Search for Stable Decommission Orbits for SXM HIEO Satellites

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Abstract: The SiriusXM Satellite Radio's HIEO (Highly Inclined Elliptical Orbit) constellation consists of three GEO synchronous satellites at inclinations close to 63.4 degrees. SiriusXM provides S-band radio service to North America and chose these orbits to provide elevated look angles for the radio receivers. Each satellite's orbit is separated by 120 degrees in RAAN (Right Ascension of Ascending Node). The three satellites are highly eccentric with eccentricity close to 0.27 which results in apogee altitudes that are about 10,000 km above GEO altitude and the perigees that are about 10,000 km below the GEO altitude. In preparing for the end-of-life operations of the satellites we have studied various possible orbit geometries as options for disposal orbits. One of our objectives is to find a stable disposal orbit without entering the orbit regions of active GEO and MEO satellites to minimize the risks of conjunctions with active satellites. We are also looking for fuel optimal orbit geometry in order to maximize the useful operation life of the HIEO satellites. Because of the high inclination and the high altitude the satellites are influenced by the luni-solar resonance effects which limit the choices of the stable decommission orbit geometry. We will briefly describe the operations of the HIEO satellites and present the results of our studies and our conclusions.

Keywords: *Decommission, HIEO, Luni-solar Perturbations*

1. Introduction

SiriusXM (SXM) has three GEO synchronous satellites with orbital period close to 24 hours in highly inclined elliptical orbits (HIEO) that provide mobile radio service to the United States and Canada. The satellites provide continuous coverage to the North America with elevated look angles to the radio receivers for improved service availability. This was achieved by placing the satellites at an inclination of 63.4°. The satellites are also separated by 120° in right ascension of ascending node (RAAN) which provides an eight-hour separation between the three satellites in the ground track. The argument of perigee was selected and maintained to center the peak over the central US with the apogee longitude at 96 degW . See Fig 1. The high eccentricity in the orbit provides a figure-8 ground track and ensures a 16-hour period above the equator and 8-hour period below the equator. Originally, the two of the three HIEO satellites provided service in the period above the equator. When a satellite reached its descending node, the satellite service was transferred to the satellite at the corresponding ascending node. The satellites were built by Space Systems Loral (SSL) and were launched in the second-half of 2000. They are generally referred to as FM-1, FM-2 and FM-3.

