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EXAMINING SIMPLIFYING ASSUMPTIONS OF PROBABILITY OF COLLISIONS IN LEO

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ABSTRACT

This paper presents results of further investigation into the particular features of sun synchronous orbits and enhancements required to more accurately estimate the probability of Collision (PC). The approach taken here is to compare PC estimates using "typical" input values with "enhanced" input values specific to the sun synchronous case. The meteorological satellite NOAA-12 is used as an example. Results suggest that the collision probability for NOAA-12 using "enhanced" values is larger than the "typical" value by a factor of about 5.

INTRODUCTION

Sun synchronous Low Earth Orbits (LEO) have been used for many Earth sensing operations since the launch of the TIROS-9 weather satellite in 1965. These orbits allow satellites to pass through their ascending nodes at the same local sun time (same sun angle) on each revolution, adding to their value for meteorological sensing. As such, sun synchronous orbits can be viewed as scarce resources. Most new launches are accompanied by the insertion of final rocket stages and other objects in nearly similar orbits.

Collision risks faced by Earth orbiting satellites can be estimated using the probability of collision (PC) as a common measure of merit. For satellites in sun synchronous orbits, the hazard posed by other objects may require special consideration because the sun synchronous orbits are constrained to narrow sets of altitude and inclination. These orbits are popular for Earth resources measurements, weather, land use, and geology.

Overall, collision risks in LEO have increased. Since 1989, there have been seven breakups of satellites and rocket bodies in LEO, as shown in Table 1. Three breakups have been in sun synchronous orbits and have added fragments to this orbital space.

Collision probabilities are useful to satellite designers, operators, and users. Designers of satellites may supplement shielding or relocate wiring to account for an increased PC (Ref. 1). Mission designers can use the extra knowledge gained from PC calculations to select orbits which may have lower collision risks. Operators can make use of the more specific mission PC values to be aware of mission-threatening collision risks during anomaly analyses. Users can use more accurate PC values to understand the potential for data losses.

Table 1. Recent Low Earth Orbit (LEO) Breakups.

Name	SSO?	Launch Date	Breakup Date	Apogee	Perigee	Inclination	Trackable Pieces
FENGYUN 1-2 R/B	SSO	3 Sep 90	4 Oct 90	895 km	860 km	98.9°	72
COSMOS 2101	-	1 Oct 90	30 Nov 90	260	195	64.8°	4
DMSP-10	SSO	1 Dec 90	1 Dec 90	850	610	98.9°	25
COSMOS 2125-32 R/B	-	12 Feb 91	5 Mar 91	1725	1460	74.0°	65
NIMBUS 6 R/B	SSO	12 Jun 75	1 May 91	1105	1095	99.6°	229
COSMOS 2153	-	9 Oct 91	6 Dec 91	260	185	64.8°	1
COSMOS 1603	-	28 Sep 84	5 Sep 92	848	830	66.6°	62

COLLISION PROBABILITY CALCULATIONS

The probability of collision can be calculated with equation (1) (Ref. 2). As shown in Table 2, VR is the relative collision velocity between the parent (the satellite in question) and the impacting object, AC is the collision cross-section area, SPD is the spatial density, and T is the time at risk. Due to the near-random orientation of orbits in the Earth satellite population, and the relative sparseness of orbiting objects, principles of the kinetic theory of gases are assumed and are coupled with the Poisson distribution to determine PC.

$$PC = 1 - \exp\left(-VR * AC * SPD * T\right) \quad (1)$$

Typical values shown in Table 2 are based on studies treating all orbiting objects as an aggregate. Further examination of these input parameters shows that VR varies with altitude and inclination of the parent, AC is actually the average collision cross-section between the parent and all possible objects it might encounter, and spatial density is a function of altitude and resolution of the altitude bins used. With this as a basis, the next step is to look more closely at specific implications for sun synchronous orbits.

Table 2. Components of the Probability of Collision (PC) Equation.

