JOURNAL OF SPACECRAFT AND ROCKETS
Vol. 42, No. 6, November–December 2005

Orbital Evolution of Cloud Particles from Explosions of Geosynchronous Objects

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Current orbital debris search strategies for telescopes observing in geosynchronous Earth orbit are designed around the known orbital distributions of cataloged objects. However, the majority of cataloged objects are believed to be intact spacecraft and rocket bodies, not the debris particles the searches are intended to locate. If there have been breakups in geosynchronous Earth orbit, the explosions may have put the debris into orbits that are significantly different from those in the catalog. Consequently, observation plans optimized for the catalog population may not be optimized for any unseen debris populations. Some hypothetical cases and a real near-synchronous U.S. Titan IIIC transtage explosion will be presented to demonstrate this effect. Perturbing accelerations to be considered for orbital evolution are the nonspherical part of the Earth's gravitational attraction and gravitational attractions due to the sun and moon. Solar radiation pressure effects are omitted in this analysis, not because they are unimportant for this type of analysis, but to concentrate on the primary orbit perturbations.

Nomenclature

a = semimajor axis, km
e = eccentricity
F = disturbing acceleration, km/day^2
f = true anomaly, rad
i = inclination, rad
M = mean anomaly, rad
n = mean motion, rad/day
r = radius, km
t = time, day
u = $\omega + f$, rad
Ω = right ascension of ascending node, rad
ω = argument of perigee, rad

Introduction

ONLY two breakups in or near geosynchronous Earth orbit (GEO) have been confirmed. One is the Commonwealth of Independent States (CIS) Ekran 2 breakup of 23 June 1978, revealed by Russian officials in an orbital debris meeting in February 1992 in Moscow.[1] This is the first known geostationary orbit fragmentation and was detected by the space surveillance network (SSN). The assessed cause was a malfunction of the nickel–hydrogen battery. Another is the U.S. Titan IIIC transtage breakup of 21 February 1992 (Ref. 1). This was the second major fragmentation of a Titan IIIC transtage. This transtage released Environmental Research Satellite (ERS)-28 [also known as Orbiting Vehicle (OV)5-2] in synchronous orbit, before slightly decelerating and releasing OV2-5 into a slightly lower orbit. This rocket body successfully completed its mission and remained on-orbit 281 months before the breakup. A total of 20 objects were reported from the breakup, but no orbital data on any fragments have been generated by the SSN.

Recent observations made by the NASA charge-coupled device (CCD) debris telescope indicate a population of uncorrelated target satellites in or near the GEO ring.[2] These objects, observed to a limiting size of approximately 0.6 m in diameter, constitute an on-orbit population 20% larger than the cataloged population. The majority of these objects are likely debris. Other observations performed by the ESA with larger optics indicate that the GEO population, to a limiting diameter of approximately 0.1 m, exceeds the cataloged population by a factor of four.[3]

The large amount of debris recently detected by both NASA and ESA cannot be associated with the aforementioned breakups, but may have originated from energetic explosions that have occurred in or near GEO. Indeed, Krag[4,5] has indicated that 11 artificial events should be taken into account to describe the present GEO orbital debris environment. In addition, some scientists have found the evidence for historical satellite fragmentations in and near GEO.[6–8]

Current debris search strategies for telescopes observing the GEO environment are designed around the known orbital distribution of cataloged objects. However, most cataloged objects are believed to be intact spacecraft and rocket bodies. These strategies may not effectively observe small debris populations from energetic explosions that have occurred in or near GEO. If there have been breakups in GEO, the explosions may have put the debris into orbits that are significantly different from those in the catalog. Consequently, observation plans optimized for the cataloged population may not be optimized for any unseen debris populations.

We will present some hypothetical cases to demonstrate the aforementioned effects. We simulate explosion of a GEO object in the year 2001 using the NASA standard breakup model revision 2000 and propagate the evolution of the debris cloud from the explosion at 10-year intervals using an orbit integrator developed by the first author. Finally, we will apply the aforementioned technique to the actual near-synchronous U.S. Titan IIIC transtage explosion of 21 February 1992.

GEO Propagator

In addition to the spherically symmetric gravitational force of the Earth, a number of perturbing accelerations affect the orbit of a GEO or near-GEO object. The forces that need to be considered for geosynchronous satellites are 1) the nonspherical part of the Earth's gravitational attraction, 2) gravitational attractions due to the sun and moon (approximated as point masses), and 3) solar radiation pressure. In this analysis, however, solar radiation pressure effects are omitted, not because they are unimportant for this type of analysis, but because we would like to concentrate on the primary orbit perturbations. The following subsections will describe the details of a numerical orbit integrator used in this analysis, including its basic equations, to find the rate of change of the osculating elements, lunar and planetary theories to calculate their true positions in space, and an Earth gravity model to take account of the nonspherical part of the Earth's gravitational attraction.

