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2D LT ASHLEY DAVID M

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RISK ASSESSMENT OF SPACE DEBRIS HAZARDS FOR GLOBAL POSITIONING SPACECRAFT

2ND LT. DAVID M. ASHLEY

8 MAY 1998

ENGINEERING IN SPACE OPERATIONS

UNIVERSITY OF COLORADO AT COLORADO SPRINGS, CO

Abstract

An important concern of USSPACECOM has been developing a policy to reduce orbital debris, including ensuring proper spacecraft end-of-life disposal to minimize the number of spacecraft left on mission orbit beyond their useful lifetimes. This paper provides insight to the pertinent issues related to space debris and spacecraft disposal in addition to a detailed analysis of debris hazards for the Global Positioning System (GPS) family of spacecraft as outlined by M. E. Sorge. Results of the analysis show that inactive GPS satellites pose the most significant hazard to the GPS constellation of all space debris of large size, thus reaffirming recent U.S. space policy mandating de-orbiting for all GPS satellites deemed non-mission capable. Additional analysis is recommended to explore collision probabilities for medium sized debris, since this category is also capable of disabling GPS satellites.

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Introduction

A short 50 years ago, before the launch of sputnik, the idea of man-made garbage cluttering space was difficult even to imagine. But trash in space, or more precisely, debris in orbit around the Earth, is no longer just an abstract problem. It is now the subject for heated international debates, policy-making, and constitutes an undeniable threat to all space programs.

NASA defines orbital debris as a man-made hazard caused by previous space missions.[1] Categories of debris include spent satellites and rocket bodies, accidental explosions, collisions, and debris from the operations of spacecraft. Currently, the most serious problem with debris is that it can occur in a size small enough to avoid earth sensors, yet large enough to damage most satellites bus systems. Debris larger than approximately 10 cm is trackable from Earth and most often avoidable. Although unseen from Earth, shielding protects spacecraft from most debris smaller than 1 cm. Debris smaller than 10 cm but larger than 1 cm has the potential to disable a satellite while remaining invisible to Earth sensors. All types of space debris are potential threats to any spacecraft and impacts spacecraft design, operation, and disposal procedures.

The Navigation System with Timing and Ranging (NAVSTAR) Global Positioning System is a collection of several similar satellites in a MEO constellation. GPS was primarily designed to provide accurate radionavigation to users on Earth 24 hours a day through the transmission of precise time and satellite position. Run by the Joint Program Office (JPO) at the U.S. Air Force Systems Command's Space Division, the GPS systems provides critical coded location and time information to all branches of the U.S. military as well as similar but less accurate uncoded information to civilian users around the world.

Current policy established by USSPACECOM (in compliance with the National Space Policy) provides direction and guidance for the proper disposal of satellites to prevent the space environment from being polluted by space debris. The purpose of these procedures is to "reduce the risk of potential collision of operational satellites and space debris."[2] The policy defines guidelines for determining non-mission capable status, monitoring of payload and vehicle health, and proper disposal procedures. In addition, specific disposal requirements are listed and categorized by orbit type; Low Earth Orbit (LEO) of 160-1600km, Medium Earth Orbit (MEO) of 1600-35896km, and Geostationary orbit (GEO) at approximately 35896km.

The semi-synchronous orbit selected for GPS currently has few space debris hazards that fall in the dangerous size range (larger than 1 cm). However, the risk of hitting debris does exist. While colliding with a small piece of debris might only damage a satellite, the collision of a GPS satellite with large piece of debris (such as an inactive GPS satellite) has a high probability for creating a cloud of debris. This cloud would increase the probability of other satellites hitting debris of varied size by several orders of magnitude, having the potential to disable the entire constellation.

Once deemed non-mission capable, the satellite operators attempt to dispose of the spacecraft in accordance with Air Force policy. In some cases, fully complying with current policy is impossible for the operators. The reasons for this include a lack of design requirements for end-of-life disposal during the satellite production, disposal procedures changing over the mission life, and the satellite becoming prematurely inactive. In other cases, a satellite is declared non-mission capable even though sufficient propellant and service capability exist to extend the mission life. This cost the GPS program more money, since the satellite could continue to operate until propellant levels mandate de-orbiting. However, cutting the propellant margin too thin could prevent a proper disposal and put the constellation in potential danger from active satellites becoming non-functional while still in semi-synchronous orbit.[3]

A Summary of Space Debris

Debris began to accumulate shortly after the beginning of the space age as some 3750 launches led to more than 23,000 observable objects in orbit.[4] At the end of 1991 there were over 7,000 cataloged objects still in orbit, most deposited by the Soviet Union and the United States.[5] Currently there are over 8000 cataloged objects. These numbers do not represent the full story, for only objects over 10 cm are tracked from Earth. NASA has estimated that roughly 35,000 to 150,000 pieces exist in the 1-10 cm range, while 3-40 million are 1 cm or less.[6] These estimates are subject to large uncertainties due to inadequate observational capabilities, but are based on models that can project the growing amount of debris relative to the number of spacecraft launched, collisions between catalogued objects, and explosions that occur.

Although the growth rate of debris will increase the potential for collision with an active spacecraft, a more significant worry over a longer time period is the collision of debris with other debris, leading to a domino effect of collision-induced breakups. In this way more debris is produced by collisions, increasing the number of fragments and probability for hits. In the worst-case scenario, "an unstable, run-away environment of self-generating debris could result as early as the next century, if no steps are taken to address the problem."[7]

The risk of colliding with space debris is a function of the orbit and altitude of both the operational spacecraft and debris. Satellites in LEO have the highest risk, since six out of seven pieces of cataloged debris reside in that altitude range. Well known for overcrowding, the GEO orbit is a very narrow band that has much economic value. Since it is so high above the Earth, objects smaller than 1 meter are not easily seen. Current estimates place the numbers at 400 trackable objects and 2000 objects under 1 meter.[8] GEO satellites are often very close to each other, but move in the same general direction and velocity (to maintain a 24 hour period) typically reducing velocity of impacting debris. MEO has the largest range of altitudes, has the fewest number of catalogued debris, and has the fewest number of satellites. Debris hazards for MEO vary with altitude, but are currently minimal for the semi-synchronous height of the GPS constellation.

