RISK ANALYSIS OF 1 - 2 CM DEBRIS POPULATIONS FROM SOLID ROCKET MOTORS AND MITIGATION POSSIBILITIES FOR GEO-TRANSFER ORBITS

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ABSTRACT

The problem of 1 - 2 cm ablative debris from solid rocket motor (SRM) burns is discussed. Included are the size, velocity, and time distributions for their production. Results of calculations showing the possible spatial densities of the ablative debris due to SRM burns during the 1980's is shown. The use of lunar and solar perturbations to accelerate reentry are presented as possible mitigation methods for SRMs and their debris.

1. INTRODUCTION

Solid rocket motors (SRMs) are commonly used to make large changes in the orbits of certain types of Earth-orbiting satellites. When the SRM stages are routinely ejected from the operational satellite and left to follow their own orbital path. The lifetimes (time until decay in the atmosphere) of many of these orbits are very long. Consequently, the presence of discarded SRMs presents a long-term debris hazard to the future space environment.

The use of SRMs also adversely affects the orbital environment in other ways. It has long been recognized that the use of SRMs produces unwanted clouds of small (μm) dust particles. These dust particles present a hazard to sensitive spacecraft surfaces that may be "sand blasted" by intersecting such a cloud at orbital velocities. It appears, however, that the lifetimes of these dust objects are very short compared to those of larger debris, and the long-term threat may be small.

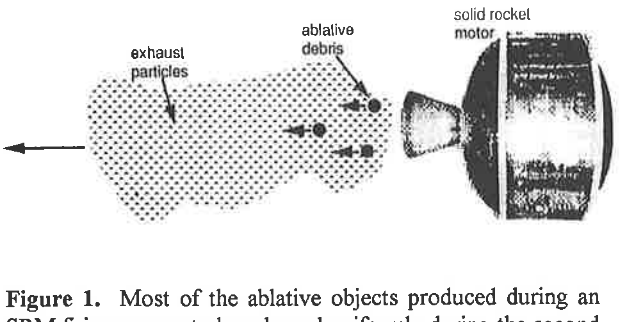

Figure 1. Most of the ablative objects produced during an SRM firing appear to be released uniformly during the second half of the burn or at low relative velocity toward the end of the burn.

Another potential problem concerns the production of much larger debris objects (~1 cm) during SRM burns. These objects have long been known in the SRM community and much work has gone into mitigating their production because of their deleterious effects on motor reliability and performance. They are thought to be composed of either the metallic oxides used to dampen burn-rate instabilies in these motors (e.g. Al_2O_3), or from the thermal insulation burning inhibitors that line the combustion chambers. Recently, ground tests conducted at Marshall Space Flight Center in Alabama and at the Arnold Engineering and Development Center, Arnold AFB, Tennessee, have confired the production of this ablative debris, and examinations of the high-speed videos and movies of the burns have allowed us to make simple estimates of the debris properties. If these tests are indicative of how SRMs behave in orbit, then the high number of these ablative objects combined with the difficulty in tracking objects in this size range presents a serious debris problem.

Based on the reviews of the movies of the ground firing tests, the following simple assumptions are made to model the behavior of these debris objects. We assume that a lower limit of 400 spherical ablative objects (with an average diameter of 1.5 cm) produced per burn is a reasonable estimate to evaluate their possible space debris hazard. They appear to be emitted from the SRM with an average exit velocity of 75 m/s in the plume direction (see figure 1). The characteristic density of the thermal insulation is 1.8 g/cm³, while the measured density of the Al_2O_3 slag samples recovered from the ground tests is 3.5 g/cm³. It is not clear at this time what percentage of the debris is insulation, and what is Al_2O_3, so for our calculations we examine the behavior of both. From the observations of ground tests, it appears that about half of the ablative objects are ejected uniformly during the last half of the burn, and half are ejected in the last few seconds of the burn. Consequently, for actual burns in space, most of the objects will produced in orbits similar to the final orbit of the discarded SRM itself.

Using the orbital parameters associated with a particular SRM burn, each of the 400 ablative objects may be assigned its own orbit. Using computer propagation routines, we attempt to assess their future impact on the orbital environment. In addition, we compile a catalog of historical SRM firings to determine the possible current distribution of this debris.

