SUN-SYNCHRONOUS ORBIT SLOT ARCHITECTURE
ANALYSIS AND DEVELOPMENT

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Abstract

Sun-Synchronous Orbit Slot Architecture Analysis and Development

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Space debris growth and an influx in space traffic will create a need for increased space traffic management. Due to orbital population density and likely future growth, the implementation of a slot architecture to Sun-synchronous orbit is considered in order to mitigate conjunctions among active satellites. This paper furthers work done in Sun-synchronous orbit slot architecture design and focuses on two main aspects. First, an in-depth relative motion analysis of satellites with respect to their assigned slots is presented. Then, a method for developing a slot architecture from a specific set of user defined inputs is derived.

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List of Acronyms

CV	control volume
GEO	geosynchronous Earth orbit
HPOP	High-Precision Orbit Propagator
LEO	low Earth orbit
MLT	mean local time
MOE	mean orbital elements
OOE	osculating orbital elements
RAAN	right ascension of the ascending node
RGT	repeat ground track
TLE	two line element
SRP	solar radiation pressure
STK	Satellite Toolkit
SSO	Sun-synchronous orbit

List of Symbols

a	semi-major axis
AT_{ROA}	along-track relative oscillation amplitude
A/M	area to mass ratio
BC	ballistic coefficient
C_D	coefficient of drag
C_R	coefficient of reflectivity
$\frac{da}{dt}$	altitude loss rate
e	eccentricity
i	inclination
J_2	second order zonal harmonic
J_3	third order zonal harmonic
N_{slots}	number of slots in altitude layer
P	period
R	radial
$R_{\oplus}$	radius of the Earth
R_{ROA}	radial relative oscillation amplitude
R/D	revolutions per day integer
t	time
T_{SK}	time between station-keeping maneuvers
α	along-track angle
Θ_{SK}	relative along-track sweep angle
θ	mean local time angle
μ	Earth's gravitational parameter
ν	true anomaly
ξ	cross-track angle
Ω	right ascension of the ascending node
ω	argument of perigee
ω_{rel}	relative angular velocity

Chapter 1

Introduction

There are currently over 22,000 pieces of tracked orbital debris in near-Earth space and tens of millions of untracked pieces of debris, with the majority in low Earth orbit (LEO). This population brings about the need for satellite operators to perform close approach or conjunction analysis and possibly maneuver to avoid high-risk collision situations.^{1,2} An expected expansion in space traffic, especially in the commercial sector, will cause an increased concern over the growing orbital debris population.³ If this space traffic increase occurs without the needed precautionary steps being taken, the debris growth rate could multiply due to collisions. These collisions would create more debris, eventually resulting in collisional cascading or the Kessler effect.

Currently, there is no regulation on satellite placement in Sun-synchronous orbit (SSO). New satellites can be placed into an orbit without consideration of other active satellites or pieces of debris. There are also no standards placed on station-keeping or collision avoidance maneuvers. The high inclination of SSO orbits causes satellites with similar semi-major axes but differing right ascension values to have intersecting orbit planes near both poles. Avoidance maneuvers

are not uncommon among high value active SSO satellites to avoid other active satellites and orbital debris. One way to reduce the frequency of avoidance maneuvers and the risk of collision is to place active satellites in strategic orbits and restrict the amount of allowable drift from that original orbit. Implementation of a slot architecture mitigates conjunctions among active SSO satellites. On an individual level, satellites would experience performance losses due to the discretized orbit parameters available and restricted motion. However, on a global scale the satellites would gain safety and stability from the mitigation of active satellite conjunctions and collisions.

This work creates a strategy for creating a useful SSO slot architecture without imposing unreasonable satellite requirements, as the architecture is developed from user defined inputs. Analysis completed in the process of establishing this strategy is also shared. The SSO dynamics, discussed in Section 2.1, cause any slot architecture applied to this region to be far more complex than the geosynchronous Earth orbit (GEO) binning method. This work is not claiming an immediate need for slot architecture implementation in SSO, rather it is to assist in developing such a framework should it be deemed necessary in the future. The largest hurdle to overcome in implementing a SSO slot architecture would be in getting international political buy in to the concept and to the implementation of it. First, SSO will be briefly introduced, including an analysis of the current population. Then, the proposed solution of a slot architecture will be discussed in more depth and analysis of SSO dynamics will be shown. The general slot architecture design process will be presented as well as a proposed specific slot architecture development process. Finally, the effects of a slot architecture on future missions will be discussed.

Chapter 2

Sun-Synchronous Orbits

2.1 Dynamics

SSO is one of the most frequently utilized orbits. Its popularity arises from a number of beneficial characteristics. Two attributes of SSO are a wide range of available altitudes and near polar inclination. This high inclination allows almost global latitude coverage. If desired, an altitude can also be selected to provide repeat ground tracks, which will be discussed later. One main benefit of SSO is its nearly constant Sun lighting condition, which is imperative in accomplishing some missions and also results in a relatively continuous thermal environment. This constant Sun lighting condition is accomplished by setting the nodal precession rate equal to the mean angular rate the Earth makes around the Sun, resulting in a constant angle between the orbit plane and the Sun, shown in Figure 2.1 as θ . The constant Sun lighting condition assumes the Earth has a circular orbit and that the Earth's equatorial plane is equal to the ecliptic plane. This idealization is accurate enough for a first order calculation.

Figure 2.1: Sun-synchronous orbit constant Sun lighting condition

The constant Sun lighting condition can be used to determine the inclination and eccentricity of the desired SSO using

$$\cos i = \frac{-2\dot{\Omega}a^{7/2}(1-e^2)^2}{3J_2R_{\oplus}^2\sqrt{\mu}} \quad (2.1)$$

where i is the orbit inclination, $\dot{\Omega}$ is the time rate of change of right ascension of the ascending node, a is the orbit semi-major axis, e is the orbit eccentricity, J_2 is the second order zonal harmonic, $R_{\oplus}$ is the Earth's radius, and μ is Earth's gravitational parameter.⁴ $\dot{\Omega}$ is set to the Earth's mean rotational rate around the Sun causing a constant Sun lighting condition. The eccentricity is often assumed zero in order to solve Equation (2.1) for orbit inclination given a chosen altitude. However, since circular orbits are not practical in reality, a frozen orbit is often used by SSO satellites to minimize the amplitude of oscillation of both eccentricity and argument of perigee (ω). The primary frozen orbit effect is the minimization of altitude variations. This is accomplished by using perturbation theory to set the J_2 and J_3 long period oscillations in e and ω equal to zero. The most common method of nulling the long period e oscillation is by setting

$\omega = 90^\circ$ or 270° . In this work $\omega = 90^\circ$. Then, the first order equation for zeroing argument of perigee oscillation is

$$e_o = -\frac{J_3 R_\oplus}{2J_2 a} \sin(i) \sin(\omega) \quad (2.2)$$

where J_3 is the third order zonal harmonic term.⁵ Equation (2.1) and Equation (2.2) can be used to solve for both the orbit inclination and eccentricity for constant Sun lighting condition and a frozen orbit using these approximate equations and a desired altitude. RAAN and true anomaly (ν) are the classical orbital elements remaining to be defined.