Techniques for minimizing debris produced by spacecraft upon completion of their mission include two methods of disposal. LEO satellites perform a thrust maneuver that reduces altitude until reentry occurs in the Earth's atmosphere where most spacecraft completely disintegrate. The only risks for this method include spacecraft that do not completely burn up and satellites with a nuclear power system or payload. For GEO and MEO spacecraft, the fuel required to perform a reentry burn makes the option impractical. Current standards require GEO craft to perform a burn up into a graveyard orbit high enough over GEO to prevent interference. Satellites in MEO must make a similar burn either higher or lower, depending upon where other satellites are located relative to the non-mission capable craft. For all of these alternatives, a budget for disposal propellant must be in the design.

Current GPS Constellation Characteristics

GPS satellites have nearly circular orbits (eccentricity = 0.02) with an approximate altitude of 20,200 kilometers above the Earth. This gives a period of approximately 12 hours. The current constellation has 24 operational satellites and four spares deployed in six evenly spaced planes, inclined at 55°, with four active satellites per plane.

Since the first GPS satellite launch in 1978 there have been many changes in the design. There are five main classes of GPS satellites, Blocks I, II, IIA (advanced), IIR (replacement), and IIF (follow-on). Only blocks II, IIA, and IIR are currently on orbit. All block II and IIA satellites built are either active or out of service, and block IIR has launch predictions through 2002 (see Figure 1). Block IIF is currently under development.

Block I satellites, built by Rockwell International, weighed about 845 kg, had 60 lbs. of propellant, and had a mission design life of 4.5 years (although one was operational for over 10 years). Block II and IIA satellites, also made by Rockwell International, weigh approximately 1850 kg, have 130 lbs. of propellant, and were designed for a six year mission life but carry a 10 year supply of expendables. There are 8 block II and 18 block IIA active satellites on orbit as of March 1, 1998 (see

Figure 2). Block IIR satellites, made by Lockheed-Martin, weigh more than 2000kg and have a mission life of 10 years. Only two have been launched to date, and currently one is operational (the first exploded due to booster failure). Block IIF satellites, under contract by Boeing, will have a design life of 10 years minimum.

Mission	Launch	Orbital Slot	Operational	Nav Lost	Reason	Months Operational
II-1	14 Feb 89	E1	14 Apr 89	Operating		106.6
II-2	10 Jun 89	B3	12 Jul 89	Operating		103.7
II-3	17 Aug 89	E5	13 Sep 89	Operating		101.6
II-4	21 Oct 89	A4	14 Nov 89	Operating		99.6
II-5	11 Dec 89	D3	11 Jan 90	Operating		97.7
II-6	24 Jan 90	F3	14 Feb 90	Operating		96.6
II-7	25 Mar 90	B5	19 Apr 90	10 May 96	Reaction Wheels	72.7
II-8	02 Aug 90	E2	31 Aug 90	Operating		90.1
II-9	01 Oct 90	D2	20 Oct 90	Operating		88.4
IIA-10	26 Nov 90	E4	10 Dec 90	Operating		86.8
IIA-11	03 Jul 91	D1	30 Aug 91	Operating		78.1
IIA-12	23 Feb 92	A2	24 Mar 92	Operating		71.3
IIA-13	10 Apr 92	C5	25 Apr 92	05 May 97	Nav Hardware	70.2
IIA-14	07 Jul 92	F2	23 Jul 92	Operating		67.3
IIA-15	09 Sep 92	A3	30 Sep 92	Operating		65.1
IIA-16	22 Nov 92	F1	11 Dec 92	Operating		62.7
IIA-17	18 Dec 92	F4	05 Jan 93	Operating		61.9
IIA-18	03 Feb 93	B1	04 Apr 93	Operating		58.9
IIA-19	30 Mar 93	C3	13 Apr 93	Operating		58.6
IIA-20	13 May 93	C4	12 Jun 93	Operating		56.7
IIA-21	26 Jun 93	A1	21 Jul 93	Operating		55.4
IIA-22	30 Aug 93	B4	20 Sep 93	Operating		53.4
IIA-23	26 Oct 93	D4	01 Dec 93	Operating		51.0
IIA-24	10 Mar 94	C1	28 Mar 94	Operating		47.1
IIA-25	28 Mar 96	C2	09 Apr 96	Operating		22.8
IIA-26	16 Jun 96	E3	15 Aug 96	Operating		18.6
IIA-27	12 Sep 96	B2	01 Oct 96	Operating		17.1
IIA-28	06 Nov 97	A5	18 Dec 97	Operating		2.5

Figure 1[9]
GPS Constellation Status as of 1 March 98

Survivability of the GPS constellation, in addition to other factors, was considered in the design due to the importance of the system to the DOD. The GPS constellation spaces satellites about 44,000 kilometers apart in each orbital plane, bringing no two satellites closer than 8,100 kilometers. This separation will prevent a nuclear attack from severely damaging the constellation coverage, forcing an attack on each individual satellite.

