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A commercial architecture for satellite imagery

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THESIS

A COMMERCIAL ARCHITECTURE FOR SATELLITE IMAGERY

by

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September 2006

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The objective of this research is to determine the possibility of an alternative for government-developed satellites which produce high resolution imagery. This study focuses on the concept of the U.S. government purchasing proven and successful commercial satellites with minimal non-recurring engineering costs to help augment current national systems. The benefit with this alternative is the reliability and affordability of a system that is currently used in space and therefore reduces a significant amount of risk as well as production time. A constellation of commercial satellites that are reconstituted on a monthly or quarterly cycle could also invigorate the commercial satellite work force and better produce future systems. A disadvantage with an architecture of commercial satellites are potential limitations with geolocation accuracy and data rate downlink transmission capability.

This thesis evaluates constellation design factors such as orbit types, number of satellites, life-cycle and ground segment implementation. A coverage capability evaluation is provided to determine how a commercial system would be able to fulfill national imagery collection requirements. Eight different constellation types were created, ranging from one to 12 satellites in size. Orbit analysis settled on a sun-synchronous polar elliptical orbit at 185 km x 700 km, using an existing commercial satellite with a 0.6m optic. This provided imaging with a resolution range between 10-37 inches. The largest constellation of 12 satellites would provide a daily area collection of 43,000 km2 and 150 point images for a region the size of Iraq and would have an estimated $1-2B cost for an annual life cycle cost. Revisit time for mid-latitude targets was approximately one day at 10 inch resolution.

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A COMMERCIAL ARCHITECTURE FOR SATELLITE IMAGERY

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I. INTRODUCTION

The military and intelligence communities have an ongoing need for timely, high-spatial resolution imagery. Historically, such imagery has been provided by a system termed National Technical Means (NTM). Current classified imaging satellite systems are enormously capable because of their agility, accuracy and quality of the products which are produced. They will continue to be a valuable strategic and operational asset in order to meet national security needs and tactical objectives. These systems, however, are also very large, heavy, complex and expensive. Continuing fund reductions for space systems will affect the development of these complex imagery satellites and will continue to make it more challenging to develop and deploy as future imaging systems. The existence of problems with this system has recently been demonstrated by the cancellation of the optical component of the Future Imagery Architecture (FIA).[1] This indicates the need for alternate approaches to obtaining the imagery products needed by the military and intelligence communities. One such approach is to make use of smaller commercial satellites, effectively exploiting Commercial-Off-The-Shelf (COTS) hardware.

A. STATEMENT OF THE PROBLEM & OBJECTIVE

The problems which evolved during the program noted above are part of a larger systemic problem in the military space business – insufficient industrial base, lack of technical oversight, contractors 'buying-in' to programs, all leading to failed designs and startling cost growth.

The objective of this study is to determine the effectiveness for the United States (U.S.) government to purchase proven and successful commercial satellites to meet a subset of the strategic and operational goals of imagery collection in support of the national security of the United Sates. This idea of a COTS solution for FIA is in no way intended to replace the systems of our current national technical means. It is intended to be a way to provide an affordable and reliable method to augment and reduce the demands imposed on these national systems. A logical method of study is to first review

[1] Defense Tech, "Boeing: We Screwed Up, Give us $500 Mil.," http://www.defensetech.org/archives/002142.html, accessed August 2006.

current national Electro-Optical (EO) imagery requirements and determine how a commercial product can fulfill these requirements. The requirements set forth by FIA have been collected and are used to determine how much of these requirements can be met by a commercial system (% requirements met). In order to keep this work unclassified, some simplified versions of those requirements will be set.

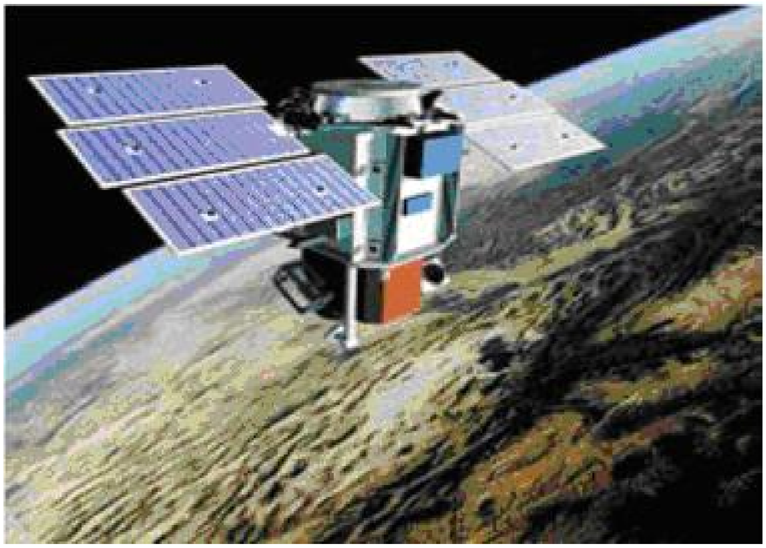

Figure 1. Digital Globe's QuickBird Satellite.[2]

1. Study Boundaries

The study boundaries of this thesis are to research and analyze the qualitative behavior of a commercial imaging satellite constellation and evaluate to what degree such a system can meet imagery collection requirements. This study includes a physical analysis of the orbital mechanics of a commercial satellite operating with various orbital parameters in order to determine a general estimation of orbit life and coverage capability. This study only addresses, in a preliminary way, the nature of point and area coverage and associated resolution. No analysis is done for different launch systems or techniques for orbital insertion. Additionally, this study does not include an in-depth analysis of orbital determination for precise orbit life prediction or present an explicit acquisition model and implementation method for commercial satellite constellation procurement.

[2] Digital Globe, QuickBird Imagery Products Guide, December 2002, http://www.aeromap.com/downloads/diglo/QuickBirdImageryProducts-ProductGuidev3-4.pdf, accessed July 2006, 2.

2. Assumptions

Several early assumptions were made to limit the volume of work. Effective orbit design requires a clear understanding and identification of the reasons of orbit selection and should be continuously evaluated for changes in mission requirements. As a result, a given constellation cannot meet all requirements all of the time. For this project, there are three assumptions made at the beginning of research.

- Existing commercial systems would be used to minimize Non-Recurring Engineering (NRE) costs
- The orbit life for a commercial satellite will be one (1) year; facilitating low orbits and reducing the need for system redundancy
- More sophisticated NTM systems would continue to fly

These assumptions are intended to keep total program budget at or below the level of the longer lived, more robust national systems. Having little or no NRE costs will help ensure lower program costs. A one year orbit life was an arbitrary selection based on expected resolution capabilities and simplicity when analyzing total system life cycle costs. The third assumption illustrates that a COTS architecture is not intended to replace current or future national systems; merely a method of augmenting these systems. This is an important point to understand in an era of increasing military utilization of imagery reconnaissance. Overall, these assumptions are guidelines that help provide and architecture that meet majority of our national imagery requirements.

B. BACKGROUND

Currently, the commercial remote sensing industry has demonstrated a strong and robust relationship with the National Geospatial-Intelligence Agency (NGA) to produce and sell images for government use. In January 2003, Digital Globe was awarded a multi-million dollar contract not to exceed $500M to provide satellite imagery to the NGA for a period of three years.[3] This agreement was termed the ClearView contract and has had several modifications to acquire additional commercial images since then. ORBIMAGE was also awarded a $500M, four year contract with the NGA for high

[3] Digital Globe, "National Geospatial-Intelligence Agency Awards $24 Million Clear View Contract to DigitalGlobe," http://media.digitalglobe.com/index.php?s=&ITEM=98l, accessed Sept 2006, 1.

resolution imagery sales.[4] In turn, this provides a funding method for technological growth. The next-generation OrbView-5 satellite will be able to produce a 40 cm resolution panchromatic image and augment OrbView-3 to produce over 1.2 million square kilometers of imagery every day with point target revisit of 1.5 days.[5]

Despite the success of this collection method from commercial products, consideration must be given towards a government owned system to ensure security of national interests and the collection of higher resolution images. This greater resolution collection in a classified venue can be accomplished without the need of developing new complex and costly systems but instead, purchasing commercial satellites for government use and operating in modified orbits.

Several commercial satellites were considered as a model for this study such as IKONOS, QuickBird, OrbView and SPOT. A decision was made to use the QuicBird-2 satellite as a design example since this system is currently in orbit and is a major supplier of commercial products for commercial and government use today.

1. Coverage Considerations

Imagery mission requirements can drive a design requirement for a given constellation. Such requirements present image collections that can be grouped into one of three general categories and have an associated quantitative description:

- Medium resolution: total square kilometers per day (area targets)
- Highest resolution: total number of pictures per day (point targets)
- Access area: The ability to see a terrestrial region per day with a given amount of persistence

The evaluation of simple area coverage of a single satellite in Low Earth Orbit (LEO) was the first step in determining the value of this thesis. A question that was posed was to determine how many commercial imagery satellites flying in a 150 km circular orbit would be required to image an area of interest (such as a large city) once a day. The 150 km orbital altitude was a starting parameter since it was considered the lowest possible altitude a constellation of commercial satellites would fly. From there, an incremental analysis of coverage versus increasing altitude was accomplished for

4 Orbimage, "Orbimage Selected as NGS's Second NextView Provider," http://www.orbimage.com/news/releases/09-30A-04.html, accessed July 2006, 1.

5 Ibid, 1.

optimum orbit determination ton include elliptical orbits. Multiple iterations were accomplished to determine an ideal orbit which provides improved resolution in addition to acceptable area coverage with reasonable lifetime.

2. Orbital Constraints

When designing a low altitude constellation, it is necessary to determine orbit life of a LEO satellite while taking into account all available fuel. To meet as much of the EO imagery requirements as possible, several orbits and constellation designs were analyzed. Bounds were determined and set in order to know which orbit would produce the highest quality images and yet sustain a reasonable orbit life. At one extreme, the 150 km circular orbit altitude could provide high quality imagery products but with a tremendously short life cycle—roughly 3 days for QuickBird.

A difficult question to answer is to determine an optimum orbit which can provide quality imagery resolution and yet maintain desirable orbit life and is the thrust of this thesis. The aforementioned assumption for a one year orbit life was used to design a low flying orbit in order to generate respectable high resolution quality images.

3. The Cost Factor

The orbit life and number of satellites in a constellation directly relates to the lifecycle cost of such a system. Flying at a lower altitude will produce higher quality images but will reduce the total area covered or sensed by the satellite. With less total "mapable" area from a lower altitude, additional satellites are required to effectively meet coverage requirements. Additionally, lower flying satellites will reduce orbit life and therefore increase constellation population and satellite reconstitution. All of these constraints factor into the life cycle costs and need to be evaluated to determine if a low flying commercial satellite with a short life span is worth the investment.

In the sections that follow, additional elements of the existing commercial systems are defined, and the results of a large number of orbital analysis efforts are described. The capability of the resulting architecture is then reviewed.

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II. REVIEW OF LITERATURE

A. NIIRS REQUIREMENTS

To better understand the directions taken for this study, it is necessary to discuss the method and tools of measuring the quality of an image for analysis. Among these tools is the National Image Interpretability Rating Scale (NIIRS). This scale has been created for applications related to remote sensing and simply quantifies the quality of an image. NIIRS was based on the ability to detect, distinguish or identify a specific object or part of an object and is divided into 10 separate rating scales[6]. The scale augments other measurement techniques such as Ground Separation Distance (GSD), signal-to-noise ratio and modulation transfer function. A Civilian Image Interpretability Rating Scale (CIIRS) is used for commercial applications from commercially operated satellites and relates closely to NIIRS.

GSD is a commonly used imaging term which represents a minimum distance between two objects or components attached to an object that can be distinguishable from observation or study of an image.[7] Spatial resolution alone does not determine the actual NIIRS value of an image. Other factors will have an affect on interpreting information potential such as noise, sharpness and contrast. These effects can be due to system limitations (e.g., optical and focal plane quality), atmospheric conditions (e.g., sun lighting, shadow, haze), and exploitation conditions (e.g., duplicate film quality, monitor quality). By design, the NIIRS was intended to be independent of a specific imaging system. The table below presents an example CIIRS scale as defined by the Imagery Resolution Assessments and Reporting Standards Committee. A classified NIIRS rating scale can be found in the Joint Tactical Exploitation of National Systems (JTENS) manual in Chapter 4, Figure V-4-30 (July 2005) and presents associated descriptions with greater accuracy. Additionally, a scaling factor and conversion column was added for clarification purposes:

[6] Integrated Publishing, "Joint Preparation of the Battlespace, Appendix B," http://www.tpub.com/content/USMC/mcr3353a/css/mcr3353a_87.htm, accessed July 2006.

[7] Richard C. Olsen. *Remote Sensing from Air and Space* (November 2005), 70.

Rating	in	cm	Definitions
0	--	--	Interpretability is precluded by obscuration or degradation.
1	320	813	Detect the presence of aircraft dispersal parking areas. Detect lines of transportation (either road or rail), but do not distinguish.
2	160	406	Detect the presence of large bombers or transports. Detect large non-combatant ships at a known port facility.
3	80	203	Detect medium-sized aircraft (e.g., FENCER, FLANKER, F-15). Determine the location of the superstructure on a medium-sized freighter.
4	40	101	Distinguish between large rotary-wing and medium fixed-wing aircraft. Detect all rail/road bridges.
5	20	50	Distinguish bow shape and length/width differences of SSNs. Detect the break between railcars (count railcars).
6	12	30	Distinguish between small support vehicles and tanks. Detect cargo on a railroad flatcar or in a gondola.
7	6	15.2	Identify small fighter aircraft by type (e.g., FISHBED, FITTER, F-16). Detect road/street lamps in an urban, residential area or military complex.
8	3	7.6	Identify the SA-6 trans-loader when other SA-6 equipment is present. Identify the dome/vent pattern on rail tank cars.
9	~2	5	Identify the forward fins on an SA-3 missile. Identify trucks as cab-over-engine or engine-in-front.

Table 1. Visible Civil Imagery Interpretability Rating Scale-March 1994.[8]

To better illustrate how a NIIRS rating can be inferred from an image, an example is shown with an image taken by QuickBird. Based on what is intended to be distinguishable, detected or identified in an image, different NIIRS ratings can be labeled for a given image. The following image and resultant NIIRS rating was assessed for commercial interpretability purposes. Their focus is to be able to identify features commonly mapped in civil government and commercial applications.

[8] Civil NIIRS Reference Guide, Appendix III, http://www.fas.org/irp/imint/niirs_c/app3.htm, accessed July 2006.

Figure 2. Civil NIIRS Assessment.[9]

The cultural criteria for the above image can be assessed in a number of different categories. A CIIRS level of 4.0 will allow detection of overpasses which this image clearly shows. Detection of man-made dividers and Jersey barriers are rated at a CIIRS level of 4.8. Level 5.5 will provide the ability to detect cross-walks and 5.7 is the scale to discern arrow direction for traffic flow. All of the aforementioned cultural criteria can be detected and identified from the above image which illustrates the rating level of the photograph. For purposes of this report, a high resolution image is defined as an image of the NIIRS category level of 6.5 or greater (<10 inches, <22cm).

B. FIA REQUIREMENTS

System design should begin with a comprehensive review of valid and derived user requirements. Although the spectrum of users of satellite imagery is considered vast, FIA requirements were collected from the National Geospatial Intelligence Agency (NGA) as a starting point. These classified requirements were reviewed in order to better understand the capabilities that are of interest for our national users as well as users in the

[9] Digital Globe, *Developing New Standards for a Changing Geospatial World-Part 4: Development of Digital Data Standards* (June 2004), slide 7.

theater. Much of the capabilities output from this thesis were formatted in a familiar fashion in order to provide recognizable data that can be easily understood throughout the image intelligence (IMINT) community.

C. QUICKBIRD SPECIFICATIONS

QuickBird is an agile panchromatic and multispectral EO imaging satellite and is operated by Digital Globe with Ball Aerospace as the primary contractor for satellite construction. QuickBird was launched on 18 October 2001 on a Delta-II booster. Other launch vehicles for QuickBird are registered with Titan II, COSMOS SL-8, Taurus, Athena and Long March.[10]

QuickBird operates in a 450 km circular orbit with a ~97 degree inclination (sun-synchronous) and has an expected operating life of 5 years.[11] QuickBird's satellite bus utilizes Ball Aerospace's BCP 2000 configuration that uses a simple panel-post aluminum honeycomb structure. Image quality and accuracy incorporates some of the commercial industry's leading technologies. Average drag area of QuickBird in a sun-synchronous orbit is 7.1 square meters.[12] This value is based on the size of the satellite bus relative to the direction of velocity and the solar arrays maintaining a positive orthogonal track to the sun. Best resolution in panchromatic form is approximately 60 cm at nadir (NIIRS rating ~6) with a large area collection of 16.5 km swath and a 45 degree field of regard.[13] Geolocation accuracy is rated as <10-23 meters (3 sigma; circular error).[14]

1. Fuel and Power Systems

Various fuel loads range from 76-315 kg can be utilized and easily incorporated in QuickBird construction to customize with users requirements. The attitude control system uses Anhydrous Hydrazine (N_2H_4) and can provide roughly 590 m/s Delta-V.[15]

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10 Ball Aerospace & Technologies Corp., *BCP 2000,* marketing sheet, 2.

11 Ibid, 2.

12 Scott Mitchell, Re: QuickBird Drag Area, Available e-mail: from smitchel@ball.com, accessed March 2006.

13 Digital Globe, *QuickBird Imaging Spacecraft,* marketing sheet, 1.

14 Ibid, 2.

15 Scott Mitchell, Re: The rocket equation: $Delta-V = 230s * 9.81\frac{m}{s^2} * LN\left(\frac{1367kg}{1052kg}\right) = 590\frac{m}{s}$, Available e-mail: from smitchel@ball.com, accessed March 2006.

The power subsystem contains a power control and distribution unit that is fully redundant. This system utilizes two single-axis drive solar array panels and a 40 amp-hour NiH_2 battery with a spare cell. Attitude determination is provided by the use of two star trackers, sun sensors, magnetometers and redundant inertial reference units. Attitude control is maintained from four low-vibration reaction wheels and three torque rods. Slew rate capability is 4 deg/sec with an angular accelerations capability of 0.1 deg/s^2. The agility of this system is measured in the along and across track directions for re-pointing and stabilization for data acquisition. Nominal maneuvering time for 10 degrees transition and settling is accomplished in 20 seconds; 50 degrees in 45 seconds.[16]

2. Communications, Command & Data Handling

Communications with QuickBird uses a STDN-compatible S-band transmitter for narrow band data transmission and X-band transmission for downlink at 320 Mbps. Command and data handling is provided from a dedicated unit with 256 MB storage capability. Solid state recorders provide support for real-time telemetry and data handling at 576 Mbps input rates while simultaneously maintaining a 320 Mbps output rate.[17] 200 GB of onboard scalable storage capability is provided.

3. Imagery Capability

QuickBird provides imagery products in a variety of options. Generally, their products are available in three processing levels; 1) basic imagery with the least amount of processing and fastest delivery, 2) standard imagery with radiometric and geometric corrections and 3) orthorectified imagery with radiometric, geometric and topographic correction. The second and third level of processing is provided in a map projection format and requires additional processing time for delivery.[18]

In addition to the three different processing levels, QuickBird imagery is offered in five different quality formats based on the collection spectrum. These options include 1) panchromatic (black & white) products, 2) Multi-Spectral Imagery (MSI) products which incorporates image detection from the visible and near-infrared wavelengths, 3)

[16] Ball Aerospace & Technologies Corp., *BCP 2000,* marketing sheet, 2.

[17] Digital Globe, *QuickBird Imaging Spacecraft,* marketing sheet, 2.

[18] Digital Globe, *QuickBird Imagery Products Guide* (December, 2002), http://www.aeromap.com/downloads/diglo/QuickBirdImageryProducts-ProductGuidev3-4.pdf, accessed July 2006, 7.

bundle products which include both panchromatic and MSI images, 4) individual products in natural three-band color (blue, green and red wavelengths) and finally 5) pan-sharpened (four-band) image.[19]

The products produced by QuickBird vary based on the needs of the user and pointing requirements. A typical nadir pointing image from 450 km produces a swath width of 16.5 km (272.25 km^2 imaged footprint). Product ordering is ranked on one of three priorities based on the users need and will generate appropriate levels of tasking orders. For standard tasking priority, a maximum area to be collected with 5 collection attempts (easily accomplished with in one day) would collect 10,000 km^2 of imagery (nadir pointing).[20] Off nadir pointing would produce larger area images but with reduced resolution based on the amount of across track (distance away from nadir).

4. Accuracy

Standard imagery is enhanced to normalize for topographic relief with respect to the reference ellipsoid.[21] The degree of normalization for the standard imagery is relatively small, and is therefore not considered orthorectified even though there are terrain corrections. Ortho ready imagery has no topographic corrections, making it suitable for orthorectification.[22] Orthorectification is the act of removing terrain distortions to facilitate generating reliable image data in areas of varying heights or altitudes.[23] The more topographically diverse the terrain, the more distortion that is inherent in the photograph.

