DEVELOPMENT OF AN ARCHITECTURE OF SUN-SYNCHRONOUS ORBITAL SLOTS TO MINIMIZE CONJUNCTIONS

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Sun-synchronous orbit (SSO) satellites serve many important functions, primarily in the areas of Earth reconnaissance and weather. The orbital parameters of altitude, inclination and right ascension which allow for the unique utility of Sun-sync orbit limit these satellites to a very specific region of space. The popularity of these satellite missions combined with the use of similar engineering solutions has resulted in the majority of current Sun-sync satellites within this region having very similar inclinations and altitudes while also spaced around the Equator in right ascension, creating the opportunity for conjunctions at the polar crossing points and a serious safety issue that could endanger long-term sustainability of SSO. This paper outlines the development of a new architecture of SSO zoning to create specific slots separating SSO satellites in altitude, right ascension and time at all orbital intersections while minimizing the limitations on utility. A methodical approach for the development of the system is presented along with the work-to-date and a software tool for calculating repeating ground track orbits. The slot system is intended to allow for continued utility of and safe operation within SSO while greatly decreasing the chance of collisions at orbital intersections. This architecture is put forward as one possible element of a new Space Traffic Management (STM) system with the overall goal of maintaining the safe and continued used of space by all actors.

I. Introduction

In the summer of 2007, a group of 117 students from 24 countries participated in the International Space University Space Studies Program, held in Beijing, China. A subset of 30 students worked on a team project on the subject of Space Traffic Management [1]. One of the concepts discussed as part of that paper is the feasibility of establishing a slot system for the Sun-synchronous region of Earth orbit, similar to that which is used in geostationary orbit. The goal of this paper is further examine the concept of SSO slots through a more rigorous treatment of the subject. In the process, several issues with the original SSO slot proposal in the ISU report will be discussed.

This paper outlines the current situation with regards to SSO, including that of both operational satellites and debris. From there it discusses the current solutions to the problem and how the slot concept works in conjunction with those. This paper then presents a methodology for designing the slot architecture, based on the unique mission design elements of SSO. Finally, it discusses the next steps to be taken and areas for further analysis. The intent of this paper is not to thoroughly explain the underlying orbital mechanics that create the utility of SSO, but rather to build on those concepts and discuss the issue of designing a slot architecture. The author suggests reading the excellent paper entitled “A-B-Cs of Sun-Synchronous Orbit Mission Design” by R. Boain for background on basic Sun-synchronous orbital mechanics and mission design concepts [2].

II. Current Situation in SSO

The primary entity tracking objects in Earth orbit is the United States Strategic Command’s Joint Space Operations Center (JSpOC) at Vandenberg Air Force Base, California. The JSpOC currently tracks man-made objects in Earth orbit, including both debris and operational spacecraft data is published publically in the satellite catalog on the Space Track website found at http://www.space-track.org. This catalog consists of objects greater than 10 cm in diameter, as this is the generally-accepted lower limit of current tracking capability [3,4]. As of 1 August 2007, out of the entire satellite catalog there were 4192 tracked objects in low Earth near-polar orbits, defined as objects with apogees less than 2,000 kilometers and inclinations between 96.5 and 102.5 degrees [2]. Of these, approximately 138 were active satellites [2]. The region bounded by the aforementioned inclination and altitude ranges will be used in this paper to define the SSO region of Earth orbit. Fig. 1 through 4 below were developed using the data from the Space Track catalog and show the distribution of all near-polar objects and all active satellites, respectively, as a function of this inclination and altitude.

