COMMERCIAL REGIONAL SPACE/AIRBORNE IMAGING

THESIS

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Abstract
In most recent years, both high-resolution imagery systems and images were only available to military and national security organizations. Distinctive changes within the commercial image industry allowed space-borne pioneers to provide high-resolution images. Space-borne Image Company's Ikonos satellite provides a 1-meter resolution for the past 3 years. Current development of .5-meter resolution will be offered in the near future. Access of these images is available in ground stations located worldwide in different regions. Studies have shown that these high quality images are eye-catching and may serve a purpose through its design; on contrary high cost and accessibility does not met all the requirements of a nation or a region. A nation certainly cannot rely on a foreign commercial company for reconnaissance needs in times of crisis. The best frequency of coverage for a single point on earth is available once every 2.9 days on an average with high resolution. This study seeks a commercial imaging solution for regional applications. Mission requirements are set well above the existing commercial imaging systems including; continuous coverage during daylight hours, and daily re-visitation; service 5 to 25 'simultaneous' customers in addition to competitive resolution and cost. Alternatives considered included satellites, small satellites, UAV's and mixed systems. Inflatable technologies that permit higher orbit attitude and solar-powered UAV's with extended on-station times are also evaluated in this study.

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2. Atmospheres (atm)
3. Command and Control Operator (CCO)
4. Defense Systems Management College (DSMC)
5. Electro Magnetic (EM)
6. Electro-Optical Imaging (EOI)
7. Electronics Industries Association (EIA)
8. Environmental Research Aircraft and Sensor Technology (ERAST)
9. Field of view (FOV)
10. Final Operational Capability (FOC)
11. Geosynchronous Earth Orbit (GEO)
12. Initial Operational Capability (IOC)
13. Institute of Electrical and Electronics Engineers (IEEE)
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36. Turkish Armed Forces (TAF)
37. Unmanned Air Vehicles (UAVs)
38. Value System Design (VSD)

ABSTRACT

In most recent years, both high-resolution imagery systems and images were only available to military and national security organizations. Distinctive changes within the commercial image industry allowed space-borne pioneers to provide high-resolution images. Space-borne Image Company's Ikonos satellite provides a 1-meter resolution for the past 3 years. Current development of 0.5-meter resolution will be offered in the near future. Access of these images is available in ground stations located worldwide in different regions.

Studies have shown that these high quality images are eye-catching and may serve a purpose through its design; on contrary it's high cost and accessibility does not meet all the requirements of a nation or a region. A nation certainly cannot rely on a foreign commercial company for reconnaissance needs in times of crisis. The best frequency of coverage for a single point on earth is available once every 2.9 days on an average with high resolution.

This study seeks a commercial imaging solution for regional applications. Mission requirements are set well above the existing commercial imaging systems including: continuous coverage during daylight hours, daily re-visitation, service 5 to 25 'simultaneous' customers, competitive resolution and cost. Alternatives considered include satellites, small satellites, UAVs and mixed systems. Inflatable technologies that permit higher orbit altitude and solar-powered UAVs with extended on-station times are also evaluated in this study.

COMMERCIAL REGIONAL SPACE/AIRBORNE IMAGING

Chapter 1 - Introduction

1.1 Chapter Overview

This thesis will be comparing different alternatives for a cost-effective and competitive method of regional airborne and/or space-based high resolution imaging. This chapter includes background, problem statement, objectives, hierarchy, and target area description as well as scope, limitations and assumptions of research.

1.2 Background

The current space-based commercial technology of Space Imaging's IKONOS satellite marked a new era in satellite imagery. Previously, high-resolution satellites were exclusively the domains of the military, but now IKONOS has opened the door for a variety of new commercial applications. (13).

IKONOS is the first commercial satellite that provides space imagery of the earth surface with a high-resolution of one-meter using panchromatic technology or four-meter using multi-spectral technology. Despite the fact that the IKONOS has been providing this capability for less than two years, the imagery from IKONOS has had a positive impact on the people's lives, businesses and governments in all parts of the world. A few of the vast noticeable benefits of IKONOS' space imagery are: urban planning, agriculture, mapping, national security, insurance and risk management, telecommunications, and disaster response. One disadvantage of the IKONOS satellite is the inability to provide continuous daily coverage of a particular area. Moreover, IKONOS is also restricted to provide coverage for latitudes no higher than $\pm 45^0$.

Besides existing technologies, some unconventional approaches are studied and tested to build competitive and more effective space systems.

One of these studies is inflatable technology, which enables us to launch less weight, and volume, therefore the system costs less. Inflatable technology is still under study but the experiments and tests confirm the promised objectives of this technology will be achieved. Based on these facts and with the encouragement from the sponsor to study new technologies we are going to include inflatable technology besides conventional rigid space systems.

Another alternative for regional space imaging is the use of minimum-cost spacecrafts (small satellites). Small satellites, which are simpler, smaller and cheaper than conventional systems, sometimes can be more effective for especially regional applications. Due to simplicity, small satellites cost less and require shorter time to build with small number of people, which happen to be the main advantages of miniature technology.

Since this is a regional imaging application, high altitude conventional Unmanned Air Vehicles (UAVs) like Global Hawk and solar-powered UAVs like Helios are considered as other alternatives in this study. Global Hawk can provide high-resolution images to the customer near real time, it flies at high-altitude and has long-endurance. Helios is also a promising technology as a solar powered UAV. " I believe we will be operating solar-powered aircraft as stratospheric satellites in the next century," says Jeff Bauer, National Aeronautics and Space Administration (NASA) Centurion Deputy Program Director. (50) This technology has promising advantages such as significantly reduced launch costs, reduced fuel cost, long flight duration, payload mass equivalent to LEO satellites, ability to upgrade after launch, and many more. Since this research is seeking a solution for a regional imaging application solar-powered UAVs are also going to be studied.

The goal of this thesis is to make use of the existing commercial space-based imaging technology to improve or at least maintain the current one-meter high-resolution capability. Another important aspect is to design a more efficient orbit to provide continuous coverage during daylight hours with a 24-hour re-visitation. Last but not least, one of the most important of all the requirements, it is desired to provide this service at a competitive cost on a life cycle basis and be able to observe up to five different client-specified areas of interest on the earth's surface at initial operational capability (IOC).

The target area for this regional space/airborne imaging application is chosen to be Turkey and the region surrounding Turkey due to nationality of members of research team. See Target Area section this chapter for details on target area.

The Space Mission Analysis and Design (SMAD) and the Satellite Tool Kit (STK) software were the main resources used for this research. SMAD is an iterative process that allowed us to refine and improve the results of each design step. The STK software reduced the time for coverage calculations and orbit design. We used a tailored Systems Engineering Process (SEP) for this study. This SEP is explained in chapter 3.

1.3 Mission Statement

The mission statement (MS) is a qualitative statement that never changes throughout the design process: The sponsor provided the MS specifying the expectations and utilization of the space imaging system once it is in operation. The mission statement follows:

"Current space-based visual imaging available commercially provides the opportunity to observe client-specified areas of interest on the earth's surface on an intermittent basis. The imaging satellites operate in near polar LEO orbits which permit the revisit frequency to be as low as once every three days at 45 degree latitude and even more frequently at higher latitudes. Average revisit frequency at the equator is significantly less frequent. It is desired to commercially market reduced revisit frequency to user-specified locations within low-latitude regions of the globe. Specifically, the sponsor is a commercial image provider that would like to offer two levels of client-specified low latitude service: 1) high-resolution multi-pass imaging with re-visitation as short as 24 hours, and 2) continuous imaging of a location during daylight hours at reduced resolution. It is also desirable to offer service to customer locations outside the provider-specified region when practical that is competitive with existing space imaging service. The system(s) should provide resolution comparable to the best offered by existing imaging systems and be cost competitive with them on a life cycle basis.

Remarks: The sponsor is willing to consider the use of new imaging technology that would provide the required resolution in MEO, LEO orbits that might be more cost effective and enhanced propulsion capability that could maintain daily and continuous daylight coverage of a single user location for the life of the imaging system."

1.4 Mission Objectives

The mission objective is the first step in analyzing and designing a space mission. The mission objectives are broad goals that must be achieved in order for the system to be successfully productive. The mission objectives are inherently qualitative since they come directly from mission statement.

1. To provide visual imaging to a customer specifying location, time, revisit, frequency and duration.
2. To provide commercial imaging service that is cost competitive with existing commercial service.
3. To provide commercial imaging service that outperforms competitive service.
4. To provide low latitude service with up to daily revisit at high image resolution.
5. To provide low latitude continuous service during daylight hours at moderate image resolution.
6. To provide image quality that meets or exceeds current quality.
7. To develop a commercial imaging business plan that is attractive to investors.

1.5 Preliminary Mission Requirements

Requirements identify the levels of accomplishment necessary to obtain specific objectives. Requirements are a means to control, measure and accomplish the required space system's performance, cost, development and deployment schedule, mission constraints and risks. Therefore, it is necessary to transform the mission objectives into preliminary sets of numerical requirements and constraints to ultimately accomplish the performance and operation of the space imaging system in a costly and timely manner. SMAD lists three areas of requirements:

Functional (Performance) requirements, which define how well the system must perform to meet its objectives.

Operational requirements, which determine how the system operates and how users interact with it to achieve its broad objectives.

Constraints, which limit cost, schedule, and implementation techniques available to the system designer. (3: 15)

Table 1-1 Preliminary Mission Requirements

Requirement	***Description***	***Preliminary Level***
Performance:		
Coverage frequency	Level 1	Daily revisit
	Level 2	Continuous daylight coverage 6am-6pm local time
Resolution (surveillance)	Level 1	1 m panchromatic
	Level 2	5 m multi-spectral
Location accuracy		10 m
Image region location	User specified prior to launch	Latitude and Longitude 40^0
Image region size	Delta Lat.	20^0
	Delta Lon.	25^0
Image processing	Maximum area per pass	10^6 km^2
Image size	Level 1	10^4 km^2
Image distribution delay	Level 1	2 hours (not time critical)
	Level 2	30 minutes (time critical)
Data downlink speed	Level 1	Store and forward
	Level 2	Continuous (TDRS or equiv.)
Simultaneous Customers	IOC	5 Customers
	FOC	25 Customers
Image quality	Sun elevation	$> 15^0$
	Image elevation	$> 20^0$
	Image format	Quick look; georeferenced; Geometrically corrected; geocoded
Operational:		
Availability	Level 1	98%(excluding cloud cover)
	Level 2	98%(excluding cloud cover)
Image service:	Lead time	10 days
	Duration max, level 2	15 days
	Max. Revisit frequency	5 days
Refueling frequency	Minimum	1 year
Survivability		Space radiation hardening
Programmatic:		
Cost	Life cycle (Year 2000$)	Cost competitive
Schedule	IOC	5 years
	FOC	10 years
Design Life		10 years
Constraints:		
Launch system	Use of existing launch capability	< 10 systems
Launch reliability		> 95%
Refueling/Recovery		Shuttle
Data downlink	Technology export	TDRS (or equivalent)
Regulation		NOAA

Table 1-1 summarizes the first initial estimate of the spacecraft mission requirements obtained from both the mission objectives as well as insight from the sponsor and the design team. During the design process, these quantitative requirements were traded.

1.6 Scope And Limitations

The purpose of this research is to come up with the best alternative for a regional commercial space imaging application. The alternatives include conventional satellites with rigid structures, conventional satellites with inflatable structures, small satellites, and conventional and solar-powered UAV's.

Since some of the alternatives include new technologies that are not practically used yet and due to limited access to some amount of data, further analysis should be conducted. Additionally, estimated costs are first-cut estimates that have very large standard variations. Thus, before giving a final decision more accurate cost models should be built.

1.7 Target Area

The requirement for the target area for this study was ±?20 degrees latitude by ±?25 degrees longitude area whose center latitude is at 40 degrees. We arbitrarily chose the area between 30-50 degrees latitude and 20-45 degrees longitude, which is shown in Figure 1-1.

Figure 1-1 Target Area

1.8 Assumptions

All technologies and structures, even recently explored ones, are assumed to be available for this research.

The data available to the public is assumed to be reliable and valid.

We assumed that Tracking and Data Relay Satellite (TDRS) or equivalent communications system would be used for data downlink.

Other assumptions related to calculations are specified in related parts of the study.

1.9 Contribution

Information is power, and reconnaissance is one of the major means of collecting information about interests of a nation. There are worldwide companies that are providing high-resolution imagery products. They are serving customers all over the world with fine quality imagery. However, the price of the imagery is too expensive and never enough to satisfy regional reconnaissance needs since the constellations are designed to serve customers all over the world. Hence, nations especially whose interests rarely go beyond their neighbor countries geographically should design an imaging system solely for their regional interests. In this study, we want to design a space-borne or airborne imaging system that is optimum for regional interest and requirements. We intend to design a high-resolution imaging system, which will provide at least same quality imagery for less cost as the existing worldwide imaging systems. Each system-engineering project is unique so we will develop a systems engineering process special for our design project.

Chapter 2 - Literature Review

2.1 Chapter Overview

This chapter starts with the space history of Turkey and follows with the definitions about mission module types for different space missions as well as information about existing and future systems. Other feasible technologies such as Global Hawk, Helios and inflatable space structures are also introduced in this chapter.

2.2 Space History in Turkey

The usage of satellites for communication purposes started in 1965 with the first communication satellite Early-Bird of INTELSAT. Turkey became a member of INTELSAT in 1968 and first phone lines were connected to USA. The first ground station AKA-1 was established in 1979 in Ankara. In 1977, EUTELSAT was formed by Turkey and 17 European countries. AKA-2 ground station became operational in 1985.

In 1990, Turkey made an arrangement with the French firm Aerospatiale for the first communications satellite of Turkey for $315 million. After the malfunction of TURKSAT-1A during the launch, TURKSAT-1B was successfully placed in 42° East Geosynchronous Earth Orbit (GEO) in 1994. TURKSAT-1C was placed in 31.3°East GEO in 1996. Then, in 1996, since TURKSAT-1C had a larger coverage, their positions changed; now TURKSAT-1C is in 42° East, TURKSAT-1B is in 31.3° East. (40)

According to the cooperation between Turk Telekom, Kalitel and Hughes companies' Anatolia-1 satellite was put in 50°East GEO on 21 December 2000 from its previous location at 150.5° East. Anatolia-1's tests are being completed and satellite service is commercially available from February 2001. High quality regional satellite communications services in both C- and Ku-Band covering Africa, part Middle East and

Europe are available on ANATOLIA 1. The satellite has 30 C-Band transponders of 36MHz, and 4 Ku-Band transponders of 72MHz. The satellite is less than five years old, is fully geostationary, and carries high downlink power payloads in both bands. (41;26)

Arianespace Flight 137 is the first success of the millennium in Kourou, January 10, 2001 Arianespace successfully kicked off its 2001 launch activity by orbiting Turksat 2A/Eurasiasat 1, an Alcatel Space communications satellite for Turkish operator Eurasiasat S.A.M. Eurasiasat 1 will bridge the continents of Europe and Asia, providing communications links between Western Europe, the Middle East, Central Asia and the Far East. Turksat 2A/Eurasiasat 1 is the third Turkish satellite to be boosted into orbit by Ariane, following Turksat 1B in August 1994, and Turksat 1C in July 1996. The Turksat 2A/Eurasiasat 1 spacecraft is designed for a service life exceeding 15 years. This launch was part of a turnkey contract awarded by Eurasiasat S.A.M. to Alcatel Space.Based in Monaco, Eurasiasat S.A.M. is jointly owned by Turk Telekom and Alcatel Space. (17)

Turk Telecom has completed the decree concerning the satellites, which are being organized as State Economic Enterprises (SEEs), and sent it to the Ministry of Communications. According to law that arranges the conditions concerning the privatization of Turk Telecom, which was enacted on Turksat 1B, Turksat 1C, Turksat 2A and Anatolia 1 satellites and the base stations should be kept out of the structure of Turk Telecom before the privatization. It is envisaged that the satellites will be reorganized and called the "Directorate General of Satellite Communications" as another SEE status. (16)

Lockheed Martin Space Systems Company has formed an alliance with Space Imaging and Cukurova Holding/INTA to provide the Turkish Armed Forces (TAF) with high-resolution remote sensing capabilities. This cooperation addresses critical Turkish

Government imaging needs, including defense, urban planning and disaster preparedness and response and will enable the TAF to acquire an earth imagery satellite at higher resolutions with better technical characteristics. (38)

Space Imaging Eurasia Ground station is established in Ankara recently. It is one of the six stations in the world that gets high-resolution images up to 1m from IKONOS satellite. This station can capture images from 33 countries. (23)

2.3 Mission Module Types

The payload or mission equipment of any spacecraft is generally considered to be that particular spacecraft's reason for existing. The payload is, after all, compromised of the equipment, which the spacecraft owners and users desire to employ for the collection or distribution of very specific mission information. (15)

2.3.1 Electro-Optical Imaging (EOI)

The least expensive, lightest weight, lowest power, and probably the widest used payload type for tactical missions is the simple yet capable, high-resolution camera system. The EOI mission module is very closely constrained to a Sun –Synchronous orbit for optimal orbit selection, due to the radiometric equipment's dependence upon reflected sunlight for illumination of a target. (15)

2.3.2 Multispectral Imaging (MSI)

The MSI mission module uses several different arrays of detectors, each optimized to detect a specific band of Electro Magnetic (EM) radiation. Image processing produces simultaneous images of a target area characterized at various regions of the EM spectrum. Due to its wider range of detectable radiation bands, the MSI mission module is not as closely constrained to the Sun-Synchronous orbit, although this type of orbit is still advantageous. Specific orbit selections for MSI mission modules will vary, in accordance with varying detector types and specific mission objectives. Physical characteristics for the MSI mission module are similar, but more massive and more power consuming, than the EOI mission module. (15)

2.3.3 LASER/LIDAR Applications

Using optics similar to the EOI package, the laser-imaging payload adds a LASER head and power supply (LASER pump) in order to illuminate a target with a specific wavelength of EM radiation. These payloads can produce very accurate three-dimensional imagery, making them well suited for topographical missions and atmospheric/meteorological observations. (15)

2.3.4 Synthetic Aperture Radar (SAR)

By far the payload with possibly the greatest potential tactical “payoff” is the SAR mission module, which can produce very high-resolution images. SAR mission modules, like LASER- based modules, is active sensing systems and, as such, generally require an order of magnitude greater power to operate than passive systems (EOI and MSI). Day and night, all weather operations are possible with SAR. (15)

2.4 Current Imaging Systems

Commercially available space imaging is becoming a big market business. It is being used in various manners from weather forecast to traffic monitoring. As technology and system capabilities increase, the demand for such images will also increase. Table 2-1 shows resolution, swath width and daily revisit in formations of existing and future systems.