Block IIR Launch Predictions					
Fiscal Year	98	99	00	01	02
Launches	4	4	4	4	1

Figure 2[11]
Future Launch Predictions

Hazards to GPS from Space Debris

Although in an altitude not known for heavy amounts of space debris, the GPS satellite constellation has potential for several types of disabling collisions that shielding will not absorb. The satellites are located in a relatively narrow altitude range of approximately ± 50 kilometers. Also, the mission lifetime of individual satellites is long and exposes the system to a number of hazards. These hazards include USSPACECOM cataloged objects whose orbits cross GPS orbital altitude, GPS apogee kick motor explosions, the Soviet GLONASS constellation, and inactive GPS satellites.[12]

In a 1991 report entitled "Global Positioning System Long-Term Collision Hazards," M. E. Sorge of the Aerospace Corporation analyzed the potential space debris hazards to the GPS system. Each type of hazard was investigated using available debris information and statistical modeling, and Sorge found that the largest debris risk to GPS is "from inactive GPS satellites which continuously remain in the vicinity of the active constellation."[13] The results of the study support the current Air Force disposal policy.

Catalogued Objects

Between 500 and 600 catalogued objects pass through an altitude of 20,200 kilometers (not counting active GPS satellites themselves). The probability of random collisions between objects at a given orbit becomes more likely over a long period of time. Thus the propagation of individual satellites to predict specific encounters time consuming and often not useful in evaluating collision hazard. Instead an overall evaluation gives more useful results. For this analysis the PARADOX database software and sorting routines developed by C. Johnson were used. Some examples of catalogued debris that has the potential to hit a GPS satellite include the Cosmos 1030 and ASC-1 rocket body (object #11015 and #16007 respectively, see Figure 2). These objects have a high eccentricity and are characteristic of the orbit types that tend to approach GPS.

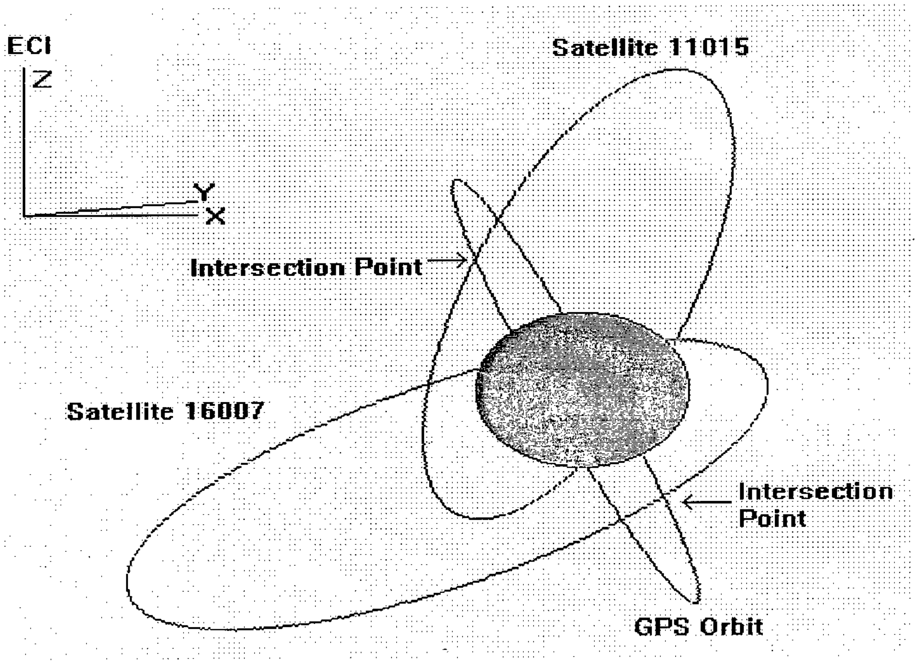

Figure 2
Note: Not drawn to scale

Next Sorge found the fraction of a GPS orbit that a GPS satellite that was within an encounter radius (close approach).[14] First the motion is modeled assuming that the sections of the debris orbit and the GPS satellite orbit near approach are linear. This is reasonable considering the radii of both orbits are much larger than the length of the arcs being examined. Figure 3 shows the approach geometry.

