Results in Orbital Evolution of Objects in the Geosynchronous Region

Larry Jay Friesen* and Albert A. Jackson IV†
Lockheed Engineering and Sciences Company, Houston, Texas 77058
and
Herbert A. Zook‡ and Donald J. Kessler‡
NASA Johnson Space Center, Houston, Texas 77058

The orbital evolution of objects at or near geosynchronous orbit (GEO) has been simulated to investigate possible hazards to working geosynchronous satellites. Both large satellites and small particles have been simulated, subject to perturbations by nonspherical geopotential terms, lunar and solar gravity, and solar radiation pressure. Large satellites in initially circular orbits show an expected cycle of inclination change driven by lunar and solar gravity but very little altitude change. They have little chance of colliding with objects at other altitudes, provided that the initial eccentricities of their orbits are small. However, if such a satellite is disrupted, debris can reach thousands of kilometers above or below the initial satellite altitude. Small particles in GEO experience two cycles driven by solar radiation: an expected eccentricity cycle and an unexpected inclination cycle. This inclination cycle results from a precession of the orbit plane driven by asymmetric torque effects of the radiation pressure on an eccentric orbit. Particles generated by GEO insertion stage solid rocket motors typically hit the Earth or escape promptly; a small fraction remain in orbits that persist longer than 10 years.

Introduction

ORBITAL evolution simulations have been carried out for certain classes of objects initially in orbits at, near, or crossing geosynchronous orbit (GEO). The purpose for these investigations is to learn whether the orbital evolutions of such objects can generate hazards to working geosynchronous satellites. Previous studies of the orbital behavior of objects at geosynchronous distance have included investigations by Allan,[1] Hechler and Van der Ha,[2] Hechler,[3] and Van der Ha.[4] The studies reported here are intended to extend this earlier work with an extremely accurate orbital integrator[5] and investigate certain specific cases in detail.

Cases Studied

Simulations have been carried out for orbits of both large satellites and small particles. The size and mass assumed for a large satellite are taken from the parameters for a communication satellite listed in the Civil Needs Data Base.[6] This satellite has a cross-sectional area of 9.8 m^2 and a mass of 1275 kg. Small particles may include such things as paint flakes, debris fragments, or aluminum oxide particles from solid rocket motor (SRM) exhaust. The particle sizes considered are described later with the small particle case discussions.

Large satellite cases have been simulated both for a satellite initially at GEO and for satellites in storage orbits ranging from 300 km below GEO to 600 km above. Placing satellites in storage orbits of this sort at the ends of their operational lifetimes has been considered as one possible means to reduce the likelihood that they will collide with satellites still operating. For both the geosynchronous and storage orbit cases, the initial large satellite orbit is assumed to be circular and equatorial.

That assumption does not mean that initial placement of a satellite in one of these orbits is guaranteed to be circular or equatorial. As will be seen later, a small velocity change can noticeably change apogee or perigee altitude. The initial condition of circular, equatorial orbits was chosen because the intent of this investigation was to study orbital evolution effects that resulted from perturbing forces rather than from initial eccentricity or inclination.

The small particle cases treated have been of two classes: particles initially in circular equatorial geosynchronous orbits and aluminum oxide particles in the exhaust streams of GEO injection stage SRMs.

Simulation Description

The simulations were performed by following the paths of individual particles (Cartesian position and velocity components) forward from specified initial orbit conditions. This was done on VAX and Cray computers using a 15th-order numerical integrator developed by Everhart.[5]

Perturbative forces simulated included 1) geopotential harmonic terms through 4×4 as given in a model by Bond et al.,[7] 2) lunar and solar gravitation, with lunar and solar positions based on analytical expressions taken from the *Astronomical Almanac*,[8] and 3) solar radiation pressure. This is important primarily for small particles.[9,10]

Orbits for objects initially in circular, equatorial GEO were often started at longitudes near the stable points resulting from the Earth's $J_{2,2}$ potential term, located near 75° east and 105° west.

Current Results

Further specifications of the cases simulated, and results obtained to this point, are given here.