Table 2-1 Existing and Future Systems
(36)

Satellite	Operator	Panchromatic Multispectral	Optical or Radar	Resolution (m)	Swath (km)	Revisit (day)
SPOT 1/2/3	CNES/SPOT	Panchromatic Multispectral	Optical	10 20	60 60	1-4 1-4
SPOT 4	CNES/SPOT	Panchromatic Multispectral Multispectral	Optical	10 20 1000	60 60 2200	1-4 1-4 1
Landsat 5	Space Imaging	Multispectral Multispectral	Optical	30 80	185 185	16 16
LandSat 7	US. Government	Panchromatic Multispectral	Optical	15 30	185 185	16 16
RS IC/D	SRO-India	Panchromatic Multispectral Multispectral	Optical	5.8 23 188	70 150 810	5 24 3-5
RADARSAT	Canadian Space Agency	N/A	Radar (SAR, C-Band)	8-100	50-500	3-35
ERS-1/2	European Space Agency	N/A	Radar	30-50	100-500	3-35
IKONOS	Space Imaging	Panchromatic Multispectral	Optical	1 4	11 11	3.5-5 3.5-5
QuickBird	EarthWatch	Panchromatic Multispectral	Optical	0.82 3.28	22	1.5-4
SPIN-2	Russia	Panchromatic Panchromatic	TK-350 (Cameras)	10 2	200 180	8 8
OrbView 2	ORBIMAGE	Multispectral	Optical	1.1 km	2800	1
OrbView 3	ORBIMAGE	Panchromatic Multispectral	Optical	1 4	8 8	3 3

2.4.1 IKONOS

On September 24, 1999, a new generation of imaging satellites arrived with the successful launch of IKONOS. IKONOS satellite, which is seen in Figure 2-1 is classified as a high-resolution satellite because it can see objects on Earth's surface as small as one meter. Launching satellites is a risky business. The first IKONOS was launched in April 1999, but plummeted into the Pacific Ocean. (19)

Figure 2-1 IKONOS Satellite

"IKONOS orbits Earth North to South, travels more than 4 miles per second and circles Earth every 98 minutes. IKONOS can collect more than 20,000 square kilometers of images on a single pass. IKONOS transmits digital images to receiving stations at rates comparable to watching 50 TV stations simultaneously.

IKONOS boasts the world's most powerful digital camera. A brilliant design allowed Eastman Kodak engineers to shrink the resolving power of a 30-foot-long telescope down to 1.5 meters by "folding" light with a system of precisely aligned mirrors. The camera's mirror alignment is so precise that it's measured in wavelengths of light. The mirrors were polished one molecule at a time to near perfection. Thanks to a special honeycomb design, engineers removed 85% of the glass from the core of the largest mirror, reducing its weight from nearly a ton to just 240 pounds.

The compartment that houses the camera's digital sensor chips is climate controlled to maintain a constant 68° F temperature. The camera's digital circuits squeeze together 115 million image pixels per second and produce images with eight times better contrast than images from other satellites.” (19)

The IKONOS camera telescope is seen in Figure 2-2.

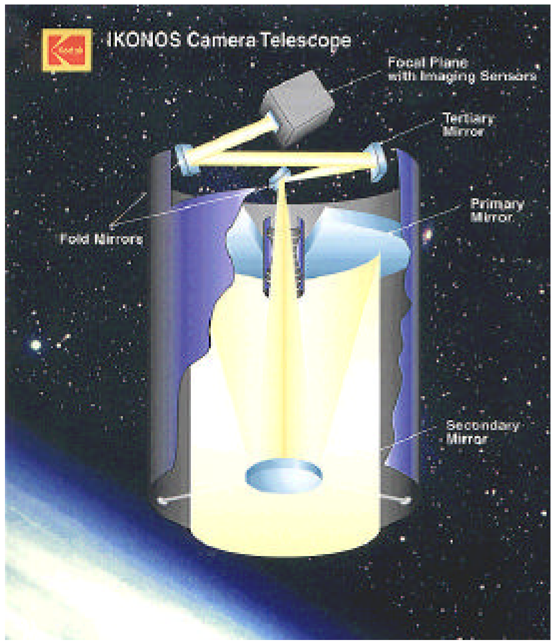

Figure 2-2 IKONOS Camera Telescope

2.4.2 Conventional UAVs

Global Hawk is accepted as a baseline design for conventional UAV alternatives. ”The RQ-4A Global Hawk is a high altitude, high endurance unmanned aircraft and integrated sensor system to provide intelligence, surveillance, and reconnaissance (ISR) capability. The Global Hawk's exceptional range and endurance coupled with its ability to provide near-real-time transmission of imagery to multi-service and joint exploitation make it a true force multiplier. Global Hawk began as an Advanced Concept Technology Demonstration (ACTD) in 1994 in response to long standing ISR deficiencies. The

Demonstration Phase of the ACTD was completed in June 2000 and a favorable Military Utility Assessment was completed in September 2000. A Spiral Development approach to system acquisition is planned in order to support rapid deployment of improved ISR capability to war fighters while providing for incremental development of alternative system configurations with added / improved mission capabilities.

The first production deliveries are scheduled for fiscal year 2003. During the transition period, residual ACTD assets will be flown in exercises to further refine the system Concept of Operations, provide training to Global Hawk operators, and to develop Tactics, Techniques and Procedures. The Environmental Impact Analysis Process (EIAP) is underway with the Air Force considering five bases for Global Hawk." (29)

"The data gathered by Global Hawk will be relayed to decision-makers via world-wide satellite communication links to its ground segment. A typical reconnaissance mission for Global Hawk might involve operating at a range of 12,500 nautical miles, at altitudes up to 65,000 feet for 38 to 42 hours. Capable of flying 3,000 miles to an area of reconnaissance interest, Global Hawk could then survey an area the size of Illinois (40,000 square nautical miles) for 24 hours, relaying intelligence data via ground and airborne links -- and return 3,000 miles to its operating base." (42)

"Global Hawk ground stations include the Mission Control Element (MCE) and the Launch and Recovery Element (LRE). The MCE is the Global Hawk's ground control station for reconnaissance operations. It contains four workstations: mission planning, sensor data and processing, air vehicle command and control operator (CCO), and communications. The Mission Commander is the fifth crewmember, responsible for overall mission management. The LRE includes a mission planning function as well as air vehicle command and control. During split site operations, the senior operator will function as mission commander until air vehicle control is passed to the MCE. (29)

The RQ-4A Global Hawk is seen in Figure 2-3 and the general characteristics can be seen in Table 2-2.

Figure 2-3 Global Hawk

Table 2-2 General Characteristics of Global Hawk

Primary Function	Surveillance and reconnaissance
Contractor	Northrup Grumman Ryan Aeronautical Center
Power Plant	Single Allison AE3007H (approximately 7,000 pounds thrust)
Length	44 feet
Height	15 feet
Weight	Approximately 25,600 gross take-off
Wingspan	116 feet
Speed	300 to 400 Knots true air speed (KTAS)
Range	1,200 nautical mile radius with 24 hours on station
Loiter Altitude	50,000 to 65,000 feet
Fuel Capacity	14,800 pounds, JP-8

2.5 Other Feasible Technologies

2.5.1 Helios

"During a 17hr mission on August 13 near the Hawaiian island of Kauai, Helios surpassed the 85,069ft absolute altitude record for sustained horizontal, nonrocket-powered flight set by a Lockheed SR-71 in 1976.

Having just set a new altitude record for more than 96,500 ft, the Helios solar-powered aircraft team is preparing to integrate an energy storage system that should enable the flying wing to maintain altitude at night for multi-day missions." (12: 47)

The Helios is a remotely piloted flying wing UAV developed to demonstrate the capability of achieving two significant milestones for NASA's Environmental Research Aircraft and Sensor Technology (ERAST) project: reaching and sustaining flight at an altitude of 100,000 ft and flying non-stop at least 4 days above 50,000 ft.

The lightweight, electrically powered Helios is constructed mostly of composite materials such as carbon fiber, graphite epoxy, Kevlar, Styrofoam, and a thin, transparent plastic skin. The main tubular wing spar is made of carbon fiber. The spar, which is thicker on the top and bottom to absorb the constant bending motions that occur during flight, is also wrapped with Nomex and Kevlar for additional strength. The wing ribs are also made of epoxy and carbon fiber. Shaped styrofoam is used for the wing's leading edge and a durable clear plastic film covers the entire wing.

The all-wing aircraft is assembled in 6 sections, each 41 feet long. An underwing pod is attached at each panel joint to carry the landing gear, the battery power system, flight control computers, and data instrumentation. The five aerodynamically shaped pods are made mostly of the same materials as the wing itself, with the exception of the transparent wing covering. Two wheels on each pod make up the fixed landing gear rugged mountain bike wheels on the rear and smaller scooter wheels on the front.

Helios will eventually be powered by solar cell arrays that will cover the entire upper surface of the wing. For long duration missions the solar cells will not only power the electric motors but charge an on-board fuel-cell based energy storage system that will power the motors and aircraft systems through the night.

The only flight control surfaces used on the Helios Prototype are 72 trailing-edge elevators, which provide pitch control. Spanning the entire wing, they are operated by tiny servomotors linked to the aircraft's fight control computer. To turn the aircraft in flight, yaw control is applied by applying differential power on the motors speeding up the motors on one outer wing panel while slowing down motors on the other outer panel.

The Helios seen in Figure 2-4 is controlled remotely by a pilot on the ground, either from a mobile control van or a fixed ground station that is equipped with a full flight control station and consoles for systems monitoring. A flight termination system, required on remotely piloted aircraft flown in military restricted airspace, includes a parachute system deployed on command, plus a homing beacon to aid in the aircraft's location. In case of loss of control or other contingency, the system is designed to bring the aircraft down within the restricted airspace area to avoid any potential damage or injuries to fixed assets or personnel on the ground. (30)

The general characteristics of Helios Aircraft can be seen in Table 2-3.

Figure 2-4 Helios

Table 2-3 General Characteristics of Helios Aircraft

Wingspan	247 ft
Length	12ft
Wing Chord	8 ft
Wing Thickness	11.5 in (%12 of chord)
Wing Area	1,976 ft^2
Aspect Ratio	30.9 to 1
Empty Weight	1,322 lb
Gross Weight	Up to 2,048 lb, varies depending on power availability and mission profile
Payload	Up to 726 lb, varying between ballast and instrumentation
Power	On-board lithium batteries for current flight series. Later to be powered by bi-facial solar cells covering upper wing surfaces
Airspeed	From 19 to 25 mph cruise
Altitude	Designed to operate at up to 100,000 ft, typical endurance mission at 50,000 to 70,000 ft
Endurance	Currently configured to operate 1 to 3 hours on batteries. When equipped with solar power, limited to daylight hours plus up to 5 hours of flight after dark on storage batteries. When equipped with an energy storage system, from several days to several months
Primary Materials	Carbon fiber and graphite epoxy composite structure, Kevlar, Styrofoam leading edge, transparent plastic film wing covering. Kevlar and Nomex are registered trademarks of E.I. Du Pont de Nemours and Co.

2.5.2 Inflatable Space Structures

An inflatable structure can be defined as any form, which expands to a predefined shape by increasing the air pressure within the structure. This is usually done by introducing gas into the structure. Due to the vacuum of space, the pressure required to maintain in inflation is very low, on the order of 10^{-4} atmospheres (atm). (14)

Most purely inflatable structures require make-up gas to maintain pressure within the structure. This is especially true for systems that are expected to have an on-orbit lifetime of five to ten years. These structures usually carry relatively low loads and therefore require a low inflation pressure. For structures that are intended to carry a high load, there are two choices. Either use a much higher pressure within the structure, which will last only a short time, or rigidize the structure after inflation. The second method, rigidization, shows the most promise for future applications.

The primary advantages of inflatable structures, compared to mechanical structures, are: weight and packaging, strength, production cost, reliability, engineering complexity, and the ability to form complex shapes, as well as favorable thermal and dynamic characteristics. Inflatable systems offer up to a 50-percent weight reduction over the best mechanical systems and up to a 25-percent volume savings. (28)

With regard to strength, inflatable structures offer several advantages to mechanical systems. Conventional mechanical systems require many joints and hinges to fold into the launch configuration. For example, a 100-meter boom deployed from the Space Shuttle would require at least six connected sections, whereas an inflatable boom could be rolled or folded for a continuous shape once deployed. In mechanical systems the loads are concentrated on the joints, which must be reinforced (making them heavier and more complex). In inflatable systems the loads are distributed over the entire boom, therefore making them potentially stronger. Where mechanical systems draw their strength from material properties, inflatable systems use the inflation pressure and/or rigidization to achieve desired strengths.

An inflatable system is essentially made up of at material assembled with seams, a package to hold the material, and an inflation system. Complex shapes are also much easier to design and build using inflatables. The material is simply cut and assembled such that at equilibrium pressure the desired shape is achieved. Although specialized tools may be required, overall production costs can be one-tenth that of large complicated systems.

Innovators such as JPL's Dr. Mark Dragovan say that inflatable technology is the wave of the future. "Lightweight, flexible inflatable materials will someday replace traditional steel and glass materials on space antennas and telescopes to the point that the whole telescope will consist of a reflector and detector as thin as plastic kitchen wrap," he said. "The challenge for NASA is to launch structures that are one hundred times lower density than the Hubble Space Telescope. If the telescope is extremely low-mass, then one can make it very large and inexpensive in our quest to put big eyes in the sky." (39)

In low Earth orbit, inflatable structures encounter attack by oxygen atoms. Some coatings appear promising to slow down the attack. Since the large structures are mainly composed of hydrocarbon films, coatings (such as silicon oxide) are needed to protect them. Along with the O-atom attack, at low altitudes, the lightweight inflatable may experience significant aerodynamic drag. This creates the need for a reboost, resulting in increased weight/cost. Therefore, the large inflatable structures will most likely spend most of their lives at altitudes above 300 km not to undergo O-atom attack and drag.

Finally, inflatable structures offer favorable dynamics and thermal responses. Inflatable systems resist distortion due to the constant inflation pressure, which reduces the vibration and frequencies of motion. If the system is rigidized after inflation, it still resists vibration because of the material properties. Similarly, the materials used in inflatables possess desirable thermal properties. The large, continuous surface of inflatables allows uniform heat transfer, which minimizes distortions due to thermal expansion.

With regard to support structures, the use of inflatable systems can also lower the weight and size of the solar array and sunshades. This enables more weight and area for the actual payload of the spacecraft. As with booms, solar arrays are increasing in size to provide the necessary power for spacecraft. By implementing inflatable structures, the solar arrays can become larger, without sacrificing payload weight or size.

2.5.3 Small Satellites

In the mid 1980's, a new satellite design methodology emerged - the low cost, high-risk designs of the "Small Satellites Revolution". Instead of developing satellites weighing thousands of kilograms and costing hundreds of millions of dollars, engineering teams of only a handful of people began designing " Small Satellites " weighing 200 kg or less and costing only a couple of million dollars. The size of these small satellites also reduces operational costs, for now the satellite may be launched on a $9 million dollar Pegasus rather than a $78 million Atlas class rocket. (35)

Traditionally satellites have become ever larger and more powerful. INTELSAT-6, a trunk communications satellite, has a design life of 10-14 years, weighs 4600kg at launch, and has deployed dimensions of 6.4 x 3.6 x 11.8m. It generates 2600W, and can support up to 120,000 two-way telephone channels, and three TV channels. Consequently development times and satellite costs have been rising, and a single in-orbit failure can be costly. A typical modern micro-satellite weighs 50kg, has dimensions 0.6m x 0.4 x 0.3m, and generates 30W. Smaller satellites offer shorter development times, on smaller budgets and can fulfill many of the functions of their larger counterparts. As micro-satellites can benefit from leading edge technology, their design lifetime is often more limited by the rapid advances in technology rather than failure of the on-board systems. A perfect example of this is the Digital Store and Forward satellite UoSAT-2 launched in 1984. It carries a 128kbytes on-board message store and operates at 1200bps data rate, but was superceded by UoSAT-3 in 1990 with 16MByte message store, operating at 9600bps. The current satellite in this series, FASat-Alfa (1995) has 300MBytes of solid-state message store, and operates at 76,800bps. The significant reductions in costs make many new applications feasible. Recently it has been recognized that small satellites can complement the services provided by the existing larger satellites, by providing cost effective solutions to specialist communications, remote sensing, rapid response science and military missions, and technology demonstrators.

Some small satellites further reduce costs by employing a single string design in which subsystems lack redundancy, leaving the spacecraft susceptible to single-point failures. Small satellites also carry fewer instruments than their larger counterparts. The proponents of this methodology assert that launching many small, less capable, high risk, low cost satellites to perform a mission will in the long run prove cheaper than launching a few large, highly capable, overly redundant, lower risk, very high cost satellites.

Small spacecraft do offer opportunities for low-cost missions, but very low costs are experienced only with simple spacecraft performing limited missions. Small spacecraft can be relatively expensive when they retain the complexity required to meet demanding science objectives (pointing accuracy, power, processor speed, redundancy, etc.).

Therefore on the positive side, small satellites are cheaper than conventional satellites and afford space flight opportunities for groups that would otherwise be unable to afford one aboard a conventional satellite. On the negative side, small satellites cannot carry as many instruments as, have a shorter lifetime than, and are more susceptible to single point failures than conventionally designed and sized satellites. (33)

Technology has advanced to the point where very capable buses are currently available for performing many Earth observation missions. However, some Earth observation payloads are too large, too heavy, too demanding of power, or generate too much vibration to be accommodated efficiently with small satellite missions. Future advances in payload technology should mitigate this situation, but there are fundamental laws of physics that in some cases restrict the degree of miniaturization that can be achieved while retaining sufficient performance to meet the observation requirements. Thus, small satellites can be seen as a complement to larger satellites, not a replacement for them. (15)

Chapter 3 - Systems Engineering Process

3.1 Chapter Overview

The topic of this chapter is systems engineering process that will be used in our design project. First, system and systems engineering are defined from various sources. After clarifying the significance of the systems engineering process, some well-known systems engineering processes are explained. At the end of the chapter, by tailoring other processes and by adding some necessary steps required in this design project, the systems engineering process followed in our study is created.

3.2 Definition of Systems Engineering

In our thesis, we use a systems engineering process to find out the optimum solution to our problem. However, before we handle systems engineering process, we should define systems engineering. There is no generally accepted definition of systems engineering in the literature due to its variety of interest areas.