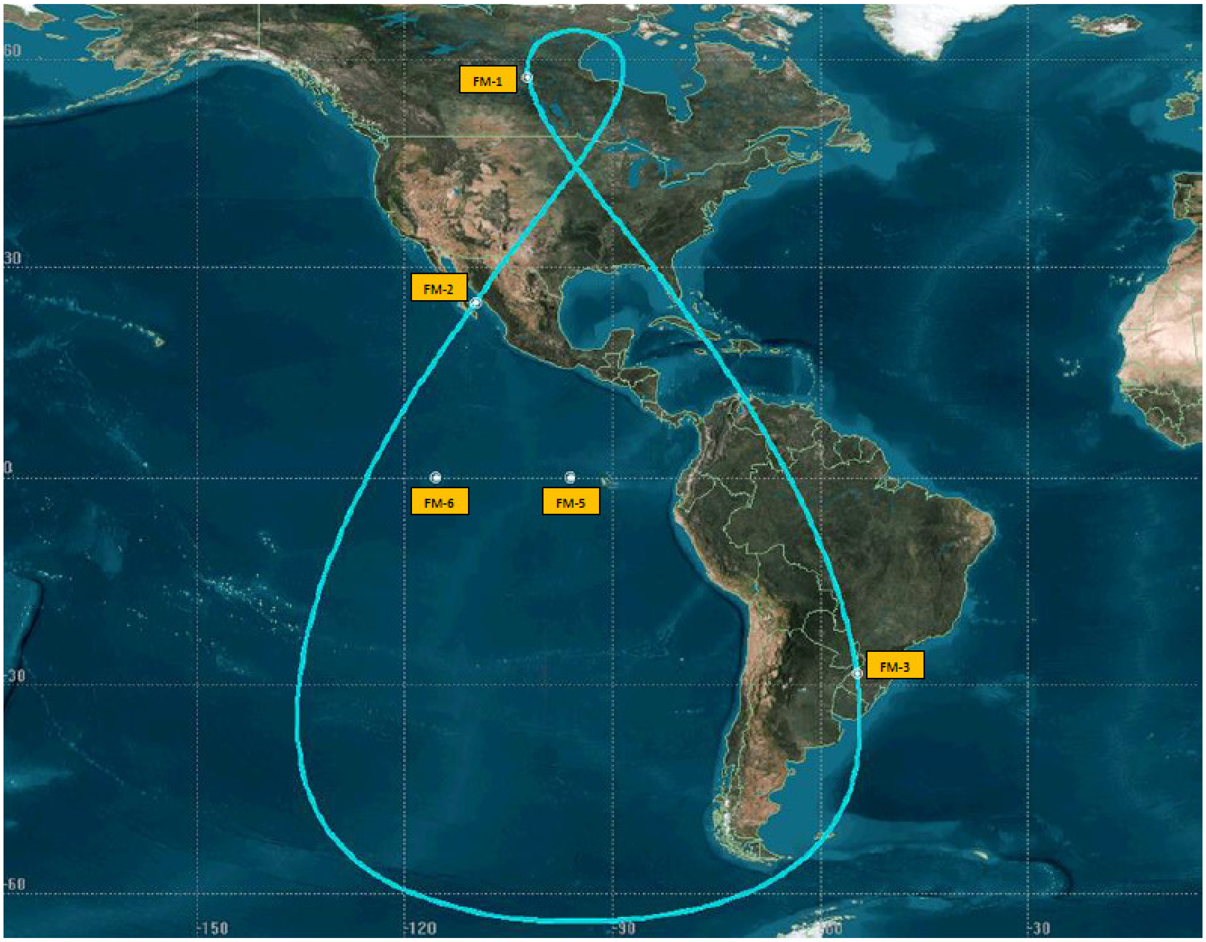

Fig 1. Ground Track of SXM HIEO Satellite

Over the course of a year the angle of the Sun to the plane of the orbit can be quite high. For power-consideration reasons the HIEOs are operated by steering the s/c body around the yaw axis from most of the year to keep the solar array facing the sun. Twice a year at the lower sun angles, the satellites are kept upright and not steered around the yaw-axis. These periods are centered on the eclipse season and most of the station-keeping maneuvers are performed during this period.

In 2008, a new high powered satellite, FM-5, was added to the fleet and located in a geostationary slot. In this hybrid satellite constellation, FM-5 provides continuous service and the HIEOs service delivery period was reduced to an eight hour period near the upper loop. As a result, the service transfer point between the HIEOs moved from the ascending node to near the upper loop.

A couple of years ago SXM and Intelsat explored different options for the HIEO disposal orbit and started working to finalize the planning for the HIEO decommission to coordinate with the ground and space infrastructure to support the end-of- life activities and successful service transition. This is an extension of the initial work performed by SSL. Although Intelsat has experiences in decommission GEO stationary satellites, the unique geometry of the HIEO satellites it poses a new challenge to search of a stable disposal orbit within the allocated decommission propellant. It is important to consider in the design of the disposal orbit the significant ground resources for the decommission activities as well as the shutdown process including the venting of all propellant and pressurant tanks.

2. Disposal Orbit Criteria

One important criterion is to identify a disposal orbit with minimum propellant impact that can meet the FCC requirements. Our goal is to search for a disposal orbit which allows for maximum usage of onboard propellant for station-keeping and thus optimize orbital maneuver life.

It is also very important that the disposal orbit is a stable orbit. The HIEO operation orbit geometry with a 24 hour period and eccentricity close to 0.268 the satellite apogee is above the GEO radius while the perigee is between the GEO and MEO radius and the satellite crosses the GEO arc twice daily. One criteria for the selected disposal orbit is such that the satellite will either remain above the GEO radius at all time or stay between the GEO and MEO (GPS) radius with minimal crossing into the GEO or the MEO region in order to minimize the risk of close conjunction with other active or non-active space objects in the region. In addition we also need to consider the robustness of the selected decommission orbit. The stability of the target disposal orbit needs to have sufficient tolerance to the initial conditions. The final achieved orbit will have dispersions from the target parameters due to thruster mis-performances, the venting of propellant and pressurant in the tanks before shut down and etc.