Received 5 July 2004; revision received 16 December 2004; accepted for publication 14 January 2005.

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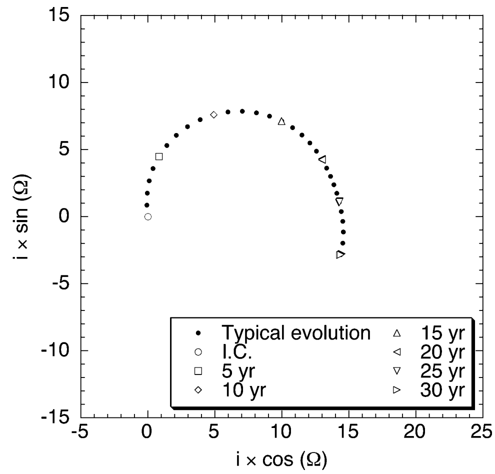


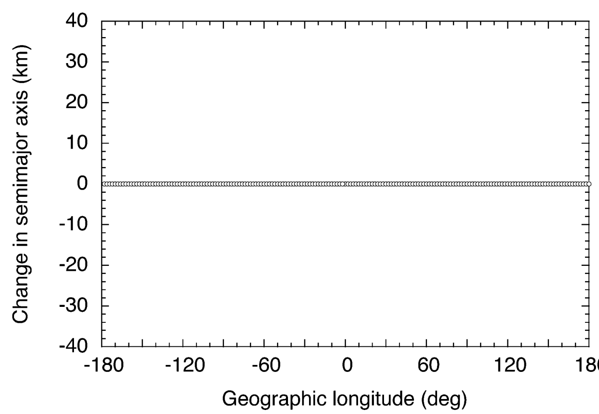
Fig. 1 Simulated evolution of 180 hypothetical satellites initially in GEO at 2-deg intervals between longitude slots.

Gaussian Planetary Equations of Motion

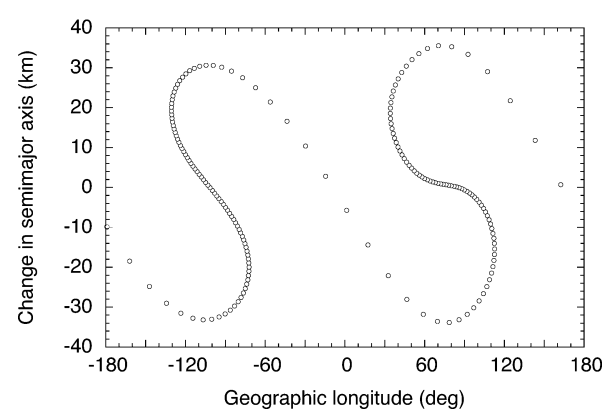
For finding the rates of change of the osculating elements, we have adopted the Gaussian form of the variation of parameters equations using the disturbing forces with specific force components resolved in the *RSW* coordinate system. The *R* axis is defined as always pointing from the Earth's center along the radius vector toward the spacecraft as it moves through the orbit, and the *W* axis is fixed along the direction normal to the orbital plane. The *S* axis

Table 1 Initial elements of 180 hypothetical satellites in nominal geostationary orbit

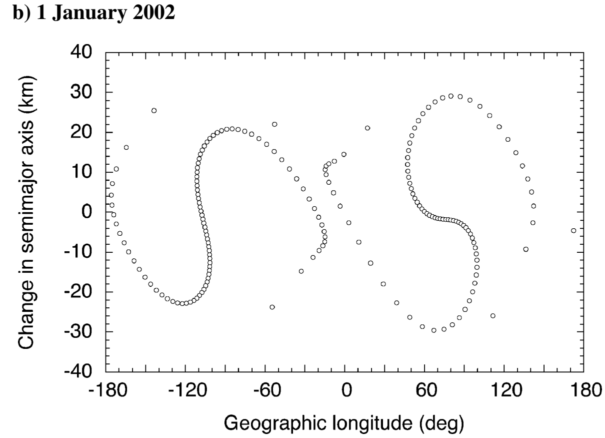
Element	Value
Epoch	01001.00000000–0000 GMT on 1 January 2001
Right ascension, deg	270.0000
Inclination, deg	0.0001
Eccentricity	0.0000001
Mean anomaly, deg	90.0000
Mean motion, revs/day	1.00273191



