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Refined orbital architecture for targets of naval interest

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THESIS

REFINED ORBITAL ARCHITECTURE FOR TARGETS OF NAVAL INTEREST

by

Andrew Konowicz

March 2015

Thesis Advisor: Richard C. Olsen
Co-Advisor: Alan D. Scott

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This thesis considers orbital plane inclinations of 30°, 45°, and 60°; designs a few 24-satellite prograde constellations; and compares the performance of these newly formed constellations to the traditional sun synchronous orbit. As anticipated by the orbital mechanics, the results show that annual coverage can increase up to 6.5 times, average access increases up to 6.94 per day, and revisit time can be reduced to as low as 2.0 hours. In addition, the approximate annual life-cycle cost will likely fall beneath $0.5 billion.

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REFINED ORBITAL ARCHITECTURE FOR TARGETS OF NAVAL INTEREST

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Submitted in partial fulfillment of the
requirements for the degree of

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from the

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LIST OF ACRONYMS AND ABBREVIATIONS

AIS	Automated Information System
COTS	commercial off-the-shelf
C-SIGMA	Collaboration in Space for International Global Maritime Awareness organization
DARPA	Defense Advanced Research Projects Agency
EO	electro-optical
FIA	Future Imagery Architecture
FOR	field of regard
FOV	field of view
FY	fiscal year
GA	genetic algorithm
GSD	ground spatial resolution
HPOP	high precision orbit propagator
ICRF	International Celestial Reference Frame
LEO	low earth orbit
MDA	maritime domain awareness
MIT	Massachusetts Institute of Technology
NPS	Naval Postgraduate School
NRL	Naval Research Lab
ORS	Operationally Responsive Space
RAAN	right ascension of the ascending node
SBMDA	space based maritime domain awareness
SLOC	sea lanes of communication
SMAD	Space Mission Analysis and Design (textbook by James R. Wertz)
SSO	sun-synchronous orbit
STK	Systems Tool Kit
TENCAP	tactical exploitation of national capabilities
UTCG	Universal Time Coordinated, Gregorian

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I. INTRODUCTION

A. STATEMENT OF THE PROBLEM AND OBJECTIVE

Space commercial imaging has existed for four decades, ever since Landsat-1 launched in 1972, and today's demand for satellite images remains insatiable. Over the last decade, several commercial satellite startups have emerged offering powerful technology at cheaper costs.[1] Consequently, there also comes the prospect to redefine the current way of imaging from space.

Orbital mechanics has been extensively studied over the past century; the intent of this thesis is to simply revisit some neglected fundamentals that might prove useful given the current state-of-the-art. Instead of resigning electro-optical imagers to the traditional sun synchronous orbit (SSO), the goal here is to reaffirm the benefits and understand the challenges of utilizing a prograde constellation. To that end, the designs offered here focus on small, inexpensive, but capable commercial satellites, similar to SkySat-1 of SkyBox Imaging Inc. It is believed that in the near future, it will be feasible to populate an electro-optical constellation that can access populated regions of the globe more frequently and for lesser expense than was once believed.

The practicality of prograde orbits has been debated enthusiastically over the last ten years.[2] Based on a review of the orbital mechanics, it is expected that common metrics for measuring the performance of a constellation, such as *coverage duration, average daily access,* and *revisit times,* can be markedly improved over those for current SSOs. It is understood, however, that the laws of orbital mechanics will also necessitate the use of multiple satellites in multiple planes to deliver these benefits. A point worth emphasizing now, however, is that the cost to procure and launch larger quantities of capable satellites, though not trivial, is more manageable today because of the technological advances in the commercial market.

[1] Jean Kumagai, "9 Earth-Imaging Start-ups to Watch: A tech boom will shake up commercial satellite imaging," http://spectrum.ieee.org/aerospace/satellites/9-earthimaging-startups-to-watch, accessed January 2014.

[2] Edward B. Tomme, "The Myth of the Tactical Satellite," *Air & Space Power Journal* (June 2006): 1.

B. THESIS BOUNDARIES

This study assesses the performance of a prograde constellation. The designs created here are modelled loosely on existing commercial remote sensors. The study includes an analysis of three prograde orbits inclined at 30°, 45°, and 60°, respectively. Performance metrics include 1) the number of accesses per day, 2) coverage duration, and 3) revisit time. These values are then compared to those extrapolated from sun synchronous orbits. The ground spatial distances (GSD) achieved by the illustrative remote sensing system are assumed to be acceptable for a hypothetical user, but the study does not actually quantify values during the simulations presented. This assumption is based on previous work in the field. The modelling assumes the satellite will be able to maintain altitude against atmospheric drag for its operational lifetime, an assumption that might not be possible for all commercial imagers. Launch techniques and orbital insertion are not explored and but will have significant impact to the overall cost of this design. Furthermore, the impact of this constellation design to the ground architecture has not been addressed and will also have substantial consequences. All other modelling assumptions are described in Chapter IV.A.

II. REFERENCE MATH AND VOCABULARY

This chapter will familiarize the reader with some basic orbital terminology and a few physics concepts which will be used to interpret the results of later chapters. A comprehensive review of orbital mechanics can be found in several valuable textbooks.[3]

A. ORBITAL TERMS

The position of a satellite can be defined by six common orbital elements, sometimes called the Keplerian elements:

- Eccentricity (e)
- argument of periapsis
- mean anomaly at epoch
- semimajor axis
- inclination
- right ascension of the ascending node (RAAN)

The assumptions made for this research, to be fully described in Chapter IV, include satellites being placed into a circular orbit (e = 0) about the Earth. The *argument of periapsis* is meaningless for circular orbits and will be ignored. The *mean anomaly at epoch* (in this case represents the location of the satellite at the start of the simulations) is initiated at 0° N / 0° E. Deviations from this will be noted accordingly. The three remaining elements are the ones relevant to the work presented here: *semimajor axis*, *inclination,* and *right ascension of the ascending node (RAAN).*

[3] James R. Wertz and Wiley J. Larson, *Space Mission Analysis and Design (SMAD)*, 3rd ed. (Torrance, California: Microcosm, 1999), chapters 6 and 7; Jerry Jon Sellers, *Understanding Space* (New York: McGraw-Hill, 2005), chapters 4 to 8; and Richard C. Olsen, *Remote Sensing from Air and Space* (Monterey, California: Naval Postgraduate School, November 2013), chapter 5.

1. Semimajor Axis for Low Earth Orbit (LEO)

The resolution of a remote sensing spacecraft is directly related to the distance from its target: the closer the imager is to its target, the better the consequent resolution. Current imaging technology and the limits of physics (i.e., the Rayleigh Criteria) drive remote sensors into lower orbits, namely Low Earth Orbit (LEO). LEO is conventionally considered between 150 and 1000 km. Below 150 km, the thicker atmosphere of the Earth creates excessive drag that deorbits a satellite prematurely. Above 1000 km, satellites start penetrating into the inner region of the Van Allen Belts, where high levels of radiation impact daily spacecraft operation and reduce spacecraft life. For this research, satellites are held to a fixed altitude of 500 km (semimajor axis = 6878.15 km).

2. Inclination and Prograde Orbits

Inclination is defined as the angle between the Earth's equator and the satellite's orbital plane (see Figure 1). **The focus of this study is to explore the tradeoffs of varying the inclination of a satellite's orbit and the subsequent outcomes when an entire constellation utilizes that same inclination.** *Retrograde orbits* (those with an inclination of *more than* 90°) are considered, but only in the specific case of Sun Synchronous Orbits (SSOs), as discussed below. *Prograde orbits* (those with an inclination of *less than* 90°) are the focus of this study.

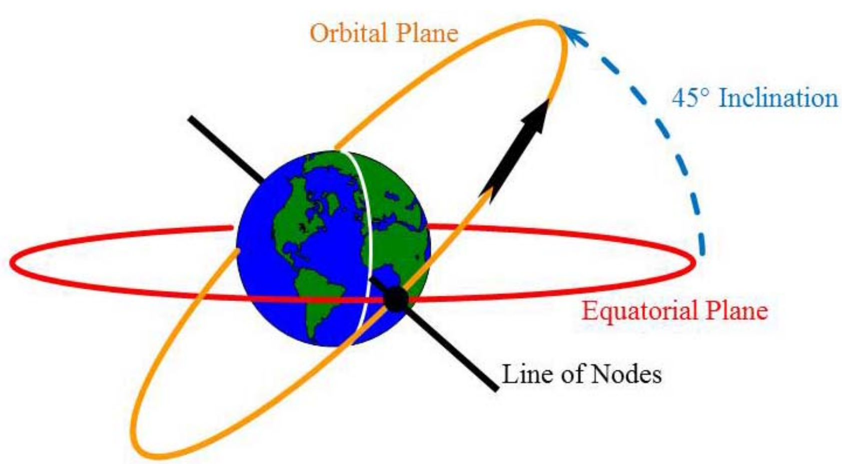

Figure 1. Example of a prograde orbit inclined at 45° and a right ascension of the ascending node (RAAN) at approximately 10° W.

3. RAAN and Orbit Precession

Assuming the Earth was a perfect sphere, the RAAN would remain stationary. The Earth is not exactly spherical; however, it bulges at the equator. This bulge causes the orbital plane of a satellite to “precess,” or rotate, from its original position—in a motion not unlike a spinning top that begins to wobble as it slows. This phenomenon, known as the *J2 effect*, is most significant in LEO. All orbital planes in LEO, besides those inclined at exactly 0° or 90°, are influenced by J2. The effects of J2 magnify as inclination increases from 90° (retrograde) or decreases from 90° (prograde).

a. Prograde Orbit Precession Effects

Without revisiting the complex math that describes orbital plane precession, the salient point is that a prograde orbit will rotate westward, or clockwise, about the Earth’s spin axis. Figures 2 through 4 help illustrate this point.

(1) Precession: Day 0 (Figure 2)

At the start of the epoch, all satellites are aligned at 0° N / 0° E. For orientation, green curves are added in Figures 2–4, representing the inertial 0° N / 0° E at time 00:00.