2. SRM USE

A compilation of SRM motors used during the 1980's is shown in figure 2 (Ref. 1). The objects with low apogee altitudes represent a family of small multi-stage launch systems such as the American Scout and Japanese MU-3S. These rockets lift the payload on a ballistic orbit, and then use the last stage SRM burn to establish the final orbit.

The majority of the SRMs used in the 1980's were used to put satellites into geosynchronous orbits (GEO). These SRMs are divided into two types; "perigee kick" and "apogee kick". The "perigee kick" SRMs are used to transfer a satellite from a circular orbit in low Earth orbit (LEO) to an eccentric orbit with an apogee at near-GEO altitudes. This eccentric geosynchronous transfer orbit (GTO) is circularized at GEO altitudes by firing an "apogee kick" motor at the apogee of the orbit.

The "perigee kick" stage is burned at the point in the orbit which will become the perigee for the new orbit (the length of the SRM burn is much shorter than the orbital period). Because the centimeter debris particles will be created with a retrograde velocity near the end of the SRM burn, they will share the same perigee as the new GTO, but have a range of apogee altitudes as shown in figure 3. Similarly, the "apogee kick" burn to place the satellite into a circular orbit will produce debris with orbits sharing the same apogee, but a range of perigees as shown in figure 4.

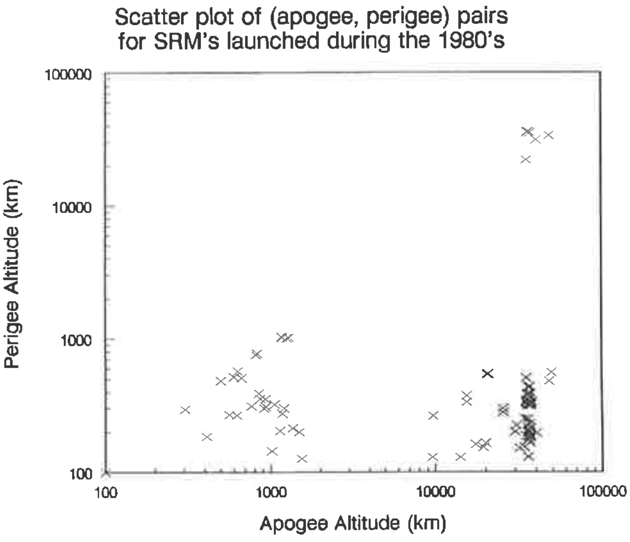

Figure 2. Apogee/perigee plot of SRMs used during the 1980's. The objects in the lower right are spent "perigee kick" motors. The ones in the upper right are spent "apogee kick" motors. The objects in the lower left are from small multi-stage launch systems.

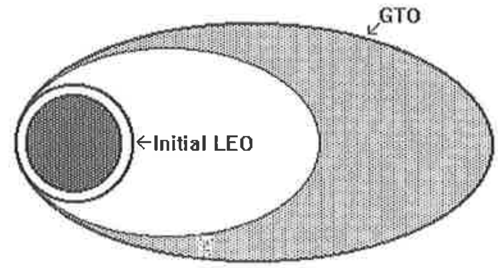

Figure 3. The shaded area shows the region between the initial low Earth orbit and the GTO where the ablative debris from a "perigee kick" SRM will be found. Most of the debris occupies orbits near that of the discarded SRM itself.

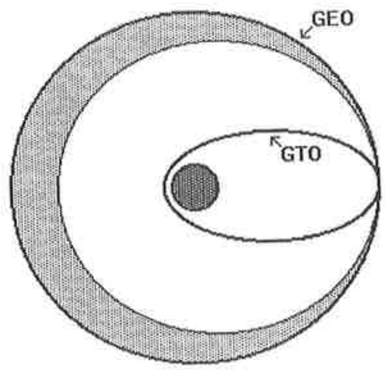

Figure 4. The shaded area shows the region between the initial GTO and the final GEO where the ablative debris from an "apogee kick" SRM will be found. Most of the debris occupies orbits near that of the discarded SRM itself.

By calculating the orbital elements of the ablative objects produced from these burns, effective spatial densities as functions of altitude may be computed using the equations of Kessler (Ref. 2). The spatial densities for objects expected to be produced from "apogee kick" and "perigee kick" SRMs are shown in figures 5 and 6. The compilation of the spatial densities of the debris from the historical 1980's launches is shown in figure 7. In addition we show the results of applying the propagation model DECAY to this debris under two different density assumptions and compare the results to the expected density of other objects from EVOLVE model results. Note that while some of the debris have decayed from the lower altitudes, a significant density remains at higher altitudes. The calculated densities of the debris shown are based on the value of 400 objects produced per burn. There is some evidence to suggest that this number may be as much as a factor of 10 too small. If the SRM burns are producing closer to 4000 objects per burn, then the contribution to the debris environment, especially at low altitudes, is substantial.