All standard imagery products have an average absolute geolocation accuracy of 14-meter RMSE (23-meter circular error of 90% and 17-meter linear error of 90%), excluding any topographic displacement and off-nadir viewing angle. Additionally,

[19] Digital Globe, *QuickBird Imagery Products Guide* (December, 2002), http://www.aeromap.com/downloads/diglo/QuickBirdImageryProducts-ProductGuidev3-4.pdf, accessed July 2006, 21.

[20] Ibid, 4.

[21] Ibid, 16.

[22] Ibid, 13.

[23] Satellite Imaging Corporation, *Orthorectification* http://www.satimagingcorp.com/svc/orthorectification.html, accessed August 2006.

ground location is derived from refined satellite attitude and ephemeris information without requiring the use of ground control points.[24]

D. THE RESOLUTION FACTOR

The sequence of events that determine resolution of a given optical system start with the collection of photons traveling through the atmosphere. In general, three environmental factors that constrain resolution of any EO system in orbit are absorption, scattering and turbulence.[25] For commercial imaging satellites, these photons are to be collected and require an optical system and detectors.

Resolution of a system can be determined in one of two ways, calculating expected GSD based on given optics and detectors or linear interpolation of a system from a known altitude. Resolution accuracy based on a linear representation from apogee to perigee is limited based on the variance of atmospheric density. For a given optic system, geometry holds true when determining the size of an image; hence its resolution. For optics, magnification is equal to the ratio of the distance from the image to the lens and object to the lens.[26]

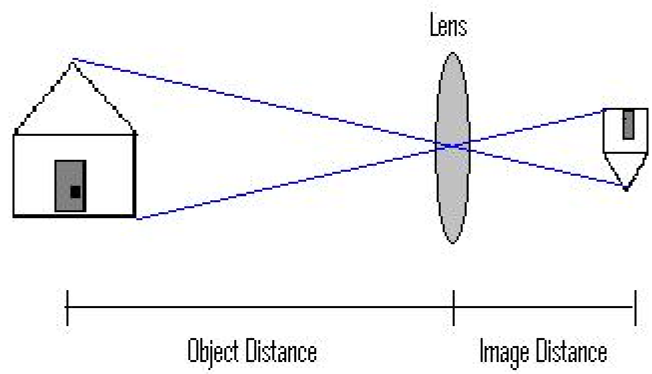

Figure 3. Magnification Illustration.[27]

Similarly, as the object distance is reduced (flying at a lower orbital altitude) the larger the image size will be and therefore greater resolution. As previously stated, a goal

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[24] Digital Globe, QuickBird Imagery Products Guide (December, 2002), http://www.aeromap.com/downloads/diglo/QuickBirdImageryProducts-ProductGuidev3-4.pdf, accessed July 2006, 16.

[25] Richard C. Olsen. *Remote Sensing from Air and Space* (November, 2005), 61.

[26] Ibid, 70.

[27] Ibid, 66.

for this thesis is to determine a *practical* orbit where a commercial imaging satellite could fly and capture higher resolution images that would otherwise not have been obtained from higher altitudes.

Accurate values of resolution can be determined when calculating resolution based on the Rayleigh criterion. For rectangle apertures, GSD is the product of the distance between the target and imaging device (range) and the angular resolution.[28]

$$GSD = \Delta\theta * Range$$

where $\Delta\theta$ is the angular resolution.[29]

For purposes of simplicity, determining resolution was based on linear interpolation despite atmospheric differences for different altitudes. To find GSD at a new altitude, the ratio interpolation can be used as follows:

$$\frac{GSD}{Altitude} = \frac{NewGSD}{NewAltitude}$$

$$\therefore NewGSD = \frac{NewAltitude * GSD}{Altitude}$$

Incorporating the use of the Rayleigh criterion, the same equation above can be represented with known wavelength and the aperture diameter of the optic:

$$\frac{GSD}{Altitude} = 1.22\frac{Wavelength}{OpticDiameter}$$

The table below shows the linear interpolation of resolution from the known GSD of QuickBird--60 cm resolution from 450 km altitude (highlighted in blue). These values listed below are representative of the satellite when it is nadir pointing. Upon review, one can see the differences in resolution based on altitude of the satellite. Flying QuickBird down to 225 km altitude will double the resolution capability of the current operating system. Further discussion of these values and how they will incorporate into constellation construction are presented in the following chapters.

[28] Richard C. Olsen. *Remote Sensing from Air and Space* (November, 2005), 70.

[29] The Rayleigh criterion: $\Delta\theta = \lambda / Aperture$.

Altitude		*NIIRS*	*cm*	*in*
150 km	93 miles	6.7	20.3 cm	8 in
185 km	115 miles	6.5	25 cm	9.7 in
200 km	124 miles	6.3	26.7 cm	10.5 in
225 km	140 miles	6.0	30 cm	11.8 in
250 km	155 miles	5.7	33.3 cm	13 in
300 km	186 miles	5.5	40 cm	15.8 in
450 km	**280 miles**	**4.7**	**60 cm**	**23.6 in**
600 km	373 miles	4.5	80 cm	31.5 in
700 km	435 miles	4.3	93.3 cm	36.8 in
800 km	497 miles	3.8	106.7 cm	42 in
1000 km	621 miles	3.6	133.3 cm	52.5 in

Table 2. Simple Resolution Interpolation.

A good starting point for designing a new constellation would be a review of a desirable resolution capability and thus operating altitude. The numbers shown above are for QuickBird-2 optics and detectors when flown at various altitudes. These values are fairly representative of what would be obtained from competing commercial systems.

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III. ORBITOLOGY

The purpose of this section is to present general factors and related considerations of atmospheric drag, orbit types and orbit life when considering methods of improving resolution. Satellite Took Kit (STK) version 7.0 was the primary professional modeling software used for technical analysis of orbital life calculation, orbital element analysis, coverage persistence and revisit. A significant source of assistance was provided by the application and technical engineering department of Analytical Graphics Incorporated (AGI) in Exton, PA.

A. HOW TO INCREASE RESOLUTION

A simple question to consider is how can resolution be increased with a commercial imaging satellite? The answer is quite simply, fly at a lower altitude. A major challenge is from the effects of the Earth's atmosphere since drag is the primary driving factor for orbit life estimation among lower altitude orbits. Since atmospheric drag is inversely proportional with the altitude of the satellite--a lower orbit is subject to greater atmospheric drag.

1. Drag Affects

The affect of atmospheric drag on a satellite is greatly dependent on the size, mass and shape of the satellite. The basic aerodynamic equation for determining the affect of atmospheric drag (D_{ref}) is a function of the area cross section of the satellite (A), orbital velocity (v), atmospheric density (ρ_{ref}) and coefficient of drag (Cd):[30]

$$D_{ref} = \frac{1}{2} C_d \rho_{ref} A v^2$$

The area cross section of a satellite refers to the area which is exposed to the "relative wind" of the atmosphere as the satellite traverses in Low Earth Orbit (LEO). In this equation, both v and ρ_{ref} are at a reference altitude and are not static. C_d and A are

[30] Lawrence Halbach, *A Numerical Study of Fuel-Optimal Low-Earth-Orbit Maintenance* (December 2000), 11.

physical properties of a satellite and remain constant. Atmospheric drag creates perturbations on the orbital period and should be also be evaluated for satellite operations in LEO.[31]

Solar activity must also be considered since its affects will impact the overall density of the Earth's atmosphere as well as the effects onto the satellite itself. The 11-year solar cycle impacts the Earth's atmospheric density from the effects of sun spots, solar flares, Coronal Mass Ejections (CME) or other solar prominences.[32] With an increase in solar activity, the Earth is bombarded by heavy doses of photon activity which increases the atmospheric density. Below ~150 km altitude, however, atmospheric density is not strongly affected by solar activity since the atmosphere is so dense.[33] Satellite deployment during solar max will retain a shorter overall life cycle compared to a satellite deployed during solar min periods. This is due to the immediate effects of solar max activity on the satellite's orbit. This thesis used the average solar flux of the Scheften model along with the NRL MSISE 2000 atmospheric density mode as presented in STK.

Another important factor that should be considered with LEO missions are the effects of atomic oxygen. This is a form of oxygen that can react with thin organic films and other materials. This atmospheric constituent forms when solar ultraviolet radiation dissociated molecular oxygen. Atomic oxygen has its greatest effects on orbiting satellites between 200-600 km altitude.[34]

For QuickBird-types satellites, the drag area varies based on satellite orientation with respect to the sun. If the sun is normal (perpendicular) to the satellite's velocity vector (flight path), the solar panels are considered "stream-lined" to the relative wind and presents less overall drag. When the direction to the sun is along the velocity vector, then the solar panels present the greatest drag area. Determining average drag area for a given orbit is dependent primarily on inclination and how it is related to the Beta angle—

31 James Wertz and Wiley Larson, *Space Mission Analysis and Design, 3rd Ed*. (1999), 162.

32 Richard C. Olsen. *Introduction to the Space Environment* (January, 2005), 59-63.

33 James Wertz and Wiley Larson, *Space Mission Analysis and Design, 3rd Ed*. (1999), 208.

34 Ibid, 211.

the angle between the center of the Earth's sun line and the orbit plane. A comprehensive numerical analysis was completed by Digital Globe to determine the average drag area of 7.1 m^2.[35]

2. Orbit Types

A sun-synchronous orbit is typically a high inclination orbit (roughly 97 degrees) which a satellite will pass over the equator at approximately the same time local time each day. This capability presents a meaningful consideration for imagery analysis and is the direction for orbit selection in this study. Additionally, the 97 degree inclined orbit is where QuickBird currently operates with a known average drag area. The two general directions that were evaluated were circular or elliptical orbits.

Circular orbits present the advantages of consistent imagery resolution and well as area access rate. At the same time, these elements could also be considered disadvantages when considering various resolution needs. Although less complex, orbit life estimation for circular orbits requires a higher altitude to remain aloft for one year when compared to the lower points of elliptical orbits.

An elliptical orbit can provide improvement in overall resolution capability if compared to a circular orbit. An elliptical orbit will be able to fly at a low perigee (where highest resolution occurs) but must also fly a higher at apogee. Operations at apogee could be used for broad area image collections. Orbit life determination for an elliptical orbit is more challenging due to the changing (non-uniform) affects of atmospheric drag on the satellite.

B. ORBIT LIFE

As a general rule, the lifetime of a satellite in LEO can be estimated based on the Ballistic Coefficient (*BC*) of the satellite:[36]

$$BC = {}^{m}\!/_{C_d A}$$

where m equals the mass of the spacecraft, C_d is the coefficient of drag and A is the drag cross sectional area.

[35] Scott Mitchell, Re: QuickBird Drag Area, Available e-mail: from smitchel@ball.com, accessed March 2006..

[36] David Vallado, *Fundamentals of Astrodynamics and Applications, 2nd Ed*. (2001), 545.

Common *BC* values of various satellites are represented with a minimum and maximum for analysis purposes. When the *BC* value is low, the affects of the atmospheric drag on the satellite are greater than satellites with higher *BC* values (balloons are affected by drag more than bowling balls). Determining the lifetime of a satellite can be estimated by the figure below as a function of two main factors: BC and altitude.[37]

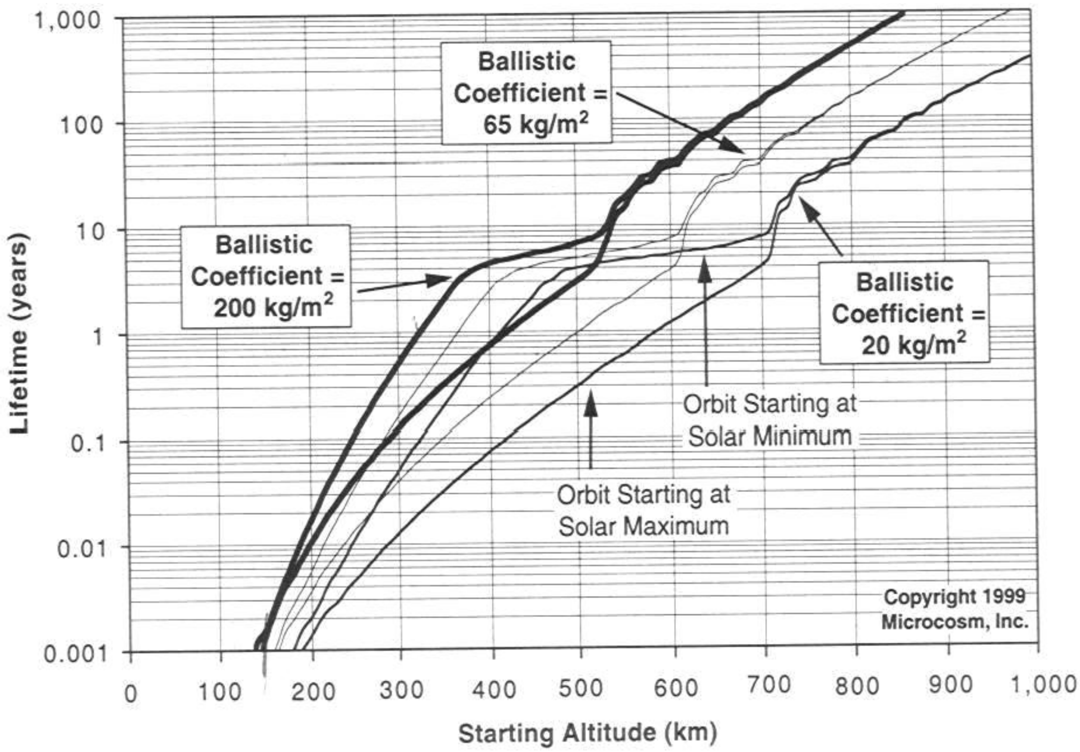

Figure 4. Lifetime Estimation as a function of Ballistic Coefficient.

Upon review of the life estimation figure above, a "dense" satellite (*BC* = 200kg/m^2) will need to fly a circular orbit of 320 km altitude to maintain an orbit life of one year. This considers a deployment of the satellite during solar min (~410 km altitude at solar max) without the use of fuel for orbit maintenance. As a result, orbital insertion during solar minimum or maximum has an impact on the overall lifetime of a satellite. As stated earlier, satellites below ~150 km are not affected by the differences on solar activity as well as satellites above ~800 km.[38] The *BC* values for the QuickBird satellite is 87.5 kg/m^2.

[37] James Wertz and Wiley Larson, *Space Mission Analysis and Design, 3rd Ed*. (1999), 210.

[38] James Wertz and Wiley Larson, *Space Mission Analysis and Design, 3rd Ed*. (1999), 209.

The first goal of orbital analysis was the determination of orbit life for a QuickBird sized and shaped satellite operating at various altitudes. For orbit life estimation, there are several propagators used in STK that determine orbit life based on given initial conditions. Results of these propagators differ based on variations taken into account with the satellite itself as well as atmospheric density and solar activity as well as the effects of other orbiting bodies such as the sun and moon.

1. High-Precision Orbit Propagator

The High-Precision Orbit Propagator (HPOP) routine used in STK is a good selection to determine orbit life for a simple satellite in LEO. This is due to the way HPOP incorporates variations of the Earth's atmospheric model beyond simple solar flux like that found in the Long Term Orbit Predictor (LTOP). Since the orbits studied in this thesis involve low altitudes, the HPOP routine incorporates a more accurate atmospheric model as well as other factors such as reentry warnings, graphs and reports that are best for use with this study. The major drawback with the HPOP routine (as with all of the other propagators) is the lack of ability to incorporate on-board fuel that would re-boost a satellite to repair orbit decay and extend orbit life. This requires building additional subroutines in a programmable propagator in STK known as Astrogator.

2. Astrogator

The Astrogator component browser within STK is a powerful programmable propagator that enables the user to refine components of a space mission and can include changes in orbital conditions, such as making a burn to complete a Hohmann transfer, re-circularize an orbit, etc. In the case of this study, a complex Astrogator routine was developed which accounts for on-board propellant to determine total life of the satellite before orbit decay into the Earth's atmosphere. Astrogator subroutines were created for both circular and elliptical orbits. The methodology creating these subroutines is located in Appendix A at the end of this report. These Astrogator subroutines are complex propagators that require detailed programming within each propagator sequence. A limitation with Astrogator was that the sequences would stop converging against desired values when onboard fuel was expended. From this point, the HPOP propagator described above would be used to calculate orbit decay and sum the two trial periods for total orbit life. Variables involved with the Astrogator routine and satellite specifications are listed in the following table:

Element	*Value*
Dry Mass of Spacecraft	1052 kg
Fuel Mass	315 kg
Ballistic Coefficient	87.5 kg/m^2
Drag Area	7.1 m^2
Coefficient of Drag	2.2
Coefficient of Reflectivity	1.0
Coefficient of Radiation Pressure	1.0
Radiation Pressure Area	7.1 m^2
Fuel Type	Hydrazine
Tank Pressure	400 psi
Tank Volume	1.5E-9 km^3
Tank Temperature	293 K
Fuel Density	1E12 kg/km^3

Table 3. QuickBird Initial Conditions.

C. QUICKBIRD'S ORBIT LIFE

Astrogator was used to propagate several scenarios with different orbital initial conditions and determine orbit life while using 315 kg of fuel. In order to achieve a respectable resolution capability, a goal was to determine if an orbit life of one year could be achieved with an orbit having a perigee of 225 km or less. An optimum orbit was determined based on a combination of a desirable perigee that provides quality resolution and orbit life. As discussed earlier, a one year orbit life was the goal for selecting a desirable orbit type. In order to acquire greater NIIRS capability than the current QuickBird satellite flying at 450 km, a much lower orbital altitude is required and therefore a shorter orbit life. The following table presents lifetime of a given orbit based on results from Astrogator (calculating orbit life when burning fuel) and the HPOP routine (calculating orbit after all fuel is consumed):

Name	*Perigee*	*Apogee*	*Eccentricity*	*Orbit Life*
A	185 km	600 km	0.030648	9.5 months
B	**185 km**	**700 km**	**0.037754**	**12.1 months**
C	185 km	800 km	0.044757	15.5 months
D	200 km	500 km	0.043617	9.4 months
E	200 km	600 km	0.029507	13.3 months
F	150 km	150 km	0.0	6 months

Table 4. Orbit Lifetime Comparison.

Taken into account the assumption of a one year orbit life, satellite B was further analyzed and used for coverage calculations that are discussed in Chapter IV. This evaluation of resolution capability, area coverage and access rate were considered to determine an optimum orbit type. The output data for all six orbit types listed above are in Appendix B at the end of this report. Orbital elements for the type B orbit are:

Orbital Element	*Value*
Apogee Altitude	185 km
Perigee Altitude	700 km
Semi Major Axis	6,820.5 km
Eccentricity	0.0377538
Period	93.43 minutes
Radius of Apogee	7,078 km
Velocity at Apogee	7.36 km/sec
Radius of Perigee	6,563 km
Velocity at Perigee	7.94 km/sec

Table 5. QuickBird's Modified Orbital Elements.

A quick observation of the velocity at perigee (almost 8 km/sec), the area access rate will limit the number of high resolution pictures that can be collected based on how fast the Earth is moving under the satellite and the agility of QuickBird to reposition for subsequent collection requirements. At apogee, area coverage could prove beneficial with a longer loiter time, but the tradeoff is, of course, resolution. These important differences are factors that need to be considered when making the decision for an optimum orbit. Unfortunately, there is no obvious right answer.

D. PERTURBATIVE EFFECTS

Since the Earth is not spherical, its center of gravity is not coincident with its center of mass. This results in changes with the orbital elements of a given orbit. Although these affects are not significant for many other LEO satellites, they are not negligible. There are two principal effects from perturbation which are regression of the lone-of-nodes and rotation of the line-of-apsides (major axis).[39] Once a satellite is placed in a given orbit, there are several factors that will have an impact on the properties of the orbit. These are important concepts to consider when designing an optimum constellation that you intend to provide coverage in areas of interest over a long period of time.

There are cumulative effects that will present a gradual shift or variation in the epoch values of certain orbital parameters. These perturbative effects can be caused by several factors including atmospheric drag, radiation pressure from the sun (producing acceleration) and the gravitational affects of neighboring celestial bodies.[40] The rate of change of classical elements can be analyzed to present perturbative effects. These known perturbations can be incorporated with planning and operational decisions. Only the impact on the argument of perigee (ω) and the right ascension of the ascending node (Ω) were evaluated since changes in these elements have the greatest affect with coverage. The changes imposed on these elements from perturbative effects are represented from the following differential equations:[41]

$$\frac{\partial \omega}{dt} = -\frac{\cos(i)}{na^2\sqrt{1-e^2}\,\sin(i)}\frac{\partial R}{\partial i} + \frac{\sqrt{1-e^2}}{na^2 e}\frac{\partial R}{\partial e}$$

$$\frac{\partial \Omega}{dt} = \frac{1}{na^2\sqrt{1-e^2}\,\sin(i)}\frac{\partial R}{\partial i}$$

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[39] Bate, Muller and White, *Fundamentals of Astrodynamics*, 156.

[40] Pedro Ramon Escobal, *Methods of Orbit Determination, 2nd Rev. Ed.*, 360.

[41] Ibid, 365.

