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DETECTABILITY OF SATELLITE FRAGMENTATIONS IN HIGHLY ECCENTRIC ORBITS

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ABSTRACT

We consider the fragmentation of a satellite initially in a highly elliptical orbit (HEO) following hypervelocity collision with a debris object in low Earth orbit (LEO). The probability of such a collision is found to be small in the short term, but but the orbital lifetime for objects in HEO is much higher than for objects in circular orbits of similar perigee altitude. Thus the collision hazard they represent to LEO will continue in some cases for many hundreds of years. A 1.5m optical telescope equipped with fast read-out CCD arrays can detect debris of diameter ~1cm in LEO. However, Molniya objects are detected much more efficiently using longer integration times and detecting them at high altitudes with a limiting size ~5 cm at 20000km. The choice of observing site and telescope pointing direction can have a significant effect on the detection rate and size dependent selection effects.

INTRODUCTION

Attention continues to focus on the capability to observe objects within the operational satellite population. We are becoming aware of the limitations of the Space Surveillance Network (SSN) for detecting and tracking certain families of orbital debris on an operational basis. Selectivity in the SSN architecture may cause under-representation of eccentric orbits in the catalogue /1/ (85% of catalogued objects are in circular orbits). Objects in highly elliptical orbits will pass through the densely populated regime of low Earth orbit (LEO) close to their perigee point. We determine the risk of such a collision, the resulting orbit and size distribution of fragments, and assess our ability to detect them.

HEO ORBITAL LIFETIMES AND POPULATION STATISTICS

The orbit of an object moving within a highly eccentric orbit with its perigee below 1000km will experience perturbing forces predominantly from the gravitational anomalies of the Earth, interaction with the atmosphere, solar radiation pressure and solar and lunar gravity. However, the dominant behaviour is a decrease in apogee altitude and attendant circularisation of the orbit until ultimately, re-entry occurs. To the first order the orbital lifetime of an object in HEO can be formulated /2/ in terms of perigee altitude and eccentricity, shown in figure 1 for average solar conditions (exospheric temperature = 1200K). For an object with $e=0.7$, the orbital lifetime can vary between 10 and 10000 years. It is apparent that the collision hazard from these objects will be extended over a very significant period of time.

The number of catalogue objects in HEO at 1 May 1994 is shown in figure 2. We can see peaks of objects in inclinations 0° -10°, 20° -30° and 60° -70° representing families of objects launched from Kourou, Kennedy Space Center and Plesetsk respectively. The peak in eccentricity occurs between 0.7 and 0.75 which is the nominal injection value for objects in geostationary transfer orbit (GTO) or "Molniya" orbits. There is a smaller but significant proportion of objects of lower eccentricity whose orbits have begun to decay from their normal values under the influence of atmospheric drag.

COLLISION PROBABILITY AND BREAKUP SCENARIO

The probability of collision between an object in a HEO orbit and a piece of debris in LEO is shown in figure 3. This estimate is made by flying a satellite through a control volume which contains the time averaged flux of catalogued objects passing through those cells /3/. The maximum collision probability will exist for an object in a "Molniya-type" orbit with $e \sim 0.7$, $a \sim 26600$ km, $i \sim 63°$. We will therefore use a Molniya satellite as our characteristic collision partner with a debris object in LEO.

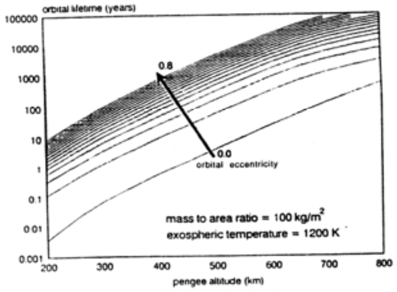

Fig. 1. Orbital lifetimes as a function of perigee altitude and eccentricity for an object with ballistic coefficient 100 kg m^{-2}.

We consider the breakup of a 1000kg satellite following a Molniya orbit and a 2kg debris object in LEO in a near polar orbit which is massive enough to cause a catastrophic breakup. The distributions of fragments and their associated orbital parameters following the encounter, predicted by current empirical models /4/ assuming isotropic breakup are shown in figure 4. Although a number of fragments decay from orbit immediately, a significant proportion remain clustered about the nominal orbital parameters of the parent satellite.

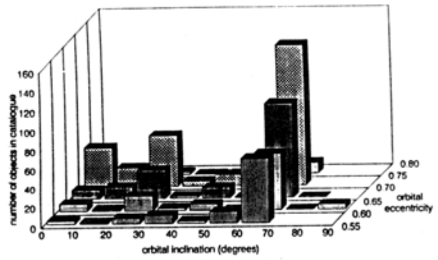

Fig. 2. Number of catalogued objects in HEO at 1 May 1994.