2.1.1 Mean Local Time

Mean local time (MLT) is a way of describing the constant Sun lighting condition of a particular SSO, θ in Figure 2.1. MLT is a direct transformation of right ascension of the ascending node (RAAN). This transformation is

$$MLT = \text{mod}_{24} \left\{ \frac{24hrs}{360^\circ} \left[\Omega + 180^\circ - \frac{360^\circ}{365.242199days} (\text{Days Since Vernal Equinox}) \right] \right\} \quad (2.3)$$

where MLT is in hours, Ω is RAAN in degrees, Days Since Vernal Equinox is simply the decimal number of days since the vernal equinox last occurred, and mod represents modular arithmetic with a modulus of 24. For example, a MLT of 12:00 means the satellite passes through its RAAN on the Earth-Sun line between the Earth and the Sun. In Figure 2.1 the orbit shown has a MLT of approximately 10:00.

2.1.2 Repeat Ground Tracks

One additional desirable characteristic is to have repeat ground tracks (RGT) by choosing a particular orbit altitude. With a RGT, after an integer number of revolutions (R) and an integer number of days (D) the satellite will begin to retrace its ground track pattern. Here, a day is defined as a nodal day, which is the time required for the Earth to rotate once with respect to the satellite's orbital plane. In general, a sidereal day is used to calculate RGT orbits, but for SSO the orbital plane makes one more rotation around the Earth per year. Therefore, for SSO, a nodal day is equal to a mean solar day. The common RGT notation is, for example, 2D29R which means that every two days and 29 revolutions the ground tracks will begin to repeat. The available RGT orbits within a desired altitude range are found from combining Kepler's third law

$$P = 2\pi \sqrt{\frac{a^3}{\mu}} \quad (2.4)$$

and

$$P = \frac{86400}{R/D} \quad (2.5)$$

with P being the period in seconds, 86,400 seconds per solar day, and R/D is the revolutions per day integer. This results in

$$a = \left(\frac{86400 \sqrt{\mu}}{2\pi R/D} \right)^{2/3} \quad (2.6)$$

Based on the requirement that there be an integer number of revolutions before the ground tracks repeat, the solution set is discrete. After the repetitive solutions are removed, for example 1D14R is the same RGT orbit as 2D28R, the

resulting RGT orbits in LEO are shown in Figure 2.2. This lobe pattern continues for both lower and higher altitudes, this range of LEO is shown because it is the most popular SSO region. It can be seen that as the number of RGT days increases the solution density rises. There are also a large amount of solutions for every prime number value of days because there are fewer duplicate solutions.

Figure 2.2: Repeat ground track orbits

2.2 Current Population

To better understand the SSO situation the current population is briefly analyzed. Some of the precise information on current active satellites and debris is either unavailable to the public or unknown, so the data presented is approximate.

2.2.1 Space Debris

Orbital debris in near-Earth space is consistently growing as shown in Figure 2.3. The few known collisions between large objects have dramatically increased the amount of debris. If these collisions continue, the Kessler effect would take over and eventually near-Earth space would be unusable. LEO, including SSO, has a relatively dense orbital debris population due to the low altitude and high satellite density.

Figure 2.3: Growth of Earth orbiting space objects¹

2.2.2 Active Satellites

Approximately half of active satellites are located in LEO and of those, about 44% are in SSO.⁶ Figure 2.4 displays the clustering of active SSO satellites at certain altitudes and MLTs showing an overall preference for certain altitudes and MLTs throughout the regime.

Figure 2.4: Sun-synchronous orbit active satellite population⁷

A recent study including 201 active SSO satellites and no orbital debris, using two line elements (TLE) and the SGP-4 propagator,⁸ found 103 unique conjunctions involving 61 different satellites over the course of just 5 days. Here a conjunction is a close approach including an object of interest, and is strictly defined as any breach by another object of an elliptical threat volume with an along-track dimension of 25 km, cross-track dimension of 25 km, and radial dimension of 2 km.⁶

An increase in space traffic would certainly impact the population of the SSO regime. If the current lack of organization and regulation continued, the occurrence of conjunctions would grow and therefore the risk of a collision in SSO would also rise. A lack of orbit organization not only increases the risk of collision, but more commonly it causes a need for conjunction analysis and collision avoidance maneuvers (both costly), even between two active satellites.

2.3 Mission Design Parameters

SSO mission designers have two main design parameters to select, altitude and MLT. From these two parameters, along with the assumptions of SSO condition and a frozen orbit, the SSO is defined excluding true anomaly. Altitude selection is the only factor that determines the RGT characteristics and therefore relates to a number of mission requirements including distance to Earth, access frequency, and distance between adjacent ground tracks. The optimal RGT solution for a particular mission is a systems level trade mainly between access frequency and distance between adjacent ground tracks. If a RGT orbit is chosen with a small number of revolutions between ground track repeat there will be a short time between target access. However, this orbit will also have a larger distance between adjacent ground tracks, possibly requiring a large sensor swath width. Altitude also effects orbital perturbations, as lower satellites in general have higher drag causing more frequent station-keeping to maintain the required altitude.

MLT selection should be influenced by payload, thermal, and power requirements. The Sun shadow of the image is directly affected by MLT selection as is the time the satellite spends in Sunlight and eclipse. Reference 4 is a valuable source for SSO mission parameter selection.

Chapter 3

Slot Architecture Concept

The proposed solution in this work is a SSO slot architecture that will define regulations that separate and organize SSO satellites in order to mitigate conjunctions among active satellites without imposing prohibitive requirements. The slot architecture idea is similar to that in place for GEO satellites. However, when applied to the Sun-synchronous regime, the more complicated astrodynamics do not allow for a simple and intuitive solution such as dividing up a circular area as in GEO. Not only is the nominal location of each slot defined by the slot architecture, the allowable volume around this nominal location for a satellite assigned to a slot is also specified.

3.1 Slot Definition

A slot is the idealized location of the satellite assigned to that particular slot at a given time.

