SAKARYA UNIVERSITY JOURNAL OF COMPUTER AND INFORMATION SCIENCES
VOL. 1, ID. SAUCIS-5-2018, APRIL 2018

Comparative Analysis of Sub GTO, GTO and Super GTO in Orbit Raising for All Electric Satellites

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Received 29 March 2018; Accepted 30 March 2018; Published online 2 April 2018

Abstract

Electric propulsion system has been used on many geostationary communication satellites for station keeping maneuver because of having high specific impulse values. But in general chemical propulsion system is being used for orbit rising from transfer orbit to GEO. Recently all electric satellites market is emerging and those satellites use electric propulsion system to reach final GEO orbit. It takes 4-8 months to reach final orbit and during this progress satellites subject to extreme environmental conditions. It is mandatory to minimize number of Van Allen belt crossing to keep spacecraft healthy. Transfer orbit types and orbit rising strategies affect duration to final orbit, number of radiation belt crossing and required delta V to final orbit. In this study reaching final GEO belt for different initial transfer orbits sub GTO, GTO, super GTO are investigated in terms of duration to GEO and number of Van Allen belt crossing.

Keywords: all electric satellites, geosynchronous orbit, transfer orbit, sub GTO, GTO, Super GTO, van allen belt, electric propulsion system, low thrust

1. Introduction

Communication satellites requirement trends is to have larger payload and higher power system spacecraft. Electric propulsion spacecraft technology offers high exhaust velocity and high trust efficiency. As a result of that reduced propellant mass and reduced satellite wet mass can be achieved (Pergola 2015; Yang 2009). When spacecraft launched, depending on launch vehicle performance, satellite has been injected into transfer orbit (Konstantinov at al. 2001). This transfer orbits as shown in figure 1 could be sub geosynchronous transfer orbit (sub GTO) which has apogee altitude of 34000 km or less, geosynchronous transfer orbit (GTO) which has apogee altitude of 35786 km or super synchronous transfer orbit (super GTO) which has apogee altitude of 36500 kilometer or more. Satellite final Target is geosynchronous circular orbit, which has 35786 km altitude as seen in figure 1.

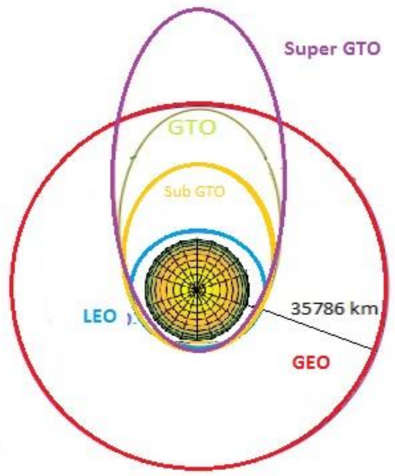

Figure 1 Communication satellites transfer orbits, Sub GTO, GTO and Super GTO.

Electric propulsion satellites are subject to extreme environmental conditions during orbit rising which is harder than chemical propulsion satellites transfer orbit environmental conditions because of low trust capability of all electric propulsion system (Horne 2015; Dutta at al. 2015).

Communication satellites design lifetime requirement is about 15 years as an industry approach but it takes 4 -8 months to to reach GEO for all-electric propulsion satellite (Horne 2015). This long duration causes exposing radiation dose due to electrons and amount of that dose is equal to many years operation in geosynchronous orbit. Even this amount of dose can reach the value, which is half of the typical spacecraft lifetime. Additionally environmental conditions of transfer orbit altitude about 8000 km causes satellite internal charging (Horne 2015). To overcome this problem spacecraft should have more shielding but this causes design manufacturing and testing procedure change and results cost increase. In this work, keeping satellite shielding requirement as nominal and by analyzing transfer orbit rising strategy to mitigate radiation effect due to Van Allen belt electrons has been studied.

There are many strategies to reach from transfer orbit to final geostationary orbit (Yang 2009; Geng 2016; Guelman 2016; Kibmrel 2002). Each approach has some advantages and some disadvantages. In general, minimizing transfer orbit duration, Van Allen belt cross or required delta V are considered and any of them can be taken into account as a target. In this study first reaching final geosynchronous orbit from inner sub geosynchronous transfer orbit analyzed and then geosynchronous transfer orbit and super geosynchronous orbit have been analyzed. Transfer orbit, orbit rising strategies has different duration to reach GEO. At the same time they have difeeerent radiation belt crossing numbers, which is important to analyse spacecraft exposed radiation dose.