First define a system. Institute of Electrical and Electronics Engineers (IEEE) defines system as:

"A set or arrangement of elements (people, products –hardware and software- and processes –facilities, equipment, material, and procedures-) that are related and whose behavior satisfies customer/operational needs, and provides for the life cycle sustainment of the products." (7:8)

In the light of this system definition, there are several published definitions of systems engineering. In their textbook, named "Systems Engineering and Analysis", Benjamin S. Blanchard and Wolter Fabrycky give some useful definitions from Defense

Systems Management College (DSMC), and Electronics Industries Association (EIA). According to DSMC, systems engineering is:

"The application of scientific and engineering efforts to: (a) transform an operational need into a description of system performance parameters and a system configuration through the use of an iterative process of definition, synthesis, analysis, design, test, and evaluation; (b) integrate related technical parameters and ensure compatibility of all related, functional, and program interfaces in a manner that optimizes the total system definition and design; (c) integrate reliability, maintainability, safety, survivability, human engineering and other such factors into the total technical effort to meet cost, schedule, and technical performance objectives." (5: 12)

EIA defines systems engineering as:

"An interdisciplinary approach encompassing the entire technical effort to evolve and verify an integrated and life cycle balanced set of system, people, product, and process solutions that satisfy customer needs. System engineering encompasses (a) the technical efforts related to the development, manufacturing, verification, deployment, operations, support, disposal of, and user training for, system products and processes; (b) the definition and management of the system configuration; (c) the translation of the system definition into work breakdown structures; and (d) development of information for management decision making." (6: 43)

The IEEE gives the following definition for systems engineering:

"An interdisciplinary collaborative approach to derive, evolve, and verify a lifecycle balanced system solution which satisfies customer expectations and meets public acceptability." (7:11)

And the International Council on Systems Engineering (INCOSE) defines systems engineering as:

"An interdisciplinary approach, which focuses on defining customer needs and required functionality early in the development cycle, documenting requirements, then proceeding with design synthesis and system validation while considering the complete system: operations, performance, test, manufacturing, cost & schedule, training & support, and disposal." (25)

By the term "interdisciplinary", it is meant that system engineering requires people from a variety of different engineering and non-engineering specialties. Their knowledge and skills are needed to create a comprehensive systems engineering approach to the problem by using them efficiently and effectively.

3.3 Systems Engineering Process (SEP)

Among the systems engineering definitions, there is a general concurrence for what systems engineering is. However, since the implementation of the system engineering is not the same for every problem, the process followed in the project will be different depending on the features of the problem, backgrounds and experiences of the individuals joined the process.

The SEP is a generic problem-solving process, which provides the mechanism or identifying and evolving the product and process definitions of a system. In the SEPs, there is always an iterative attitude among their steps until the optimum solution for the system design is accepted.

Fundamental to the application of the systems engineering is an understanding of the system life cycle process as seen in the Figure 3-1. According to Benjamin S. Blanchard and Wolter Fabrycky, the life cycle process begins with the identification of a need and extends through conceptual and preliminary design, detail design and development, production and/or construction, product use, phase out, and disposal.

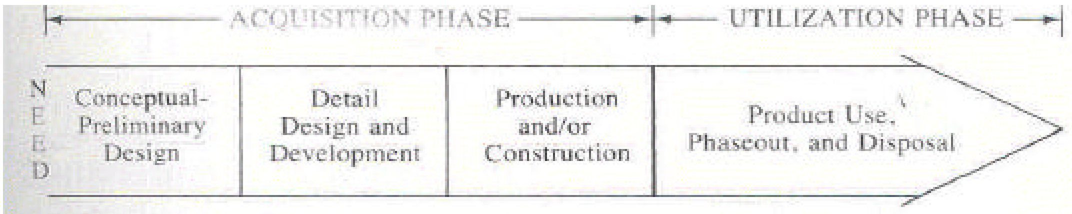

Figure 3-1 System life cycle process (3: 19)

In general, a SEP should be applied to a component if any of the following are true (8:3):

- The component is complex.
- The component is not available off-the-shelf.
- The component requires special materials, services, techniques, or equipment for development, production, deployment, test, training, support, or disposal.
- The component cannot be designed entirely within one engineering discipline.
- To be able to implement the systems engineering successfully into a design project, an appropriate systems engineering approach must be chosen. There are some SEPs, which are created or “tailored” for specific areas.

  Some of these SEPs will be outlined in the following pages.

3.3.1 Hall's Seven Steps

The approach of Hall’s Seven Steps was one of the first widely accepted systems engineering process. Hall's SEP, developed by Arthur D. Hall in 1969, outlined a three-dimensional box, shown in Figure 3-2, which categorized the three fundamental dimensions to systems engineering: time, logic/procedure, and knowledge.

The time dimension relates to the phases of a systems development, from initial planning to system retirement. The knowledge dimension is a scale specialized professions and disciplines, ranging from engineering to business, law, and arts. And, the logic dimension provides the steps for problem solving and system development performed at each phase.

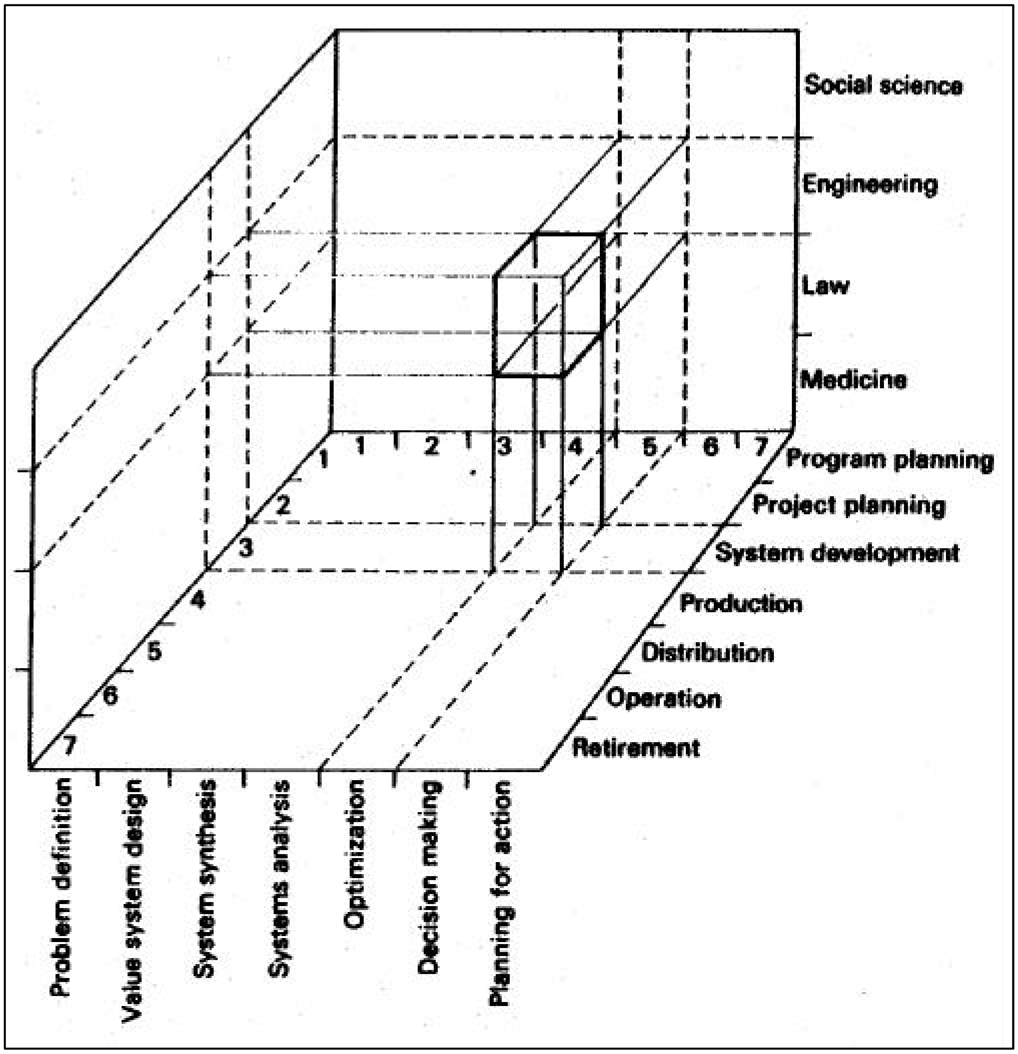

Figure 3-2 Hall's Morphological Seven Steps

This iterative system engineering process consist of seven steps:

1. Problem definition
2. Value system design
3. System synthesis
4. System analysis

5. Optimization of alternatives
6. Decision making
7. Planning for action

3.3.2 NASA Systems Engineering Process

The NASA Systems Engineering Handbook was written to apply to the development of large NASA projects by providing broad descriptions of processes, tools, and techniques.

According to the NASA systems engineering approach, a system is designed, built, and operated so that it accomplishes its objective in the most cost-effective way, considering performance, cost, schedule, and risk. Since space is a very expensive area, and cost is a fundamental constraint, the cost-effective focus is a key consideration in this process.

The process also focuses on the iterative nature of systems engineering, called The Doctrine of Successive Refinement.

The SEP used by NASA is outlined in these following 7 steps:

1. Recognize Need/Opportunity
2. Identify and Quantify Goals
3. Create Alternative Design Concepts
4. Do Trade Studies
5. Select Concept
6. Increase the Resolution of the Design
7. Perform the Mission

3.3.3 IEEE Standards for Application and Managing of the SEP

This standard developed by the IEEE (7:3) is more comprehensive and covers most aspects outlined in the other processes. The focus of the IEEE Standards is on engineering activities necessary to guide product development while ensuring that the product is properly designed to make it affordable to produce, own, operate, maintain, and eventually to dispose of, without undue risk to health or the environment.

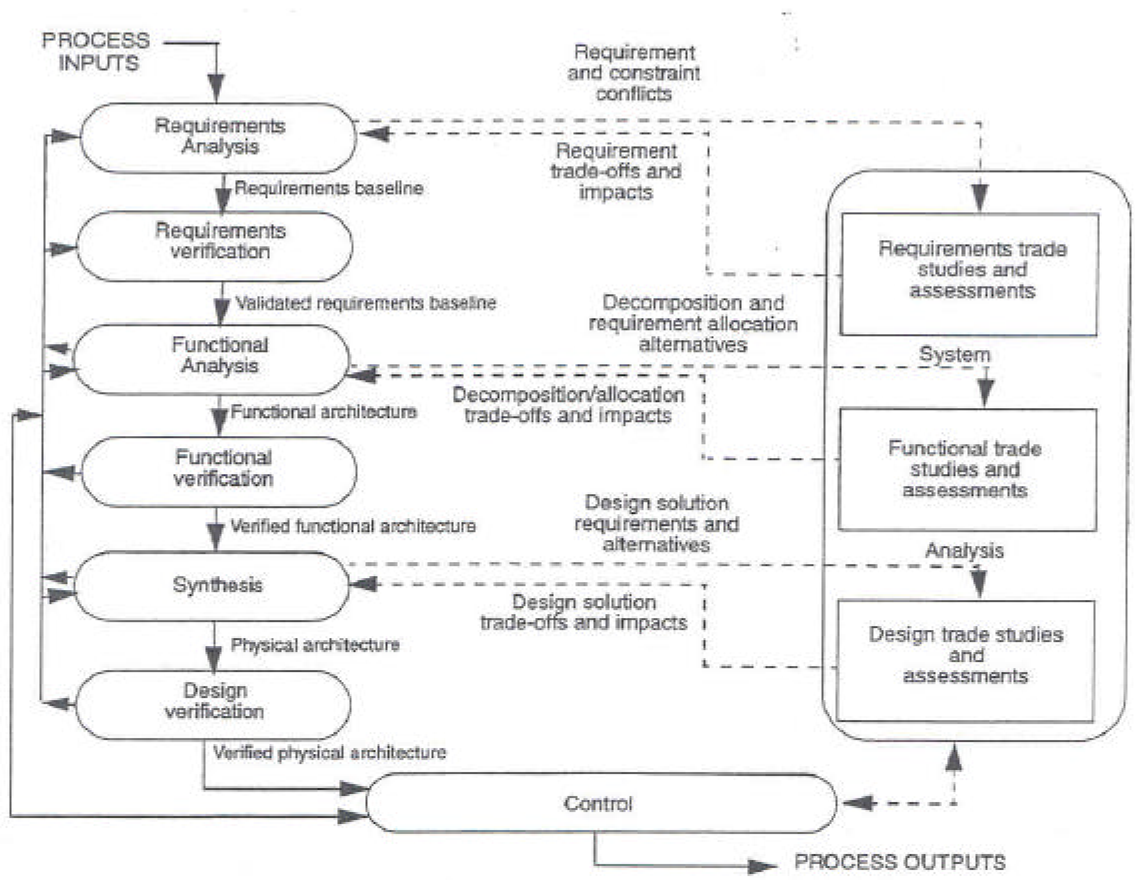

Figure 3-3 IEEE System Engineering Process

As seen in Figure 3-3, this SEP provides a standard from initial phase through development, operational, and disposal. IEEE Standards can be differentiated from the other processes because it includes human factors, which is not frequently seen in other SEPs.

3.3.4 The Space Mission Analysis and Design (SMAD) Process

The SMAD process summarizes an iterative approach evolved over the first 40 years of space exploration, and now is widely used as a reference throughout the astronautics community. It begins with one or more broad objectives and constraints and then proceeds to define a space system that will meet them at the lowest possible cost. Cost is the primary restriction almost for all space projects.

SMAD Process outlines eleven steps in four phases: (11:2)

Define Objectives

1. Define Broad Objectives and Constraints

2. Estimate Quantitative Mission Needs and Requirements

Characterize the Mission

3. Define Alternative Mission Concepts

4. Define Alternative Mission Architectures

5. Identify System Drivers for each

6. Characterize Mission Concepts and Architectures

Evaluate the Mission

7. Identify Critical Requirements

Evaluate Mission Utilities

Define Mission Concept (Baseline)

Define Requirements

10. Define System Requirements

11. Allocate requirements to System Elements

3.3.5 Systems Engineering Approach of James N. Martin

Martin’s approach can be accepted as a guide for systems engineering. In this SEP, he asks questions to check the steps if properly organized. In this SEP, there are 8 steps: (8:13)

1. Need
2. Operations Concepts
3. Functional Requirements
4. System Architecture
5. Allocated Requirements
6. Detailed Design
7. Implementation
8. Test

3.4 SEP Selection

We reviewed some of the systems engineering processes that are used in systems design problems. After assessing these SEPs, we will decide on the proper SEP to apply to our conceptual design process.

3.4.1 Critique of SEPs for the project

Although the Hall’s process, the NASA SEP, and Martin’s Approach provide valid approaches for the systems engineering projects, their steps do not fit exactly into our project. Before applying any of them to our design project, they should be tailored very carefully.

IEEE Standards are developed to be one methodology that can be applicable in all areas of business and industry. Because of that, the steps of this process are very detailed so that they can cover all issues in their areas. For our project, IEEE Standards require an extensive tailoring; therefore this SEP is not the appropriate process.

In this project, the user has already defined many aspects of the design. However, the SMAD process would require tailoring at many steps, and could not be executed as a whole process. On the other hand, the SMAD process is an effective guideline for space-related design project.

3.4.2 SEP adopted for the project

Though these SEPs are well defined, and developed for the system design projects, none of them is entirely suited to the size, scope, and complexity of our design process, and therefore cannot be accepted as an adequate SEP. Tailoring a system engineering process to fit the features of this project is a valid choice to follow, providing that the systems engineering principles remain intact.

After evaluating the SEPs, we decided that the SMAD process and Hall's Seven Steps are not the best, but the closest approaches to our design project. The steps of their process should be tailored to be able to meet the requirements of the user. In addition to these SEPs, we used the questions of Martin's Approach in some steps of our design process.

Our SEP consists of eleven steps in three phases:

Identify the Problem

1. Define the Objectives
2. Define Mission Requirements
3. Identify Design Characteristics
4. Conduct Trade-off Analysis

Evaluate the Mission Concepts

5. Define Alternative Mission Concepts

6. Analyze Alternative Mission Concepts

7. Optimize Top-Alternative Mission Concepts

8. Decision Making

Evaluate the Optimum Design Concepts

9. Design Verification

10. Sensitivity Analysis

11. Recommendations and Future Implementation

3.4.2.1 Define the Objectives

The first step of our SEP is similar to the first step of the SMAD process. Instead of the broad objectives and constraints, we define the exact mission needs determined by the user that are firm and will not be changed. And then we build objective hierarchies from the mission statement.

- What things are we trying to fulfill?
- Is the need clearly articulated?

3.4.2.2 Define Mission Requirements

This step is also derived from the SMAD process. We describe performance, operational and programmatic requirements and other constraints defined by the user. The whole design process is created to meet these mission requirements.

- What specific service will we provide?
- To what level of detail?

3.4.2.3 Identify Design Characteristics

In this step, we identify system design characteristics for parameters that are essential in creating alternative mission concepts. These characteristics include System Drivers, the Measures of Effectiveness (MOEs), Value System Design (VSD), and Utility Functions.

The system drivers can be described as parameters or components, which have the most impact on the design of the overall system. Although system drivers are not normally system requirements, a critical requirement for a parameter may result in a parameter becoming a system driver.

3.4.2.4 Conduct Trade-off Analysis

This step is developed from the NASA SEP, and provides trade-off analyses between significant parameters and their impacts on the projects. By using outcomes of the trade-off studies, alternative mission concepts will be defined in the next step.

3.4.2.5 Define Alternative Mission Concepts

This step is same as the third step of the SMAD. By using the system drivers, we define alternative mission concepts that meet the requirements and constraints.

- Are the details correct?
- Do they meet the requirements?
- Are these complete, logical, and consistent?

3.4.2.6 Analyze Alternative Mission Concepts

The fourth step is developed from the Hall's process. We analyze these alternative mission concepts by applying proper evaluation techniques. There are different groups of alternatives; our approach will be to select the best alterative for each group.

3.4.2.7 Optimize Top-Alternative Mission Concepts

This is an iterative step where we redesign our requirements according to the priorities of the user. After synthesizing the whole alternative concepts, some of them in the top list can be very close to each other, and it would be not easy to select the best alternative. By means of redesigned requirements, we optimize these top-alternative concepts, and analyze them again. Synthesizing only these alternatives is the last part of this step.

3.4.2.8 Decision Making

As it is stated in the Hall's process, we select the best alternative for our mission design project among the top-optimized alternative mission concepts.

3.4.2.9 Design Verification

Since space is an exceptionally expensive and risky area, it would be useful to place a step where we can check our optimum alternative. In this step, we control how well the optimum alternative meets our objectives, requirements, and constraints.

- Will the user's need be met?
- Will the solution be satisfactory in terms of cost, performance, and risk?

3.4.2.10 Sensitivity Analysis

Within iterative process, user may change some of the requirements or constraints according to the systems engineering findings. To be flexible in our research, we put this step derived from SMAD process. The decision maker may want to understand his/her limits and how the decision changes when he or she redefines the requirements or constraints for the constellation system design. To answer these questions, we analyze the sensitivity of the main parameters.

3.4.2.11 Recommendations and Future Implementation

We make our decision about the optimum alternative for the design process according to objectives, the requirements, constraints, and current technology. However, in the future, some of these factors may change. In this step, recommendations about implementations of the results of this study, and possible follow-on studies will be mentioned.

Chapter 4 - Systems Design Characteristics

4.1 Chapter Overview

This chapter includes the definition of mission requirements, identification of design characteristics such as system drivers, system architecture, MOEs and their relations with objectives, VSD and utility functions. The trade-offs between MOEs are also included in this chapter.