Findings for Large Satellites

A large satellite initially in geosynchronous orbit has been simulated for periods up to 100 years. Orbital parameters from one run are shown plotted vs time in Fig. 1. The delta semimajor axis parameter is the difference in semimajor axis from the geosynchronous value.

Large satellites have also been simulated in storage orbits at altitudes 100, 300, 500, and 600 km above the geosynchronous

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*Principal Engineer, Mail Code B12, 2400 NASA Road One.
†Principal Scientist, Mail Code C102, 2400 NASA Road One.
‡Space Scientist, Mail Code SN31.

distance, and 300 km below GEO (initially circular, equatorial orbits) for intervals ranging from 400 days up to 1000 years. Orbital parameters vs time for a typical case, 100 years for GEO + 100 km, are shown in Fig. 2.

The clearest pattern observed for all the large satellite simulations is an orbital inclination cycle with a maximum value on the order of 14.5 to 15 deg and a period of approximately 53 years. This inclination pattern was predicted by Hechler.[3] As Hechler states, the cause of the inclination cycle is that the orbital plane is precessing about an axis displaced approximately 7.4 deg from the polar axis of the Earth. The pattern for the right ascension of the ascending node is consistent with this, having the same period as the inclination. It may seem odd that a precession of the orbit plane generates an oscillation of the ascending node. This is a consequence of the precession taking place about the displaced axis rather than the Earth's polar axis and of the initial inclination to the Earth's equator being 0 deg.

Radial excursions for the large satellites are quite small. The combination of the most extreme semimajor axis change observed for any case with the most extreme eccentricity observed for the same case results in a maximum total radial displacement of around 50 km. This displacement will be added to whatever radial displacement may result from the initial eccentricity of a satellite's orbit.

Debris from Disrupted Satellites

Although large satellites exhibit little change in radial distance from the Earth for intervals up to the 1000 years simulated, will that remain true for fragments of such a satellite if it is disrupted for any reason? A delta-velocity (ΔV) of 1.8 m/s directed tangentially to the initial velocity is sufficient to enable an object initially in a near-GEO orbit to intersect orbits as much as 100 km higher or lower. This ratio of 1.8 m/s per 100 km is nearly linear over several hundred kilometers above and below GEO.

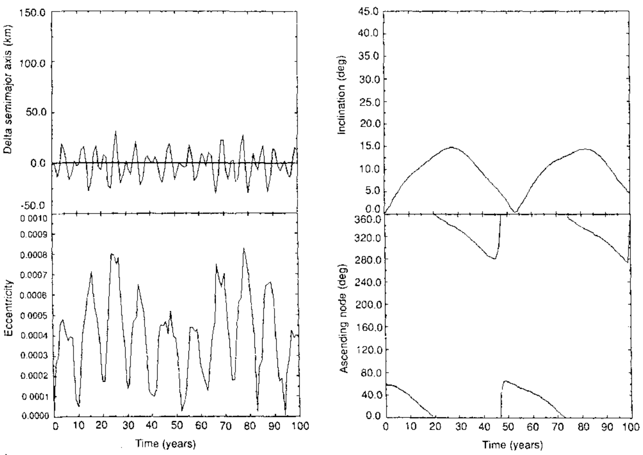

Fig. 1 Orbital parameters vs time for a large satellite initially in GEO.

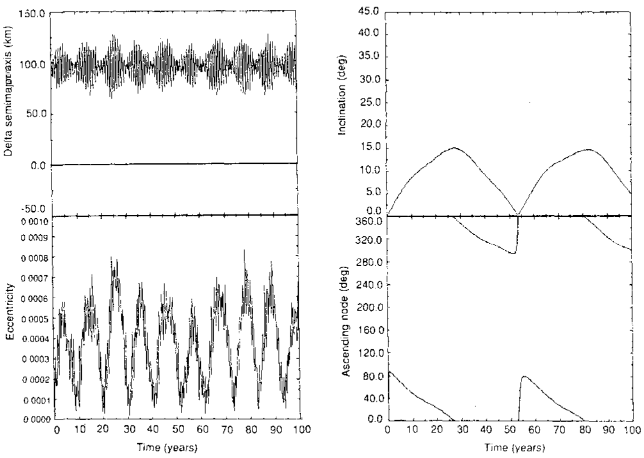

Fig. 2 Orbital parameters vs time for a large satellite in a storage orbit at GEO + 100 km.

