such a belt could exceed the natural meteoroid flux in the not too distant future if present trends continue (Ref. 8).

C. DENSITY OF OBJECTS AS A FUNCTION OF ALTITUDE

1. LOW ALTITUDE ORBITS

A total of 4174 space objects from the NORAD Catalog for April 28, 1980 have been examined numerically to determine the distribution with altitude. The results are presented in Figs. 5 and 6. It can be seen that the majority of satellites are within 1.5 earth radii (E.R.) with a small increase to synchronous altitude where an increment occurs at 6.62 E.R. Figure 6 indicates that the greatest density of objects occurs between 500 and 1500 km altitude. Distributions by semimajor axis A (normalized with respect to earth

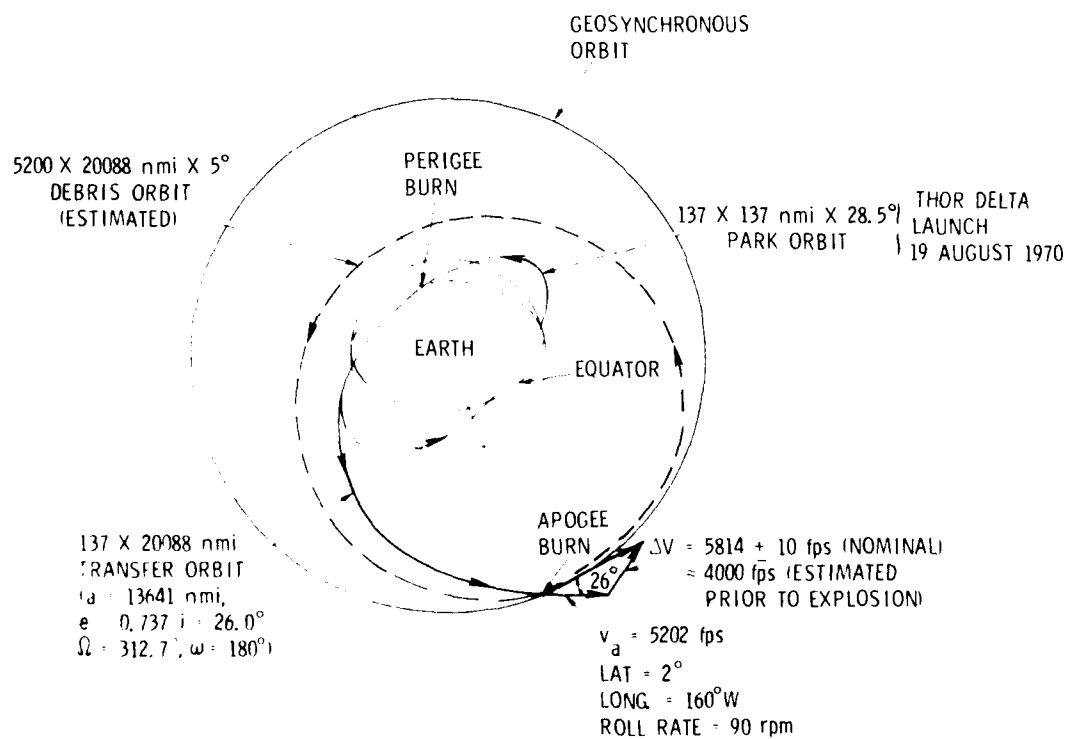


Fig. 4. SKYNET 1B Geosynchronous Orbit Injection Geometry

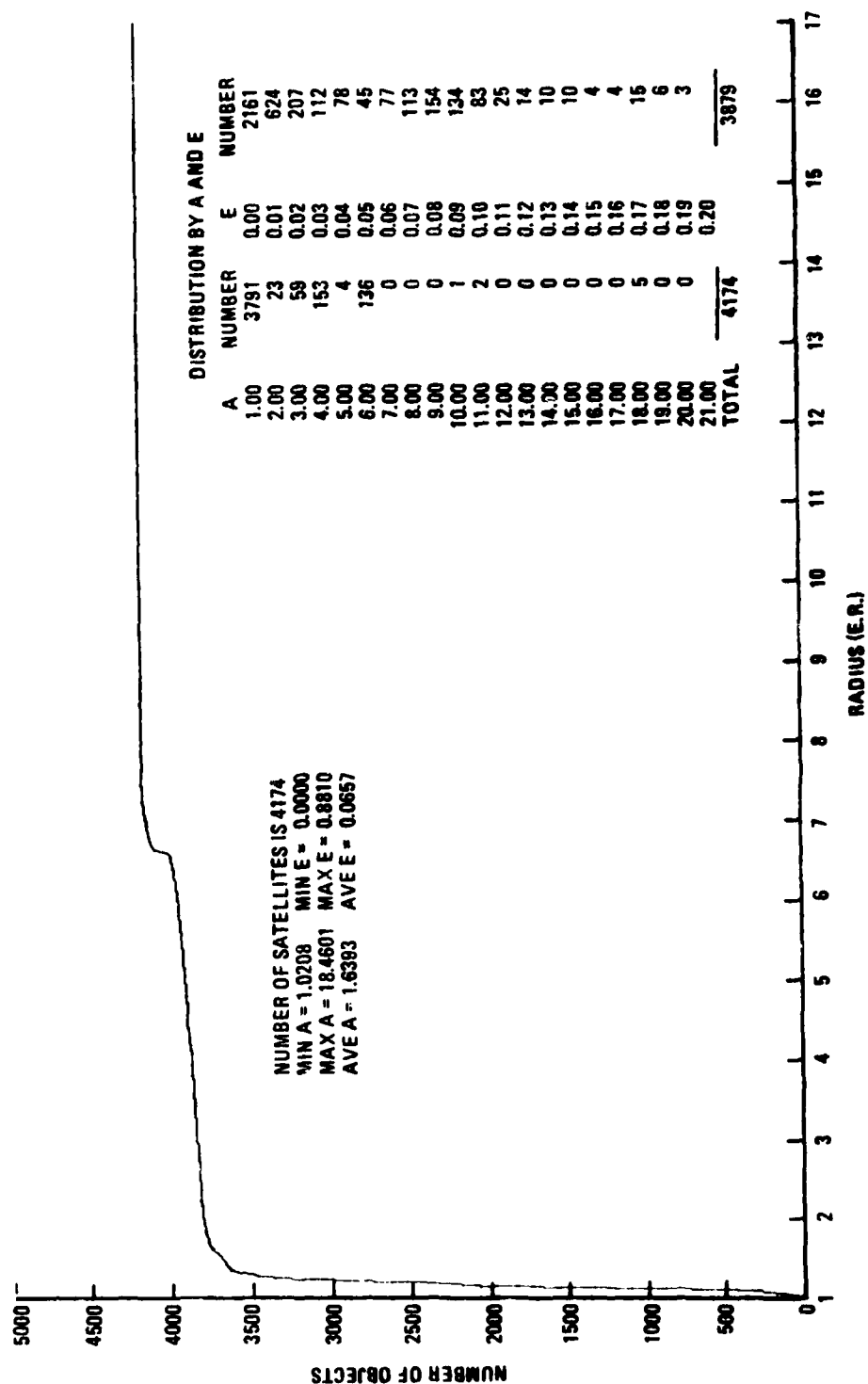


Fig. 5. Cumulative Number of Objects vs. Geocentric Radius in Units of Earth Radius

NOTE:
4174 OBJECTS
(APRIL 1980
NORAD CATALOG)

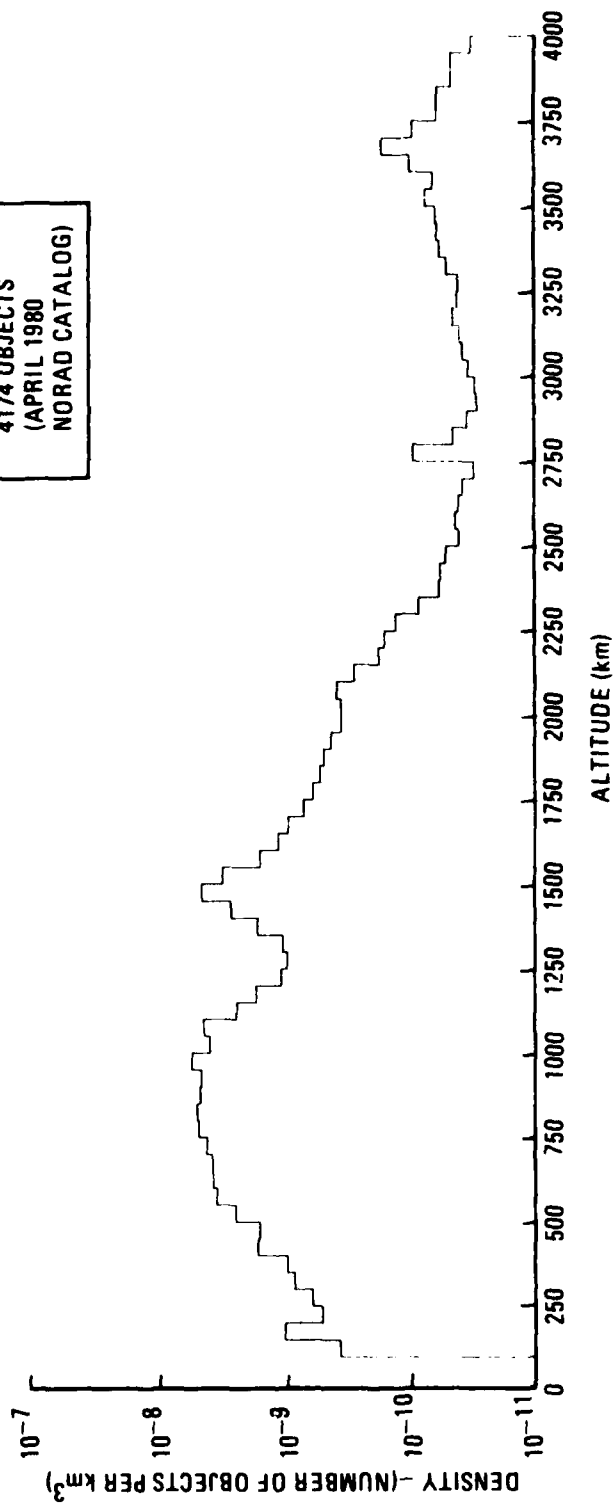


Fig. 6. Space Object Density vs. Altitude

radius), eccentricity E, ascending node (NODE) and the argument of perigee (OMEGA) are given in Fig. 7. It can be seen, for example, that there are 3791 objects with A greater than 1 but less than 2, and E greater than zero but less than 0.01. The distribution with respect to orbital inclination (INC) is given in Fig. 8.

2. GEOSYNCHRONOUS ORBITS

The geosynchronous region of space is a unique corridor where most of the present and future communication satellites are or will be located. The principal reason for this is that these satellites appear to be either stationary with respect to the earth or are slowly drifting relative to some initial longitude. The satellites are stationary when they are in circular orbits in the equatorial plane with periods of revolution equal to the rotational period of the earth. Secular or continuous drifting occurs due to slight differences in the orbital periods of revolution. Periodic drifting may also occur because of orbital eccentricity or inclination effects as well as perturbing effects of the geopotential field. For example, the $J_{2,2}$ tesseral harmonic causes an oscillatory (librational) motion about the geopotential stable points at 75.3°E and 255.3°E longitudes with long periods (on the order of years) of libration (see Fig. 9). A large number of objects librating about these points may pose an additional hazard to the active payloads placed at or near these locations. The longitudinal location for 154 geosynchronous objects listed in the appendix is illustrated in Fig. 10. NORAD publishes the orbital elements on these objects on the basis of data obtained from NORAD, the Satellite Control Facility (SCF), NASA and Intelsat tracking networks. The data on the orbital elements is provided by NORAD in the form of punched cards received via TWX on a daily basis. Updates for any given object are provided typically within a one or two week period.

Figure 11 presents the longitudinal location of the current and planned communication satellites in geosynchronous orbit (Refs. 9 to 11). Many of these comsats are station-kept within small longitudinal and latitude bands while others drift as the result of natural forces. A few have also been removed from geosynchronous orbit after the completion of their mission (e.g.,