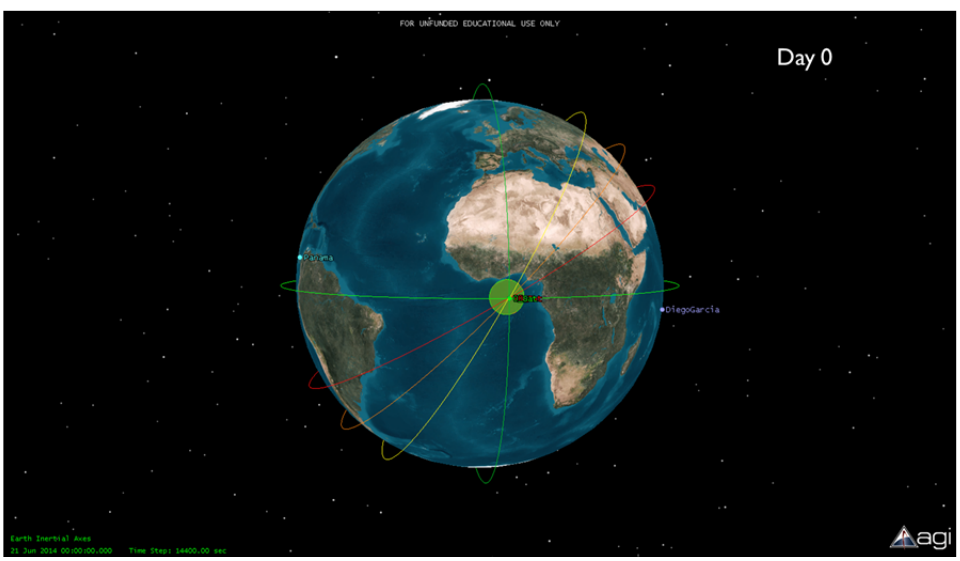

Figure 2. Three orbital planes (red: 30°, orange: 45°, red: 60°) at Day 0.

(2) Precession: Day 5 (Figure 3)

After just a few days, the inconsistency between the precessions of the three orbital planes becomes apparent. All three planes have precessed west from the Prime Meridian, but the 30° plane has traversed the farthest west (note where it crosses the equator near the Northeast coast of South America). Also note that the satellite in the 30° plane has advanced the most in its orbit (it has reached east, beyond the Arabian Gulf). Without the J2 effect, all satellite will return to cross the equator at the same time and location; the reality of prograde orbits is they are dramatically affected by J2.

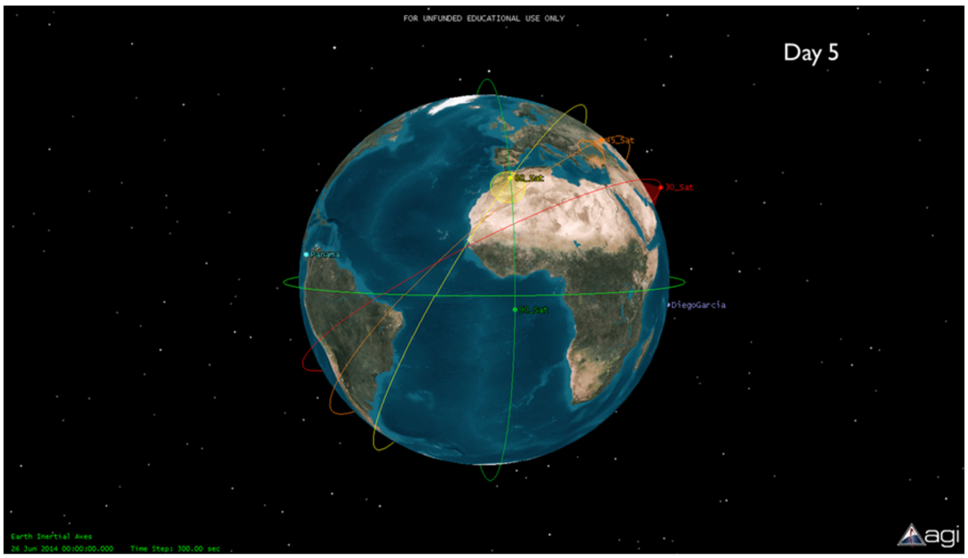

Figure 3. Three orbital planes (red: 30°, orange: 45°, red: 60°) at Day 5.

(3) Precession: Day 30 (Figure 4)

After a month, the difference between the three orbital planes is significant. All three planes will continue precessing west at different rates. It can be seen that after one month, the satellite in the 30° orbit has nearly lapped the satellite in the 60° orbit. It can be inferred how difficult it might be keeping track of satellites in mixed orbits, especially when each has a different precession rate, as shown on the table inset in Figure 4.

AN EARLY CONCLUSION IS THAT DESIGNING A CONSTELLATION FROM MIXED INCLINATIONS WILL BE FAR MORE UNSTABLE AND COMPLICATED THAN KEEPING WITH ONE INCLINATION. Furthermore, after having to wait for the precession rate to bring a plane back into alignment over a launch facility, the orbital insertion will be complicated by having to account for the proper placement of apogee if the orbit design included any eccentricity.

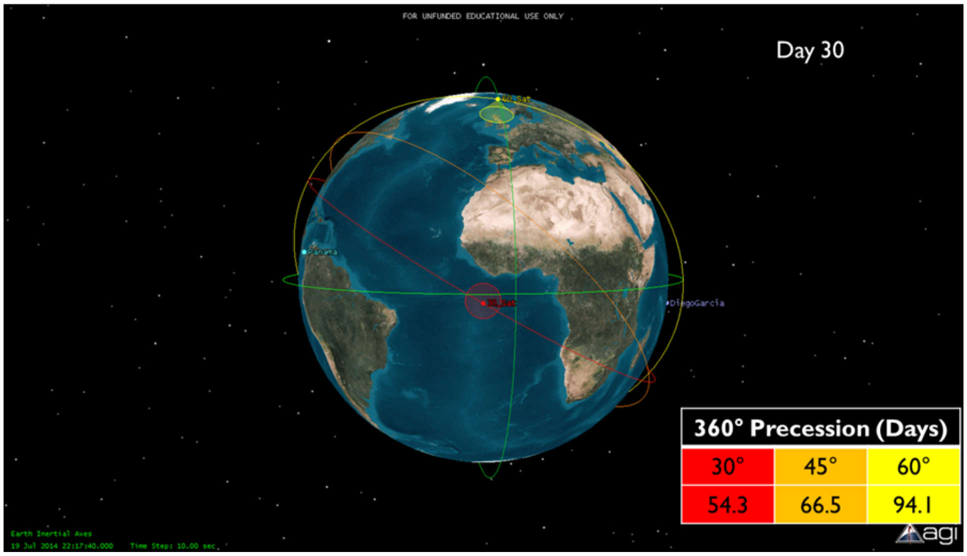

Figure 4. Three orbital planes (red: 30°, orange: 45°, red: 60°) at Day 30.

(4) Precession and Sun Elevation (Figure 5).

In certain cases, the orbit plane precesses into a particularly disadvantageous location where it is temporarily placed in the sun's penumbra. In this example, a 60° orbit has momentarily aligned itself into the continuous sunrise/sunset of the sun, a place where too little light is available on the ground for EO imaging. EO sensors usually need their ground targets to have at least a 30° sun elevation angle (Chapter IV.A.1.d), and in this case, a target directly below this satellite would have roughly 0° sun elevation. Based on the precession rate of this inclination listed in Figure 4, one can see it could take several days for this plane to move out of this EO "dead zone" and become useful again for EO. This phasing issue is the principal reason why a *constellation* is needed if exploring prograde EO orbits (Figure 6).

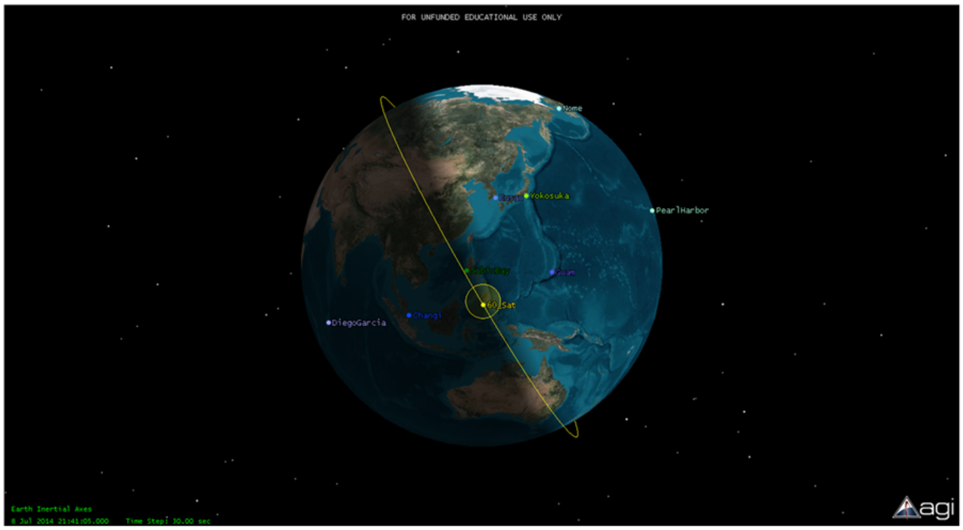

Figure 5. A 60° inclined satellite temporarily phased with the sun’s penumbra.