3.1.1 Slot Classical Orbital Elements

In order to develop a slot architecture, each slot must have its six orbital elements strictly defined. This slot architecture definition strategy is similar to that proposed in Reference 9, discussed in Reference 10, and defined in Reference 6. For each particular slot, the semi-major axis and MLT (therefore RAAN) are determined. Then, the inclination, eccentricity, and argument of perigee are set as needed to satisfy Equation (2.1) and Equation (2.2) for the SSO nodal precession rate and frozen orbit (with $\omega = 90^\circ$). Finally, ν is defined by

$$\nu = 2\Omega \tag{3.1}$$

in order to allow spacing at the orbital intersection points located near the poles.⁶ Without this rule determining ν , active satellites in the architecture could possibly be in conjunction at orbital intersection near the poles.

3.2 Slot Motion

Now that the slot locations are defined at some epoch, it is necessary to describe their motion to define the slots through time. In order to have a maintainable slot architecture without degradation, slot motion needs to be defined as idealized motion. In fact, the simplest motion possible that still retains the characteristics of the SSO regime is used. Slots are defined as moving according to simple two-body motion with the exception of a constant nodal precession rate equal to the mean rotational rate of the Earth around the Sun. This results in simple unperturbed repeating motion.

3.3 Control Volume

The volume around the slot in which the satellite is to remain is here defined as the control volume. A control volume can be defined in any number of ways such as an ellipsoid, sphere, cube, etc. The key concept is that the control volume is defined around each slot so that no two control volumes intersect. With this accomplished and all satellites remaining within their assigned control volumes, separation among active satellites is guaranteed. Control volumes are determined to be continuously separated either through analytical or numerical analysis. The relative motion between a satellite and its slot should be considered in designing the control volume in order to have the satellite remain within its control volume with a reasonably small amount of control and station-keeping. Within any slot architecture if just one satellite drifts too far away from its assigned slot location there could be separation loss leading to conjunction. Therefore, it is important to keep active SSO satellites within their assigned control volumes. Determining control volume shapes and dimensions will be discussed in Sections 5.1 and 6.1.2.

Chapter 4

Satellite Motion Relative to Slot

Actual satellite motion will be much more complicated than the greatly simplified slot motion. The following is an analysis of this relative motion using a two-body with added Sun-synchronous nodal precession rate propagator of the slot motion (this will be used to propagate slot motion throughout this work) and Satellite Toolkit's (STK) High-Precision Orbit Propagator (HPOP) with different levels of fidelity to propagate the satellite motion.¹¹ It is clear that the satellite will never stay at the slot location through time due to the simplified slot motion. This analysis of the relative motion between the satellite and slot will help determine both appropriate slot architecture dimensions and the dimensions of the volume around the slot within which an assigned satellite is to remain for guaranteed separation.

4.1 Analysis Method

HPOP has the ability to include or ignore certain perturbations during satellite propagation. For example, HPOP could be used as a simple two-body prop-

agator if every perturbation was disabled or it can be one of the highest fidelity propagators when many more perturbations are included in the analysis. For this work, the perturbations included begin at a minimum and are slowly increased once the resulting relative motion is understood, building from simple cases to more complex ones.

Relative motion is described using a unique coordinate system. The three defining dimensions are centered at the slot and are radial (R), along-track angle (α), and cross-track angle (ξ). The radial dimension is simply the distance from the center of the Earth with outward being the positive direction and the measurement originating at the slot. The radial dimension is calculated using

$$R = R_{sat} - R_{slot} \quad (4.1)$$

where R is the relative coordinate system radial dimension, R_{sat} is the distance the point of interest (normally satellite) is from the center of the Earth, and R_{slot} is the distance the slot is from the center of the Earth. The along-track angle is the angle from the slot in the slot radial-velocity plane with the velocity direction being positive. The cross-track angle is the angle from the slot in the cross-track direction with a right hand coordinate system being the positive direction. Along-track and cross-track angle are calculated using

$$\alpha = \sin^{-1} \left\{ \left[\left(\hat{R}_{slot} \times \hat{V}_{slot} \right) \times \hat{R}_{slot} \right] \cdot \hat{R}_{sat} \right\} \quad (4.2)$$

$$\xi = \sin^{-1} \left\{ \left[\hat{R}_{slot} \times \hat{V}_{slot} \right] \cdot \hat{R}_{sat} \right\} \quad (4.3)$$

where $\hat{R}_{sat}$ is the unit vector of the location of interest, most commonly the satellite. A diagram showing this coordinate system is shown in Figure 4.1

Figure 4.1: Radial (R), along-track angle (α), cross-track angle (ξ) relative coordinate system

Since slots are defined at epoch and propagated using two-body dynamics, the slots are initialized by their mean orbital elements (MOE). However, with the inclusion of perturbations on satellite propagation, MOEs lose their meaning. They are replaced by osculating orbital elements (OOE) which are constantly varying because of the perturbation effects. OOE are often called instantaneous orbital elements because it is the instantaneous transformation of the position and velocity to orbital elements. If the satellites are not properly initialized at epoch they will quickly drift away from the slot, which is not desired. Rather, the goal is to initialize the satellites to match the slot motion as closely as possible

(minimal drift) and then analyze the resulting dynamics caused by particular perturbations through time.

The satellite initialization method arrived upon is not intuitive, rather it stems from a combination of research and ad hoc approaches stemming from the analysis. The perturbation with the largest impact on satellite initialization to a slot is the secular argument of latitude (sum of ω and ν) drift caused by high-order gravity effects. Slot motion does not include the secular argument of latitude drift that satellites experience. This difference is managed by setting the satellite to a slightly lower altitude, resulting in a shorter satellite period that, when coupled with the negative secular argument of latitude effect, matches to the period of the slot.

First, a second order transformation from MOE to OOE is used following Reference 12. With only high-order gravity propagation, differences between the second order MOE to OOE transformation and the much higher-order gravity field cause the slot and satellite to have slightly (but very noticeably) different periods and a quick along-track separation. This drift is partially caused by the secular argument of latitude drift mentioned above. To rectify this, period matching is performed where both the slot and satellite are propagated for a few periods, again using high-order gravity for satellite propagation, and the period is found for each. The satellite semi-major axis is then iterated until the periods match within an acceptable tolerance. Still, most likely due to the complex dynamics of a high gravity field, it was found that only the satellites that were initialized near the equator did not have quick along-track separation. The final solution was to initialize the satellites at their descending node immediately prior to the common epoch time. This means each satellite is initialized to its slot near the equator at times before epoch and propagated to a common epoch

slot architecture beginning time. This initialization method is not optimal, but is sufficient for the analysis contained in this work.