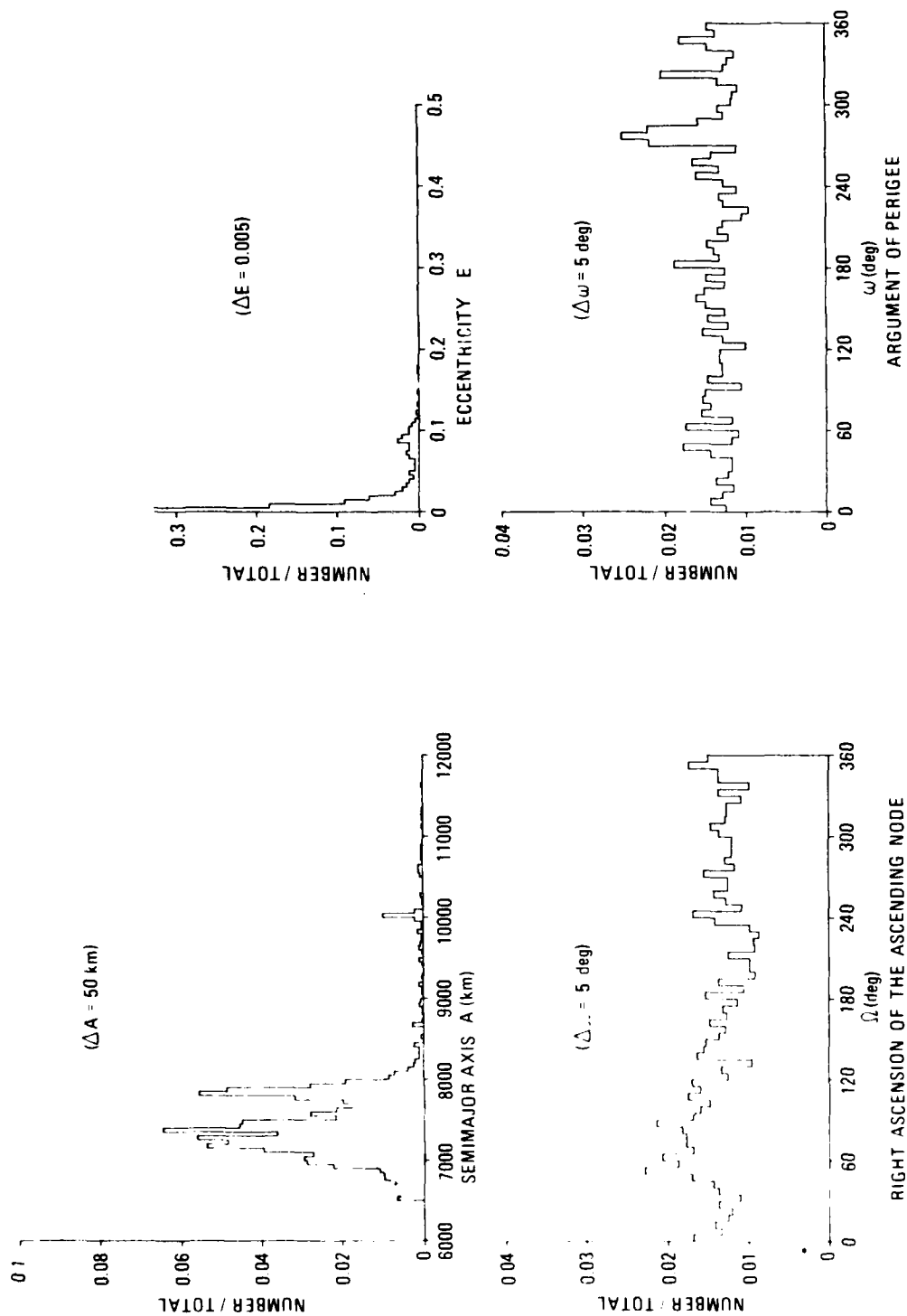


Fig. 7. Fraction of Objects vs. Orbital Parameters

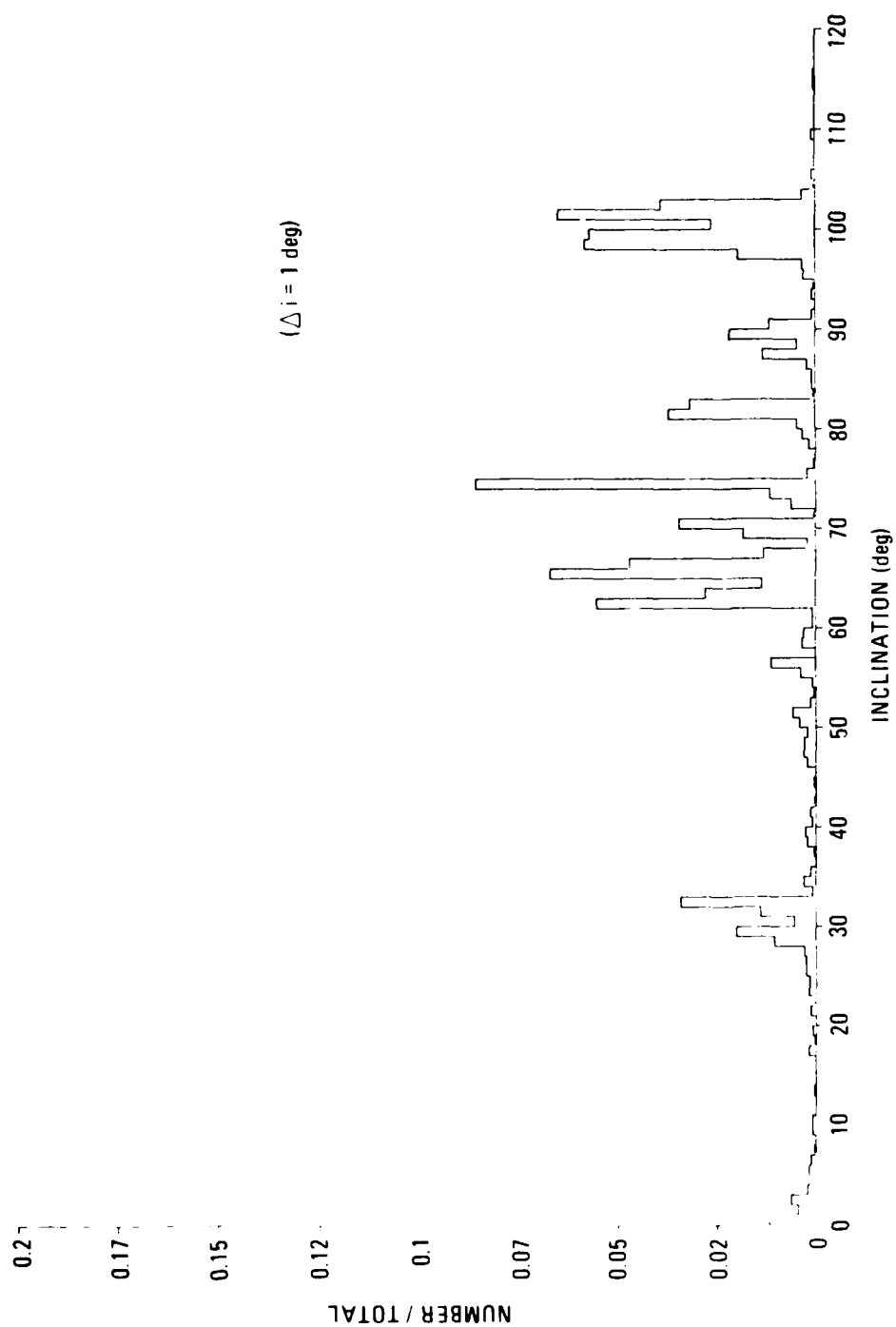


Fig. 8. Fraction of Objects vs. Inclination

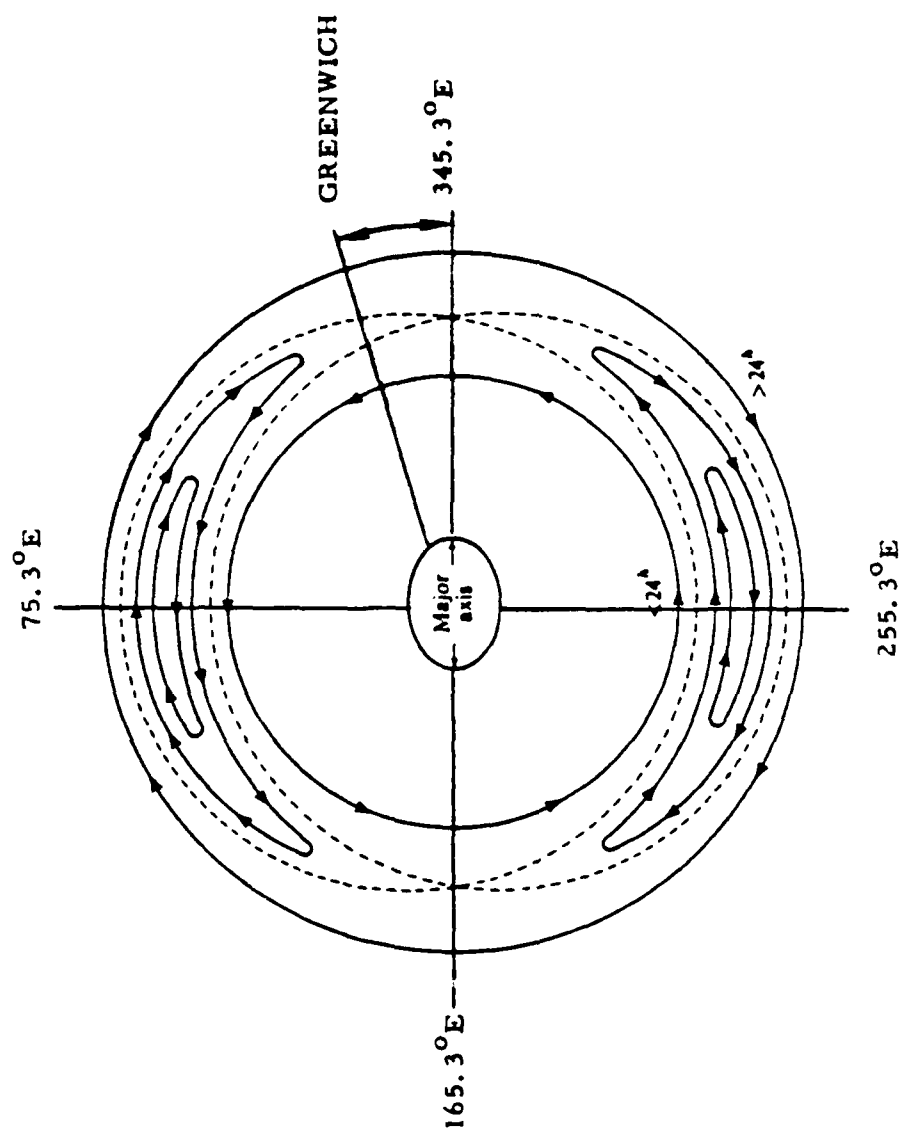


Fig. 9. Representative Satellite Trajectories Relative to Geopotential Stable Points

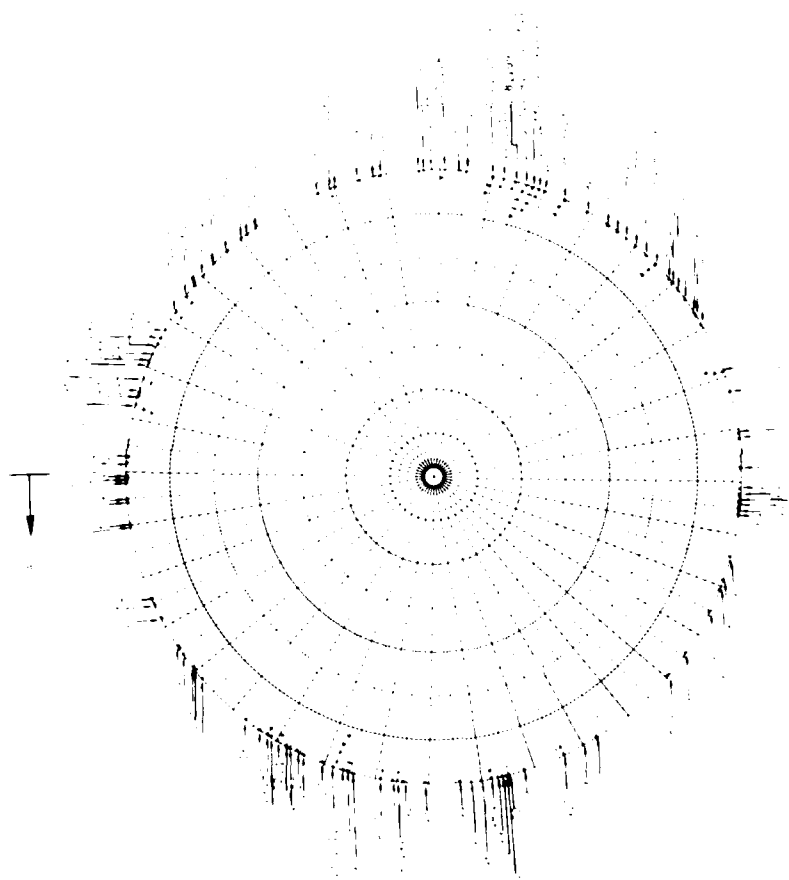


Fig. 10. VORAD Unclassified Geosynchronous Catalog

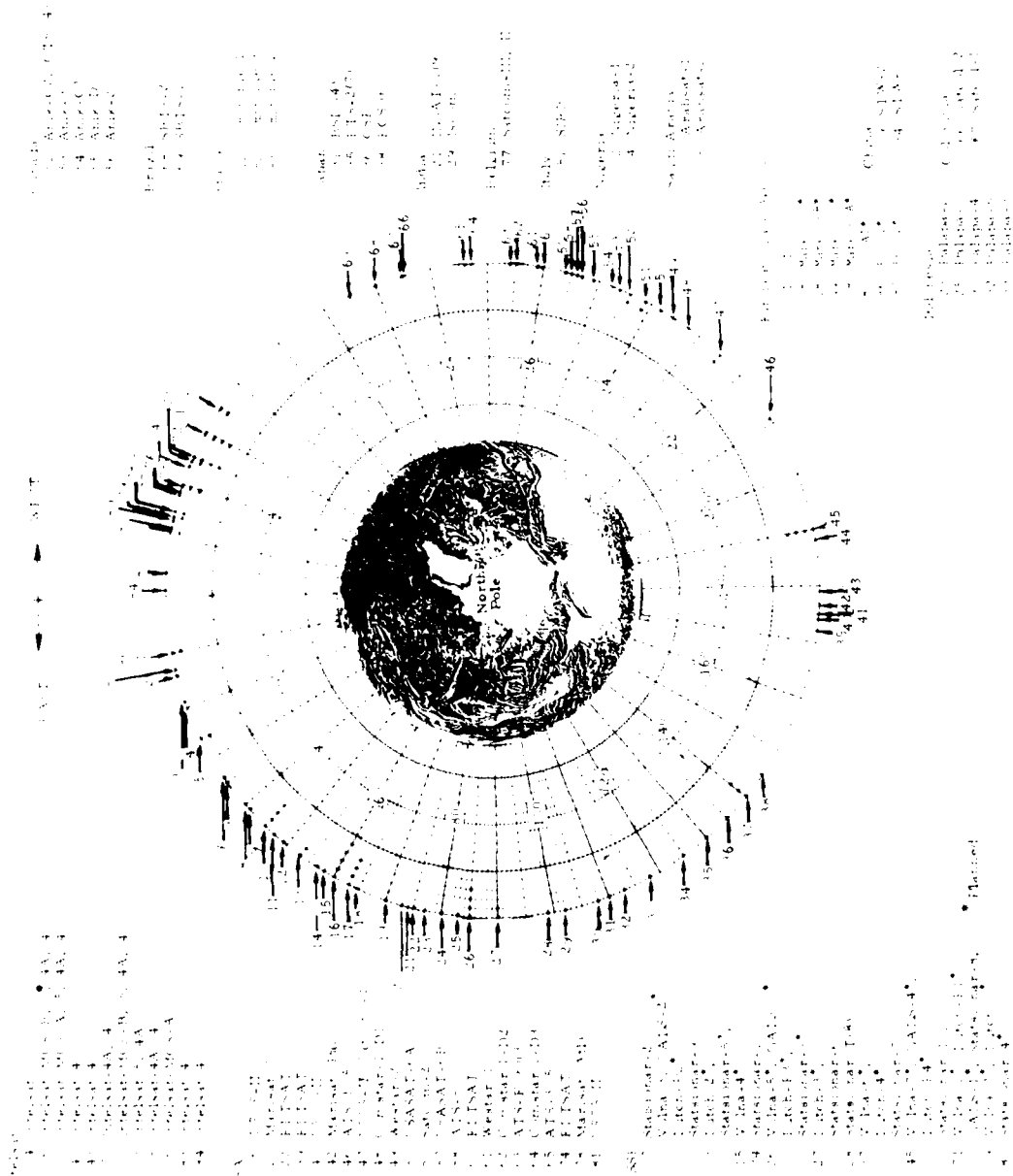


Fig. 11. Geostationary Communication Satellites

Intelsat 3, F-2, F-4 and F-6 to altitudes of 400 to 3700 km above synchronous altitude)(Ref. 12). The ATS-F has been removed from the synchronous altitude orbit to an altitude 250 nmi below synchronous. The distribution of a sample of 134 geosynchronous objects with inclination and eccentricity is given in Figs. 12 and 13, respectively. These results indicate that typical geosynchronous orbits are nearly circular with low inclinations relative to the equator. A few satellites (e.g. ELECTRON, and their rocket bodies have inclinations above 60° (see Appendix). Object density, illustrated in Fig. 14, decreases as the altitude from the geosynchronous orbit and latitude increase. The results in Fig. 14 were obtained numerically by taking "snapshots" of objects once each hour over a period of twenty-four hours within a torus of latitude band $\Delta\phi$ and altitude band Δh centered about the geosynchronous altitude. The total number of observations was then summed and divided by 24 to get an average number of sightings in each band. The average density is the number of sightings divided by the volume of the torus. The nonuniformity of the inclinations of the objects orbits within each latitude band is illustrated in Fig. 14 by the average inclination $\bar{i}$ as noted.

The ascending node distribution for 154 geosynchronous objects presented in Fig. 15 indicates that the orbital planes are not distributed uniformly, but tend to be concentrated in certain regions of space. The impact of this is to increase the probability of collision for some satellites above the representative figures calculated for the synchronous class of satellites.