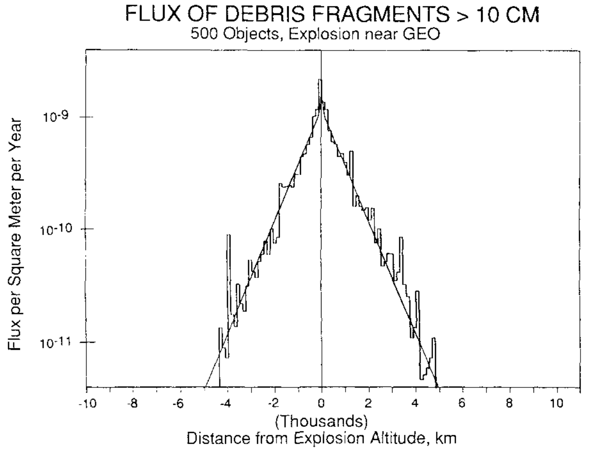

Fig. 3 Debris fragment flux from a satellite breakup near GEO altitude.

To estimate the potential reach of satellite debris from a disruption near GEO, a satellite disruption modeled in low Earth orbit (LEO) has been extrapolated to the GEO region. The LEO model was based on actual observed disruptions. Based on these observations, it is expected that the breakup creates about 500 fragments with dimensions of 10 cm or larger. The initial dispersion velocity of the fragments with respect to the center of mass of the original satellite is likewise expected to average 100 m/s.

On these assumptions, fragments of this debris can reach orbits as much as 5000 km above or below the breakup altitude. As Fig. 3 illustrates, the flux of fragments peaks at the breakup altitude and is on the order of 10^{-9} objects per m^2/yr at that altitude. The flux decreases approximately exponentially away from the breakup altitude, as shown by the straight-line approximation. The rate of decrease is approximately a factor of two for every 600 km above or below the breakup altitude.

The conclusions that can be drawn from this information are twofold. Moving a satellite to a storage orbit a few hundred kilometers above or below GEO at the end of its operational lifetime will significantly reduce the chances of that satellite hitting anything in GEO, as long as it remains intact and the initial eccentricity of the parking orbit is sufficiently small. However, if the moved satellite breaks up for any reason, such as a propellant tank rupture or collision with a meteoroid, the chances of GEO targets being hit by debris from that breakup are only moderately reduced, compared to the chances of being hit if the breakup occurs at GEO altitude.

Findings for Small Particles Initially in GEO

Particle sizes assumed for this portion of the study ranged from 1 mm down to 6.28 μ in diam. For determining cross-sectional area-to-mass ratios for calculating solar radiation force, all are assumed to be aluminum oxide spheres. These spheres are assumed to be perfect absorbers of solar radiation, although the same results would be obtained for perfect reflectors.[10]

Initial orbits for all of these cases were assumed to be circular equatorial geosynchronous, for the same reason that the initial orbits for large satellites were assumed circular and equatorial. The object of this series of cases was to study orbital parameter excursions generated by perturbing forces, rather than those due to initial eccentricity or inclination.

The gravitational perturbations on these particles are, of course, the same as for larger objects having the same positions and velocities, and so what we are looking for from these particles are effects due to the addition of the solar radiation force.

Solar radiation effects on orbital evolution are barely detectable for 1-mm particles. The radiation pressure brings orbital eccentricities up to 0.09 for 0.1-mm particles. Radiation perturbations become quite important for particles 40 μ in diam and smaller.

Orbital parameters vs time for a particle 10 μ in diam are shown in Fig. 4. The length of ascending node and length of descending node are the orbital distances at which the nodal crossings of the equatorial plane occur. The horizontal line in each plot is at the GEO distance; thus, each time a curve crosses the line, the particle has an opportunity to hit objects in geosynchronous orbit.