For this chapter two separate altitude levels at 500 and 800 km are analyzed with 24 satellites and their slots per level distributed every hour in MLT (totaling 48 satellites). This is shown in Figure 4.2, in each altitude layer the satellites adjacent each other in MLT, and therefore also ν , are connected by an arch. If the altitude layers were more densely populated the satellites would create this same pattern, but would be more tightly packed with additional satellites inserted along the arches. Each flight level forms a pattern similar to the seams on a baseball. Each case is run from September 1, 2011 to October 31, 2011. The relative motion of each satellite with respect to its slot is very similar throughout an altitude layer. One representative satellite is chosen and its relative motion with respect to its slot is analyzed. The representative satellite is chosen to be the one with MLT of 17:00 by visually inspecting a large amount of the satellites in each flight level and choosing one which has about average relative motion. Again, all satellites at a particular altitude have very similar relative motions. In general, the following analysis can be extrapolated and applied to architectures different than the exact one analyzed here.

4.2 Drag Perturbation Only

First, the effect of drag is analyzed by propagating satellites with two body gravity and drag. The satellite drag parameters used are a coefficient of drag (C_D) of 2.2 and area to mass ratio (A/M) of $0.0069 \text{ m}^2/\text{kg}$. These values were chosen to be relatively average values from Reference 13. These values result in a ballistic coefficient (BC) of 65.9 kg/m^2 . Using estimated values is not ideal, but they are

Figure 4.2: Relative motion analysis slot architecture

reasonable estimates and the important take away from this analysis is the general relative motion and order of magnitude results. The drag model used assumes a cannonball model with no attitude effects on drag. The STK built in Jacchia-Roberts atmosphere density model is used and the solar intensity measured at a wavelength of 10.7 cm, known as the F10.7 index, is shown in Figure 4.3. After June 2010 the built in density model used transitions from actual recorded data to predicted values, the smooth predicted curve is noticeable. The majority of the analysis takes place at the second red highlighted line in Figure 4.3. The solar cycle is at a mid-level during this 2011 propagation and is at a high intensity during the first highlighted portion in 2001. Some analysis is done at this high solar cycle time period and compared to the mid-level analysis. This solar cycle does not follow the normal approximately eleven year cycle. Solar intensity alters the atmosphere and density dramatically, from solar minima to solar maxima it can have an effect of approximately two orders of magnitude.¹³ Table 4.1 shows the differences in altitude decay for satellites analyzed at both 2001 and 2011 at multiple altitude levels.

Figure 4.3: Solar intensity measured at 10.7 cm wavelength

Table 4.1: Altitude loss at several mean altitudes averaged over 60 days for both September-October 2001 and September-October 2011

	Mean Altitude [km]			
	400	500	700	900
Year	Mean Altitude Loss [km/s]			
2001	6.9E-6	1.7E-6	1.4E-7	2.1E-8
2011	2.3E-6	4.4E-7	2.6E-8	4.4E-9

The main effect of drag is altitude decay. Figure 4.4 shows the effect of drag on the satellite with respect to slot relative motion for a satellite at 500 km altitude. The top graph in this figure shows the difference between the slot and satellite semi-major axis. Initially, the satellite and slot have equal semi-major axes, but as drag causes altitude decay, the satellite drops below the slot. As the satellite drops below the slot it speeds up due to Kepler's third law. This causes the satellite to drift in front of the slot in the along-track direction as seen.

Figure 4.4: Along-track drift with altitude loss of a 500 km altitude satellite

4.3 High-Order Gravity Perturbation Only

The satellite's relative motion with respect to its slot is analyzed using only a high-order gravity field (WGS84 EGM96 70x70 without tides) for satellite propagation. As expected from perturbation theory there are both short and long period as well as secular effects of the high-order gravity field compared to the slot motion. The general short period motion is depicted in Figure 4.5. This short periodic motion shows the satellite will (as expected) not remain at the slot location through time, but rather the satellite will make an ellipse relative to the slot. The satellite is in front of the slot ($+\alpha$) at its descending node, above the slot ($+R$) when near the South Pole at apogee, behind the slot ($-\alpha$) at its ascending node, and below the slot ($-R$) near the North Pole at perigee. The characteristics of this elliptical oscillating motion will be useful in determining both the shape and dimensions of the control volume and the overall slot architecture.

Figure 4.5: General satellite circling slot motion

The representative satellite chosen here is at an altitude of 500 km and a MLT of 17:00. In Figure 4.6 the relative motion is shown over the course of one day in order to display the short period motion. The motion in all three axes has the same period as the satellite’s orbit and all oscillate around zero, which is the slot location. The along-track motion has the highest initial amplitude of about 17 km. It is interesting to note the radial motion amplitude is approximately 9 km as predicted by perturbation theory and short period oscillations in semi-major axis for the SSO regime.^{5,12}

The relative motion of the same representative satellite is shown for the entire 60 day analysis period in Figure 4.7. The same short period oscillations are present, but are mostly unidentifiable; due to the long time frame shown they appear as one thick line. Some long period and secular effects can be seen with this extended time frame. The relative motion in the radial dimension is complex due to long period and secular perturbations. The radial axis oscillations visibly vary through time and do not have a zero average value, resulting in a slight dif-

Figure 4.6: The angular relative motion of one satellite at 500 km altitude and a MLT of 17:00 with respect to its slot over 24 hours with only high-order gravity field propagation

ference in mean semi-major axes. Differing semi-major axes between the satellite and slot results in slightly different periods and therefore along-track drift which can be seen in Figure 4.7.

Cross-track oscillation amplitude is growing linearly. This satellite was propagated for six months using the same conditions and the cross-track oscillation amplitude growth continued at the same rate. This mostly rules out a long period cause and points to secular perturbation. The effects are extremely similar at different altitude layers, with the exception of slight amplitude decrease with altitude increase as the effects of Earth's oblateness lessen at higher altitudes. This

Figure 4.7: The angular relative motion of one satellite at 500 km altitude and a MLT of 17:00 with respect to its slot over 60 days with only high-order gravity field propagation

analysis shows that without control a satellite would stray from an assigned volume around its slot given enough time even when the satellite is only propagated using a high-order gravity field.

4.4 High-Order Gravity and Drag

This analysis combines drag and high-order gravity for satellite propagation. These are the two largest perturbations on LEO SSO satellites.

The same representative satellite is chosen as in the gravity-only case above. There is no noticeable difference in the short period relative motion over 24 hours

when drag is added, however the effects of drag are major when viewed over a longer time. Figure 4.8 shows the relative motion of this one representative satellite for 60 days. As expected, the inclusion of drag causes the satellite to lose altitude, speed up, and drift away from the slot in the positive along-track direction. Compared to the relatively large short period radial oscillations the altitude loss over 60 days is small and not visually obvious. Along-track drift, however, is quite large, showing that just a small altitude difference from slot altitude results in substantial along-track drift. The cross-track motion is not noticeably changed with the inclusion of drag. Cross-track oscillation amplitude growth no longer is the main concern as in gravity-only analysis. Along-track drift grows much quicker with drag included.