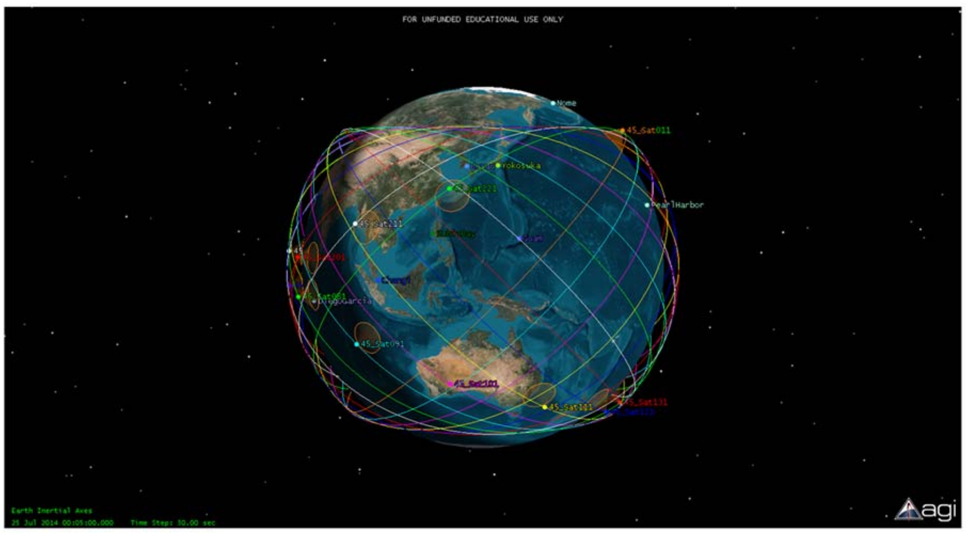

Figure 6. A sample prograde constellation inclined at 45°.

b. Sun Synchronous Orbits (SSO)

A Sun Synchronous Orbit offers a unique case where the gradual precession of its plane *eastward* (because it is retrograde) is designed to coincide with the slight movement of the Earth about the Sun throughout the year (see Figure 7).

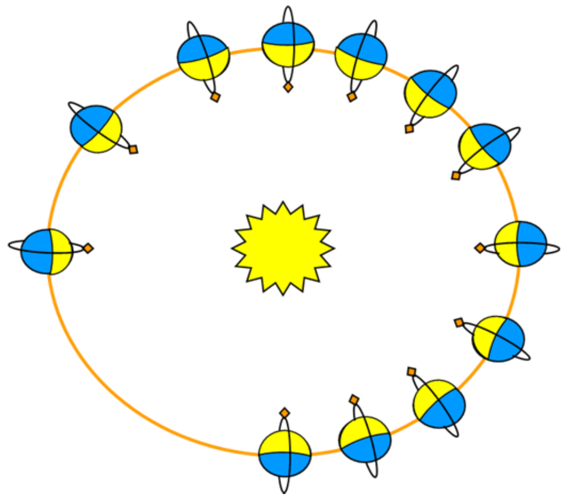

Figure 7. SSO plane precesses while the Earth orbits the sun.[4]

Most remote sensing satellites that utilize electro-optical (EO) imagers are found almost exclusively in SSOs between 400 and 900 km and have a consequent retrograde inclination of roughly 98° (Figure 8).[5]

[4] Illustration courtesy of Professor Charles Racoosin, "Lesson 5.9.2: Orbital Mechanics," PH3011 Lecture Slides, Naval Postgraduate School, Monterey, California, September 2013.

[5] Nigel Bannister, "SBMDA with Commercial Earth Observation Satellites Carrying Electro-Optical Imagers" (University of Leicester, Leicester, United Kingdom, August 2013), 9.

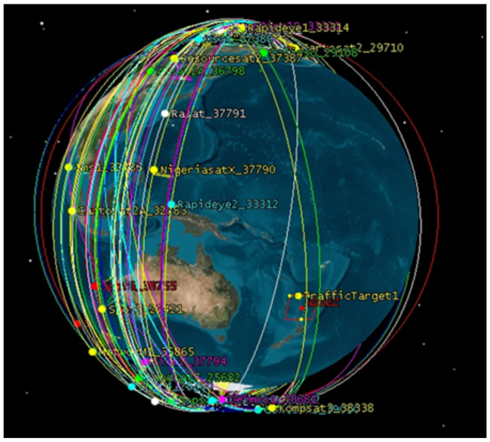

Figure 8. A collection of the commercial EO remote sensors.[6]

B. MEANINGFUL METRICS FOR SATELLITE ACCESS

The following is a short list of applicable terms for orbital dynamics and STK use.

- ***Access*** *– the ability for a sensor to obtain a line-of-sight view with the target's latitude and longitude at the surface of the Earth.*
- ***Coverage*** *– the amount of time a sensor has access to a target for a given time period.*
- ***Revisit*** **or** ***gap*** *– the length of time that elapses from the termination of one access to the start of the next access. These two terms are used interchangeably in this work.*
- ***Walker Notation: (t/p/f)*** *– Walker Constellations (described in* **Chapter** *`V.C.1) use the convention* t/p/f *when describing their composition: total satellites, "t," number of planes, "p," and relative spacing between satellites in adjacent planes "f." For example,* (24/6/1) *denotes a constellation with 24 satellites parsed into 6 orbital planes and spaced out evenly.*[7]

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[6] Bannister, "SBMDA," 9.

[7] A comprehensive discussion of Walker constellations can be found in James R. Wertz, *SMAD*, (2006), chapter 7.6.1.

III. BACKGROUND

A. THESIS FOLLOW-ON

In 2006, a former NPS student, C. J. Didier, wrote a thesis attempting to fill a void left by the cancelling of the Future Imagery Architecture (FIA) optical component.[8] At the time, there was a strong demand for electro-optical images but it was unclear how that need would be met. He proposed building a constellation of imaging satellites based on a then-state-of-the-art commercial remote sensor, QuickBird-2. His thesis work found that a commercial-off-the-shelf (COTS) architecture could adequately meet the needs of the imaging community and relieve some demands on the national systems.[9] His research revealed that a COTs design is feasible, beneficial, and relatively inexpensive. For an annual life cycle cost under $2 billion (FY 2006), a constellation of 12 commercial satellites could improve revisit time around the globe from three days down to about a day. This was a marked improvement on the existing design. However, only sun-synchronous orbits were explored in that study; this work aims to continue where it stopped and explore different orbital inclinations. Additionally, the previous design was configured to investigate elliptical orbits which can result in resolution of imagery obtained over an orbital revolution; this study focuses on circular orbits for ease of constellation reconstitution.

B. ARGUMENT AGAINST MYTHICAL TACTICAL SATELLITES

In addition to the previous NPS thesis, several space professionals were seeking methods to "optimize" all types of satellites in creative ways, but there was also significant trepidation that the advertised benefits of these new designs were misleading. LtCol Tomme, then-Deputy Director of Air Force TENCAP, championed that satellites can only offer a finite amount of capability and that it can come at high cost.[10] He voiced

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[8] C. J. Didier, "A Commercial Architecture for Satellite Imagery" (Master's thesis, Naval Postgraduate School, September 2006), 1.

[9] Ibid., 59–60.

[10] Edward B Tomme, *The Strategic Nature of the Tactical Satellite* (Colorado Springs, Colorado: Airpower Research Institute, 2006).

credible concerns that unique "tactical satellites," though promising immense value, must be portrayed realistically. His meticulous calculations proved it would take a constellation of hundreds of satellites—under faultless conditions—to achieve appreciable benefits (Figure 9).

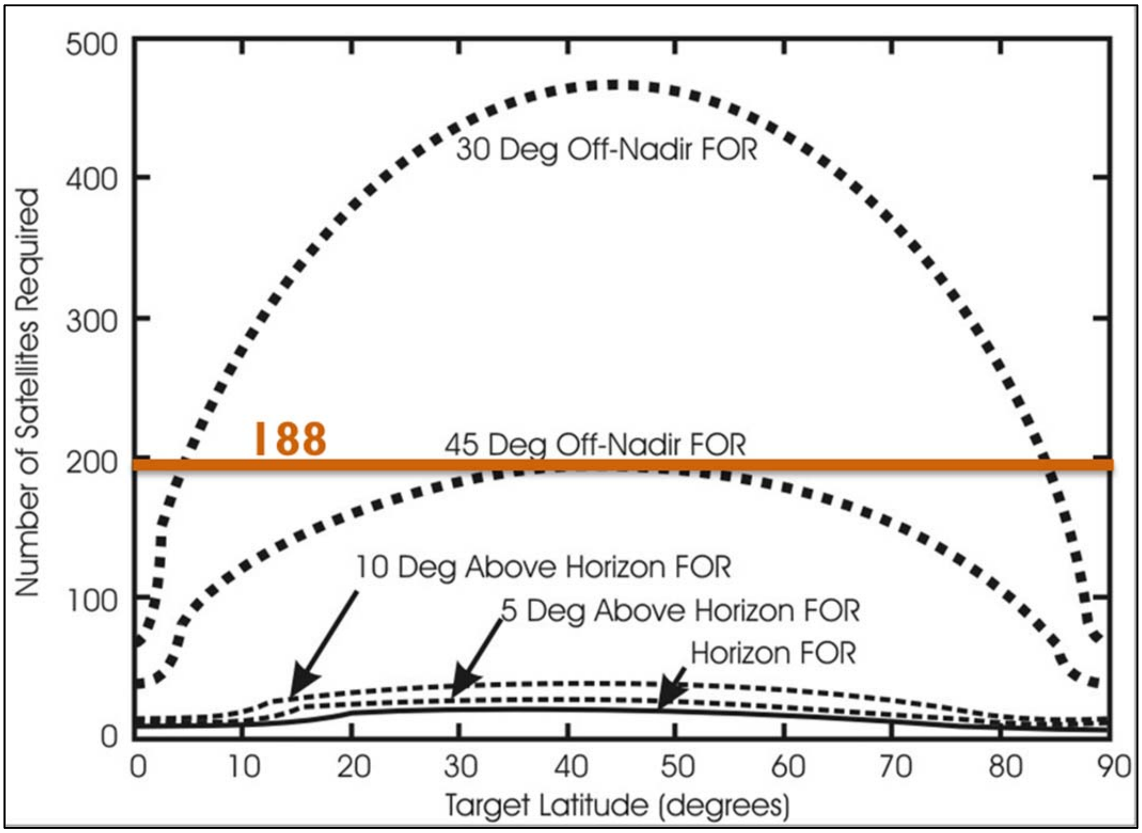

Figure 9. It is estimated that hundreds of satellites are required for 24/7 persistence over a mid-latitude targets.[11]

The figure represents an unreasonable number of satellites, under unobtainable conditions (including, day and *night* coverage for an EO sensor). From the graph, a mid-latitude target would require 188 satellites imaging both day and night to achieve persistent 24/7 coverage from a 500 km constellation of remote sensors with a 45° FOV. His seminal research cautioned for circumspect approaches to constellation designs.