We considered three different classifications of stable orbits. (1) Stable: a circular (or near circular) orbit such that the satellite stay in this condition for decades (> 100 years). This orbit does not intersect the GEO or the MEO arc. (2) Semi-stable: orbits stay at low eccentricity ($e < 0.1$) for extended durations, similar to the stable condition the GEO arc is never entered but the MEO arc might periodically be crossed. (3) Unstable: this results in orbit behavior that is very difficult to predict. The orbit can cross the GEO for short periods and will certainly cross into the GPS arc routinely, and can eventually reenter the atmosphere.

2. Disposal Orbit Options

Since one of the criteria for stability is a circular orbit we considered different options to circularize the HIEO satellites via a combination of lowering the apogee and raising the perigee to compute an initial bound of delta-v requirements. The results of this computation are shown on Fig 2.

Without considering inclination changes the maximum delta-v for circularization is about 460 m/sec by lowering apogee to the perigee altitude and the minimum delta-v requirement is about 400 m/sec by raising perigee to the apogee altitude. The difference between the lower and upper bond is about 60 m/sec which is equivalent to about 1 year of station-keeping operation. Please note that it takes roughly about 50 m/sec for 1 degree change in the orbital plane.

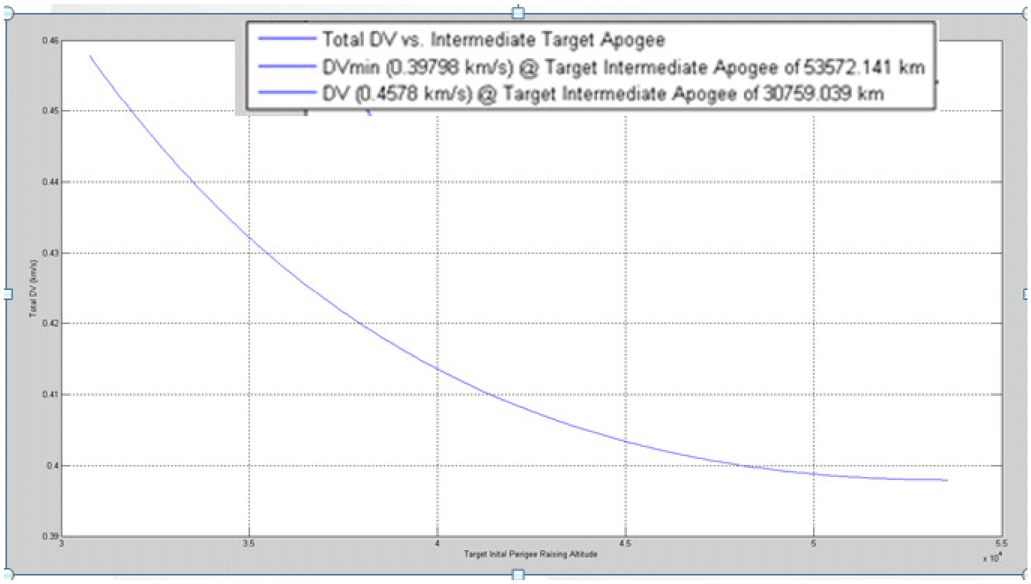

Fig 2. Delta-v Requirements for Circularizaing HIEO Satellites

The computation provided an upper and lower bound of the delta-v requirements. We consider the following limiting scenarios to spend the delta-v within the bound:

Tangential direction only:

(1) Raise perigee by 23,000 km to circularize at radius of 53,500 km
(2) Lowering apogee by 21,000 km to circularize at radius of 31,000 km
(3) Raise apogee by 47,000 km and increase eccentricity to 0.5
(4) Lowering perigee by 13,000 km and increase eccentricity to 0.5

Normal direction only

(5) Increase or decrease inclination by about 7.4 degrees
(6) Increase or decrease RAAN by about 11 degrees

Radial directions are not considered since the results will be similar to the tangential case but with less maneuver efficiency.