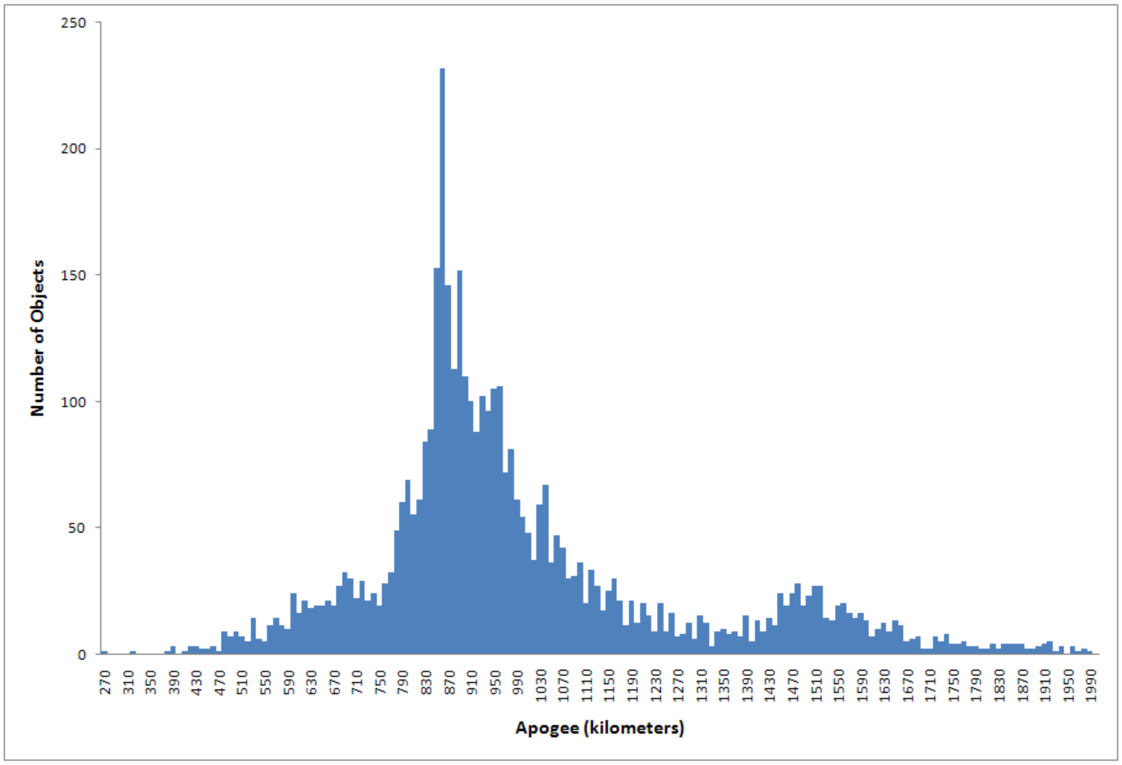

Fig. 1. All space objects in near-polar LEO orbit by apogee

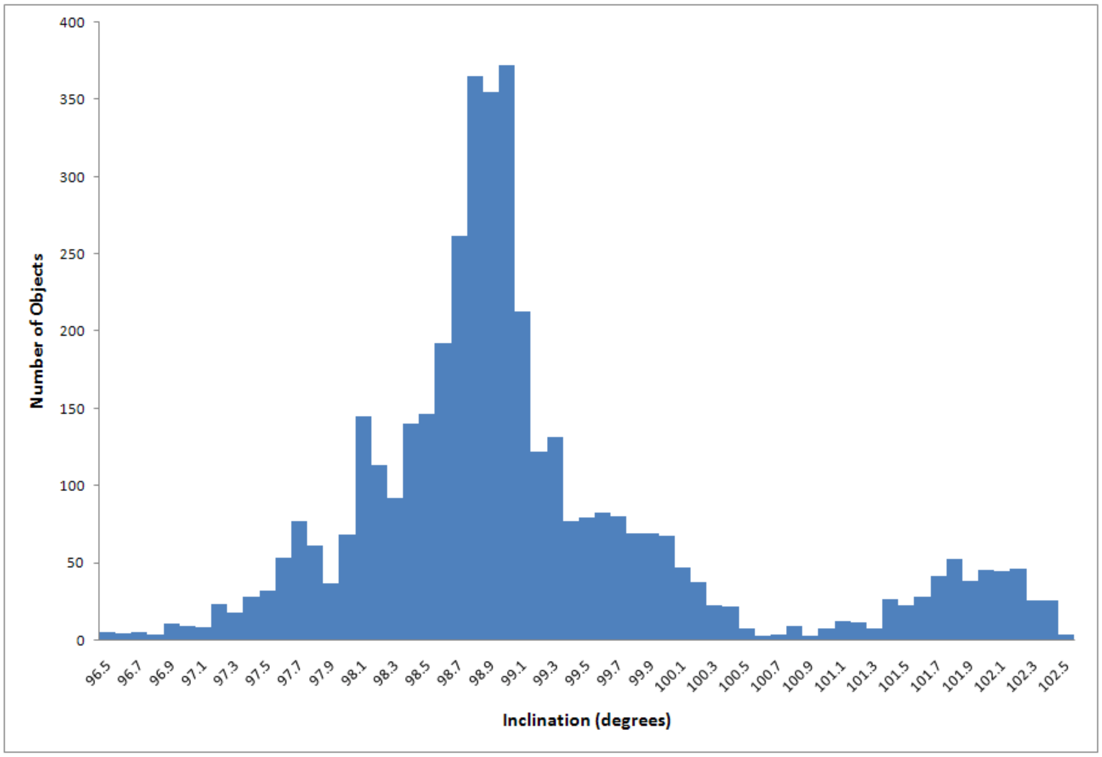

Fig. 2. All space objects in near-polar orbit by inclination

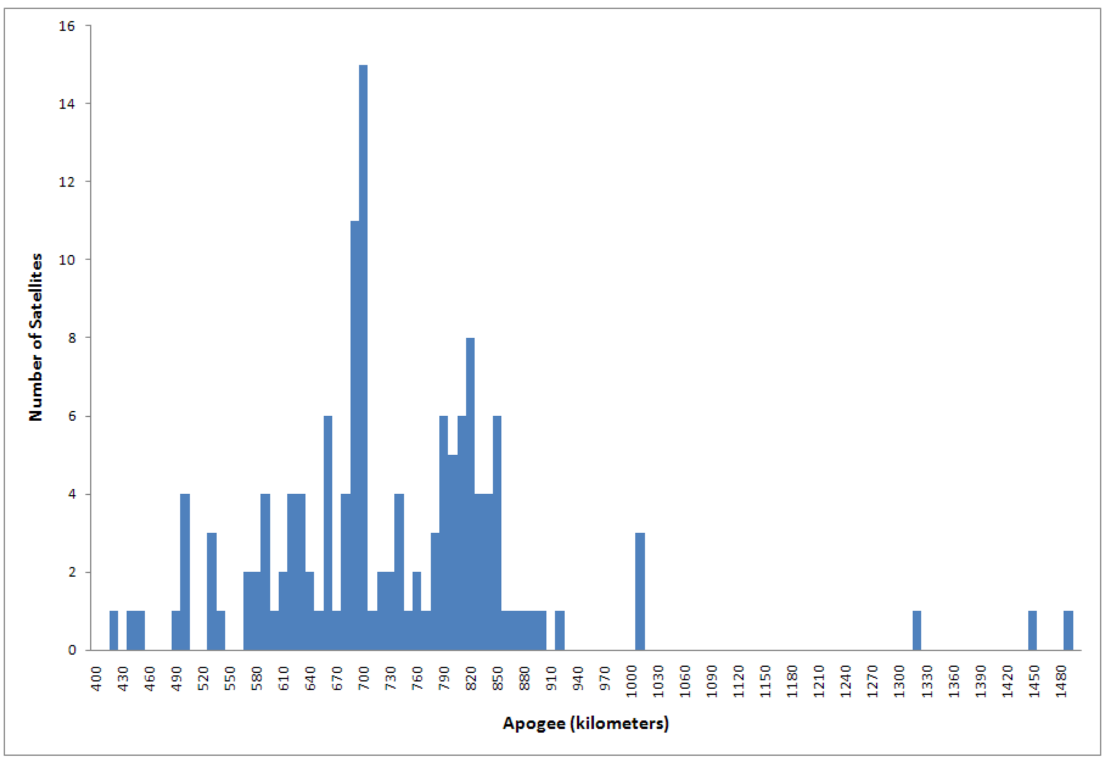

Fig. 3. All active spacecraft in near-polar LEO orbit by apogee

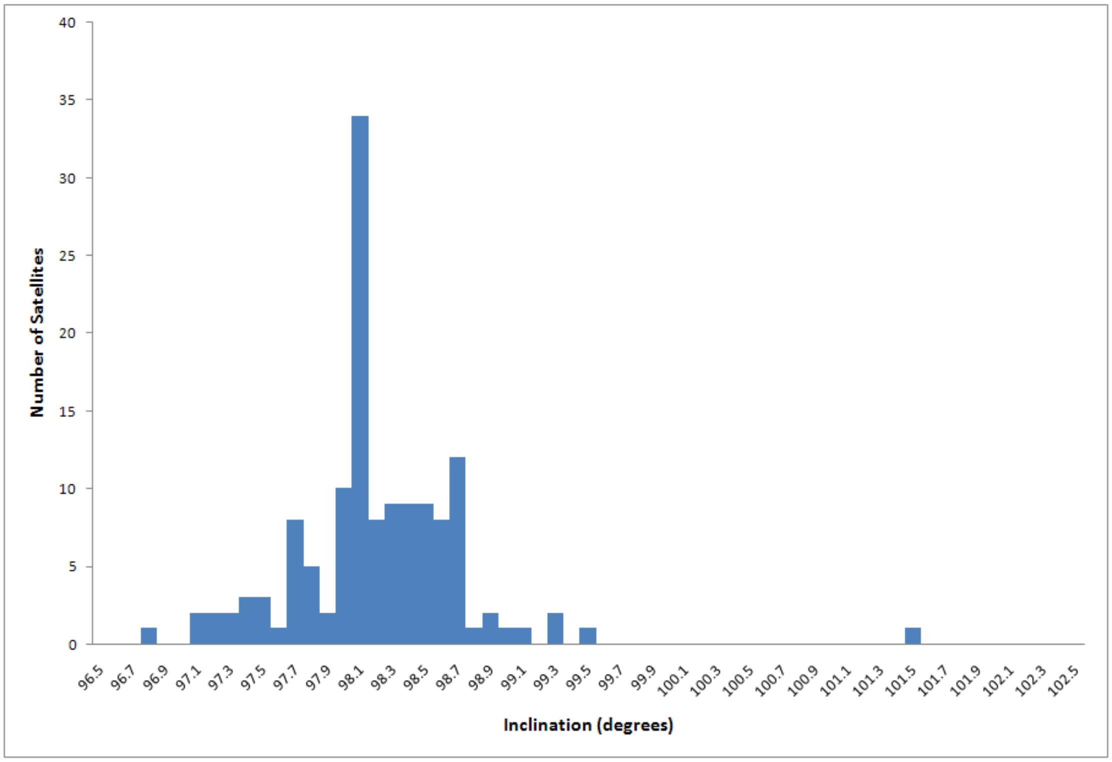

Fig. 4. All active spacecraft in near-polar LEO orbit by inclination

From these plots, two things are apparent. First, the two populations, all objects and active satellites, share similar distributions and are located in the same regions of space. This is not surprising as the debris is largely a function of space activity and thus the location of the debris should be strongly correlated with the locations of high space activity. Sun-synchronous orbit certainly counts in this regards. Secondly, the active satellites are clustered in a narrow band of inclinations between 97° and 99° and between 500 km and 900 km in altitude. This indicates that there is a "sweet spot" in the Sun-synchronous zone where mission designers and engineers have coalesced towards common designs and solutions.

Similar graphs showing the geostationary (GSO) population would show an even higher correlation to a specific altitude and inclination, as operational satellites in that region are essentially all following the same orbit but are spaced along that orbit in anomaly (or latitude as seen from the Earth's surface). The situation in SSO is different because there is an additional orbital parameter that is critical to SSO mission design but not GSO: right ascension. SSO satellites are spaced in right ascension around the Equator which creates zones at both poles where the orbits cross every revolution. Fig. 5 shows the orbits of the active SSO satellites and these zones can clearly be seen [5].