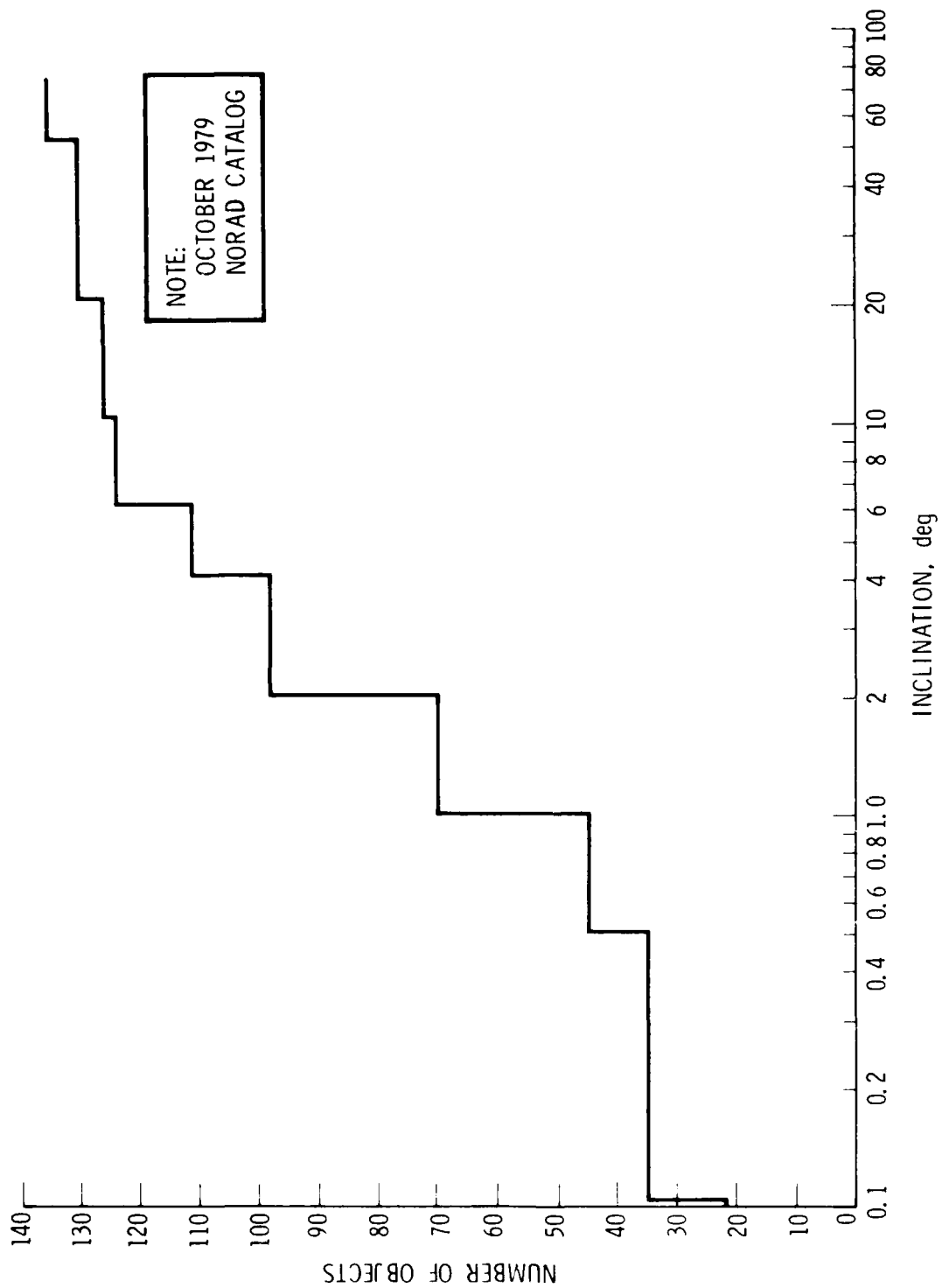


Fig. 12. Cumulative Number vs. Inclination for
Geosynchronous Objects

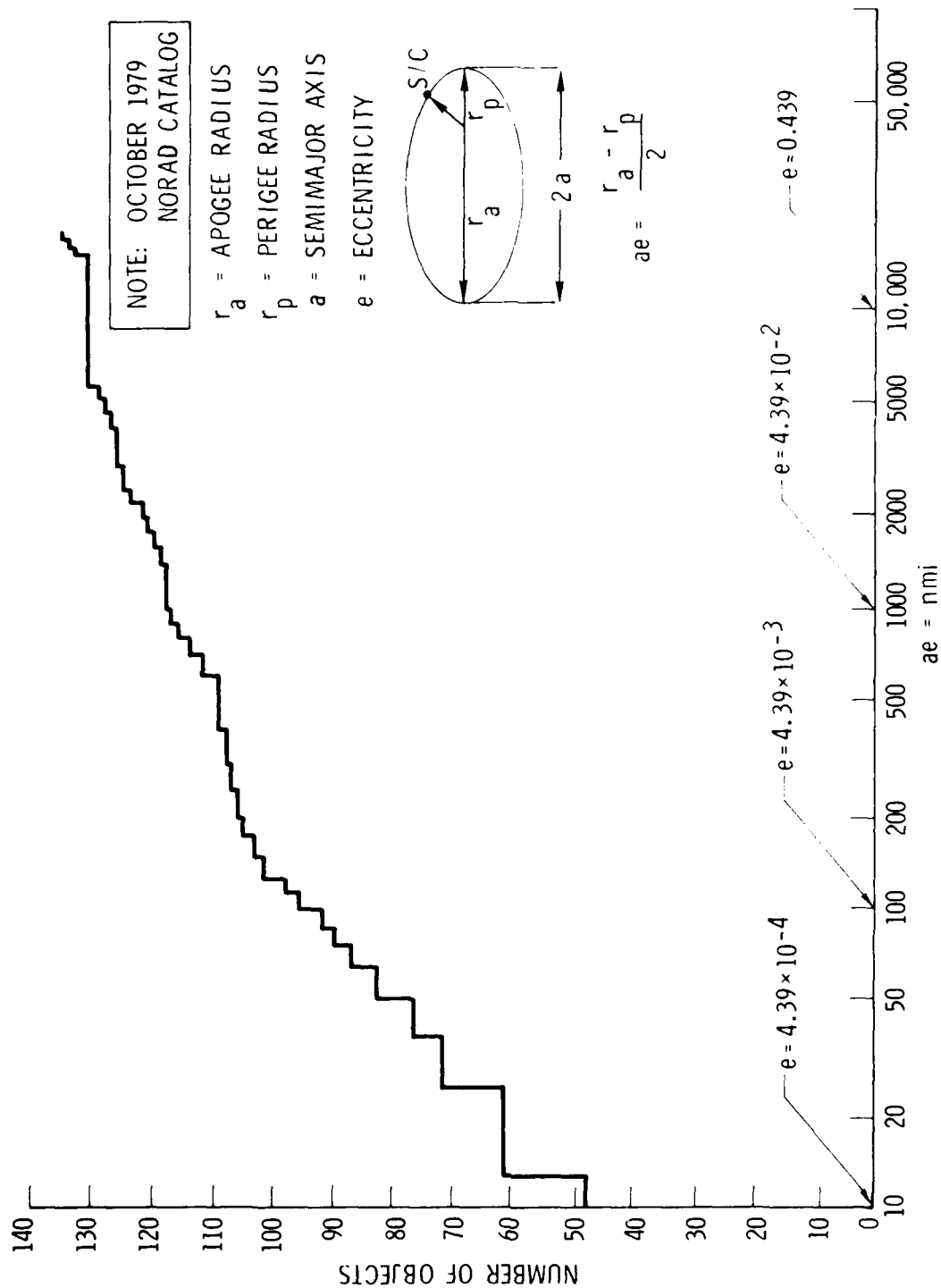


Fig. 13. Cumulative Number vs. Eccentricity for Geosynchronous Objects

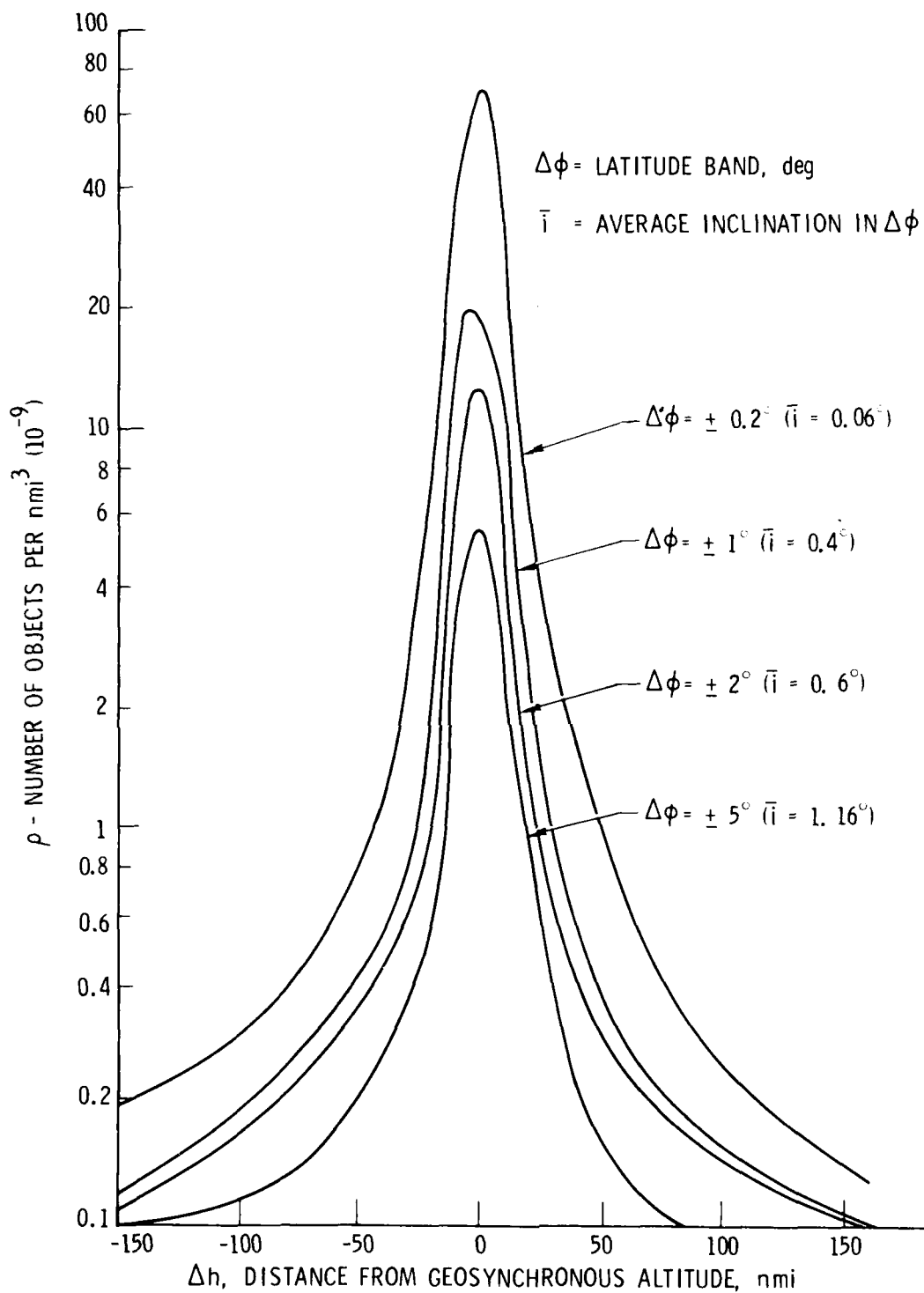


Fig. 14. Object Density in Geosynchronous Orbits

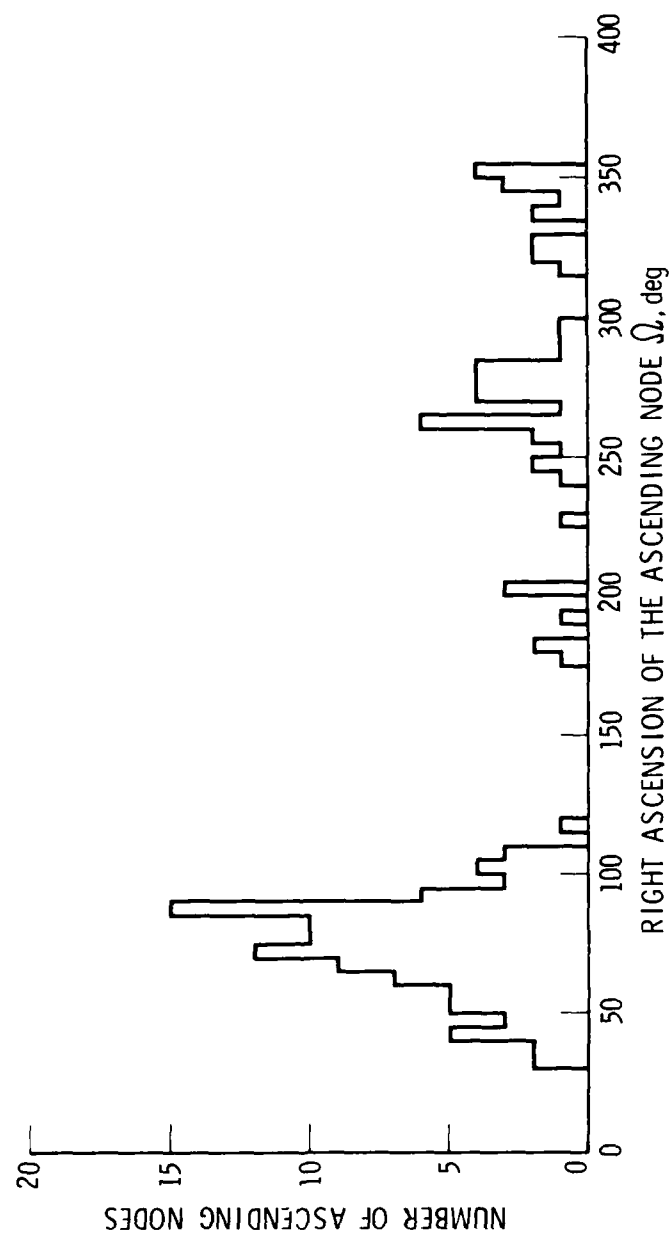


Fig. 15. Right Ascension of the Ascending Node in Geosynchronous Orbits

III. ANALYSIS AND RESULTS

A. UNIFORM DENSITY METHOD

The probability that any two satellites will collide is generally a function of their orbital parameters, size and time. The collision cannot take place until the orbits intersect or approach each other to within the dimensions of the satellites of interest. This may occur even for initially nonintersecting orbits because of the effects of the earth's oblateness, air drag and solar-lunar perturbations which alter the orbital parameters in time.

An approximate, yet reasonably accurate method for estimating the probability of collision between a target satellite of projected area A_c and a debris object is based on the assumption that the space object density ρ is uniform (constant) and that the target area A_c sweeps out a volume $A_c \Delta t$ in time Δt . It can be shown (Ref. 1) that the fractional number of objects encountered in the volume $A_c \Delta t$ is then equal to the probability of collision if it is much less than unity. Thus,

$$p(\text{col}) = \rho v_r A_c \Delta t \quad (1)$$

where v_r is the average relative velocity between the satellite and the set of objects considered. For example, $v_r \approx 7$ km/sec for circular orbits up to 2000 km in altitude (Ref. 8).

The relative velocity v_r at the trace intersection between any two satellites in orbit planes with a mutual inclination of Δi can be expressed as (Ref. 1):

$$v_r = \sqrt{\frac{\mu}{r_x}} \left\{ 4 - \left(\frac{1}{A_1} + \frac{1}{A_2} \right) - 2 \sqrt{\left[2 - \frac{1}{A_1} - A_1(1 - e_1^2) \right] \left[2 - \frac{1}{A_2} - A_2(1 - e_2^2) \right]} - 2 \sqrt{A_1(1 - e_1^2) A_2(1 - e_2^2)} \cos \Delta i \right\}^{1/2} \quad (2)$$

where r_x is the radius at trace intersection and $A_1 = a_1/r_x$, $A_2 = a_2/r_x$. Here a_1 , a_2 , e_1 , e_2 , μ are the semimajor axes, eccentricities and the gravitational constant, respectively.