A few cases of the above scenarios can be eliminated immediately. Case (3) results in an apogee radius of 100,800 km and perigee radius of 30,800 km and the satellite will cross GEO daily. Similarly, case (4) was rejected as it will cross both the GEO and MEO arc with the orbit apogee at 53,500 km and perigee at 18,000 km.

2.1 The Do Nothing Option

We considered the scenario if we just stop station-keeping maneuvers and just turn off the satellite at its current orbit geometry, the "do nothing case". The current geometry of the spacecraft has an apogee 10,000 km above GEO radius and perigee 10,000 km below the GEO radius. Fig 3. showed the eccentricity evolution based on simulation to 100 years in this geometry.

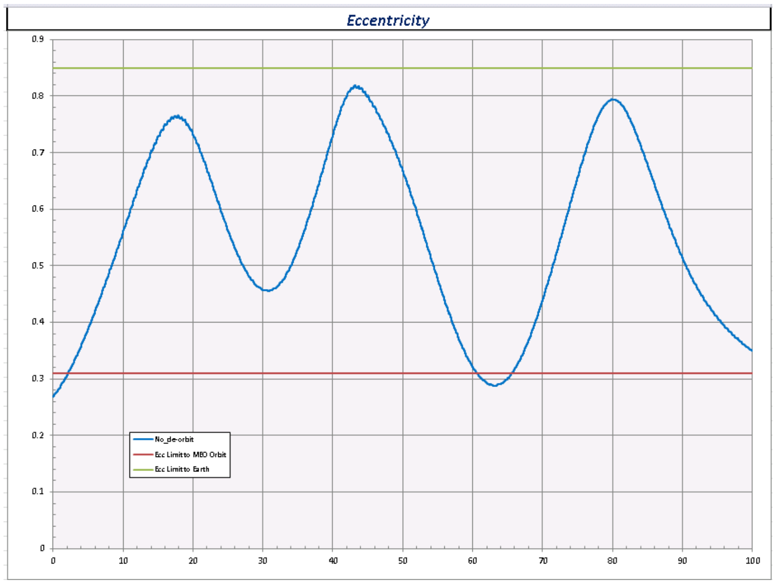

Fig 3. 100 years of simulation at HIEO at Current Orbit Geometry

Based on the initial condition we expect the HIEO satellite will cross the GEO arc twice daily and from Fig 3. we also noticed that the eccentricity will grow and the satellite will enter into the MEO arc within a few years without any station-keeping maneuvers. After about 43 years the eccentricity will grow so large that the satellite is within 1500 km from the earth surface. The option of "do nothing" by just turning off the satellite at its current orbit geometry is rejected.

Fig 4. showed the eccentricity from 100 years simulation by applying the 460 m/sec delta-v to modify the satellite inclination. Similar results are observed as in the "do nothing" case, although we noticed a slight decrease in the eccentricity growth with the case when inclination was reduced.