11 Tomme, *Strategic Nature*, 47.

C. THE WORK CONTINUED

In 2009, researchers at the Massachusetts Institute of Technology (MIT) pursued a remote sensing system that would improve the current level of imaging performance (i.e., coverage and revisit).[12] They analyzed constellations designed to "optimize" these metrics for one hypothetical mid-latitude target (corresponding to MIT's campus). For a life cycle cost of $98.8 million (FY 2000), they theorized a 4/2/1 constellation possible of yielding 24-hour mean revisit.[13] This is a further improvement from Didier's earlier work and illustrates the benefit of commercial satellites to revisit mid-latitude targets. Their survey, though properly thorough, uses only a single point target and sun synchronous orbits exclusively. This work aims to advance that study, as well, and will present the findings of a prograde constellation's performance for a variety of targets.

D. A NOTE ON OPTIMIZATION

This study does not seek to *optimize* a constellation—that would entail, among other things, an assessment of every orbital inclination, at every satellite altitude, and every sensor field of view—*for every target latitude*. That math has already been tackled extensively by Tomme,[14] and repeated by the work of Systems Engineer Dr. Roger Burk, U.S. Army Space and Missile Defense Command.[15] To be clear, the thesis that follows merely reflects those same underlying physics, but does so to emphasize that **exploring prograde orbits, and understanding their tradeoffs, could result in a reasonable design solution for future remote sensing systems.**

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[12] Jared K. Krueger, et al., "Spacecraft and Constellation Design for a Continuous Responsive Imaging System in Space (CRISIS)" *American Institute of Aeronautics and Astronautics* (September 2009), 1.

[13] Ibid., 17–18.

[14] Tomme, *Strategic Nature*, 13–60.

[15] Roger C. Burk, "A Closed-Form Approximation of Revisit Rate for Low-Altitude Spacecraft" (academic paper, United States Military Academy, West Point, New York, September 2011).

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IV. SINGLE SATELLITE DESIGN AND TESTING

This chapter is devoted to the characteristics of a single satellite in different prograde (< 90°) inclinations. All model assumptions will be discussed and then selected inclined orbits will be showcased against more traditional SSOs to highlight some trends.

A. MODEL ASSUMPTIONS

Systems Tool Kit (STK) version 10.1.1 was used to model and simulate different orbital designs. The following reflects the set-up used to create the resulting data and assumes the reader has a functional understanding of STK.

1. Analysis Period

The Analysis Period was selected to span a three year epoch, starting on the summer solstice: 21JUN2014 00:00 UTCG to 21JUN2017 00:00 UTCG. This time period allowed for adequate sampling without excessive computer processing. Aliasing would have resulted if the analysis period was too short—specifically, below the Nyquist Frequency of either the Earth's seasons or the J2-induced revolutions of the orbital plane about the Earth (Chapter III.A.3).

2. STK Propagator and Coordinate System

The J4 Perturbation Propagator was chosen over the High-Precision Orbit Propagator (HPOP). The HPOP requires creating a detailed model to realistically simulate the effects of atmospheric drag in LEO—a process that requires precise satellite engineering details that were not readily accessible. Nonetheless, a "best guess" HPOP SkySat model was created and its results from a one year test run closely mirrored what the J4 Perturbation model produced for the same period. Because the time required to execute just a one year HPOP sample was prohibitively long with results that were reasonably similar, the decision was made to proceed with the J4 model. Also, the coordinate reference was International Celestial Reference Frame (ICRF) to reflect the most current modeling practice.

3. Eccentricity

In contrast with previous work from 2006,[16] where elliptical orbits were chosen to enhance resolution, circular orbits (*e* = 0) were selected herein. The most significant factor was the requirement to replenish a prograde constellation quickly. It could theoretically take a prograde orbital plane weeks to align itself with one of the few launch sites the U.S. maintains, without needing excessive fuel to position the apogee/perigee. Add to this a small launch window that might be impinged by weather or other launch facility constraints and it might take months before the timing works out for a successful orbital insertion. A circular orbit simplifies this by making the apogee, perigee, and every point between them, the same from a launch perspective. The circular orbit conceded the higher spatial resolution that Didier was pursuing with relatively low-altitude perigee ranges.

4. Sun Elevation Angle

Electro-optical (EO) imagers are passive sensors that require sunlight to illuminate their target. It is common practice to use a **sun elevation angle of 30°** to provide adequate sunlight.[17] There is certainly much more than just sunlight that affect the clarity of an image, this is just an assumption made for this research.

5. Optical Field of View (FOV)

The highest resolution obtained from a remote sensor occurs by placing a target closest to its lens, and for satellites that means directly beneath it, along its nadir axis. Angling away from nadir increases the distance between the optics and the target. For satellites, that increase in slant range for off-nadir targets, as well as added atmosphere the sensor must now stare through, decrease resolution. Because of these constraints induced by physics, this research uses a generous assumption, generally accepted by the remote sensing community as the limit: **FOV = 45°**.

[16] Didier, "A Commercial Architecture for Satellite Imagery," 19.

[17] Conversation with Jim McClelland of SkyBox Inc., Mountain View, California, September 5, 2014.

6. Variables Not Considered

Due to time constraints related to processing capabilities, not every variable that could affect the overall results of this research was examined. **Since each of these variables below impede sensor access to targets, it should be noted that if any of them were included in the simulations the results would be expected to *change for the worse.*** Nonetheless, in the interest of seeking out the initial feasibility of the proposed designs, these items were not considered for the purposes of this thesis:[18]

- Cloud Coverage
- Atmospheric Effects
- Terrain Masks

For completeness and accuracy, these will need to be accounted in future work.

7. Targets of Naval Interest

The focus of this research is to study how well an EO constellation can access places that are important to the Navy: namely ports and the sea lines of communication (SLOCs) that connect them. When generating a sample of appropriate naval targets for an EO constellation, the first question to ask was "What are commercial satellites currently imaging?" SkyBox has carefully processed archived metadata from the last three decades to produce a graphic that represents historical commercial image collects (Figure 10). In that figure, color represents total number of images collect for a 10 km x 10 km area; black represents zero images and red represents 15,000 images. It becomes apparent where the commercial companies have been paid to image. There are many interesting trends that can be extracted from this graphic, but the focus for this research is the over-water collects.

[18] A thorough discussion of atmospheric effects and imaging geometry can be found in R. C. Olsen's *Remote Sensing from Air and Space* (November 2013), chapter 3.

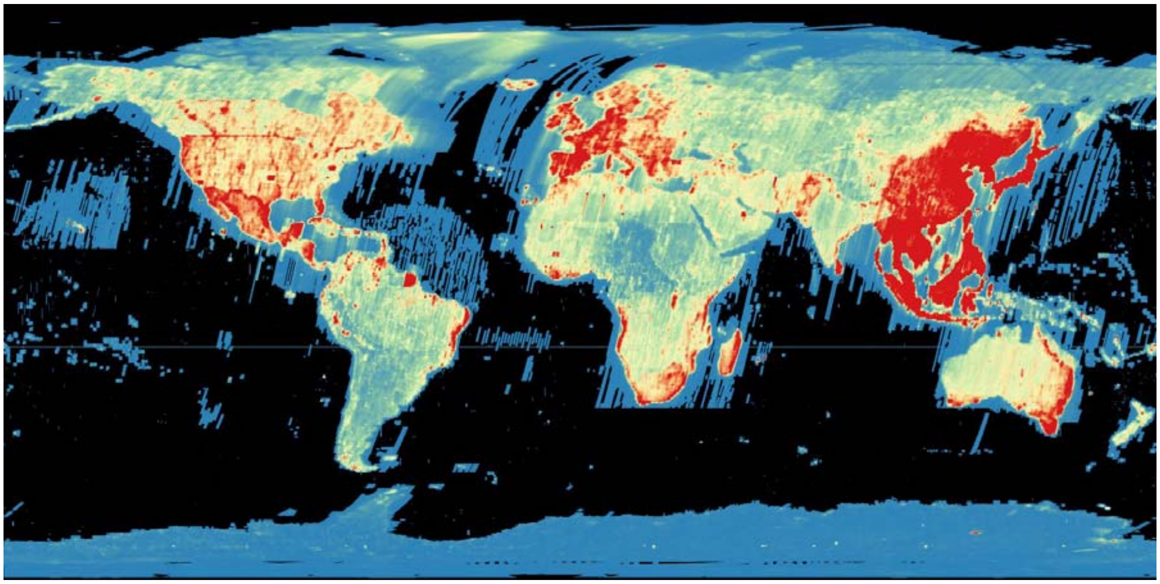

Figure 10. SkyBox analysis of commercial satellite metadata, 1986–2012.[19]

To help put this into a better context, it is important to understand the routes of sea-going vessels. One way to visualize SLOCs is to plot the returns from the Automatic Identification System (AIS), a ubiquitous monitoring system that is the maritime equivalent of transponders in aviation. From these charts, such as Figures 11 and 12, we can gain insight to where the shipping "highways" are located. A common latitude range is evident: most global SLOCs exist below 65° N (Figure 11). Comparing the commercial metadata with the AIS tracks, it can also be observed that much of the SLOCs go unobserved. To be fair, it is admittedly different to have a ship tell you where it is (like AIS) rather than try to passively find it in a random corner of the ocean (using EO). But perhaps we can use this knowledge to better cue our sensors and enhance the benefit EO satellites bring to the maritime domain.

[19] Ty Kennedy-Bowdoin, "Satellite Metadata in Video," accessed January 2015, http://www.skybox.com/blog/satellite-metadata-in-video.