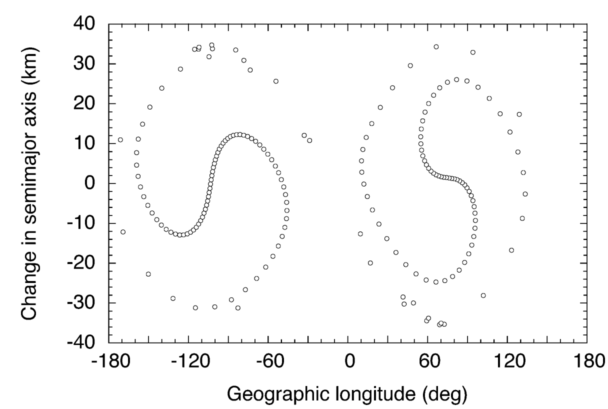
a) 1 January 2001



b) 1 January 2002



c) 1 January 2003



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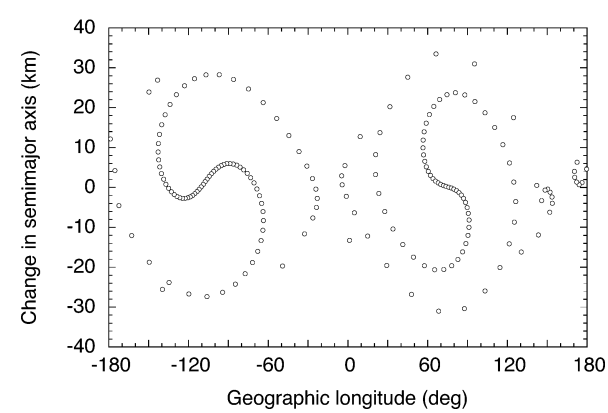
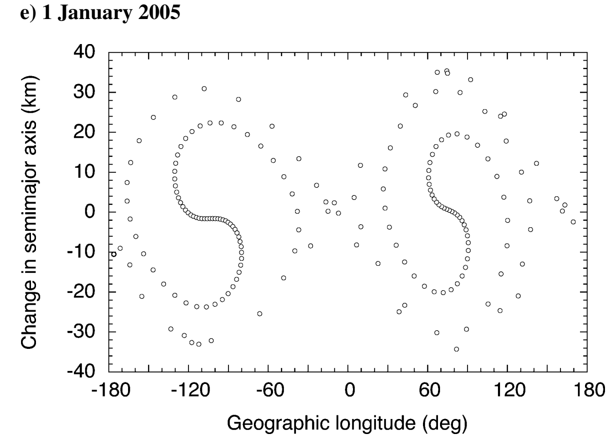


e) 1 January 2005



f) 1 January 2006

Fig. 2 Simulated longitude drift of 180 hypothetical satellites initially distributed in GEO at 2-deg intervals between slots.