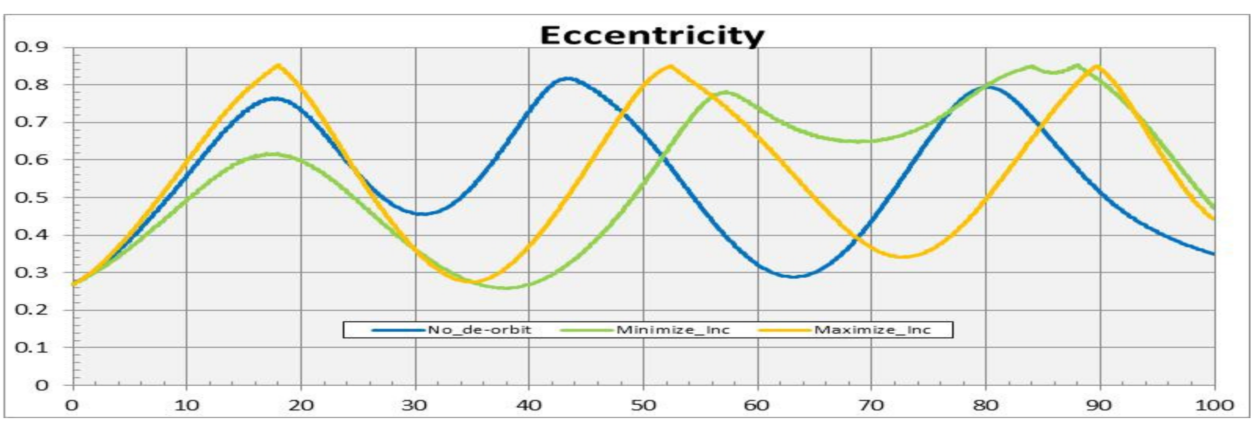

Fig 4. 100 years of simulation at HIEO at Current Orbit Geometry at different Inclinations

2.2 Circularization at HIEO Apogee Altitude Options

We consider the case that we circularize at the apogee altitude using 400 m/sec delta-v. In this case a stable orbit will have the satellite remain above the GEO radius and does not re-enter in the GEO arc.

Figure 5. shows the eccentricity predictions from 100 year simulation for the case when circularization at the HIEO apogee. The initial condition has the satellite at a radius about 10,000 km above the GEO arc.

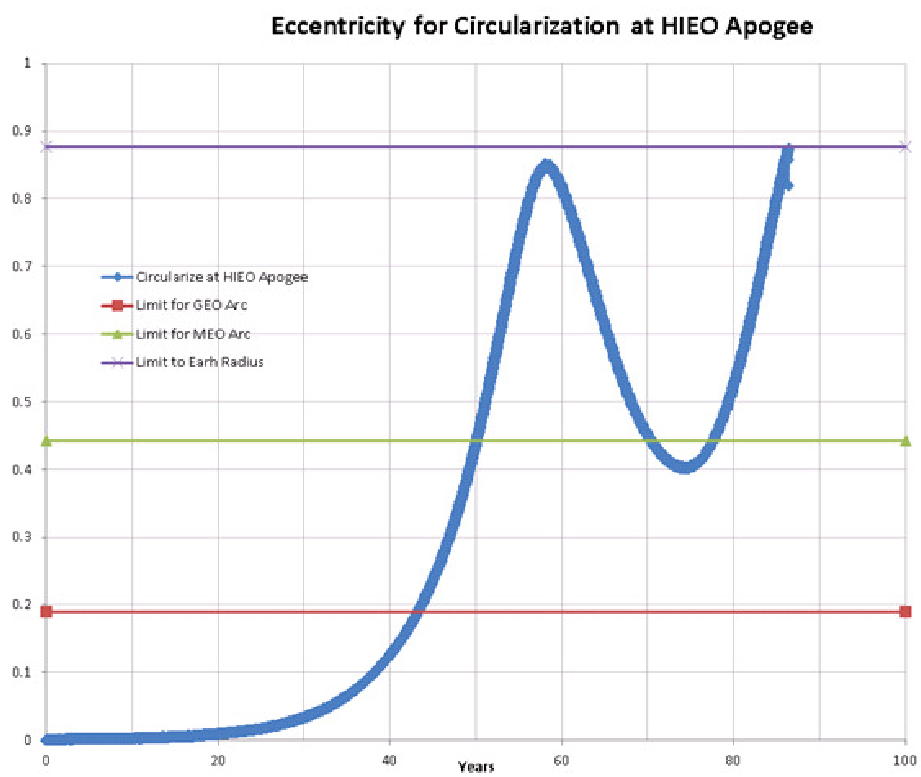

Fig 5. 100 year simulation of HIEO circularized at Apogee Altitude

As observed from the plot the eccentricity grows quickly after about 30 years and by about 45 years the satellite will re-enter the GEO arc and the eccentricity continues to grow quickly and it enters into the MEO arc and comes very close to Earth re-entry. This is a very interesting case.