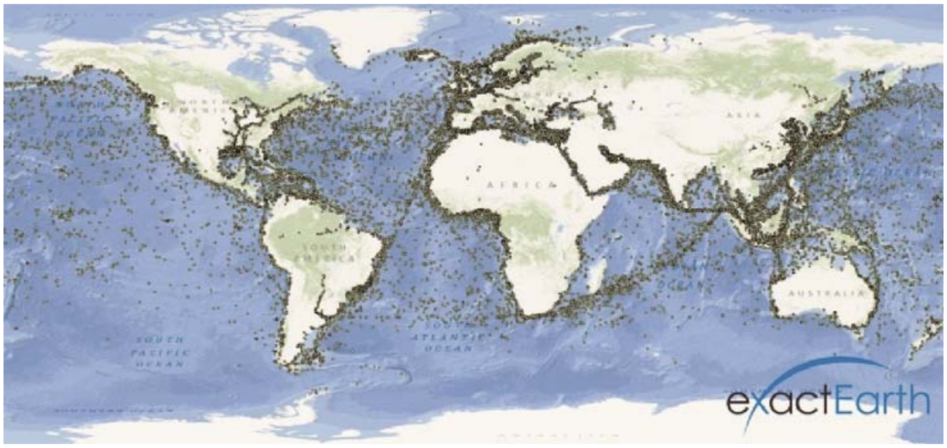

Figure 11. A chart showing AIS returns across the world.[20]

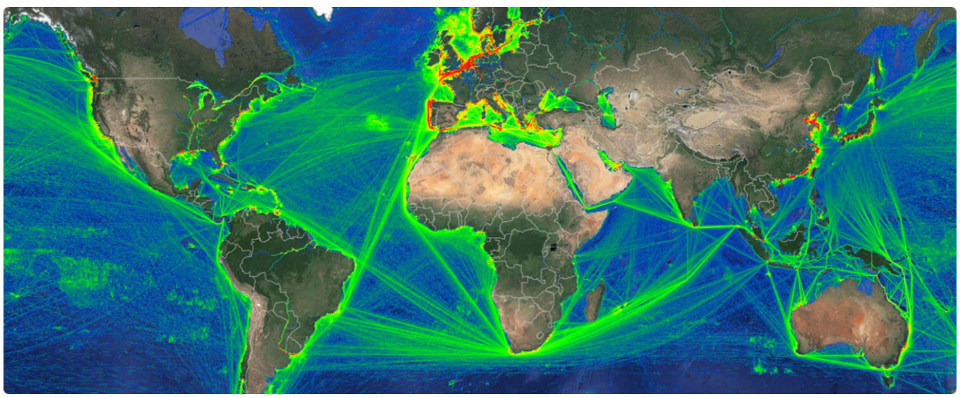

Figure 12. An example of an AIS density map.[21]

For the purpose of detecting "Targets of Naval Interest," ideally every point of the ocean would be selected for calculation, or at least along the common SLOCs, but current computer processing constrains that option. Therefore, point targets of busy maritime ports at varied latitudes around the Pacific Ocean were chosen to highlight the effects of the new orbit designs (Figure 13 and Table 1). Symmetry about Earth's equator allows southern hemisphere locations to be omitted at this time to help further reduce processing time.

20 Earth Imaging Journal, "Benefit from a New Wave in Satellite AIS Technology," accessed February 2015, http://eijournal.com/resources/geoint/maritime-security.

21 MarineTraffic, "Global Satellite AIS Coverage," accessed January 2015, http://www.marinetraffic.com/en/p/satellite-ais/.

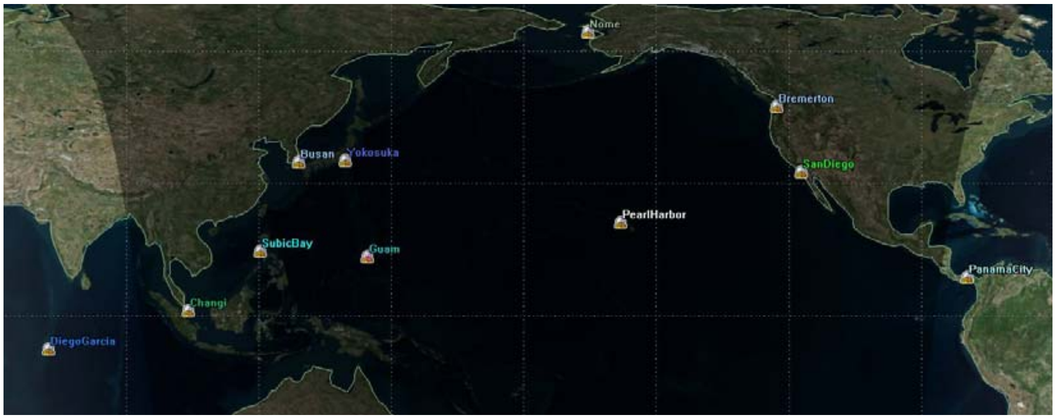

Figure 13. Point Targets of Naval interest, selected for satellite access data.

Table 1. Point targets of naval interest, arranged by latitude.

City Name	Latitude	Longitude
Diego Garcia	-7.32	72.42
Changi, Singapore	1.31	104.03
Panama	8.95	-79.57
Guam	13.46	144.66
Subic Bay, Philippines	14.81	120.29
Pearl Harbor, HI	21.36	-157.95
San Diego, CA	32.71	-117.18
Busan, South Korea	35.09	129.11
Yokosuka, Japan	35.3	139.66
Bremerton, WA	47.55	-122.65
Nome, AK	64.49	-165.44

B. SINGLE SATELLITE DESIGN RESULTS

With the assumptions above, simulations were run and the following tables show results for the following metrics:

- Number of Passes per Day (Daily Access)
  - Min
  - Max
  - Mean
  - Total per Year
- Pass Duration
  - Min (seconds)
  - Max (seconds)
  - Mean (seconds)
  - Yearly Average (hours)
- Gap between Passes
  - Min (hours)
  - Mean (hours)
  - Max (days)[22]

[22] The table convention changes for the last column to emphasize that the maximum gap durations can be excessive due to seasonal eclipse as targets sit farther from the equator.

1. Performance: One Satellite at Prograde Inclinations

Table 2. One satellite, 30° inclined performance.

One Satellite - 30° Inclination - 500 km Circular Orbit													
City Name	Latitude	Number of passes per day				Pass duration (seconds)				Gap between passes (hours)		
		min	max	mean	total per year	min	max	mean	per year (hrs)	min	mean	max (days)
Diego Garcia	-7.32	0	1	0.51	185	2	157	122	6.3	23.5	47.1	24.0
Changi, Singapore	1.31	0	1	0.49	179	5	156	122	6.1	23.5	48.7	16.2
Panama	8.95	0	1	0.50	184	12	157	124	6.3	23.5	47.5	22.1
Guam	13.46	0	2	0.55	201	1	157	122	6.8	23.5	43.5	21.1
Subic Bay, Philippines	14.81	0	2	0.55	201	51	157	125	7.0	8.4	43.5	24.1
Pearl Harbor, HI	21.36	0	4	0.70	257	16	158	122	8.7	1.6	34.0	24.2
San Diego, CA	32.71	0	3	0.56	203	8	136	108	6.1	1.6	41.7	38.1
Busan, South Korea	35.09	NO COVERAGE										
Yokosuka, Japan	35.30											
Bremerton, WA	47.55											
Nome, AK	64.49											
Average		**0**	**2**	**0.55**	**202**	**14**	**154**	**121**	**6.8**	**15.1**	**43.7**	**24.3**

Table 3. One satellite, 45° inclined performance.

One Satellite - 45° Inclination - 500 km Circular Orbit												
City Name	Latitude	Number of passes per day				Pass duration (seconds)				Gap between passes (hours)		
		min	max	mean	total per year	min	max	mean	per year (hrs)	min	mean	max (days)
Diego Garcia	-7.32	0	1	0.36	133	6	155	121	4.5	23.6	64.5	57.9
Changi, Singapore	1.31	0	1	0.36	131	13	155	122	4.4	23.6	65.0	38.3
Panama	8.95	0	1	0.35	128	8	155	122	4.3	23.6	65.5	57.9
Guam	13.46	0	2	0.36	132	5	155	121	4.4	23.6	64.2	41.3
Subic Bay, Philippines	14.81	0	2	0.37	135	9	155	121	4.5	23.6	63.8	41.3
Pearl Harbor, HI	21.36	0	2	0.37	136	5	156	121	4.6	8.3	63.4	55.0
San Diego, CA	32.71	0	3	0.46	168	6	157	123	5.7	6.6	52.1	48.2
Busan, South Korea	35.09	0	3	0.49	180	4	157	122	6.1	5.0	48.6	35.1
Yokosuka, Japan	35.30	0	3	0.51	184	1	157	123	6.3	5.0	46.7	40.0
Bremerton, WA	47.55	0	3	0.39	143	8	140	114	4.5	1.6	61.1	203.3
Nome, AK	64.49	NO COVERAGE										
Average		**0**	**2**	**0.40**	**147**	**7**	**154**	**121**	**4.9**	**19.0**	**59.5**	**61.8**

Table 4. One satellite, 60° inclined performance.