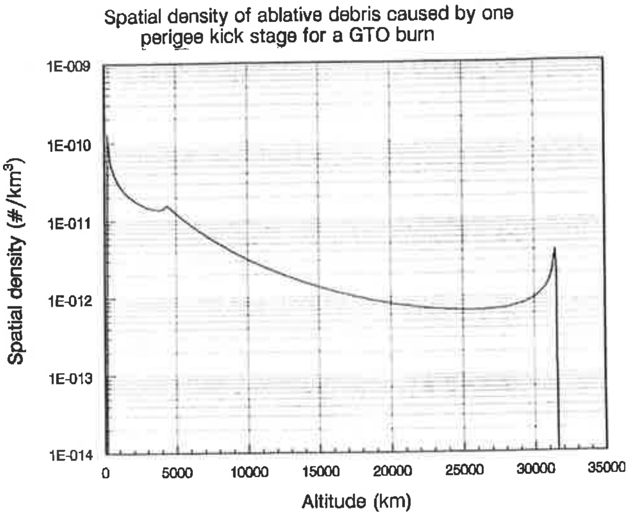

Figure 5. Spatial density of ablative debris produced from a "perigee kick" burn. For these calculations, it is assumed that half of the particles are emitted uniformly during the second half of the SRM burn, and half are emitted at the end of the burn.

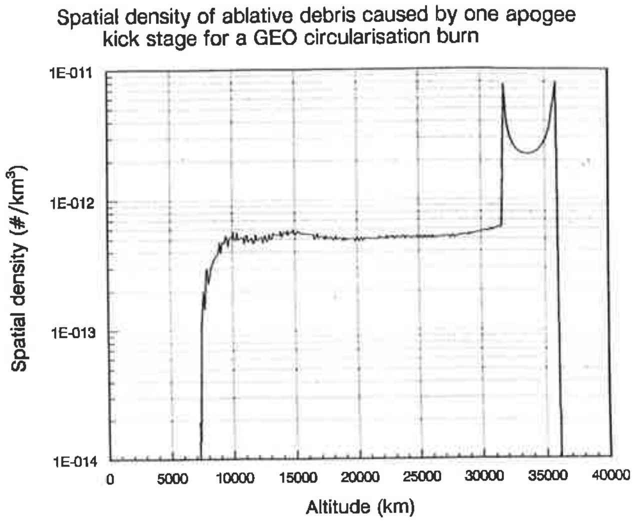

Figure 6. Spatial density of ablative debris produced from an "apogee kick" burn. For these calculations, it is assumed that half of the particles are emitted uniformly during the second half of the SRM burn, and half are emitted at the end of the burn.

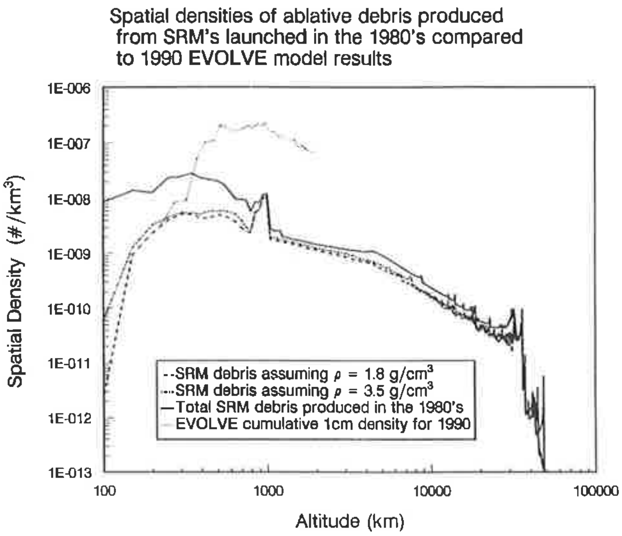

Figure 7. Compilation of total spatial density of ablative debris from historical 1980's launches compared to spatial densities from EVOLVE model results for 1990. Also included are the modeled densities due to atmospheric drag using the DECAY code for two different debris density assumptions.