From simple observation, it is worthwhile to note that ***e*** and sin (***i***) in the denominator are not a problem as they approach zero. This is because the perturbation effects of ω and **Ω**, respectively are not observed since these orbits will be either circular (no perigee) or an orbit that is always over the equator (no **Ω**). Perturbative effects on other elements were not considered since their changes had a smaller degree of impact on coverage. Since the orbit used for perturbative analysis is greatly affected by atmospheric drag, only average values of the orbital elements are used to determine changing ω and **Ω**. The table below shows the effects of perturbation for a given orbit, circular and elliptical, at the given altitudes. The results show how many days it will take for a change in ω and **Ω** to travel 90 degrees.

Orbit Types:	320 km circular	450 km circular	700 km A 185 km P	600 km A 185 km P	600 km A 200 km P	500 km A 200 km P
$\Delta\ \Omega$	88 days	94 days	94 days	91 days	91 days	89 days
$\Delta\ \omega$	N/A	N/A	26 days	25 days	25 days	25 days

Table 6. Number of days for a 90^o change from Perturbative Effects

When designing a constellation, it is necessary to consider these perturbative effects to ensure that the territories under perigee are what you expect them to be. For example, if it is desirable to have several satellites with perigee over 30 degrees latitude, it will only take just under two months for apogee to be in its place. This leads to our discussion in the next Chapter, Coverage.

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IV. COVERAGE

A. INTRODUCTION

Various constellations of QuickBird satellites have been studied to determine optimum coverage for different areas of interest. Factors that were involved were total area coverage, persistence and revisit.

Satellites that collect imagery are typically accomplished from a circular sun-synchronous orbit in order to ensure that crossing the equator will occur at roughly the same local time everyday. With an elliptical orbit, latitude crossing times will vary changing eccentricity and inclination. This study focused on sun-synchronous orbits for purposes of simplicity and with the assertion that this system could utilize already existing ground segments of Digital Globe or other national assets. Additionally, using the same inclination as QuickBird for constellation analysis will allow us to use the same area drag since Beta angles are consistent.

As previously discussed in the Introduction chapter, coverage and revisit requirements are typically volatile and rarely stay the same. To better understand coverage from a satellite, the values of quantity (amount), quality (resolution), regional access (revisit) and accuracy (Geolocation) are good ways to measure a system's capability. For this project, coverage analysis of the aforementioned orbit type "B" was accomplished. As a prelude to constellation design and coverage analysis a discussion of a sensor's field of regard will first be discussed.

B. SENSOR FIELD OF REGARD

The field of regard is defined as the angular limits of the side-to-side movement of the optical axis with in the satellite sensor.[42] QuickBird is best utilized when acquiring images within 45 degrees off nadir in order to ensure accuracy and greatest resolution.[43] This 45 degree field of regard was a programmed constraint when calculating coverage capability in STK. For elliptical orbits, there are obvious

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[42] Robert E. Ball, *The Fundamentals of Aircraft Combat Survivability Analysis and Design, 2nd Ed.*, 361.

[43] Dr. Walter Scott, Re: QuickBird Resolution Capability, Available e-mail: from wscott@digitalglobe.com, accessed May 2006.

differences in the size of the field of regard "footprint" for QuickBird as it operates in its trajectory between 185 km and 700 km altitude. Intuitively, the field of regard is smallest when the satellite is a perigee.

1. Spherical Analysis

To determine the diameter of the field of regard, the arc length must be calculated for a satellite with a 45 degree "cone" projected onto the Earth's surface that represent the field of regard. Once the diameter of the field of regard is known, total area can then be determined from simple geometry. First, a simple cartoon presents a satellite at perigee (185 km altitude) showing an obtuse triangle with the three angles of 45 degrees, θ and ϕ.

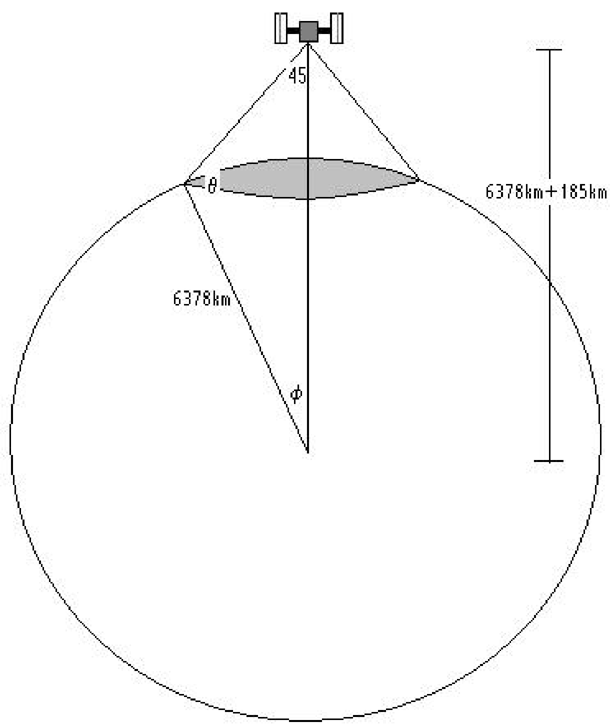

Figure 5. Field of Regard Cartoon.

In this case, the known quantities are the Earth's radius, the altitude of the satellite and a 45 degree field of view cone. The Law of Sines say that for given a triangle, if a side and opposite angle are known, another angle can be determined if its opposite side is also known[44]. The law of sines for a general triangle is defined as follows:[45]

[44] Hyper Physics, http://hyperphysics.phy-astr.gsu.edu/hbase/lsin.html, accessed July 2006.

$$\frac{a}{SinA} = \frac{b}{SinB} = \frac{c}{SinC}$$

Summing the Earth's radius and satellite altitude, the long side of the obtuse triangle can be solved. The Earth's radius is the length of another side of the triangle with 45 degrees as the value for the opposite angle. From here, the Law of Sines can be used to determine the unsolved angle of θ:

$$\frac{6378km}{Sin45} = \frac{(6378 + altitude)km}{Sin\theta}$$

$$\therefore \theta = \sin^{-1}\left[\frac{(6378 + altitude)km * Sin(45^o)}{6378km}\right]$$

After solving for θ, we can also find the value for ϕ using the general triangle law which the sum of all angles must equal 180 degrees. Recall that the value calculated for θ will be less than 90 degrees due to the double-value results of the sine function. Therefore, the true value of θ is 180 from the calculated value for an obtuse triangle. From there, the rest of the unknowns can be solved.

When the angle for ϕ is known, the arc length can be solved when relating the ratio of the circumference of a circle to 360 degrees.[46] The following formulas show a step-by-step process to find the results of both diameter and area of the 45 degree field of regard when the satellite is at perigee and apogee:

a. Field of Regard at Perigee

$$\theta = \sin^{-1}\left[\frac{(6378 + 185)km * Sin(45^o)}{6378km}\right] = 46.69^o \rightarrow (180^o - 46.69^o) = 133.3^o$$

$$\phi = 180^o - 45^o - 133.3^o = 1.69^o$$

$$\frac{2 * \pi * 6378km}{360^o} = \frac{arc}{1.69^o}$$

$$\therefore arc = \frac{1.69^{\not o} * 2 * \pi * 6378km}{360^{\not o}} = 187.8km$$

$$Diameter = 2 * arc = 2 * 187.8km = \boxed{375.6km}$$

$$Area = \pi r^2 = \pi * 187.8km^2 = \boxed{110,788.5km^2}$$

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[45] Hyper Physics, http://hyperphysics.phy-astr.gsu.edu/hbase/lsin.html, accessed July 2006.

[46] Circumference of a circle: $C = 2 * \pi * radius$.

b. *Field of Regard at Apogee*

$$\theta = \sin^{-1}\left[\frac{(6378+700)km * Sin(45^o)}{6378km}\right] \rightarrow 128.3^o$$

$$\phi = 180^o - 45^o - 128.3^o = 6.69^o$$

$$\frac{2*\pi*6378km}{360^o} = \frac{arc}{6.69^o}$$

$$\therefore arc = \frac{6.69^o * 2*\pi*6378km}{360^o} = 744.7km$$

$$Diameter = 2*744.7km = \boxed{1489.4km}$$

$$Area = \pi*744.7km^2 = \boxed{1,742,258.5km^2}$$

The images below represent the 45 degree field of regard of QuickBird at perigee and apogee respectively. Notice the differences in the field of regard:

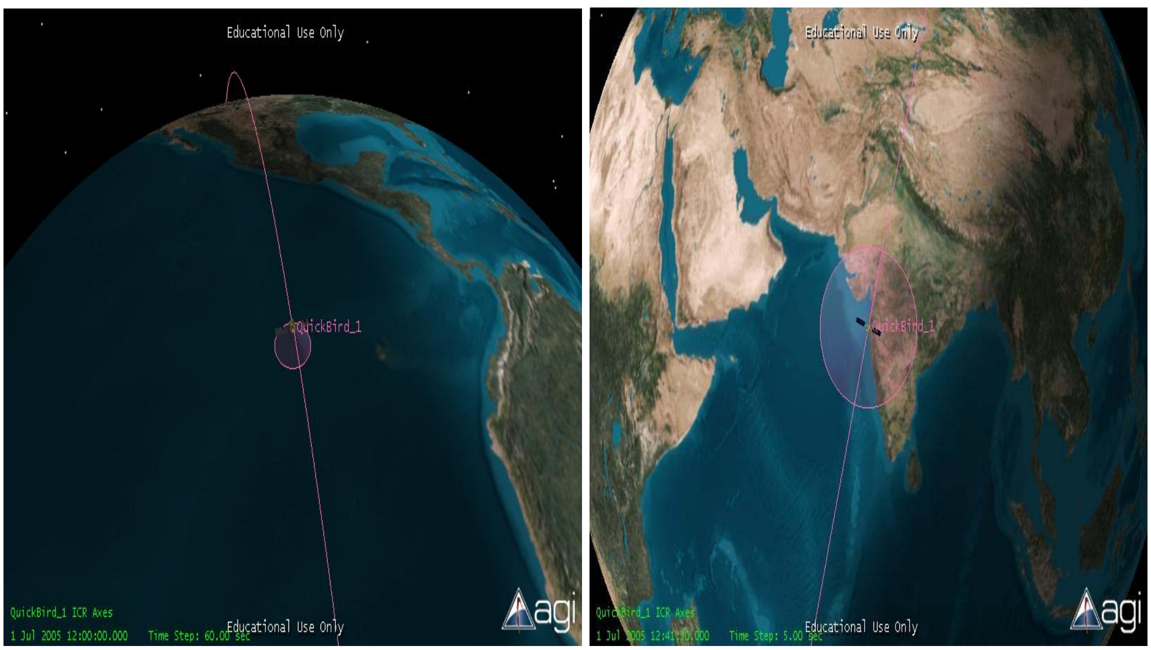

Figure 6. Field of Regard Comparison at 185 km (Perigee) and 700 km (Apogee).

C. CONSTELLATION DESIGN

Designing a constellation of multiple QuickBird satellites can be accomplished several different ways in order to meet different objectives. A measurable method to compare constellations include total area mapped in a given period, total number of high resolution point targets collected in a given period and the ability to revisit a particular area or point of interest. In all, the requirements for coverage which include resolution, persistence and revisit can never be absolute. The changing needs of imagery products will vary from user to user at the national level down to the operational/theater level.

Constellation building began with the simple Walker design as described below. In total, several dozen constellations were designed and developed of which eight constellations were selected for comparative analysis. The results of coverage and revisit for these orbits are presented below. Other non-Walker designed constellations were also analyzed for comparison and are described.

1. Walker-Derived Constellation Design

The Walker method can be used to create a constellation of multiple satellites within STK. The purpose of a Walker delta pattern constellation was to provide continuous coverage of the Earth's surface with as few satellites possible.[47] In general, Walker designed constellations are optimized for target points located in the mid-latitudes. Walker constellations are based on satellites that are evenly distributed within a plane and each of the planes are evenly distributed through 360 degrees around the equator. For constellation design, procedures listed in Chapter 7.1 of the Space Mission and Design text were used as a starting point.[48] For this study, all satellites share the same inclination and involved one or more satellites per plane in order to maximize coverage to reduce the revisit rate. Constellations varied from one to 12 satellites.

2. STK Coverage Output

To better understand the performance of a constellation, the evaluation of point target revisit is a good method when using STK. This is because STK presents revisit data by showing when a point is visited, how long it is in view of the satellite and how long it will be until the next imaging opportunity. These results are compiled into two forms: graphical and tabular (data only). In STK, the coverage module is located under the "Target Tool" for each defined point target. From there, assets can be assigned for analysis as well as the revisit tool in the figure of merit. Below, a graphical representation of revisit gaps from STK is an example of a three satellite constellation that is looking at a target at 85 deg North and 0 deg east:

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[47] James Wertz and Wiley Larson, *Space Mission Analysis and Design, 3rd Ed*. (1999), 194.

[48] Ibid, 160.

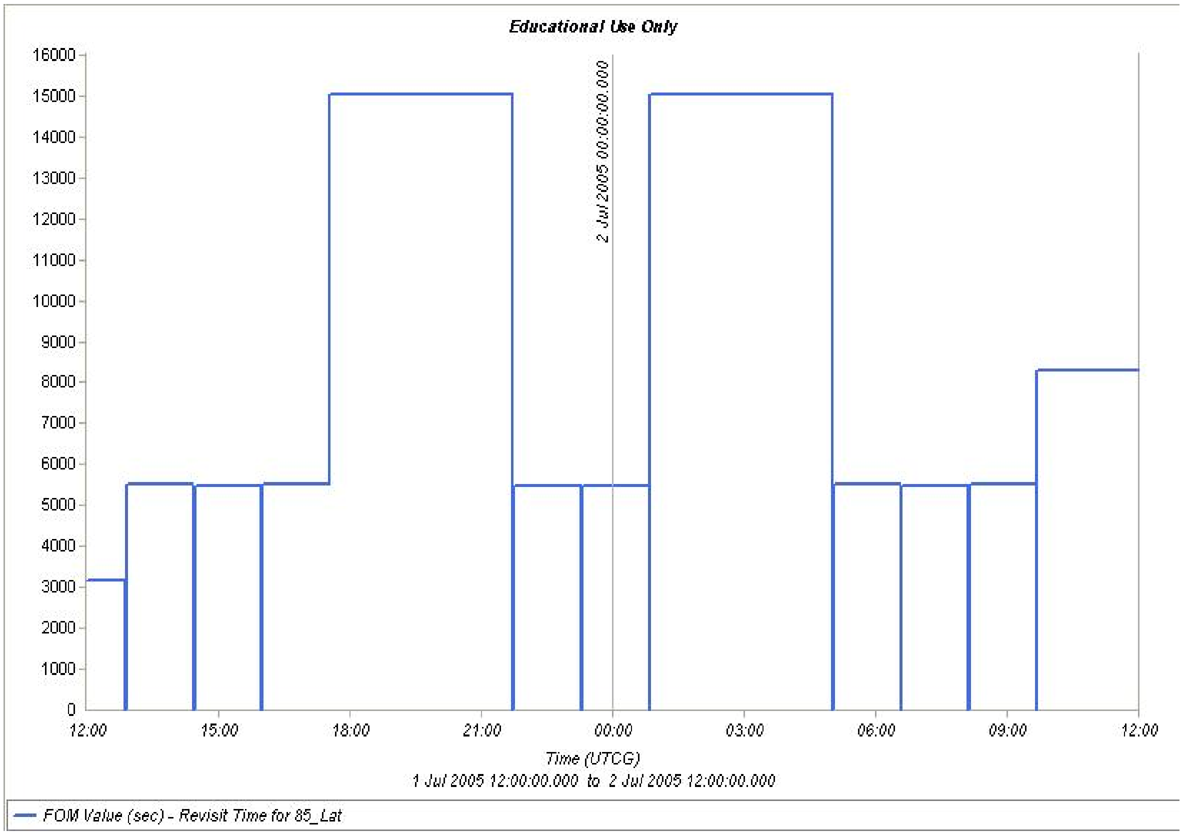

Figure 7. STK Revisit Output for a Three Satellite Constellation.

The blue lines in the graph above show when a gap occurs during the mission and for how long. The x-axis shows the mission elapsed time (when the gap starts and stops) and the y-axis shows the gap duration in seconds. A gap has been defined as a time when a given point on the ground is outside the 45 deg field of regard "cone" of a satellite as described earlier. It can be seen that during a 24-hour period, there are two large gaps which lasts 15,000 seconds—roughly 4 hours for this three satellite constellation (the first gap begins just before 18:00 UTCG). An optimum constellation design can be inferred from graphical analysis alone. A constellation with very low revisit gaps and only a few large revisit peaks may be more desirable than a system with a more uniform average revisit gaps. Again, coverage output will need to be compared with coverage requirements for a given system.

3. Microsoft Excel Coverage Analysis

The revisit results from STK that are in data form were compiled and transferred into Microsoft Excel for analysis and numerical evaluation. Below is a snap-shot of revisit times for a constellation with various target locations that was used in Excel:

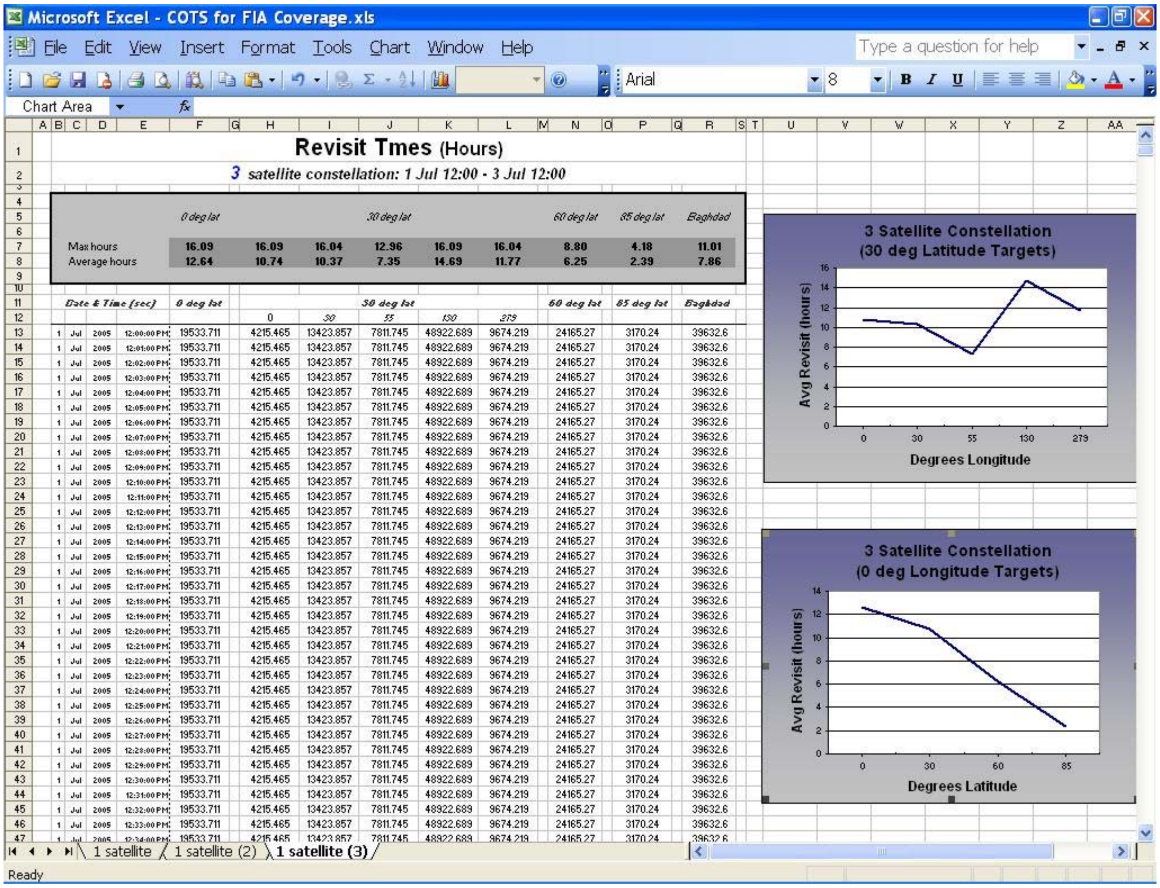

Figure 8. STK Revisit Output Data in Microsoft Excel.

There were several terrestrial areas that were programmed into STK as simple point targets and were used to analyze a constellation's coverage capability with respect to revisit as described above. For constellations in elliptical orbits, the revisit rates varied between different locations on the ground even if areas shared the same longitude or latitude.

a. Longitudinal Coverage Rates

Areas of interest which share the same longitude but have different latitude values yielded an expected result of revisit capability. This is primarily due to the fact that high inclined orbits present a “candy-striping” effect which allows more coverage over the poles and the least coverage near the equator.