One Satellite - 60° Inclination - 500 km Circular Orbit													
City Name	Latitude	Number of passes per day				Pass duration (seconds)				Gap between passes (hours)			
		min	max	mean	total per year	min	max	mean	per year (hrs)	min	mean	max (days)
Diego Garcia	-7.32	0	1	0.28	104	2	153	121	3.5	23.6	84.5	101.2
Changi, Singapore	1.31	0	1	0.30	109	2	153	119	3.6	23.6	80.0	51.3
Panama	8.95	0	1	0.28	103	2	153	119	3.4	23.6	85.0	84.9
Guam	13.46	0	2	0.30	111	14	153	119	3.7	23.6	75.6	83.9
Subic Bay, Philippines	14.81	0	2	0.31	113	6	153	117	3.7	23.6	74.0	49.9
Pearl Harbor, HI	21.36	0	2	0.31	112	11	154	118	3.7	23.6	77.3	56.2
San Diego, CA	32.71	0	2	0.33	120	10	155	115	3.8	23.6	73.2	48.0
Busan, South Korea	35.09	0	2	0.32	116	2	155	121	3.9	8.3	75.3	52.0
Yokosuka, Japan	35.30	0	2	0.31	114	7	155	122	3.9	8.3	76.0	63.1
Bremerton, WA	47.55	0	3	0.34	123	8	157	123	4.2	6.5	71.3	183.2
Nome, AK	64.49	0	3	0.13	48	10	74	55	0.7	1.6	175.3	278.3
Average		**0**	**2**	**0.29**	**107**	**7**	**154**	**114**	**3.5**	**23.6**	**77.2**	**95.6**

2. Performance: One Satellite in Sun Synchronous Orbit Inclination

Most imaging satellites in sun synchronous orbits are positioned to cross the equator around 11 am, so it was deemed appropriate to compare my orbit designs against the established standard.[23]

Table 5. One satellite, SSO (11 am) performance.

One Satellite - SSO (11am) - 500 km Circular Orbit													
City Name	Latitude	Number of passes per day				Pass duration (seconds)				Gap between passes (hours)			
		min	max	mean	total per year	min	max	mean	per year (hrs)	min	mean	max (days)
Diego Garcia	-7.32	0	1	0.41	148	13	147	116	4.8	23.7	59.0	5.0
Changi, Singapore	1.31	0	1	0.40	147	17	147	116	4.7	23.7	59.6	4.0
Panama	8.95	0	1	0.41	149	6	147	116	4.8	23.7	58.8	4.0
Guam	13.46	0	1	0.41	151	10	147	116	4.9	23.7	57.8	4.0
Subic Bay, Philippines	14.81	0	1	0.42	152	12	147	116	4.9	23.7	57.5	4.0
Pearl Harbor, HI	21.36	0	1	0.43	157	15	148	117	5.1	23.7	55.5	4.0
San Diego, CA	32.71	0	1	0.48	175	5	149	118	5.7	23.7	50.0	4.0
Busan, South Korea	35.09	0	1	0.47	173	6	149	118	5.7	23.7	50.4	5.0
Yokosuka, Japan	35.30	0	1	0.48	176	1	149	117	5.7	23.7	49.8	5.0
Bremerton, WA	47.55	0	1	0.42	155	5	151	116	5.0	23.6	56.7	124.0
Nome, AK	64.49	0	2	0.45	166	8	153	118	5.4	1.6	52.9	204.0
Average		**0**	**1**	**0.44**	**159**	**11**	**148**	**117**	**5.2**	**23.7**	**55.5**	**33.4**

[23] Banniser, "SBMDA," 11.

3. Comparisons of Prograde to SSO – One Satellite

Table 6. Single satellite comparison – mean accesses per day.

Single Satellite - Mean # Accesses per Day					
PORT	**Lat.**	**30°**	**45°**	**60°**	**SSO**
Diego Garcia	-7.32	0.51	0.36	0.28	0.41
Changi, Singapore	1.31	0.49	0.36	0.30	0.40
Panama	8.95	0.50	0.35	0.28	0.41
Guam	13.46	0.55	0.36	0.30	0.41
Subic Bay, Philippines	14.81	0.55	0.37	0.31	0.42
Pearl Harbor, HI	21.36	0.70	0.37	0.31	0.43
San Diego, CA	32.71	0.56	0.46	0.33	0.48
Busan, South Korea	35.09		0.49	0.32	0.47
Yokosuka, Japan	35.30		0.51	0.31	0.48
Bremerton, WA	47.55		0.39	0.34	0.42
Nome, AK	64.49			0.13	0.45
Average		**0.55**	**0.40**	**0.29**	**0.44**

Table 7. Single satellite comparison – annual coverage.

Single Satellite - Annual Coverage (hours)					
PORT	**Lat.**	**30°**	**45°**	**60°**	**SSO**
Diego Garcia	-7.32	6.3	4.5	3.5	4.8
Changi, Singapore	1.31	6.1	4.4	3.6	4.7
Panama	8.95	6.3	4.3	3.4	4.8
Guam	13.46	6.8	4.4	3.7	4.9
Subic Bay, Philippines	14.81	7.0	4.5	3.7	4.9
Pearl Harbor, HI	21.36	8.7	4.6	3.7	5.1
San Diego, CA	32.71	6.1	5.7	3.8	5.7
Busan, South Korea	35.09		6.1	3.9	5.7
Yokosuka, Japan	35.30		6.3	3.9	5.7
Bremerton, WA	47.55		4.5	4.2	5.0
Nome, AK	64.49			0.7	5.4
Average		**6.8**	**4.9**	**3.5**	**5.2**

Table 8. Single satellite comparison – mean gap time.

Single Satellite - Mean Gap Time (hours)					
PORT	**Lat.**	**30°**	**45°**	**60°**	**SSO**
Diego Garcia	-7.32	47.1	64.5	84.5	59.0
Changi, Singapore	1.31	48.7	65.0	80.0	59.6
Panama	8.95	47.5	65.5	85.0	58.8
Guam	13.46	43.5	64.2	75.6	57.8
Subic Bay, Philippines	14.81	43.5	63.8	74.0	57.5
Pearl Harbor, HI	21.36	34.0	63.4	77.3	55.5
San Diego, CA	32.71	41.7	52.1	73.2	50.0
Busan, South Korea	35.09		48.6	75.3	50.4
Yokosuka, Japan	35.30		46.7	76.0	49.8
Bremerton, WA	47.55		61.1	71.3	56.7
Nome, AK	64.49			175.3	52.9
Average		**43.7**	**59.5**	**86.1**	**55.3**

4. Trends

A single satellite in a 30° orbit outperforms the others, but it is unable to access targets above approximately 35° N. What is not obvious, though, is that the 30° orbit is in eclipse significantly longer (due to precession, as explained in Chapter II.A.3.a). Table 9 better reflects this fact. Of note, the times included here *include* the time the satellite is in eclipse.

The tables also show that a single satellite in SSO actually outperforms 45° and 60° orbits. At this point, it does not seem beneficial to utilize a prograde orbit if only a single satellite can be launched.

Table 9. Max gap time comparison between 30° and SSO.

City Name	Max Gap (days)	
	30°	**SSO**
Diego Garcia	24.0	5.0
Changi, Singapore	16.2	4.0
Panama	22.1	4.0
Guam	21.1	4.0
Subic Bay, Philippines	24.1	4.0
Pearl Harbor, HI	24.2	4.0
San Diego, CA	38.1	4.0
Average	**24.3**	**4.2**

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V. CONSTELLATION DESIGN AND TESTING

In this chapter, constellation designs are considered, the one pursued for data collection is highlighted, and the results of that design are showcased using tables similar to the previous chapter.

It is an assumption, made in Chapter II.A.3.a.(4), that a single EO satellite in prograde orbits cannot successfully image year-round because of their precession into eclipse; they must be launched into a constellation. There are several ways to populate a constellation and what follows are the few that were considered.

A. MESHED COMBS

As mentioned in the earlier 2006 thesis work, a meshed comb constellation might be used to improve coverage.[24] Although it was suggested that these types of constellations are optimal for circular orbits, they are not considered for further study here. The meshed comb design requires half of the constellation to launch into retrograde (e.g., half of the satellites go into 30° and the other half go into 150° inclinations). Retrograde launches require significantly more thrust to get to orbital speeds *against* the Earth's rotation. One requirement of the designs proposed here is inexpensive launch cost, and the added expense to achieve retrograde insertion—for half of the constellation—was deemed excessive. It is worthy to note here, however, that modern space lift is approaching the point where rockets may have the excess capability launch a cluster of SkyBox-like satellites into retrograde orbit at no greater cost.

B. GENETIC ALGORITHMS

Genetic Algorithms are used to solve optimization problems throughout science. In 2004, students at NPS used this novel approach to design satellite constellations: specifically, they studied the performance of architectures designed using genetic

[24] Didier, "A Commercial Architecture for Satellite Imagery," 40.

algorithms (GAs) against traditional Walker constellations.[25] For their test case, they compared an 8/3/1 Walker inclined at 53° at 770 kms and compared the results to their simulated constellation designed using a GA.[26] Their research demonstrated that if less than 24 satellites are being employed, GA-designed constellations are preferred for increasing coverage and decreasing revisit time and number of gaps across any target latitude.[27] Others have come to the similar conclusions.[28] An assumption of my study is that 24 satellites will be utilized and, for that reason, GAs are *not* exploited for this research.

C. 24-PLANE WALKER CONSTELLATIONS

1. Constellation Design

a. Walker

The most common convention for designing circular satellite constellations came about in 1984, when J. G. Walker pioneered the *Walker delta pattern*.[29] The technique distributes *t* total satellites into *p* orbital planes, evenly spaced with a *f* relative phasing. This approach was used for this research because Walkers are typically manipulated to obtain continuous Earth coverage with the least amount of satellites.[30]

b. Walker Variation with (t/f/p)

There are many ways to employ Walker constellations. One current example of a Walker design is the European's Galileo Navigation System that uses a 27/3/1 constellation.[31] Initially, three designs were analyzed using STK's Walker Tool: 24/**24**/1,

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[25] Douglas J. Pegher and Jason A. Parish, *Optimizing coverage and revisit time in spare military satellite constellations: A comparison of tradition approaches and genetic algorithms* (September 2004), v.

[26] Ibid., 38.

[27] Ibid., 68.

[28] Edwin Williams, et al., "Average and maximum revisit time trade studies for satellite constellations using a multiobjective genetic algorithm," *The Journal of the Astronautical Sciences*, (July 2001), 1.

[29] Wertz, *SMAD*, 194.

[30] Ibid., 194.