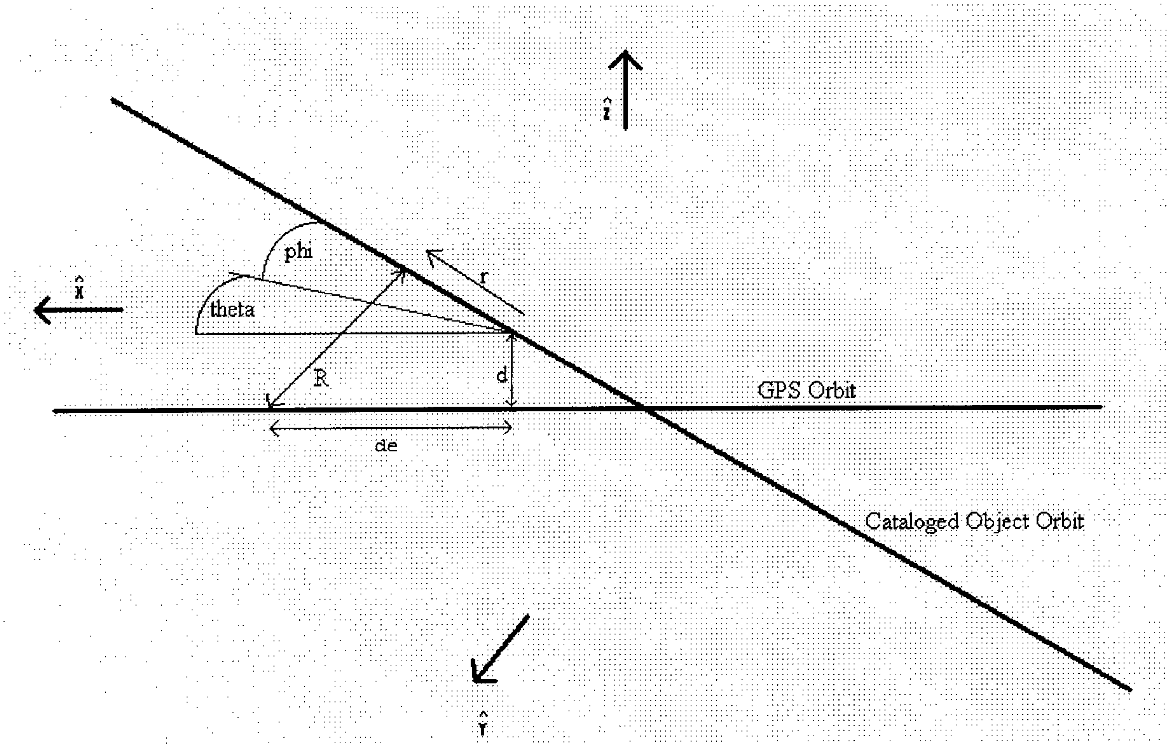

Figure 3
Approach Geometry of GPS Satellite and Cataloged Object

From this diagram the length along the GPS line that is within R of the cataloged satellite's line is determined, where R is the value of maximum encounter radius. Let

$$\vec{R} = R_x \hat{x} + R_y \hat{y} + R_z \hat{z}$$

$$\vec{r} = r\cos\phi_o \cos\theta_o \hat{x} + r\cos\phi_o \cos\theta_o \hat{y} + r\sin\phi_o \hat{z}$$

$$\vec{d}_e = d_e \hat{x}$$

Assuming a beginning of encounter and adding vectors

$$\vec{d}_e = d\hat{z} + \vec{r} + \hat{R}$$

$$d_e = r\cos\phi_o \cos\theta_o + R_x$$

$$0 = r\cos\phi_o \sin\theta_o + R_y$$

$$0 = d + r\sin\phi_o + R_z$$

We also know the magnitude of $\vec{R}$ and $\vec{r} \bullet \vec{R}$. This gives us

$$R^2 = R_x^2 + R_y^2 + R_z^2$$

$$\vec{r} \bullet \vec{R} = 0 = R_x r\cos\phi_0 \cos\theta_o + R_y r\cos\phi_o \sin\theta_o + R_z \sin\phi_0$$

Solving the previous equation for R_x and substituting for R_y and R_z results in a new expression for R_x

$$R_x = \frac{r\cos^2\phi_0 \sin^2\theta_o + (d + r\sin\phi_o)\sin\theta_o}{\cos\phi_0 \cos\theta_o}$$

Using the expression for d_e and substituting results in

$$d_e = \frac{r + d\sin\phi_o}{\cos\phi_o \cos\theta_o}$$

The term d_e is a measure of the distance from the beginning of the encounter region to the closest approach point along the GPS line. The length of the encounter region is therefor $2d_e$. If d_u is equal to the total length of the encounter region and F is the probability a GPS satellite is within the encounter region, then

$$F = N_{spp} \frac{d_u}{2\pi a}$$

N_{spp}= number of satellites per orbit plane

a=Semi major axis of the GPS orbit (assuming circular)

The number of encounters N for a given time period t can be found with the following expression

$$N = N_{sc} R_{oc} N_p F t$$

N_{oc}= Number of cataloged objects that approach each GPS orbit plane

R_{oc}= Rate of orbital crossings for a cataloged satellite, or the number of approaches per time by one cataloged object

N_p= Number of GPS orbit planes

Multiplying N_{sc} by R_{oc} gives the average rate of approaches for one GPS orbit plane, while the product of this and N_p gives the rate for the whole constellation. Next multiplying by F yields the rate of encounter for the system. Taking this result and multiplying by t gives the total number of encounters over time t.

The probability of collision is

$$p(col) = \frac{2}{\pi}\left(\frac{R_s}{\sigma}\right)^2 e^{-1/2(R_{\min}/\sigma)^2}$$

R_s= Radius of the effective collision area

$R_{\min}$= Nominal miss distance

σ= Variance of the positional uncertainty of the satellite

This expression is based on the assumption that one satellite's position is known perfectly while the other has some positional uncertainty. This uncertainty is assumed Gaussian in the three dimensions. Additionally, the variances are assumed to have equal variance, zero biases, and are uncorrelated (correlation coefficient = 0).

Thus the probability that at least one collision will occur within time t is

$$\text{p(at least on collision)} = 1-(1-p(col))^{N}$$

For a complete 24 satellite GPS constellation, $N_p = 6$. There are approximately two cataloged objects that approach each of the six planes within 50 kms every 12 hours. Thus $N_{sc} = 2$ and $R_{oc} = 2$ approaches/day. R_s was found to be approximately 0.004 km and the mission length $t = 7.5$ years or ≈ 2740 days. Let $R = 50$ km and $d = 25$ ($R_{\min} = d$) since the approach distances are assumed uniform, then to find the number of encounters over the mission lifetime solve for N.

$$r = R^2 - d^2 = 43.3 \text{ km}$$

$$d_{uave} = 122.5 \text{ km}$$

$$F_{ave} = 0.0029$$

$$N = (2)\left(2\frac{1}{days}\right)(6\,planes)(0.0029)(2740\,days)$$

$$N \approx 191 \text{ encounters}$$

The probability that one of these encounters will result in a collision is found as a function of variance σ. This leads to the probability of at least one collision over the mission life.

$$p(col) = \frac{2}{\pi}\left(\frac{0.004}{\sigma}\right)^2 e^{-1/2(25/\sigma)^2}$$

$$\text{p(at least one collision)} = 1 - \left(1 - \frac{2}{\pi}\left(\frac{0.004}{\sigma}\right)^2 e^{-1/2\left(\frac{25}{\sigma}\right)^2}\right)^{191}$$

Figure 4 is the probability of at least one collision vs. σ for the average case. Figure 5 shows a plot if d (nom. miss distance)=1 for a near "worst case" analysis.