Two principal effects of the solar radiation perturbations are observed. The first is an eccentricity cycle with a period of about 1 yr. Peak eccentricity increases with decreasing particle size. For particles with diameters less than 7.25 μ, the peak eccentricity becomes so pronounced that the minimum perigee becomes less than one Earth radius; i.e., the particle hits the Earth in the first year. This effect was expected from previous studies of the effects of solar radiation pressure on objects in Earth orbit, such as that of Allan (1961).[9]

The second effect is a variation of inclination with time. This has a period of several years — about eight years for the example in Fig. 4. Smaller particles have both shorter inclination cycles and higher peak inclinations than larger particles.

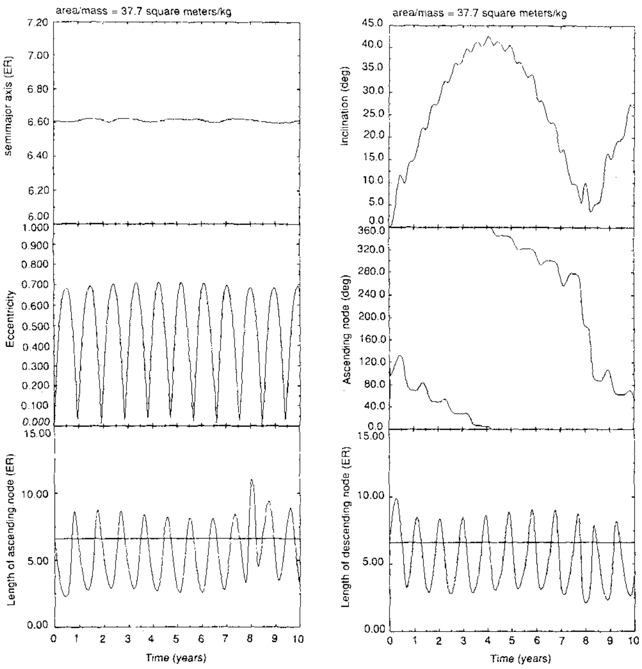

Fig. 4 Orbital elements vs time for a 10-μ particle initially at GEO.

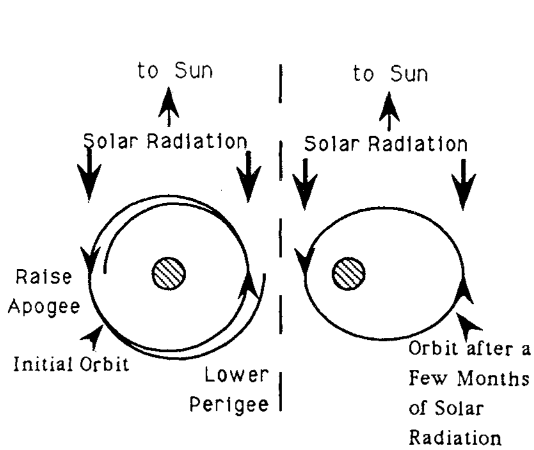

Fig. 5 Orbital eccentricity effects of solar radiation.