2. Transfer Orbit Environment

The earth's trapped particle radiation belt were discovered at the beginning of the space travel. It was recognised as a hazard to spacecrafts. After that trapped electron and proton models have been developed Trapped electron and proton population is shown in figure 2 and figure 3 according to NASA AP-8 and AE-8 model (Rodgers 2003). In this study to mitigate environmental harmful effect perigee cross of Van Allen belt has been minimized for different transfer orbits. Assuming most hazard belt for orbit rising is between 2000 km and 8000 km altitude (Koppel 1999). So that each orbit rising or changing strategy is characterized by its number of perigee crossing Van Allen belts.

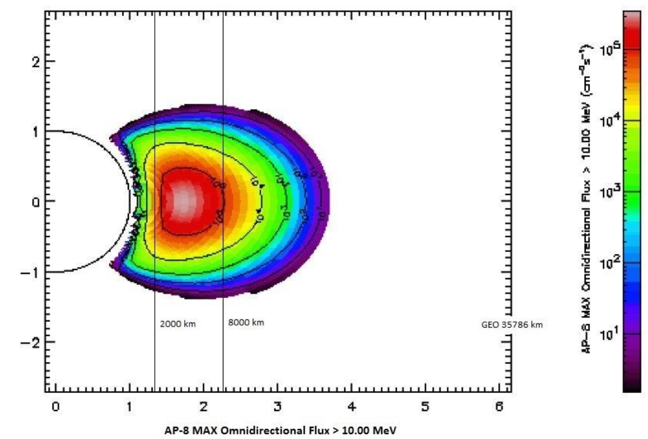

Figure 2 Map of the AP-8 MAX integral proton flux >10 MeV. The semi-circle represents the surface of the Earth, distances are expressed in Earth radius.

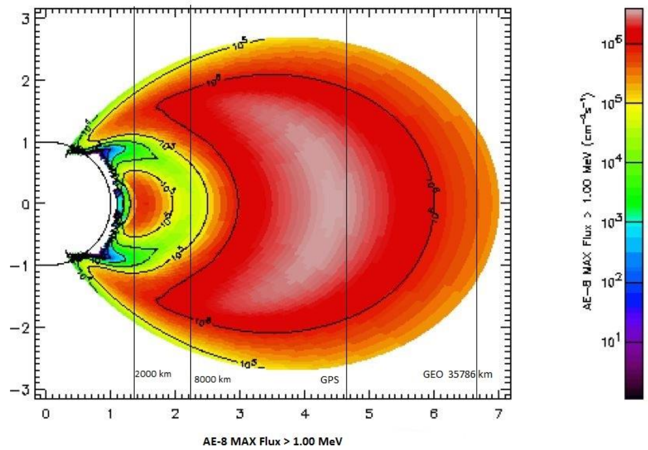

Figure 3 Map of the AE-8 MAX integral electron flux >1 MeV.

In order to evaluate radiation dose, while satellite is in transfer orbit and in orbit rising phase number perigee crossing of Van Allen belt has been counted. Accumulated radiation dose for 200 days of electric orbit rising is equal to 6.7 years operation in geosynchronous orbit as shown in figure 4 (Horne 2015). It shows that it is very important to leave Van Allen radiation belt as soon as possible to reduce exposed radiation dose. Instead of 200 days electric orbit rising which is equal to 6.7 years operation at geo, reduced electric orbit rising duration will save satellite from high radiation dose and consequently the risk of satellite anomalies associated with energetic electrons in the Van Allen belt will be reduced.

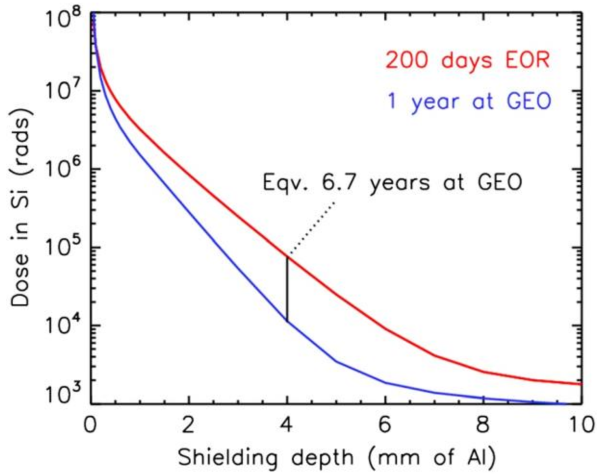

Figure 4 Comparison between radiation dose (perigee crossing) and operation at geo.