For the case of a circular and an eccentric orbit (e.g. $e_2 = 0$, $r_x = a_2$) Eq. (2) becomes

$$v_r = \sqrt{\frac{\mu}{r_x}} \left[3 - \frac{1}{A_1} - 2\sqrt{A_1(1 - e_1^2)} \cos \Delta i \right]^{1/2} \quad (3)$$

For circular orbits of equal period (i.e., $a_1 = a_2$, $e_1 = e_2 = 0$), Eq. (2) reduces to

$$\begin{aligned} v_{rc} &= 2v_c \sin \frac{\Delta i}{2} \\ &\approx v_c \sin \Delta i \quad \text{for } \Delta i \text{ small.} \end{aligned} \quad (4)$$

which is equal approximately to the cross-track (normal) component of relative velocity at encounter with v_c = circular orbital velocity. An average relative velocity $\bar{v}_{rc}$ for this case can be defined as an average value of v_{rc} over a mean anomaly range $-\pi/2 \leq M \leq \pi/2$, i.e.

$$\begin{aligned} \bar{v}_{rc} &\approx \frac{v_c}{\pi} \sin \Delta i \int_{-\pi/2}^{\pi/2} \cos MdM \\ &\approx \frac{2v_c}{\pi} \sin \Delta i \end{aligned} \quad (5)$$

An approach which can be applied to the case of a spacecraft in a circular, inclined orbit is based on the determination of object density in a spheroidal torus containing the spacecraft orbit (Fig. 16). This approach is similar to that used in the theory of interplanetary encounters (Ref. 13). The spheroidal torus is defined by the relative orbit plane inclination Δi and the spacecraft orbit radius R . The probability of the object colliding with the spacecraft in a time interval Δt is

$$\begin{aligned} p(\text{col}/\Delta t) &= 1 - e^{-\lambda \Delta t} \\ &\approx \lambda \Delta t \quad \text{for } \lambda \Delta t \ll 1 \end{aligned} \quad (6)$$

where

$$\lambda = \rho v_r A_c$$

$$= \frac{S^2 v_r}{2 T |u_r| \sin \Delta i}$$

= impact rate per unit time

T = object orbit period of revolution

S = R_s/R

R_s = spacecraft radius

v_r = relative velocity at encounter

$|u_r|$ = absolute value of the radial component of v_r

For a circular target orbit and an eccentric object orbit (Refs. 1, 13)

$$\frac{v_r}{|u_r|} = \left[\frac{3 - \frac{1}{A_1} - 2\sqrt{A_1(1 - e_1^2)} \cos \Delta i}{2 - \frac{1}{A_1} - A_1(1 - e_1^2)} \right]^{1/2} \quad (7)$$

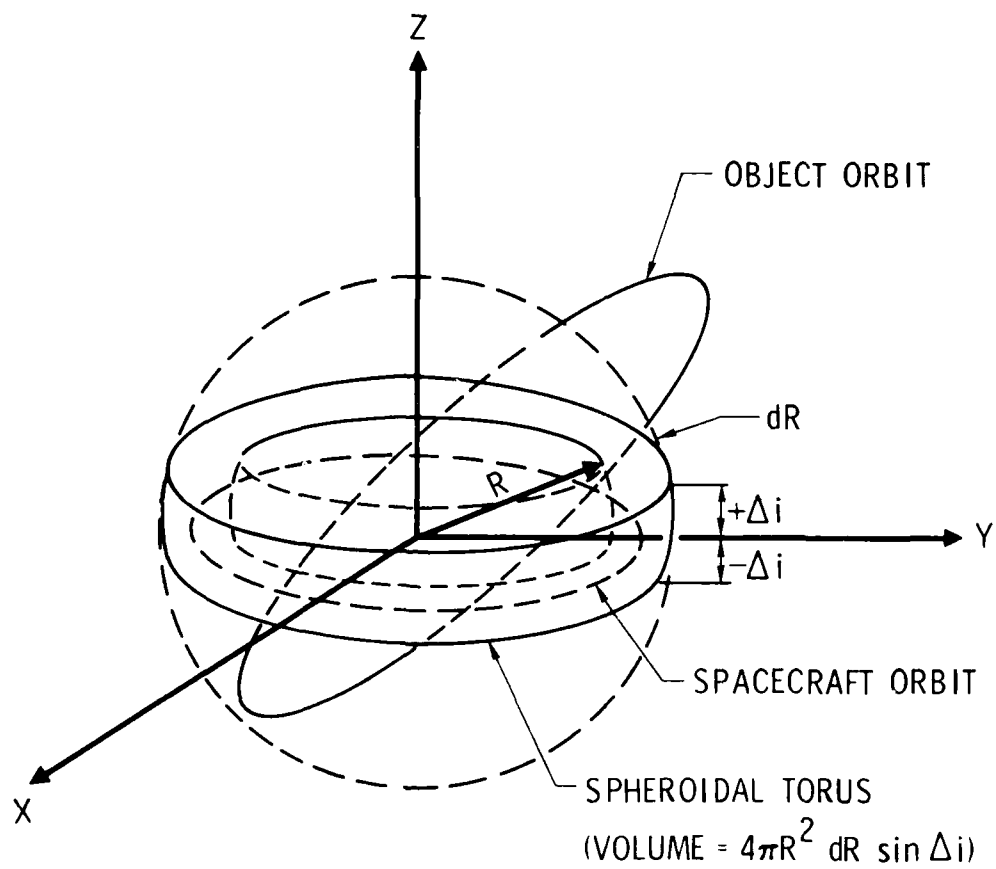


Fig. 16. Toroidal Geometry for Geosynchronous Orbits

where $A_1 = a_1/a_2$. Also, a_1 , a_2 , are the semimajor axes of the object and target orbits, and e_1 is the eccentricity of the object orbit.

The probability of the target spacecraft colliding with N objects in the torus (defined by an average inclination Δi_{av} of the objects' orbits relative to that of the target orbit) is equal to N times that given by Eq. (6). For example, if a set of 62 geosynchronous objects is considered with an average eccentricity $e_1 = 0.00113$ and orbit plane inclination $\Delta i = 1.07^\circ$ relative to the equatorial plane, then the velocity relative to a spacecraft in a circular geosynchronous equatorial orbit at encounter is from Eq. (3) $v_r = 57.5$ m/sec where $a_1 = 1$ and $r_x =$ geosynchronous radius. Consequently, a 1000 day probability of collision for a spacecraft of 50 m radius is by Eq. (6) equal to 3.88×10^{-5} .

Using Eq. (1), $v_r = 7$ km/sec, which is the average relative encounter velocity between satellites below 2000 km (Ref. 8) and the spatial density ρ in Fig. 7, the probability of collision for circular low altitude missions of 1000 days is given in Fig. 17 for the trackable population of 4174 objects and an estimated population of 8400 objects of smaller cross-section. The results show that the 1000 day probability of collision for a very large spacecraft (~ 50 m radius) is on the order of 4 to 8% and for a 20 m radius satellite it is on the order of 0.6 to 1.2%. However, for smaller spacecraft (~ 3 m radius), current probability of collision is an order of magnitude lower. The results for a sample of 62 to 620 objects in the geosynchronous corridor are given in Fig. 18 where an average relative velocity of only 36.5 m/sec was assumed. This velocity is the north-south (inclination) component of the average relative velocity. Average collision probabilities in the geosynchronous orbit are thus seen to be about three orders of magnitude lower than those at low altitudes. However, the effects of density variation with altitude, inclination (latitude) or longitude are not included in these results.

B. VARIABLE DENSITY METHOD

Figure 14 shows that the observed object density $\rho(h, \phi)$ is a function of height h above or below geosynchronous orbit and latitude ϕ . Since a satellite whose orbit plane is inclined to the equatorial plane spends only a

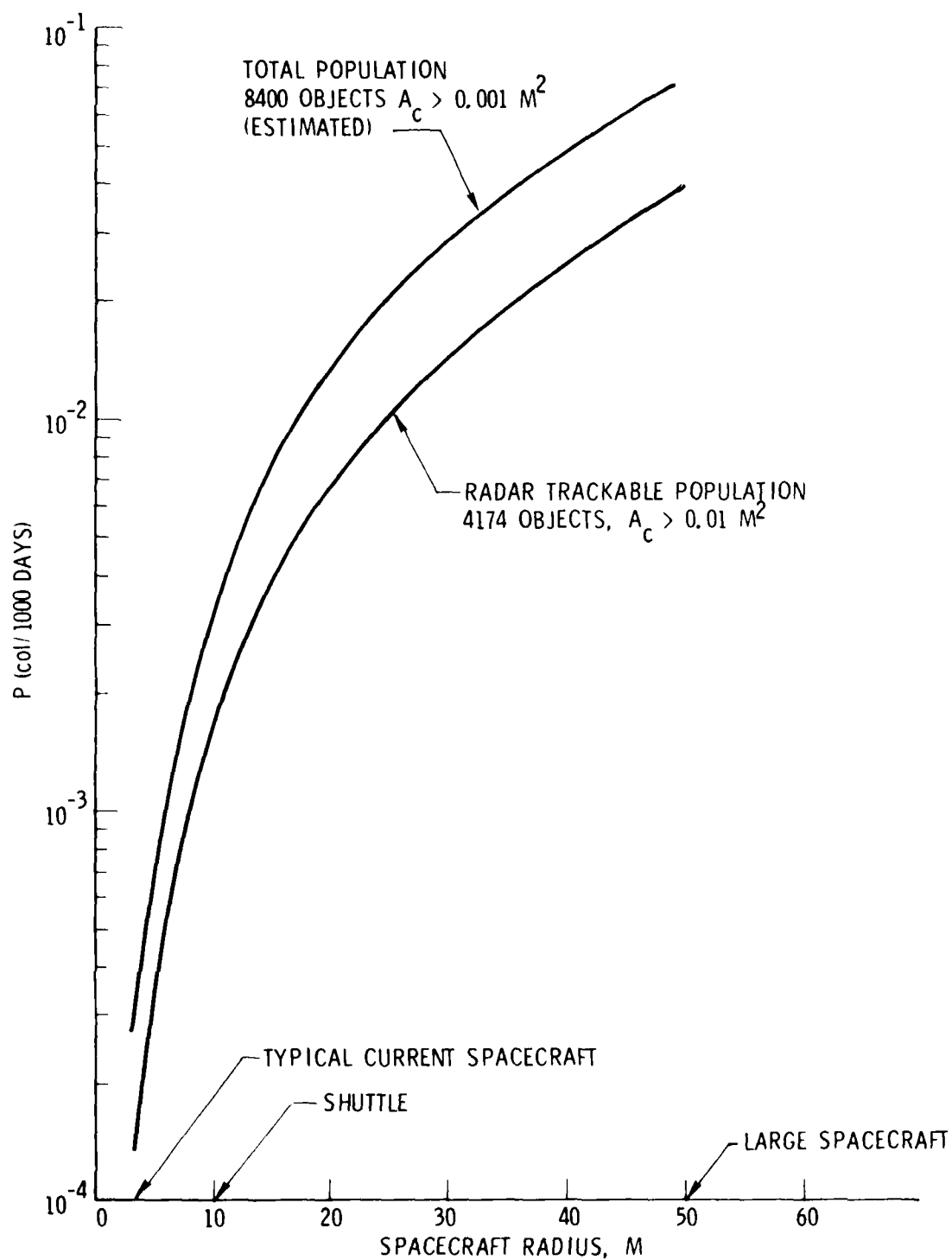


Fig. 17. Probability of Collision - Low Earth Orbits
(800 to 1500 km) for 1000 Days

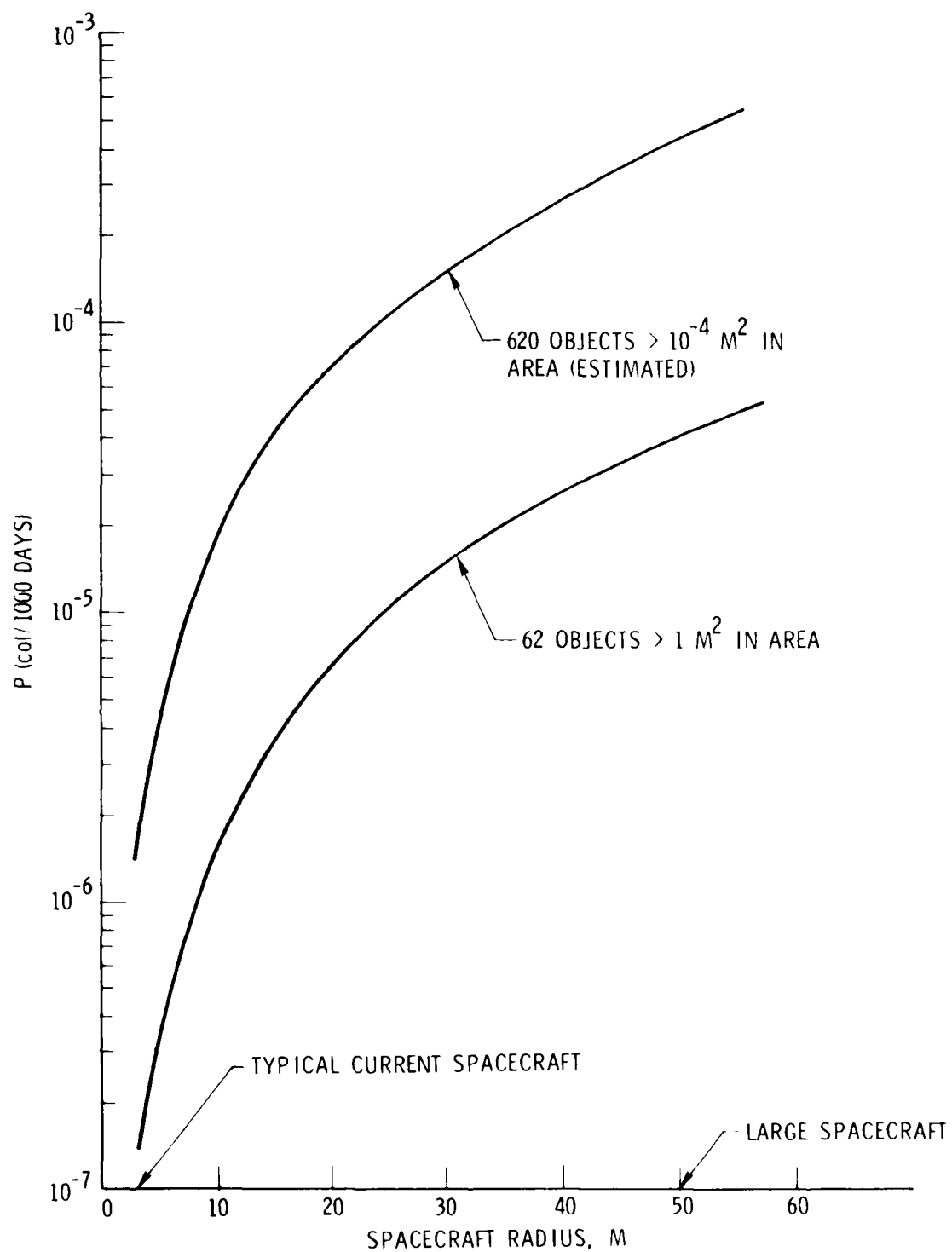


Fig. 18. Probability of Collision - Geosynchronous Orbits for 1000 Days

fraction of its period of revolution T near the equator where the density is greatest, the probability of collision is similarly affected. In general, the probability of collision in any altitude band $\Delta h = h_2 - h_1$, per one revolution of the satellite, is

$$p(\text{col/rev}) = A_c \bar{v}_r T \int_{h_1}^{h_2} \int_{-\phi}^{\phi} \rho(h, \phi) f(\phi) d\phi dh \quad (8)$$

where $\rho(h, \phi)$ is the object density function, $f(\phi)$ is a weighting function which can be derived from the time fraction spent by a satellite in a latitude band $\Delta\phi$ as shown in Fig. 19 and $\bar{v}_r$ is the average velocity of the target satellite relative to the objects of interest. For the case of a target satellite with inclination i and a set of geosynchronous objects with an average inclination $\bar{i}$ and average right ascension of the ascending node $\bar{\Omega}$, the angle Δi between the target orbit plane and that of the "average plane" of the objects is

$$\Delta i = \cos^{-1}(\cos i \cos \bar{i} + \sin i \sin \bar{i} \cos \Delta \Omega) \quad (9)$$

where

$$\Delta \Omega = |\bar{\Omega} - \Omega|$$

Ω = right ascension of the ascending node of the target satellite.