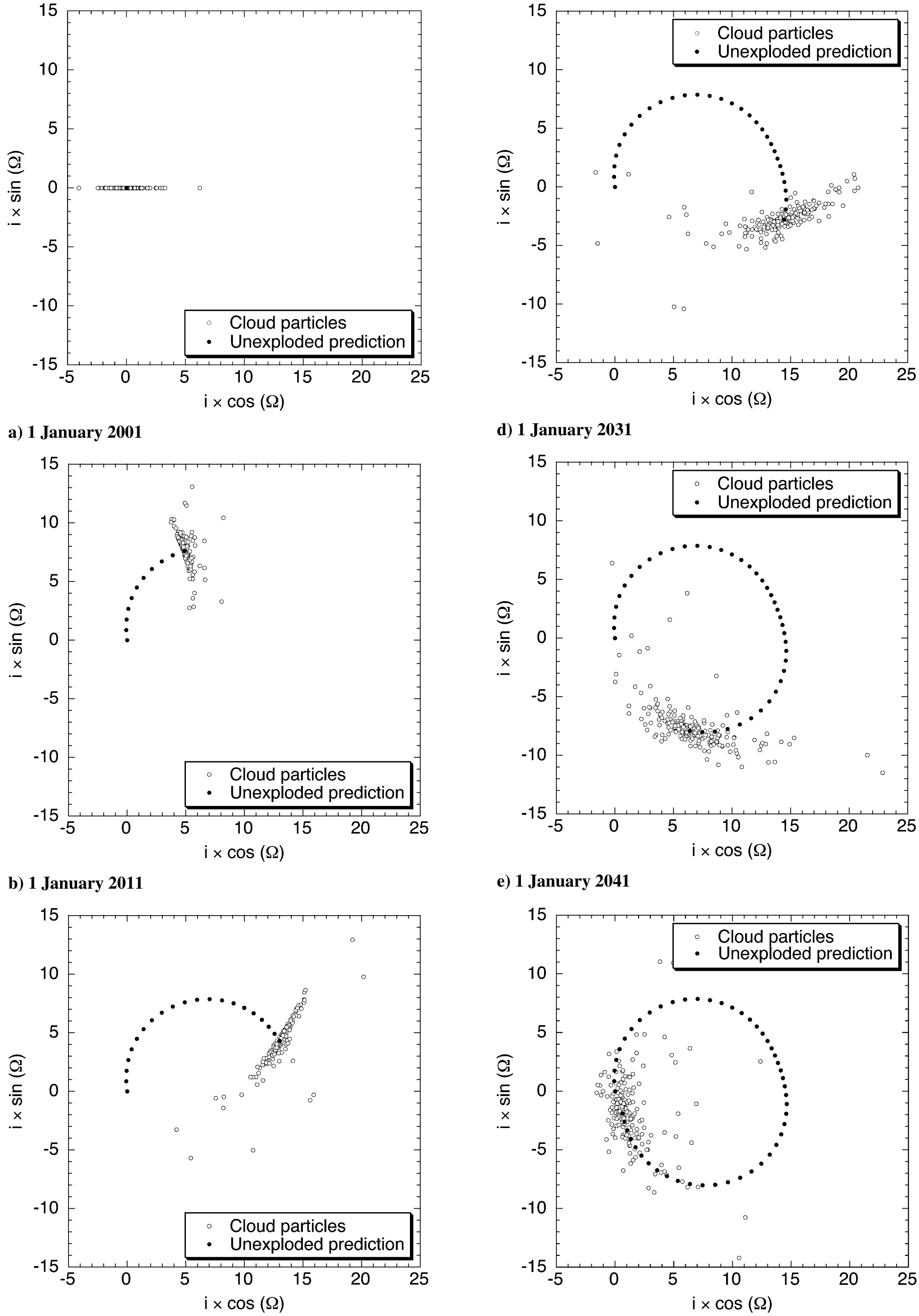


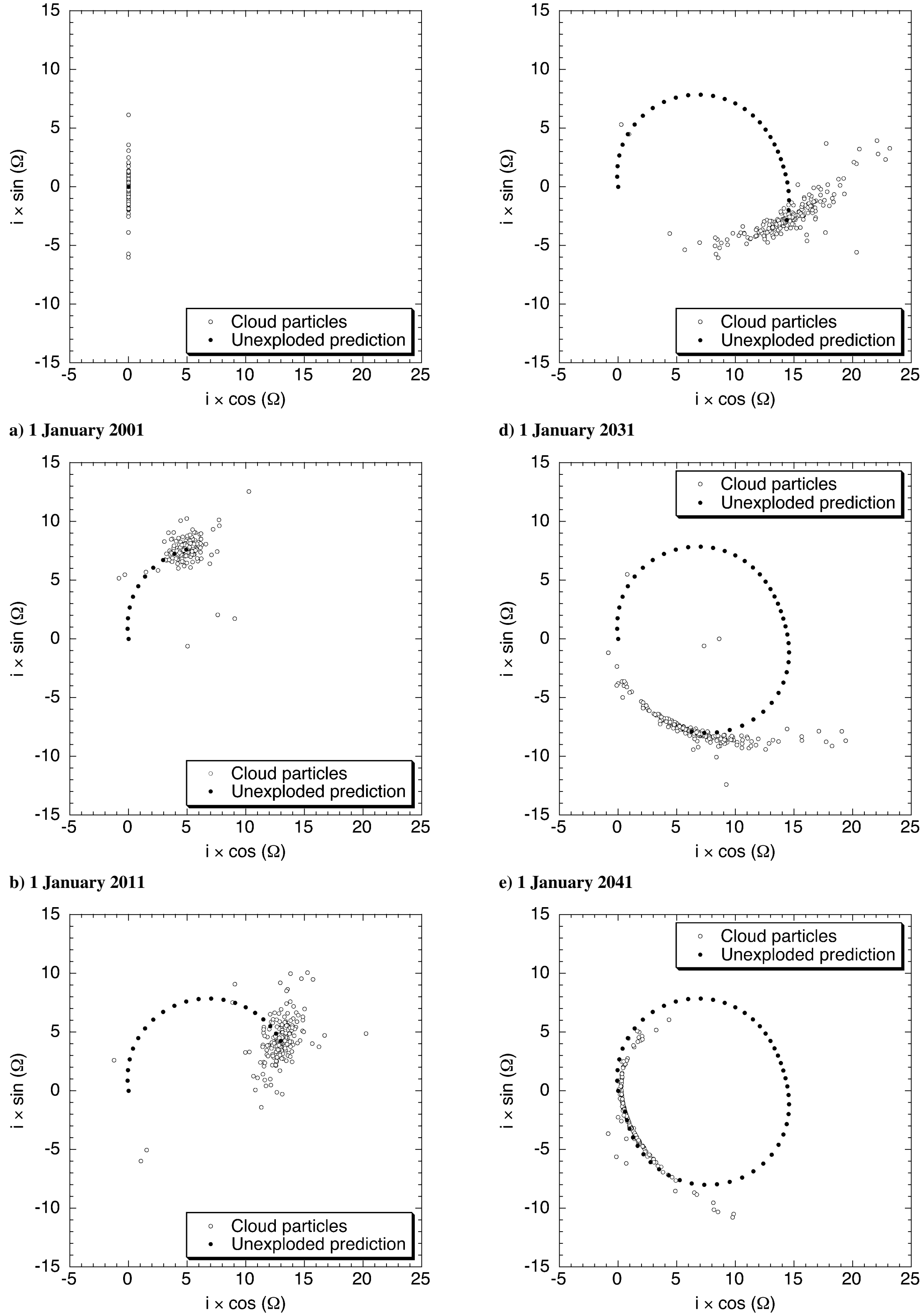
Fig. 3 Simulated evolution of debris cloud from explosion initially in GEO at 0-deg RA.

completes the right-handed orthogonal coordinate system, points in the direction of the circumferential component of the velocity vector, and is perpendicular to the radius vector. The Gaussian form of the variation of parameters equations is advantageous for nonconservative forces because it is expressed directly from the disturbing acceleration.[9] It also works well for conservative forces because the forces are simple gradients of the potential functions.