Chao [1] gave the doubly averaged equations in eccentricity obtained from an expansion of the distribution function from Sun and Moon perturbations and it takes the following form:

$$
\begin{aligned}
de/dt = c0^* (&c1 * \sin 2(\omega - \Omega) \\
&+ c2 * \sin (2\,\omega - \Omega) \\
&+ c3 * \sin \omega \\
&+ c4 * \sin (2\,\omega + \Omega) \\
&+ c5 * \sin 2(\omega + \Omega)\ )
\end{aligned}
$$

Where

ω = the argument perigee of the satellite and Ω = the right ascension of the ascending node.

c0, c1, c2, c3, c4, c5 are constants terms involving the third body parameters.

Fig 6. showed the time plot of the ω and Ω of the satellite from the 100 year simulation.

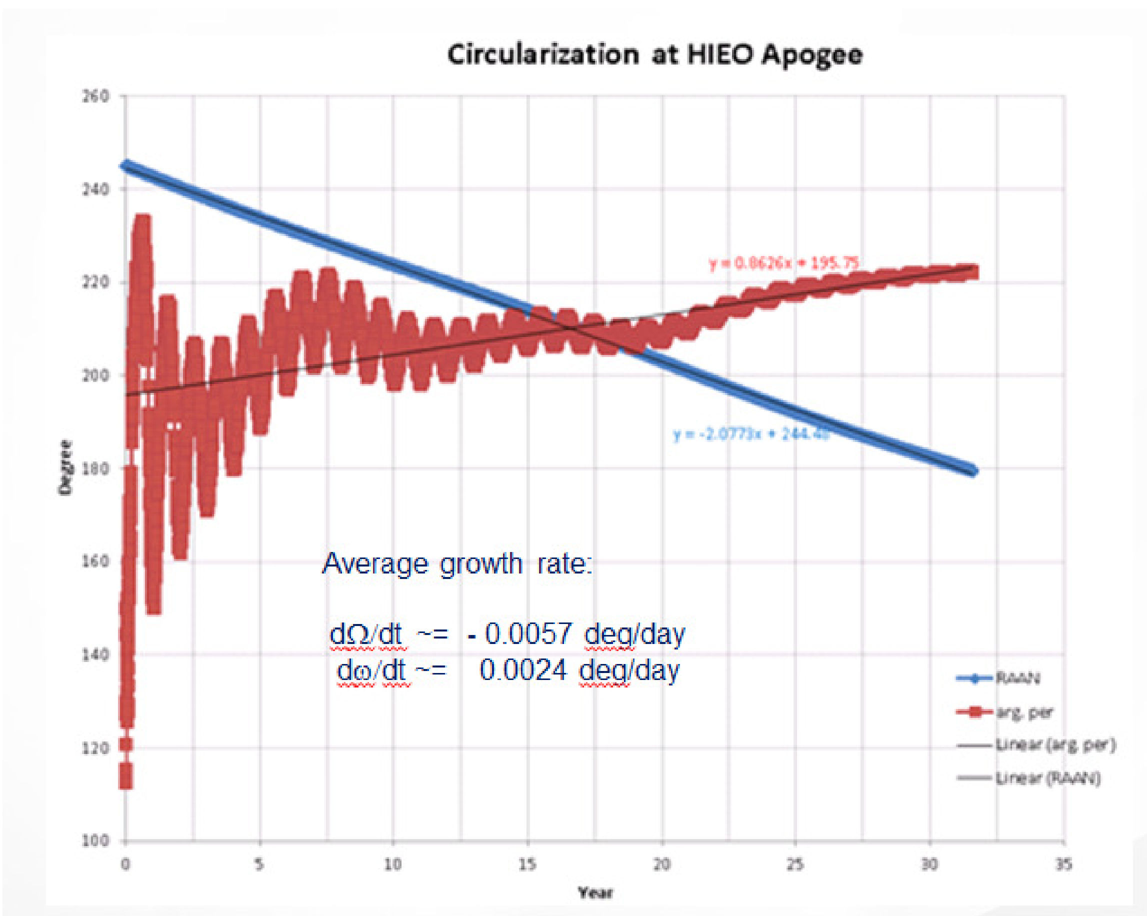

Fig 6. 100 year simulation of HIEO circularized at Apogee Altitude

In this case the $(2\omega + \Omega)$ term has a very long period since the combined rate for $d\Omega/dt$ and $2^* d\omega/dt$ is very small. By comparison the periods of the remaining terms are about an order of magnitude shorter.