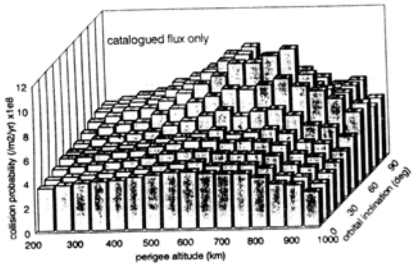

Fig. 3. The collision probability between an object in a HEO orbit and debris in LEO.

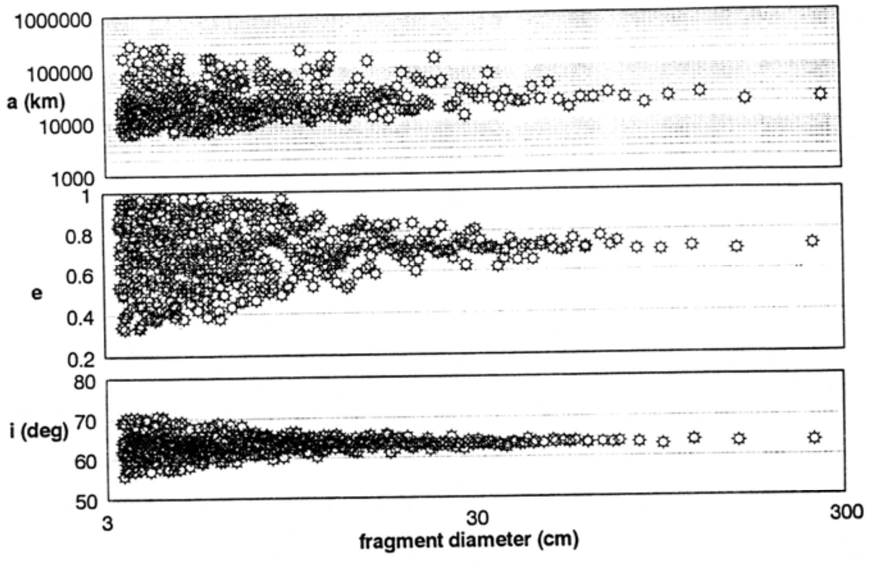

Fig. 4. Orbital elements of fragments produced by collision of a Molniya satellite with LEO debris object.

DETECTABILITY

The significance of a fragmentation event can only be determined if the resultant fragments can be distinguished from the "background" population. We consider here an optical rather than radar detection system since it is relatively more sensitive at higher altitudes where high eccentricity objects spend most of their time. The predicted detection rates and characteristics described below have been derived for a 1.5m optical telescope with a 1° x 1° field of view, 500x500 pixel CCD arrays with 1.5 arcsec pixels, 2x2 on-chip binning, and readout at 1μs per pixel with 6e$^-$ pixel^{-1} rms readout noise.. In order to maximise the on-sky observation time and the debris signal relative to the sky background and readout noise, a trade-off between pixel size, integration time and read-out time has to be made. Large pixels (by binning) allow the rapidly moving debris to remain on the pixel for longer, and reduce the read-out time, but also have a large sky background signal and reduced positional accuracy. A more detailed discussion of optical detection systems can be found in Dick et al /5/.

Background debris detection rates have been calculated using a population model based on the orbits of tracked debris (derived from the DISCOS database /6/) using a,e and i and assuming nodes and apsides are randomly distributed. The model size distribution is derived by fitting the shape from the model by Kessler et al /7/ to the total numbers of catalogued objects in LEO /8/ at the largest sizes (where observational selection is not significant). The model assumes that observations can be made when the sun is 18° below the horizon and debris is not in Earth shadow. Debris albedos are assumed in the range 0.09-0.12 depending on phase angle. For further details see /9/. The detection rates as a function of debris size and altitude at detection are listed in tables 1 and 2 for a zenith pointing telescope situated at a high altitude site near the equator, with integration times of 10ms and 100ms. "Molniya" orbits are defined here as any object with $e > 0.65$ and $55° < i < 70°$ which represent 8% of the total model population. Since the model has randomised nodes and apsides, the detection rates (NB not necessarily different objects) for "Molniya" objects from the equator will be similar to those at other sites *within the model.* However, a site in, for example, northern Europe will not detect "real" Molniya satellites near perigee and a site in South America will not detect them near apogee.