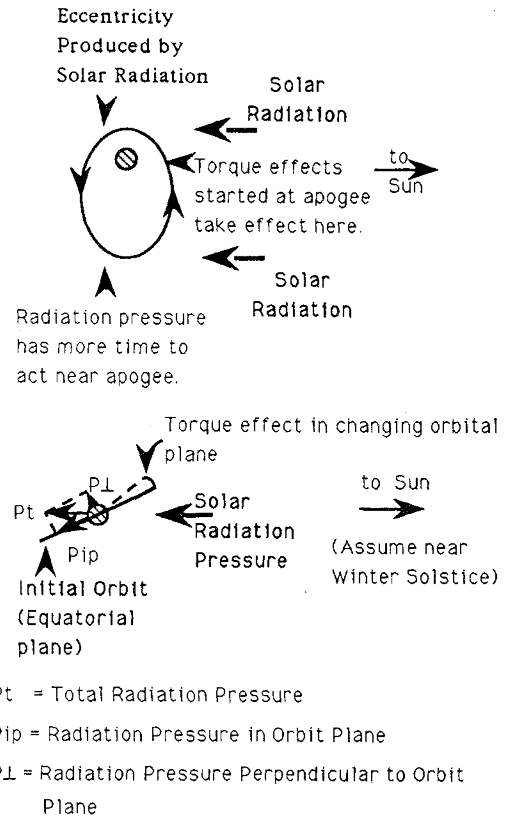

Fig. 6 Orbital inclination effects of solar radiation.

For the smaller end of the size range considered (just above the size that hits the Earth in the first year), the inclination pattern can be as short as 4.5–5 yr, and the peak inclination as high as 45–50 deg. The difficulty in pinpointing the values more precisely is a result of a secondary inclination pattern, with a shorter period and smaller amplitude, that is superimposed on the major patterns.

The importance of these patterns is that an object with high eccentricity, high inclination, or both has a high relative velocity when it crosses the geosynchronous belt, and therefore a greater potential for causing damage if a collision occurs than an object with low eccentricity and inclination.

The inclination pattern was not anticipated, although such an effect was implicit in a 1967 paper by Allan and Cook.[11] They did not explicitly discuss an inclination effect of solar radiation. What they did predict was that for particles in high Earth orbit, solar radiation would drive a precession of the particle's orbit-plane axis about the ecliptic axis. If the orbit plane maintains a uniform angle to the ecliptic plane during this precession, its angle to the Earth's equator, i.e., the orbital inclination, must change. As shall be shown in subsequent discussion, we obtain somewhat different results than did Allan and Cook.

The mechanism by which solar radiation pressure induces changes in eccentricity is well understood and is illustrated in Fig. 5. Particles approaching the Sun are decelerated by the radiation, causing a reduction in orbital radius 180 deg later. Particles receding from the Sun are accelerated, causing an increase in orbital radius 180 deg after that. This combination of acceleration and deceleration generates an increasing apogee and decreasing perigee from an initially circular orbit. Later, as the Earth moves around the Sun and the line of apsides precesses, perigee and apogee will shift sides with respect to the sun. When that occurs, the acceleration/deceleration forces will begin to have the reverse effect: they will lower the apogee and raise the perigee, tending to recircularize the orbit.

The mechanism by which radiation pressure induces inclination changes depends on the induced eccentricity, as illustrated in Fig. 6. Because the ecliptic plane is at an angle to the orbital plane (which is initially in the equator), solar radiation pressure will have one component parallel to the orbital plane and one at right angles to it. During part of the orbit, the perpendicular component will tend to tilt the orbit toward the ecliptic. On the opposite side of the orbit, it will tend to tilt the orbit away from the ecliptic. As long as the orbit is circular, these torques will cancel. However, once the orbit becomes eccentric, the particle will spend more time near apogee than near perigee. The torque near apogee will then act for a longer time and be more effective than the torque near perigee. Because the tilt takes place 90 deg later than the torque is applied, the torque will be most effective at tilting the orbit when the line of apsides is at right angles to the Earth-Sun line.

Part of the net torque will act to change the inclination, and part will act to cause the line of nodes to precess. The relative values of these two components will depend on the orientation of the orbit with respect to the Sun at any given time.

The orbit plane precession predicted by Allan and Cook also depends on a nonzero eccentricity to work. Figure 4 shows that the right ascension of the ascending node drifts with a period that matches the inclination pattern period (although like the inclination pattern, the node position drift has some bumps and ripples superimposed on it). To that extent, this study supports their prediction.

However, the periods for the inclination and nodal patterns we observe do not match the precession periods predicted by Allan and Cook. Nor are peak inclination values always 47 deg (twice 23.5), as would be expected if the pole about which precession occurred were the ecliptic pole. Two reasons for these disagreements are suspected. First, Allan and Cook calculated their periods using an approximation valid for small eccentricities, but this is not the case for many of the simulations of this study. Second, gravitational forces are still trying to drive an inclination pattern of their own, with a very different period and peak inclination value. The overall effect seen results from a weighted combination of the gravitational and radiational perturbations, where gravity is relatively more effective for larger particles and less effective for smaller particles.