As the case for the GPS orbit geometry this resonance effect is a function of the luni-solar perturbations due to the satellite inclination and high altitude. This effect reduces if the moon perturbations are turned off or the inclination is greatly reduced. Fig 7. showed the different scenario.

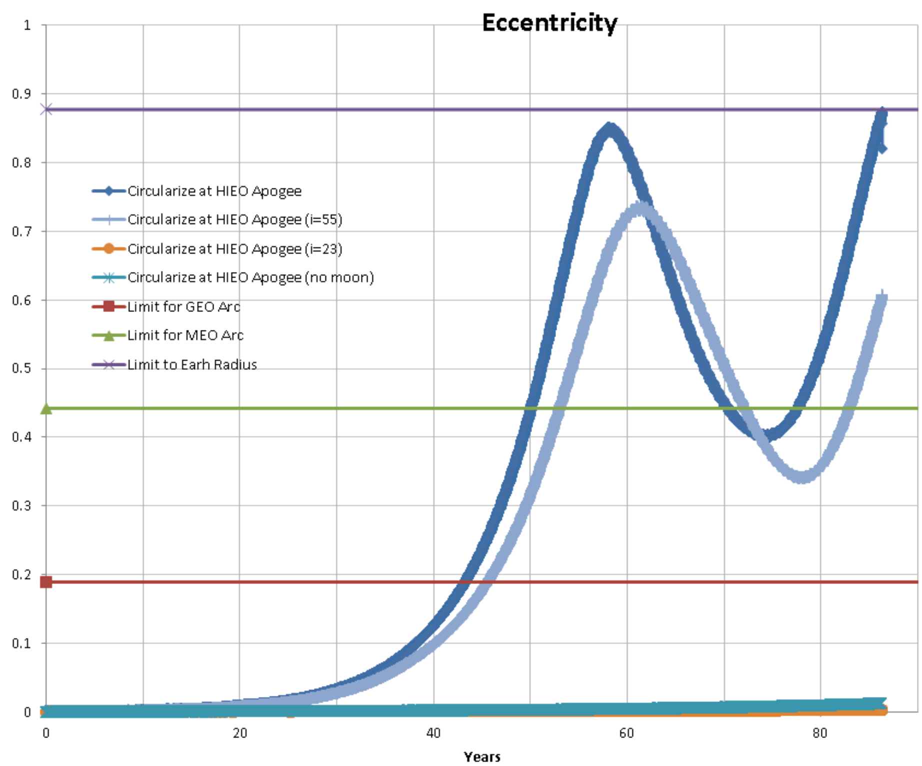

Fig 7. 100 year simulation of HIEO circularized at Apogee Altitude

In this figure we noticed the eccentricity behaves very well in the cases when the moon perturbation is switched off as well as when the inclination is decreased greatly.

Unfortunately both scenarios are not realistic. We do not have the option to switch off the moon perturbations and the delta-v to reduce inclination sufficient enough. The delta-v required to reduce 1 degree of inclination is about 50 m/sec.

2.3 Circularization at HIEO Perigee Options

Next we considered the case to circularize at the HIEO perigee using 460 m/sec delta-v. In this case a stable orbit will have the satellite remain in the altitude between GEO and MEO radius and do not enter into either the GEO or MEO arc.

Different initial conditions for the orbit eccentricity are considered to test the robustness of the stability of the final disposal orbit geometry. The results are shown on Fig 8.