3. MITIGATION METHODS

If, as we suspect, these ablative objects are contributing a significant fraction of the orbital debris to the environment, then mitigation measures must be considered to control their numbers. These measures fall into two categories: preventative and remedial. Preventative measures are probably the most difficult to implement. While much work has already gone into improving the designs of the SRMs that reduce their production of debris, no major breakthroughs are foreseen in the near future. In addition, curtailing of the use of SRMs could prove prohibitively expensive. Remedial methods hold greater promise, however. If the conditions can be found that accelerate the reentry rates of the discarded SRMs or their debris, then it might be possible to limit their long-term impact on the space environment. One method is to use SRMs at times and places where the solar and lunar gravitational perturbations work together to lower the perigee of the orbit. Because most of the ablative objects appear to be released during the last portion of the SRM burn at low relative velocities, the debris may be assumed to belong to a family of orbits similar to that of the SRM itself. Consequently, choosing orbits that will accelerate the decay of the debris should simultaneously accelerate the decay of the SRM as well.

The magnitude of solar and lunar perturbations on a particular orbit is primarily dependent on the eccentricity of that orbit. Highly elliptical orbits are the most susceptible, while circular orbits are the least. Unfortunately, this precludes the use of this method to impact the orbits of "apogee kick" SRMs and their debris because of their low eccentricities. However, GTO SRMs ("perigee kick" motors) and their debris do end up with highly elliptical orbits. In addition, the perigees of these orbits are usually low enough to make atmospheric reentry feasible. In the next section, we present the results of calculations that show how gravitational perturbations from the Sun and Moon influence the orbital lifetimes of these objects and how this information may be used to minimize the lifetimes of the SRMs and their debris.

4. LUNAR AND SOLAR PERTURBATIONS

Our work on long term orbital behavior is based on the theory for orbital perturbations due to a third body by P. E. El'Yasberg (Ref. 3). His equations show the change in the eccentricity by solar and lunar forces over a single orbit. We extended his results to describe the behavior over many orbits analytically by integrating the change in eccentricity over time. We will soon be publishing details of this analytic theory, but for the purposes of this work, we present the basic results as they pertain to SRMs.

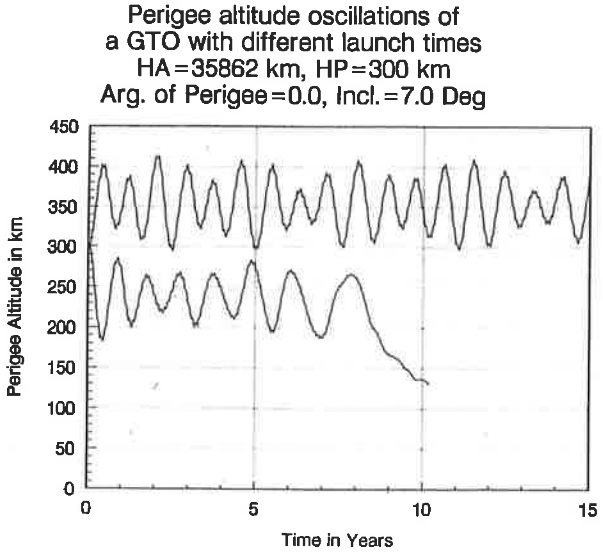

Figure 8. Time evolution behavior of the perigee altitude for two GTOs with inclinations of 7°. The only difference between the two orbits is the initial right ascension of the ascending node and position of the Sun. Note that for both cases the perigee altitude oscillates about an average value dependent on the initial conditions. The lower altitude case decays rapidly compared to the high altitude case.