[31] ESA, "Galile Satellites," http://www.esa.int/Our_Activities/Navigation/The_future_-_Galileo/Galileo_satellites, accessed January 2015.

24/**8**/1, and 24/**6**/1 (Table 10). The results were similar across the performance parameters studied and a decision was made to pursue a 24/24/1 design.

Table 10. Different configurations of Walker constellations considered.

24 Satellites, 30° Inclination, 500 km Circular Orbit													
City Name	Walker	Number of passes per day				Pass duration (seconds)				Gap between passes (hours)			
		min	max	mean	total per year	min	max	mean	per year (hrs)	min	mean	max (days)
Changi, Singapore	24/24/1	10	15	11.80	4316	1	156	122	146.4	0.1	3.2	0.8
Changi, Singapore	24/8/1	8	14	11.80	4312	0	156	122	146.4	0.5	3.2	0.8
Changi, Singapore	24/6/1	9	14	11.82	4319	0	156	122	146.7	0.2	2.0	0.8
Pearl Harbor, HI	24/24/1	10	24	16.92	6182	1	157	122	209.4	0.1	1.4	0.8
Pearl Harbor, HI	24/8/1	9	23	16.91	6178	1	157	122	209.3	0.0	1.9	0.9
Pearl Harbor, HI	24/6/1	10	22	16.92	6181	1	157	122	209.5	0.2	1.4	0.8
Subic Bay, Philippines	24/24/1	9	19	13.51	4934	0	157	123	168.0	0.1	1.7	0.8
Subic Bay, Philippines	24/8/1	9	17	13.52	4940	0	157	123	168.1	0.2	1.7	0.8
Subic Bay, Philippines	24/6/1	6	20	13.52	4940	0	157	123	168.2	0.1	1.7	0.9

c. "Hourly" Walker

Given the utility of the STK Walker Constellation Tool, an attempt was also made to simulate an hourly launch of satellites into orbit. It was difficult to use the tool to accurately fabricate this type of constellation and, ultimately, the results from a few test simulations underperformed against the other Walkers. Therefore, "Hourly" Walkers were discarded immediately and a 24/24/1 Walker became the sole focus of this paper.

D. 24-PLANE WALKER DESIGN RESULTS

1. Performance: 24 Satellites at Prograde Inclinations

Table 11. 24 satellites, 30° inclined performance.

24 Satellites - 30° Inclination - 500 km Circular Orbit													
City Name	Latitude	Number of passes per day				Pass duration (seconds)				Gap between passes (hours)		
		min	max	mean	total per year	min	max	mean	per year (hrs)	min	mean	max (days)
Diego Garcia	-7.32	8	18	12.13	4433	1	157	123	150.6	0.1	1.9	0.8
Changi, Singapore	1.31	10	15	11.80	4316	1	156	122	146.4	0.1	3.2	0.8
Panama	8.95	8	17	12.35	4511	1	157	122	153.3	0.1	1.9	0.8
Guam	13.46	8	20	13.16	4809	1	157	122	163.5	0.1	1.8	0.8
Subic Bay, Philippines	14.81	9	19	13.51	4934	0	157	123	168.0	0.1	1.7	0.8
Pearl Harbor, HI	21.36	10	24	16.92	6182	1	157	122	209.4	0.1	1.4	0.8
San Diego, CA	32.71	5	21	13.31	4864	0	136	108	146.6	0.1	1.8	1.0
Busan, South Korea	35.09	NO COVERAGE										
Yokosuka, Japan	35.30											
Bremerton, WA	47.55											
Nome, AK	64.49											
Average		**8**	**19**	**13.31**	**4864**	**1**	**154**	**120**	**162.6**	**0.1**	**2.0**	**0.8**

Table 12. 24 satellites, 45° inclined performance.

24 Satellites - 45° Inclination - 500 km Circular Orbit													
City Name	Latitude	Number of passes per day				Pass duration (seconds)				Gap between passes (hours)		
		min	max	mean	total per year	min	max	mean	per year (hrs)	min	mean	max (days)
Diego Garcia	-7.32	4	12	8.48	3097	0	155	121	104.2	0.1	2.8	0.9
Changi, Singapore	1.31	4	12	8.39	3066	0	155	121	103.1	1.4	4.8	0.9
Panama	8.95	4	12	8.55	3125	1	155	121	105.1	0.1	2.8	0.9
Guam	13.46	4	14	8.74	3194	0	155	121	107.5	0.2	2.7	0.8
Subic Bay, Philippines	14.81	6	14	8.83	3226	0	155	121	108.7	0.2	2.7	0.8
Pearl Harbor, HI	21.36	4	12	9.36	3420	3	156	122	115.8	0.3	2.5	0.9
San Diego, CA	32.71	4	20	11.37	4155	0	157	122	141.3	0.1	2.1	0.9
Busan, South Korea	35.09	2	20	12.21	4459	1	157	122	151.5	0.1	1.9	1.0
Yokosuka, Japan	35.30	2	20	12.30	4496	1	157	122	152.8	0.1	1.9	1.0
Bremerton, WA	47.55	0	21	9.74	3560	2	140	114	112.4	0.1	2.4	115.0
Nome, AK	64.49	NO COVERAGE										
Average		**4**	**16**	**9.80**	**3580**	**1**	**154**	**121**	**120.2**	**0.3**	**2.7**	**12.3**

Table 13. 24 satellites, 60° inclined performance.

24 Satellites - 60° Inclination - 500 km Circular Orbit													
City Name	Latitude	Number of passes per day				Pass duration (seconds)				Gap between passes (hours)		
		min	max	mean	total per year	min	max	mean	per year (hrs)	min	mean	max (days)
Diego Garcia	-7.32	4	12	7.00	2556	1	153	120	28.3	0.0	3.4	0.8
Changi, Singapore	1.31	4	12	6.94	2537	0	153	120	28.1	1.4	6.1	0.9
Panama	8.95	4	12	7.04	2570	1	153	119	85.3	0.0	3.4	0.8
Guam	13.46	4	13	7.10	2594	1	153	120	28.8	0.2	3.3	0.9
Subic Bay, Philippines	14.81	4	13	7.13	2604	1	153	120	86.7	0.2	3.3	0.9
Pearl Harbor, HI	21.36	3	12	7.34	2681	0	154	120	89.5	0.2	3.2	0.9
San Diego, CA	32.71	2	13	7.73	2825	0	155	121	95.0	0.4	3.1	1.0
Busan, South Korea	35.09	1	13	7.76	2837	1	155	121	31.9	0.4	3.1	1.0
Yokosuka, Japan	35.30	1	13	7.76	2837	0	155	121	95.4	0.4	3.1	1.0
Bremerton, WA	47.55	0	22	8.51	3109	8	157	123	35.1	0.1	2.8	114.0
Nome, AK	64.49	0	13	3.27	1196	1	78	57	18.8	0.1	7.3	205.0
Average		**4**	**14**	**7.05**	**2577**	**1**	**154**	**115**	**56.6**	**0.3**	**3.5**	**29.7**

2. Performance: 24 Satellites in Sun Synchronous Orbit Inclination

Table 14. 24 satellites, SSO (11 am) performance.

24 Satellites - SSO (11am) - 500 km Circular Orbit													
City Name	Latitude	Number of passes per day				Pass duration (seconds)				Gap between passes (hours)		
		min	max	mean	total per year	min	max	mean	per year (hrs)	min	mean	max (days)
Diego Garcia	-7.32	4	9	6.36	2325	0	147	115	74.2	0.0	3.7	0.9
Changi, Singapore	1.31	4	12	6.33	2312	2	147	115	73.7	0.0	7.1	0.9
Panama	8.95	4	9	6.37	2326	2	146	115	74.2	0.0	3.7	20.7
Guam	13.46	4	10	6.38	2331	1	147	115	74.5	0.1	3.7	0.9
Subic Bay, Philippines	14.81	4	10	6.39	2335	2	147	115	74.8	0.1	3.7	0.9
Pearl Harbor, HI	21.36	3	10	6.50	2373	1	148	115	76.0	0.1	3.7	0.9
San Diego, CA	32.71	2	12	6.55	2392	1	149	116	77.1	0.2	3.6	1.0
Busan, South Korea	35.09	0	13	6.47	2364	0	149	116	76.5	0.2	3.7	2.0
Yokosuka, Japan	35.30	0	12	6.47	2364	0	149	116	76.5	0.2	3.7	2.0
Bremerton, WA	47.55	0	13	5.99	2188	2	151	118	71.6	0.3	4.0	115.1
Nome, AK	64.49	0	21	6.32	2308	2	153	119	76.3	0.0	3.8	204.0
Average		**4**	**11**	**6.38**	**2329**	**1**	**148**	**116**	**75.0**	**0.1**	**4.1**	**31.7**

3. Comparisons of Prograde to SSO – 24 Satellites

Table 15. 24 satellites comparison – mean access per day.

24 Satellites - Mean # Accesses per Day									
PORT	Lat.	30°		45°		60°		SSO	
		1 sat	24 sats	1 sat	24 sats	1 sat	24 sats	1 sat	24 sats
Diego Garcia	-7.32	0.51	**12.1**	0.36	**8.5**	0.28	**7.0**	0.41	**6.4**
Changi, Singapore	1.31	0.49	**11.8**	0.36	**8.4**	0.30	**6.9**	0.40	**6.3**
Panama	8.95	0.50	**12.4**	0.35	**8.6**	0.28	**7.0**	0.41	**6.4**
Guam	13.46	0.55	**13.2**	0.36	**8.7**	0.30	**7.1**	0.41	**6.4**
Subic Bay, Philippines	14.81	0.55	**13.5**	0.37	**8.8**	0.31	**7.1**	0.42	**6.4**
Pearl Harbor, HI	21.36	0.70	**16.9**	0.37	**9.4**	0.31	**7.3**	0.43	**6.5**
San Diego, CA	32.71	0.56	**13.3**	0.46	**11.4**	0.33	**7.7**	0.48	**6.6**
Busan, South Korea	35.09			0.49	**12.2**	0.32	**7.8**	0.47	**6.5**
Yokosuka, Japan	35.30			0.51	**12.3**	0.31	**7.8**	0.48	**6.5**
Bremerton, WA	47.55			0.39	**9.7**	0.34	**8.5**	0.42	**6.0**
Nome, AK	64.49					0.13	**3.3**	0.45	**6.3**
Average		**0.55**	**13.31**	**0.40**	**9.80**	**0.29**	**7.05**	**0.44**	**6.38**

Table 16. 24 satellites comparison – annual coverage.