The Gaussian form of the variation of parameters equations may be given by

$$\frac{\mathrm{d}a}{\mathrm{d}t} = \frac{2}{n\sqrt{1-e^2}}[e\sin f \cdot F_r + (1 + e\cos f)\cdot F_s] \tag{1a}$$

$$\frac{\mathrm{d}e}{\mathrm{d}t} = \frac{\sqrt{1-e^2}}{na}\left[\sin f \cdot F_r + \left(\cos f + \frac{e+\cos f}{1+e\cos f}\right)\cdot F_s\right] \tag{1b}$$



a) 1 January 2001

b) 1 January 2011

c) 1 January 2021

d) 1 January 2031

e) 1 January 2041

f) 1 January 2051

Fig. 4 Simulated evolution of debris cloud from explosion initially in GEO at 90-deg RA.

$$\frac{\mathrm{d}i}{\mathrm{d}t} = \frac{r\cos u}{na^2\sqrt{1-e^2}}F_w \tag{1c}$$

$$\frac{\mathrm{d}\Omega}{\mathrm{d}t} = \frac{r\sin u}{na^2\sqrt{1-e^2}\sin i}F_w \tag{1d}$$

$$\frac{\mathrm{d}\omega}{\mathrm{d}t} = -\frac{\sqrt{1-e^2}}{nae}\left[\cos f\cdot F_r - \left(\sin f + \frac{\sin f}{1+e\cos f}\right)\cdot F_s\right] - \frac{\mathrm{d}\Omega}{\mathrm{d}t}\cos i \tag{1e}$$

$$\frac{\mathrm{d}M}{\mathrm{d}t} = n - \frac{2r}{na^2}F_r - \sqrt{1-e^2}\left(\frac{\mathrm{d}\omega}{\mathrm{d}t} + \frac{\mathrm{d}\Omega}{\mathrm{d}t}\cos i\right) \tag{1f}$$

VSOP87 Planetary Theory

A very high accuracy (better than 0.01 arc-s) is obtained by using the complete Variations Séculaires des Orbites Planétaires

(VSOP)87 planetary theory, which consists of long series of periodic terms for calculating the planets' heliocentric coordinates directly, namely, the ecliptic longitude, latitude, and radius vector (distance from the center of the sun). However, for the Earth, this theory contains 2425 periodic terms: 1080 terms for the Earth's longitude, 348 for the latitude, and 997 for the radius vector. Instead, according to Meeus (pp. 217–221),[10] we use the most important terms from the VSOP87, allowing the calculation of the position of the sun with an error not exceeding 1 arc-s between the years −2000 and +6000. To obtain the geocentric longitude and latitude of the sun, we add 180 deg (or π rad) to the Earth's longitude and change the sign of the latitude.

ELP2000 Lunar Theory

To calculate accurately the position of the moon for a given instant, it is necessary to take into account hundreds of periodic terms in the moon's geocentric longitude, latitude, and distance. As with the VSOP87 planetary solution, we use the most important periodic terms from the complete lunar theory using the procedure outlined by Meeus (pp. 337–344).[10] The periodic terms used in this analysis are based on the Chapront Éphémérides Lunaires Parisiennes (ELP)2000/82B lunar theory. However, for mean arguments such as the mean longitude of the moon, mean elongation of the moon, mean anomaly of the sun, mean anomaly of the moon, and argument of latitude of the moon, the improved expressions given in 1998 by Chapront have been used (see Ref. 10, pp. 337–344). The accuracy of the results is approximately 10 arc-s in the longitude of the moon and 4 arc-s in its latitude.

EGM96

Earth gravity model (EGM)96 (Ref. 11) is a spherical harmonic model of the Earth's gravitational potential complete to degree and order 360. It is a composite solution consisting of 1) a combination solution to degree and order 70, 2) a block diagonal solution from degree 71 to 359, and 3) the quadrature solution at degree 360. This model, just completed, is the result of collaboration between the National Imagery and Mapping Agency, the NASA Goddard Space Flight Center, and the Ohio State University. The EGM96 coefficients and ancillary information can be obtained from Ref. 11. Note that the degree and order taken into account in this analysis is eight.