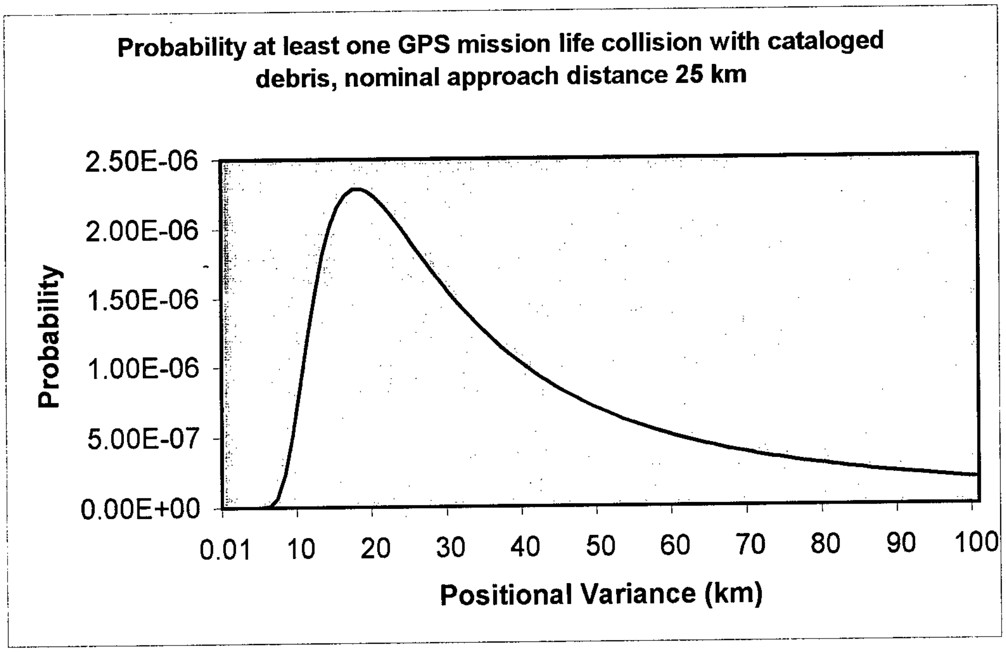

Figure 4
Probability vs. Positional Variance for Nominal Approach Distance 25 km

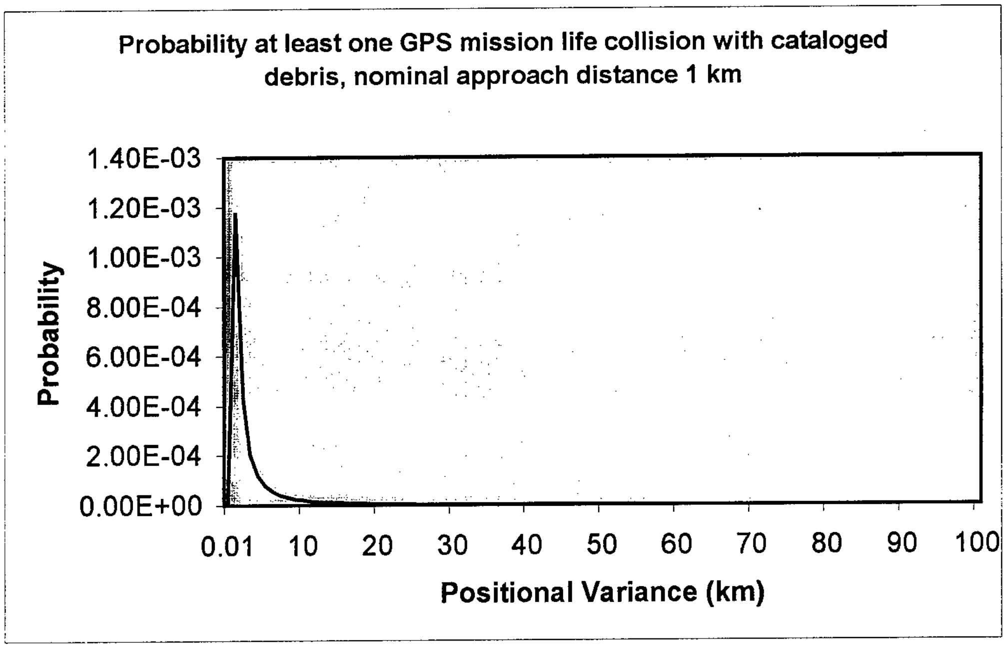

Figure 5
Probability vs. Positional Variance for Nominal Approach Distance 1 km

The results of the study showed that the probability of collision over the mission lifetime is relatively small, peaking at about 2 x 10^{-6} for an average case.[15] Typically there are about 12 satellites that approach within 50 kilometers of an idealized GPS orbit every 12 hours. The volume of space in such an area is considerably larger than either of the satellites, making collision risk very low. The probability of future collision will increase linearly with a rise in the number of debris satellites that cross the GPS altitude and orbit.

GPS AKM Explosions

Before placement into final orbit, a GPS satellite has an elliptical orbit used for transfer purposes with a perigee of 150km and an apogee slightly higher than the operational orbit. A firing of the AKM at apogee of this orbit circularizes the GPS satellite. A small percentage of AKM firings malfunction in some way to include explosion of the AKM itself. Such an explosion places fragments into an orbit that would have the potential to intersect GPS satellites.