Variable	Definition	"Typical" LEO Value	"Enhanced" Value
VR	Relative Collision Velocity, km/sec	10 km/sec	Function of Altitude and Inclination of Parent Satellite
AC	Collision Cross-section, km^2	Physical Cross-section of Parent Satellite	Average Collision Cross-section in Combination with all Possible Encounters
SPD	Spatial Density, objects/km^3	Latitude Averaged and Altitude Binned	Function of Latitude and Resolution of Altitude Bins
T	Time at Risk, Sec	N/A	N/A

SUN SYNCHRONOUS ORBITS

Sun synchronous orbits are unique resources designed to pass over the same latitude on the Earth at the same sun time on each orbit, for weather, land use, geology, and other purposes (Ref. 3,4). This requirement constrains the selection of orbits to certain combinations of altitude and inclination. Altitudes are frequently chosen, say for weather satellites, as a trade-off between ground resolution (the lower the altitude the better) and contiguous coverage at the edges of the scan (the higher the altitude the better in most cases). In some situations, such as for land use surveys, repeatable ground tracks are more important than contiguous edges in selecting altitude-inclination combinations. Equation (2) defines these combinations, where n is the orbit mean motion, J_2 is the zonal harmonic component for the Earth's oblateness, R is the Earth equatorial radius, p is the semi-latus rectum $a(1-e^2)$, and i is the inclination (Ref. 3)

$$-\frac{3}{2} n\, J_2 \left(\frac{R}{p}\right)^2 \mathrm{COS}(i) = 0.9856\ \frac{\text{degrees}}{\text{days}} \quad (2)$$

As shown in Figure 1, these orbits have attracted a multinational collection of satellites. Many of the most publicized space systems reside in sun synchronous orbits. According to the 1 March 1992 catalog of trackable space objects, nearly one quarter (1594 out of 6465) of trackable objects are in sun synchronous inclinations. Note the clustering, in Figure 1, near 99 degrees and 850 km.

COLLISION PROBABILITY INPUT PARAMETERS

Each input to the PC in equation (1) is now examined. Weather satellite NOAA-12 is used as an example to highlight differences between typical PC values and values calculated with enhanced detail. NOAA-12, according the 1 March 1992 catalog, is in an orbit between altitudes 809 and 829 km, with an inclination of 98.7 degrees. It has a spacecraft cross-sectional area (main body) of 7 m^2.

Relative Collision Velocity (VR)

The relative velocity can be estimated by examining the distribution of inclination and right ascension of cataloged objects in NOAA-12's altitude band. Analysis of these data results in an average impact angle of 91.1 degrees. Simple vector subtraction yields a mean relative velocity of 10.6 km/sec. Due to the uncertainties of this initial approach, a value of 11 km/sec is used for this paper. Clearly, much more study is required in this area.

