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Tether Impact Rate Simulation and Prediction with Orbiting Satellites

Final Report
to
David V. Smitherman, Jr. (FD02)
NASA/Marshall Space Flight Center 35805

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Alpha Technology, Inc.
3322 South Memorial Parkway, Suite 630
Huntsville, Alabama 35801

I. Introduction

Space elevators and other large space structures have been studied and proposed as worthwhile by futuristic space planners for at least a couple of decades. In June 1999 the Marshall Space Flight Center sponsored a Space Elevator workshop in Huntsville, Alabama, to bring together technical experts and advanced planners to discuss the current status and to define the magnitude of the technical and programmatic problems connected with the development of these massive space systems. One obvious problem that was identified, although not for the first time, were the collision probabilities between space elevators and orbital debris. Debate and uncertainty presently exist about the extent of the threat to these large structures, one in this study as large in size as a space elevator. We have tentatively concluded that orbital debris although a major concern not sufficient justification to curtail the study and development of futuristic new millennium concepts like the space elevators

II. Description of three tethered structures

Tether concepts were selected that roughly correspond to common operations associated with new millennium space systems that have been discussed in recent symposia and workshops (Smitherman). For example, the propellant depot operations may use projectiles lunched to the base of a 400-km long tether hence the first tether chosen for this study was 400 km in length.

Another space system that has received attention for the new millennium is the LEO space elevator concept shown in Figure 1. Its length of 4000 km dictated the second tether length. A space elevator is a physical connection from the surface of the Earth to some point in space. Its purpose is to provide mass transportation to space in a way similar to current highways, railroads, ocean vessels, power lines, and pipelines across the Earth's surface. Payloads, power, fuel, and people will be transported into space at a considerable savings compared to present-day cost.

And finally to simulate systems that will benefit from access to a geo-synchronous orbit and continue beyond even to the altitude for earth escape a 47000-km long tether was selected. A GEO space elevator reaching to such distances would rotate in synchronous with the Earth's surface and thus provide a stationary platform. This GEO system would connect our planet to space and enormously enhance the opportunities to make space exploration an economically successful endeavor.

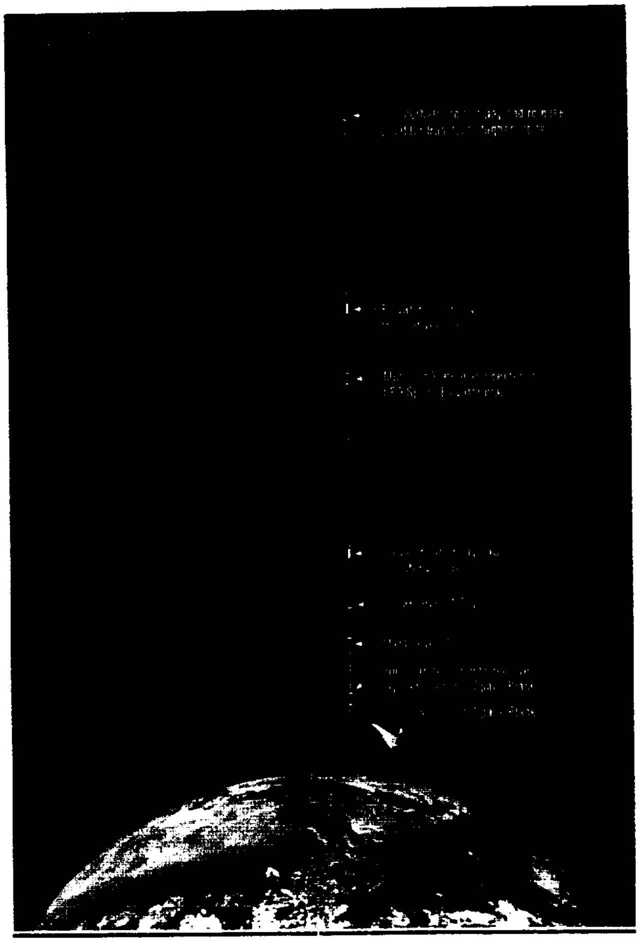

Figure 1. LEO Space Elevator Concept (Smitherman)

To examine the collision probabilities between future structures as depicted in Figure 1 and orbital debris three very simple concepts for earth orbiting tethers were developed and used in the collision calculations. All three tethers are assumed to be gravity gradient and non-swinging.

Table 1 below summarizes the size and location of the three tether concepts.

Table 1. Three Tether Concepts

Tether No.	Length (Km)	Diameter (M)	Orbit Inclination (Deg)	CG Altitude (Km)	Orbital Period (Hrs)
1	400	0.01	0	400	1.5
2	4000	10.00	0	2000	2
3	47000	30.00	0	35748	24

III. Debris Model

The debris model was obtained from GSFC and contains twelve catalogs (each with approximately 8200 objects). Each catalog has a different start date or epoch between January and April 2001.

It is important to point out that the debris in this model are radar tracked objects and therefore larger in size than approximately 10 cm. There is a considerable amount of space debris smaller in size than 10 cm which will also impose a threat to tethers in space.