Since Δi will in general vary in time because of external perturbations, the average value of Δi is

$$\Delta i_{av} = \frac{\Delta i_{max} + \Delta i_{min}}{2} \quad (10)$$

i - SATELLITE ORBIT
INCLINATION

T = ORBIT PERIOD
 t = TIME IN LATITUDE
BAND $\pm \phi$

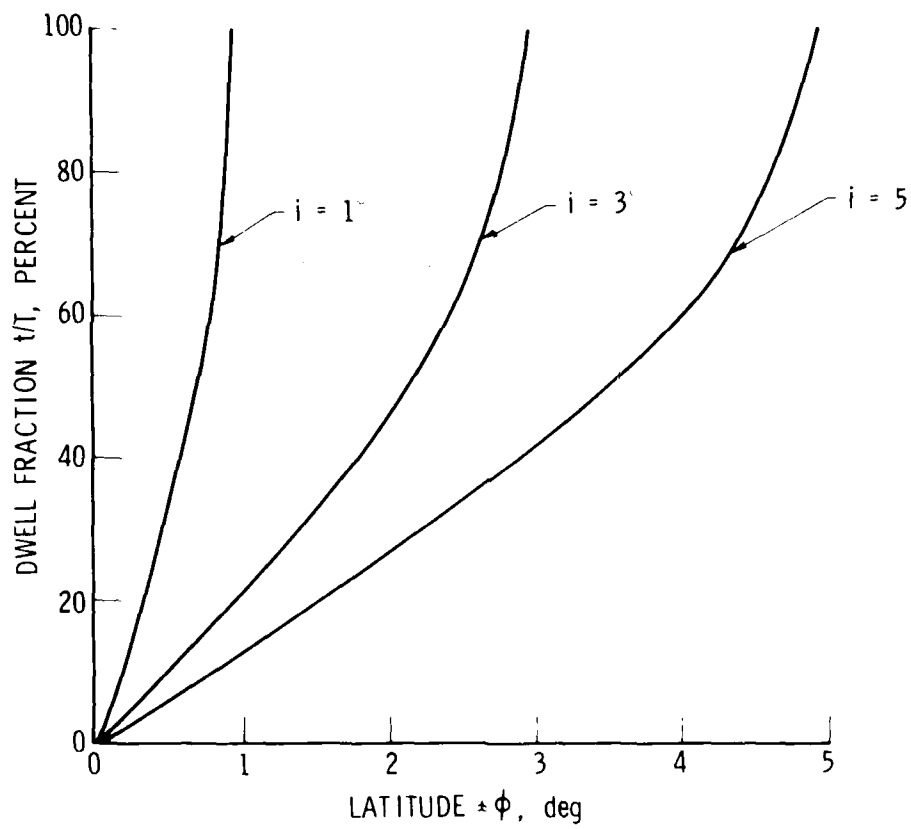


Fig. 19. Dwell Fraction vs. Latitude for Circular Orbits

where

$$\Delta i_{\max} = i + \bar{i} \quad \text{when} \quad \Delta \Omega = \pi \quad (11)$$

and

$$\Delta i_{\min} = |i - \bar{i}| \quad \text{when} \quad \Delta \Omega = 0 \quad (12)$$

Therefore,

$$\Delta i_{\text{av}} = \begin{cases} i & \text{for } i > \bar{i} \\ \bar{i} & \text{for } i < \bar{i} \end{cases} \quad (13)$$

The average relative velocity v_r for the case of nearly circular geosynchronous orbits can be approximated by Eq. (5) because the normal (out-of plane) or north-south component predominates.

Equation (8) has been evaluated approximately for circular orbits with $i = 1^\circ, 3^\circ$ and 5° and object densities of Fig. 14 for different altitude bands above and below geosynchronous orbit. The results, given in Fig. 20, are valid for a typical small satellite (effective collision radius $R_S = 20$ ft (6.1 m)) and a mission duration of 1000 days. The results for other values of R_S are proportional to the square of the effective radius of collision and time. The collision probability for a target satellite in an elliptic geosynchronous orbit can be obtained by averaging the results of Fig. 18 as shown in Fig. 21.

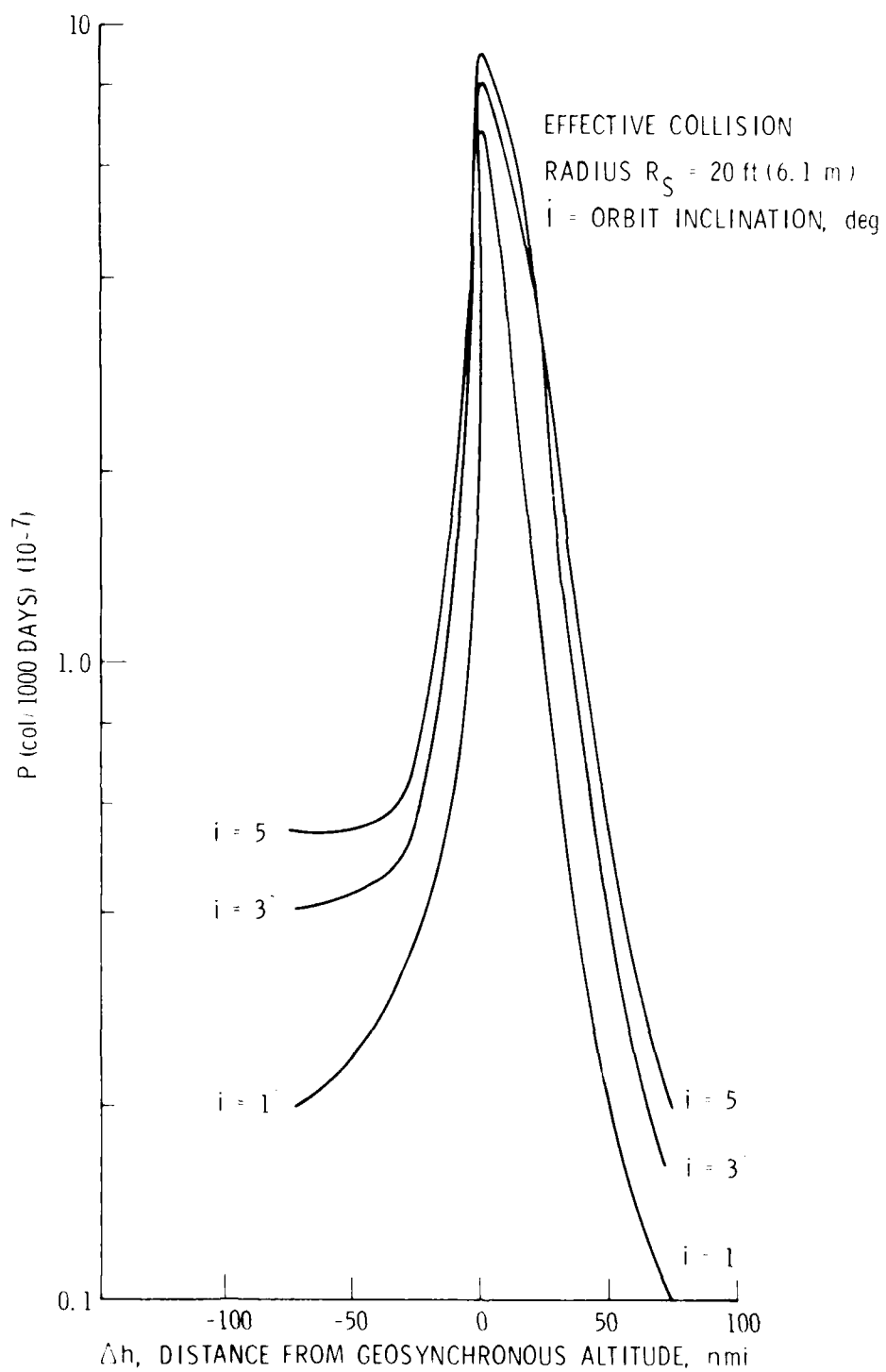


Fig. 20. Collision Probability for Objects in Circular Geosynchronous Orbits in 1000 Days

EFFECTIVE COLLISION
 RADIUS $R_c = 20 \text{ ft (6.1 m)}$
 $i = \text{ORBIT INCLINATION}$

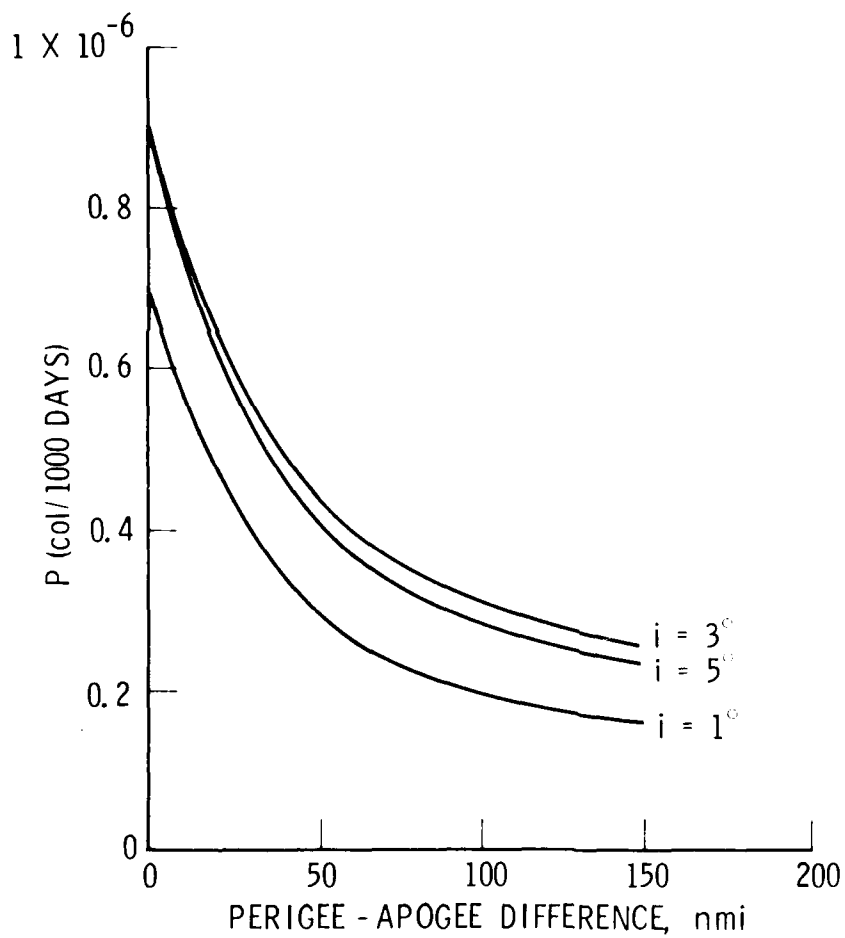


Fig. 21. Collision Probability for Objects in Eccentric Geosynchronous Orbits in 1000 Days

C. DISTANCE OF CLOSEST APPROACH METHOD

1. GENERAL CONSIDERATIONS

A collision between two objects can take place at or near a trace intersection point if the distance of closest approach R_{MIN} is equal to or is less than the effective collision radius R_S . For satellites in circular orbits with a mutual orbit plane inclination α , R_{MIN} occurs twice per revolution in the vicinity of the intersection between the orbit planes (nodal axis) as illustrated in Fig. 22. For each instant when satellite 1 is at or near the nodal axis, satellite 2 is at a position 4, 3, 2 or 1 corresponding to an R_{MIN} for that pass. The angular increment $\Delta u = n_1 |(T_2 - T_1)|$ where n_1 is the mean motion of satellite 1 and T_1 , T_2 are the periods of revolution for satellites 1 and 2, respectively. The angular change Δu per revolution is typically a fraction of a degree for geosynchronous satellites. For example, R_{MIN} for north and south bound passes of OPS 6391 (SDC object No. 10669) and WESTAR-A (SCD object No. 7250), is given in Table 2 for several days in April of 1980 as was determined approximately via the numerical simulation described in Ref. 14. Different R_{MIN} values can thus be seen to have occurred before and after the lowest value $R_{MIN} = 5.28$ nmi of 21 April 1980. The probability of collision between the objects for each pass is, in general, a function of R_{MIN} , the tracking uncertainty σ in the location of each object and the effective collision radius R_S . The latter can be defined as one half the sum of the maximum dimensions for both objects. For $\sigma = 0$ and $R_{MIN} > R_S$ no collision can take place. For $\sigma \neq 0$, there is a nonzero probability of collision.