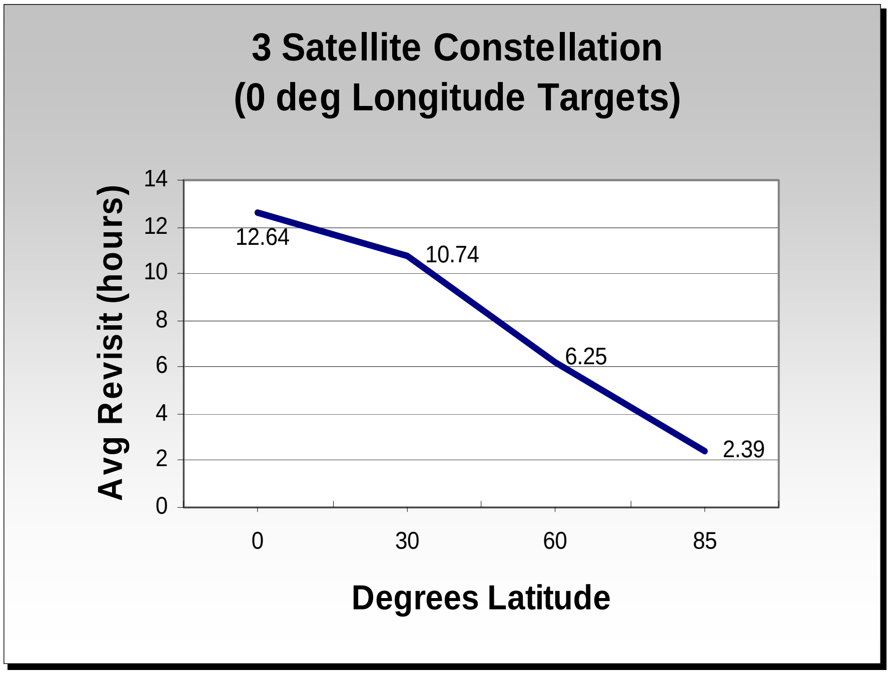

Figure 9. Average Revisit of a Three Satellite Constellation—0-degree Longitude Targets.

The graph above shows the revisit results (in hours) of four separate point targets each with the same longitude but with different latitudes. Using a three satellite constellation, there appears to be a trend in revisit based on target latitude. This makes sense due to polar convergence with the lines of longitude. These three satellites fly over the poles and can see the 85 deg north latitude target more frequently with an average revisit of 2.4 hours. Conversely, the target on the equator has a higher revisit of 12.6 hours.

b. Latitudinal Coverage Rates

For targets with the same latitude but different longitude, the results were much more dynamic. It is difficult to determine a uniform revisit rate for targets which share similar latitudes based on a given constellation. This is primarily due to the uniqueness of elliptical orbits with a very low perigee. The affects from perturbation and atmospheric drag make it difficult, if not impossible, to derive an “optimum” constellation that can provide consistent revisit over an area of similar latitudes.

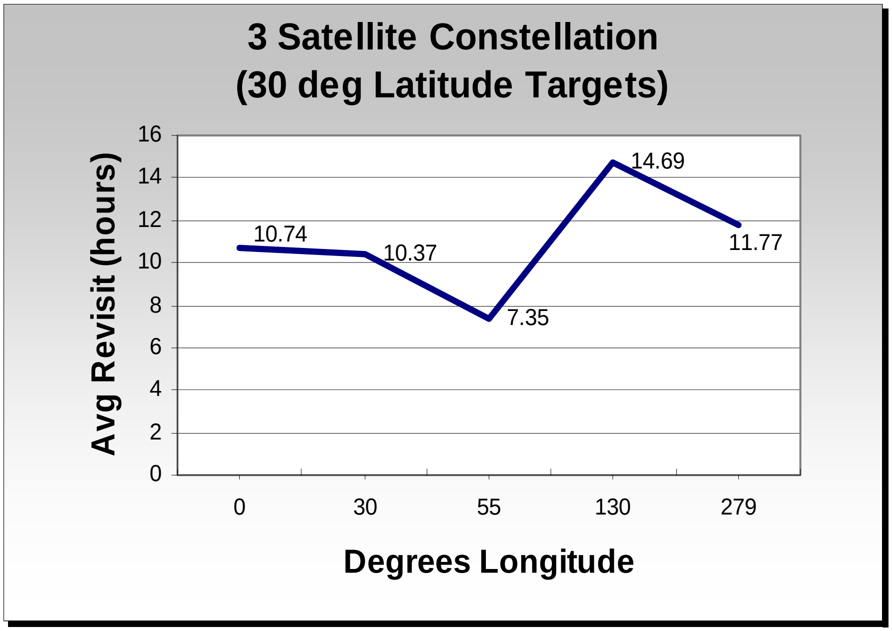

Figure 10. Average Revisit of a Three Satellite Constellation—30-degree Latitude Targets.

The figure above shows how revisit varies with targets at different longitudes but all with the same latitudes. For constellations with an even number of satellites, an out of phase technique may be considered for an optimum design. This method provides two satellites that share roughly the same orbit plane but their associated apoapsis or periapsis are 180 degrees apart.

4. Phasing Techniques

With orbit decay and perturbation of the argument of perigee, ω, their coverage would remain out of phase and can still provide optimum coverage. The graph below is a four satellite constellation which illustrates the out of phase concept where one satellite's apogee point matches another satellite's perigee point.

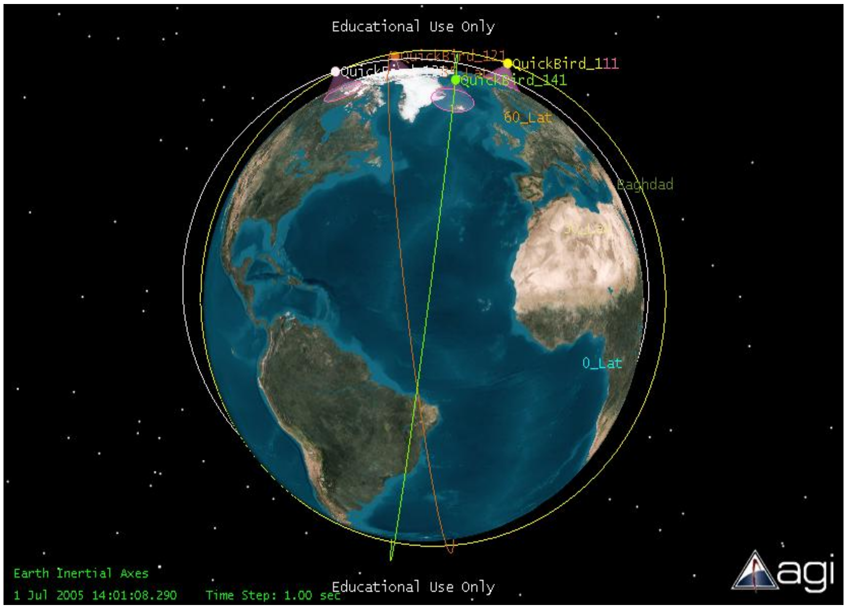

Figure 11. Out-of-Phase Four Satellite Constellation.

Figure 11 merely illustrates the orbits that are out-of-phase from each other. Where the white orbit is at perigee, the yellow orbit is at apogee and vice-versa. STK shows the perturbation effects of ω for both orbits at a uniform rate. Although ω will not remain fixed over the same latitude, the two opposing satellites will continue to provide perigee on opposite sides of the planet.

Several constellations were created using the one year satellite orbit that was presented earlier. There were multiple iterations of all constellations with adjustments to the following variables:

- # of planes
- # of satellites in a plane
- Inter plane spacing
- Phasing techniques (adjustments with ω and true anomaly).

The results in the coverage capabilities of various constellations were parsed down to eight final constellations. Table 7 below illustrates the optimum constellation configuration based on revisit capability of various terrestrial point targets. Further discussion and description of each constellation is presented in the next section below. The advantages of each constellation's coverage ability can be further measured based on outputs with revisit and access.

Best Performing Constellation Configuration								
Constellation Size:	1	2	3	4	5	6	9	12
Nomenclature:	**1**x**0**x**0**	**2**x**1**x**1**	**3**x**1**x**1**	**4**x**1**x**1**	**5**x**1**x**0**	**6**x**1**x**1**	**9**x**1**x**0**	**6**x**2**x**1**
# of satellites	1	2	3	4	5	6	9	6
# of planes	0	1	1	1	1	1	1	2
inter plane spacing	0	1	1	1	0	1	0	1
Legend (AxBxC): *A = # satellites* *B = # plan* *C = inter-plane spacing*								

Table 7. Optimized Walker Constellations.

a. One & Two Satellite Constellation

The purpose of analyzing a constellation of only one satellite is to determine a baseline for what a single satellite can provide with regard to coverage. A two satellite constellation (two planes, one satellite each) was similar to the single satellite system but with two planes that are symmetric along the Earth's inertial referenced z-axis. Based on STK output, a two plane (one satellite each) constellation provides better revisit than two satellites sharing the same plane.

A Walker designed constellation creates the two planes such that one satellite flies in a 97 degree inclination. The two planes are phased 180 degrees apart and both fly a retrograde orbit. As previously discussed, ω between two satellites can be phased 180 degrees from each other. A specific range of latitudes, such as 30 degrees North latitude, may be more desirable for high resolution imaging due to areas of interest on the globe that rest near the 30 degree belt. From STK analysis, this technique of symmetric planes, as shown in the figure below, yields a greater revisit performance than a two-plane system that is oblique:

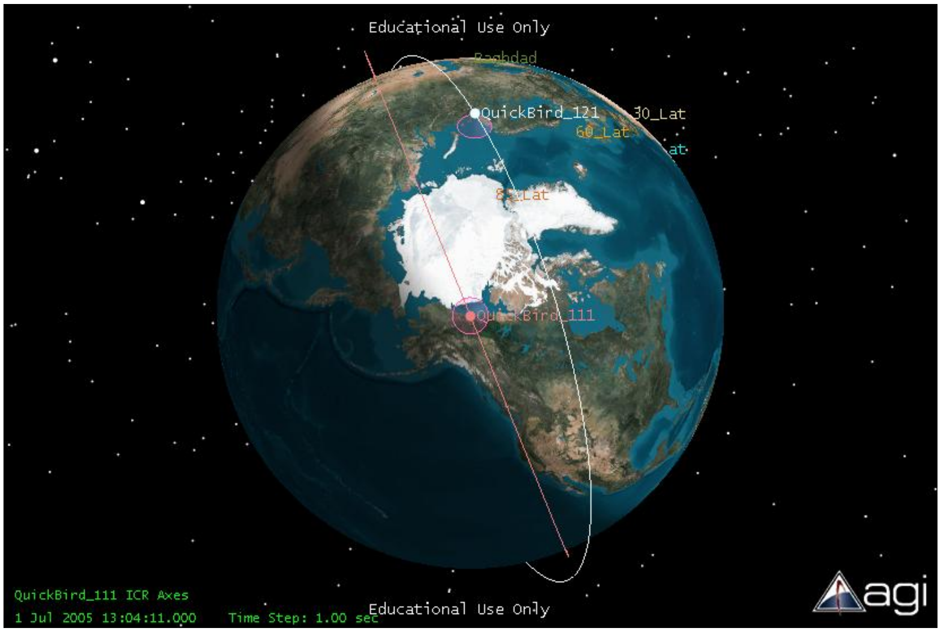

Figure 12. Two Satellite Constellation.

Assigning both satellites to have simultaneous perigee coverage over the 30 degree latitude may provide greater high resolution coverage at these latitudes. This would only last, however, for a limited time due to the effects of perturbation. An optimum design would be to keep both satellites in a similar plane but with opposing ω that are 180 degrees apart. This would minimize the gap of obtaining highest resolution images (only from perigee) for any given terrestrial point. Adding additional satellites to a common plane with ω spread evenly apart within that plane would further minimize the gap to capture highest resolution images.

b. Three Satellite Constellation

The three satellite constellation (one satellite in three planes) is a departure from the two satellite constellation since Ω for all three planes are equally spread over 360 degrees. This type of constellation design provides the greatest revisit capability for given terrestrial targets when compared to a combination of three satellites in either or one or two planes.

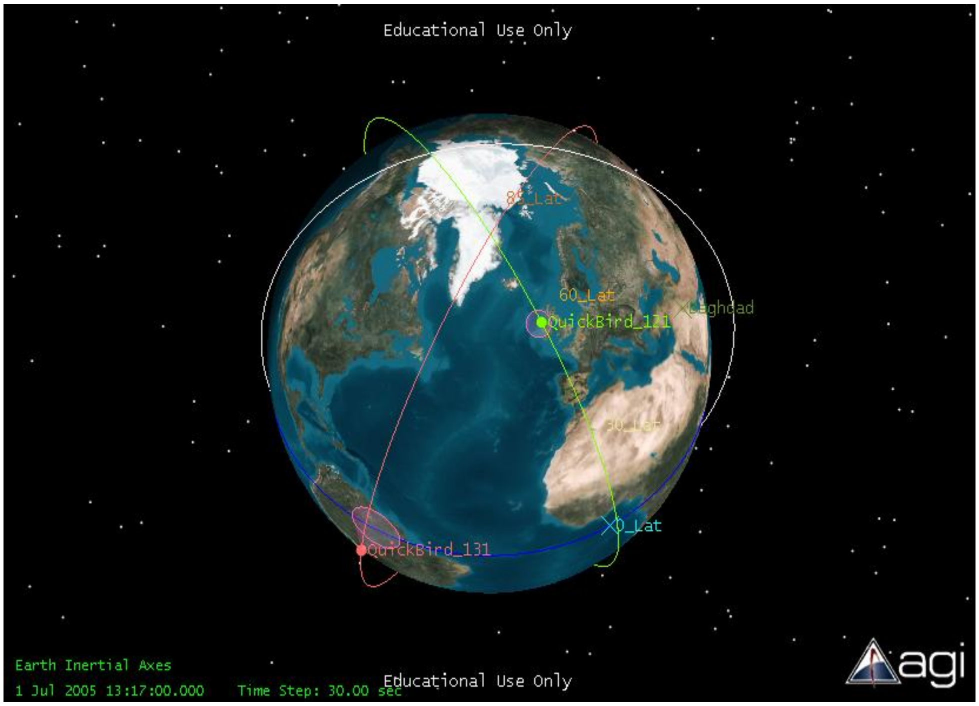

Figure 13. Three Satellite Constellation.

c. Four, Five and Six Satellite Constellation

These three different constellations showed the best "bang-for-the-buck" based on the increased coverage and revisit capability when compared to other larger constellations. Interestingly, it was discovered that with Walker designed constellations of 4 or more planes, revisit values were greatest with inter plane spacing set to one (1) for an even number of planes. An inter plane spacing value of zero (0) shows better revisit capability for odd number of planes. This will become even more evident with larger constellations and is further discussed in the 12 satellite constellation below.

d. Nine and 12 Satellite Constellation

Obviously, more satellites in a constellation will yield greater coverage and revisit capability. The purpose of generating such robust constellations is to present their capabilities and compare differences with smaller constellations. Larger sized constellations show marked improvement in coverage when varying design methods. These variations include adding more than one satellite in a plane and varying phasing techniques to help space the field of regard footprints equally throughout the globe. A common nomenclature with creating Walker designed constellations is AxBxC—total number of satellites-**x**-total number of planes-**x**-inter-plane spacing. The table below illustrates performance differences between variations of the 12 satellite constellations. The revisit times are representative of Baghdad, Iraq as the area of interest:

Baghdad Revisit Times (Hours)					
12 Satellite Constellation: 1 Jul 12:00 – 3 Jul 12:00					
Constellation Configuration:	12x1x0	12x1x2	6x2x0	6x2x1	4x3x0
Max Hours:	6.19	4.14	3.88	3.76	5.70
Average Hours:	4.29	3.43	3.29	3.28	4.42
Legend (AxBxC): *A = # satellites* *B = # plane* *C = inter-plane spacing*					

Table 8. 12 Satellite Constellation Revisit

5. Other Constellations

Walker designed constellations with 45 and 63.4 degree inclinations (non-synchronous orbits) were also evaluated for revisit capability. Additionally, other non-Walker constellations were created in order to evaluate and compare coverage results. These constellations included multiple planes which were orthogonal to each other and meshed comb constellations. In all cases above, the greatest revisit capability for true global coverage capability remained with the sun-synchronous orbit. Although the lower inclination constellations offered better revisit times in the mid latitudes, areas of interests in terrestrial areas above 70 degrees North latitude showed degraded revisit times. Obviously, these lower inclined orbits do not utilize the advantages of the sun-synchronous when assessing images collected at various times.

One notable constellation worth further discussion was the meshed comb. Meshed combed orbits utilize an altitude that is optimized to provide synoptic coverage at the equator for a specified minimum elevation angle at the edge of the field-of-regard.[49] Inclination selection for meshed comb constellations are based on desired latitude coverage. Half of the constellation flies at a given inclination (***i***) and the remaining half of the constellation fly at 180-***i***. This results in the two sets of satellites to act as "combs" as they move in opposite direction relative to each other and create a counter-rotating comb as viewed from a 2D graphical chart. As a result, meshed comb constellations work best for satellite which all operate at the same altitude (constant size

[49] Bill Jackson, *Performance of Meshed Comb Constellations For Minimizing Target Revisit Time*, (May 1998), 60.

in the field of regard) and is not will fitted with elliptical orbits as this thesis implies. Additionally, a sensor with a smaller field of regard implies a larger constellation size. Given the assertion that an optimum one year orbit is an elliptical one, the inefficiency of overlapping fields of regard suggests that the meshed comb constellation is not optimum for imagery collection as described in this thesis. Additionally, for a meshed comb constellation, half of the satellites fly in a prograde orbit and the other half would be flown in retro-grade orbit. This requires that half of the constellation requires boost to mid-inclinations in a retro-grade orbit which can be a difficult constraint for the launch vehicle.

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V. COST PLAN

A. PROJECT MANAGEMENT

The Clementine spacecraft program was launched in 1994 and launched a new era in the effective use of smaller satellite design. It was a smaller (508 pounds dry weight) and cheaper ($80M) satellite which was built faster (22 months) than any other system in recent generations returning, in some sense, to the early days of quick response satellite programs.[50] A primary objective of project Clementine was to design, build and launch a satellite using a streamlined acquisition process while utilizing COTS products in order to reduce the development cycle and overall project costs. Spacecraft construction has shown that without a valid and comprehensive process, the concept of "better, faster and cheaper" does not always yield successful results.[51] Due to the lack of experience, early satellite construction of the 1950s and 60s were based on sound project management and expert engineering judgment. As technology matured, a more formalized process was present and the design approach became requirements-driven.[52]

An important point to consider is to not lose focus on the larger picture and include simplicity whenever possible in the design of complex systems. Incorporating the use of COTS products and components or Non-Development Items (NDI) which provides a capability that meets user requirements could ultimately lend to project success. Space programs have not typically achieved a match between needs and resources before starting development. The U.S. General Accounting Office's (GAO) findings describe how space acquisition policies, requirements and technologies that are not ready for implementation continue to hamper product development:

> The [acquisition] policy will not result in the most important decision, to separate technology development from product development to ensure that a match is made between needs and resources. Instead, it allows major investment commitments to be made with unknowns about technology readiness, requirements, and funding. By not changing its current practice, DOD will likely perpetuate problems within individual programs that

[50] Pedro Rustan, "Clementine: Measuring the Results," Aerospace America, (February 1995), 33-38.

[51] Kevin Forsberg, Hal Mooz and Howard Cotterman, *Visualizing Project Management, 2nd Ed.*, (2000), 313.

[52] Ibid, 315.

> require more time and money to address than anticipated. More important, over the long run, the extra investment required to address these problems will likely prevent DOD from pursuing more advanced capabilities and from making effective tradeoff decisions between space and other weapon system programs.[53]

The Department of Defense's (DoD) practice of committing major investments before knowing what resources will be required to deliver promised capability is the first step towards failure. In space systems development, there is a Tendency to build a new spacecraft for each new set of requirements.[54] These requirements-driven satellite designs are elements which lead a program into an unrecoverable area of const overruns and timing delays. This impedes the effectiveness with earned value management and the Joint Capabilities Integration and Development System (JCIDS) model of defense acquisition management.

B. JCIDS FOR SPACE PROGRAMS

Clearly, the cost of developing, launching and operating a constellation will vary based on the components of the space and ground segments. The intent of this study is to purchase already existing designs of a commercially proven satellite such as QuickBird and utilize existing facilities in order to mitigate rising costs in satellite systems development. Although Digital Globe owns and operates QuickBird, Ball Aerospace is the satellite manufacturing company.

A recurring point of tension are tradeoffs between spatial resolution, coverage, and temporal sampling. The mix of quality, quantity and collection time are drivers that affect the final outcome of any imagery constellation, thus, the total number of satellites. An estimated cost for each QuickBird satellite is roughly $200M.[55] which includes the satellite bus, payload and launch system. An example constellation of five satellites would be in the neighborhood of $1B plus ground segment training, setup and operating

[53] General Accounting Office, *Improvements Needed in Space Systems Acquisition Policy to Optimize Growing Investment in Space* (Nov 2003), ii.

[54] Pete Rustan, *Testimony of Dr. Pete Rustan before the House Armed Services Committee, Hearing on Space Acquisition* (July 2005), 3.

[55] Dr. Walter Scott, Re: QuickBird Acquisition, Available e-mail: from wscott@digitalglobe.com, accessed March 2006.

costs. With an assumed deployment rate of one satellite per month, the total life cycle of such a system would be time for construction plus one year and five months from the date of first launch.