The short-period fluctuations superimposed on both the inclination and nodal position patterns have been found to result from the details of the orientation of the particle orbits with respect to the sun over the course of a year. By plotting the orbit shape and orientation to the sun at various times during a year for one case, it has been observed that the radiation-induced torque can indeed cause occasional short-term reversals in the direction of inclination change and nodal precession.

Findings for GEO Insertion Stage SRM Exhaust Particles

In addition to following the orbital evolution for small particles initially in GEO orbits, the orbits of aluminum oxide particles in the exhaust streams of GEO insertion stage solid rocket motors have been considered. The object for this study is to determine whether all SRM particles are quickly lost, either by hitting the Earth or escaping Earth orbit, or whether some may persist for long periods in orbits that can intersect GEO.

For the cases treated so far, the insertion burn is assumed to be from a transfer orbit inclined 28.5 deg (Kennedy Space Center launch). Particle sizes considered were 0.1, 1.0, and 10.0 μ. These span the range of sizes expected from Mueller and Kessler (1985).[12] Expected ejection velocities from the rocket nozzle and maximum cone angle from the center of the exhaust plume depend on particle size. The values shown in Table 1 are based on Burris (1978).[13]

The sample space used to define orbit initial conditions included the centerline of the rocket plume and the maximum cone angles left, right, and vertical from the centerline. Particle orbits were derived for the start of the insertion burn, midway through the burn (when one-half of the required delta-V has been achieved), and at burn end. From 36 initial conditions defined by this sample space of particle size, cone angle, and burn phase, the following results have been obtained thus far:

Table 1 SRM aluminum oxide exhaust particle ejection velocities and maximum cone angles

Particle size, μ	Ejection velocity, km/s	Maximum cone angle, deg
0.1	3.5	43
1.0	3.0	27
10.0	2.0	12

1) Seventeen cases have such small initial semimajor axes or large initial eccentricities that the particles hit the Earth on their first orbits.

2) In nine cases, the particles hit the Earth in fairly short order (within 60 days for 0.1- and 1.0-μ particles, within 10 years for 10-μ particles), after their orbits were altered by solar radiation pressure.

3) In three cases, the particles escaped Earth orbit within days, under the influence of radiation pressure.

4) For six cases, particles appeared to be in orbits persisting longer than 10 years, but hit Earth in a short time when cases were rerun with different values for the initial right ascension of the ascending nodes, i.e., when the transfer orbit's orientation to the solar direction was changed.

5) For one case, a 10-μ particle seems to remain in orbit for at least 10 years, even when several values for the initial right ascension of the ascending node are tried.

It can be seen from item 4 of this list that the injection orientation to the Sun can strongly affect orbital lifetime for some cases. However, item 5 indicates that a fraction of SRM particles on the order of 3% will apparently remain in persistent orbits, regardless of the orientation of the transfer orbit with respect to the sun. A question still to be investigated is whether a large enough particle flux can build up over time from this persistent fraction to create a significant hazard to working geosynchronous satellites.

Conclusions

The following major conclusions can be drawn from this study thus far:

Satellites stored in circular parking orbits a couple of hundred kilometers or so above GEO are unlikely to intersect the GEO distance, even over 1000-yr time intervals, provided the initial orbits are circular. However, if a satellite stored in one of these parking orbits breaks up for any reason, these separation distances will not significantly reduce the flux of the resulting fragments passing through GEO, compared to a breakup occurring at the GEO altitude.

Perturbation by solar radiation induces large eccentricity excursions and large inclination excursions in the orbits of small particles at GEO.

Attention to the orientation of a GEO transfer orbit with respect to the solar direction can significantly reduce the fraction of aluminum oxide particles from the insertion motor exhaust that remain in persistent orbits. This result is consistent with findings by Akiba et al.[14]

Acknowledgment

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