2. MISS DISTANCE AND POSITION UNCERTAINTY

An approximate collision probability method, described briefly in (Ref. 15), considers the effects of the uncertainties associated with the three dimensions (coordinates) of the miss distance R_{MIN} . It is assumed that the uncertainties are Gaussian (normal) with zero biases and equal variance and that they are uncorrelated. The assumption is applied to the position data of each of the tracked satellites. In view of this and the fact that the orientation of the coordinate system containing the distance of closest

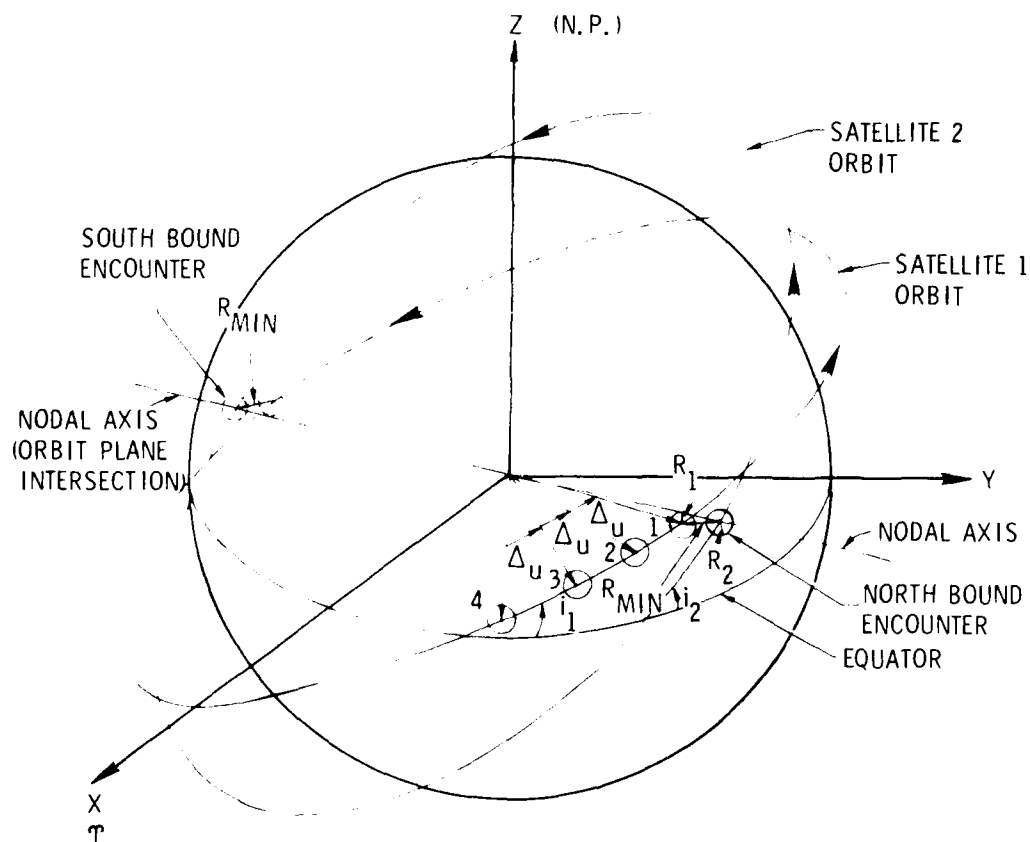


Fig. 22. Encounter Geometry for Mutually Inclined Circular Orbits

Table 2. Close Encounters Between OPS 6391 and WESTAR-A Geosynchronous Satellites

R _{MIN} - (Relative Minimum) (nmi/km)	Date	10669 (OPS 6391)			7250 (Westar-A)		
		lat (deg)	long. (deg)	alt (nmi)	lat (deg)	long. (deg)	alt (nmi)
26.55/	12. Apr 9:42:58.1	.0317	-99.2406	19329.05	.0337	-99.1751	19323.83
14.31/	12. Apr 21:41: 8.0	-.0341	-99.1765	19316.98	-.0336	-99.1437	19322.82
23.63/	13. Apr 9:38:58.3	.0316	-99.2429	19329.07	.0334	-99.1850	19323.84
11.68/	13. Apr 21:37: 5.7	-.0332	-99.1791	19316.98	-.0328	-99.1537	19322.83
20.76/	14. Apr 9:35: .5	.0307	-99.2455	19329.09	.0322	-99.1950	19323.86
9.26/	14. Apr 21:33: 5.2	-.0315	-99.1817	19316.98	-.0312	-99.1636	19322.84
17.94/	15. Apr 9:31: 4.1	.0290	-99.2479	19329.10	.0303	-99.2047	19323.87
7.25/	15. Apr 21:29: 5.7	-.0295	-99.1839	19316.98	-.0292	-99.1732	19322.84
15.16/	16. Apr 9:27: 8.2	.0272	-99.2499	19329.12	.0282	-99.2141	19323.88
6.02/	16. Apr 21:25: 6.3	-.0274	-99.1858	19316.99	-.0272	-99.1824	19322.85
12.44/	17. Apr 9:23:12.2	.0256	-99.2515	19329.13	.0264	-99.2231	19323.90
6.08/	17. Apr 21:21: 6.6	-.0258	-99.1873	19316.99	-.0257	-99.1913	19322.86
9.84/	18. Apr 9:19:15.8	.0247	-99.2529	19329.14	.0253	-99.2319	19323.91
7.41/	18. Apr 21:17: 6.6	-.0249	-99.1888	19317.00	-.0250	-99.2002	19322.87
7.48/	19. Apr 9:15:19.1	.0246	-99.2544	19329.16	.0250	-99.2410	19323.92
9.53/	19. Apr 21:13: 6.2	-.0251	-99.1907	19317.01	-.0252	-99.2096	19322.88
5.73/	20. Apr 9:11:22.2	.0255	-99.2566	19329.17	.0256	-99.2508	19323.93
12.04/	20. Apr 21: 9: 5.6	.0260	-99.1934	19317.02	-.0262	-99.2198	19322.89
5.28/	21. Apr 9: 7:24.9	.0270	-99.2598	19329.18	.0269	-99.2615	19323.94
14.74/	21. Apr 21: 5: 4.5	-.0274	-99.1971	19317.03	-.0277	-99.2312	19322.90
6.43/	22. Apr 9: 3:27.2	.0288	-99.2642	19329.19	.0285	-99.2735	19323.96
17.56/	22. Apr 21: 1: 2.9	-.0290	-99.2021	19317.03	-.0294	-99.2438	19322.90

approach at encounter is arbitrary, a plane xy which is normal to the relative velocity vector and which contains the vector of closest approach R_{MIN} can always be found. The bi-variate normal density function for this case can be expressed as (Ref. 16)

$$f(x,y) = \left(\frac{e^{-\frac{x^2}{2\sigma^2}}}{\sigma\sqrt{2\pi}} \right) \left(\frac{e^{-\frac{y^2}{2\sigma^2}}}{\sigma\sqrt{2\pi}} \right)$$

$$= \frac{1}{2\pi\sigma^2} e^{-\frac{1}{2}\left(\frac{R_{MIN}}{\sigma}\right)^2} \quad (14)$$

where

$$R_{MIN} = (X_{min}^2 + Y_{min}^2)^{1/2}$$

Since a collision can occur only if

$$\left. \begin{aligned} Y_{min} - R_s &\leq y \leq R_s + Y_{min} \\ X_{min} - R_s &\leq x \leq R_s + X_{min} \end{aligned} \right\} \quad (15)$$

where X_{min} , Y_{min} are the coordinates of R_{MIN} and where R_s is the effective collision radius for both satellites, the probability of collision is

$$p(\text{col}) = \int_{(X_{\min} - R_s)}^{(X_{\min} + R_s)} \int_{(Y_{\min} - R_s)}^{(Y_{\min} + R_s)} f(x,y) dy dx \quad (16)$$

$$\approx \frac{2}{\pi} \left(\frac{R_s}{\sigma} \right)^2 e^{-\frac{1}{2} \left(\frac{R_{\min}}{\sigma} \right)^2} \quad (17)$$

for $R_s \ll R_{\min}$.

Equation (17) represents the probability of collision between two satellites per encounter when the distance of closest approach $R_{\min}$, the 1σ tracking uncertainty in the position of each satellite, and the effective radius of collision R_s are given.

A similar result can be obtained by orienting the x, y coordinates along $\hat{R}_{\min}$ and normal to it respectively. The probability of collision is then

$$p(\text{col}) = p_x p_y \quad (18)$$

where

$$\begin{aligned} p_x &= p[A \leq x \leq B] \\ &= p\left[\frac{A}{\sigma} \leq x' \leq \frac{B}{\sigma}\right] \\ &= \frac{1}{\sqrt{2\pi}\sigma} \int_{A/\sigma}^{B/\sigma} e^{-\frac{\mu^2}{2}} du \\ &= \text{probability of collision along } x \end{aligned}$$

$$p_y = p[-R_s \leq y \leq R_s]$$

$$= p\left[-\frac{R_s}{\sigma} \leq y' \leq \frac{R_s}{\sigma}\right]$$

$$= \frac{1}{\sqrt{2\pi}\sigma} \int_{-R_s/\sigma}^{R_s/\sigma} e^{-\frac{u^2}{2}} du$$

$$= \text{probability of collision in a direction normal to } \vec{R}_{\text{MIN}}$$

Here

$$A = R_{\text{MIN}} - R_s$$

$$B = R_{\text{MIN}} + R_s$$

and A/σ , B/σ and R_s/σ are standardized Gaussian variables.

Assuming now that the probability of collision at j -th closest approach is $p_j(\text{col})$ the probability of miss is

$$p_j(\text{miss}) = 1 - p_j(\text{col}) \quad (19)$$

The probability of missing at all n closest approaches is

$$p(\text{miss}/n) = \prod_{j=1}^n [1 - p_j(\text{col})] \quad (20)$$

if all probabilities are independent. Therefore, the probability that there will be at least one collision during this period of encounter is

$$p(\text{col}) = 1 - p(\text{miss}/n)$$

$$\approx \sum_{j=1}^n p_j(\text{col}) \quad (21)$$

when all $p_j(\text{col}) \ll 1$.

A plot of Eq. (17) for $R_s = 20, 50$ and 100 ft is given in Figs. 22 to 26 as a function of σ with R_{MIN} as a parameter. It can be seen that a maximum probability of collision occurs when

$$\sigma = \frac{R_{\text{MIN}}}{\sqrt{2}} \quad (22)$$

which is plotted as a function of R_s/R_{MIN} in Fig. 28. The use of Eqs. (17) and (21) is illustrated in Fig. 29 for the case of the close encounters between the WESTAR-A and the OPS 6391 satellites given in Table 2. The collision probabilities for several passes are plotted as a function of σ . The maximum probability of collision for 17 passes is given as the sum of the maximum probabilities for each pass. Assuming no correlation between passes, the maximum (upper-bound) probability of collision for these encounters is 2.0×10^{-6} for the 8-day time period.

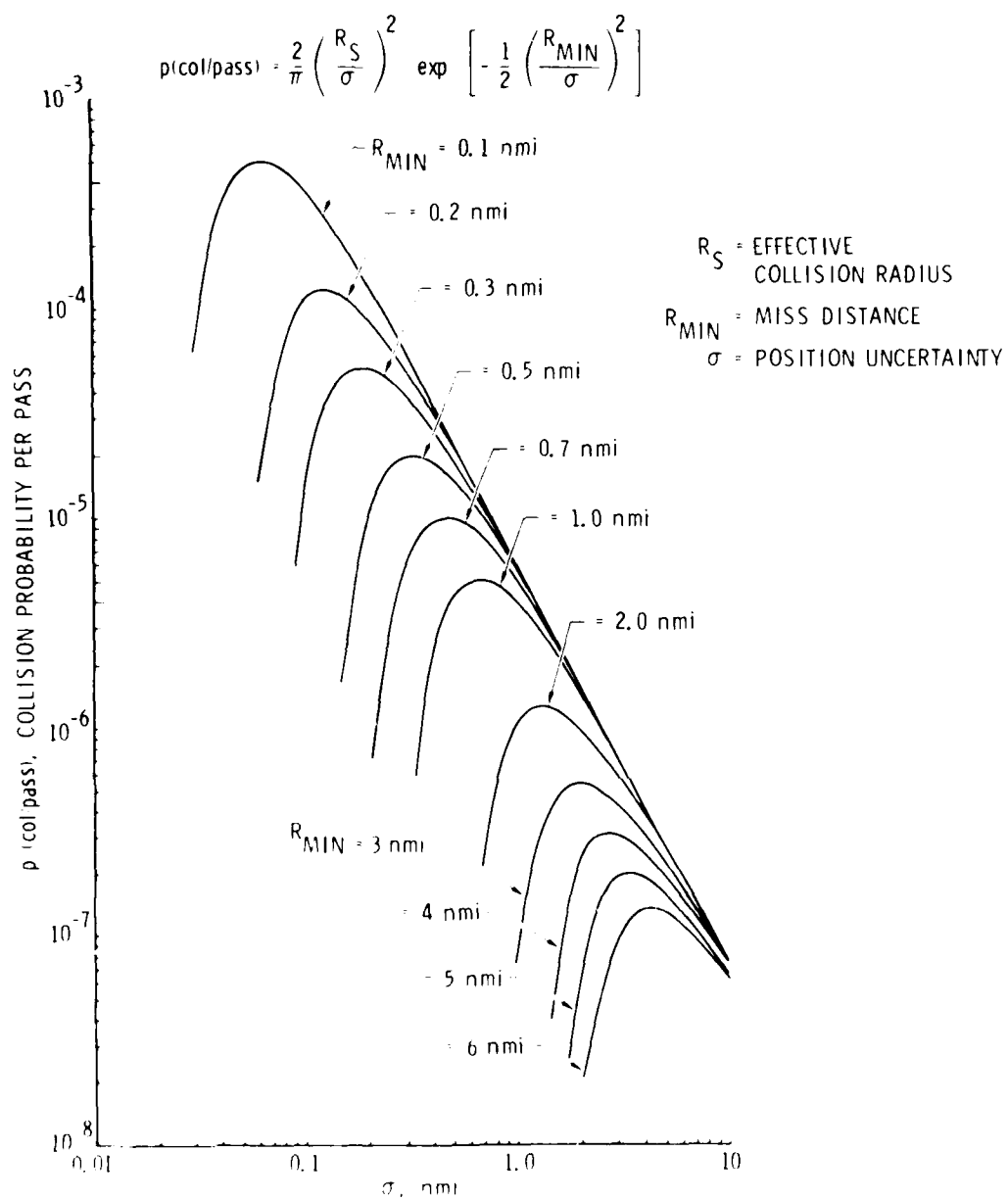


Fig. 23. Collision Probability as a Function of Position Uncertainty and Miss Distance ($R_S = 20 \text{ ft}$)

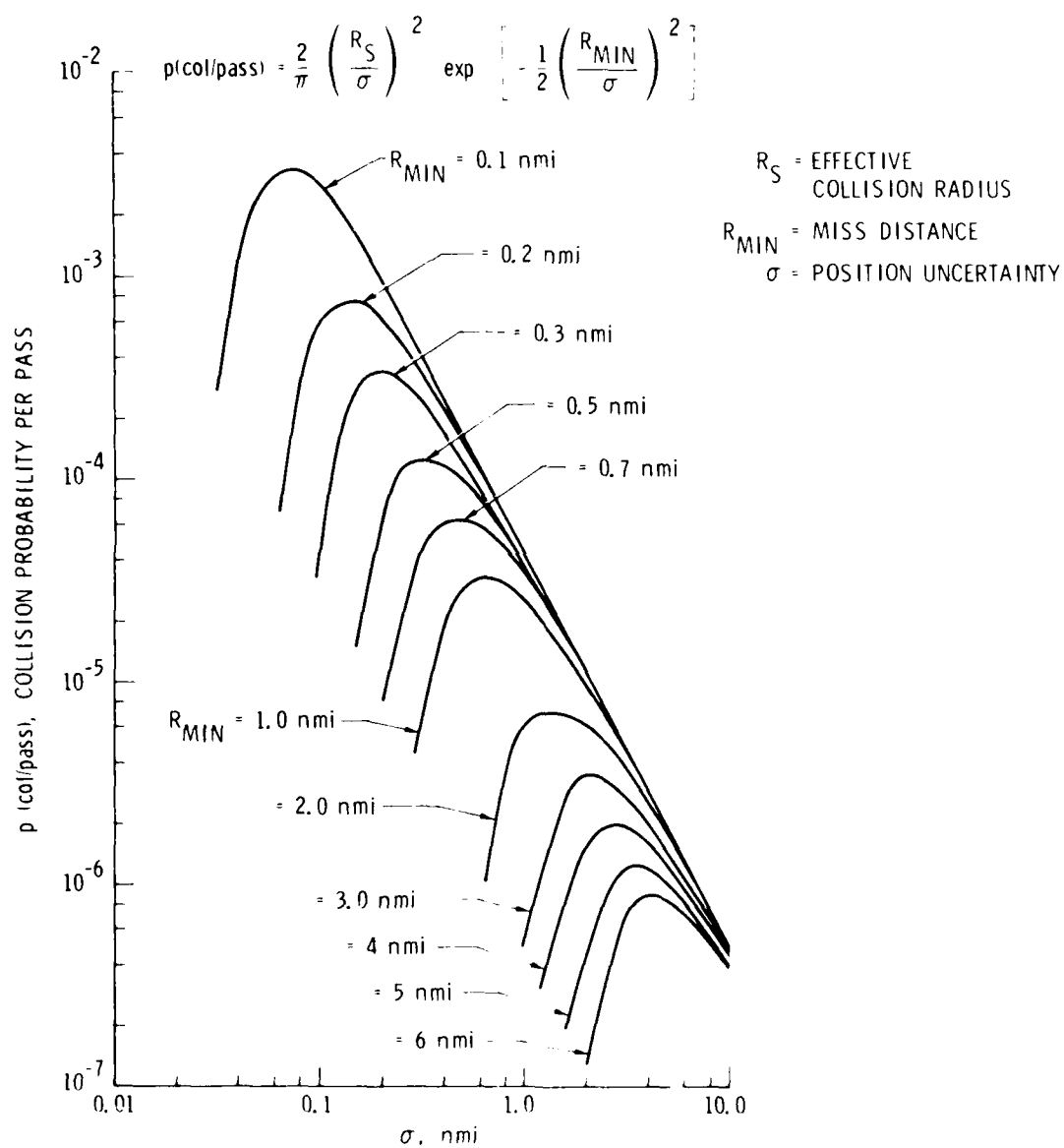


Fig. 24. Collision Probability as a Function of Position Uncertainty and Miss Distance ($R_S = 50$ ft)

$$p(\text{col/pass}) = \frac{2}{\pi} \left(\frac{R_S}{\sigma} \right)^2 \exp \left[-\frac{1}{2} \left(\frac{R_{\text{MIN}}}{\sigma} \right)^2 \right]$$