GEO Perturbations

The perturbing accelerations considered in this analysis for geosynchronous satellites cause two interesting orbital phenomena that can be observed in GEO: 1) precession of a satellite's orbit plane and 2) mean longitude drift.[12] The following subsections will demonstrate these orbital phenomena by propagating the evolution of 180 hypothetical satellites initially in nominal geostationary orbit at 2-deg intervals between longitude slots for 30 years using the propagator mentioned in the preceding section.

Precession of Satellite's Orbit Plane

The lunar and solar gravitational attractions combined with the Earth's zonal terms of the Earth's gravitational attraction drive a precession of a geosynchronous satellite's orbit plane with a period of about 54 years. This precession generates a cycle of orbital inclination with respect to the equator, yielding a maximum inclination of 14–15 deg. (The precise value varies from cycle to cycle.) What is happening is that the orbital angular momentum vector for the satellite's orbit is precessing about an axis displaced approximately 7.4 deg from the Earth's rotation axis toward the ecliptic pole. The cycles of orbital inclination and right ascension of the ascending node caused by this precession can be found in Ref. 13.

Let us consider 180 hypothetical satellites initially distributed along the nominal geostationary orbit at 2-deg intervals between longitude slots. Table 1 shows their initial elements, excluding argument of perigee. Argument of perigee is specified differently for each satellite so that the initial radius at each longitude slot is equal to the nominal geostationary radius. Figure 1 shows the simulated evolution of 180 hypothetical satellites at five-year intervals. Disks in Fig. 1 represent the typical evolution of a geostationary satellite at 1-year intervals. Note that a plot in the coordinate system adopted in Fig. 1 represents the orbital angular momentum direction, or orbit pole, as seen from celestial north. As seen from Fig. 1, the simulated evolution of hypothetical satellites follows the typical evolution of a geostationary satellite so that we cannot observe any differences in their orbital evolution.

Mean Longitude Drift

The acceleration perturbations of the Earth's tesseral harmonics, involving the nonspherical part of the Earth's gravitational attraction distributed in terrestrial longitude, are smaller than other forces. However, the resonance effect of the 24-h geosynchronous orbits induces a mean longitude drift. The primary tesseral harmonic is designated by J_{22}, which combines the C_{22} and S_{22} terms. The longitude of symmetry of the J_{22} harmonic denoted by λ_{22} is determined from observations and has a typical value of −14.7 deg. The equilibrium points are divided into stable (75.1° east and 105.3° west) and unstable (11.5° west and 161.9° east) longitudes. Uncontrolled geosynchronous satellites will librate around the stable longitudes.

Figure 2 shows the simulated longitude drift of the 180 hypothetical satellites in Fig. 1 at 1-year intervals. As shown in

Table 2 Preevent elements of U.S. Titan IIIC transtage

Parameter	Value
Epoch	92043.23217642–0931 GMT 21 February 1992
Right ascension, deg	21.8025
Inclination, deg	11.9035
Eccentricity	0.0084771
Argument of perigee, deg	76.2786
Mean anomaly, deg	284.5600
Mean motion, revs/day	1.01459126

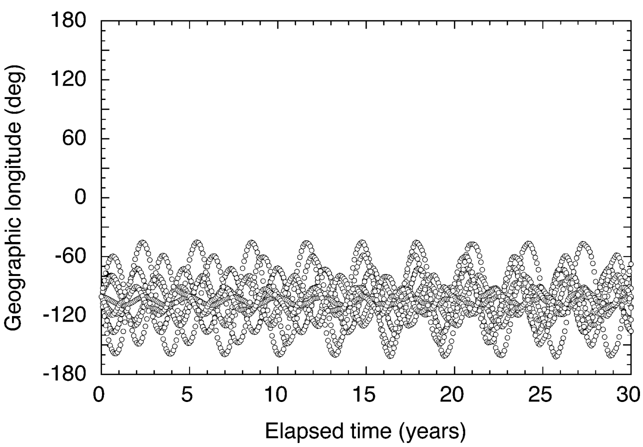


Fig. 5 Simulated longitude drift of librating cloud particles from explosion initially in GEO at 0-deg RA.