4.2 Define Mission Requirements

The objectives hierarchy of this study is stated in chapter 1. According to the objectives hierarchy and the sponsor's needs, the requirements are updated frequently during the iterations of the SEP. The redefined and refined final requirements are as seen in the Table 4-1.

The only changes are: The first requirements table was prepared by using IKONOS as a baseline. IKONOS is a global commercial application. For our study we changed it according to a regional application and our study is commercial but also designed to fulfill the high-resolution image needs of Turkey so the primary area contains most of the actual customers and secondary area may have other potential customers. Instead of defining as Level 1 and 2 requirements are redefined according to primary and secondary regions. Instead of image distribution delay we defined another MOE and called it image downlink delay and we assumed all distribution delays from ground station to customer equal so the only difference between alternatives are the data downlink delays. We do not have a requirement on image downlink delay. But the alternative with the shortest delay is the most desirable for us. In the operational requirements image service with a lead-time is not considered as a requirement. We require continuous coverage in the primary area. Instead of defining a lead-time we calculated the number of simultaneous customers we can serve and the image downlink delay. The primary region customers have priority and the requirements are more important in this area because the sponsor is interested in the primary region. And the sponsor expects to be operating commercially in the secondary region. A NOAA regulation is not a constraint any longer. We assumed that this regulation is not considered in the target area.

Table 4-1 Final Mission Requirements

Requirement	*Description*	*Preliminary Level*
Performance:		
Coverage frequency	Primary Region & Secondary Region	Continuous daylight coverage 6am-6pm local time Daily revisit
Resolution (surveillance)	Primary Region	1 m panchromatic
	Secondary Region	5 m multi-spectral
Location accuracy	User specified prior to launch	10 m
Image region location		Latitude and Longitude 40^0
Image region size	Delta Lat.	20^0
	Delta Lon.	25^0
Image processing	Maximum area per pass	10^6 km^2
Image size		10^4 km^2
Data downlink speed		Continuous (TDRS option or equiv.)
Simultaneous Customers	Primary Region	5 Customers
	Both regions	25 Customers
Image quality	Sun elevation	> 15^0
	Image elevation	> 20^0
	Image format	Quick look; georeferenced; Geometrically corrected; geocoded
Operational:		
Availability	Primary Region	98%(excluding cloud cover)
	Secondary Region	98%(excluding cloud cover)
Refueling frequency	Minimum	1 year or electric propulsion or solar
Survivability		Space radiation hardening
Programmatic:		
Cost	Life cycle (Year 2000$)	Cost competitive
Schedule	IOC	5 years
	FOC	10 years
Design Life		10 years
Constraints:		
Launch system	Use of existing launch capability	< 10 systems
Launch reliability		> 95%
Refueling/Recovery		Shuttle
Data downlink		TDRS (or equivalent communications satellite system)

4.3 Identification of Design Characteristics

4.3.1 System Drivers

"Systems drivers are the main mission characteristics that influence directly performance, cost, risk, or schedule and which the user or designer can control."(11:37) It is important to identify them not to cause some mission analysis errors. To identify system drivers, it is necessary to explicitly identify the area of interest (performance, cost, risk or schedule) and parameters (measure of effectiveness) to measure the area of interest. For this research, the systems drivers are:

- **Cost**

It is the most fundamental limitation of all spacecraft systems which constraints its performance. Mass and altitude directly influence how affordable the system will be. We eventually seek a solution to our problem at minimum possible cost.

- **Performance**

An important characteristic is resolution. The resolution dictates how high spacecraft can be and with what diameter size.Both are contributors to overall cost of the system. To reach a certain level of resolution can become technically unachievable or very expensive with the existing satellite technology. To overcome this we included inflatables and UAVs in this study.

- **Risk**

For this research two of the alternatives are technologies that are still being tested and have not been practically or operationally proven. These are inflatable technology and solar-powered UAVs. Since they are recently being developed, they have their inherent risks of success, feasibility and effectiveness. For example, to place satellites into high altitude orbits to get absolute continuous coverage during daylight hours can add a lot of risk to the system design because this spacecraft will require bigger apertures for the optics and this will result in a massive payload. Placing the spacecraft at high altitude orbits can be a risky task because it may require the use of inflatable technology to achieve the design requirement of one-meter high resolution. Since the inflatable technology is not proven and it is still under development, these may set back and delay the important milestones of the design.

4.3.2 System Architecture

IEEE defines system architecture as a composite of design architectures. (347:8) The system architecture helps understand the system at component level and built according to the mission statement, objective hierarchy and requirements. In a space or airborne high-resolution image missions the main subsystems are determined as project management, space/air segment, launch segment, ground segment. The measurable terms to calculate the performances of each system are explicitly shown by their units. These measurable terms are the candidate MOEs for this study.

The systems architecture is seen in Figure 4-1.

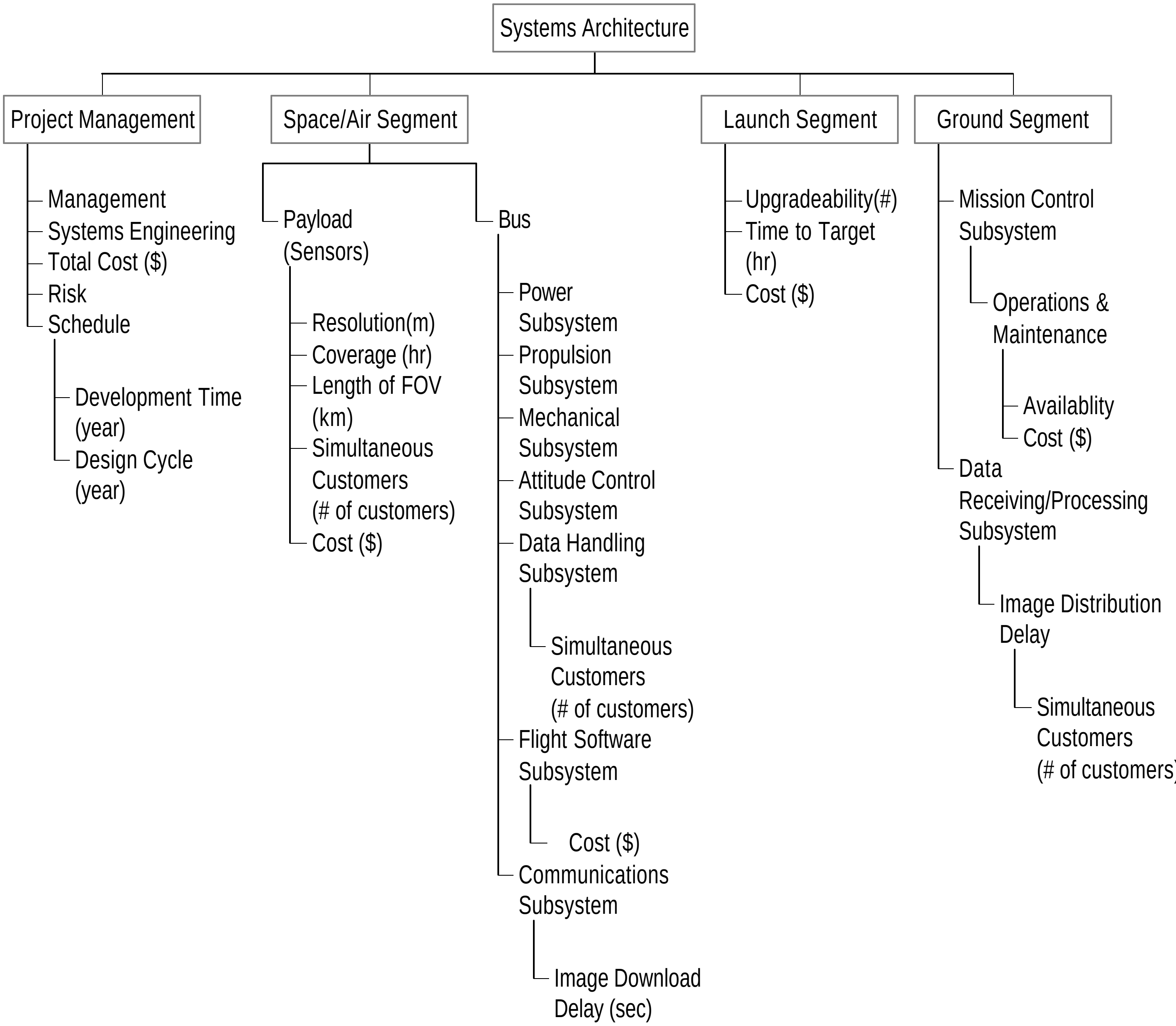

Figure 4-1 System Architecture

4.3.3 Measures of Effectiveness (MOEs)

According to IEEE measures of effectiveness are the metrics by which a customer will measure satisfaction with products produced by the technical effort. (7:8)

After a meeting with our advisor Dr. Spenny we determined the priorities in this study and prepared an MOE list. This list is also updated several times during the iterations of our SEP. We started with requirements, eliminated some of them make a MOE list and we refined our list after we made a systems architecture diagram. This helped us to find out the measurable variables in our system and their importance for our decision. We focused on the things we can measure, their units and their meanings to us. We made a systems architecture to see the parts we have in our system and the ways to measure their performance. The last item in the hierarchy shows the measurable terms of that system part. Only the parts we are going to include in our VSD are explicitly shown with their units the other parts are either same in all our alternatives or their differences are already accounted in the total life cycle cost calculations of each alternative. We do not only have satellite alternatives but also UAV alternatives. In some alternatives these are used together so in our systems architecture we tried to capture all the alternatives by calling one of the main part Space/Air segment. In both satellites and UAVs the payload contains the sensors and the bus contains other related flight equipment and software.

4.3.3.1 Relations between MOEs and Objectives

At this stage we already had some ideas after our meeting with our sponsor but we also wanted to show every decision we made in detail so that the values our decision based on can be understood thoroughly and can be changed according to values of other decision makers to be able to use this study. We decided to make the matrix on Table 4-3 showing the relative importance of each MOE to the others. First we put all MOEs in an order of importance: Cost, Risk, Resolution, Coverage, Time to Target, Number of Simultaneous Customers Upgradeability, and Image Downlink Delay. Resolution and coverage MOEs are separated into primary and secondary regions. In addition to coverage, which we measured in terms of hours, there was another coverage issue called Length of Field of View that is measured in terms of kilometer. Then we analyzed these MOEs in pairs and evaluated their relative importance.

- **Cost**

Cost is the most important MOE for our study. First three of our objectives in the table are directly related with the life cycle cost of the system and to manage all other objectives we need money so that we can state that all objectives are implicitly related with cost. The costs of each alternative are calculated as total life cycle costs and in year 2000 dollars.

- **Risk**

In our study we handled risk as schedule, performance and technology risks. We evaluated each alternative in terms of these risks.

Technology risk is due to lack of experience and knowledge on the technology worked on. Technology risk is handled in the cost calculations by using a heritage factor. Higher the technology risk, higher the heritage factor. Newly explored technologies have high technology risks.

Performance risk depends on our confidence about the performance of our system. For example, inflatable technologies have high performance risk, since they have not been proven to perform high-resolution imaging satisfactorily.

Schedule risk is whether we will be able to come up with a system that will satisfy mission requirements in required amount of time or not. Again, working with new technologies may raise questions about being on schedule.

Performance and schedule risks are handled under one common name as “risk”, whereas technology risk is imbedded in cost as “heritage factor”. Each of the alternatives consists of two new systems, one new system and existing technology or two existing technology systems. All three kinds of risks increase as we switch from existing technologies to new technologies.

- **Primary Resolution**

Since the current technology provides 1m resolution we should develop our alternatives to give at least 1m resolution in the primary region according to user’s requirements. This high resolution is technologically difficult and costly to achieve with satellites, so we determine to use UAVs for the primary region in some alternatives.

- **Secondary Resolution**

User requires 1 m resolution service in the secondary region. However, due to cost considerations, user can accept up to five-meter resolution.

- **Primary Coverage**

Primary Coverage is calculated by using STK in unit of hours. It is the time period space/air vehicle is over the target between 6am and 6pm.

- **Secondary Coverage**

Secondary Coverage is calculated in the same way as the coverage in primary region. It shows coverage in the secondary region in unit of hours between 6am and 6pm.

- **Length of Field of View (LOFOV)**

This is the length of the field of view calculated in kilometers. We summed all length field of view provided by all space/air vehicles. Then we divide this number by the number of simultaneous customers in that alternative which gives the length of field of view per customer for this alternative. For instance, if we have 5 UAVs providing 2 km LOFOV, and one satellite with 20 km LOFOV, we have total LOFOV 30 km LOFOV; since each system can be used for different areas. The number of simultaneous customers is 6. We will have an average of 5 km LOFOV per simultaneous customers.

- **Image Downlink Delay**

Satellite data downlink rate is calculated as 2.5 gigabytes per second and UAV data downlink rate is 270 megabytes per second. The detailed information about these numbers can be found in our trade-off study. (24)

Downlink delay of an alternative is found by dividing its total data size by data downlink capacity. After finding downlink delay for all space and air vehicles in the system, we sum all and calculate the total delay of the system. Then we divide this total downlink delay by the number of simultaneous customers and find the average downlink delay per customer.

- **Upgradeability**

Upgradeability is the average number of times a system can be upgraded during 10 years of mission life. After we lauch conventional satellites we do not have the opportunity to upgrade except by replacement. However small satelites (they are designed to have 5-year design life and can be upgraded before re-lauch) and UAVs can be upgraded. For example, “satellite&UAV” alternatives have an upgradeability of 5 time on average in 10 years (average of 10 years from UAVs and 0 years from satellites equals 5).

- **Time to over Target**

Since the satellites are flying in orbit, satellite alternatives are assumed to be always over the target and ready for operation (although there may be some delays with satellites, we assumed time to target as zero for ease of calculation), but UAVs need some time to take off and go over the target. UAVs (Global Hawk) have a cruise speed of 350 knots and it can travel to the farthest point of the target area in about 2.43 hours. So we assumed an average time of 1.25 hours (which is approximately ½ of 2.43 hours) for UAVs to reach target area. This time is calculated in hours for each alternative.

- **Simultaneous Customers**

This number shows the number of customers that can be served simultaneously. Regardless of the number of satellites in an orbit, one orbit can only serve only one simultaneous customer. However, each one of the UAVs can serve one simultaneous customer.

At this point we checked the relationships between our objectives and MOEs. If an MOE is related with more objectives than the others this might show its importance. But we cannot decide the importance of an MOE only by the number of objectives it is related because there are complex relationships between these objectives and MOEs. We are trying to justify the validity of our VSD by looking at interrelations between objectives and MOEs. Therefore we can check if our MOEs satisfactorily measure all of our objectives. Later some other objectives can be added to this study or because of some technological developments some MOEs like field of view or image down link delay may not be an issue any more. But the objective of providing commercial imaging service that outperforms competitive service will still be same and it may be related with another MOE in this case. The MOEs and related objectives can be seen in Table 4-2.

Table 4-2 MOEs and Related Objectives

OBJECTIVES	RELATED MOE's
To provide commercial imaging service that is cost competitive with existing commercial service.	• Cost
To develop a commercial imaging business plan that is attractive to investors.	• Cost • Image Downlink Delay • Time to Target • Simultaneous Customers
To perform sufficient development and demonstration to reduce program technical risk.	• Cost • Risk
To provide low latitude service at low image resolution with daily revisit.	• Cost • Primary Resolution • Primary Coverage • LOFOV
To provide low latitude continuous service during daylight hours at moderate image resolution.	• Cost • Secondary Resolution • Secondary Coverage • LOFOV
To provide image quality that meets or exceeds current quality.	• Cost • Primary Resolution • Secondary Resolution • LOFOV
To provide commercial imaging service that outperforms competitive service.	• Cost • Primary Resolution • Secondary Resolution • Primary Coverage • Secondary Coverage • Image Downlink Delay • Time to Target • Simultaneous Customers
To provide for growth in service level to five times current level.	• Cost • Image Downlink Delay • Time to Target • Simultaneous Customers

4.3.3.2Weights of MOEs

The MOEs should be specified in terms of some level of importance, as determined by the sponsor or user and according to the criticality of the functions they are measuring in our system.

After considering the relationships of MOEs with the objectives, we evaluated all MOEs in pairs and arranged a matrix showing the relative importance of each MOE to others.

For example, we decided that cost was 3 times more important then risk, which means that risk is 1/3 times important then cost. So the relative importance matrix is symmetric. The ones in diagonal mean that everything is as important as itself. This matrix in Table 4-3 is used as the preference matrix used in Thomas Athey's Systematic Systems Approach book the weights are also calculated by using this approach. The total of weights add up to 100 percent. (1: 206-210)

To calculate the weights for each MOE we added all the numbers in that MOE's column and divided it by the grand total of all cells in the matrix. This shows the relative importance of an MOE in the system. Then we took the averages of these percentages. We used that in our VSD as a weight for that MOE. Table 4-3 shows the relative importance matrix and final weights of MOEs:

Table 4-3 Relative Importance Matrix

MOEs	COST	RISK	PRIMARY RESOLUTION	SECONDARY RESOLUTION	PRIMARY COVERAGE	SECONDARY COVERAGE	LOFOV	IMAAGE DLINK DELAY	UPGRADEABILITY	TIME TO TARGET	NUMBER OF SIMULATANEOUS CUSTOMERS	TOTAL
COST	1.00	0.33	0.30	0.10	0.30	0.10	0.13	0.20	0.20	0.33	0.33	
RISK	3.00	1.00	0.90	0.30	0.90	0.30	0.40	0.60	0.60	1.00	1.00	
PRIMARY RESOLUTION	3.33	1.11	1.00	0.33	1.00	0.33	0.44	0.67	0.67	1.11	1.11	
SECONDARY RESOLUTION	10.00	3.33	3.00	1.00	3.00	1.00	1.33	2.00	2.00	3.33	3.33	
PRIMARY COVERAGE	3.33	1.11	1.00	0.33	1.00	0.33	0.44	0.67	0.67	1.11	1.11	
SECONDARY COVERAGE	10.00	3.33	3.00	1.00	3.00	1.00	1.33	2.00	2.00	3.33	3.33	
LOFOV	7.50	2.50	2.25	0.75	2.25	0.75	1.00	1.50	1.50	2.50	2.50	
IMAGE DLINK DELAY	5.00	1.67	1.50	0.50	1.50	0.50	0.67	1.00	1.00	1.67	1.67	
UPGRADEABILITY	5.00	1.67	1.50	0.50	1.50	0.50	0.67	1.00	1.00	1.67	1.67	
TIME TO TARGET	3.00	1.00	0.90	0.30	0.90	0.30	0.40	0.60	0.60	1.00	1.00	
NUMBER OF SIMULTANEOUS CUSTOMERS	3.00	1.00	0.90	0.30	0.90	0.30	0.40	0.60	0.60	1.00	1.00	
TOTAL SCORES	54.16	18.05	16.25	5.41	16.25	5.41	7.21	10.84	10.84	18.05	18.05	180.52
WEIGHTS	0.300	0.100	0.090	0.030	0.090	0.030	0.039	0.060	0.060	0.100	0.100	1.000
AVERAGE WEIGHTS	0.30	0.10	0.09	0.03	0.09	0.03	0.04	0.06	0.06	0.10	0.10	1

4.3.4 Value System Design (VSD)

VSD defines importance of MOEs according to the objectives. The VSD we stated for this particular system is developed by the help of the sponsor and analyzing the internal relationships as system engineers. The MOEs stated in Table 4-4 are the parameters that can be traded during the conceptual design to give the sponsor/user better alternatives.