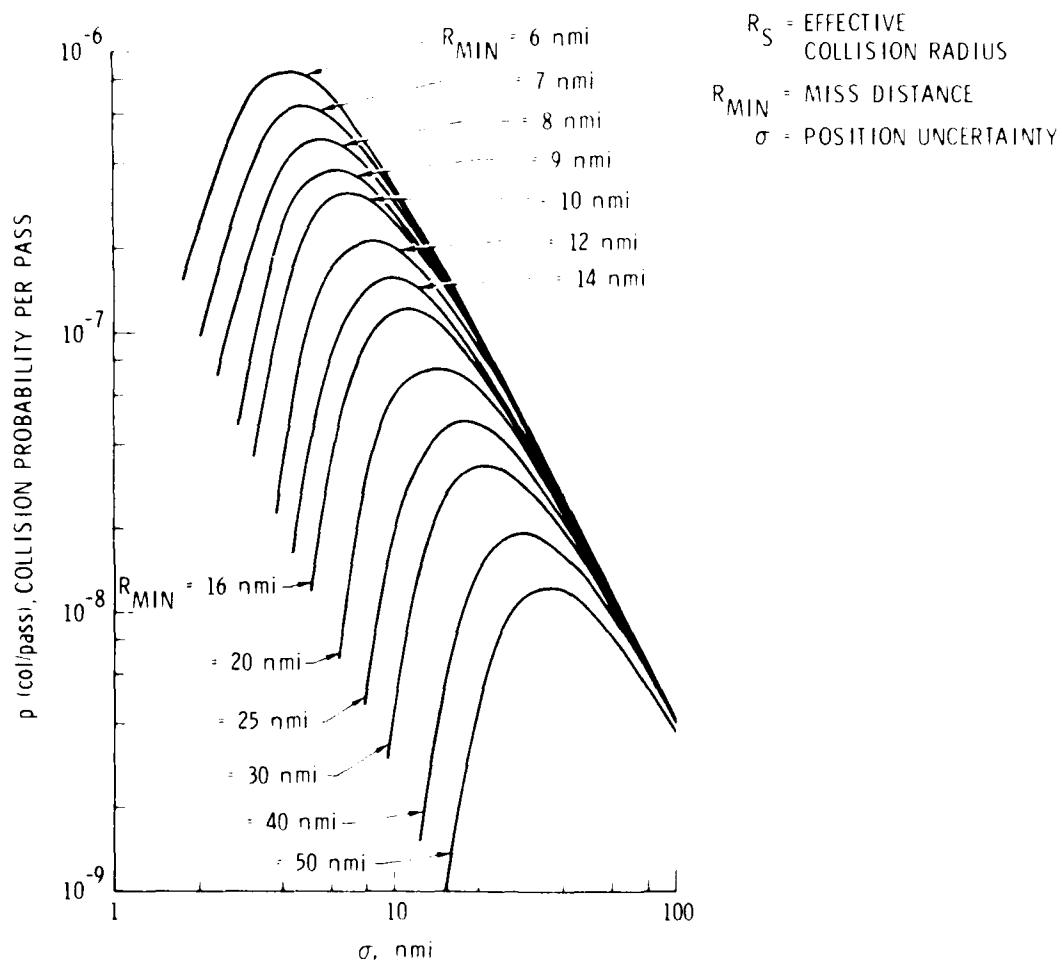


Fig. 25. Collision Probability as a Function of Position Uncertainty and Miss Distance ($R_S = 50$ ft), Continued

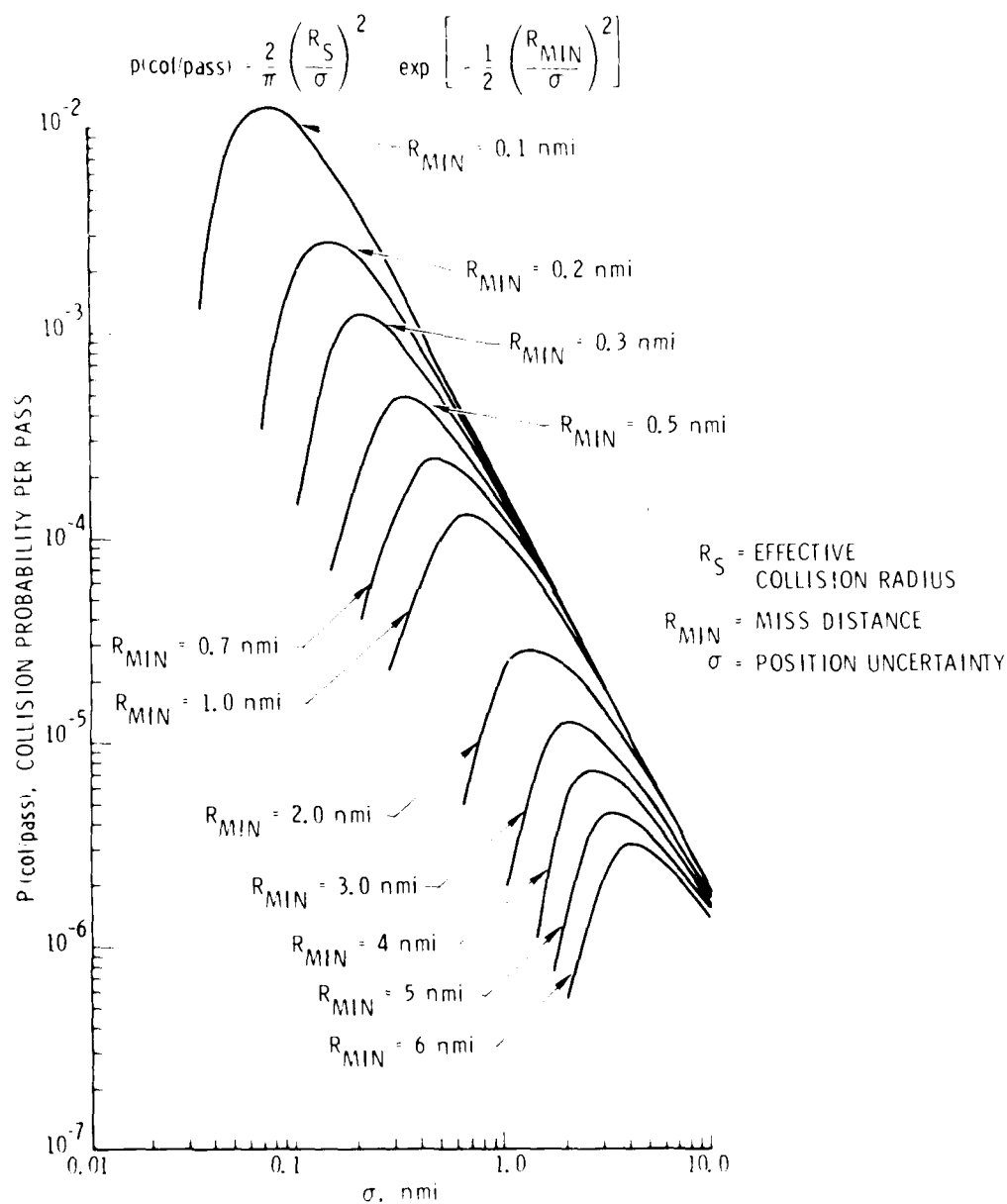


Fig. 26. Collision Probability as a Function of Position Uncertainty and Miss Distance ($R_S = 100$ ft)

$$p(\text{col/pass}) = \frac{2}{\pi} \left(\frac{R_S}{\sigma} \right)^2 \exp \left[-\frac{1}{2} \left(\frac{R_{\text{MIN}}}{\sigma} \right)^2 \right]$$

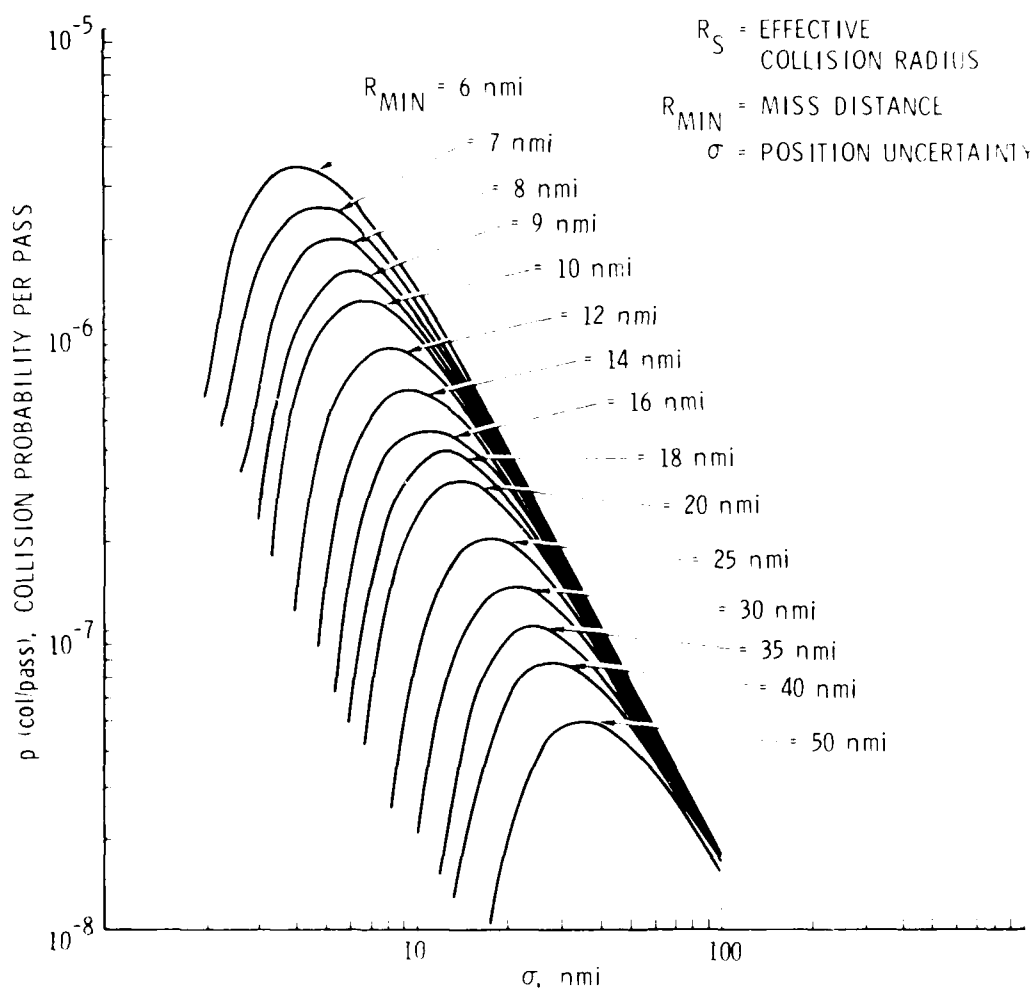


Fig. 27. Collision Probability as a Function of Position Uncertainty and Miss Distance ($R_S = 100$ ft), Continued

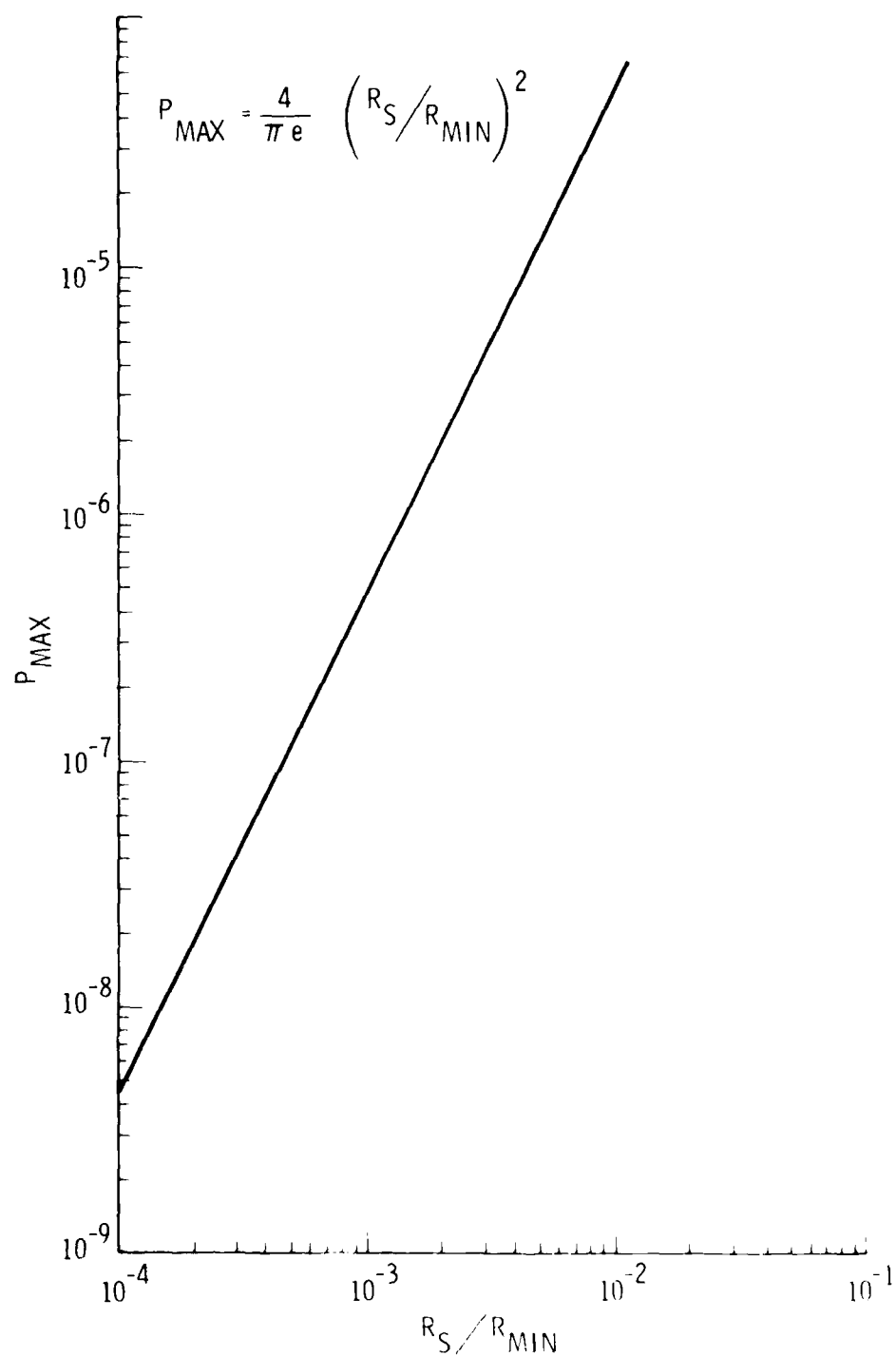


Fig. 28. Maximum Collision Probability Per Pass (P_{MAX}) as Function of Effective Collision Radius to Distance Ratio (R_S/R_{min})

$$\left[\text{EFFECTIVE COLLISION RADIUS } R_S = 30 \text{ ft, } p(\text{col})_{\text{max}} = \sum_{i=1}^{17} p_{i\text{max}} = 2.0 \times 10^{-6} \right]$$