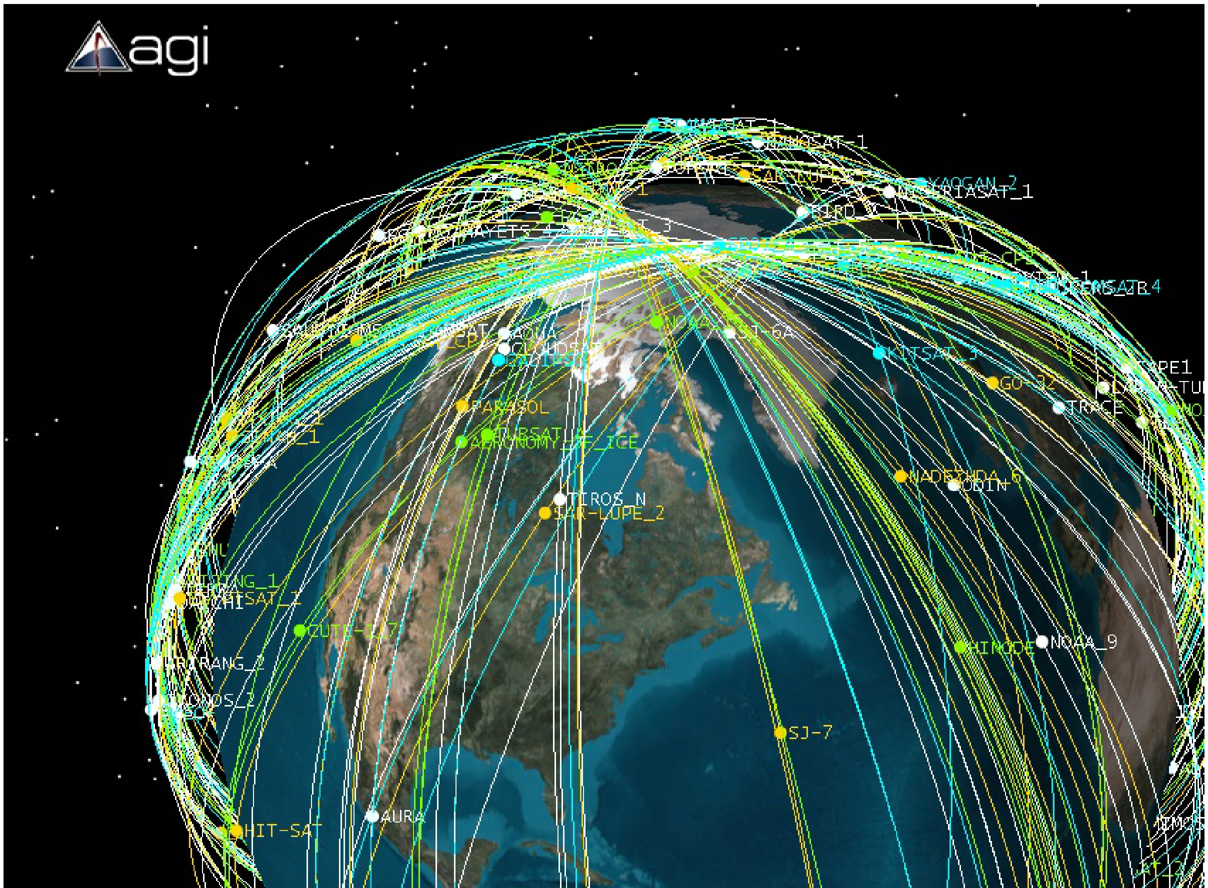

Fig. 5. Sun-synchronous satellite orbit crossing at the North pole.

These crossing zones, coupled with the higher debris density, creates a much higher risk of collision for SSO as compared to GSO where all the satellites are essentially moving in the same direction and thus head-on collisions are rare. Collisions in SSO are still rare but the number of conjunctions is steadily increasing, resulting in more spacecraft performing avoidance maneuvers.[6] A spacecraft conjunction is defined here as the situation in which two spacecraft trajectories intersect presenting the possibility of a collision. The process used to determine if such a case exists is called conjunction assessment.