Figure 4.8: The angular relative motion of one satellite at 500 km altitude and a MLT of 17:00 with respect to its slot over 60 days with high-order gravity and drag included in propagation

4.5 High-Order Gravity, Drag, Solar Radiation Pressure, and Lunisolar Third Body Effects

The final relative motion analysis included adds solar radiation pressure (SRP) and lunisolar (Moon and Sun) third body effects to the high-order gravity and drag perturbations. Similar to drag, the SRP parameters, coefficient of reflectivity (C_R) and A/M were estimated using Reference 13 to be $C_R = 1.4$ and $A/M = 0.0069 \text{ m}^2/\text{kg}$. STK's spherical cannonball model was used with a dual cone shadow model for SRP.

Again, the same representative satellite was chosen and there are no noticeable changes from the high-order gravity case when viewed over one day, however there are some slight differences over a longer time. This is shown in Figure 4.9, which is very similar to Figure 4.8 except perhaps that there appears to be more chaotic and less obviously periodic motion on the shorter time scale. However, the trends of satellite altitude loss leading to along-track drift and increasing cross-track oscillation amplitude are the same with the inclusion of SRP and lunisolar third body effects.

There are slightly larger effects of SRP and lunisolar effects at higher altitudes because both drag and high-order gravity effects are weaker at higher altitudes. These differences are hardly noticeable, drag and high-order gravity are by far the largest perturbations.

The short period oscillatory relative motion was analyzed at different altitude levels and the average amplitude of oscillation is shown in Table 4.2.

Figure 4.9: The angular relative motion of one satellite at 500 km altitude and a MLT of 17:00 with respect to its slot over 60 days with high-order gravity, drag, solar radiation pressure, and lunisolar third body effects included in propagation

Table 4.2: Satellite about slot relative motion for radial and along-track oscillation amplitude at several altitude levels

	Mean Altitude [km]			
	400	500	700	900
Dimension	Oscillation Amplitude [km]			
Along-Track	16.1	15.9	15.7	15.6
Radial	8.0	8.0	7.9	7.8

4.6 Chapter Conclusion

This chapter shows and discusses both the short and long term effects of different perturbations and allows a better understanding of satellite with respect to slot relative motion. The natural long term effects of drag, altitude decay and along-track drift will be taken into account by control volume shape and dimensions so unnecessarily stringent requirements are not placed on satellites. The short period relative motion will also have an effect on control volume development. The oscillation amplitude, such as the values in Table 4.2, will have a direct effect on needed control volume size.

Chapter 5

General Slot Architecture Design Process

There is no explicit or analytic optimal slot architecture to apply to the SSO regime. This stems from the subjectivity of the important parameters in question. What is an adequate number of SSO slots? What altitudes and RGT values are most useful? What approximate station-keeping frequency is reasonable? There is no obvious optimal answer that will result in the highest level of utility for the most SSO satellites in the future without imposing overly strict requirements. Some slot architecture design inputs are subjective due to this. A design flow diagram is depicted in Figure 5.1 and will be discussed in detail in the following sections.

There are some basic relationships governing this design process. A tradeoff exists between the level of requirements placed on satellites and the number of satellites available within an architecture. Large control volumes give a satellite more freedom of motion and therefore an increased time between station-keeping,

along with greater orbital freedom. However, in order to maintain continuous separation, large control volumes result in a smaller number of available slots. Strictly defined sets of desired mission parameter availabilities will also result in a smaller number of slots. For example, if there are certain flight level altitudes that must be included they might not be accommodated without reducing the number of flight levels for a given altitude range of a slot architecture.

5.1 Control Volume Development

The control volume is the foundation of a slot architecture. Control volume dimensions are determined from the nominal satellite parameters, study of satellite motion relative to slot, and individual slot parameters. All three of these inputs can be customized per altitude level or even per slot. The key feature of control volumes is continual separation. This in turn guarantees no satellite collisions, assuming satellite control volume compliance.

5.2 Flight Level Selection

Once control volume dimensions are determined, a slot architecture is developed by specifying slots and control volumes to guarantee continual separation and meet the desired mission parameter availability. The total altitude range of the slot architecture needs to be divided into altitude bins or flight levels. Flight levels are chosen to satisfy the control volume separation constraint and to meet desired mission parameter availability, such as repeat ground tracks.

5.3 Mean Local Time and True Anomaly Selection

For an individual flight level the location of the slots within must be determined. In Equation 3.1, Ω and ν are directly related. Since MLT is a transformation of Ω , MLT and ν are related. First, the minimum along-track angle separation is determined. Then, the most desirable discretization of MLTs are found and the corresponding Ω and ν calculated. MLT and ν are selected to satisfy the control volume separation constraint and to meet desired mission parameter availability.

Figure 5.1: General slot architecture design flow

Chapter 6

Proposed Slot Architecture Design

The general design process presented above is further distilled through relative motion analysis to a more user friendly form that simply requires user input to arrive at a slot architecture. Then, the design process is shown on an example slot architecture. The important aspect is not the slot architecture arrived at in the example, but rather the demonstration of the design process. Altering input parameters would result in a different slot architecture. This process is derived to allow for ease of slot architecture creation from a set of decided input parameters. Ultimately, an empowered body could use this design process to create a SSO slot architecture after performing an in-depth study of appropriate inputs.

6.1 Proposed Process

6.1.1 Nominal Design Satellite Parameters

Several nominal satellite parameters are inputs to the design process. Control volumes and the slot architecture are designed to have an optimal shape for these parameters, resulting in simply sub-optimal design for satellites with differing parameters. For example, a satellite with parameters other than those input into the architecture design would not take advantage of the entire control volume and would therefore not have a minimum station-keeping frequency as desired. The input parameters, customizable to each flight level, are slot semi-major axis (a_{slot}), time between station-keeping maneuvers (T_{SK}), altitude loss rate ($\frac{da}{dt}$), relative motion oscillation amplitude, and margins.

In this process, control volume dimensions are designed per flight level and input parameters are specified per flight level. The slot mean altitude or semi-major axis is needed to specify the particular dynamics of a flight level. However, the need for a_{slot} in control volume dimension determination means the process is iterative. In general, flight level mean altitudes will not be known until after the slot architecture is designed. Flight level minimum separation is a direct result of the radial control volume dimension. The radial control volume dimension decreases as the flight level semi-major axis increases.

Time between station-keeping maneuvers is the designed time a satellite will be able to drift uncontrolled before it must burn to remain compliant with the control volume. This parameter is defined for each flight level and will hold relatively accurate for a satellite having similar parameters to the input satellite parameters, most notably, for a satellite experiencing an altitude loss rate equal

to that input. Station-keeping frequency is mainly dependent on control volume dimensions and altitude, solar cycle level, and satellite ballistic coefficient. These variables are merged into nominal altitude loss rate that will be used to design the control volume dimensions.