Table 4-4 MOEs, Units, and Weights

MOEs (Measures of Effectiveness)	**Units**	**Percentages / Weights**
COST	$	0.30
RISK	One new, two new, existing	0.10
PRIMARY RESOLUTION	m	0.09
SECONDARY RESOLUTION	m	0.03
PRIMARY COVERAGE	hr	0.09
SECONDARY COVERAGE	hr	0.03
LOFOV	km	0.04
IMAGE DLINK DELAY	sec	0.06
UPGRADEABILITY	#	0.06
TIME TO TARGET	hr	0.10
SIMULTANEOUS CUSTOMER NUMBER	#	0.10
TOTAL	-	1

These percentages/weights show their values in the overall system. For example the weight of cost is 0.30 points and it affects 30% of our decision context.

This VSD is developed to evaluate specifications of UAVs and satellites on the same scale so that we can look at all aspects of the issue and take all details into account before we can make a decision.

4.3.5 Utilities of MOEs

Utility has had an equally profound influence on psychology and philosophy, for Bernoulli set the standard of defining the standard for human rationality. For example, people for whom the utility of wealth rises, as they grow richer are considered by most psychologists- and moralists- as neurotic; greed was not part of Bernoulli's vision, nor is it included in most modern definitions of rationality.

Utility theory requires that a rational person be able to measure utility under all circumstances and to make choices and decisions accordingly – a tall order given the uncertainties we face in the course of a lifetime. The core is difficult even when, as Bernoulli assumed, the facts are same for everyone. Different people have different information; each of us tends to color the information we have in our own fashion. Even the most rational among us will often disagree about what the facts mean. (2: 110,111)

MOEs are the criteria used in developing the system utility function as explained by Thomas H. ATHEY in Systematic Systems Approach, Chapter 7. The utility function establishes the desired performance for the system over the planning horizon. Desirability of a performance is shown by a utility changing between 0-1, 1 meaning most desired and 0 meaning least desired. The expected performance for each alternative is compared to the desirability of the various levels of performance within the evaluation matrix. The outcome of this matrix is an overall ranking on the relative desirability of each alternative. (See in Appendix D) (1, 103)

To draw the utility curves, we checked our requirements to put them as the minimum levels. Sometimes, the minimum limits were not specified in our requirements so we made some assumptions according to our user's needs. Then we decided maximum levels of utility for each MOE. We decided the maximum levels according to current technologies, our needs and 10-year system life. We asked the question " what is the maximum meaningful level we are willing to achieve for this MOE?" Our utility curves for each MOE are as follows:

- **Cost**

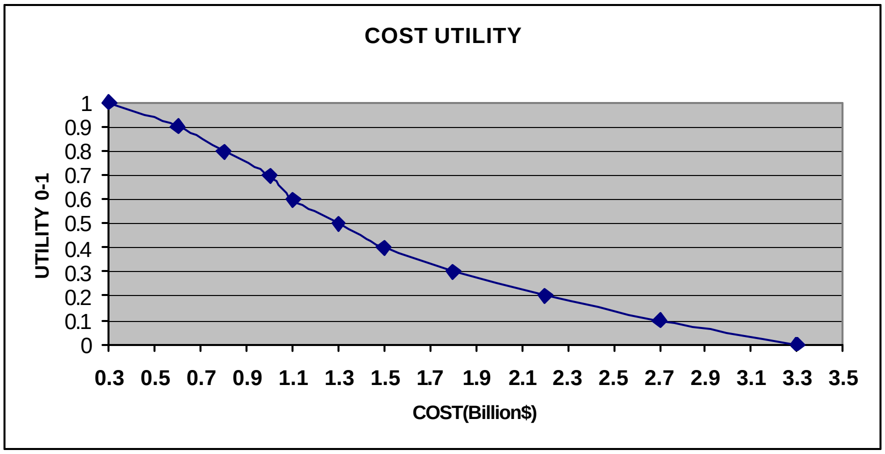

Figure 4-2 Cost Utility

The minimum utility cost is \$3.3 billion. The maximum utility cost is \$0.3 billion; anything that costs \$0.3 billion and under gets 1. The alternatives that cost \$3.3 and over get a utility of 0. The slope of the curve changes at around \$1.5 billion, till passing this amount the utilities fall faster meaning that the cost differences at the less cost areas has more utility for us. Although the utility difference is same and equal to 0.1 the difference between \$0.6 billion and \$0.8 billion is \$0.2 billions while the difference between \$2.7 billion and \$2.2 billion is \$0.5 billions. This shows that the money has less utility in relatively higher cost areas above \$1.5billion.

- **Risk**

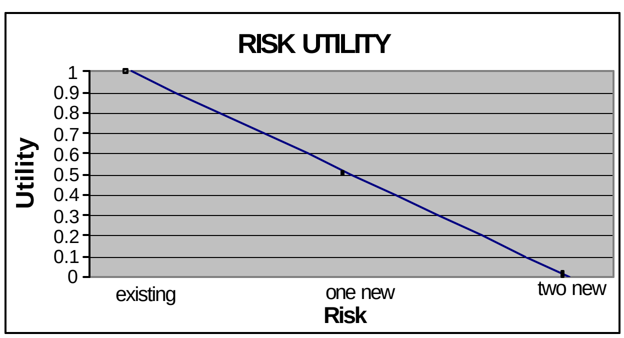

Figure 4-3 Risk Utility

In terms of performance, technology and schedule risk we can group the alternative systems in this study in three different categories: existing systems, new system, two new systems.

The existing technologies are conventional UAVs, small satellites and conventional satellites and their combinations. The existing systems get a risk utility of 1. The new technologies are solar-powered UAVs and inflatable technologies. When we use these two technologies together they are categorized as two new systems and get a risk utility of 0. Their combinations with existing systems are categorized as new system and get a risk utility of 0.5.

- **Primary Resolution**

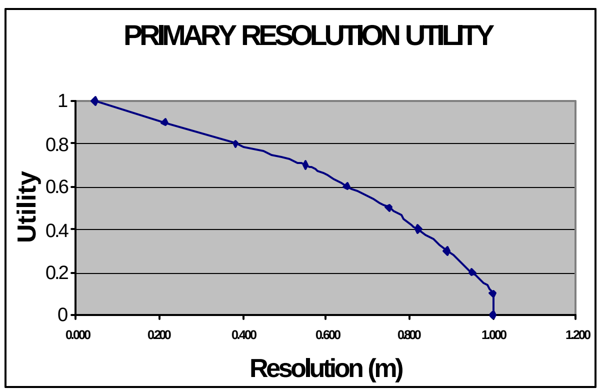

Figure 4-4 Primary Resolution Utility

The primary region has high-resolution requirements. To be able to be competitive with the current technologies resolution should be 1m or under in this region.

The utility of 1m and over is 0. The 0.045 resolution is the resolution needed to technically analyze a vehicle. This is the maximum meaningful resolution for the purposes of our study so 0.045m resolution and under has the maximum utility of 1.

- **Secondary Resolution**

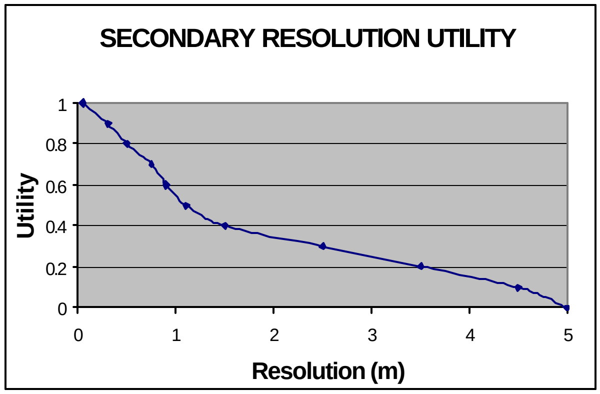

Figure 4-5 Secondary Resolution Utility

Because of cost constraints we had to relax the resolution requirements in the secondary region. We give the minimum utility to 5m resolution, which is considered as the lowest resolution user can accept to be competitive with current technologies. Although IKONOS has higher resolution, 5m can also be commercially valuable to the user. Same as the primary region maximum utility is given to 0.045m and better resolutions. 1m resolution is nearly at the middle point with a 0.55 utility.

- **Primary and Secondary Coverage**

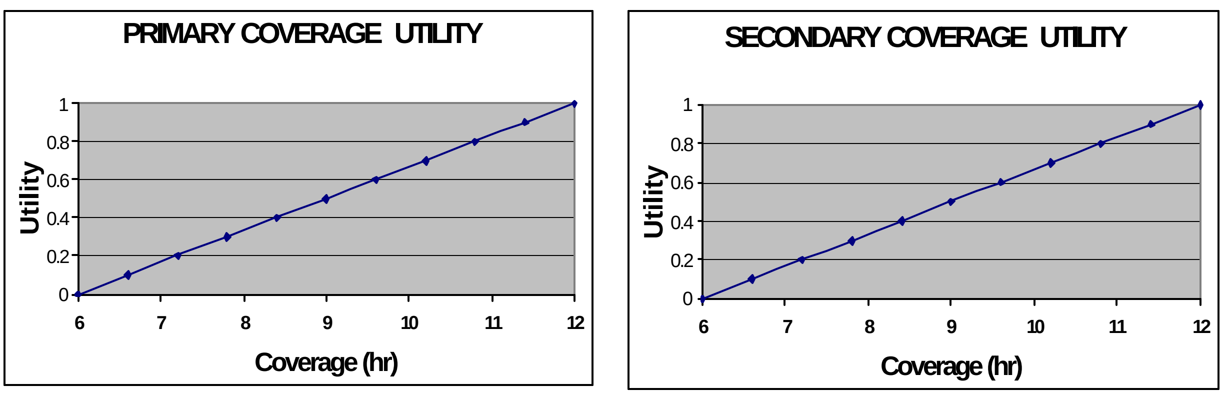

Figure 4-6 Primary and Secondary Coverage Utilities

The coverage requirement for both regions is 12 hours during daylight between 6am and 6pm. The least coverage user can accept is 6hr daylight coverage so 6hr coverage has a utility or 0. Each additional hour has a utility of 0.1 so the 12 hr daylight coverage has a utility of 1.

- **LOFOV**

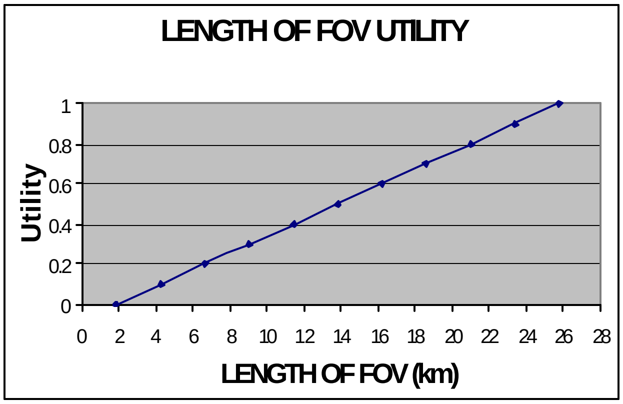

Figure 4-7 LOFOV Utility

The best alternative has 25.8km LOFOV and gets the maximum utility of 1. The worst alternative has 1.88km LOFOV and gets the minimum utility of 0. Between 1.88km and 25.8 km the utilities change directly proportional to LOFOV. This parameter is important because it affects the number of customers that can be served and the area that can be imaged.

- **Image Downlink Delay**

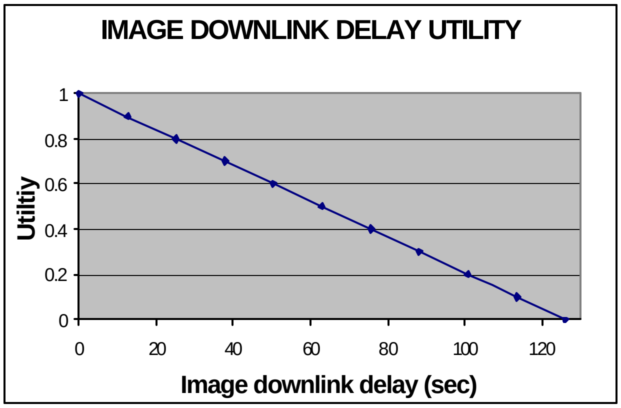

Figure 4-8 Image Downlink Delay Utility

The best alternative has zero delay and gets the maximum utility of 1. The worst alternative has a delay of 126 sec and gets the minimum utility of 0. Between 0 and 126 seconds the utilities change directly proportional to image downlink delay. This parameter have to addressed because of the requirement of continuous coverage of the target area.

- **Upgradeability**

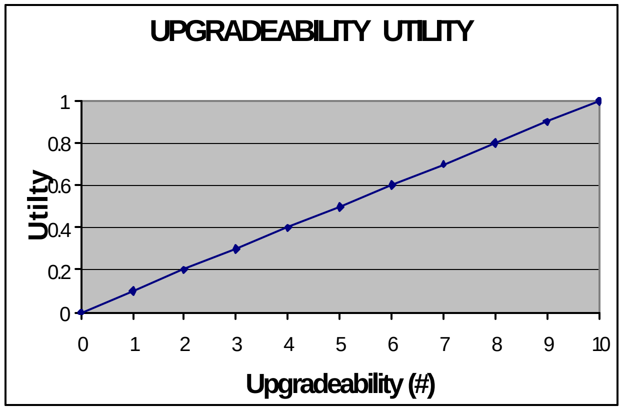

Figure 4-9 Upgradeability Utility

Upgradeability shows the number of times an alternative can be upgraded in 10-year system design life. Satellites cannot be upgraded in this period so their utility is 0. Small satellites can be upgraded every 5 years so their upgradeability in 10-years is 2 so they get a utility of 0.2. UAVs can be upgraded every year so their upgradeability is 10 and they get the maximum utility of 1.

- **Time to Target**

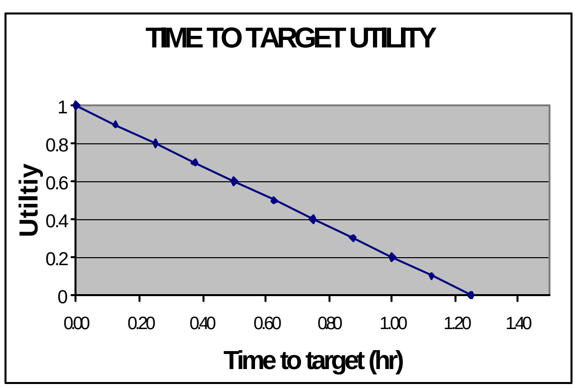

Figure 4-10 Time to target

The satellites are always over the target so they can be ready to service in no time. Satellites get the maximum utility of 1. The worst alternative needs 1.25 hr to be over target and gets the minimum utility of 0. Between 0and 1.2 hr the utilities change directly proportional to time to target.

- **Simultaneous Customers**

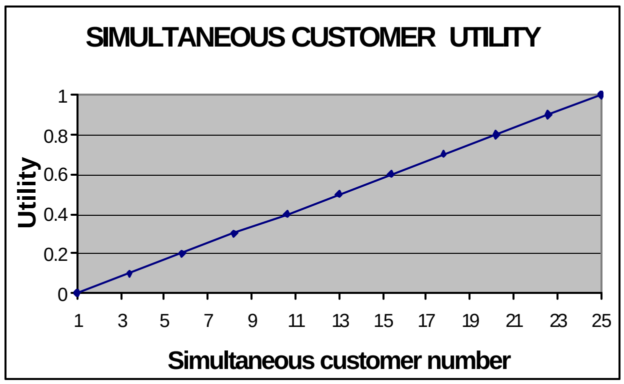

Figure 4-11 Simultaneous Customer Utility

The user wants to serve as much as 25 customers simultaneously. So 25 customers and more get the maximum utility of 1. The least we can achieve is to serve 1 customer and this gets the minimum utility of 0. The middle point is 13 customers with a utility of 0.5.

4.3.6 System Utility Function

Using requirements we developed the utility curves. An alternative gets a rating between 0-1 according to its expected performance from these utility curves. The confidence level of expected performances are assumed to be same because we use the same SMAD process for calculating costs of all alternatives. So we did not use a confidence level coefficient. If we have more reliable data on the cost or other expected MOEs of some of our alternatives in the future then the comparison can be made by using higher confidence levels for these alternatives and less confidence levels for the remaining.

"Systems utility is a measure of the contribution of performance on a particular dimension to the total utility of the system, if a specific alternative were implemented. It is determined by multiplying the rating times the relative importance of the particular criterion." (1: 223)

Total utility of an alternative is determined by adding the multiplications of the MOE utilities of each alternative with the relative importance or weight of that MOE. The weights in the VSD are used to calculate the total utilities of each alternative.

Total Utility = Utility(Cost) * 0.30 + Utility(Risk) * 0.10 + Utility(Primary Resolution) * 0.09 + Utility(Secondary Resolution) * 0.03 + Utility(Primary Coverage) * 0.09 + Utility(Secondary Coverage) * 0.03 + Utility(LOFOV) * 0.04 + Utility(Image Downlink Delay)*0.06+ Utility(Upgradeability)*0.06+ Utility(Time to Target)*0.01+ Utility(Simultaneous Customers)*0.10

The outcome of this function is an overall ranking on the relative desirability of each solution. (1: 103)

4.4Trade-Off Studies

There are several related parameters that have to be taken in account while configuring the optical features of the satellite sensor and quality of the image. These features and quality issues some of which are explained in the following, can be stated as:

- Resolution
- Field of view (FOV)
- Aperture diameter

- Focal Length
- Data size
- Downlink capacity and delay
- Altitude
- Wavelength
- Elevation Angle

4.4.1 Resolution

4.4.1.1 Spatial Resolution

Spatial resolution refers to the size of the smallest object or ground feature that can be distinguished in an image. It is a function of the range from the sensor to the target, the aperture, and the wavelength of the incident energy, and can be obtained by

$$\text{Equation 4-1} \quad R = 2.44 h \lambda / D$$

where h is altitude, λ is wavelength used, and D is aperture diameter. This is one of the most important features to take into account when choosing imagery because it directly dictates what surface features you can map. You must determine the size of objects you plan to map and then find imagery with resolution sufficient to identify and locate them. This is very important to the project costs because generally, the more detailed an image are; the more expensive it is per unit area. (37)

4.4.1.2 Spectral Resolution

This term defines the wavelengths in which the sensor is capable of measuring reflected energy. Wavelengths are expressed in micrometers (µm), or microns. The number of bands is also used to explain how many separate wavelength reflectance are measured by the system. The number of spectral bands and bandwidth of each band determine the resolving power of a spectral sensor. Higher spectral resolution is achieved by narrower bandwidths, but using narrower bandwidths tends to reduce the signal to noise ratio for the measurement which is a measure of signal strength relative to background noise.