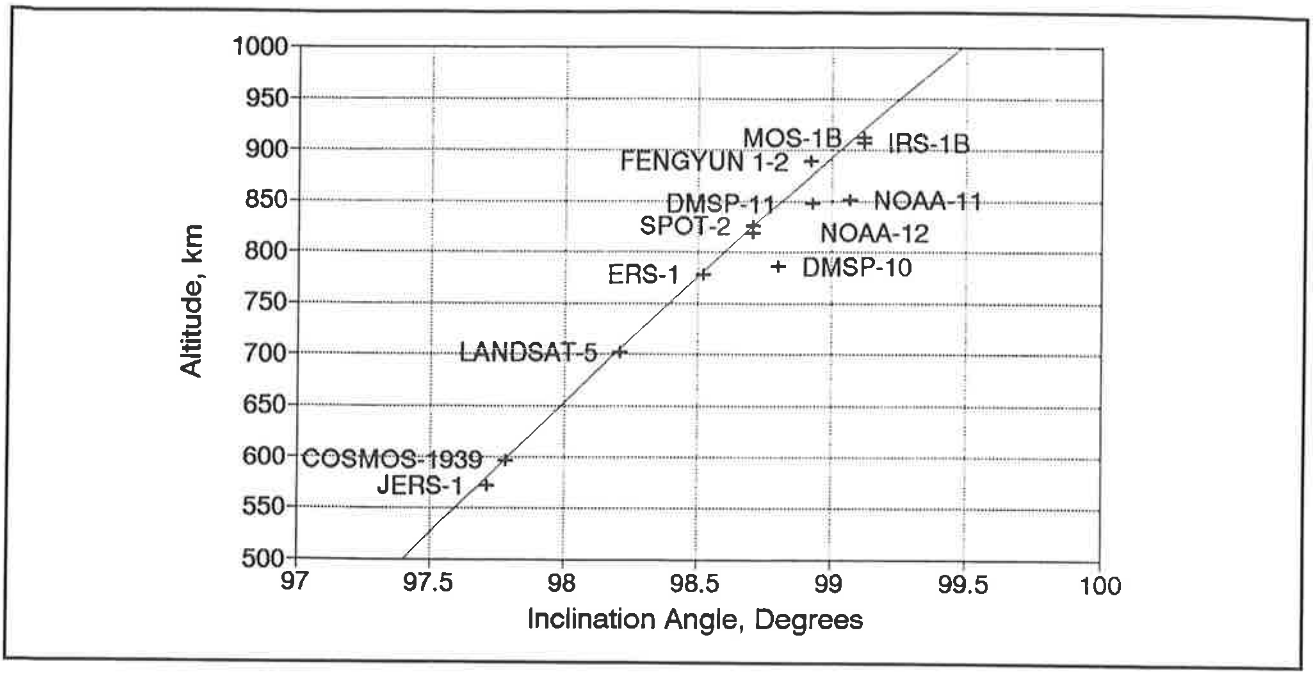

Figure 1. Sun Synchronous satellites relative to eqn. (2).

Collision Cross-Section Area (AC)

The collision cross-section area is commonly taken to be the actual physical size of the parent satellite considered. For the main body of NOAA-12, this is 7 m^2. In this paper, the actual collision cross-section is found with equation (3). The enhanced value (AC_e) is the mean collision cross section using the NOAA-12 satellite area (AC_s) and the areas of each of the other n objects (AC_i, i = 1 to n) in the NOAA-12 altitude band, here defined as 810 - 830 km.

$$AC_e = \sum_{i=1}^{n}\left[\left(\sqrt{AC_s} + \sqrt{AC_i}\right)^2\right]\frac{1}{n} \qquad (3)$$

The actual collision cross-section is found to be larger by a factor of as much as two to four, depending on assumptions relating physical area to radar cross section, and whether solar panel area is included. Based on actual spacecraft dimensions of objects in the 1 March 1992 catalog, and the actual area of the NOAA-12 main body, a value for AC_e is found to be about three times the actual NOAA-12 size. More study is necessary to fully understand this effect.

Spatial Density (SPD)

The spatial density for a given altitude in LEO is typically latitude-averaged despite the fact that there may be distinct variations by latitude (Ref. 5). For the 810 - 830 km altitude band of NOAA-12, the average SPD value over all latitudes is $9.93*10^{-9}$ objects/km^3. The actual average SPD encountered by a satellite is a function of its altitude and inclination. Figure 2 was calculated from the 1 May 1992 catalog using the Kaman Sciences SUPER model and shows the spatial density in one degree increments of latitude. For comparison, SPD values for 810 - 830 km and inclinations of 30 degrees and 60 degrees are $5.9*10^{-9}$ and $7.9*10^{-9}$, respectively.

NOAA-12, with its inclination of 98.7 degrees, spends more of its orbit between 80 - 85 degrees than between 0 - 5 degrees latitude, and quite a bit of time above 80 degrees. Figure 2 depicts spatial density for the NOAA-12 altitude range. Note the large spike near 82 degrees. Not only are there many sun synchronous objects with inclinations near 98 degrees that linger at this latitude (82 is the supplement of 98 degrees), but there are several other objects with inclinations near 82 degrees. Both sets of objects contribute to the large SPD at 82 degrees latitude. Using these data, an enhanced value of SPD = $1.53*10^{-8}$ is calculated by accounting for the time NOAA-12 spends in each latitude band.