3. Orbit rising strategies to GEO

The main drawback of low thrust is long duration of orbit transfer. Many strategies have been investigated to find better transfer duration (Koppel, 1999; Pergola 2015; Dankanich and Woodcock 2007). In this study sub GTO, GTO and super GTO types of initial orbits have been considered. Thus orbit rising or adjusting depend on initial orbit types and Van Allen belt crossing number. Apogee centered firing has been investigated. Thruster on time duration is long and during that time, satellite moves on its orbit in all electric propulsion system. Because of that overall delta V and duration increases compared to theoretical apogee centered impulse maneuver.

Firstly, from sub GTO to GEO orbit has been studied as shown in figure 5. First thrust applied from around apogee point and perigee altitude has been raised to apogee altitude and circular orbit obtained. This orbit then extended to circular GEO by using Hohmann transfer. Hohmann transfer method applied many times to reach final orbit.

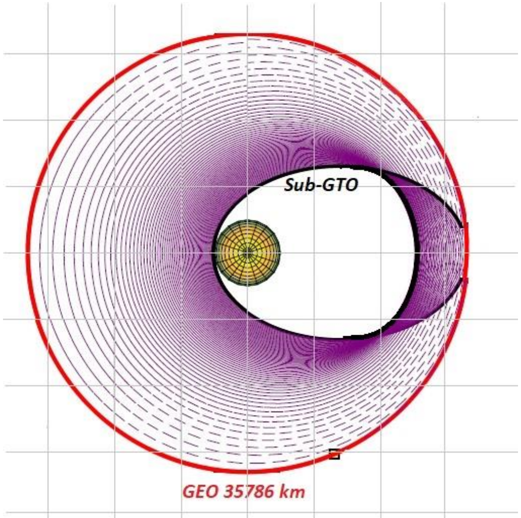

Figure 5 Schematic representation of orbit rising from sub GTO to GEO

Secondly, orbit rising of GTO to GEO has been studied. In this case thrust applied around apogee point several times and perigee increased to apogee value and final GEO altitude has been obtained as shown in figure 6.

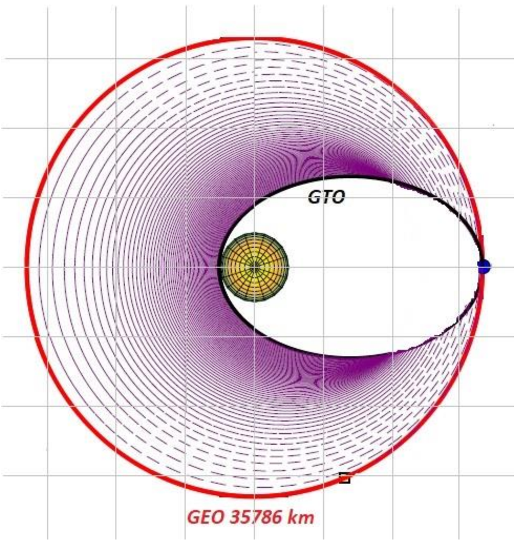

Figure 6 Schematic representation of orbit rising from GTO to GEO

Finally, from super-GTO to GEO orbit adjustment has been studied. Initially thrust applied from around apogee point several times and perigee altitude raised to GEO then thrust applied around perigee point and apogee altitude decreased to final GEO belt. Consequently, circular GEO has been obtained as shown in figure 7.

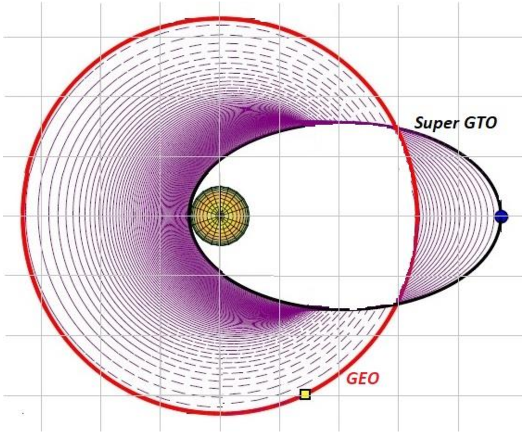

Figure 7 Schematic representation of orbit rising from super GTO to GEO

The Tsiolkovsky rocket equation allows for computing required ΔV to achieve the orbit transfer.

$$m_1 = m_0 e^{\frac{-\Delta V}{g_0 I_{sp}}} \tag{1}$$

$$\Delta V = V_e Ln(\frac{m_0}{m_1}) \tag{2}$$

$$v_e = I_{sp} g_0 \tag{3}$$

where m_0 and m_1 are the satellite initial and final mass respectively. I_{sp} is specific impulse determined by thruster and g_0 is earth gravity acceleration.