4.4.1.3 Radiometric Resolution

This is the finest distinction that can be made between objects viewed in the same part of the EM spectrum. While the arrangement of pixels describes the spatial structure of an image, the radiometric characteristics describe the actual information content in an image. The finer the radiometric resolution of a sensor, the more sensitive it is to detecting small differences.

Imagery data are represented by positive digital numbers, which vary from 0 to (one less than) a selected power of 2. This range corresponds to the number of bits used for coding numbers in binary format. Each bit records an exponent of power 2 (e.g. 1 bit $= 2^1 = 2$). The maximum number of brightness levels available depends on the number of bits used in representing the energy recorded. Thus, if a sensor used 8 bits to record the data, there would be $2^8 = 256$ digital values available, ranging from 0 to 255. However, if only 4 bits were used, then only $2^4 = 16$ values ranging from 0 to 15 would be available. Thus, the radiometric resolution would be much less. Image data are generally displayed in a range of gray tones, with black representing a digital number of 0 and white representing the maximum value (for example, 255 in 8-bit data). The difference in the image quality can be seen in the Figure 4-12.

Figure 4-12 Comparison of 2-bit image with 8-bit image

(21)

4.4.1.4 Choosing the right spatial resolution

The following are the important criteria that should be taken into account while designing the spatial resolution of the system. The table in the Appendix B gives more detailed information about this subject. (37)

One-Meter

- Identify and map human-scale features larger than one square meter such as manhole covers, benches, automobiles, bus shelters, highway lanes, sidewalks, utility equipment, fence lines, and freestanding trees and bushes.
- Identify characteristics of many of above-mentioned features.
- Detect small areas of stress in farm fields or tree stands.
- Locate and map house additions, roads, buildings, courtyards, and small farm fields.
- Differentiate among types of buildings and houses.

10-Meter

- Locate and map buildings, yards, roads, property boundaries, athletic fields, farm fields, and side streets.
- Differentiate farm fields and tree stands by relative vegetative health.
- Make small-area land-cover classifications.

20/30-Meter

- Locate airports, city centers, suburbs, shopping malls, sports complexes, large factories, extensive forest stands, and large farm fields.
- Make generalized land-cover classifications.

80-Meter

- Map regional geologic structure.
- Assess vegetative health in a relatively large region.

4.4.2 Field of View Area

It is the actual area that the sensor of the satellite can see at any moment. It should not be confused with the access area, which is the total area on the ground that can potentially be seen at any moment by turning the sensor spot. Just like a camera lens, every satellite sensor has a field of view, or maximum area it can cover in any one image. The factors that limit this area are discussed in the following pages.

4.4.3 Aperture Diameter

The aperture is the hole in a camera that allows light to hit film. The amount of light that gets through the aperture determines what a picture will look like. The larger the aperture, the more light it collects and the brighter (and better) the image will be. Greater detail and image clarity will be apparent as aperture increases.

4.4.4 Focal Length

Distance from the focus to the nearest point on the reflecting surface. It is determined based on field of view and the size of the image plane. Focal length needed to record an object or scene of radius R is given by

$$\text{Equation 4-2} \quad \frac{f}{h} = \frac{r_d}{R} = magnification$$

where h is the distance from the spacecraft to the object, rd is the radius of the detector array in the image plane, and R is the radius of the object. The longer the focal length of the satellite, generally the more power it has, the larger the image and the smaller the field of view.

4.4.5 Relations between parameters

All the formulas and relations that lead to calculate these features can be seen in Table 4-5, in which an example is given and important outputs are highlighted to make the subject as clear as possible by adapting the SMAD procedure (3: 287). The inputs and outputs of this chart can be expressed as:

<u>Inputs</u>

- Orbital altitude
- Minimum elevation angle
- Resolution on the horizon
- Number of bits used to encode each pixel, which we preferred to use 8 bits in all designs
- Number of pixel lines per imager, which is a feature of the camera and obtained by examining present applications
- Operating wavelength

Outputs

- Swath width
- Ground pixel resolution at nadir
- Data size
- Aperture diameter
- Length of field of view

Table 4-5 Formulas

Astrodynamical Constants

Gravitational parameter:	$\mu := 398600.4418 \cdot 10^{9} \frac{m^3}{s^2}$	Earth radius:	$R_E := 6378136.49m$
Planck's constant:	$h_p := 6.6260755 \cdot 10^{-34} W \cdot s^2$	Speed of light:	$c := 299792458 \frac{m}{s}$
Boltzmann's constant:	$k := 1.380658 \cdot 10^{-23} \frac{W \cdot s}{K}$	$PI := 3.14$	

Design Parameters

Define orbital altitude	$h := 1666.219km$
Define max incidence angle	$IA := 70deg$
Specify max along-track ground sampling distance (Resolution at horizon)	$Y_{max} := 0.955483124m$
Specify # of bits used to encode each pixel	$B := 8$
Specify # of pixel lines for imager	$N_m := 5000$
Specify width for square detectors	$d := 7 \cdot 10^{-6} m$
Specify quality factor for imaging	$Q := 1$
Specify operating wavelength	$\lambda := 0.9 \cdot 10^{-6} m$
Define equivalent blackbody temp	$T := 290K$

Step 1. Define Orbit Parameters

Define orbital altitude	$h = 1.666 \times 10^{6}\,\mathrm{m}$	{Design parameter}
Define semimajor axis	$a := R_E + h$	$a = 8.044 \times 10^{3}\,\mathrm{km}$
Compute orbit period	$P := 2\pi\sqrt{\dfrac{a^3}{\mu}}$	$P = 119.673\,\mathrm{min}$
Compute ground track velocity	$V_g := 2\pi \dfrac{R_E}{P}$	$V_g = 5.581\,\dfrac{\mathrm{km}}{s}$

Step 2. Define Sensor Viewing Parameters

Compute angular radius of earth (as seen from spacecraft)	$\rho := \mathrm{asin}\left(\dfrac{R_E}{R_E + h}\right)$	$\rho = 52.455\,\mathrm{deg}$
Compute max distance to the horizon	$D_{max} := \sqrt{(R_E + h)^2 - R_E^{\,2}}$	$D_{max} = 4.902 \times 10^{3}\,\mathrm{km}$
Define max incidence angle	$IA = 70\,\mathrm{deg}$	{Design parameter}
Compute min elevation angle	$\varepsilon := 90\mathrm{deg} - IA$	$\varepsilon = 20\,\mathrm{deg}$
Compute sensor look angle (nadir angle)	$\eta := \mathrm{asin}(\cos(\varepsilon)\cdot\sin(\rho))$	$\eta = 48.164\,\mathrm{deg}$
Compute max ECA	$ECA_{max} := 90\mathrm{deg} - \eta - \varepsilon$	$ECA_{max} = 21.836\,\mathrm{deg}$
Compute slant range	$R_s := R_E \cdot \left(\dfrac{\sin(ECA_{max})}{\sin(\eta)}\right)$	$R_s = 3.184 \times 10^{3}\,\mathrm{km}$
Find swath width (deg)	$Swath := 2 \cdot ECA_{max}$	$Swath = 43.672\,\mathrm{deg}$
(m)	$Swath\_m := 43.672 \cdot \left(R_E \cdot \dfrac{PI}{180}\right)$	$Swath\_m = 4.859 \times 10^{6}\,\mathrm{m}$

Step 3. Define Pixel Parameters and Data Rate

Specify max along-track ground sampling distance	$Y_{max} = 0.955\,\mathrm{m}$	{Design parameter}
Determine IFOV	$IFOV := \dfrac{Y_{max}}{R_s}$	$IFOV = 1.7193 \times 10^{-5}\,\mathrm{deg}$
Find max cross-track pixel resolution	$X_{max} := \dfrac{Y_{max}}{\cos(IA)}$	$X_{max} = 2.794\,\mathrm{m}$
Determine cross-track ground pixel resolution at nadir	$X := IFOV \cdot h \cdot \dfrac{\pi}{180\mathrm{deg}}$	$X = 0.5\,\mathrm{m}$
Determine along-track pixel resolution at nadir	$Y := IFOV \cdot h \cdot \dfrac{\pi}{180\mathrm{deg}}$	$Y = 0.5\,\mathrm{m}$
Determine # of cross-track pixels	$Z_c := \dfrac{2 \cdot \eta}{IFOV}$	$Z_c = 5.603 \times 10^{6}$
Find # of swaths recorded along-track in 1 second time	$Z_a := \dfrac{V_g}{Y} \cdot 1s$	$Z_a = 1.116 \times 10^{4}$
Find # of pixels recorded in 1 sec	$Z := Z_c \cdot Z_a$	$Z = 6.254 \times 10^{10}$
Specify # of bits used to encode each pixel	$B = 8$	{Design parameter}
Compute data rate	$DR := Z \cdot B$	$DR = 5.003 \times 10^{11}$ bps

Step 4. Define Sensor Optics

Specify # of pixel lines for imager	$N_m = 5 \times 10^3$	{Design parameter}
Specify width for square detectors	$d = 7 \times 10^{-6}\,m$	{Design parameter}
Specify quality factor for imaging	$Q = 1$	{Design parameter}
Specify operating wavelength	$\lambda = 9 \times 10^{-7}\,m$	{Design parameter}
Define focal length	$f := \frac{h \cdot d}{X}$	$f = 23.328m$
Find diffraction-limited aperture diameter	$D := \frac{2.44\lambda \cdot f \cdot Q}{d}$	$D = 7.318m$
Compute F-number of optics	$F_{num} := \frac{f}{D}$	$F_{num} = 3.188$
Compute FOV of optical system	$FOV := IFOV \cdot N_m$	$FOV = 0.086\,deg$

1 deg FOV on surface at altimeter 1669.219 km: 28.799 km

$FOV\_km := 0.086 \cdot 28.799$

$FOV\_km = 2.477\ km$

Step 5 . Define Data Link Capacity

Rmax : Data link capacity

B : Bandwidth

C/N : Carrier to noise power ratio

For TDRS= Rmax = 800 Mbps

B = 650 MHz

Rmax = B*log $_2$(1+C/N)

C/N = 1.346 dB

For Skybridge= B = 2 Ghz

For our system= B = 2 Ghz (sampling from Skybridge)

C/N = 1.346 dB (sampling from TDRS)

Rmax =2.5 Gbps

After lossless compression of 5 to 1 ratio

Data downlink delay = $\frac{500.3}{5 \cdot (2.5)} = 40.024$ sec

Although the above chart is especially designed to calculate the optical features of a satellite sensor; it is somehow applicable for UAV sensors. The most significant difference is lack of orbital parameters for a UAV, since it doesn't have an orbital navigation like a satellite. Therefore we didn't use same formulas to calculate ground velocity (V_g) of UAVs. We assumed the velocity of a Global Hawk as 360 km/h depending on its cruise speed of 350 miles/h, and used the same formulas to calculate its data rate, downlink delay, LOFOV, aperture diameter, and resolution; because we didn't have an accurate velocity value.

High-resolution optical instruments typically generate data sizes on the order of several hundred Mbps and above. To send this data stream to a ground station in real time, the system may need high capacity downlink channels. Data processing can reduce the data rate by a factor of 3 to 10 or more by compression, depending on the nature of the data. As seen in Table 4-5, data downlink capacity of 2.5 Gbps is designed by sampling from current systems; data downlink delay is reduced by the help of data compression techniques. The required data to design our own data link is provided from two well-known constellations of TDRS and SKYBRIDGE; since they were the most capable ones in their areas. TDRS is capable of 800 Mbps Downlink capacity with 650 Mhz of bandwidth, which ends up with a carrier to noise ratio (C/N) of 1.346 dB. However this bandwidth was not the largest one that is currently used. Assuming that we can use 2 Ghz bandwidth alike SKYBRIDGE, and 1.346 dB C/N alike TDRS; we calculated the capacity of our direct link to the ground station, which is 2.5 Gbps. The image taken by the satellite sensor used in the example has a data rate of 5.003×10^{11} bps that is compressed onboard with a technology of 5 to 1 lossless ratio and sent to the ground station with a delay of 40.024 sec using our new designed downlink.

Resolution gets better when the sensor looks at the points closer to the Sub-satellite Point (SSP), which means larger elevation angle. However, this will cause smaller field of view area on the ground surface. Working in a very small region directly under the spacecraft provides very poor coverage but excellent mapping accuracy and resolution. On the other hand, working near the horizon provides very broad coverage but poor mapping accuracy. We used a minimum elevation angle of 20 degrees in our design, which usually provides good resolution and enough FOV. Also it is strictly required in the mission statement.

As stated in our requirements, the designed system is to offer continuous daylight coverage. In continuous it is mentioned that the satellite or the UAV will have the ability to send different image data in every second alike a live connection. The biggest restriction of continuous coverage is the limited capacity of downlink, which usually causes some delays in sending the data to the ground stations. High quality and large pictures have higher data rates, which result with higher downlink delays. The satellite of an alternative with 50 seconds delay can send only one picture in every 50 seconds. It doesn't take another picture at that time, since that will overfill the satellite memory. This is a challenging trade-off between better resolutions, larger coverage area, and smaller downlink delay.

The wavelength used for catching the images also has an important role in defining the resolution. As seen in Table 4-5, the higher wavelength we use, the worse resolution we get. We preferred to use a wavelength of 0.9 microns, which provides the required resolution in feasible aperture and altitudes. The Ikonos satellite that we sampled in many ways also uses same wavelength.

Table 4-6 Wavelength Comparisons
(3: 265)

Altitude H	Aperture Size D	Visible (λ =0.5 μm)	IR (λ =3 μm)	Passive Microwave (λ =3 cm)
900 km	1 m 3 m	11 m 0.366 m	6.59 m 2.2 m	65.9 km 22 km
35,800 km	1 m 3 m	43.7 m 14.6 m	262 m 87.4 m	2,620 km 874 km
20 km	0.3 m	0.081 m	0.488 m	4.88 km

The larger the image, which means a long length of FOV, the higher the data rate. Either smaller image continuously or larger image with a reasonable delay can be sent to ground station from the satellite.

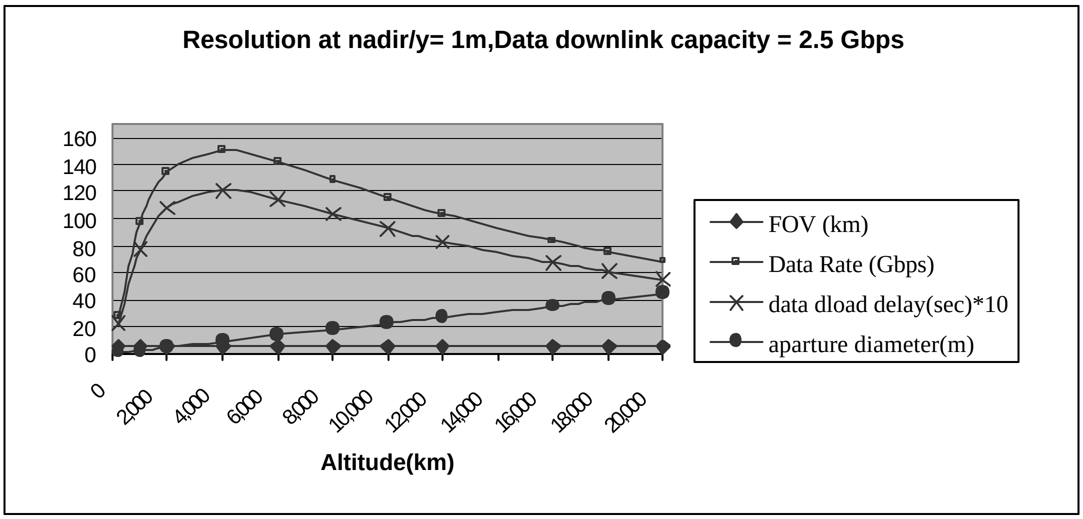

Figure 4-13 Changing altitudes – Constant resolution

The relationship of data rate, downlink delay, aperture diameter and length of FOV to rising altitude can be seen in the Figure 4.13, in which resolution at nadir has a constant value of 1 m. FOV on the ground is not changing with the altitude; since aperture diameter of the sensor is to be increased by arranging the focal length. Data rate and downlink delay shows a decreasing tendency after 4000 km contrary to before, as a result of cross-related formulas. While calculating data rate of an image in an altitude with a predefined resolution, number of cross-track pixels (Z_c) is calculated in advance. s t is seen in Table 4-5 the nadir angle(η) and slant range(R_s) values have a direct proportional impact on Z_c. With the rising altitude, the nadir angle gets smaller and slant range gets larger. In spite of smaller nadir angle, the rising slant range value causes a rising data rate value up to approximately 4000 km. But after this altitude the rising R_s value loses its dominance on decreasing η value; which causes a decreasing data rate value relative to the preceding altitudes.

In a constant altitude, the desire of better resolutions causes a narrower FOV, higher aperture diameter, higher data rate and delay proportionally. It can be seen both in Figure 4-14 (for satellite) and Figure 4-15 (for UAV), in which data downlink rate is 270 Mbps.