Clearly, purchasing a small constellation of commercially build imaging satellites can prove to be beneficial when considering what you get for the cost. Based on simple coverage analysis of location and revisit rates, a three satellite system would be a good addition to the IMINT directorate's resources. The primary direction of this thesis was to study the idea of a COTS solution that would incorporate the use of existing an EO satellites in an effort to minimize the risk and expense of researching, developing and operating a new satellite program.

Implementing a COTS satellite architecture to provide near real-time imagery from commercial satellites could be in the Government Owned Contractor Operated (GOCO) structure in order to maintain positive control of satellite operations and sensitive collection data.

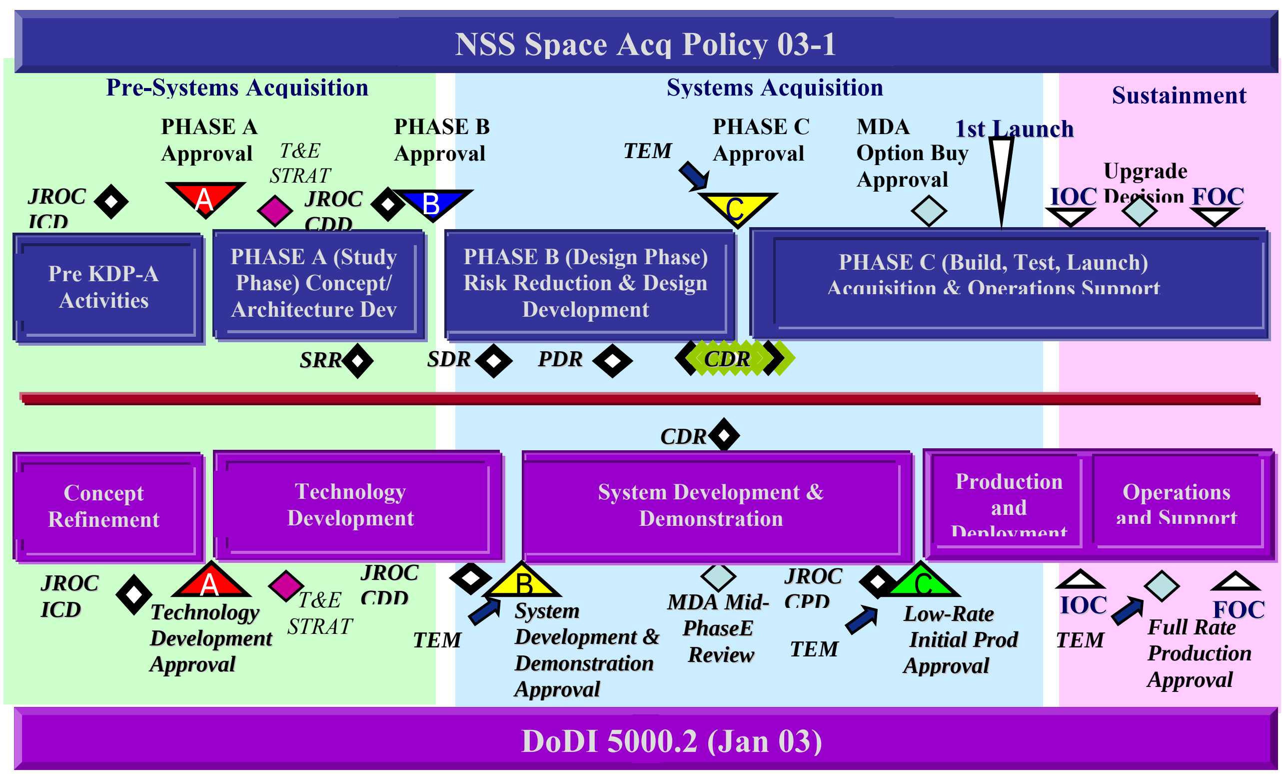

Figure 14. Acquisition Phase Comparison.[56]

[56] National Security Space Architecture, *NSSA Process*, Figure provided from Space Systems and Operations class notes, Naval Postgraduate School (November 2005).

Satellite Systems and Ground Station Systems acquisition is very different from the typical Department of Defense (DoD) program profile because the number of systems that are built is so few. For the typical DoD program, the Milestone C Low Rate Initial Production (LRIP) decision is very important because it produces the initial Operational Test & Evaluation (OT&E) items and verifies the production and manufacturing tools. Satellite systems are typically purchased in very small quantities (usually less then five of the same satellite system) for the total buy. Even the 24 satellite GPS constellation is small in terms of production numbers when compared to typical production runs of aircraft, tanks and other DoD weapon systems.

In addition to non-standard DoD ACAT-1D acquisition (Defense Acquisition Board major programs), a satellite system usually does not have an acquisition competition phase dedicated to the creation and testing of two or more on-orbit prototypes by which to base the selection of a winner for a production contract. Due to the nature of the space environment and excessive costs of satellite systems, a "fly-off", down-select between satellite system contractors usually occurs at some point during Phase B by having some sort of a "design-off". These differences tend to cause the life-cycle cost curve for a satellite system to be front loaded, thus causing the program's key decision points to be earlier. The figure below depicts differences with the major milestones of a DoD acquisition program to that of a satellite system:

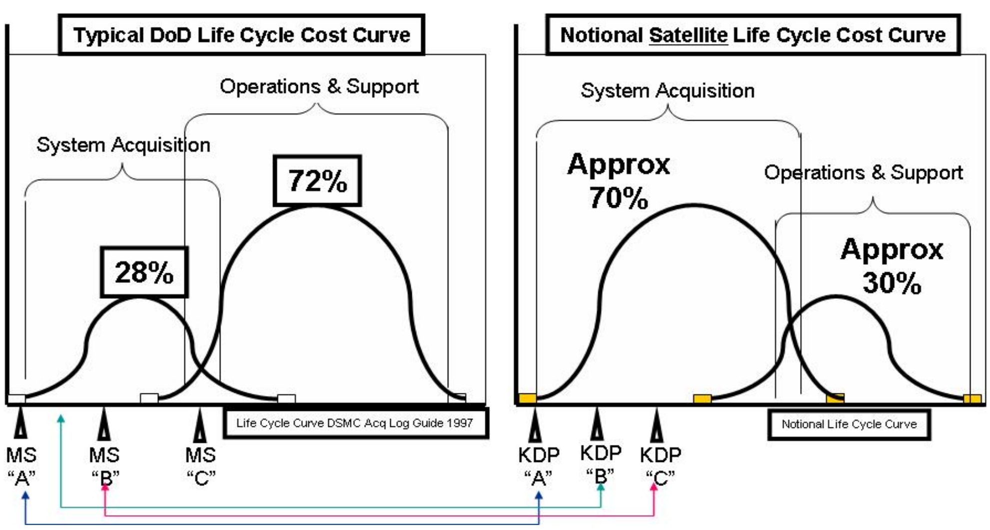

Table 9. Satellite LCC Curve.[57]

[57] Space Systems and Operations, "DoD5k and NSS Acquisition Comparison," Figure provided from Space Systems and Operations class notes, Naval Postgraduate School (November 2005).

The bottom line is that for space systems acquisition is that the biggest costs occur with developing and deploying a satellite into orbit. There are many risks associated with satellite acquisition since there are important milestones that force a program to go past the point of no return before system deployment and operation all with no field testing.

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VI. ANALYSIS & FINDINGS

Designing a constellation than can best meet mission requirements requires multiple iterations with variations in orbit specifications and capability. As previously discussed in Chapter I, these variations will affect the overall capability with the system's ability to provide a combination of the total area coverage, total number of point targets at the greatest resolution and when these products can be acquired. For a given orbit type, multiple iterations can be accomplished with the Walker-derived constellations by varying the following elements:

- Number of satellites
- Number of orbital planes
- Orbit inclination
- True anomaly
- Argument of perigee
- Satellite phasing

With adjustments in any of the above elements, there are tradeoffs which affect the overall capability of the system. These tradeoffs need to be evaluated to achieve the greatest benefit for orbit life and coverage capability.

A. ORBIT LIFE

Once a working subroutine in Astrogator was achieved, determining an orbit that meets the one year orbit life requirement was a matter of deciding which orbit design would support user's needs the best. A circular orbit that can sustain a one year life time will have a uniform resolution that will be less than an elliptical orbit with a very low perigee. Obviously, an elliptical orbit will generate greatest resolution near perigee but present limited total area coverage since the field of regard is smallest. The opposite is true for resolution and total area coverage near apogee. The 185 km perigee and 700 km apogee orbit was selected for study primarily for two reasons: First, the advantages of using an elliptical orbit were apparent due to varying resolution and total area capture capability. Second, an elliptical orbit provides a resolution capability to produce images with a GSD less than 10 inches and remain in orbit for one year. The average resolution capability of this orbit is illustrated in the figure below.

Orbit Averages:

(285km x 700 km orbit)

Avg Altitude: 459.2 km
28.5 km

Avg Resolution: 0.61 meters
2 4.1 inches

Avg Time:
<10 inches: 9 minutes (9.7% of orbit)
<20 inches: 37 minutes (39.8% of orbit)
<30 inches: 61 inches (65.6% of orbit)

** Orbital Period = 93 minutes*

Table 10. Orbit Averages.

The average values of altitude and resolution are remarkably similar to the QuickBird satellite currently on orbit. The main point of discussion, however, is the average time of high resolution. Note that approximately 10% of each period, the modified orbit will provide the highest resolution of <10 inches GSD which is of interest. If a 60 minute vulnerability time period of high resolution is desired, a six satellite constellation properly phased apart from each other can meet such a requirement. The next step is to decide how large of a system (total number of satellites) is best for meeting valid user needs.

B. COVERAGE

There are limitless methods for construction a constellation depending on how many satellites can be produced and how rigorous the coverage and revisit requirements. In general, coverage outputs were organized into one of two categories: quantity and quality. For regional collection analysis, the country of Iraq was used based on the needs and interest of current operational objectives. Collection analysis was from STK which defined the boarders of Iraq as the collection area and counted access time which any satellite in the constellation fulfilled the 45 degree field of regard constraint. The quantity category can be further broken into product types: point and area collection

1. Total Point Images

For one QuickBird satellite, a daily collection of 13 regional images or 150 global images can be collected. This collection rate for regional collection is based on a nominal point separation of 200 km in cross-track. This produces a collection rate of 2 point images per minute based on known QuickBird agility and is considered a conservative value.[58]

First, a single point of interest was analyzed as a baseline capability estimation. Since longitudinal variations had little influence on improving revisit rates, Baghdad, Iraq was an arbitrary location to be used for coverage analysis. Of course, other locations can be selected for revisit analysis. It is also a good representation of coverage revisit capability for other targets that are near the popular, yet volatile 30 degree North latitude line. Coverage analysis for Baghdad was evaluated with the same constraints presented earlier. This city was only considered observable when it was within 45 degrees field of regard cone for each of the eight constellations.

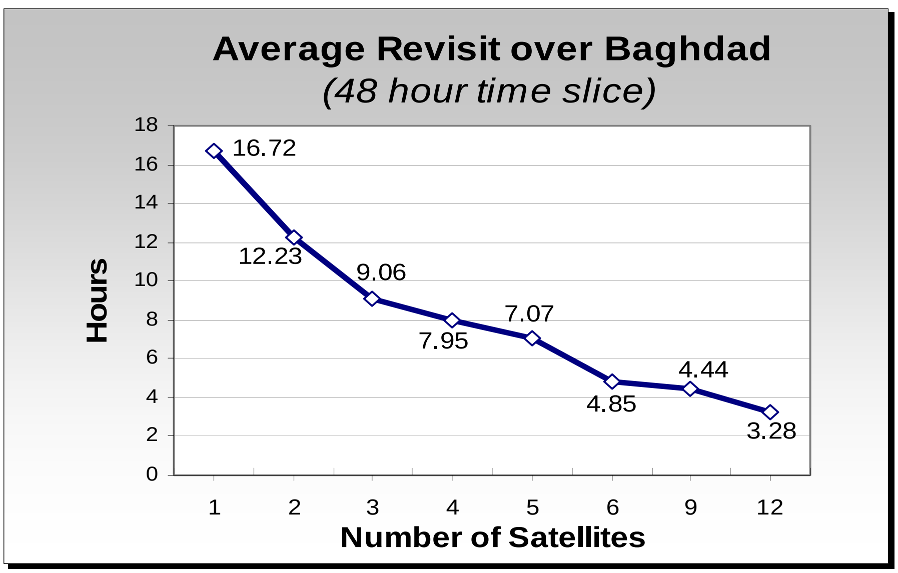

Figure 15. Average Revisit Over Baghdad, Iraq.

The data above represents the average revisit duration of Baghdad city for the respective constellations. The graph shows how the revisit rate is improved as the number of satellites in the constellation increase. Again, these figures are average values

58 Victor Solanyk, Re: QuickBird Collection Capability, Available e-mail: from vsolanyk@digitalglobe.com, accessed March 2006.

based on computational analysis over a 48 hour time period. For instance, a two satellite constellation has an average revisit over Baghdad of 12.23 hours within a 48 hour time period. The average mean time to access Baghdad (33 degrees North latitude) is 16.72 hours throughout the entire operating envelope. Based on average resolution of the chosen orbit, the average mean time to access of 167 hours is required for NIIRS quality of six or better.

Although this research did not incorporate a coverage analysis against known classified or unclassified target decks, coverage analysis was obtained against a smaller list of randomly chosen targets. Multiple point target collection per day included nine of the falling areas:

- Baghdad
- Beijing
- Belgrade
- Hong Kong
- Mogadishu
- Pyongyang
- Seoul
- Severodvinsk
- Tehran

Clearly, a twelve satellite system is superior (as well as the most expensive) when considering average revisit or total area coverage. From a global perspective, a single QuickBird satellite can image all nine of the aforementioned cities in two days and achieve a total collection area of 10,200 km^2 and 38 point images. A twelve satellite constellation would obviously provide roughly 12 times the capability depending on orbit orientation and phasing techniques. A smaller constellation, however, may be considered more economical based on the performance provided for the cost. Naturally, comparing the capabilities between different constellations can be measured from overall capability but also improvements between constellation sizes.

Note the improvement with revisit in Figure 15 above when jumping from three to five satellites--a 1.99 hour improvement in revisit. A 7.66 hour improvement in revisit exists when increasing from a one to three satellite constellation. Obviously, this is greater than two times the improvement with the addition of two satellites from 1-3 versus 3-5 satellites. In general, as the constellation size grows, revisit improvements diminish and will asymptotically show increased capability.

2. Total Area Collection

For QuickBird in the modified orbit, a total regional area of 3,720 km^2 or 125,000 km^2 global area can be captured on a daily basis. A four satellite constellation ground track after two days of travel are illustrated in the chart below:

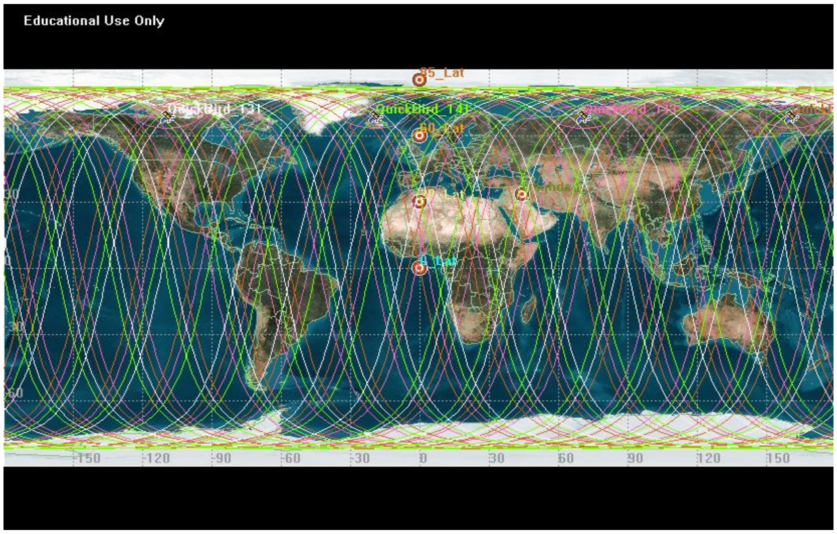

Figure 16. Four Satellite Constellation Ground Track (48 hour time slice).

The primary drivers for design result from requirements set forth by government users such as FIA and the national IMINT directorate. A two day sample size was used for coverage determination due to the relatively short orbital period resulting in approximately 32 evaluated orbits. Evaluating coverage over a longer time period (>48 hours) involves large computations that caused computer over-saturation and resulted in program lock-up within STK. A 48 hour period was estimated as a good sample size and would approximate true revisit numbers effectively.

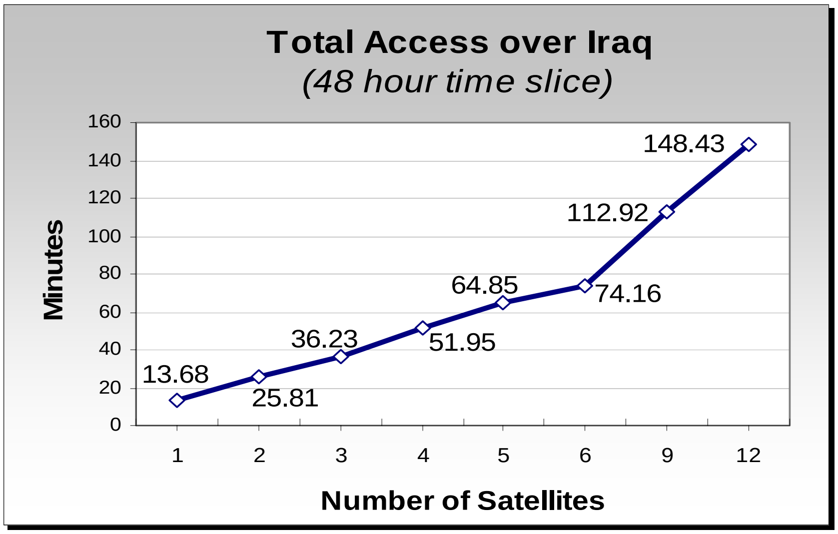

Figure 17. Regional Coverage: Access Time over Iraq.

Regional coverage analysis included how often the country of Iraq could be captured per day. For the QuickBird satellite, it can map approximately 3,720 km^2 per day while using the elliptical orbit described earlier. Again, these figures are based on a collection rate of 2 images per minute as described for point target collection. With the total access rate shown above and roughly 2 pictures per minute collection rate, an estimation of total regional collection can be calculated. This is presented in the following figure:

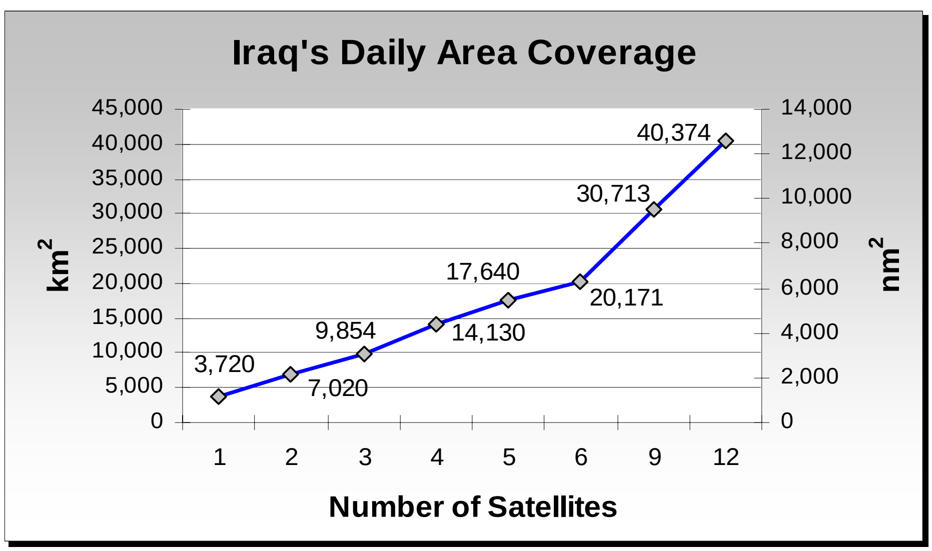

Figure 18. Daily Regional Area Collection.

It can be observed that a 12 satellite constellation can produce over 43,000 km^2 (over 12,000 nm^2) of imagery every day as an average value. This takes into account the full spectrum of resolution that ranges between 10-37 inches an does not incorporate duty cycle. To provide a daily area collection with a given NIIRS or resolution value (for instance, 10 inches or better) is difficult to determine. This is due to the nature in the perturbative affects of elliptical orbits and timing. A time window would need to be established for a given orbit and given region to determine a more accurate area collection at a minimum resolution.