Two basic scenarios exist for AKM explosions on the GPS satellite. In the first case the AKM explodes shortly after firing, when most fuel is unused. For this case there would be roughly 10,000 fragments with a diameter of over 1 cm (capable of disabling a satellite on impact).[15] Because the satellite would still have almost the same orbital characteristics of the transfer orbit at the time of explosion, most of the fragments would reenter the Earth's atmosphere within 3 years.[17] Thus fragments from this case would only by a threat to the GPS constellation for a few months before their orbital characteristics were changed significantly by atmospheric drag to the point that collision would be impossible. However the probability of an object hitting a GPS satellite would increase by a factor of 10 during this time.

The second likely case involves the explosion of the AKM near burnout. The GPS satellite has almost achieved operational orbit at this point, and fragments from the explosion would experience no atmospheric drag. Therefore the debris would continue pose a collision hazard throughout the lifetime of the GPS system. However, since most of the fuel is consumed at the time of explosion the force is much less and the number of fragments is reduced to approximately 600 with a diameter greater than 1cm.[18] This number would double the current number of objects crossing the GPS altitude and would approximately double the collision probability.

GLONASS Constellation

Although not a significant threat to the GPS constellation, the explosion of the GLONASS satellite boosters would have a similar but less severe effect on collision probability for GPS satellites. The current GLONASS constellation is located about 1000km below the GPS constellation, in a circular orbit. The GLONASS satellites pose no hazard the GPS due to the difference in altitude between the orbits, but the explosion of a booster (which orbits along with the GLONASS satellites) could throw a significant amount of debris into orbits that could intersect GPS satellites.

GLONASS satellites are launched with a booster similar to the U. S. Delta second stage. A number of these boosters have exploded after months to years in orbit. Due to the many similarities of the boosters, a Delta second stage was used for the analysis. Simulation showed that over 200 fragments capable of disabling a GPS satellite that would pass through the GPS altitude after such an explosion. Proper venting of fuel from the booster would eliminate this hazard. It is unlikely that GLONASS poses any other threat to the GPS constellation.

GPS-GPS Collisions

GPS satellites normally maintain proper phasing by correcting drift in the longitude of the ascending nodes of their orbits. This correction is needed due to low amplitude, long period oscillation in the semi-major axis of a satellite's orbit.[19] Once a GPS satellite becomes inactive these corrections are no longer possible since it is by definition not maneuverable, and the drifting satellites poses a significant hazard to the constellation. Analyzing the semi-major axes drift of inactive satellites over time yields the angular drift relative to the nominal phasing. Drift angles of over 300° are possible over the 7.5-year mission lifetime of GPS.[20] This drifting poses collision hazards when it results in drifting into or crossing over another satellites plane.

Encounters between an inactive GPS satellite colliding with an active GPS satellite will take two possible forms.

For drift in the plane, low relative velocities (several meters per second or less) would provide ample time for movement of the active satellite. The drifting satellite would remain near the active satellite for up to 2 days when their orbital period differential separated them. This type of encounter would involve collision at a low velocity resulting in little or no debris but probable damage to both satellites (probability of collision = $9x10^{-8}$).[21] However, due to the large amount of time required for the inactive satellite to traverse the distance between active satellites in the plane, the in plane encounter would not occur often (approximately 3 times in 7.5 years).[22]

Encounters between a drifting satellite crossing the plane of an active satellite would occur more often and involve relatively high velocities. This would result in a much quicker encounter with less reaction time. Additionally the encounters would repeat every half orbit as long as the phasing between the two satellites remained similar, resulting in several repeated close encounters (550 total encounters over 7.5 years).[23] If a collision occurred, both satellites would almost certainly have a catastrophic breakup due to the large velocity differential. The cloud of debris would spread around both orbital planes and inhibit the entire constellation.

Air Force Satellite Disposal Guidelines

In an effort to reduce the risk to USAF satellites posed by space debris, U.S. Space Command has established guidelines for the proper disposal of spacecraft in order to reduce the potential for collision of satellites and debris. This document, UPD10-39, was effective as of 3 November 1997, and is applicable over all satellites, which USCINCSPACE exercises Combatant Command (COCOM) authority over. The procedures in the document stem from Presidential Decision Directive (PDD) NSC-48/NSTC-8, National Space Policy, 14 September 1996, and Chairmen of the Joint Chiefs of Staff, Memorandum of Policy 37 (CJCS MOP-37), 14 May 1992.[24]

The Air Force disposal policy mandates that satellites designated for disposal be placed in a "position (slot/plane/orbit) of non-interference with existing systems"[25] (the requirements of a non-interfering position are not specified, although consideration must be given to operational orbit contamination, radio frequency interference, and future constellation development). Safing the spacecraft bus is the first and critical step. This includes depletion of all fuel to the maximum possible extent, discharging of all battery systems and shorting of the electrical subsystem, stabilization in a neutral thermal mode (usually a slow spin), and disabling of transmitters.

Removal of the spacecraft from operational orbit is the next step, usually carried out in the bus safing process due to fuel requirements. LEO satellites must move to less than 650 kilometers to allow for natural orbit decay (25 years or less). GEO satellites must boost up at least 300 kilometers higher to a new orbit with a perigee of no less than 36,896 kilometers and as circular as possible (eccentricity = 0). The GPS constellation is the only USSPACECOM COCOM system in the MEO region. GPS satellites are required to boost up at least 500 kilometers with a perigee above 20,685 and an apogee below 35,396 kilometers with eccentricity = 0.

Space Command's policy also recognizes that some satellites were not designed to achieve the final orbits discussed above. In such cases, the satellite should be boosted as far as available fuel will allow.