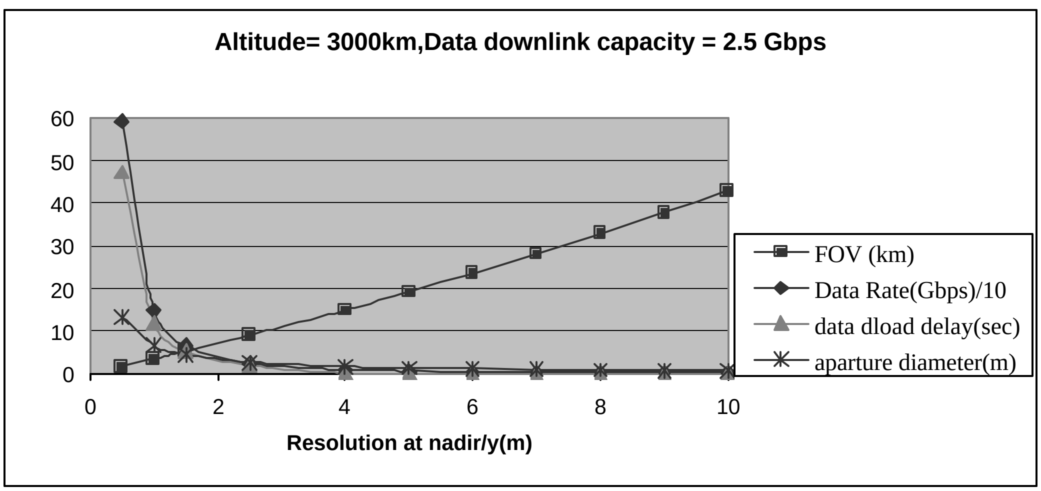

Figure 4-14 Changing resolutions – Constant altitude (for satellite)

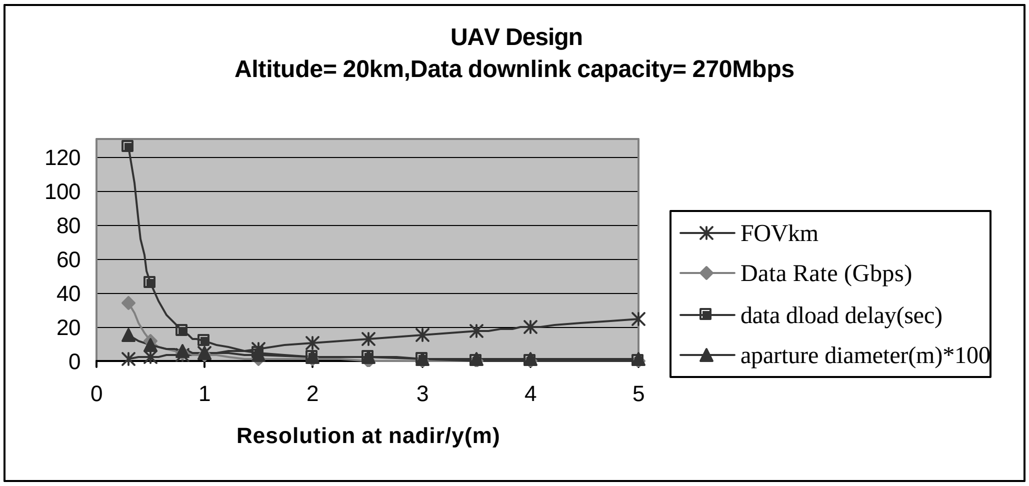

Figure 4-15 Changing resolutions – Constant altitude (for UAV)

Resolution at nadir decreases significantly when the aperture diameter increases at the same altitude. It is significant in the Figure 4.16 that there is a quick drop in resolution from 14.64 m to 4.88 m when the aperture diameter size is increased from 1 m to 3 m. But this dropping tendency is relatively slow after 5 m aperture diameter size. However larger aperture will cause more weight and require more power for payload, and will end up with a higher cost. In addition, launch vehicle volume capacity is an important issue that will limit the size of aperture. Inflatable technology can be used to eliminate this restriction.

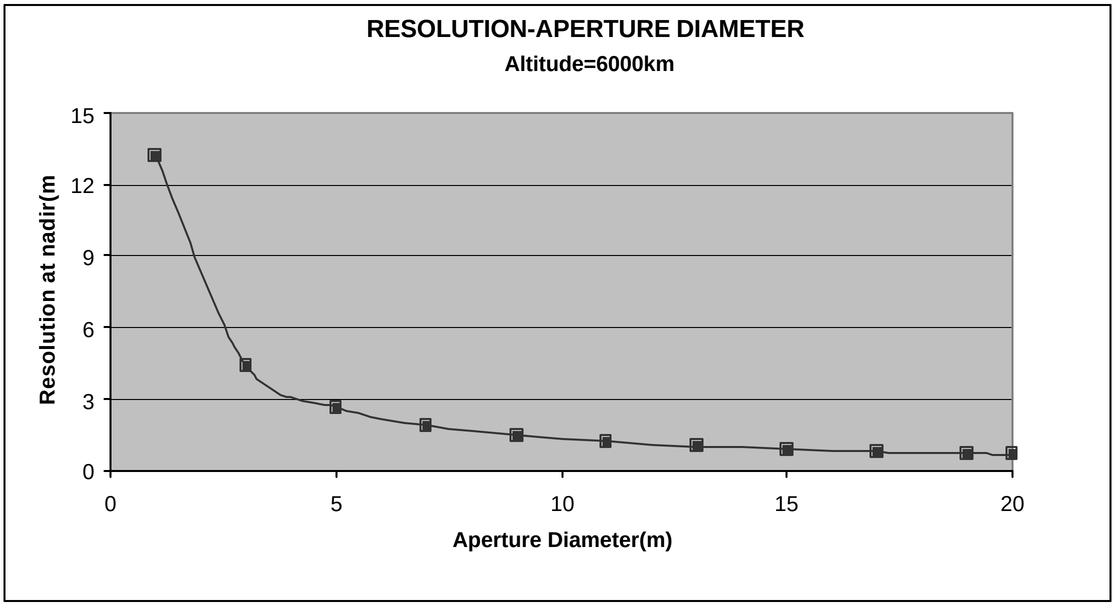

Figure 4-16 Resolution- Aperture Diameter

As seen in Figure 4.17 and Figure 4.18, the resolution gets worse at the moment that we raise the satellite to higher altitudes in order to get larger FOV area using the same aperture size. Using a sensor with a larger aperture diameter will be the most important factor to improve the resolution; however it will have a higher cost.

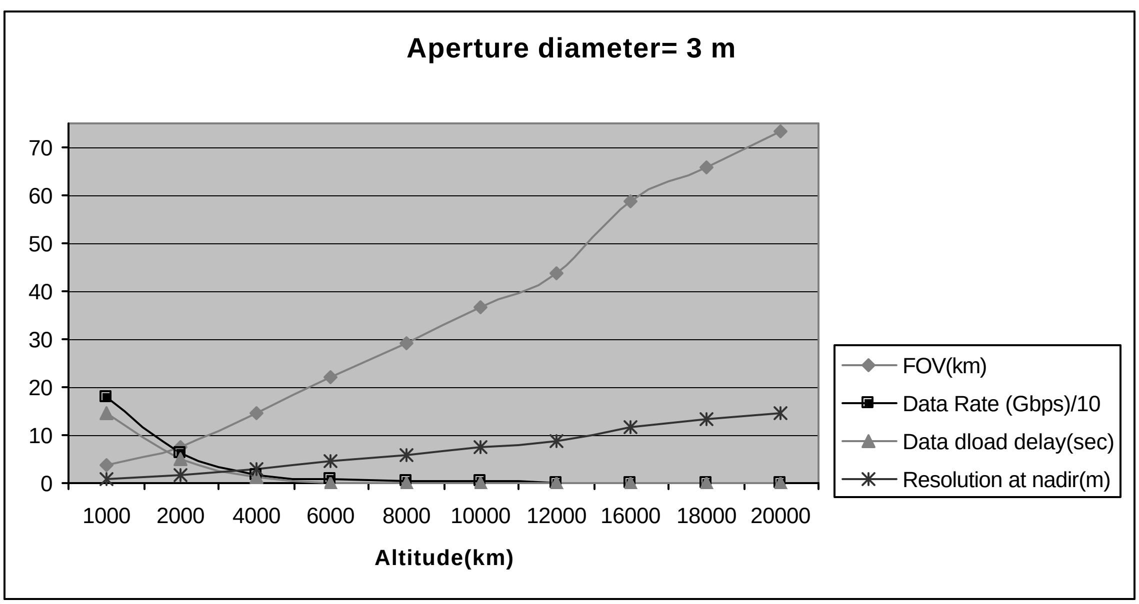

Figure 4-17 Changing resolutions and altitude for 3 m diameter

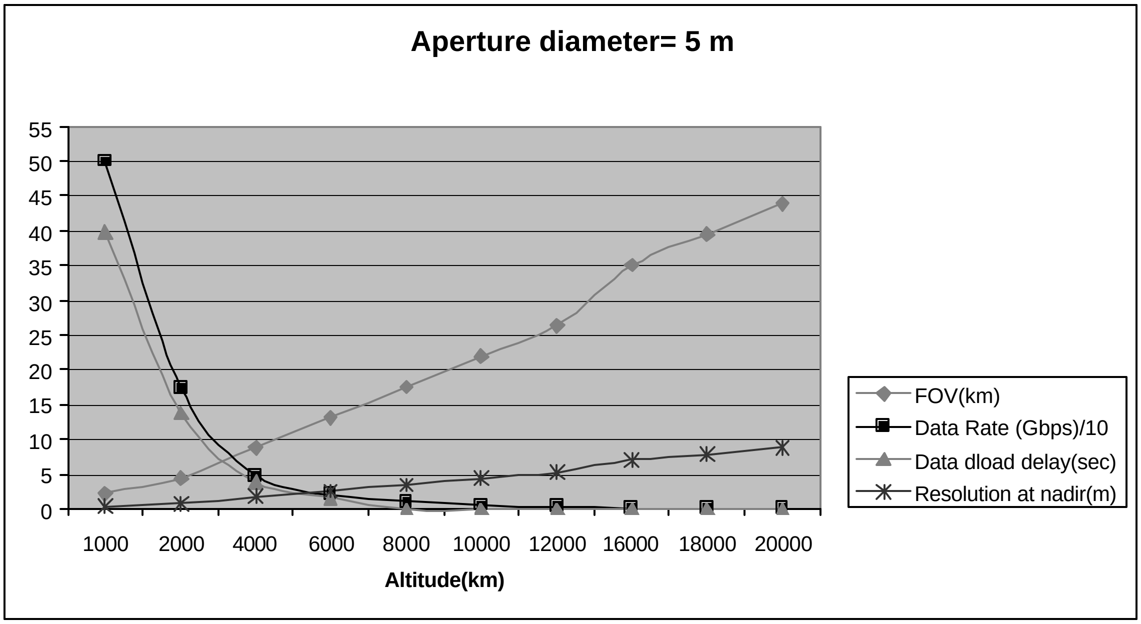

Figure 4-18 Changing resolutions and altitude 5 m diameter

The above figures show that the need of required resolution forces us to define our alternatives in the 1000-3000 km alternative range. Even in that feasible area, it is not possible to get 1 m resolution with a desired FOV and Downlink Delay using a small sized aperture. As it is stated in the following paragraphs, considering the weight and cost issues we had to look different combinations of our alternatives.

Recall from the requirements documents that mission coverage requirement was 12 hours with 1-meter resolution. The emphasis of mission being cost competitive was mentioned in the mission need statement. We are going to try to verify if we can really accomplish these tasks with current technology and then analyze the results to come up with a feasible solution.

Table 4-7 Payload Data

Altitude (km)	1 m Resolution		5 m Resolution	
	Aperture (m)	Focal Length (m)	Aperture (m)	Focal Length (m)
1666	3.66	13.33	0.73	2.67
2705	5.94	21.65	1.19	4.33
3366	7.39	26.94	1.48	5.39
4162	9.14	33.30	1.83	6.66
5144	11.30	41.15	2.26	8.23
6391	14.03	51.13	2.81	10.23
7762	17.05	62.10	3.41	12.42
10354	22.74	82.83	4.55	16.57

As seen in Table 4-7 when altitude increases for a fixed resolution, the diameter and focal length required resolving also increases. For a fixed altitude, as resolution increases diameter and focal length decreases almost linearly. As resolution is raised to 5 meter from 1 meter, diameter and focal length decreases approximately 5 times. Since focal length can be folded we will talk about diameter and spacecraft dimensions for now.

Now let's look at an altitude and see if we can satisfy our requirements without forcing the boundaries of feasibility. Let our altitude pick be 2705 km. At 2705 km, for 1-meter resolution the diameter is 5.9 meters. The diameter number is a quite big number comparing with the existing commercial imaging systems and available launch systems. For example, Ikonos has an aperture diameter about 1-1.5 meters (32). As the diameter increases the mass to be launched into orbit also increases. Due to huge mass of the payload and therefore the total spacecraft, we are going to launch our system with space shuttle which are 1552 kg and 9500 kg respectively (1:285,312) According to launch mass capabilities of the existing launch vehicles 9500 kg is off limits for an altitude of 2705 km (1:802) Space shuttle has a cargo bay of 60 ft (approximately 20 meters long), 15ft (approximately 5 meters) in diameter where the height of the spacecraft 8.26 meters and aperture diameter is 5.94 meters.(20)

So, even if we will be able to build a high-resolution design, we won't be able to launch it to altitudes higher than LEO.

With these feasibility concerns in mind, there is an answer to this question of dimensions and launch system limits, which is referred to as inflatable technology. As mentioned in the previous chapters inflatable technology is a new technology that is still being experimented. This implies the performance and schedule risks associated with the new inflatable technology. Since it has not been used practically and widely in the industry it is also an expensive technology too. From SMAD's cost model (Appendix A) due to high technologic inheritance number for inflatable structures they cost three times the rigid- structure payloads and we immediately lose the cost competitiveness with the existing imaging systems. From SMAD's cost model, rigid-structure costs about $105,000(FY00$K) and inflatable-structure payload cost about $350,000(FY00$K).

At this point of the analysis, these are our options to proceed with:

1. Proceed with inflatable technologies, take high risk and pay 3 times more money than equivalent rigid-structure payloads and satisfy 1-meter resolution and 12 hour coverage requirements. Recall from VSD that cost is the most important parameter with percentage of 30, where resolution and coverage are 24% together. So, this seems like a really expensive and risky option.

2. Select lower mission altitudes. In this option, we get 1-meter resolution but to accomplish a 12-hour coverage we need 30-40 spacecraft, which drives the cost high. Even to get 6 hours coverage, which is our threshold for coverage parameter, we need 12 to 20 spacecraft depending on the altitude and cost is still high.
3. Select a lower altitude and use few spacecraft. This is a low cost option and we can satisfy 1-meter resolution. However, we cannot accomplish 6-hours coverage, which is our threshold for coverage parameter.
4. Use one of the mission altitudes above, get 12-hour coverage but give up on resolution requirement. Require a payload with a resolution more than 1 meter so we do not have deal with high cost and risks of inflatables or worry about the dimensions of the payload or spacecraft or limits of launch vehicles.
5. Analyze other means of imaging. UAVs or combinations of UAVs and satellites.

As a conclusion, we cannot satisfy the low cost, 1-meter high resolution and 12-hour coverage requirements altogether with satellites. We have to consider another means of imaging which will enable us satisfy all of the mission requirements. These might be UAVs or satellite and UAVs together. In the next chapter, we will analyze all of these alternatives including satellites, small satellites, UAVs, satellite&UAVs and small satellite&UAVs.

4.4.6 Availability of Different Alternative Concepts

One of the requirements of the user is " *The system availability should be at least 98 %*". To be able to meet this requirement, the term of availability must be first well defined.

A request or more requests from the customer or customers may come anytime through the lifetime of the system, and this request can be fulfilled only if the system is available. Availability is defined herein as the time portion in which the system is available to serve customers.

The system availability includes more than one factor, which are responsible only for a part of the total system availability. However, failures of any of them will make the whole system unavailable. From receiving the image request to delivering to customer, the success of this process depends on the success of each factor.

In this system design project, availability has three main parts: reliability of the system, time to go over target, and downlink from satellite/UAV to ground station. In our thesis, we assumed that image delivery time from ground stations to customers are the same for all alternatives.

4.4.6.1 *Reliability*

The reliability issue plays an important role in the availability of a system. To be available at a specific time, the system should first be working properly at that time.

As a definition, reliability is "The probability that a device will function without failure over specified time period or amount of usage." (11: 765) In this project, "without failure" is interpreted as "without failure that impairs the mission", and it defines *mission reliability.*

The process for designing mission reliability of a system requires assembling program data concerning mission and performance requirements, anticipated environments, and mission reliability. A reliability estimate should be made for each item of equipment independent of completing the initial apportionment. (4) However, in our design project, calculation of the reliability will be very hard due to difficulty of obtaining proper data for each component in the alternatives. For this reason, we assumed that the reliabilities of all alternatives are equal.

4.4.6.2 *Time to target*

When an image request comes from a customer, or customers, the system may not be ready to meet this request because of the position of the S/C. There is a time interval needed for the S/C to reach over the target whose image is requested. This term defines time between receiving the image request from customer /customers, and beginning the image process by sending the S/C over the target.

Each alternative has different capability of time to go over target due to their features. Our alternatives are mainly derived from three different systems. These three systems are:

a. Satellites
b. Small satellites
c. UAVs (Helios and Global Hawk)

To be able meet the daily coverage requirement between 6 am and 6 pm, a properly designed satellite constellation can offer continuous service. Our target area is small enough for one satellite to see the whole target area at a time, and a satellite can provide a requested image just by moving its spot. Because of this reason we accepted that satellites are always over the target, and Time to Target for satellites alternatives 0 which makes its utility is 1.

The similar situation is also correct for alternatives containing small satellites. The other advantage of small satellites is their high number in the constellation. These features make Time to Target of small satellites 0, which means their utility is 1.

In the alternatives with UAVs, the issue of time to go over target is different from satellites and small satellites alternatives. UAVs are different from satellites flying over the interest area continuously. Once an image request from customer is received, they are sent to the target area, and Time to Target for UAVs is measured as average time period between take-off and arrival to the target area. In our project, we will calculate Time to Target by taking the furthest distance that UAVs will have to fly and dividing it by average speed of the UAVs. These are the two issues that specify Time to Target for UAVs as a part of their availabilities, and also their utilities.

4.4.6.3 *Data Downlink Size and Downlink Delay*

One of the important issues in specifying the availability for a system is downlink speed and capacity. System could be functioning properly and over the target at the given time, but depending on the details of the requirement of customer, it should have enough downlink speed and capacity to be able to meet the customer's requirement. These qualities are also important to increase the probability of servicing more then one customer in a short time.

Alternative design concepts consist of mainly two components: satellites, either classical satellites or small satellites, and UAVs. Each alternative has different data rate and data downlink delay.

Table 4-8 Data rates of Alternatives

Alternative	**Data Downlink Capacity**
Satellite	2.5 Gbps
UAV's	270 Mbps

Data downlink delay is the other issue creating the availability of a system, and depends on the data downlink rate. The response of the data downlink delay to the downlink rate can be observed in the Figure 4-19, which resolution at nadir has a constant value of 1 m and altitude is 1000 km, downlink delay is decreasing with the increasing of the downlink rate. The decrease of delay for downlink data rate capacity until approximately 0.5 Gbps is quicker than other downlink data rate values.