In this study, Snecma PPS-5000 high power electric thrusters has been considered. Those thruster parameters were taken into account as Isp=1700 s and thrust 300 mN for transfer orbit optimized performance (Duchemin at al. 2015). Satellite mass is taken as 3500 kg.

Duration to reach final GEO and number of Van Allen belt cross have been calculated by considering different transfer orbits and different commercial launch vehicle.

4. Results and Discussion

Transfer orbit duration and number of perigee crossing have been simulated by using apogee centered firing and results were calculated according to Tsiolkovsky equations. For sub GTO to GEO with perigee altitude of 250 km and apogee 29500 km and 26500 km have been analyzed. It takes 125 days to reach GEO altitude and 93 perigee cross Van Allen belt for apogee altitude of 29500 km. For apogee altitude 26500 km, those values a little bit worse and they are 131 days to reach GEO altitude and 112 perigee cross of Van Allen belt as seen in Table 1 and figure 8.

Table 1 Satellite transfer orbit after Launch Vehicle Injection Apogee firing

Orbits	Perigee km	Apogee km	Duration (days)	Perigee Crossing Van Allen	Launch Vehicle
Sub GTO 1	250	29500	125	93	Ariane
Sub GTO 2	250	26500	131	112	Falcon 9
GTO 1	250	35786	118	79	Ariane
GTO 2	4432	35786	97	32	Proton
Super GTO 1	185	45000	150	69	Falcon 9
Super GTO 2	5262	65000	181	17	Proton

GTO 1 case perigee altitude is 250 km and apogee altitude is 35786 km. It has 118 days to reach GEO altitude and 79 perigee Van Allen belt crossing. For GTO 2 case, transfer orbit perigee is 4432 km and apogee altitude is 35786 km. Orbit rising duration is 97 days and number of perigee crossing 32. GTO 2 result is better than GTO 1 because of higher perigee altitude due to powerful launch vehicle.

Super GTO 1 perigee altitude is 185 km and apogee altitude is 45000 km. Duration to GEO orbit is 150 days and number of Van Allen belt perigee cross 69. For last case super GTO 2 perigee altitude is 5262 km and and apogee altitude is 65000 km. It takes 191 days to reach final GEO and number of perigee crossing is only 17.

Tables 1 shows summary of transfer orbits and results of apogee firing maneuver method.

Figure 8 Transfer orbit to GEO duration in days

It has been recognized that, launch vehicle transfer orbit trajectory is very important. While performing orbit rising, number of Van Allen belt crossing should be taken into account. For sub GTO and GTO case, perigee altitude is one of the key parameter to avoid radiation belt and reach final GEO belt. For super GTO case both perigee and apogee altitude are important to minimize number of radiation belt cross and duration to reach final GEO. Satellite launch mass is also important parameters. If satellite is heavier for the same orbit and thruster configuration, both radiation belt crossing number and duration to final GEO altitude will increase.

Selected cases shows that higher perigee and higher apogee is the best to avoid harmful effect of Van Allen radiation belt. Satellite operator should decide which parameter is better for their technical and commercial targets. Depending on that decision, they may choose launch vehicle or ask launch vehicle provider for better transfer orbit trajectory.

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Biography

Dr. İbrahim ÖZ is consultant of Turksat Satellite Operations and Cable TV Incorporation. He worked for operations of Turksat Satellites, generating and uplinking digital television bouquet, procurement and program management of new satellites, satellite manufacturing test and acceptance as well as research, development and satellite design.

Prior to his current position, he was vice president of satellite operations. He worked as a satellite control and monitoring director of Turksat AS many years. He was responsible for operations of Turksat Communication Monitoring Centre to provide its customer continuous and reliable any kind of video, voice or data transmission via Turksat satellites.

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