24 Satellites - Annual Coverage (hours)									
PORT	Lat.	30°		45°		60°		SSO	
		1 sat	24 sats	1 sat	24 sats	1 sat	24 sats	1 sat	24 sats
Diego Garcia	-7.32	6.3	150.6	4.5	104.2	3.5	28.3	4.8	74.2
Changi, Singapore	1.31	6.1	146.4	4.4	103.1	3.6	28.1	4.7	73.7
Panama	8.95	6.3	153.3	4.3	105.1	3.4	85.3	4.8	74.2
Guam	13.46	6.8	163.5	4.4	107.5	3.7	28.8	4.9	74.5
Subic Bay, Philippines	14.81	7.0	168.0	4.5	108.7	3.7	86.7	4.9	74.8
Pearl Harbor, HI	21.36	8.7	209.4	4.6	115.8	3.7	89.5	5.1	76.0
San Diego, CA	32.71	6.1	146.6	5.7	141.3	3.8	95.0	5.7	77.1
Busan, South Korea	35.09			6.1	151.5	3.9	31.9	5.7	76.5
Yokosuka, Japan	35.30			6.3	152.8	3.9	95.4	5.7	76.5
Bremerton, WA	47.55			4.5	112.4	4.2	35.1	5.0	71.6
Nome, AK	64.49					0.7	18.8	5.4	76.3
Average		**6.8**	**162.6**	**4.9**	**120.2**	**3.5**	**56.6**	**5.2**	**75.0**

Table 17. 24 satellites comparison – mean gap time.

24 Satellites - Mean Gap Time (hours)									
PORT	Lat.	30°		45°		60°		SSO	
		1 sat	24 sats	1 sat	24 sats	1 sat	24 sats	1 sat	24 sats
Diego Garcia	-7.32	47.1	**1.9**	64.5	**2.8**	84.5	**3.4**	59.0	**3.7**
Changi, Singapore	1.31	48.7	**3.2**	65.0	**4.8**	80.0	**6.1**	59.6	**7.1**
Panama	8.95	47.5	**1.9**	65.5	**2.8**	85.0	**3.4**	58.8	**3.7**
Guam	13.46	43.5	**1.8**	64.2	**2.7**	75.6	**3.3**	57.8	**3.7**
Subic Bay, Philippines	14.81	43.5	**1.7**	63.8	**2.7**	74.0	**3.3**	57.5	**3.7**
Pearl Harbor, HI	21.36	34.0	**1.4**	63.4	**2.5**	77.3	**3.2**	55.5	**3.7**
San Diego, CA	32.71	41.7	**1.8**	52.1	**2.1**	73.2	**3.1**	50.0	**3.6**
Busan, South Korea	35.09			48.6	**1.9**	75.3	**3.1**	50.4	**3.7**
Yokosuka, Japan	35.30			46.7	**1.9**	76.0	**3.1**	49.8	**3.7**
Bremerton, WA	47.55			61.1	**2.4**	71.3	**2.8**	56.7	**4.0**
Nome, AK	64.49					175.3	**7.3**	52.9	**3.8**
Average		**43.7**	**2.0**	**59.5**	**2.7**	**86.1**	**3.8**	**55.3**	**4.0**

4. Trends

The 30° orbit continues to perform the best, but now the SSO constellation is the underperformer in most cases. When populated as constellations, both 45° and 60° orbits can perform better than a similarly populated SSO. It is important to note, however, that since optimization was not the goal of this thesis, it is possible that an SSO can be designed to once again outperform these prograde constellations.

5. Cost Analysis

Costs are being driven lower as technology becomes more affordable and techniques for launching into space also become appreciably cheaper. In the 2006 thesis, it was proposed that a system of 12 commercial satellites could provide single-digit GSD with a revisit of one day for an annual life cycle cost of approximately $1-2 billion.[32] In 2013, the commercial SkySat-1 costs under $50 million in for a satellite that was purported to last four to six years.[33] It is assessed that reproductions of that satellite are

32 Didier, "A Commercial Architecture for Satellite Imagery," i.

33 David Samuels, "Inside a startup's plan to turn a swarm of DIY satellites into an all-seeing eye," http://www.wired.com/2013/06/startup-skybox/, accessed January 2015.

now likely to cost less than $20 million.[34] A commercial launch from SpaceX currently costs $61.2 million to place 13,000 kg into LEO inclined at 28.5°.[35] From these costs, some rudimentary approximations can be made to outline the basic cost proposed here (Table 18). These numbers do not reflect launching into different inclinations, inter-plane phasing of individual satellites, nor the ground stations that will support the satellites. An overall comparison can be made against a legacy system, the one proposed in 2006, and the one presented here (Table 19). From this estimate, it is plausible that a constellation could cost significantly less than $0.5 billion.

Table 18. Sample costs for different constellation designs.

Constellation	Life Cycle	Annual (4yr life)	Annual (6yr life)
Walker 8/3/1	$970 M	$242 M	$162 M
Walker 6/4/1	$725 M	$181 M	**$121 M**
Walker 24/1/1	$1949 M	**$487 M**	$325 M

Table 19. An overall comparison between a legacy system, the 2006 thesis design, and the current design.

	Legacy	Didier (2006)	Konowicz (2015)
Model	GeoEye-1	QuickBird	SkySat
Weight	1,000+ kg	1,000 kg	100 kg
Altitude	450 – 700 km	185 x 700 km	500 km
Inclination	SSO	SSO	Prograde
Optic	0.6 m	0.6 m	0.35 m
Walker	N/A	12/1/1	24/1/1
Life Span	7+ years	~1 year	4 – 6 years
Annual Life Cycle	$70 M	$1,000 M	$121 – 487 M
Revisit	1 – 3 days	3.4 hours	2 – 4 hours

34 Conversation with Dr. Chris Olsen, Remote Sensing Laboratory, Naval Postgraduate School, Monterey, California, February 15, 2015.

35 SpaceX, "Capabilities & Services," http://www.spacex.com/about/capabilities, accessed January 2015.

VI. CONCLUSION

The takeaway is that potential benefit exists if prograde orbits are utilized. The benefits include increased coverage duration, increased daily access, and decreased revisit time. The tradeoff includes a loss of high-latitude regions, more complicated ground architecture, and a higher cost due to the fact that more satellites need to be launched to populate the constellation.

(1) Space Lift

This thesis was focused on testing the feasibility of a prograde constellation design and assumed the satellites were properly inserted into orbit. Space lift capabilities need to be explored to determine how to make this a reality, particularly a hypothetical 24-plane solution suggested here.

(2) Ground Architecture

A constellation of satellites in SSO can exist with one or two ground stations; but a prograde constellation will need a suitable ground station network to support operations. Current concerns include downlinking, distributing the data, processing sites, and ultimate delivery to the end-user. It is conceivable that in the near future, this type of platform might need the potential to link into the space situational awareness network. None of these issues are trivial and deserve a concerted analysis to assess the practicality of these prograde constellations.

(3) Payloads

Exploring different types of sensors to replace an EO imager, or even an assortment of payloads hosted on a single satellite in these orbits deserves to be addressed. A single-sensor satellite was considered to keep the launch payload light; hosting multiple payloads will invariable raise the overall satellite weight and, consequently, launch cost. A cost-benefit analysis of this type will also prove insightful.

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APPENDIX. STK EXTRACTS

```
FOR UNFUNDED EDUCATIONAL USE ONLY
Coverage for SanDiego


Daily Coverage for SanDiego
---------------------------

                      # of Accesses
                      -------------

Global Statistics
-----------------
Min # of Accesses                 2
Max # of Accesses                12


Coverage for SanDiego
---------------------

                  Access    Duration (sec)
                  ------    --------------

Global Statistics
-----------------
Min Duration        3711             0.798
Max Duration        4544           148.684
Mean Duration                      116.043
Total Duration                  832726.865


Revisit Time for Point (Lat / Lon): 32.71 / -117.18
---------------------------------------------------

                      Value (hr)
                      ----------

Global Statistics
-----------------
Max Value                 24.936
```

Figure 14. Sample custom performance report for San Diego using a 24-plane SSO.

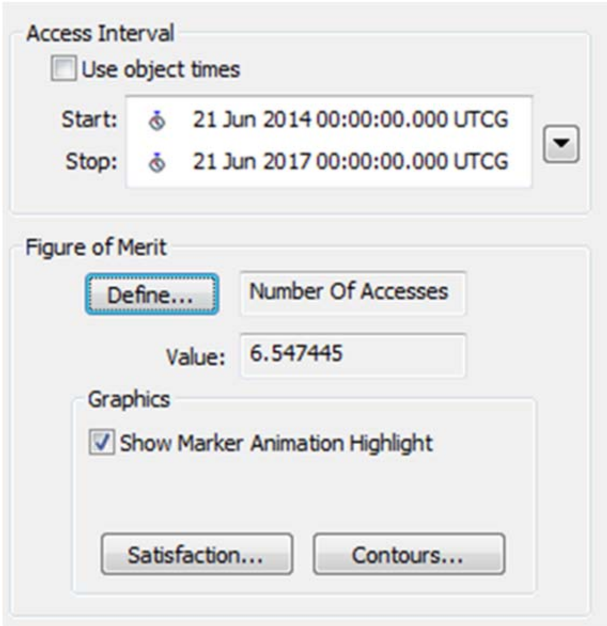

Figure 15. A sample of San Diego "Number of Accesses: Avg Per Day" from STK Coverage Tool using a 24-plane SSO.

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