3. System Capability Overview

Total global area collection is difficult to determine based on several factors to include satellite access, duty cycle and peak demand for image collection. Several random areas of interest would be required to calculate coverage against when programming STK. Digital Globe's QuickBird advertised a max daily global collection of 200,000 km^2 but routinely averages 125,000 km^2 per day.[59] The overview capability of QuickBird can be surmised in the following chart:

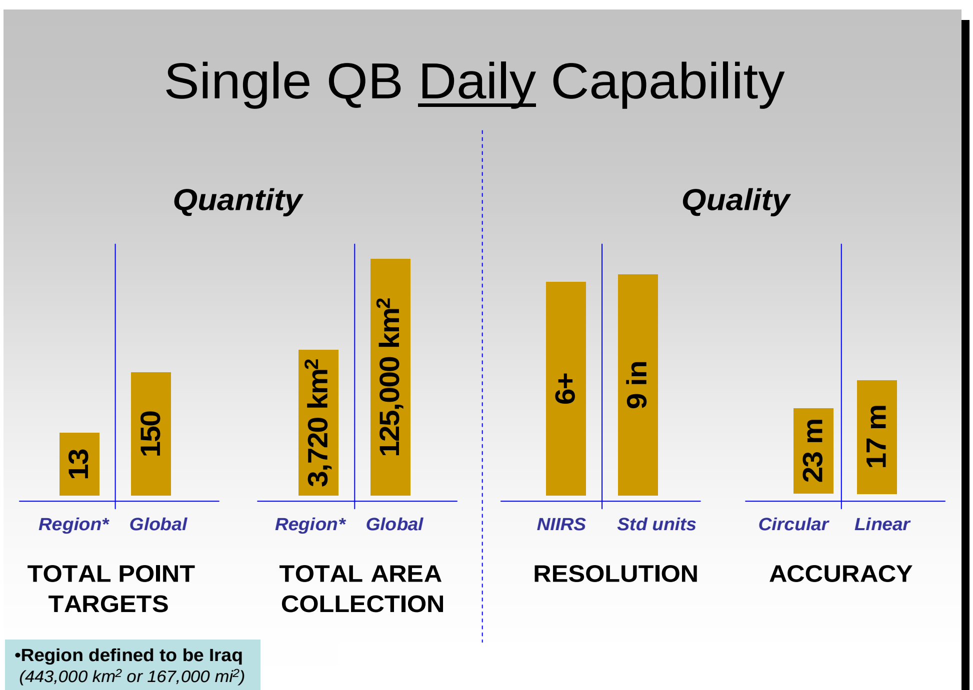

Figure 19. QuickBird Daily Capability.

[59] Victor Solanyk, Re: QuickBird Collection Capability, Available e-mail: from vsolanyk@digitalglobe.com, accessed August 2006.

It is shown that the overall system capability for a single QuickBird satellite is impressive if a one year orbit life is acceptable. It is important to note that the above figure illustrates the capability of only one QuickBird satellite in the modified orbit presented in Chapter III. Orbit Life. Theoretically, a four satellite constellation, for example, would provide four times the capability of daily collection. Accuracy is a quality factor that cannot be improved and is considered a limiting factor. The total life cycle cost for a constellation would be a determining factor when deciding the true value of a COTS solution.

C. COST ESTIMATION

Determining the life cycle cost of a four satellite constellation is difficult at best. The larger the constellation, the greater cost saving would be due to multiple production efficiency from the industry. A smaller constellation saves money however constrains coverage capability. The life cycle cost estimation can be broken into three main phases:

- Research, Development, Test and Evaluation (RDT&E)—which includes non recurring costs
- Production—which involve Theoretical First Unit (TFU) and learning curve affects
- Operations and Maintenance (O&M)

The purpose of utilizing an already existing design is to obviate the need to absorb NRE costs and exploit the true value of a COTS solution. The parametric cost estimation method can be considered as a Cost Estimating Relationship (CER). Separate cost elements can be divided into comparable physical subsystems (or components). A production rate of deploying one satellite every month may be considered truly optimistic in today's commercial satellite launch cycle. However, a high production rate of a well known and already proved system would enable a potentially effective mission capability that cannot be overlooked.

The Office of Secretary of Defense (OSD) has recently created a national security architect intended to integrate the efforts of both the NRO and DoD when designing architectures. The most significant procedural impediment facing this architect is procurement procedures. Past practice in contracting space systems has been the scale economy in large block buys. This concept of large block buys has to potential to freeze architectures far into the future. Consider the GPS program as an example. Since decisions on the design of the space segment of a given architecture are made infrequently, their processes occur within program stovepipes. This applies to organizations that vet requirements, allocate funds and execute program development.[60] A continuously updated architecture such as the one described in this thesis can provide technological improvements with the addition of new satellites during reconstitution.

[60] Peter Hays, James Smith and Alan Van Tassel, *Spacepower for a new millennium*. 67.

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VII. CONCLUSIONS

In the near future, the ability to design, develop and deploy a new imagery satellite will continue to become increasingly more challenging and subsequently decrease the likelihood of maintaining a robust collection system similar to that of today. The need for a space based quality imaging system will always be present in order to meet valid national objectives. As a result, a more innovative acquisition method for imagery satellites must be considered in order to maintain our imagery collection capabilities.

Rebuilding a QuickBird system cannot be duplicated 100% due to the nature of emerging technology and build procedures. Certain components are obsolete and currently unobtainable. For instance, QuickBird-2 utilizes a forward scanning focal plane, however newer constructed focal planes are now built with forward and reverse scanning capabilities.[61] This change in technology offers a measurable improvement for imagery collection capability. Other valuable improvements are lessons that are learned from earlier construction. For instance, articulating (movable) solar arrays are likely not necessary for a known orbit with a short mission life. Fixed arrays reduce overall weight and complexity of the spacecraft. Finally, another discovery Digital Globe has found rests with launch vehicle selection. Their concept for a QuickBird follow-on would possibly allow fitting into a Minotaur-4 or EuroRocket launch vehicle which cost only $25M per launch versus >$70M for a Delta II.[62] In general, improvements from follow-on QuickBird construction could take advantage of improvements in smarter packaging for increased agility, up-to-date imager electronics and sizing to take advantage of cheaper launchers. Additionally, for a satellite with a planned one year orbit life, reductions in costs and weight could result from reduction of redundant systems.

The concept of utilizing commercially developed satellites which have successfully demonstrated their imaging capabilities is sound. This concept can be seen as a solution for augmenting our national imaging collection capability and can greatly

[61] Victor Solanyk, Re: QuickBird Collection Capability, Available e-mail: from vsolanyk@digitalglobe.com, accessed August 2006.

[62] Ibid.

reduce the demand from current national systems. It has been demonstrated that a commercially purchased satellite constellation deployed in unique orbits can provide a marked improvement in imaging collection and meet a significant amount of our national imaging requirements. A significant amount of the collection requirements are to acquire images that have lower resolution but greater area coverage. A greater factor when supporting a tactical war fighter is the need for persistent imagery.[63] A small constellation of commercial satellites can relieve such demands on national systems which can be used to image point targets of higher resolution more often.

A constellation of commercial satellites can be used in a Government Owned, Commercially Operated (GOCO) structure. This would reduce the overall life-cycle costs of such a constellation since this would obviate the need for the construction of new satellite control networks and ground stations and reduce the demands of training new personnel.

> [W]e find in these contracts [at ***GOCO*** munitions plants] a reflection of the fundamental policy of the government to refrain, as much as possible, from doing its own manufacturing and to use, as much as possible (in the production of munitions), the experience in mass production and genius for organization that had made American industry outstanding in the world. The essence of this policy called for private, rather than public, operation of war production plants. . . . We relied upon that system as the foundation of the general industrial supremacy upon which ultimate victory [in World War II] might depend![64]

The court presiding in the above hearing noted the uniqueness of the GOCO concept, stating: "The scheme, which is involved in the present situation, of producing munitions in government owned plants, through the agency of selected qualified commercial manufacturers, on the basis of cost plus a fixed fee for carrying on the operations, with title to both the materials used and the products manufactured resting at all times in the United States, was admittedly a novel and revolutionary setup in the field of American industrial life."[65] The principle emphasis of the COTS concept is the utility

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[63] Edward B. Tomme, *The Myth of the Tactical Satellite*, Air & Space Power Journal, (July 2006), 94.

[64] Mark J. Conner, Government Owned-Contractor Operated Munitions Facilities, Military Law Review, United States Cartridge Co. v. Powell, 174 F.2d 718,726 (8th Cir. 1949), 1.

[65] Mark J. Conner, Government Owned-Contractor Operated Munitions Facilities, Military Law Review, United States Cartridge Co. v. Powell, 174 F.2d 718,726 (8th Cir. 1949), 1.

of purchasing a system that has a proven capability and exploiting the advantages of commercial-off-the-shelf. Such a strategy would provide a working system in short order with an aggressive deployment schedule to populate the constellation which is a capability that would be unmatched by any newly developed, never-been-flown system.

As mentioned earlier, the primary direction of this thesis is to study the idea of a COTS solution that would incorporate the use of existing, commercially developed EO satellites. This effort would help mitigate a tremendous amount of risk and expense for research, development and launching a new satellite program. Another immeasurable advantage is the effect of multiple satellite construction to the work force. Such a scenario would certainly invigorate the marketplace and greatly improve construction quality and capability which only serves to improve future satellite systems. The benchmark is for a price that is roughly a tenth of the much more capable traditional intelligence EO systems.[66]

Commercially-derived imagery systems have the potential to provide information at a rate that is needed to support the vision of global engagement. The acquisition of images alone, however, will not support the demands of DoD. Generally, this is because industry will not supply enough satellite to provide access for support of national and military needs since industry market alone does not require it. Additionally, commercial satellites cannot satisfy all intelligence imagery needs alone.[67] An appropriate mix of capability and quantity will be required to meet the technical imagery needs.

[66] Peter Hays, James Smith and Alan Van Tassel, *Spacepower for a new millennium*. 79.

[67] Peter Hays, James Smith and Alan Van Tassel, *Spacepower for a new millennium*. 79.

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VIII. RECOMMENDATIONS

Currently, the United States spends billions annually to develop, acquire and operate satellite and space related systems. A majority of these programs in the last two decades have experienced problems that have led to increased costs, delayed schedules and increased performance risk. A fundamental driver for these cost overruns and schedule delays are attributed to overly detailed requirements provided from the stakeholders with little or no flexibility. Doctor Pedro Rustan illustrates this acquisition problematic to the U.S. House of Representatives at the House Armed Services Committee's Space Acquisition Hearing in July 2005.

> During the first 30 years of the space program, we built capability-driven systems that provided the best that our advanced technologies could offer. That strategy worked well in offering innovative solutions, but it did not always represent the customers' needs. During the last 15 years, however, we have swung the pendulum to the other extreme by collecting overly broad requirements sets that our space systems should meet. This strict requirements-driven process often includes mutually exclusive capabilities that cannot be easily integrated on the same spacecraft. When we attempt to do so, it can drive significant increases in cost and schedule. Our requirements driven stakeholders often do not understand the cost implications of the various elements of their respective wish lists, and when we proceed to blindly integrate these capabilities, considerable problems develop. This problem is exacerbated when we are asked to hold fixed performance, cost and schedule at the beginning of any space acquisition, thereby inexorably increasing program risk.[68]

In some cases, capabilities and related products from these space systems have not been delivered to the intended user or war-fighter even decades after initial development. It is essential that other innovative acquisition methods be considered with an in-depth review of analysis of alternatives in order to ensure a successful and timely system that meets valid user requirements. It is important to understand the significance of conducting a comprehensive review of alternatives that meet the needs of imagery intelligence.

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[68] Pete Rustan, *Testimony of Dr. Pete Rustan before the House Armed Services Committee, Hearing on Space Acquisition* (July 2005), 3.

A. ITEMS FOR FOLLOW-ON STUDY

This research has a significant potential for further study particularly in light of world-wide current events. A continued analysis and refinement of various orbit selection, constellation design and coverage scenarios could provide additional information and help make better informed decisions when considering an optimum constellation design.

Variations of a constellation could include further detailed research of different orbital properties. A more accurate representation of total area drag may allow for prolonged orbit life if programming the solar arrays to always fly parallel to the velocity vector ("stream-lined") and rely on battery power for perigee operations. A mix of low and high inclined orbits coupled with a combination of circular and elliptical orbits could be evaluated.

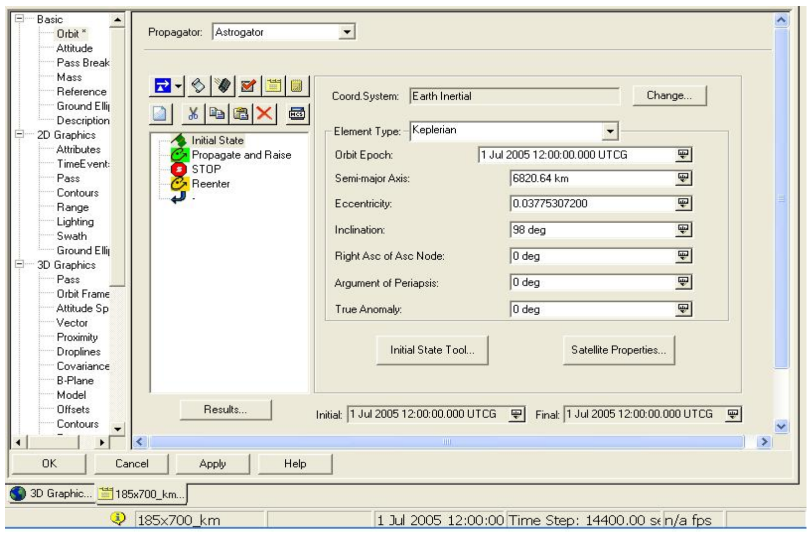
A significant step for further research is to use the orbits generated from this thesis against known decks. Cooperation with the NGA may be able to provide known civil target decks with thousands of civil points of interest globally. From there, coverage capability can be determined for a given constellation and measure how the commercial satellite architecture can meet collection needs. Total area coverage, revisit and access capability can be evaluated against these known target decks.

Another significant area for further analysis falls with in the acquisition policy. Acquisition transformation for future space procurements will be critical to the success of tomorrow's space systems. A part of this analysis could include a study with launch rates from various vendors. This topic is one of the most interesting considerations for future work.

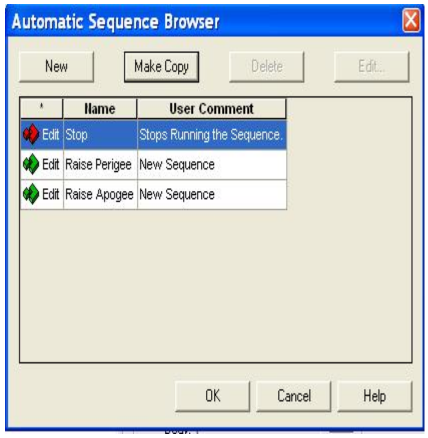
APPENDIX

A. ASTROGATOR PROPAGATOR BUILD

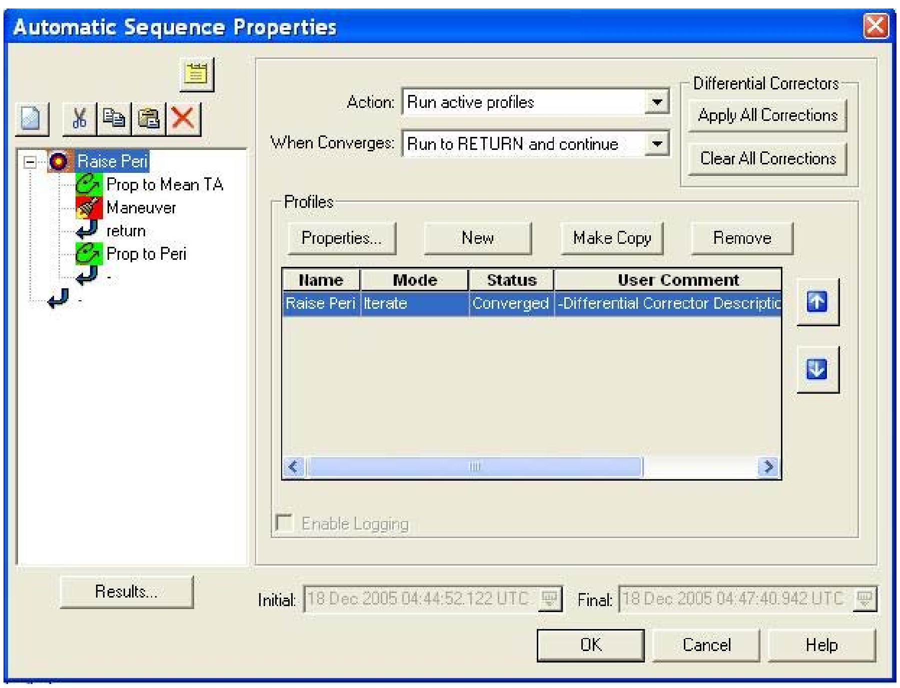
- Start STK and create a generic satellite scenario
- Generate a desired orbit profile for the satellite using the STK orbit setup wizard.
- Open the satellite "Properties Browser"
  - Make orbit element adjustments as necessary
  - Select "Astrogator" in the Propagator field
  - The following photo shows the Astrogator property page:



- The primary goal is to click on each icon in the programmable fields starting with the Initial State section (click on the green flag icon).
  - Make initial state conditions for your satellite:
    - Click on "Satellite Properties" tab (lower right corner)
    - Set proper orbit values for Spacecraft Parameters
    - Click on "Fuel Tank" tab (top of page) and input fuel tank properties
  - Generate a Target sequence to propogate:
  - Left click on green "Propagate" (under Initial State) to highlight
  - Left click on MCS icon (near the top)
  - Add new automatic sequence:
    - Click on "Add" and then "OK" to add new sequence
    - You can rename the sequence "Raise Perigee"
    - Add another sequence and rename "Raise Apogee"
    - Now click on "Edit" on the Raise Perigee sequence
    - This opens up the Automatic Sequence Properties page

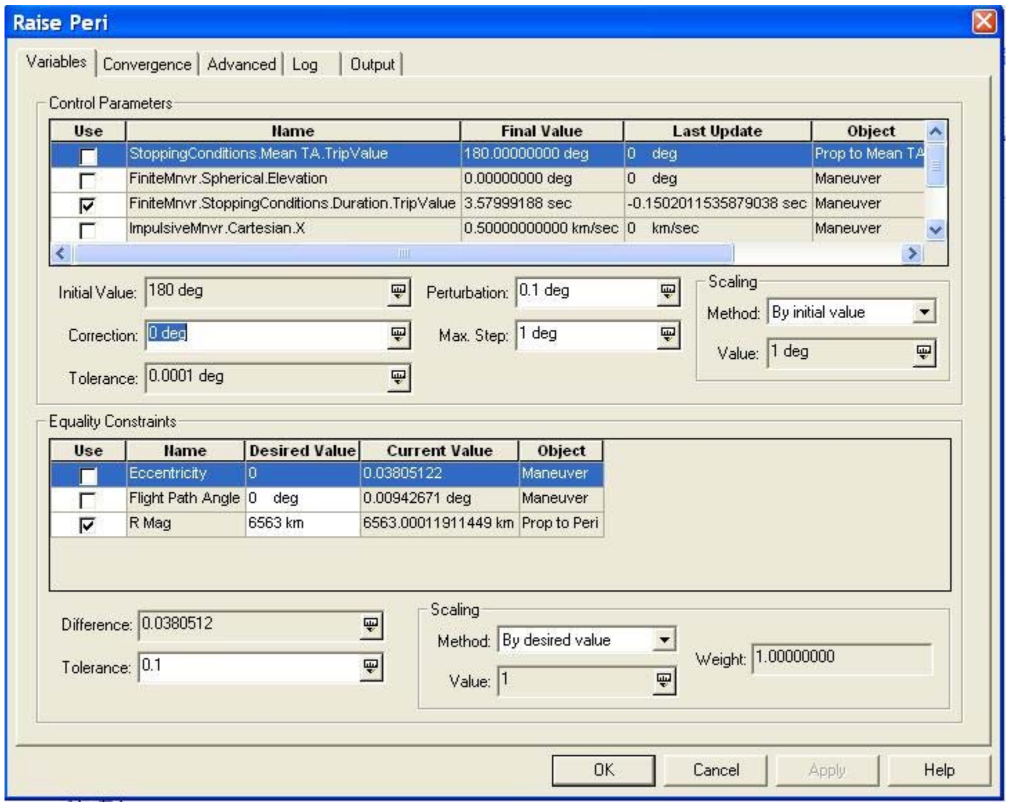


- Edit new automatic sequence:
  - Click on white icon  called "Segment Selection"
  - Click on "Target Sequence"  icon to add a new sequence to the propagation sub-list then hit "OK"
  - Rename Target icon to "Raise Perigee"
  - Click on white icon again to add additional segments to match the figure below (add: Propagate, Maneuver, Return, Propagate and another Return sequence:



- Edit "Raise Perigee" Target sequence:
  - Left click on Raise Perigee  icon to highlight

- Click on Properties… tab to the right
- Input the following variables in all appropriate fields as shown in the figure below
- Adjustments apply only to the Variables tab
    - Note values under “Desired Value” columns are based on the desired perigee value
- Default settings to the remaining four tabs at the top (Convergence, Advanced, Log and Output) are adequate and can be left alone



- Repeat above procedures for Raise Apogee sequence
    - Ensure Desired Value inputs are for the desired apogee

B. DESIRED ORBIT-LIFE PARAMETERS

The following represent outputs from the Astrogator subroutine in STK when accounting for 315 kg of fuel:

1. 150 km circular orbit: 6 months

Maneuver	Segment	Start Time (UTCG)	Stop Time (UTCG)	Duration (sec)	Delta V (m/sec)	Fuel Used (kg)
1	Raise Apogee	7 Jul 2005 02:44:51.311	7 Jul 2005 02:45:50.703	59.392	29.029829	10.094
2	Raise Perigee	15 Jul 2005 15:51:16.218	15 Jul 2005 15:52:04.331	48.113	23.728982	8.177
3	Raise Perigee	26 Jul 2005 05:14:56.525	26 Jul 2005 05:15:41.424	44.898	22.317232	7.631
4	Raise Apogee	6 Aug 2005 14:32:15.181	6 Aug 2005 14:33:12.073	56.893	28.524545	9.669
5	Raise Perigee	14 Aug 2005 07:00:58.730	14 Aug 2005 07:02:01.627	62.897	31.860229	10.689
6	Raise Perigee	19 Aug 2005 10:54:19.971	19 Aug 2005 10:55:22.022	62.051	31.773484	10.546
7	Raise Perigee	23 Aug 2005 06:13:33.065	23 Aug 2005 06:14:32.065	59.000	30.532863	10.027
8	Raise Perigee	23 Aug 2005 21:00:05.001	23 Aug 2005 21:00:21.749	16.747	8.724913	2.846
9	Raise Perigee	29 Aug 2005 15:49:31.781	29 Aug 2005 15:50:22.101	50.319	26.371652	8.552
10	Raise Perigee	3 Sep 2005 11:38:02.475	3 Sep 2005 11:38:09.309	6.833	3.599538	1.161
11	Raise Apogee	5 Sep 2005 00:01:20.673	5 Sep 2005 00:02:04.516	43.844	23.200660	7.451
12	Raise Perigee	12 Sep 2005 13:54:26.879	12 Sep 2005 13:55:08.530	41.650	22.210873	7.079
13	Raise Perigee	20 Sep 2005 05:10:51.485	20 Sep 2005 05:11:38.311	46.826	25.172618	7.958
14	Raise Perigee	26 Sep 2005 22:32:44.659	26 Sep 2005 22:33:38.033	53.374	28.958177	9.071
15	Raise Apogee	2 Oct 2005 07:12:34.113	2 Oct 2005 07:13:31.794	57.681	31.618428	9.803
16	Raise Apogee	6 Oct 2005 15:01:17.580	6 Oct 2005 15:02:15.219	57.639	31.938594	9.796
17	Raise Perigee	10 Oct 2005 08:51:27.201	10 Oct 2005 08:52:24.506	57.305	32.101337	9.739
18	Raise Perigee	13 Oct 2005 17:24:07.184	13 Oct 2005 17:25:01.502	54.318	30.754565	9.231
19	Raise Perigee	16 Oct 2005 18:13:00.976	16 Oct 2005 18:13:50.916	49.940	28.562589	8.488
20	Raise Perigee	18 Oct 2005 11:22:31.403	18 Oct 2005 11:22:42.571	11.168	6.425421	1.898
21	Raise Perigee	20 Oct 2005 15:14:30.550	20 Oct 2005 15:15:15.334	44.784	25.908353	7.611
22	Raise Perigee	25 Oct 2005 22:40:54.133	25 Oct 2005 22:41:33.516	39.383	22.974021	6.693
23	Raise Perigee	30 Oct 2005 18:31:56.027	30 Oct 2005 18:31:59.838	3.811	2.232449	0.648
24	Raise Perigee	31 Oct 2005 09:14:37.184	31 Oct 2005 09:15:14.510	37.326	21.957336	6.344
25	Raise Apogee	7 Nov 2005 02:55:12.032	7 Nov 2005 02:55:52.566	40.534	24.031536	6.889
26	Raise Perigee	13 Nov 2005 12:37:52.157	13 Nov 2005 12:38:38.720	46.563	27.850451	7.913
27	Raise Perigee	18 Nov 2005 19:46:41.810	18 Nov 2005 19:47:32.764	50.954	30.782042	8.660
28	Raise Perigee	22 Nov 2005 22:54:29.561	22 Nov 2005 22:55:22.076	52.515	32.065994	8.925
29	Raise Perigee	26 Nov 2005 04:17:29.626	26 Nov 2005 04:18:22.193	52.568	32.451691	8.934
30	Raise Perigee	28 Nov 2005 18:09:54.664	28 Nov 2005 18:10:46.101	51.437	32.104178	8.742
31	Raise Perigee	29 Nov 2005 08:55:37.561	29 Nov 2005 08:55:52.932	15.371	9.661987	2.612
32	Raise Apogee	3 Dec 2005 15:57:30.003	3 Dec 2005 15:58:16.024	46.021	29.119808	7.821
33	Raise Apogee	8 Dec 2005 15:28:16.514	8 Dec 2005 15:28:57.019	40.505	25.870028	6.884
34	Raise Perigee	10 Dec 2005 16:29:47.147	10 Dec 2005 16:29:53.872	6.725	4.317465	1.143
35	Raise Perigee	14 Dec 2005 06:34:41.050	14 Dec 2005 06:35:16.505	35.455	22.866650	6.026
36	Raise Perigee	18 Dec 2005 04:47:07.538	18 Dec 2005 04:47:11.119	3.581	2.319429	0.609

37	Raise Perigee	21 Dec 2005 11:06:41.587	21 Dec 2005 11:07:15.548	33.961	22.088587	5.772
38	Raise Perigee	29 Dec 2005 19:34:35.644	29 Dec 2005 19:35:14.444	38.800	25.440197	6.594
39	Raise Apogee	5 Jan 2006 22:19:23.304	5 Jan 2006 22:20:08.134	44.830	29.670872	7.619
40	Raise Perigee	11 Jan 2006 13:15:04.993	11 Jan 2006 13:15:52.361	47.368	31.679407	8.050
41	Raise Perigee	16 Jan 2006 06:24:54.445	16 Jan 2006 06:25:41.825	47.380	32.031995	8.052
42	Raise Perigee	20 Jan 2006 11:10:39.611	20 Jan 2006 11:11:24.528	44.918	30.692804	7.634
43	Raise Perigee	24 Jan 2006 08:12:16.864	24 Jan 2006 08:12:58.661	41.798	28.851426	7.104
44	Raise Perigee	27 Jan 2006 23:03:31.596	27 Jan 2006 23:03:59.924			

2. 185x600 km orbit: 9.5 months

Lifetime:

W/o prop: 47d

Maneuver	Segment	Start Time (UTCG)	Stop Time (UTCG)	Duration (sec)	Delta V (m/sec)	Fuel Used (kg)
1	Raise Apogee	23 Jul 2005 02:27:22.272	23 Jul 2005 02:29:12.995	110.723	42.404156	18.818
2	Raise Apogee	15 Aug 2005 08:45:24.362	15 Aug 2005 08:47:38.664	134.302	52.268263	22.825
3	Raise Perigee	21 Aug 2005 12:04:02.807	21 Aug 2005 12:04:24.976	22.169	8.717894	3.768
4	Raise Apogee	28 Aug 2005 02:27:15.344	28 Aug 2005 02:29:11.240	115.896	46.000892	19.697
5	Raise Perigee	31 Aug 2005 08:00:29.580	31 Aug 2005 08:00:38.843	9.263	3.707785	1.574
6	Raise Perigee	9 Sep 2005 04:38:14.772	9 Sep 2005 04:38:19.858	5.086	2.037820	0.864
7	Raise Apogee	20 Sep 2005 10:07:35.458	20 Sep 2005 10:09:32.812	117.353	47.417139	19.944
8	Raise Apogee	6 Oct 2005 02:41:58.379	6 Oct 2005 02:44:04.432	126.054	51.798629	21.423
9	Raise Apogee	16 Oct 2005 23:17:02.456	16 Oct 2005 23:18:51.727	109.271	45.652196	18.571
10	Raise Perigee	18 Oct 2005 12:55:01.030	18 Oct 2005 12:55:10.775	9.744	4.105744	1.656
11	Raise Apogee	2 Nov 2005 14:54:01.253	2 Nov 2005 14:55:46.722	105.469	44.809006	17.925
12	Raise Apogee	15 Nov 2005 12:10:15.996	15 Nov 2005 12:12:16.260	120.264	51.941569	20.439
13	Raise Perigee	21 Nov 2005 08:58:06.700	21 Nov 2005 08:58:30.609	23.909	10.436190	4.063
14	Raise Apogee	23 Nov 2005 13:02:43.099	23 Nov 2005 13:04:39.134	116.035	51.182249	19.720
15	Raise Perigee	3 Dec 2005 06:10:16.455	3 Dec 2005 06:10:27.038	10.584	4.713088	1.799
16	Raise Apogee	8 Dec 2005 09:46:16.726	8 Dec 2005 09:47:52.400	95.674	42.950872	16.260
17	Raise Perigee	9 Dec 2005 18:50:50.980	9 Dec 2005 18:50:55.970	4.990	2.257229	0.848
18	Raise Apogee	30 Dec 2005 17:19:38.316	30 Dec 2005 17:21:28.295	109.979	50.198674	18.691
19	Raise Apogee	12 Jan 2006 02:19:41.282	12 Jan 2006 02:21:31.673	110.392	51.263603	18.761
20	Raise Perigee	20 Jan 2006 23:01:40.627	20 Jan 2006 23:01:51.449	10.822	5.073700	1.839
21	Raise Apogee	22 Jan 2006 12:05:40.287	22 Jan 2006 12:07:15.457	95.169	45.001362	16.174
22	Raise Apogee	8 Feb 2006 23:37:11.732	8 Feb 2006 23:38:47.614	95.882	46.045210	16.295
23	Raise Apogee	20 Feb 2006 14:20:28.455	20 Feb 2006 14:22:15.589	107.133	52.315691	18.208
24	Raise Perigee	25 Feb 2006 07:48:53.042	25 Feb 2006 07:49:14.217	21.175	10.451389	3.599
25	Raise Apogee	28 Feb 2006 13:38:15.416	28 Feb 2006 13:39:20.416	65.000	32.315680	11.047

Global Statistics

Total Duration 1852.337
Total Delta V 805.066031
Total Fuel Used 314.810

Propagation Statistics:
Number of steps: 308776
Average step size: 73.3502 sec
Largest step size: 81.826 sec
Smallest step size: 0.0365118 sec

```
----------------------------------
Satellite State at End of Segment:
----------------------------------

UTC Gregorian Date: 28 Feb 2006 14:24:35.421  UTC Julian Date: 2453795.10040997
Julian Ephemeris Date: 2453795.10116441
Time past epoch: 2.09175e+007 sec   (Epoch in UTC Gregorian Date: 1 Jul 2005 12:00:00.000)

State Vector in Coordinate System: Earth Inertial

Parameter Set Type:  Cartesian
         X:      882.7617069362306700 km              Vx:       -0.8436932022464334 km/sec
         Y:    -6739.8273414207106000 km              Vy:       -1.4617225513936580 km/sec
         Z:    -1245.7494638184612000 km              Vz:        7.3035115245208182 km/sec

Parameter Set Type:  Keplerian
       sma:     6736.6020601813880000 km            RAAN:         276.0345776215904 deg
       ecc:        0.0258297083175773                  w:         169.8782462435171 deg
       inc:         97.74016072385723 deg             TA:         179.6399124212284 deg

Parameter Set Type:  Spherical
 Right Asc:         277.4619474022312 deg     Horiz. FPA:      0.009547500087046948 deg
      Decl:        -10.38527685908656 deg        Azimuth:         352.1301167067121 deg
       |R|:     6910.6029078510310000 km             |V|:        7.4959810315647166 km/sec


Other Elliptic Orbit Parameters :
 Ecc. Anom:          179.630488243721 deg       Mean Anom:         179.6209439289981 deg
 Long Peri:          85.9128238651074 deg        Arg. Lat:         349.5181586647455 deg
 True Long:         265.5527362863359 deg        Vert FPA:         89.99045249991295 deg
  Ang. Mom:         51801.74759472926 km^2/sec          p:     6732.1075755717802000 km
        C3:        -59.16936138413784 km^2/sec^2   Energy:        -29.58468069206892 km^2/sec^2
   Vel. RA:         240.0068415891717 deg       Vel. Decl:          76.9881807496849 deg
 Rad. Peri:     6562.5975939153113000 km        Vel. Peri:        7.8934822459263136 km/sec
  Rad. Apo:     6910.6065264474637000 km         Vel. Apo:         7.495977002377385 km/sec
 Mean Mot.:       0.06542295851430671 deg/sec
    Period:          5502.65546186321 sec          Period:         91.71092436438683 min
    Period:         1.528515406073114 hr           Period:       0.06368814191971307 day
              Time Past Periapsis:           2745.533800488686 sec
          Time Past Ascending Node:          5334.043881403149 sec
   Beta Angle (Orbit plane to Sun):           -60.813679538146 deg
Mean Sidereal Greenwich Hour Angle:            14.415048514724 deg

Geodetic Parameters:
  Latitude:        -10.44667698470312 deg
 Longitude:        -96.86789347578353 deg
  Altitude:      533.1636387810724500 km
```

```
Geocentric Parameters:
  Latitude:        -10.38354546916089 deg
 Longitude:        -96.86789347578353 deg



Spacecraft Configuration:
      Drag Area:  7.1e-006 km^2
       SRP Area:  7.1e-006 km^2
       Dry Mass:  1000 kg
      Fuel Mass:  0.190389 kg
     Total Mass:  1000.19 kg
Area/Mass Ratio:  7.09865e-009 km^2/kg
  Tank Pressure:  5000                     Pa
   Fuel Density:  999999999999.9999        kg/km^3
             Cr:  1.000000
             Cd:  2.200000
 Rad Press Area:  7.1e-006 km^2
Rad Press Coeff:  1.000000
```

3. 185x700 km orbit: 12.1months

Lifetime:
W/o prop: 60d

Maneuver	Segment	Start Time (UTCG)	Stop Time (UTCG)	Duration (sec)	Delta V (m/sec)	Fuel Used (kg)
1	Raise Apogee	27 Jul 2005 21:30:10.732	27 Jul 2005 21:32:02.156	111.424	42.674720	18.937
2	Raise Apogee	21 Aug 2005 18:37:05.110	21 Aug 2005 18:39:13.368	128.259	49.900883	21.798
3	Raise Perigee	26 Aug 2005 20:06:36.157	26 Aug 2005 20:06:53.524	17.367	6.822374	2.952
4	Raise Perigee	5 Sep 2005 06:24:39.040	5 Sep 2005 06:24:45.787	6.747	2.654911	1.147
5	Raise Apogee	8 Sep 2005 17:56:24.199	8 Sep 2005 17:58:08.714	104.515	41.432659	17.763
6	Raise Apogee	3 Oct 2005 13:24:23.835	3 Oct 2005 13:26:30.835	127.000	51.144466	21.584
7	Raise Apogee	18 Oct 2005 04:52:19.992	18 Oct 2005 04:54:11.855	111.863	45.797058	19.011
8	Raise Perigee	28 Oct 2005 10:13:55.947	28 Oct 2005 10:14:01.145	5.197	2.145295	0.883
9	Raise Apogee	7 Nov 2005 01:16:41.401	7 Nov 2005 01:18:28.324	106.922	44.483663	18.172
10	Raise Apogee	24 Nov 2005 07:50:24.424	24 Nov 2005 07:52:25.727	121.303	51.294653	20.616
11	Raise Perigee	1 Dec 2005 07:13:34.887	1 Dec 2005 07:13:53.397	18.510	7.906582	3.146
12	Raise Apogee	6 Dec 2005 12:03:08.706	6 Dec 2005 12:04:53.141	104.435	45.011600	17.749
13	Raise Perigee	11 Dec 2005 18:33:24.598	11 Dec 2005 18:33:31.355	6.757	2.936038	1.148
14	Raise Apogee	1 Jan 2006 18:33:54.620	1 Jan 2006 18:35:44.395	109.776	48.115910	18.657
15	Raise Apogee	18 Jan 2006 14:18:33.197	18 Jan 2006 14:20:24.287	111.090	49.506668	18.880
16	Raise Perigee	1 Feb 2006 14:01:39.994	1 Feb 2006 14:01:45.143	5.149	2.314826	0.875
17	Raise Apogee	3 Feb 2006 09:41:11.697	3 Feb 2006 09:42:43.149	91.453	41.422795	15.543
18	Raise Apogee	25 Feb 2006 19:54:10.399	25 Feb 2006 19:56:01.399	111.000	51.072963	18.865
19	Raise Apogee	8 Mar 2006 11:25:06.704	8 Mar 2006 11:26:52.377	105.673	49.459684	17.959
20	Raise Perigee	9 Mar 2006 09:54:26.735	9 Mar 2006 09:54:43.593	16.858	7.967909	2.865
21	Raise Perigee	19 Mar 2006 15:30:12.860	19 Mar 2006 15:30:19.244	6.384	3.023080	1.085
22	Raise Apogee	24 Mar 2006 17:27:21.492	24 Mar 2006 17:28:48.576	87.084	41.549644	14.800
23	Raise Apogee	12 Apr 2006 22:34:45.051	12 Apr 2006 22:36:27.473	102.422	49.630862	17.407
24	Raise Apogee	24 Apr 2006 22:32:12.312	24 Apr 2006 22:33:55.412	103.100	50.819714	17.522
25	Raise Apogee	5 May 2006 12:42:05.247	5 May 2006 12:42:38.247	33.000	16.453436	5.608

Global Statistics

Total Duration 1853.289
Total Delta V 805.542393
Total Fuel Used 314.972

Propagation Statistics:
Number of steps: 389089
Average step size: 74.1498 sec
Largest step size: 85.537 sec
Smallest step size: 0.00370106 sec

```
----------------------------------
Satellite State at End of Segment:
----------------------------------

UTC Gregorian Date: 5 May 2006 13:28:28.552  UTC Julian Date: 2453861.06144157
Julian Ephemeris Date: 2453861.06219601
Time past epoch: 2.66165e+007 sec   (Epoch in UTC Gregorian Date: 1 Jul 2005 12:00:00.000)

State Vector in Coordinate System: Earth Inertial

Parameter Set Type:  Cartesian
         X:    -4715.4957422963516000 km              Vx:       -5.0020585027009732 km/sec
         Y:      779.7751222492478300 km              Vy:        2.3134781319212112 km/sec
         Z:     5081.9256073918941000 km              Vz:       -4.9916939256278594 km/sec

Parameter Set Type:  Keplerian
       sma:     6758.0472603780208000 km            RAAN:         342.2737655058222 deg
       ecc:        0.0323107354289778                  w:         313.4629070199091 deg
       inc:          97.76494928791384 deg            TA:         179.2139680474202 deg

Parameter Set Type:  Spherical
 Right Asc:          170.6102908884642 deg     Horiz. FPA:       0.02624436703751656 deg
      Decl:          46.75636377177949 deg        Azimuth:         191.3738950987529 deg
       |R|:     6976.3828174749215000 km              |V|:        7.4357096889584673 km/sec


Other Elliptic Orbit Parameters :
 Ecc. Anom:          179.1881477359113 deg       Mean Anom:         179.1619170699613 deg
 Long Peri:          295.7366725257313 deg        Arg. Lat:         132.6768750673293 deg
 True Long:          114.9506405731515 deg        Vert FPA:         89.97375563296248 deg
  Ang. Mom:          51874.35186789279 km^2/sec          p:     6750.9919697082287000 km
        C3:         -58.98160022303599 km^2/sec^2   Energy:          -29.490800111518 km^2/sec^2
   Vel. RA:          155.1792126263082 deg       Vel. Decl:        -42.16853941706544 deg
 Rad. Peri:     6539.6897833314188000 km        Vel. Peri:        7.9322343393278203 km/sec
  Rad. Apo:     6976.4047374246220000 km         Vel. Apo:         7.435685545824925 km/sec
 Mean Mot.:        0.06511179729490824 deg/sec
    Period:          5528.951971168397 sec          Period:         92.14919951947329 min
    Period:          1.535819991991221 hr           Period:       0.06399249966630088 day
               Time Past Periapsis:           2751.604540395199 sec
          Time Past Ascending Node:           2077.470111130138 sec
   Beta Angle (Orbit plane to Sun):           -59.5769651434461 deg
Mean Sidereal Greenwich Hour Angle:            65.4005197026555 deg

Geodetic Parameters:
  Latitude:          46.89746689784604 deg
 Longitude:           105.299737975515 deg
```

```
  Altitude:      609.6042623253363200 km
Geocentric Parameters:
  Latitude:         46.72220390365819 deg
 Longitude:          105.299737975515 deg



Spacecraft Configuration:
      Drag Area:  7.1e-006 km^2
       SRP Area:  7.1e-006 km^2
       Dry Mass:  1000 kg
      Fuel Mass:  0.0284532 kg
     Total Mass:  1000.03 kg
Area/Mass Ratio:  7.0998e-009 km^2/kg
  Tank Pressure:  5000                      Pa
   Fuel Density:  999999999999.9999         kg/km^3
             Cr:  1.000000
             Cd:  2.200000
 Rad Press Area:  7.1e-006 km^2
Rad Press Coeff:  1.000000
```

4. 185x800 km orbit: 15.5 months

Lifetime:
W/o prop: 76d
w prop: d
Total:

Maneuver	Segment	Start Time (UTCG)	Stop Time (UTCG)	Duration (sec)	Delta V (m/sec)	Fuel Used (kg)
1	Raise Apogee	2 Aug 2005 11:52:54.325	2 Aug 2005 11:54:50.209	115.883	44.395321	19.695
2	Raise Apogee	26 Aug 2005 23:59:29.204	27 Aug 2005 00:01:30.367	121.164	47.146000	20.592
3	Raise Perigee	30 Aug 2005 08:43:45.677	30 Aug 2005 08:44:00.534	14.857	5.833258	2.525
4	Raise Perigee	10 Sep 2005 21:06:23.177	10 Sep 2005 21:06:29.016	5.839	2.295945	0.992
5	Raise Apogee	22 Sep 2005 06:53:32.856	22 Sep 2005 06:55:24.663	111.807	44.309040	19.002
6	Raise Apogee	14 Oct 2005 23:17:24.379	14 Oct 2005 23:19:24.636	120.258	48.415062	20.438
7	Raise Apogee	6 Nov 2005 15:50:23.940	6 Nov 2005 15:52:06.034	102.095	41.737418	17.351
8	Raise Apogee	29 Nov 2005 20:30:10.779	29 Nov 2005 20:32:10.914	120.135	49.883041	20.417
9	Raise Perigee	8 Dec 2005 17:40:14.484	8 Dec 2005 17:40:29.162	14.678	6.152921	2.495
10	Raise Apogee	15 Dec 2005 22:34:33.932	15 Dec 2005 22:36:12.312	98.380	41.576837	16.720
11	Raise Perigee	19 Dec 2005 16:55:35.150	19 Dec 2005 16:55:40.883	5.733	2.440932	0.974
12	Raise Apogee	16 Jan 2006 07:50:53.571	16 Jan 2006 07:52:51.094	117.523	50.491896	19.973
13	Raise Apogee	6 Feb 2006 04:44:58.778	6 Feb 2006 04:46:33.281	94.502	41.239489	16.061
14	Raise Apogee	6 Mar 2006 19:03:48.692	6 Mar 2006 19:05:42.657	113.965	50.514040	19.369
15	Raise Perigee	19 Mar 2006 19:27:37.922	19 Mar 2006 19:27:51.540	13.618	6.094325	2.314
16	Raise Apogee	20 Mar 2006 08:35:02.666	20 Mar 2006 08:36:42.311	99.645	44.982720	16.935
17	Raise Perigee	30 Mar 2006 10:41:10.380	30 Mar 2006 10:41:15.605	5.225	2.377765	0.888
18	Raise Apogee	13 Apr 2006 11:03:17.513	13 Apr 2006 11:04:55.358	97.845	44.885985	16.629
19	Raise Apogee	2 May 2006 14:55:49.365	2 May 2006 14:57:35.410	106.045	49.434029	18.023
20	Raise Apogee	21 May 2006 01:50:53.684	21 May 2006 01:52:19.154	85.470	40.456082	14.526
21	Raise Apogee	17 Jun 2006 11:57:07.202	17 Jun 2006 11:58:52.399	105.196	50.569577	17.878
22	Raise Perigee	27 Jun 2006 08:16:02.490	27 Jun 2006 08:16:16.542	14.052	6.821455	2.388
23	Raise Apogee	1 Jul 2006 13:40:43.157	1 Jul 2006 13:42:12.120	88.963	43.556632	15.120
24	Raise Perigee	8 Jul 2006 15:53:06.107	8 Jul 2006 15:53:11.193	5.086	2.509724	0.864
25	Raise Apogee	27 Jul 2006 17:47:50.379	27 Jul 2006 17:49:05.873	75.493	37.506607	12.830

Global Statistics

Total Duration 1853.457
Total Delta V 805.626101
Total Fuel Used 315.000

Propagation Statistics:
Number of steps: 489191
Average step size: 74.9834 sec
Largest step size: 87.759 sec
Smallest step size: 0.0111502 sec

```
----------------------------------
Satellite State at End of Segment:
----------------------------------

UTC Gregorian Date: 27 Jul 2006 18:35:40.005  UTC Julian Date: 2453944.27476857
Julian Ephemeris Date: 2453944.27552302
Time past epoch: 3.38061e+007 sec   (Epoch in UTC Gregorian Date: 1 Jul 2005 12:00:00.000)

State Vector in Coordinate System: Earth Inertial

Parameter Set Type:  Cartesian
         X:    -2882.2528274917599000 km              Vx:        1.6161125250820296 km/sec
         Y:    -4298.3707101038317000 km              Vy:        4.8746266365291104 km/sec
         Z:    -4919.7747864017119000 km              Vz:       -5.2010236286789775 km/sec

Parameter Set Type:  Keplerian
       sma:     6846.4965572312531000 km            RAAN:         63.66035120920184 deg
       ecc:        0.0429527998796705                  w:         43.49816415062851 deg
       inc:         97.82218216563072 deg             TA:         180.5658352533991 deg

Parameter Set Type:  Spherical
 Right Asc:         236.1563516375312 deg     Horiz. FPA:      -0.02539452449103661 deg
      Decl:        -43.55023751870824 deg        Azimuth:         190.8233943031376 deg
       |R|:     7140.5571261615696000 km             |V|:        7.3092031936021016 km/sec


Other Elliptic Orbit Parameters :
 Ecc. Anom:         180.5906841721566 deg       Mean Anom:         180.6160552617689 deg
 Long Peri:         107.1585153598304 deg        Arg. Lat:         224.0639994040276 deg
 True Long:         287.7243506132294 deg        Vert FPA:         90.02539452449103 deg
  Ang. Mom:         52191.77782430277 km^2/sec          p:     6833.8651612136327000 km
        C3:        -58.21962203121232 km^2/sec^2   Energy:        -29.10981101560616 km^2/sec^2
   Vel. RA:         71.65780066259931 deg       Vel. Decl:        -45.36295404695537 deg
 Rad. Peri:     6552.4203607316467000 km        Vel. Peri:        7.9652670236307941 km/sec
  Rad. Apo:     7140.5727537308594000 km         Vel. Apo:         7.309186479058451 km/sec
 Mean Mot.:       0.06385412073947287 deg/sec
    Period:         5637.850710822769 sec          Period:         93.96417851371281 min
    Period:         1.566069641895214 hr           Period:       0.06525290174563389 day
               Time Past Periapsis:           2828.573209843245 sec
          Time Past Ascending Node:           3457.948812019753 sec
   Beta Angle (Orbit plane to Sun):           -61.6235721707209 deg
Mean Sidereal Greenwich Hour Angle:            224.217313879825 deg

Geodetic Parameters:
  Latitude:        -43.74418083026945 deg
 Longitude:         12.05104142610599 deg
```

```
  Altitude:      772.6029908361923600 km
Geocentric Parameters:
  Latitude:        -43.57276770345055 deg
 Longitude:         12.05104142610599 deg



Spacecraft Configuration:
      Drag Area:  7.1e-006 km^2
       SRP Area:  7.1e-006 km^2
       Dry Mass:  1000 kg
      Fuel Mass:  8.84248e-011 kg
     Total Mass:  1000 kg
Area/Mass Ratio:  7.1e-009 km^2/kg
  Tank Pressure:  5000                     Pa
   Fuel Density:  999999999999.9999         kg/km^3
             Cr:  1.000000
             Cd:  2.200000
 Rad Press Area:  7.1e-006 km^2
Rad Press Coeff:  1.000000
```

5. 200x500 km orbit: 9.4 months

Lifetime:
W/o prop: 51d

Maneuver	Segment	Start Time (UTCG)	Stop Time (UTCG)	Duration (sec)	Delta V (m/sec)	Fuel Used (kg)
1	Raise Apogee	31 Jul 2005 03:00:30.328	31 Jul 2005 03:02:34.490	124.162	47.592910	21.102
2	Raise Apogee	17 Aug 2005 08:21:06.233	17 Aug 2005 08:23:20.805	134.572	52.467578	22.871
3	Raise Perigee	19 Aug 2005 21:38:59.936	19 Aug 2005 21:39:33.491	33.555	13.229495	5.703
4	Raise Perigee	2 Sep 2005 15:44:11.351	2 Sep 2005 15:44:27.299	15.948	6.308881	2.710
5	Raise Apogee	3 Sep 2005 08:58:26.948	3 Sep 2005 09:00:15.566	108.619	43.330965	18.460
6	Raise Apogee	28 Sep 2005 04:32:31.953	28 Sep 2005 04:34:41.923	129.970	52.701650	22.089
7	Raise Apogee	9 Oct 2005 05:50:19.572	9 Oct 2005 05:52:22.214	122.641	50.610774	20.843
8	Raise Perigee	13 Oct 2005 22:30:57.826	13 Oct 2005 22:31:21.368	23.542	9.815444	4.001
9	Raise Apogee	21 Oct 2005 07:14:44.608	21 Oct 2005 07:16:28.095	103.487	43.540257	17.588
10	Raise Apogee	7 Nov 2005 11:24:32.615	7 Nov 2005 11:26:31.810	119.195	50.961009	20.258
11	Raise Apogee	15 Nov 2005 00:00:55.089	15 Nov 2005 00:02:57.895	122.807	53.444887	20.871
12	Raise Perigee	15 Nov 2005 08:21:35.690	15 Nov 2005 08:22:09.986	34.296	15.100506	5.829
13	Raise Apogee	30 Nov 2005 20:29:41.543	30 Nov 2005 20:31:23.811	102.268	45.494173	17.381
14	Raise Perigee	1 Dec 2005 04:52:04.835	1 Dec 2005 04:52:22.999	18.163	8.154005	3.087
15	Raise Apogee	23 Dec 2005 23:07:27.506	23 Dec 2005 23:09:16.348	108.842	49.342032	18.498
16	Raise Apogee	4 Jan 2006 01:47:32.354	4 Jan 2006 01:49:28.514	116.159	53.588506	19.742
17	Raise Apogee	10 Jan 2006 15:42:38.552	10 Jan 2006 15:44:30.224	111.672	52.455283	18.979
18	Raise Perigee	11 Jan 2006 10:39:29.475	11 Jan 2006 10:39:57.391	27.915	13.259995	4.744
19	Raise Apogee	25 Jan 2006 19:34:18.747	25 Jan 2006 19:35:49.008	90.261	43.288408	15.340
20	Raise Apogee	10 Feb 2006 09:50:37.618	10 Feb 2006 09:52:21.489	103.871	50.616635	17.653
21	Raise Perigee	17 Feb 2006 02:10:52.154	17 Feb 2006 02:11:23.062	30.908	15.231350	5.253
22	Raise Apogee	18 Feb 2006 01:19:13.603	18 Feb 2006 01:20:24.206	70.603	35.091357	11.999

Global Statistics

Total Duration 1853.457
Total Delta V 805.626101
Total Fuel Used 315.000

Propagation Statistics:
Number of steps: 298028
Average step size: 72.565 sec
Largest step size: 79.04 sec
Smallest step size: 0.0144066 sec

Satellite State at End of Segment:

```
----------------------------------

UTC Gregorian Date: 18 Feb 2006 02:05:25.419  UTC Julian Date: 2453784.58709976
Julian Ephemeris Date: 2453784.58785421
Time past epoch: 2.00091e+007 sec   (Epoch in UTC Gregorian Date: 1 Jul 2005 12:00:00.000)

State Vector in Coordinate System: Earth Inertial

Parameter Set Type:  Cartesian
         X:     -275.8084878332144900 km              Vx:       -0.9727892524167100 km/sec
         Y:    -6634.2042530057324000 km              Vy:        1.7323973432492932 km/sec
         Z:     1532.8666053923589000 km              Vz:        7.3156557384434224 km/sec

Parameter Set Type:  Keplerian
       sma:     6697.1002229063361000 km            RAAN:         269.4106396594489 deg
       ecc:        0.0175422222695162                  w:         192.4460744307985 deg
       inc:         97.71109010529742 deg             TA:         180.6739741244647 deg

Parameter Set Type:  Spherical
 Right Asc:         267.6193727486098 deg     Horiz. FPA:      -0.01203381634187907 deg
      Decl:         12.99931864248932 deg        Azimuth:         352.0848151905436 deg
       |R|:     6814.5738254484622000 km             |V|:        7.5806555368209976 km/sec


Other Elliptic Orbit Parameters :
 Ecc. Anom:         180.6859023903087 deg       Mean Anom:         180.6979343551045 deg
 Long Peri:         101.8567140902474 deg        Arg. Lat:         13.12004855526315 deg
 True Long:         282.5306882147121 deg        Vert FPA:         90.01203381634187 deg
  Ang. Mom:         51658.93566155937 km^2/sec          p:     6695.0393271870444000 km
        C3:        -59.51836295306623 km^2/sec^2   Energy:        -29.75918147653312 km^2/sec^2
   Vel. RA:         119.3154211386036 deg       Vel. Decl:         74.80571188575938 deg
 Rad. Peri:     6579.6182022348867000 km        Vel. Peri:        7.8513576432159056 km/sec
  Rad. Apo:     6814.5822435777836000 km         Vel. Apo:         7.580646005152248 km/sec
 Mean Mot.:       0.06600264241924179 deg/sec
    Period:          5454.32708153286 sec          Period:           90.905451358881 min
    Period:          1.51509085598135 hr           Period:       0.06312878566588957 day
               Time Past Periapsis:            2737.73788036137 sec
          Time Past Ascending Node:           205.7929100759266 sec
   Beta Angle (Orbit plane to Sun):           -55.9423799472169 deg
Mean Sidereal Greenwich Hour Angle:            179.260986395852 deg

Geodetic Parameters:
  Latitude:         13.07452629714767 deg
 Longitude:         88.42911459895522 deg
  Altitude:      437.5229420420203600 km
Geocentric Parameters:
  Latitude:         12.99540681165986 deg
```

```
 Longitude:          88.42911459895522 deg


Spacecraft Configuration:
      Drag Area:  7.1e-006 km^2
       SRP Area:  7.1e-006 km^2
       Dry Mass:  1000 kg
      Fuel Mass:  -2.36347e-010 kg
     Total Mass:  1000 kg
Area/Mass Ratio:  7.1e-009 km^2/kg
  Tank Pressure:  5000                     Pa
   Fuel Density:  999999999999.9999        kg/km^3
             Cr:  1.000000
             Cd:  2.200000
 Rad Press Area:  7.1e-006 km^2
Rad Press Coeff:  1.000000
```

6. 200x600 km orbit: 13.3 months

Lifetime:
W/o prop: 74d

Maneuver	Segment	Start Time (UTCG)	Stop Time (UTCG)	Duration (sec)	Delta V (m/sec)	Fuel Used (kg)
1	Raise Apogee	11 Aug 2005 01:13:12.229	11 Aug 2005 01:15:27.048	134.819	51.713754	22.913
2	Raise Perigee	28 Aug 2005 09:17:39.823	28 Aug 2005 09:18:04.074	24.251	9.399315	4.121
3	Raise Apogee	30 Aug 2005 02:57:25.668	30 Aug 2005 02:59:20.011	114.343	44.727326	19.433
4	Raise Apogee	29 Sep 2005 08:32:46.818	29 Sep 2005 08:34:56.730	129.912	51.656523	22.079
5	Raise Apogee	14 Oct 2005 23:49:58.194	14 Oct 2005 23:51:55.194	117.000	47.311533	19.884
6	Raise Perigee	25 Oct 2005 16:10:54.041	25 Oct 2005 16:11:09.665	15.624	6.375941	2.655
7	Raise Apogee	5 Nov 2005 12:44:57.136	5 Nov 2005 12:46:49.943	112.807	46.449373	19.172
8	Raise Apogee	25 Nov 2005 08:58:17.491	25 Nov 2005 09:00:18.150	120.659	50.507819	20.506
9	Raise Perigee	1 Dec 2005 04:58:21.554	1 Dec 2005 04:58:45.955	24.400	10.320145	4.147
10	Raise Apogee	14 Dec 2005 10:14:13.980	14 Dec 2005 10:15:53.281	99.301	42.377077	16.876
11	Raise Apogee	7 Jan 2006 11:13:21.584	7 Jan 2006 11:15:22.167	120.583	52.293796	20.493
12	Raise Apogee	21 Jan 2006 21:24:21.103	21 Jan 2006 21:26:04.079	102.976	45.405876	17.501
13	Raise Perigee	27 Jan 2006 11:38:08.529	27 Jan 2006 11:38:23.943	15.414	6.857236	2.620
14	Raise Apogee	17 Feb 2006 12:17:26.200	17 Feb 2006 12:19:19.672	113.472	50.978989	19.285
15	Raise Apogee	4 Mar 2006 09:10:28.687	4 Mar 2006 09:12:15.787	107.099	48.940112	18.202
16	Raise Perigee	6 Mar 2006 21:43:43.411	6 Mar 2006 21:44:06.269	22.857	10.551208	3.885
17	Raise Apogee	24 Mar 2006 12:54:41.895	24 Mar 2006 12:56:15.087	93.192	43.414065	15.838
18	Raise Apogee	10 Apr 2006 18:20:08.513	10 Apr 2006 18:21:58.128	109.615	51.898944	18.629
19	Raise Apogee	21 Apr 2006 05:39:34.593	21 Apr 2006 05:41:18.296	103.703	49.956845	17.625
20	Raise Perigee	27 Apr 2006 19:46:46.919	27 Apr 2006 19:47:05.529	18.610	9.055506	3.163
21	Raise Apogee	3 May 2006 19:22:35.346	3 May 2006 19:24:01.875	86.529	42.474508	14.706
22	Raise Apogee	29 May 2006 23:02:21.346	29 May 2006 23:03:27.637	66.291	32.960210	11.266

Global Statistics

Total Duration 1853.457
Total Delta V 805.626101
Total Fuel Used 315.000

Propagation Statistics:
Number of steps: 423633
Average step size: 73.3863 sec
Largest step size: 83.073 sec
Smallest step size: 0.00807395 sec

Satellite State at End of Segment:

```
UTC Gregorian Date: 29 May 2006 23:48:49.154  UTC Julian Date: 2453885.49223558
Julian Ephemeris Date: 2453885.49299002
Time past epoch: 2.87273e+007 sec   (Epoch in UTC Gregorian Date: 1 Jul 2005 12:00:00.000)

State Vector in Coordinate System: Earth Inertial

Parameter Set Type:  Cartesian
         X:     6503.3869630826903000 km              Vx:       -1.0928740146924114 km/sec
         Y:     1905.6862996044970000 km              Vy:       -1.3980559705767346 km/sec
         Z:     1340.2391445297092000 km              Vz:        7.2840495945961372 km/sec

Parameter Set Type:  Keplerian
       sma:     6733.7431195288727000 km            RAAN:         17.88017304192973 deg
       ecc:        0.0258944629245088                  w:         190.9063156322007 deg
       inc:          97.77836461938482 deg            TA:         180.3858060423688 deg

Parameter Set Type:  Spherical
 Right Asc:          16.33215787463224 deg     Horiz. FPA:      -0.01025572513245867 deg
      Decl:           11.1868758416504 deg        Azimuth:           352.07002102839 deg
       |R|:     6908.1056179407033000 km              |V|:        7.4970869412986882 km/sec


Other Elliptic Orbit Parameters :
 Ecc. Anom:          180.3959289651585 deg       Mean Anom:           180.406181251473 deg
 Long Peri:          208.7864886741305 deg        Arg. Lat:          11.29212167456957 deg
 True Long:          29.17229471649931 deg        Vert FPA:          90.01025572513247 deg
  Ang. Mom:          51790.66758769845 km^2/sec          p:     6729.2279884760492000 km
        C3:        -59.19448287892041 km^2/sec^2   Energy:        -29.59724143946021 km^2/sec^2
   Vel. RA:          231.9849126517333 deg       Vel. Decl:          76.30843669574817 deg
 Rad. Peri:     6559.3764579770659000 km         Vel. Peri:         7.8956693398370472 km/sec
  Rad. Apo:     6908.1097810806787000 km          Vel. Apo:          7.497082303112517 km/sec
 Mean Mot.:        0.0654646278066775 deg/sec
    Period:          5499.152932834354 sec          Period:          91.65254888057257 min
    Period:          1.527542481342876 hr           Period:        0.0636476033892865 day
               Time Past Periapsis:           2755.781057584677 sec
          Time Past Ascending Node:           181.5454930506921 sec
   Beta Angle (Orbit plane to Sun):           -47.9135937094271 deg
Mean Sidereal Greenwich Hour Angle:            244.566460513895 deg

Geodetic Parameters:
  Latitude:          11.28975453966712 deg
 Longitude:          131.8493404566075 deg
  Altitude:      530.7820255701764200 km
Geocentric Parameters:
  Latitude:          11.22175820915903 deg
 Longitude:          131.8493404566075 deg
```

```
Spacecraft Configuration:
      Drag Area:  7.1e-006 km^2
       SRP Area:  7.1e-006 km^2
       Dry Mass:  1000 kg
      Fuel Mass:  -1.28092e-010 kg
     Total Mass:  1000 kg
Area/Mass Ratio:  7.1e-009 km^2/kg
  Tank Pressure:  5000                     Pa
   Fuel Density:  999999999999.9999         kg/km^3
             Cr:  1.000000
             Cd:  2.200000
 Rad Press Area:  7.1e-006 km^2
Rad Press Coeff:  1.000000
```

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