IV. Analysis Results

The analysis was done using the so-called "brute force" method where the tether and the debris are propagated along their orbital paths using different start dates. For this study dates between January and April 2001 were used for a time period of 1 and 7 days. The number of collisions (actually close approaches) were computed for all three tethers. The number of close approaches (defined as within a distance of 10 km) was computed for 1 and 7 day time periods. The results for the 30-day period were then found by scaling the 1 and 7 day numbers and are shown in Table 2.

Table 2. Number of Close Approaches for a 30-day time period for Five Distance Ranges in km

	(0 - 0.1)	(0- 0.5)	(0-1)	(0-5)	(0-10)
Tether 1 (400 km)	0	0	3	83	228
Tether 2 (4000 km)	0	13	65	1138	2578
Tether 3 (47000 km)	0	13	53	1078	2410

As can be seen from Table 2 there were no cases where the debris came within 0.1 km (100 meters) of the tether, i.e., there were no collisions---at least not for this short 30-day time period. However, in the 0 to 1 km and 0 to 5 km ranges there were considerable encounters even in this short period of time, especially so for the two longer tethers. For stay-out zones associated with current projects like the ISS this is certainly not a comforting result---although fortunately the ISS is a considerably smaller object than Tethers 2 and 3.

An interesting aspect of the Table 2 results is that the much larger structure (Tether 3) has about the same----although slightly fewer---encounters than Tether 2. This is attributed to the tether location in space and to the non-uniformity of the debris field (shown later). Also the orbital period (the smaller the period the more orbits in a 30-day period hence more encounters) is a factor in determining the number of close approaches. So Tether 2 with a period of 2 hours will complete more orbits (and experience a greater number of encounters with orbital debris) in a 30-day time period than Tether 3 with a 24 hour period. This can also be explained in terms of flux (encounters/time) which is a function of the debris number density and relative velocity. The number density is approximately the same for Tethers 2 and 3 making the flux only a function of the relative velocities which is greater for Tether 2.

Caution should be used when considering the favorable results in Table 2. First it is only for a 30-day time period and it takes into account only the tractable debris (larger than 10 cm in diameter). As already stated, the smaller debris (1 – 10 cm diameter) will also be a threat to large tethers in space.

Furthermore, theoretical collision expressions for the same conditions as here give a more pessimistic result. For example the number of encounters per month (N) for structures in equatorial orbits ranging in size between 100 and 4000 km can be computed using the following expression

$$N = 6.7 \text{ X } 10^{-5} Ld$$

where L is the length of the structure in km and d is the distance in meters between the debris and the structure. Applying this expression for distances (d) of 10 and 30 meters to Tethers 2 and 3 gives 2.68 and 94.47 hits per month, respectively! The disparity between this result and the Table 2 numbers is explained by the lack of precision associated with the "brute force" method used to generate Table 2.

V. Debris Distribution

Some of the "brute force" results (Table 2) are counter-intuitive, i.e., about equal results for tethers with an order of magnitude difference in size. This can however be explained by observing the location of the tether in space relative to the debris field. The spatial debris distribution plays a major role in the likelihood of a collision or encounter. Why this is so can be seen from the non-uniform distribution of debris with distance from the Earth's surface as shown in Figure 2.

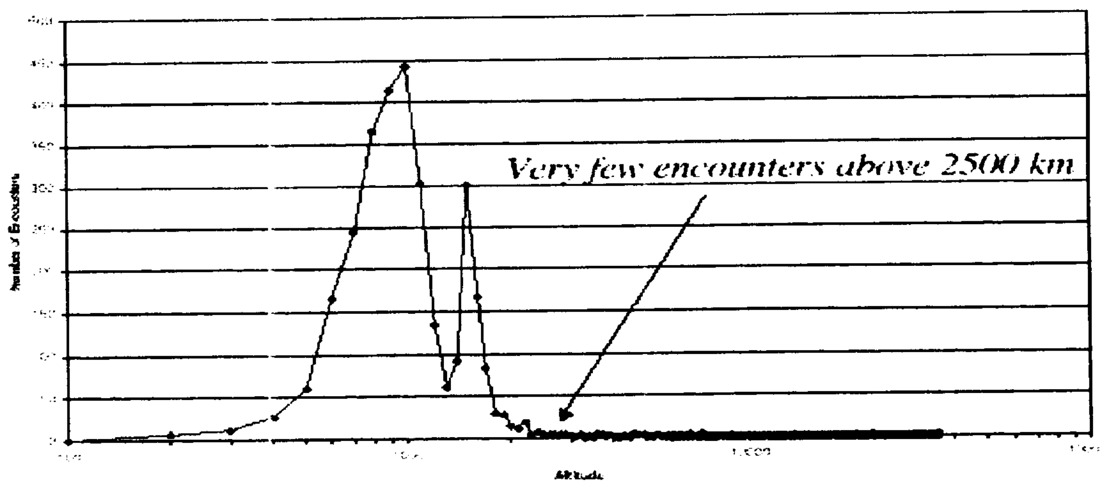

Figure 2. Distribution of encounters with altitude.