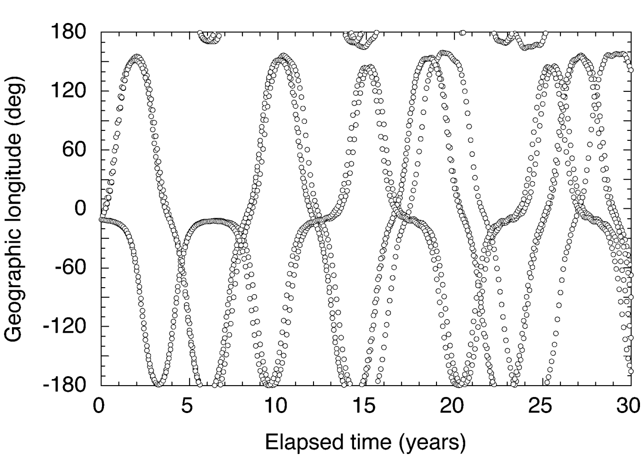
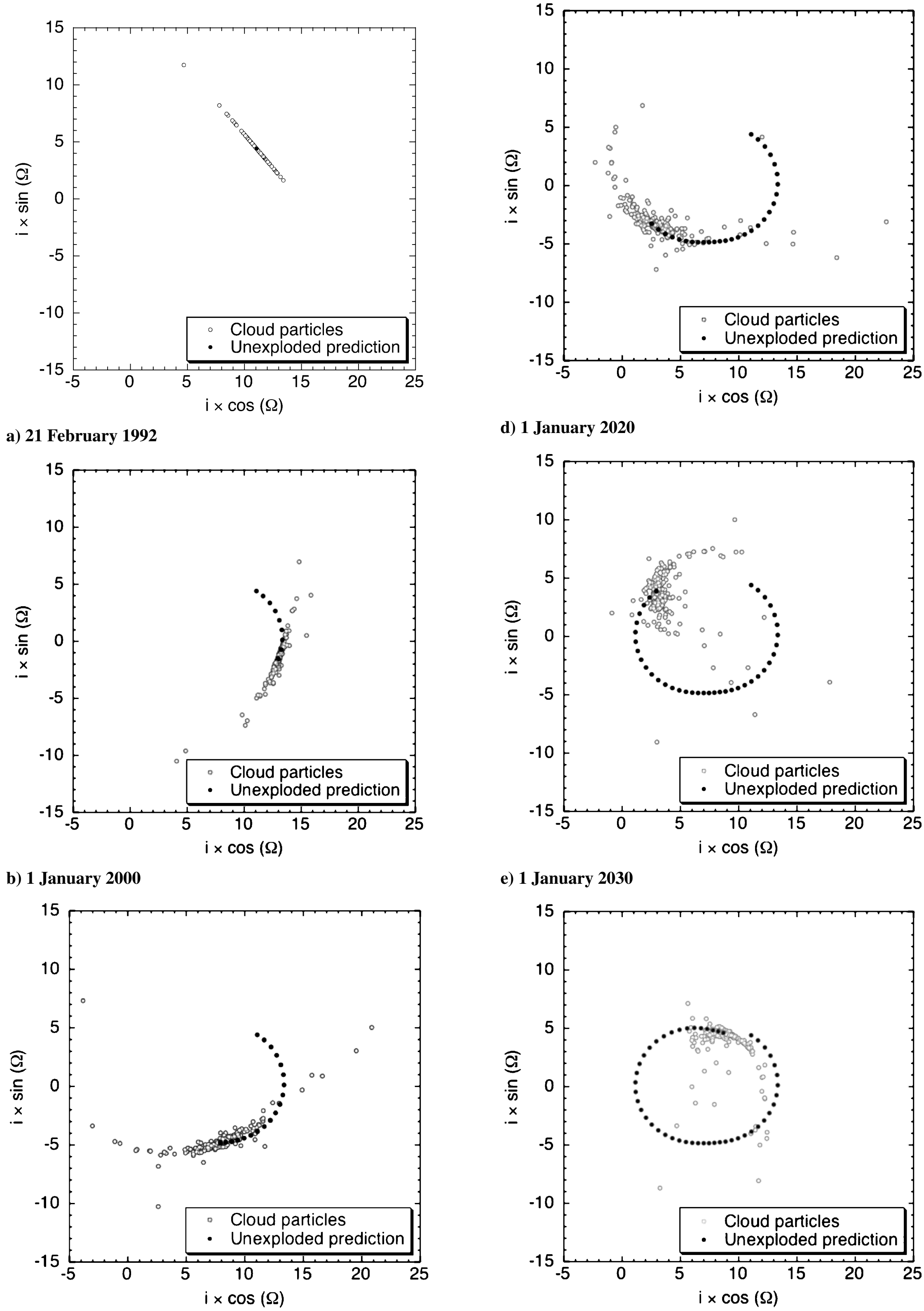


Fig. 6 Simulated longitude drift of librating cloud particles from explosion initially in GEO at 90-deg RA.



a) 21 February 1992

b) 1 January 2000

c) 1 January 2010

d) 1 January 2020

e) 1 January 2030

f) 1 January 2040

Fig. 7 Simulated evolution of debris cloud from near-synchronous U.S. Titan IIIC transtage explosion.

Fig. 2a, they are initially distributed along the nominal geostationary orbit at 2-deg intervals between longitude slots. Note that the change in semimajor axis represents a nonzero longitude drift rate. Therefore, Fig. 2 clearly demonstrates how the satellites librate around the stable longitudes in relation to the change in semimajor axis. A satellite with a positive change drifts westward, whereas a satellite with a negative change, in contrast, drifts eastward. A larger change means a satellite drifts faster. Also note from Fig. 2 that the change in semimajor axis does not exceed 40 km in absolute value. This may indicate that a satellite in an orbit the semimajor axis of which is in the range of −40 to +40 km from the nominal geostationary radius (42,164.17 km) could get trapped in a librating orbit.