Some specific relative motion characteristics between the satellites and slots at a given flight level are also user defined inputs. The short period oscillation amplitude in both the radial and along track dimensions are needed, which are both directly found from the satellite with respect to slot relative motion analysis.

Lastly, specific margins will be needed in order to cover the simplifying assumptions made and to provide a buffer zone. Margin is used to meet the desired input parameters, such as time between station-keeping maneuvers, under real world satellite motion and needs to be applied to all three control volume dimensions. Margins will be discussed in more detail in Section 6.2.1.

6.1.2 Control Volume Development

Control volume shape and dimension development are the first steps, and the first building blocks, of the architecture design process. Both the nominal design satellite parameters mentioned above, as well as an understanding of the satellite with respect to slot relative motion, are used in control volume development.

Altitude Decay and Along-Track Drift

The largest nonconservative force acting on the majority of satellites in a SSO slot architecture is drag. If the control volume is shaped and sized correctly, perturbations from conservative forces such as high-order gravity can be accommodated. However, drag will cause the satellite to drop below the slot in the

negative radial direction due to altitude decay. From Kepler's Third Law, Equation (2.4), the satellite will drift in the along-track direction due to this altitude decay and resulting satellite velocity increase. The effect of a satellite's velocity increasing due to drag is often referred to as the drag paradox.

Shape Definition

Control volume shape is defined to accommodate both high-order gravity caused oscillations and along-track drift. The relationship between radial and along-track motion is used in order to design the control volume to be the appropriate size to allow for the along-track angle drift associated with the expected radial altitude loss. The shape is formed around the general periodic satellite motion depicted in Figure 6.1, and shown for an example satellite propagated with only two body gravity and drag at 500 km altitude in Figure 6.2 and Figure 6.3. These figures show the satellite motion with respect to its slot without the short period oscillatory high-order gravity effects.

Figure 6.1: Diagram of along-track drift with radial altitude loss

Figure 6.2: Satellite at 500km altitude propagated with 2-body dynamics and drag drifting in the along-track direction within control volume while dropping in altitude

In order to best utilize the space around an assigned slot, a satellite is initially placed at a location in front ($+\alpha$) and above ($+R$) the slot. Initially, from having a higher semi-major axis, the satellite has a longer period and therefore slower orbital velocity. This causes the satellite to drift in the $-\alpha$ direction with respect to the slot, toward the back of the slot. As satellite altitude decreases, the difference between satellite and slot orbital velocity decreases. When the satellite semi-major axis becomes equal to that of its slot, the satellite is located at the $-\alpha$ portion of its control volume. This motion continues in the opposite fashion as the satellite velocity increases higher than its slot and drifts to the $+\alpha$ and $-R$ corner of the control volume. At this point, the satellite would leave the control volume if allowed to keep drifting and therefore must perform a station-keeping, altitude raising maneuver. This altitude decay and along-track drift process will

Figure 6.3: Satellite at 500km altitude propagated with 2-body dynamics and drag drifting in the along-track direction within control volume while dropping in altitude

then begin again.

Additionally, the high-order oscillatory motion is accommodated by increasing the control volume dimensions by the amplitude of these oscillations. In order to utilize the space in SSO as efficiently as possible, a unique control volume shape has been arrived at and is shown in Figure 6.4. A flight level of slots forms a shell around the Earth at an altitude equal to the mean altitude of the flight level and slightly skewed from the frozen orbit eccentricity. The proposed control volume shape is a section of this flight level shell. The three defining dimensions are centered at the slot and are radial (R), along-track angle (α), and cross-track angle (ξ). The control volumes will then be placed in an order that best utilizes the available space without intersection.

Figure 6.4: Proposed control volume shape (green) shown around slot (blue)

Dimension Functions

The control volume dimensions are derived as functions of the input parameters given in Section 6.1.1. Margin should be added to these calculated control volume dimensions, as some simplifying assumptions are made during derivation. First, assuming a constant altitude decay rate and constant amplitude of the radial relative oscillation from high-order gravity, the radial dimension is derived to be

$$R_{CV} = \frac{da}{dt} \frac{T_{SK}}{2} + R_{ROA} \quad (6.1)$$

where R_{ROA} is the radial relative oscillation amplitude between the satellite and slot. From the definition of mean motion and an assumption of a constant altitude decay rate, the relative angular velocity of a satellite with respect to its slot is determined to be

$$\omega_{rel} = \sqrt{\frac{\mu}{(a_{slot} - \frac{da}{dt}t)^3}} - \sqrt{\frac{\mu}{a_{slot}^3}} \quad (6.2)$$

where t is the time from initialization with the satellite and slot having equal semi-major axes. Integrating this relative angular rate equation with respect to time from zero to half the desired station-keeping time, $\frac{T_{SK}}{2}$, an equation for the along-track angle drift for a period of time, T_{SK} , is derived.

$$\Theta_{SK} = \sqrt{\mu} \left[\frac{2}{\frac{da}{dt} \sqrt{a_{slot}} - \frac{da}{dt} \frac{T_{SK}}{2}} - \frac{2}{\frac{da}{dt} \sqrt{a_{slot}}} - \frac{T_{SK}}{2a_{slot}^{3/2}} \right] \quad (6.3)$$

The angle Θ_{SK} is the total along-track angle the satellite will sweep through over the course of its drift between station-keeping maneuvers. This equation is validated and its accuracy studied through comparison with STK analysis. Satellites are initialized above ($+R$) and in front ($+\alpha$) of their slots and propagated with two body gravity and drag only. The altitude loss rate is determined by averaging the altitude loss over the 60 day analysis period specified by T_{SK} . The analysis is done over the 2011 propagation time period, the altitude loss rate values are shown in Table 4.1. The along-track angle the satellites moves through in the time given by T_{SK} in an STK HPOP simulation is then compared with the predicted angle from the equation. The results are displayed in Table 6.1

Table 6.1: Along-track drift angle equation validation

Mean Altitude [km]	400	500	700	900
Equation Predicted [deg]	114.3	20.4	1.11	0.176
STK Analysis [deg]	113.2	20.8	1.13	0.178
Percent Difference [%]	0.89	1.9	1.5	1.0

Assuming the along-track relative oscillation amplitude angle, AT_{ROA} , is constant, the along-track angle control volume dimension is found as

$$\alpha_{CV} = \frac{\Theta_{SK}}{2} + \tan^{-1} \left(\frac{AT_{ROA}}{a_{slot}} \right) \quad (6.4)$$

The radial and along-track control volume dimensions are both calculated by combining the nominal design satellite parameters, satellite with respect to slot relative motion analysis, and slot semi-major axis. The tradeoff between number of slots per flight level and severity of station-keeping requirements placed on the satellite is apparent here. However, the cross-track angle control volume dimension is independent and is instead determined to be the maximum possible value while still guaranteeing control volume separation. A larger cross-track angle control volume dimension results in a larger available drift in MLT. The limiting case is at the near pole crossings where slots are moving in opposite directions relatively near each other. This cross-track angle dimension is found by

$$\xi_{CV} = i_{slot} - 90^\circ \quad (6.5)$$

The inclination of a slot is defined by the slot semi-major axis, Sun-synchronous condition, and frozen orbit requirement. Control volumes are designed using the above equations and the user defined input parameters. This process is shown in Figure 6.5.