The number of satellites in SSO is expected to continue to grow as more countries seek remote sensing data and services such as Google Earth which utilize the data proliferate. Euroconsult recently released a new report which predicts that 199 additional Earth observation satellites will be launched by 29 countries between 2007 and 2016 [7]. Many of those satellites will be placed into SSO orbits. And unlike GSO, there are currently no restrictions on where actors can place satellites within SSO.

This predicted growth of the SSO population, coupled with the lack of structure, indicates there is an increasing need to develop a system or architecture to minimize the probability of collisions and better predict conjunction opportunities. The following sections will outline possible solutions to this problem and their implications on SSO design constraints. This will then lead to the rationale for construction of an SSO architecture that can be developed to minimize spacecraft conjunctions while allowing for maximum utility of Sun-synchronous orbit.

III. Possible Solutions

In order to minimize and potentially solve the problem of SSO conjunctions and safety, a three-pronged approach needs to be taken as summarized by Fig. 6. The first essential piece is debris mitigation. These efforts are aimed at both minimizing the creation of debris and the impact of debris on spacecraft. As result of the high priority given to this subject by the United Nations Committee on the Peaceful Uses of Outer Space (UNCOPUOS), the Inter-Agency Space Debris Coordination Committee (IADC) was formed. Over the course of the last few years, the IADC has developed a set of debris mitigation guidelines which have subsequently been adopted by UN COPUOS. While an important first step, these effect guidelines can have on the overall collision problem is limited. The guidelines can only apply to certain existing satellites and those new satellites launched by States which adhere to the standards.

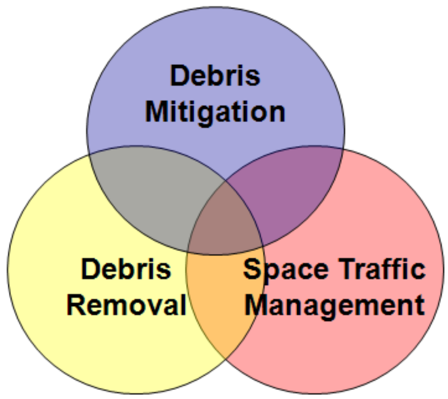

Fig. 6. The three main thrusts of space sustainability.

To tackle the problem of existing space debris and uncontrolled satellites, it is necessary to develop a means to remove debris from orbit. Many methods have been proposed, including using lasers to reduce debris' altitude and hasten natural decay, "space tugs" to physically pick up pieces and large "nets" to capture debris. A long-term feasibility study on this topic was commenced at the 2006 International Astronautical Congress in Valencia, Spain. This study is due to report in mid to late 2009. However, most of the current technologies for accomplishing removal of debris are either technically or economically unfeasible and are likely to remain so for some time. This places debris removal as a solution for the future and not the present.

The third piece of comprehensive orbital safety and collision prevention is some level of Space Traffic Management. This is defined as a set of parameters and measures with the aim of maximizing sustainable use and the continued availability of orbital resources while simultaneously minimizing the risk of unintentional physical or radio-frequency interference to operational spacecraft. Within this definition, the concept of defining slots for specific orbital regimes can be an effective solution. An example of this has already been mentioned: the geostationary belt, in which slots of a certain longitude are defined and managed under international law within the International Telecommunications Union. This paper will outline a proposal for a similar slot system for the Sun-synchronous orbit regime.

IV. SSO Mission Design Constraints

To understand why the current SSO population exists in the form that it does, the underlying orbital mechanics which dictate the unique SSO utility must be analyzed, and from this analysis the mission design considerations can be understood. The primary factor in SSO orbits is commonly referred to as the SSO condition [2]. This condition is defined as an orbit who's right ascension, referenced to the First Point of Aries, precesses Westward at a rate of 0.9856 degrees per day [2]. This precession allows the orbit to move around the Earth exactly counter to the Earth's rotation around the Sun, thus preserving the Sun-Earth-satellite angle for which the orbit is so named. For low Earth orbit, the continuum of inclinations and matching altitudes which give the proper precession rate can be calculated [2].