Orbital Evolution of Breakup Fragments

The following subsections will present some hypothetical cases and a real near-synchronous Titan IIIC transtage explosion to demonstrate how the explosions put the debris into orbits that are significantly different from those in the catalog.[14]

Hypothetical Explosion of Stationary Object

It is assumed in this subsection that a GEO object explosion occurs in the year 2001. The NASA standard breakup model, which is based on actual observed on-orbit breakup data in low Earth orbit (LEO), creates 1000 or more fragments down to 1 mm in size.[15] In this subsection, however, we count cloud particles only greater than 10 cm in size because those could be detected by ground-based observation facilities. The number of the cloud particles greater than 10 cm created by the NASA standard breakup model is about 240.

Figures 3 and 4 show the evolution at 10-year interval of the cloud particles from explosions that occurred initially at 0- and 90-deg right ascension (RA), respectively. In Figs. 3 and 4, the filled circles represent the 1-year-interval evolution of the parent object. When an explosion occurs on the equatorial plane, the breakup point becomes the ascending node or descending node for the cloud particles, depending on the ejection velocity vector. Therefore, the initial cloud makes a straight line in the adopted coordinate system. This straight line is deformed with the evolution of the cloud, but the particles maintain distinctive patterns centering around the projection of the parent object's unexploded orbit long after the explosion has occurred.

As demonstrated in Fig. 5, only 9 cloud particles of approximately 240 cloud particles simulated in Fig. 3 are affected by the resonance effect of the 24-h geosynchronous orbit to librate around the western stable longitude. Because this explosion occurs at 100.7° west, near the western stable longitude (105.3° west), they librate with a relatively small amplitude. Therefore, they seem to get trapped around the western stable longitude.

As shown in Fig. 6, only 5 cloud particles out of approximately 240 cloud particles simulated in Fig. 4 are affected by the resonance effect of the 24-h geosynchronous orbit to librate around both stable longitudes (75.1° east and 105.3° west). Because this explosion occurs at 10.7° west, near the western unstable longitude (11.5° west), they librate with a relatively large amplitude and spend much of their time paused near the unstable longitudes, not the stable longitudes.

Near-Synchronous Titan Transtage Explosion

We applied the same technique mentioned in the preceding subsection to an actual near-synchronous U.S. Titan III C transtage explosion of 21 February 1992 (Ref. 16). The preevent elements are given in Table 2 (Ref. 1). First, we propagated the preevent elements until the time this transtage exploded. Then we created fragments from this transtage explosion using the NASA standard breakup model to create breakup fragments greater than 10 cm in size. Figure 7 demonstrates orbital evolution of the debris cloud from this transtage explosion. The cloud particles begin in a straight line in Fig. 7, then the pattern is deformed with the cloud's evolution, maintaining distinctive patterns centering around the parent object long after the explosion has occurred. The overall behavior is similar to the hypothetical cases, but the details of the cloud evolution are distinctive for this breakup. Note that the particles in the cloud have different cycling periods, not just the 54-year period of a typical GEO object.

In this case, no fragments get trapped in a librating orbit. This may be because this Titan transtage exploded about 300 km below GEO.

Conclusions

We have simulated some hypothetical explosions initially occurring in GEO and a real U.S. Titan IIIC transtage explosion by using the NASA standard breakup model. Then we propagated the evolution of cloud particles from explosion for long periods (about 50 years). In the coordinate system we adopted here, breakup clouds in and near GEO maintain distinctive patterns long after the explosion has occurred. Normal GEO objects, intact objects that are left in or near GEO with minimal delta velocity, follow distinctive patterns in their evolution, but these breakup cloud particle orbits can evolve in quite different ways. GEO search strategies should consider the possibility of debris clouds with orbital elements different from the intact population distribution, especially at inclinations that exceed the typical 15-deg inclination limit of normal GEO objects. Only a fraction of breakup debris particles appear to become trapped in librating orbits. Nevertheless, searches concentrating near the unstable libration points might reveal concentrations of debris particles.

In this analysis, we concentrated on the effects of primary orbit perturbations in the geosynchronous regime. We plan to continue further investigations, including the effects of secondary orbit perturbations such as solar radiation pressure effects. After understanding the nature of orbit perturbations in the geosynchronous regime, we will devise debris search strategies optimized for unseen debris populations in GEO using breakup models and orbit propagators.

Acknowledgments

The first author thanks Nicholas L. Johnson and Eric L. Christiansen at the Orbital Debris Program Office of the NASA Johnson Space Center, Houston, Texas, for giving him an opportunity to stay at the NASA Johnson Space Center as a senior research associate of the National Research Council and for advising him on a technical approach to devise debris search strategies in GEO by using breakup models and orbit propagators.

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