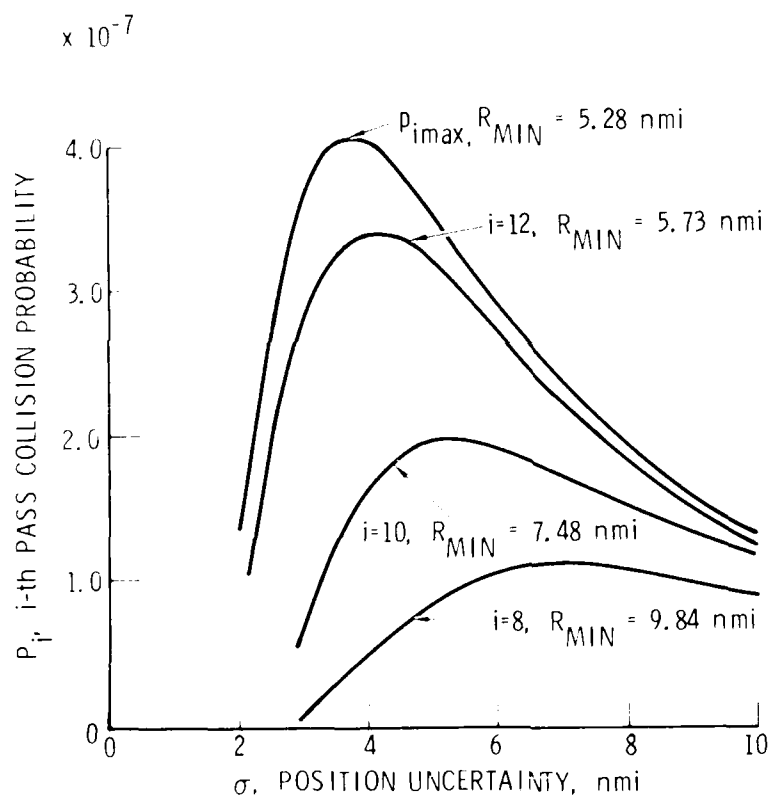


Fig. 29. WESTAR-A/OPS 6391 Collision Probability During the April 14 to April 23, 1980 Encounters in Geosynchronous Orbit

IV. SUMMARY AND CONCLUSIONS

A summary of the present and projected probabilities of collision for a ten meter radius spacecraft in low earth orbit (LEO) and the geosynchronous corridor (GEO) is given in Table 3. It can be seen that the probability of collision in low earth orbits is currently on the order of 0.15 to 0.3% for a 1000-day mission. Another way of interpreting the probability of 0.3% is that one of 90 such spacecraft would be expected to experience a collision in 10 years. Probabilities for the 1985 to 1995 time frame are on the order of 2.5 to 7.3 times current values on the basis of an assumed debris growth rate of 13% per year. On the other hand, the results for the geosynchronous orbit are some three orders of magnitude lower in value mainly because of lower relative velocities at encounter. These results, however, do not include the effects of ascending node concentrations at certain longitudes. The calculated probabilities of collision at low altitude are also likely to be too low due to the noninclusion of many smaller particles believed to be a result of satellite explosions and ASAT tests.

The picture emerging from this study indicates that the cluttering of space with debris must be reduced in the future to minimize the collision hazard and improve spacecraft survivability. It appears that the current debris growth rates of 9 to 13% are excessive and that the associated collision hazards, particularly for larger spacecraft, will become unacceptable if these growth rates remain unchanged. There is little doubt that larger satellites and space stations will be built in the future, because of increasing demands for more and better space communications, meteorology, navigation, and remote sensing.

The question of "what solutions can be postulated" can be answered only by resolution of the space debris issues falling into three categories: 1) satellite and vehicle design, 2) operational procedures and practices, and 3) national and international policies and treaties. In the area of vehicle design the principal approaches should consider space systems for litter-free

Table 3. Summary of Present and Projected Collision Probabilities for a 1000-Day Mission

Probability of Collision with Trackable Objects	1980 (4174 objects)	1985	
		(~10000 objects) (multiplying factor)	1995 (30000 objects) (multiplying factor)
Ten meter radius spacecraft in GEO(a)	10^{-6} to 10^{-5}	2.5	7.3
Fifty meter radius spacecraft in GEO	4×10^{-5} to 4×10^{-4}	2.5	7.3
Ten meter radius spacecraft in LEO(b)	1.5×10^{-3} to 3×10^{-3}	2.5	7.3
Fifty meter radius spacecraft in LEO	4×10^{-2} to 8×10^{-2}	2.5	7.3

(a) GEO - Geosynchronous Orbit

(b) LEO - Low Earth Orbit

separation, reusability, retrievability, earth escape or destructive reentry into the atmosphere. The feasibility of debris collection systems should be examined.

In the operational approach and procedure areas, consideration should be given to satellite separation techniques (use of nonintersecting orbits, etc.), avoidance of crowded regions of space, and the disposal of spent satellites to "graveyard" orbits. Accidental or deliberate destruction of spacecraft should be minimized. Some of the possible approaches are summarized in Fig. 30. In short, Planet Earth appears to need a consistent and universally observed space object management policy which could ensure that future missions would be protected from unacceptable collision hazards in orbit.

SATELLITE POSITION MANAGEMENT POLICY

1. ESTABLISH CLOSE APPROACH MONITORING CAPABILITY
2. ALERT SATELLITE USERS / OPERATORS AND OTHER APPROPRIATE AGENCIES WHENEVER PLANS ARE MADE TO REPOSITION A SATELLITE
3. REDUCE NUMBER OF DEBRIS OBJECTS DURING LAUNCHING, ORBIT INJECTION AND OPERATION OF SATELLITES (e.g. SHROUDS, COVERS, PARTS JETTISONING, ETC.)
4. REMOVE INACTIVE SATELLITES FROM ORBIT OR PLACE IN DISPOSAL ORBITS
5. TARGET BOOSTER STAGES ABOVE OR BELOW MISSION ORBIT
6. MINIMIZE POSSIBILITY OF ROCKET STAGE OR PAYLOAD BREAKUP OR EXPLOSION
7. DETERMINE EFFECTS OF ACTUAL OR PLANNED EXPLOSIONS ON THE PROBABILITY OF INADVERTENT COLLISIONS
8. USE NONINTERSECTING ORBITS
9. PERFORM COLLISION AVOIDANCE MANEUVERS WHEN NECESSARY

Fig. 30. Operational Procedures to Minimize Collision Hazard in Space

APPENDIX

SYNCHRONOUS SATELLITE CATALOG

(28 April 1980)

ALPHABETICAL

(Ref. 3)

SYNCHRONOUS DATA FOR DATE 00117, (20 APR 8)

STATION-02-5 DATA-03 FOR DATE-00112, (28 APR 8)												
STATION	TYPE	TIME	COORD	UT	LATITUDE	LONGITUDE	HEIGHT	APPROX	PERIOD	INCL	REMARKS	
13074	77 41	A	LATE SAT 44P-4	COMSAT	00117.5107	5.0	-0.0001	-84.9419	19320	19327	0.01	0.0000
13075	78 39	A	LATE SAT 44P-6	COMSAT	00117.2472	5.0	0.0006	63.0271	19325	19326	0.01	0.0000
13077	78 17	A	LATE	NASA	00116.0340	5.0	-4.0024	-84.9409	19320	24431	24.24	0.0001
13081	79 0	LES 6	LCN LAR 00112.0313	5.2	5.9006	-107.9217	19323	19327	19328	6.10	-0.0000	
13082	78577	A	LES 6 3/4	NORAD	00106.5504	12.4	-4.6000	58.0171	19224	19328	5.90	4.0000
13086	76 25	A	LES-4	LCN LAR 00117.4033	1.3	22.4000	-105.2506	19310	19328	19328	25.28	0.0000
13091	76 25	F	LES-6 3/4 00116.9 8/B 2	NORAD	00117.7607	1.2	24.7504	-146.0339	19343	19328	25.48	-7.2334
13097	76 25	B	LES-0	LCN LAR 00117.6572	5.3	10.0600	-03.4104	19325	19328	19327	25.24	0.0000
13097	76 17	A	WARSAT 1	NASA	00114.4542	4.9	0.0003	-15.2295	19319	19328	0.91	-0.0000
13098	76 53	A	WARSAT 3	NASA	00115.0141	5.1	-0.2029	176.4200	19320	19328	0.39	-0.0000
13098	78101	A	WARSAT-2	NASA	00112.1116	5.9	-0.0003	72.0504	19321	19328	1.47	-0.0000
13099	77104	A	WARSAT	ESA	00106.4348	17.0	0.4906	0.7830	19367	19328	0.92	0.0000
13102	74 63	A	WARSAT 1-S	NORAD	74210.1745	2092.0	-2.5968	154.7009	19349	19328	0.07	-0.0000
13108	76 39	A	WARSAT 1114	NATO	00 05.1209	31.4	-0.4902	-18.3801	19317	19328	1.10	-0.0000
13103	76 21	A	WARSAT 1	NATO	00106.0236	14.1	3.2550	-105.9009	19333	19327	4.98	-0.0000
13102	71 02	A	WARSAT 2	NATO	00 24.1070	94.9	-1.6020	161.3117	19327	19328	5.05	2.9404
13105	77 4	A	WARSAT 3-8	NATO	00112.1749	5.0	-0.7910	-00.6509	19449	20749	1.00	0.0000
13115	78105	A	WARSAT-1110	NATO	00113.1948	5.0	-2.4855	-50.0771	19310	19328	3.30	-0.0000
13091	72 10	A	WARSAT 1570	SCF	00113.1195	4.0	-0.2306	-162.9609	19320	19328	6.02	-0.0000
13104	78577	A	WARSAT 1570 8/B (2)	NORAD	00117.4672	1.1	4.7208	-108.7643	19123	19328	5.98	1.4514
13098	76 53	A	WARSAT 2112	SCF	00115.0144	5.2	2.6943	-40.3051	19320	19328	2.07	-0.0000
13098	76 53	C	WARSAT 2112 4/B (2)	NORAD	00111.9370	7.1	1.7071	-102.0104	19282	19328	2.09	1.0000
13093	77 4	A	WARSAT 1570	SCF	00111.4442	7.0	-1.0357	69.2972	19331	19328	2.39	-0.0000
13095	77 4	C	WARSAT 1570 8/B (2)	NORAD	00118.0146	7.2	2.1907	-70.0822	19354	19328	2.38	0.0000
13092	78110	A	WARSAT 1570	NORAD	00112.4455	5.4	2.1409	-3.1395	19333	19328	3.31	0.0000
13096	77 10	C	WARSAT 1570 8/B (2)	NORAD	00116.1270	2.7	-3.0000	103.9074	19209	19328	3.37	0.0000
13094	77 33	A	WARSAT 1570	SCF	00110.1647	17.0	-5.0504	74.4464	19320	19328	6.03	-0.0000
13098	78577	A	WARSAT 1570 8/B (2)	NORAD	00 77.4447	41.4	-5.7804	41.9940	19548	19328	7.04	0.0000
13090	77 33	A	WARSAT 1570	NORAD	00113.1211	5.0	0.1534	-28.8020	18609	19328	10.34	7.1721

STATION	DATE	TIME	COORDINATES	UT	ALTITUDE	WEIGHT	APPROX	PERCENT	INCL	DRIFT
11002	11-01-68	11:00	80117.8215	1.0	7.5747	14956	16033	11856	10.34	71.8480
11003	11-01-68	11:01	80117.8216	5.3	4.1847	19310	19148	19297	9.30	0.0450
11004	11-01-68	11:02	80118.1124	3.0	-3.9843	19317	19328	19317	5.29	-2.1284
11005	11-01-68	11:03	80118.1129	5.4	-0.9287	19321	19154	19115	1.17	-0.0181
11006	11-01-68	11:04	80118.1131	14.0	-0.1446	19344	19173	19274	2.00	0.0302
11007	11-01-68	11:05	80118.1135	3.4	-2.0377	19314	19194	19200	2.54	-0.0363
11008	11-01-68	11:06	80118.1136	4.4	0.4476	19323	19329	19316	1.29	0.0081
11009	11-01-68	11:07	80118.1136	5.0	-1.1845	19459	19351	19377	1.29	-3.6588
11010	11-01-68	11:08	80118.1136	254.7	-0.2856	19378	19356	19355	9.24	26.0717
11011	11-01-68	11:09	80118.1136	782.0	6.0193	19307	18479	19251	7.51	24.1860
11012	11-01-68	11:10	80117.8276	1.1	2.7309	19318	19338	19308	4.14	0.0043
11013	11-01-68	11:11	80118.1136	5.4	1.8376	19407	20139	19463	4.33	0.116274
11014	11-01-68	11:12	80118.1136	3.0	-1.8846	19310	19351	19323	4.02	-0.0163
11015	11-01-68	11:13	80118.1136	2.1	1.6071	19345	19346	19326	2.59	-0.0283
11016	11-01-68	11:14	80118.1136	4.0	-2.4441	20794	20807	19495	2.98	-10.7977
11017	11-01-68	11:15	80118.1136	14.5	-0.4309	19297	19354	19297	2.68	-0.0634
11018	11-01-68	11:16	80118.1136	4.0	0.4156	19321	19354	19171	0.61	1.4504
11019	11-01-68	11:17	80118.1136	3.4	-7.2238	19497	20811	19321	0.44	0.160104
11020	11-01-68	11:18	80118.1136	3.0	-0.1874	19311	19494	19311	0.47	-1.0454
11021	11-01-68	11:19	80118.1136	2.5	-0.0862	19326	19326	19321	1.42	0.0245
11022	11-01-68	11:20	80118.1136	227.0	0.7896	19243	19109	19466	1.69	26.1407
11023	11-01-68	11:21	80117.8214	1.4	1.1017	19329	19329	19323	1.48	-0.0054
11024	11-01-68	11:22	80117.8215	5.8	-2.0404	19326	19338	19318	2.19	0.0027
11025	11-01-68	11:23	80118.1136	3.7	-1.9929	19322	20870	19336	2.04	0.178546
11026	11-01-68	11:24	80118.1136	10.0	6.1071	19323	19326	19324	2.09	-0.0083
11027	11-01-68	11:25	80118.1136	4.4	0.0117	19348	19172	19277	0.03	-0.0006
11028	11-01-68	11:26	80118.1136	200.0	4.1613	19000	20578	19229	5.00	4.1244
11029	11-01-68	11:27	80118.1136	5.7	-6.1146	19377	19170	19324	6.68	-0.0431
11030	11-01-68	11:28	80118.1136	2.4	-2.5442	21079	22559	19613	3.59	-0.2220

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