Recommendations for Mitigating Debris Hazards

Although the risk of collision between a satellite and space debris may never be reduced to a zero probability, there are techniques that lower the risk and are cost effective. As mentioned earlier, GPS satellites have four primary hazards from space debris that shielding will not prevent: 1)USSPACECOM cataloged objects, 2)GPS AKM explosions, 3)GLONASS boosters, and 4)inactive GPS satellites. Avoidance of cataloged objects relies on information supplied by the USAF Space Surveillance Center (SSC) in Cheyenne Mountain, CO. Once provided with this information, operators at Falcon AFB can maneuver the GPS satellite at risk to a safer orbit. Determining why the explosions occur and changing the design to prevent future occurrences might reduce AKM explosion frequency. Proper venting of leftover fuel will prevent any possibility of explosion from GLONASS booster rockets. More importantly, proper satellite de-orbiting as mandated by USSPACECOM would reduce the probability of having a disabled GPS satellite in mission orbit, thus reducing the highest collision probability (and one with potentially catastrophic results for the constellation).

A shortfall in Sorge's report concerns debris greater than 1 cm but less than 10 cm. Debris of this size can disable a satellite upon impact. It cannot be effectively shielded against since the weight of such thick shielding required would make launch too expensive. Avoidance techniques used with larger cataloged debris are impossible since the debris is less than 10 cm and not trackable with current technology from Earth. As mentioned previously, current estimates place the number of debris particles of this size at 35,000-150,000 which is significantly more than the 8000 large debris pieces. Severe limitations are placed on calculating collision probabilities for satellites colliding with these debris pieces. Since the number of pieces and their locations are not known with certainty, precise collision calculations are not possible and estimates bases on the number of larger and smaller debris pieces must be used. Until technology enables tracking of medium debris or shielding technology protects the satellites while making launch still affordable, space debris smaller than 10 cm but larger than 1 cm will pose a risk to all satellite systems.

Conclusion

Mitigation of the space debris hazards to GPS satellites has many benefits. It will ensure continued service of the GPS system, enable the semi-synchronous orbit operational for future missions, and allow the GPS satellites to reach and perhaps extend their mission lifetime. Avoidance of large (>10 cm) debris is possible by GPS operators maneuvering the satellites when forewarned by the SSC. Reengineering the AKM, venting of all fuel from spent GLONASS boosters, and proper de-orbiting of GPS satellites at completion of mission life will help prevent more debris that would threaten the GPS constellation. The largest risk remaining to the GPS system by orbital debris lies in the medium size range (1 to 10 cm). Until technology enables the detection and tracking of these objects or shielding protects the satellite while making launch cost reasonable, medium sized space debris will continue to pose an unknown hazard to the GPS and other space systems.

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11. Hofmann-Welenhof, B., Lichtenegger, H., and Collins, J. "GPS Theory and Practice," 4th ed., Springer Wien, New York, 1997.
12. Sorge, M. E., "Global Positioning System Long-Term Collision Hazards," The Aerospace Corp., El Segundo, CA, TOR-0091(6473-33)-1, August 1991.
13. *Op. cit.*, n.9.
14. *Op. cit.*, n.9. The following analysis comes directly from Sorge.
15. *Op. cit.*, n.9.
16. *Op. cit.*, n.9. This analysis was conducted using the amount of energy potential that is released by the explosion of a GPS satellite using the mass and delta velocity information. Only a small percentage was used since most of the energy would not be released explosively.
17. *Op. cit.*, n.9. The program LIFETIME was used for this analysis.
18. *Op. cit.*, n.9.

19. *Op. cit.*, n.9. Work done by C. Chao shows that due to the resonance between the Earth's rotation rate and the satellite's periods, some of the Earth's lower order gravitational harmonics will perturb the GPS orbits. This causes the satellite to drift relative to its original phasing, a problem solved by occasional stationkeeping maneuvers for active satellites.

20. *Op. cit.*, n.9.

21. *Op. cit.*, n.9. Based on assumption that a single satellite is drifting in a plane that has four active satellites.

22. *Op. cit.*, n.9.

23. *Op. cit.*, n.9. Based on worst-case scenario with 25 satellites on orbit.

24. *Op. cit.*, n.2.

25. *Op. cit.*, n.2.

RISK ASSESSMENT OF SPACE DEBRIS HAZARDS FOR GLOBAL POSITIONING SPACECRAFT

2ND LT. DAVID M. ASHLEY

8 MAY 1998

ENGINEERING IN SPACE OPERATIONS

UNIVERSITY OF COLORADO AT COLORADO SPRINGS, CO

Abstract

An important concern of USSPACECOM has been developing a policy to reduce orbital debris, including ensuring proper spacecraft end-of-life disposal to minimize the number of spacecraft left on mission orbit beyond their useful lifetimes. This paper provides insight to the pertinent issues related to space debris and spacecraft disposal in addition to a detailed analysis of debris hazards for the Global Positioning System (GPS) family of spacecraft as outlined by M. E. Sorge. Results of the analysis show that inactive GPS satellites pose the most significant hazard to the GPS constellation of all space debris of large size, thus reaffirming recent U.S. space policy mandating de-orbiting for all GPS satellites deemed non-mission capable. Additional analysis is recommended to explore collision probabilities for medium sized debris, since this category is also capable of disabling GPS satellites.

University of Colorado at Colorado Springs

Office of Director
Master of Engineering Program Office

1420 Austin Bluffs Parkway
P.O. Box 7150
Colorado Springs, Colorado 80933-7150
(719) 262-3573 (Director)
(719) 262-3243 (Office)
(719) 548-9127 (Fax)

May 18, 1998

AFIT/CI
Wright-Patterson AFB, OH 45433-7765

To Whom It May Concern:

David M. Ashley, 226-02-0309, has completed all credits and requirements for the Master of Engineering, Space Operations option, degree at the University of Colorado at Colorado Springs. The transcript with degree posted should be sent to you in July, 1998.

If you need additional information, please contact me at (719) 262-3573 or 262-3243. Thank you.