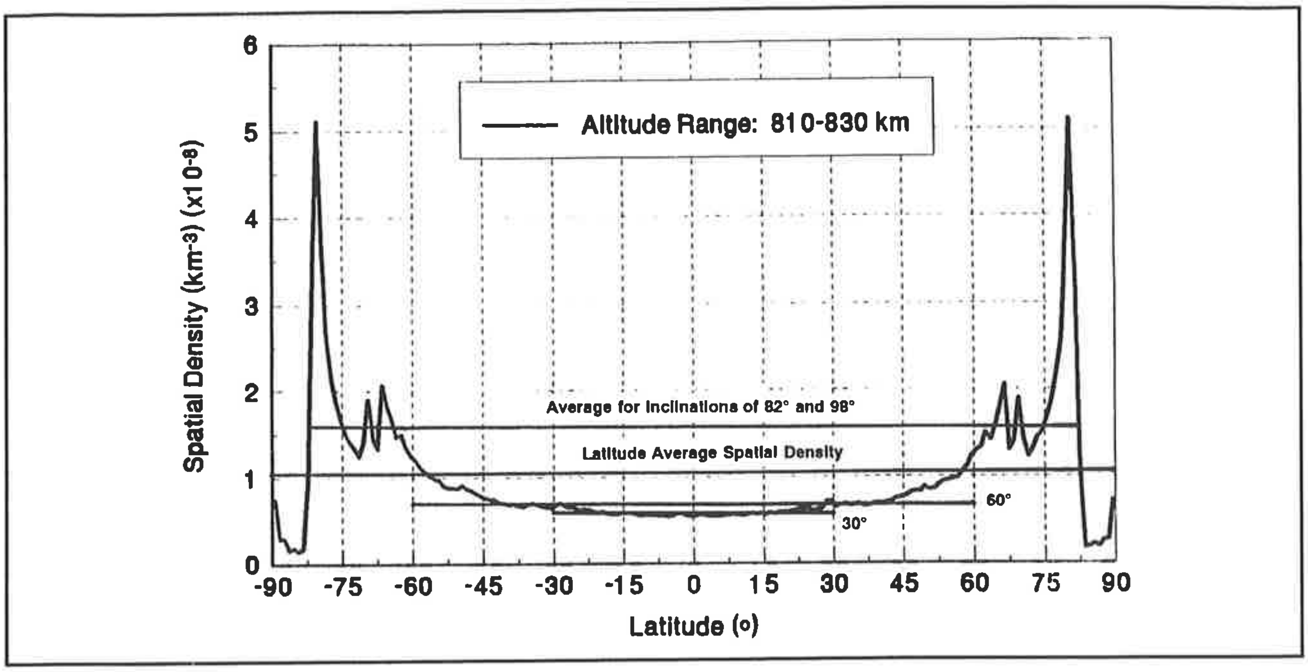

Figure 2. Earth orbit Spatial density, May 1992 catalog.

RESULTS AND SUMMARY

Table 3 summarizes inputs and collision probabilities for NOAA-12 calculated for a time frame of one year with equation (1). Values from the NASA environment definition (Ref. 6) are shown for comparison for sizes greater than 10 cm. For this example, all the "enhanced" input values are larger than the "typical" values. The "enhanced" PC estimate is considered to be a more accurate representation of the collision hazard than the "typical" approach. For the approach used here, the "enhanced" probability of collision for NOAA-12 is larger than the "typical" estimate by a factor of slightly greater than five. Obviously, additional research is needed to more completely understand the effects studied here and collision hazards for sun synchronous objects.

Table 3. Estimates of the Probability of Collision (PC) for NOAA-12.

Approach	VR	AC	SPD	PC/YEAR
SSP30425	Modeled	7 m^2	Modeled	$9.66*10^{-6}$
Typical	10 km/sec	7	$9.93*10^{-9}$	$2.19*10^{-5}$
Enhanced	11	21	$1.53*10^{-8}$	$1.12*10^{-4}$

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