Table 1. Debris detection rates for a zenith pointing, 1.5m telescope near the equator (see text). Integration time = 10ms

		Debris detections per day							
		All orbits Size (cm)				"Molniya" Size (cm)			
Altitude (km)	Nominal altitude	< 4	4-10	10-25	25-60	< 4	4-10	10-25	25-60
300-600	467	41	3	0.6	0.7	0.03	-	-	-
600-900	757	260	27	6	7	0.3	0.03	-	-
900-1200	989	470	49	11	13	0.2	0.1	-	-
1200-1600	1426	250	110	25	30	0.5	0.2	0.02	0.06
1600-4000	2663	170	160	37	44	-	7	2	2
4000-35287	19900	-	-	1200	3500	-	-	130	370
35287-36287	35754	-	-	-	8700	-	-	-	20

Table 2. As table 1 but with integration time = 100ms

		Debris detections per day							
		All orbits Size (cm)				"Molniya" Size (cm)			
Altitude (km)	Nominal altitude	< 4	4-10	10-25	25-60	< 4	4-10	10-25	25-60
300-600	467	14	2	0.3	0.4	0.02	-	-	-
600-900	757	140	15	3	4	0.03	0.01	-	-
900-1200	989	60	27	6	7	0.01	0.04	0.01	0.01
1200-1600	1426	140	62	14	16	0.3	0.1	0.02	0.03
1600-4000	2663	-	92	20	24	-	4	0.9	1
4000-35287	19900	-	1700	1600	1900	-	200	170	200
35287-36287	35754	-	-	4000	4800	-	-	9	11

Although the smallest objects (~1cm) are detected at low altitude with short integration times, a greater proportion of detections of larger (>10cm) Molniya type objects is made at high altitude since: i) they spend a greater time there, ii) the telescope searches a greater volume of space and iii) Earth shadowing is not such a significant constraint. A longer observation time of 100ms reduces the total number of debris objects detected in LEO at the smallest sizes, but increases the number of Molniya type objects detected since these have smaller angular velocities.

A single fragmentation event as described above would double the population of Molniya objects larger than 5cm. Since the model has 4000 objects of this size of which 300 are Molniya, the increase would only be apparent if orbital information could be derived from the detections. Single epoch detections allow inclination to be derived to better than 1° but are not sufficient to derive eccentricities. The mean motions do however give an indication of altitude so the high altitude observing strategy (ie ~100ms integrations) appears to be the best method of identifying such events from a single station.

In order to determine the best observing strategy from a particular site, we need to consider the detailed orbits of debris fragments. For a given fragment, and observing site, we determine the altitude and azimuth as a function of time allowing for J2 perturbations. Figure 5 shows maps of the sky from a northern hemisphere site with bins representing the total time that a particular debris fragment is detectable (S:N>2) in the 1°x1° telescope field of view for a year's observations. (Similar diagrams for debris in LEO high inclination orbits show azimuthally constant detection rates). 50cm objects are detected around the whole orbit. The "empty" region in figure 5a is above the 63.4° geocentric latitude limit for Molniya orbits. Smaller objects are not seen near apogee so the latitude limit is effectively lower (fig 5b), although apsidal advance for fragments will eventually smear out this effect. The ideal viewing direction will depend on the latitude of the site and the smallest size to be detected. For the example here, zenith viewing is ideal to minimise size dependent selection effects.

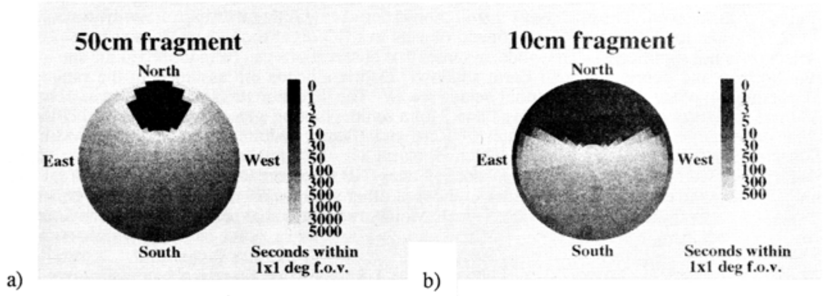

Fig. 5 Observability map for a) 50cm and b) 10cm Molniya (e=0.699, a=23325 km, i=64.1°, $\Omega=0°$ $\varpi=270°$ initially) fragments as observed from Pic du Midi (43°N, 0°W). Seeing assumed 1 arcsec. See text.

CONCLUSIONS

The long orbital lifetimes of HEO satellites and their high relative velocity in LEO provide the conditions for catastrophic breakup. The highest impact probability is for Molniya-type orbits, and a single collision with a small LEO object could double the catalogued population. Ground-based optical telescopes allow detection of fragments ~10cm in size around a sizeable fraction of an orbit, and 20cm objects at apogee. Detection rates when the objects are at low altitude, and therefore brightest, are very low due to the short observation time (Earth shadowing) and high angular velocity. The best strategy is to "tune" the detection system for observations at high altitude, where the majority of Molniya's will be detected. Choice of observing site and telescope pointing direction can have a significant effect on the detection rate.

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