Sincerely,

Charles Fosha

CHARLES E. FOSHA, Ph.D.
Director
Master of Engineering Program Office

REQUEST AND AUTHORIZATION FOR PERMANENT CHANGE OF STATION - MILITARY

(This Form is Subject to the Privacy Act of 1974 - Use Blanket PAS - AF Form 11)

The following individual will proceed on permanent change of station. ☐ PCS Without PCA ☒ PCS With PCA

TED MAY 98

1. GRADE, NAME *(Last,First,Middle Initial)* 2LT ASHLEY DAVID M

2. SSN 226020309

3. SDAFSC/CAFSC 013S1

4. SECURITY CLEARANCE *(Include date of last investigation)* DCID 1/14 SSBI 970414

5. REPORT TO COMDR. NEW ASSIGNMENT NLT 980529

6. TRAVEL DAYS AUTHORIZED IF TRAVELING BY PRIVATELY OWNED CONVEYANCE 4

7. TDY ENROUTE

8. UNIT, MAJOR COMMAND, AND ADDRESS OF UNIT TO WHICH ASSIGNED

392 TRAINING SQ (AETC)
VANDENBERG AFB CA 93437

9. UNIT, MAJOR COMMAND, AND ADDRESS OF UNIT FROM WHICH RELIEVED

AF INST OF TECH IN (AETC)
COLORADO SPRINGS CO 80907

10. TYPE OF TOUR *(Check One)* ☐ ACCOMPANIED ☐ UNACCOMPANIED ☐ UNACCOMPANIED, DEPENDENTS RESTRICTED

11. TOUR LENGTH *(Total No. of Months)*

12. EXTENDED LONG TOUR VOL ☐

13. DEPENDENT TRAVEL

- ☐ A. CONCURRENT TRAVEL IS AUTOMATIC
- ☐ B. CONCURRENT TRAVEL IS APPROVED
- ☐ C. NONCONCURRENT TRAVEL IS AUTHORIZED IN LESS THAN 20 WEEKS
- ☐ D. NONCONCURRENT TRAVEL IS AUTHORIZED IN MORE THAN 20 WEEKS
- ☐ E. TRAVEL IS AUTHORIZED TO A DESIGNATED PLACE

14. THIS IS A JOIN-SPOUSE ASSIGNMENT *(Include spouse's grade, name and SSN)* ☐

15. AUTHORITY FOR CCTVL

16. HOMEBASING/FOLLOW-ON ASSIGMENT *(Include AAN, GPAS, and RNLTD)*

17. DEPENDENT(s): *(List names, DOB of Children, relationship to member and current address)*

NONE

18. DEPARTURE CERTIFICATION: I certify that to the best of my knowledge I will depart PCS at

________ *(hrs)* ________ *(date)*

____

(Signature)

19. OVERSEAS TRANSPORTATION DATA

- ☐ A. Comply with MTA (DD Form 1482)
- ☐ B. Member will comply with reporting time and flight reservations in the MTA or as arranged by the TMO per AFI 24-10, and is not authorized to depart this station before receipt of validated MTA or GTR (SF1169) from the TMO.
- ☐ C. TDY station will obtain flight reservations. Member is not authorized to depart TDY station before receipt of validated MTA or GTR (SF1169) from the TMO
- ☐ D. Dependent(s) will comply with reporting data and flight reservations in the MTA.

20. PCS EXPENSE CHARGEABLE TO *(Insert M.D.H.I.G.F.A.S.C.T. or Y)*

5783500 328 5753.0*875825

CIC: TAC: 8 ATAC: F87B30*

NONTEMPORARY STORAGE CHARGEABLE TO: 5783500 328 5758.0N 875825

21. AUTHORITY AND PCS CODE

PCS ID: AFI 36-2110.PCS ID D

AAN: 0580NH3214

22. TDY EXPENSE CHARGEABLE TO

23. Excess Baggage Authorized

PIECES LBS

Pursuant to AFR 32-6001, you will report to the base housing referral office servicing your new duty station before entering into any rental, lease, or purchase agreement for off-base housing.

24. REMARKS *(Submit travel voucher within 5 workdays after completion of travel. If TDY en route is authorized, attach receipts showing cost of all lodgings used. All promotional items incurred with PCS/TDY must be turned in to AFO upon arrival at gaining base.)*

ITEM 2 ON REVERSE APPLY. OFFICER WILL ATND V3OBR13S1-001 CSD 980612 CGD 980821 TLN EPOJ800026. THE ABOVE MBR HAS BEEN INITIALLY SCREENED AND MEETS CRITICAL PRP CERTIFICATION AS OF 970923 CONTINUE ON REVERSE

25. DATE 5 MAR 98

26. MPF OFFICIAL *(Typed Name, and Grade)*

SHANE B. COYNE, CAPT, USAF
MILITARY PERSONNEL FLIGHT COMMANDER

27. SIGNATURE OF MPF OFFICIAL Shane B Coyne

28. DESIGNATION AND LOCATION OF HEADQUARTERS DEPARTMENT OF THE AIR FORCE

21ST MSS/DPMAR (AFSPC)
PETERSON AFB CO 80914

29. SPECIAL ORDER NO. AB-184

30. DATE 10 MAR 98

31. TDN FOR THE COMMANDER

32. DISTRIBUTION

D+

33. SIGNATURE ELEMENT OF ORDERS AUTHENTICATING OFFICIAL

SHANE B. COYNE, CAPT, USAF
MILITARY PERSONNEL FLIGHT COMMANDER

34. ADDRESS OF GAINING MPF

30 MSS/DPMAE VANDENBERG AF CA 93437

AF FORM 899, MAY 95 *(PC-III Computer Generated)* PREVIOUS EDITION IS OBSOLETE