The second major mission design consideration is the number of revolutions before the satellite's ground track repeats. Repeating Ground Track (RGT) is a key element in the temporal resolution of a SSO satellite. The preceding continuum of inclinations and altitudes can be quantized by eliminating those altitude/inclination pairs which result in a non-integer RGT [2]. Once winnowed in this fashion, an additional key characteristic is discovered. The integer number of revolutions within which the orbit repeats is equivalent to the number of Equator crossings the satellite makes before repeating its ground track [2]. Thus, the maximum swath width at the Equator that the satellite payload must cover is defined. Fig. 7 shows the 1 Day and 2 Day RGTs along with their corresponding nodal spacing.

Repeat Interval	Period (minutes)	Altitude (km)	Inclination (degrees)	Node Spacing (km)
1 Day 12 Rev	120.0	1680.78	102.96	3339.58
1 Day 13 Rev	110.77	1262.01	100.73	3082.69
1 Day 14 Rev	102.86	893.72	99.01	2862.50
1 Day 15 Rev	96	566.83	97.66	2671.67
1 Day 16 Rev	90	274.35	96.58	2504.69
2 Day 23 Rev	125.22	1912.71	104.35	1742.39
2 Day 25 Rev	115.20	1464.42	101.77	1603.00
2 Day 27 Rev	106.67	1072.19	99.81	1484.26
2 Day 29 Rev	99.31	725.58	98.29	1381.89
2 Day 31 Rev	92.90	416.66	97.09	1292.74

Fig. 7. The 1 Day and 2 Day repeating ground tracks with variation in

The third major mission design consideration is the Mean Local Time (MLT) at which the satellite passes over a location on the Earth and is as function of the orbit's right ascension around the Earth's equator [2]. This feature can be of critical importance for science applications where the satellite is measuring a precise effect requiring specific solar lighting conditions, or when a satellite is designed to add to an existing data set for a particular time of the day. Because of the primary uniqueness of SSO, i.e. the constant satellite-Earth-Sun angle, the right ascension, and thus MLT, can be set at launch and over the course of time the precession of the satellite's right ascension will maintain the proper angle.

The fourth major design consideration is the so-called "frozen orbit." These are orbits which try to "freeze" one or more Keplerian elements by utilizing perturbation effects to balance out overall changes in those elements [8]. An example is the critical inclination, most well-known for its use in the Molniya orbit [8]. These highly elliptical orbits are designed so that a satellite can hang over high latitudes of the Earth for long periods, typically 8 to 9 hours of its 12 hour period. Apsidal line rotation moves perigee around the orbital plane over time, severely limiting the utility of such an orbit. However, at the critical inclination of 63.4° (and its supplement 113.5°), the J2 effects of the Earth dampen out this rotation. A similar effect can be used for SSO satellites to remove the variances in altitude using eccentricity [2]. This is desired to maintain a constant distance between the target and the satellite for consistent imaging.

Thus the orbital characteristics of any SSO satellite is largely constrained by the particular mission that designers wish it to fulfill. The altitude and inclination are prescribed by both the required SSO precession rate and the desired temporal and spatial resolution. The satellite's right ascension of ascending node is defined by the desired MLT, and it's eccentricity by the need to minimize apsidal line rotation via "freezing." The challenge in designing a slot architecture for SSO is restricting the orbits within which a satellite can be placed while simultaneously allowing for continued flexibility in the mission design. A slot architecture which removes all possibility of collision with another satellite but also constrains the utility of SSO leaves the satellite user with a safe but useless orbit.

V. Proposed Slot Architecture Methodology

The author proposes that an SSO slot architecture should initially be designed by first calculating, within reason, all the potentially usable SSO orbits. Once this set of all possible solutions is compiled, it can be crystallized into a structure within which all current and future SSO satellites can be placed. This method also has the benefit of quantizing what is in nature a continuum of orbits and thus reduces an infinite solution set to a finite one.