6.1.3 Flight Level Selection

The desired altitude range of the slot architecture must be determined from desired mission parameter availability. The altitude range of the slot architecture will have to be discretized into the separate flight levels. Flight level selection should be done in order to ensure control volume separation and to make available the desired mission parameters, such as repeat ground tracks. The radial control volume dimension plays an important role in flight level selection. The minimum

Figure 6.5: Proposed control volume design flow

altitude separation between levels is equal to the sum of the radial control volume components of the two flight levels. If a radial buffer between control volumes is desired, it could be added here. Besides meeting this minimum flight level separation, desirable altitudes for missions need to be considered. Desirable RGT altitudes should be available to mission designers. The appropriate flight levels for a particular SSO slot architecture are subjective, and are a set of user inputs of desired mission parameter availability.

6.1.4 Mean Local Time and True Anomaly Selection

There could potentially be an optimal MLT discretization for each flight level. This discretization would be based on desired mission parameter availability. Slots would still comply with the polar timing rule, Equation 3.1. However, in

order to fit the maximum number of slots per flight level and for simplicity, here slots are evenly spaced in both MLT and ν .

In order to determine MLT and ν , the number of slots per altitude layer must first be found, using

$$N_{slots} = \left\lfloor \frac{360}{\alpha_{CV}} \right\rfloor \quad (6.6)$$

where the lower closed brackets represent rounding down the enclosed number to the nearest integer toward zero, or floor. If a buffer distance between control volumes in the along-track direction is desired it could be added here, reducing the number of slots per altitude layer. Then, MLT is evenly spread from 00:00:00 to 24:00:00 from

$$MLT_i = \frac{24}{N_{slots}}(i - 1) \quad (6.7)$$

where i is the slot number at the given particular flight level. From the polar crossing rule, Equation 3.1, the ν of each slot is found by

$$\nu_i = 2(MLT_i) \quad (6.8)$$

Now all the parameters of each slot are determined and the slot architecture is complete.

6.2 Design Example

A slot architecture is designed here using the process described above. This architecture is by no means the optimal architecture. This architecture is included

as an example demonstrating how the above process is used and showcasing trends within the design process. Every slot architecture developed using this method is a direct result of the input parameters. In order to find a near optimal slot architecture an in-depth analysis would need to be conducted on those input parameters. In this case, input definition is not a result of lengthy analysis, but rather from rules of thumb, estimation, or arbitrary selection.

6.2.1 Nominal Satellite Parameter Selection

Every nominal satellite parameter can be customized for each flight level. However, in this example some parameters are defined across the entire architecture. The selected range of the slot architecture is decided to be 400 to 900 km altitude. This altitude range encompasses the most popular SSO altitudes as is shown in Figure 2.4. Station-keeping time, T_{SK} , is chosen to be 60 days at every flight level. This means a satellite at 900 km altitude will have to station-keep as often as a satellite at 400 km altitude in order to maintain control volume compliance. The altitude loss rate, $\frac{da}{dt}$, is found uniquely at each flight level. A Satellite at each altitude level is propagated in September and October of 2011, mid-range solar cycle level, with the same ballistic coefficient as in Section 4.2 and only two body gravity and drag. The altitude loss rate of each satellite is averaged over 60 days of propagation. Relative motion oscillation amplitudes are found from analysis, Table 4.2, and after some margin is added, they are assumed to be a constant 0.15 degrees along-track and 9 km radial. Margin was added to the along-track angle control volume dimension by adding 5% to Equation 6.3. The radial control volume is inflated by adding 20% to the altitude loss portion of Equation 6.1 to compensate for the constant altitude loss rate assumption. Margin is added to the derived equations as it is seen necessary from the STK analysis. Only a fraction

of the entire possible set of satellite and slot combinations were analyzed. Even though the relative motion is similar among those satellites and slots analyzed, margin is added to cover possible slight outliers. The STK analysis completed is also not real life motion, so margin needs to cover these differences. A large study should be conducted in order to appropriately determine the margin to add for a particular slot architecture.

6.2.2 Control Volume Dimension Development

The control volumes are developed for each flight level according to the equations in Section 6.1.2 and the input parameters directly above. Since the slot semi-major axis is needed in order to determine the control volume dimensions, this is an iterative process. First, an even distribution of flight levels are analyzed within the slot architecture altitude range. The control volume dimensions are calculated for these flight levels and the approximate control volume dimensions are noted as well as the trends of decreasing radial and along-track angle dimensions with altitude increase. Then, with the approximate control volume dimensions known, the flight levels are selected. With the flight levels selected, the exact control volume dimensions are calculated and any necessary flight level altitudes are altered. The resulting control volume dimensions are shown in Table 6.2. From these control volume dimensions the rest of the slot architecture will be formed.

6.2.3 Flight Level Selection

The minimum separation between two neighboring flight levels is the sum of the radial control volume dimensions of the neighboring flight levels. This

minimum separation along with a rough estimation of the most desirable RGT altitudes is used to determine the architecture flight levels. In an attempt to minimize the discretization performance loss on future missions within the slot architecture a wide range of RGT options are chosen. There is also an effort made to vary the number of RGT days in nearby altitude layers. This is done so a mission with some optimal RGT day number and altitude will take less of a penalty by meeting the mandatory discretization of the slot architecture. This system is not optimized, but the same concepts should be considered in any SSO slot architecture flight level selection. The flight levels selected as well as the day and revolutions before their ground tracks repeat are listed in Table 6.2.

It is worthwhile to note that the radial control volume dimension decreases with flight level altitude increase. Therefore, at lower altitudes there is more separation required between adjacent flight levels. Additional separation between layers above the sum of radial control volume dimensions acts as a buffer between flight levels.