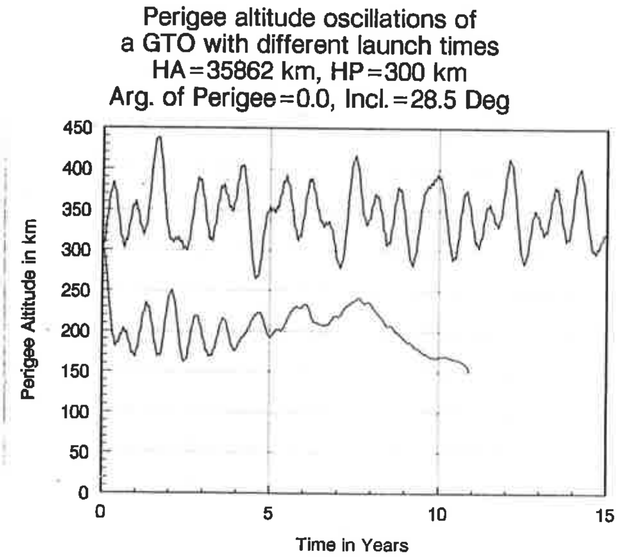

Figure 9. Time evolution behavior of the perigee altitude for two GTOs with inclinations of 28.5°. The only difference between the two orbits is the initial right ascension of the ascending node and position of the Sun.

For an orbit with a particular starting apogee, perigee, argument of perigee, inclination, right ascension of the ascending node, and time of the year (solar position), the orbit will evolve such that the perigee altitude oscillates about some average altitude with some characteristic amplitude; both of which may be easily computed using our analytic formulae. This behavior may best be shown by a series of examples. For a GTO, the argument of perigee was chosen to be 0° (the choice of 180° will give the same results). For a starting perigee we chose 300 km. For inclinations we looked at values of 7° (ESA), 28.5° (USA), and 48° (Russia). Once these values are given, the long-term behavior of the perigee altitude is only dependent on the initial date of burn and the right ascension of the ascending node. While the presence of the Moon has a strong effect on the behavior, its initial position is not critical and may be ignored for these calculations.

Figure 8 shows the oscillatory behavior of the perigee altitude for a GTO at 7° inclination, and figure 9 for a 28.5° orbit. Each figure shows two extreme cases for the average perigee altitude; one lower than the initial 300 km and one higher. As expected, the lower-altitude case reenters the atmosphere much sooner than the higher case. Because the decay rate is dependent on the average perigee altitude and not the starting perigee altitude, the reentry time can be minimized or maximized simply by changing the date and ascending node location of the SRM burn. Figures 10 and 11 show this average perigee altitude for all initial cases of date and ascending node for the GTOs mentioned above. Using these charts, one can easily pick the values of date and ascending node with minimum perigee altitudes and associated shortest orbital lifetimes.

Our analytic relations predict that resonance behavior occurs for certain values of the orbital inclination. Because 48° inclination is near one of these resonances, the average perigee altitudes of the oscillations vary wildly for different initial conditions (see figure 12) for the Russian launches. Consequently, it is possible to choose orbital parameters that give extremely short or extremely long lifetimes (see figure 13).

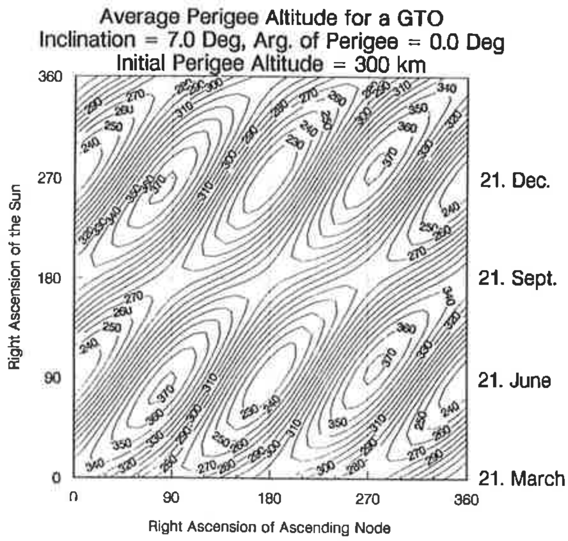

Figure 10. Average perigee altitudes of the 7° inclination GTOs as a function of initial right ascension of the ascending node and solar position.

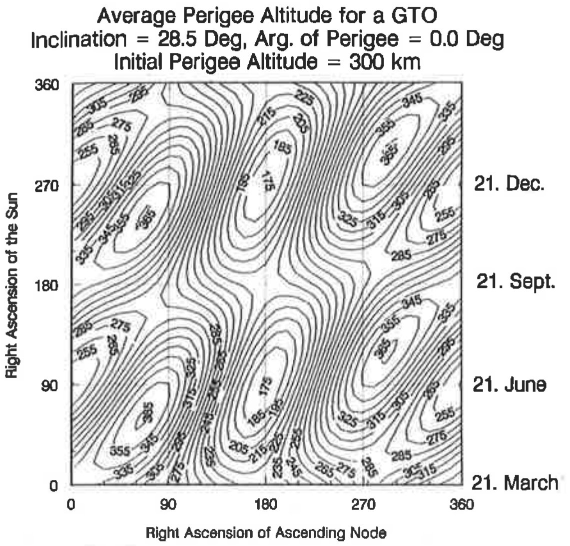

Figure 11. Average perigee altitudes of the 28.5° inclination GTOs as a function of initial right ascension of the ascending node and solar position.