The first step in this process is to calculate all of the integer RGT orbits from the SSO condition continuum. B. Weeden has written a simple C software program to do this for a given minimum and maximum altitude range. A full description of the program can be found in Appendix A. Using this program and filtering for a minimum and maximum altitude of 250 km and 2,000 km, and between 1 and 20 day repeat intervals, results in 1,673 unique altitude/inclination pairs. To minimize conjunctions, the author proposes that only orbits with an altitude separation equivalent to the positional error plus a safety margin be used. As an example, if all SSO objects were known with a positional error of 4 km, a reasonable safety margin of 1 km could be added and thus SSO orbits with at least 5 km spacing would be required. Within each of these orbital, multiple satellites could be separated by mean anomaly to allow for maximum utilization of the orbit. From the resulting solution set, satellite mission planners can choose their desired RGT and swath width and thus the slot within which they need to place their satellite.

The above slot architecture would significantly decrease the chances of collisions between operational satellites by spacing them in altitude and anomaly and the resulting orbits would never cross under normal situations. However, once mission designers start to specify a range of desired MLTs, the satellites would have varying right ascension around the Equator and the opportunity for conjunctions at the poles is once again introduced. A possible solution to minimizing these conjunctions is to develop a phasing system such that satellites at the same altitude with different right ascension cross the poles at different times. This can be achieved by varying the true anomaly for each of these satellites.

Any proposed SSO slot architecture, such as the one described above, needs to be critically analyzed to determine the proper balance between increased safety and decreased utility. The key question to answer is whether or not such a system is still flexible enough to allow for the continued utility of SSO. Any design constraints such a system imposes on satellite engineering needs to also be examined.

Additionally, the effects of temporal changes in such a slot architecture, both natural and man-made, need to be examined in detail. Many SSO satellites maneuver periodically to correct for changes in altitude and inclination caused by perturbations. Such station-keeping maneuvers need to be studied carefully for their effects on critical orbital elements, such as the anomaly spacing necessary to maintain the phasing at polar crossings. This could possibly lead to the requirement for owner-operators with polar conjuncting satellites to coordinate their station-keeping maneuvers.

VI. Conclusion

The current situation in Sun-synchronous orbit, as described in Section I, presents an increasingly dangerous scenario for the long-term sustainability of this particularly useful region of Earth orbit. This danger is compounded by the current lack of structure to where satellites can be placed within these orbits and the projected growth in usage of SSO. A Sun-synchronous zoning system, similar in theory to that of geostationary orbit, can be one effective component in a solution to this problem.

The difficulty in designing a SSO slot system lies in the restraints placed on the Keplerian elements due to the orbital mechanics of SSO. The addition of variability in right ascension makes this a much more difficult problem than developing GSO slots. However, there are potential solutions that would provide the right balance between safety through structure and utility through flexibility. Quantizing the feasible range of inclinations and altitudes provides for a selection of orbits with different ground repeats. Further analysis on methods of phasing polar crossing would allow for flexibility in MLT.

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References

1. Anilkumar, AK et al, “Space Traffic Management,” International Space University, Space Studies Session 2007, Beijing China. [online], URL: http://www.isunet.edu/index.php?option=com_docman&task=doc_download&gid=371 [cited 1 February 2008].

2. Boain, R. J., “A-B-Cs of Sun-Synchronous Orbit Mission Design,” *Advances in the Astronautical Sciences*, Vol. 119, Part 1, 2004, Pages 85-104.

3. Committee on Space Shuttle Meteoroid/Debris Risk Management, *Protecting the Space Shuttle From Meteoroids and Orbital Debris*, National Academies Press, 1997, pp. 36.

4. Klinkrad, H., Space Debris: Models and Risk Analysis, Birkhauser, Berlin, pp 2.1.

5. STK, Satellite Toolkit, Software Package, Ver. 8.1.1, Analytical Graphics Incorporated, Exton, PA, 2007.

6. NASA Orbital Debris Program Office, *Orbital Debris Quarterly News*, Vol 11, Issue 4, 2007, pp. 2.

7. Keith, A., *Satellite-Based Earth Observation – Market Prospects to 2017*, Euroconsult, Paris, 2008.

8. Vallado, D.A., *Fundamentals of Astrodynamics and Applications*, 3rd ed., Springer-Microcosm Press, New York, 2007, pp. 838.