6.2.4 Mean Local Time and True Anomaly Selection

The maximum number of slots were evenly spaced in MLT and ν for each flight level as in Section 6.1.4. The required spacing is a direct result of the along-track angle control volume dimension. Therefore, since at higher altitudes this control volume dimension is less, there are more slots per altitude layer. In this particular case, there is a dramatic difference with just six slots in the lowest level and 1463 slots in the highest flight level. The MLT and ν spacing can be seen per flight level in Table 6.3

Table 6.2: Proposed slot architecture example: repeat ground track and control volume dimensions

Repeat Ground Track Altitude			Control Volume		
Mean Altitude [km]	RGT [days]	RGT [revs]	R [km]	α [deg]	ξ [deg]
400.538	9	140	16.2	58.3	6.5
435.053	16	247	13.2	33.7	6.7
465.875	3	46	11.4	18.9	6.8
493.790	25	381	10.5	12.0	6.9
515.923	6	91	10.1	8.4	7.0
541.293	12	181	9.7	5.7	7.1
566.896	1	15	9.5	3.9	7.2
589.032	14	209	9.4	2.8	7.2
611.345	7	104	9.3	2.1	7.3
632.649	19	281	9.2	1.5	7.4
652.375	11	162	9.1	1.2	7.5
671.730	3	44	9.1	0.99	7.6
693.174	5	73	9.1	0.77	7.7
713.114	13	189	9.1	0.63	7.7
733.459	21	304	9.0	0.54	7.8
752.997	12	173	9.0	0.47	7.9
773.459	31	445	9.0	0.41	8.0
796.510	7	100	9.0	0.35	8.1
816.144	22	313	9.0	0.32	8.2
836.648	6	83	9.0	0.30	8.3
855.572	9	127	9.0	0.27	8.3
874.621	18	253	9.0	0.26	8.4
893.795	1	14	9.0	0.25	8.5

6.2.5 Slot Architecture Overview

The first three flight levels of this slot architecture example are shown in Figure 6.6. There are very few satellites at these low altitudes because of the input parameter of 60 days between station-keeping maneuvers and the relatively high drag at this altitude. Slots neighboring in MLT and ν are connected with arches to show the general SSO slot architecture geometry. The 566.896 km altitude layer is shown in Figure 6.7 and the baseball seam-like flight level geometry is apparent.

Table 6.3: Proposed slot architecture example: mean local time and true anomaly spacing

Mean Altitude [km]	MLT Spacing [hr:min:sec]	ν Spacing [deg]	Number of Slots
400.538	04:00:00	120	6
435.053	02:24:00	72	10
465.875	01:15:47	37.9	19
493.790	00:49:39	12.4	29
515.923	00:34:17	8.57	42
541.293	00:22:51	5.71	63
566.896	00:15:49	3.96	91
589.032	00:11:26	2.86	126
611.345	00:08:14	2.06	175
632.649	00:06:11	1.55	233
652.375	00:04:53	1.22	295
671.730	00:03:58	0.99	363
693.174	00:03:04	0.77	470
713.114	00:02:31	0.63	571
733.459	00:02:10	0.54	666
752.997	00:01:52	0.47	769
773.459	00:01:38	0.41	886
796.510	00:01:25	0.35	1019
816.144	00:01:17	0.32	1118
836.648	00:01:11	0.30	1216
855.572	00:01:06	0.27	1313
874.621	00:01:02	0.26	1400
893.795	00:00:59	0.25	1463
Slot Architecture Total Slots			12343

This example architecture is less than ideal. Constant time between station-keeping is used among all altitude layers and the flight level selection altitudes are based off little analysis of desired mission parameters. There are also a total of 12,343 slots within the architecture, which is almost surely more slots than are required. Control Volume size could be increased or the total slot architecture altitude could be decreased in order to reduce the number of slots and reduce the severity of satellite requirements.

Figure 6.6: First three layers of proposed slot architecture example

Figure 6.7: 566.896 km altitude layer of proposed slot architecture example

Chapter 7

Effect of Slot Architecture Implementation on Missions

Applying increased space traffic management to a regime in space benefits satellites on a global level, but can be disadvantageous for individual satellite performance. The benefit is the mitigation of conjunctions and possible collisions among active satellites, as well as order and stability. Both discretization of available mission parameters and position limitation are disadvantages for satellite mission planners.

7.1 Mission Design Parameter Discretization

As SSO currently is, there are no unavailable mission parameters. For example, a mission planner could place a satellite at any exact altitude, MLT, argument of perigee, eccentricity, and station-keeping scheme desired. The implementation of a slot architecture limits these available options through constraint and discretization. A particular optimal RGT orbit at a specific optimal altitude may

not be available for a satellite mission, which would result in suboptimal satellite performance.

7.2 Required Slot Maintenance

There are a number of satellites currently in SSO orbits that do not have propulsive capabilities. These satellites do not have stringent orbit requirements for completing their designed task. However, with the enforcement of a slot architecture, all SSO satellites within the altitude range of the architecture would be mandated to have station-keeping ability. This ability would also have some additional requirements placed on the satellite so it could maintain its assigned control volume.

Chapter 8

Conclusion

There is increasing space traffic including a growing satellite density in SSO. As the number of satellites and debris continues to rise, some form of space traffic management will be needed. The work presented here expands on the concept of implementing a slot architecture in SSO. The goal of the architecture is to mitigate conjunctions among active satellites in SSO through a position limiting organizational framework without imposing prohibitive requirements on satellites. Relative motion of satellites with respect to their slots was analyzed in order to provide a foundation for the appropriate design of a slot architecture design strategy. The control volume was developed as a satellite position limiting volume around slots in order to assure satellite separation. A general slot architecture development methodology was presented.

Finally, a proposed specific slot architecture design strategy was developed. This proposed strategy includes a specific control volume shape and derived equations for calculating control volume dimensions based on specific user defined input parameters. A flight level and MLT discretization strategy was presented to fully develop a slot architecture. Most importantly, a SSO slot architecture can

now be developed from a set of user defined inputs. In the future, if it is agreed upon as necessary, an empowered body would have a set of tools available to develop a SSO slot architecture. The analysis and architecture development tools presented could also possibly be used in deriving orbits and orbit maintenance requirements for a small constellation of satellites.

Chapter 9

Future Work

The two main aspects of this work, satellite about slot relative motion and a slot architecture development method, have areas of possible improvement. First, the relative motion could be further studied over a larger number of satellites with a variety of parameters. The performance of satellites with parameters other than those used to design the specific control volume could be further analyzed. This analysis would also give deeper insight into appropriate control volume dimension margins and buffers between control volumes. The proposed slot architecture development strategy could be improved by a superior flight level and MLT discretization method.

A slot architecture designed using the proposed strategy is purposefully entirely dependent on the user defined input parameters. An in-depth study of appropriate or optimal inputs would be extremely helpful for a group implementing a SSO slot architecture. However, the optimal set of input parameters is both partially subjective and evolving with time based on SSO mission requirements.

Two areas of further study that are absolutely necessary before implementing

a SSO architecture are radio frequency communication interference and insertion/extraction of satellites from the architecture. These are two very important concepts that must be considered before architecture implementation.

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