Notice in Figure 2 the peaks at 910 and 1525 km. Notice also that the debris count is practically nil for altitudes less than 300 km and greater than about 2500 km. So, long tethers like Tethers 2 and 3 in this study will essentially see the same debris environment as indeed Table 2 shows.

The U. S. Air Force tracks space objects 10 cm or larger in size (amounting to approximately 8700 objects). Figure 3 below shows the Air Force distribution of known objects (satellites and debris) in Earth orbit out to 50000 km (semimajor axis). Notice again the non-uniform distribution, this time however with respect to both orbit inclination and the debris semimajor axis. This plot shows a preponderance of debris at 8000 km (roughly 1600 km above the Earth's surface for debris in circular orbits) for all inclinations. This is approximately in agreement with Figure 2. Notice furthermore in Figure 3 the influence of inclination. Orbits inclined 0 degrees (as is the case in Table 2) see relatively little debris while orbits inclined 65 to 70 degrees encounter a much greater debris population. The "brute force" results obtained in Table 2 were for an inclination of 0 degrees. Judging from Figure 3 had we examined a 65-degree case a greater number of collisions would have occurred.

Because of the debris distribution shown in Figure 3 the placement of large structures in favorable inclinations with respect to debris populations may be an important consideration for future planners.

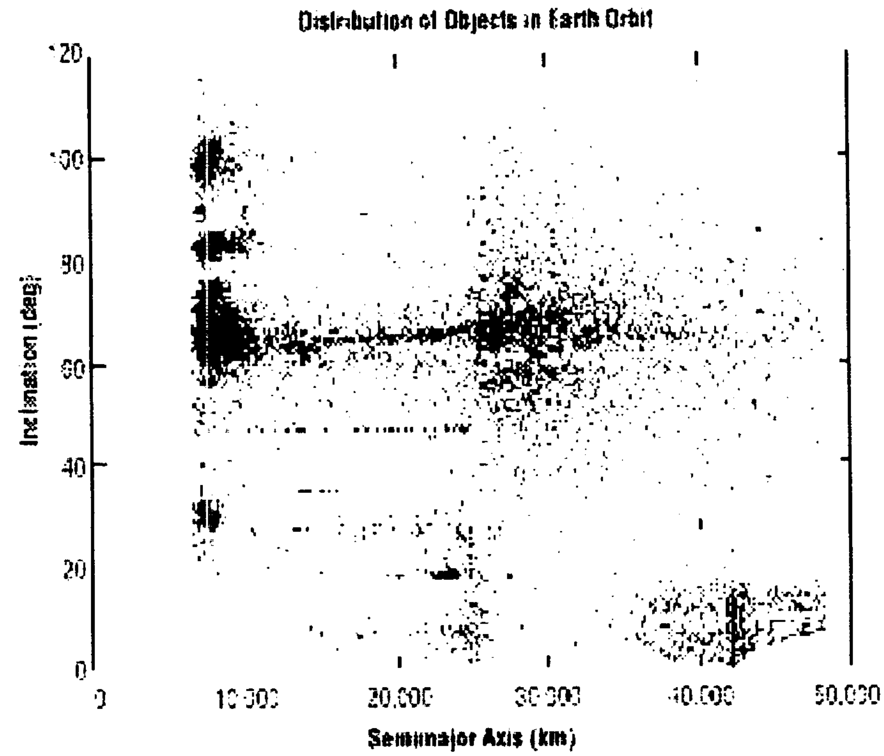

Figure 3. U. S. Air Force space satellites and debris distribution

VI. Conclusions

For Tether 2 (4000 km), 2 to 3 collisions occurred per month and for Tether 3 (47000 km), 94 collisions occurred per month when using the theoretical expression. No collisions occurred in the 0 to 100 meter distance range using the "brute force" method. This method indicates that the tether location is important when collision probabilities are estimated, e.g., the larger GEO Tether 3 received slightly fewer strikes than the smaller LEO Tether 2.

If you can solve the debris problem for the smaller system (LEO tether) then the problem for the larger system (GEO tether) may not be that much more difficult.

During the next couple of decades important developments for successful large tether missions are: (1) new millennium structures that are maneuverable and therefore able to avoid catastrophic collisions with orbital debris, (2) space-debris cleaning systems perhaps using laser pulsing for destroying small size orbital debris, (3) reusable in-space transfer vehicles, (4) improved Air Force debris tracking capabilities, and (5) more realistic information on the orbital debris problem and its solution from the ISS experiences.

References

Cooke, William J. , and Lewis, Heather (2001). Impact of the Cataloged Population on Very Large Scale Space Structures Unpublished Internal Report, Marshall Space Flight Center, Huntsville, Alabama 35812.

Smitherman, Jr., D. V. (2000). "Space Elevators -- An Advanced Earth-Infrastructure for the New Millennium, Marshall Space Flight Center, Huntsville, Alabama, 35812, NASA/CP—2000—210429.

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Jim Harrison

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Alpha Technology, Inc.
3322 South Memorial Parkway, Suite 630
Huntsville, AL 35801

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