At all the inclinations studied there are a wide range of initial conditions that should give reasonably short lifetimes for the orbits. Launch planners thus have some latitude in choosing the longitude of their SRM orbit. In addition, because ablative objects from the SRMs should have orbits very similar to the GTO stages themselves, they should also decay rapidly for the same choice of initial conditions. When the long term health of the near-Earth orbital environment is considered, this kind of mitigation procedure becomes very attractive.

5. CONCLUSIONS

In this work we have presented information on the production of centimeter-sized ablative debris from on-orbit solid rocket motor burns. While experimental verification of our assumptions is an ongoing process, it is clear that the potential debris hazard from this source is significant. In addition, the difficulties inherent in tracking and shielding for this size of debris make the use of preventative methods attractive. For the "apogee kick" motors, unfortunately, there is no clear method at this time to limit the lifetime of the debris or the discarded SRMs. In the long term, it may prove necessary to find alternate methods (such as liquid fuel stages) for providing this "apogee kick". For the GTO stages, however, the lunar and solar gravitational perturbations already under study for the reduction of orbit lifetimes for the discarded SRMs should help to reduce the lifetimes for the debris as well. While specific payloads may have constraints on launch windows, we feel confident that there is sufficient latitude in the choice of SRM burn times and positions to make this procedure practical.

6. ACKNOWLEDGEMENTS

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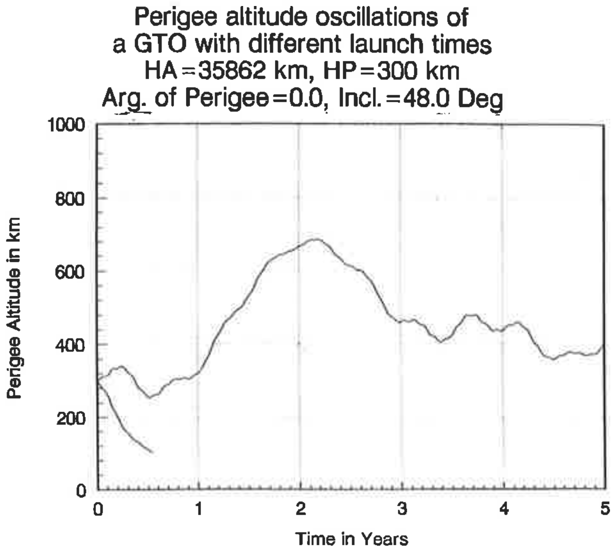

Figure 12. Time evolution behavior of the perigee altitude for two GTOs with inclinations of 48°. The only difference between the two orbits is the initial right ascension of the ascending node and position of the Sun.

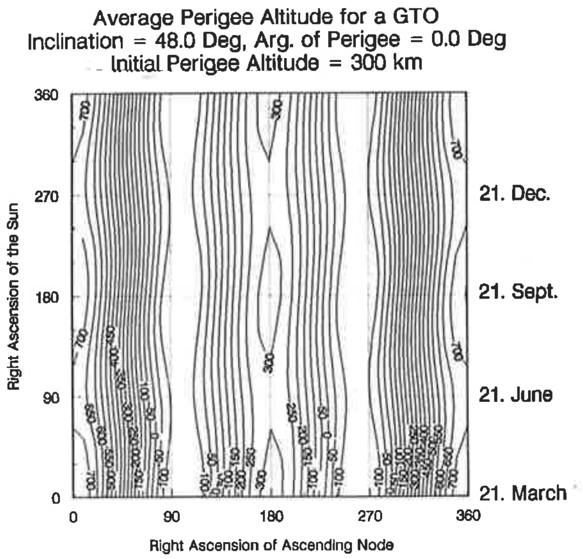

Figure 13. Average perigee altitudes of the 48° inclination GTOs as a function of initial right ascension of the ascending node and solar position.

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