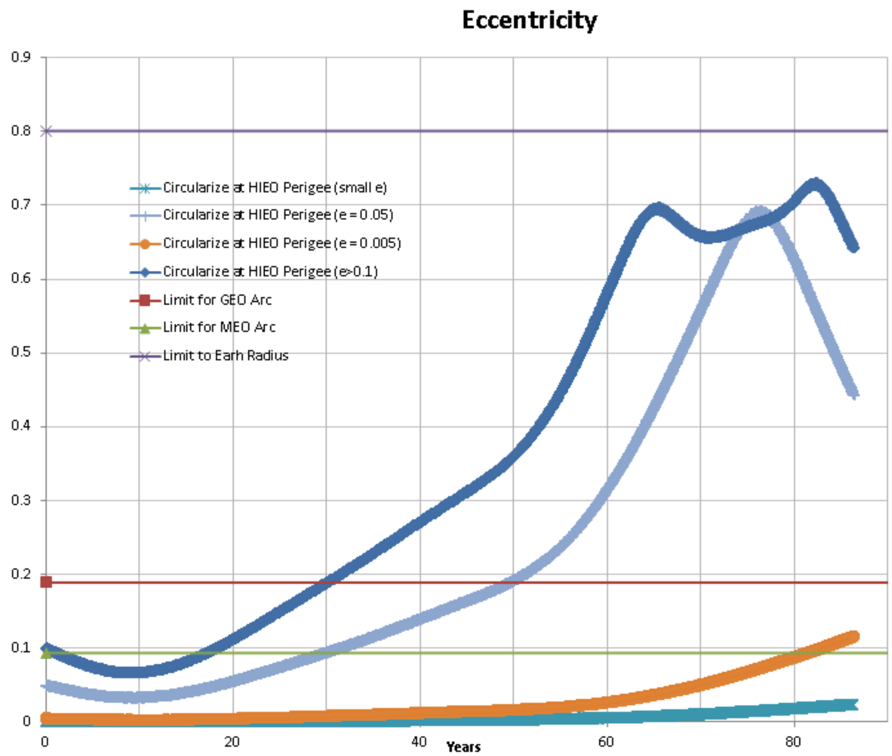

Fig 7. 100 year simulation of HIEO circularized at Apogee Altitude

The figure showed stability close to 100 years without crossing into the MEO arc even with orbit initial eccentricity to 0.005. A dispersion of 0.005 in eccentricity equates to about 300 km in the differences for the apogee and perigee altitude which provides sufficient margin to account for the orbit disturbances due to thruster performances and venting activities before shut down. Based on previous experiences this should be achievable.

4. Conclusions

We have explored the different options for the final disposal orbits for the HIEO satellites. Due to the unique geometry of the HIEO satellites with closet to 24 hour period, high inclination close to 63.4 degree and the large eccentricity of 0.268 we are limited to our options. We have shown that if we just leave the satellite in its current geometry it will continue to cross the GEO arc twice daily and will enter into the MEO arc in just a few years. The orbit eccentricity will continue to grow and within 45 years the satellite will be within 1500 km above the Earth surface based on our simulation. We have shown the two possible options of either circularizing the HIEO satellite at the apogee (10,000 km above GEO arc) or circularizing the HIEO satellite at the perigee altitude (10,000 km below GEO arc). The case to circular at the apogee altitude requires less delta-v. However, because of the satellite inclination and the high altitude in this configuration the satellite was affected by the resonance terms due to the luni-solar perturbations. The satellite will cross into the GEO and MEO arc within 30 years and will have possible Earth re-entry within 100 years. This option was rejected. We simulated the option of lowering the HIEO apogee and circularize at the perigee altitude with slightly different initial conditions to test the robustness of this disposal orbit geometry. Our results show that the orbit will remain between the GEO and MEO radius to 100 years even with a slight dispersions of the final archived eccentricity (< 0.005). Based on previous experiences this should be achievable. SXM and Intelsat have selected this disposal orbit for the decommission planning to meet the disposal orbit requirements. We have worked out a modified station-keeping plan to accommodate this selection with no change to the nominal operation life.

5. References

[1] Chao-Chun G. C (2005), Applied Orbit Perturbation and Maintenance, AIAA, El Segundo, California.