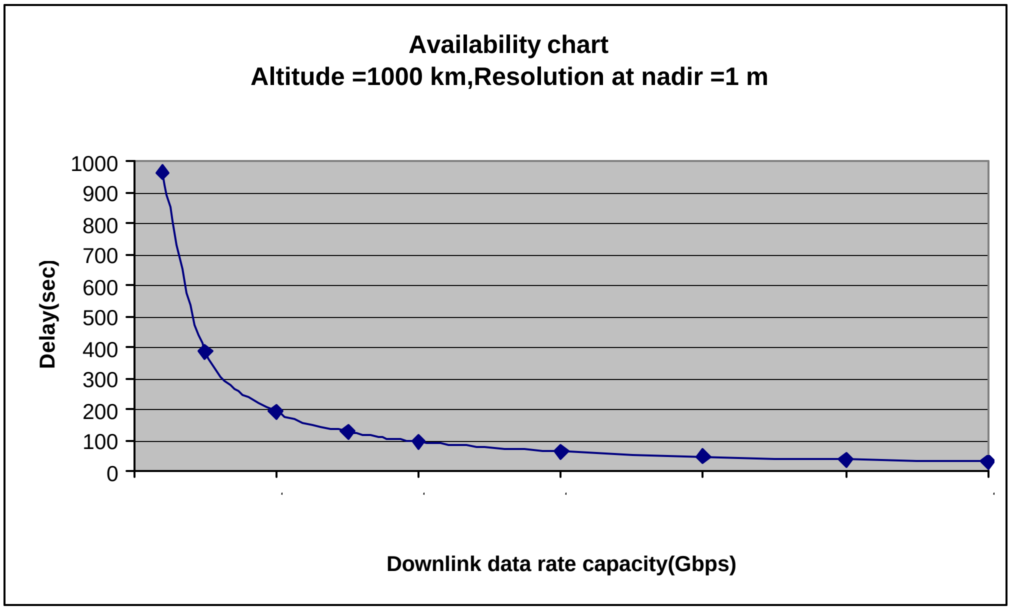

Figure 4-19 Effects of Downlink data rate capacity on the download delay

Although data downlink rate capacities for satellites design and UAV design are very different, altitudes where these systems positioned have a significant influence on their data rate and data downlink delay. In the Figure 4-20 and Figure 4-21, effects of altitude on the data rate and data downlink delay for both designs are shown in the 1 m resolution at nadir and with each downlink capacity.

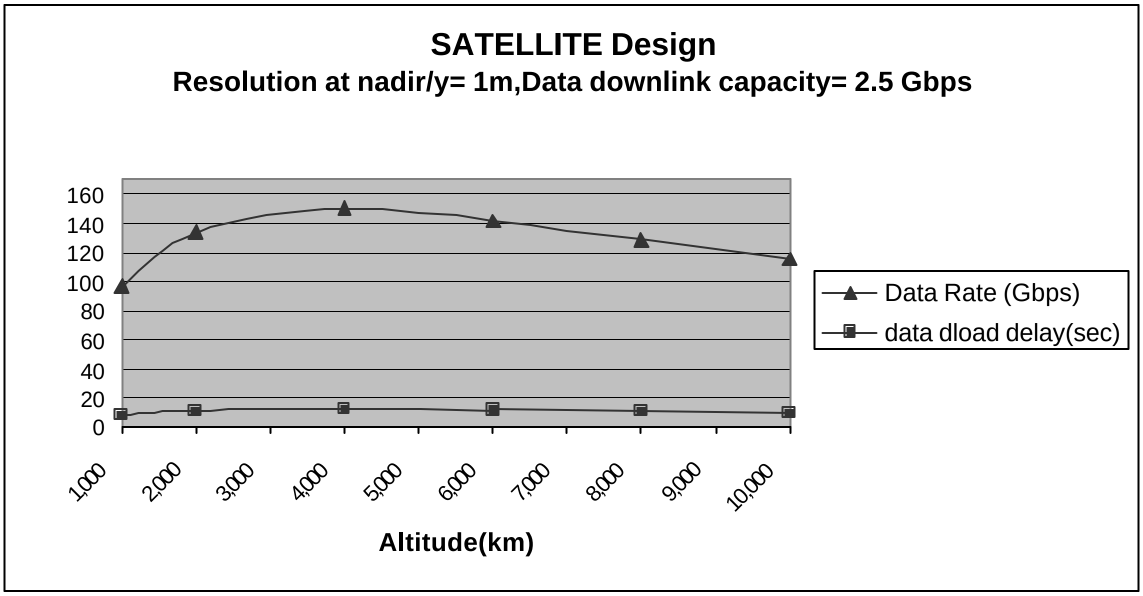

Figure 4-20 Changes of data rate and delay with altitude for Satellite design

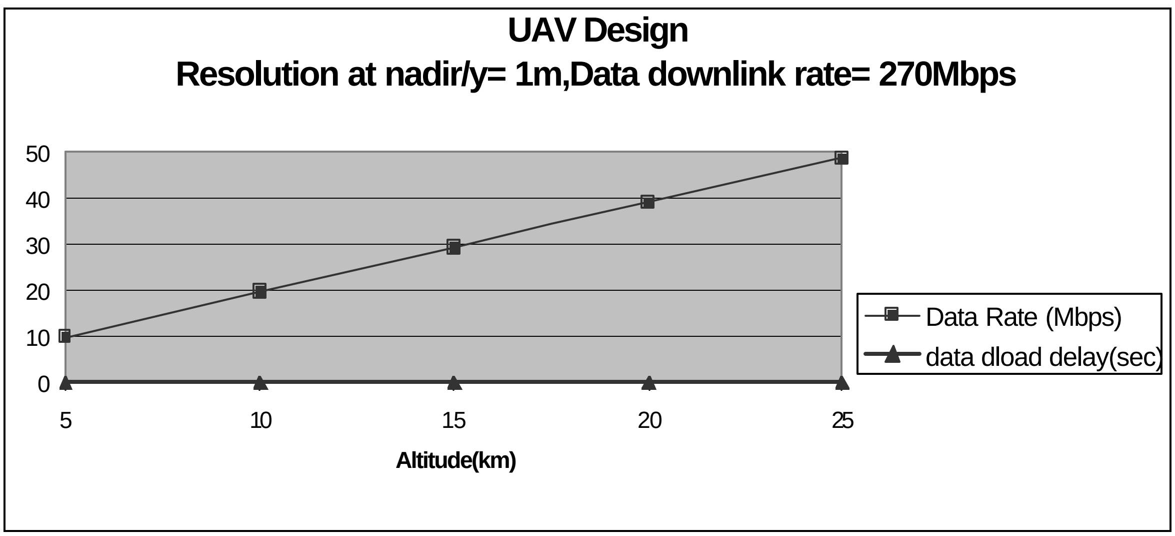

Figure 4-21 Changes of data rate and delay with altitude for UAV design

For satellite design, between 1000 km and 4000 km data size is increasing, and then decreasing after an altitude of 4000 km. For UAVs design, data size is increasing steadily with altitude. However, data size for satellite design is fairly larger than data size for UAVs design, even the smallest number in the satellites is much bigger than the biggest of UAVs.

For satellites, downlink delay does not show big variations, generally between 10 and 15 seconds for referenced altitudes in the figure. However, unlike data size, data downlink delay of UAVs is 0 delay for each altitude points.

The reason for 0-data download delay of UAVs is their speed. The average speed of UAVs is 360 km per hour, and it is slow enough to fly over the target and to download data without any delay.

Satellites and UAVs have different advantages in the issues of data size and data downlink delay. For the data size aspect, satellite design is much more advantageous than UAVs due to its higher data size, almost 12 times larger than UAVs. For the data downlink delay aspect, UAVs design with 0-downlink delay gives better solutions than satellites. 0-data downlink delay makes the utility of UAVs in the system design is 1.

As a result, satellites with higher data downlink size capability can provide images with higher resolution and serve more customers than UAVs do, and they will have an amount of data downlink delay accepted by the customers. On the other hand, UAVs can serve the customer with no delay, but will not have the capability of downloading large data size as satellites when requested by the customers.

Chapter 5 - Alternatives

5.1 Chapter Overview

This chapter consists of definition and analysis of alternatives.

5.2 Define Alternative Mission Concepts

This study will analyze five groups of system level alternatives for this particular problem. These alternatives are satellites only, small satellites only, UAVs only, satellites plus UAVs and small satellites plus UAVs. Satellite alternatives consist of conventional satellites and satellites with inflatable technologies. UAV alternatives consist of conventional UAVs (Global Hawk was chosen as baseline design UAV) and solar-powered UAVs like Helios.

5.2.1 Satellites

Satellite alternatives consist of conventional satellites with rigid structures and satellites with inflatable structures. With conventional satellites and rigid structures there is a diameter limit that can be launched due to weight limitations of launchers. However, since inflatable structures are expected to allow launching larger diameter mirrors into orbit a range of altitudes from about 275 km to 40000 km were taken into consideration in our analysis. Diameters of optical systems to be able to acquire certain resolutions are calculated from Eq. 4-1, which is repeated here for convenience:

Equation 5-1 $R = 2.44h\, l/D$ [SMAD EQ. 9-10, SAYFA 264]

Size, weight and power of the new design are estimated using the estimating method presented in Table 5-1 where A_i is the required aperture of the new instrument and A_o is the aperture of a similar instrument. Ikonos satellite is taken as the “Existing System”. After estimating size, weight and power of the new design satellite cost of the system is calculated using satellite cost model in SMAD. Calculation of diameters and estimation of size, weight, power and cost are shown in Appendix B.

Table 5-1 Scaling from existing system (3:285)

Aperture Ratio = R = A_i / A_o
Linear Dimensions = L_i = R * L_o
Surface Area = $S_i = L_i^2$
Volume = $V_i = L_i^3$
Weight = W_i = K * R^3 * W_o
Power = P_i = K * R^3 * P_o

5.2.1.1 Orbit Type and Altitude Selection

One of the requirements for the mission is continuous coverage during daylight hours (6am-6pm local time). The hours that the target area is covered shift along the year due to J2 perturbations and earth rotation around sun. For example, let's assume that a constellation can cover the target area for 8 hours, Its coverage hours are from 04:00 – 06:00, 08:00-10:00, 12:00 – 14:00 and 16:00 – 18:00. Note that daylight hour coverage is 6 hours. Due to J2 perturbations and earth rotation around the sun couple months later these hours shift and become 01:00 – 03:00, 05:00 – 07:00, 09:00-11:00 and 13:00 – 15:00. The constellation still covers the area for 8 hours but daylight coverage hours drop to 5 hours. To avoid this we have to either compensate for J2 perturbations by thrusters which mean extra fuel and extra cost and most of the time makes the system infeasible or select sun-synchronous orbits like many optical reconnaissance systems. Even though we considered inclinations from 0 degrees to 180 degrees (0, 45, 97, 116.6, 125 and 180 degrees) after calculations of fuel requirements we were constrained to certain type of orbits. Since we are dealing with a regional application we decided to design our orbits as sun-synchronous and repeating ground track orbits. Satellites will be passing over the same area at approximately same local time, with same sun angle without spending extra fuel. This is good for both picture quality and coverage. With these in mind, some different orbit types with relatively small J2 perturbations are kept for comparison reasons and compensated for J2 perturbations.

Table 5-3 basically gives all of our final satellite only alternatives. First four columns are period, eccentricity, altitude and inclinations of the alternatives, which form the general orbital characteristics of our alternatives. Fifth column is number of satellites which will determine the coverage hours for the same orbital characteristics. Altitude of 275 km was eliminated and is not in Table 5-3 due to very short lifetime of space vehicles at that altitude. (1:BACK COVER) Alternative at 880.5988 km has a very high cost due to high number of satellites required to cover the target area for only 6.39 hours [FROM STK]. Alternatives above 10000km altitude require large antenna diameters and due to increased risk and low engineering heritage (reflected as high heritage values in our cost model) cost more than the other alternatives with approximately same coverage hours. So alternatives at altitudes mentioned above will not be analyzed in detail and are eliminated at this level.

Table 5-2 Heritage Cost Factors

(3: 798)

Multiplicative Factors for Development Heritage (Apply to RDT&E Costs Only)	
New Design with advanced development	> 1.1
Nominal new design – some heritage	1.0
Major modification to existing design	0.7 – 0.9
Moderate modifications	0.4 – 0.6
Basically existing design	0.1 – 0.3

As mentioned above, we were able to enlarge the range of altitudes we can launch the high resolution payload utilizing inflatable technologies which provide reduction in weight, size and cost when compared to existing systems. However, since it is a new technology there are performance and schedule risks associated with it.

The satellite only alternatives included all satellites in one orbit serving only one simultaneous customer for 12 hours with fixed resolution at the same altitude, satellites in more than one orbits serving more than one simultaneous customers for couple hours with fixed resolution at the same altitude, satellites at different altitudes with different resolutions. After analysis results indicated that the competitive satellite only alternatives are alternatives with reduced resolution and high coverage hours (between 6 and 12 hours) serving one or two simultaneous customers which implies the lowest cost. So, our final alternatives are in Table 5-3.

Table 5-3 Final Satellite only (FSO) Alternatives

	Period (min)	**Eccentricity**	**Altitude (km)**	**Inclination (deg)**	**# sat**
ALT FSO-1	119.6723	0(s-s)*	1666.219	102.89	6
ALT FSO-2	119.6723	0(s-s)*	1666.219	102.89	8
ALT FSO-3	119.6723	0(s-s)*	1666.219	102.89	10
ALT FSO-4	119.6723	0(s-s)*	1666.219	102.89	12
ALT FSO-5	143.6068	0(s-s)*	2705.881	109.96	2
ALT FSO-6	143.6068	0(s-s)*	2705.881	109.96	3
ALT FSO-7	143.6068	0(s-s)*	2705.881	109.96	4
ALT FSO-8	159.5631	0(s-s)*	3366.878	115.88	2
ALT FSO-9	159.5631	0(s-s)*	3366.878	115.88	3
ALT FSO-10	159.5631	0(s-s)*	3366.878	115.88	4
ALT FSO-11	179.5085	0(s-s)*	4162.91	125.07	2
ALT FSO-12	179.5085	0(s-s)*	4162.91	125.07	3
ALT FSO-13	179.5085	0(s-s)*	4162.91	125.07	4
ALT FSO-14	205.1526	0(s-s)*	5144.307	141.7	2
ALT FSO-15	205.1526	0(s-s)*	5144.307	141.7	3
ALT FSO-16	205.1526	0(s-s)*	5144.307	141.7	4
ALT FSO-17	239.3447	0(s-s)*	6391.405	92	2
ALT FSO-18	239.3447	0(s-s)*	6391.405	92	3
ALT FSO-19	179.5	0.3415(s-s)*	7762.185	116.6	2
ALT FSO-20	179.5	0.3415(s-s)*	7762.185	116.6	3
ALT FSO-21	179.5	0.3415(s-s)*	7762.185	116.6	4
ALT FSO-22	359.017	0	10354.065	92	2
* s-s : sun-synchronous orbit					

Figure 5-1 is a figure of change in cost, risk, resolution (res), coverage area (cov) and width of our target area (cov required) as altitude increases. To be able to depict all parameters in the same value range, parameter values are divided by appropriate numbers. For example, coverage area for 2700 km is about 2500 km x 2500km is divided by 1000 to decrease its value between 0 and 2.5. Same procedure is applied for all parameters.

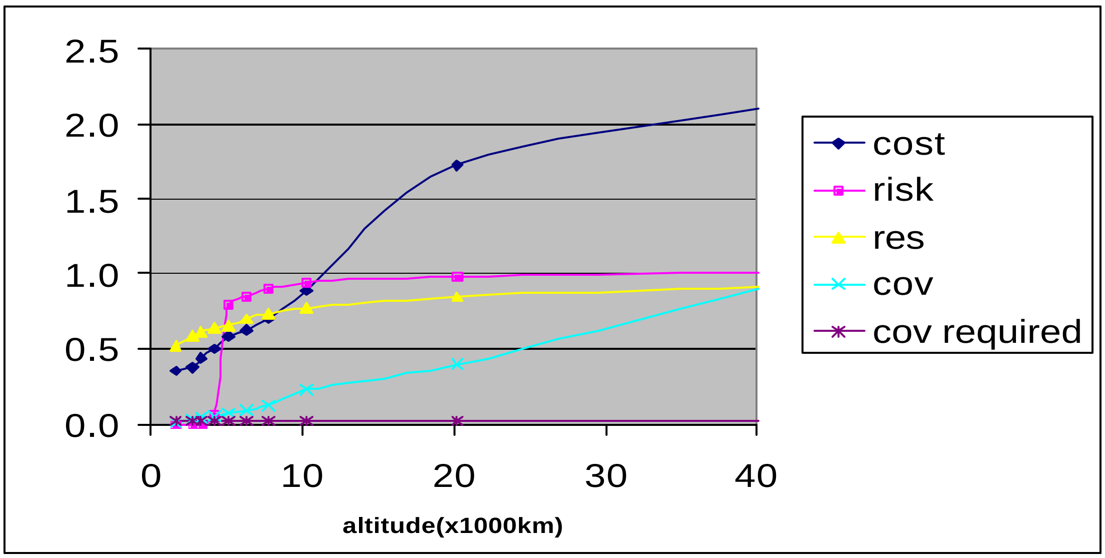

Figure 5-1 Altitudes – Drivers

Cost is increasing rapidly as altitude increases. The reasons are increasing mirror diameter for 1-meter resolution, after certain altitudes inflatable technology is used and it introduces high engineering heritage values, which imposes higher cost.

Risk remains constant for a while and then increases rapidly. The reason is that inflatable technology has to be used after a certain altitude in order to overcome launch weight limitations and since the technology has not been utilized practically it introduces performance and schedule risks.

Resolution values are getting bigger in value (getting worse) as altitude increases meaning that as the distance from the target increases resolution value gets bigger which implies that more money should be invested to get the same resolution when getting into higher altitude orbits.

Coverage is also increasing as altitude increases. Satellite can cover more area as it flies into higher orbits. However, the width of our target area is about 2400km and after about 2500km altitude the coverage area exceeds 2400km. The excess area has low or no value in this kind of regional applications.

Let's review what we want from our system: low cost, low risk, high resolution, and ability to cover the target area. When we look at the Figure 5-1 carefully, one notices that altitudes 5000km seem to satisfy our requirements.

5.2.2 Small Satellites

Table 5-4 Initial Small Satellite (ISS) Alternatives

	Period (min)	**Eccentricity**	**Altitude (km)**	**Inclination (deg)**	**# sat**
ALT ISS-1	102.5763	Circular sun-synchronous	880.5988	98.96	40
ALT ISS-2	102.5763	Circular sun-synchronous	880.5988	98.96	40
ALT ISS-3	119.6723	Circular sun-synchronous	1666.219	102.89	6
ALT ISS-4	119.6723	Circular sun-synchronous	1666.219	102.89	8
ALT ISS-5	119.6723	Circular sun-synchronous	1666.219	102.89	10
ALT ISS-6	119.6723	Circular sun-synchronous	1666.219	102.89	12

Small satellites can be launched up to certain altitudes and usually have shorter lifetimes. In this study, small satellites are assumed to be able to launch up to 1700 km.

Since mission requires acquiring and processing high-resolution imagery same payloads are used in small satellites as in large satellites so there is not a great cost difference between same altitude, same resolution small satellites and large satellites both having the same lifetimes. However, we can only launch small satellites with imaging payloads that will provide resolution slightly over 2-meters due to their launch mass constraints design characteristics which targets a cheaper satellite than large satellites. Overall cost of small satellite constellations with less than 10 year lifetime is more than the conventional satellite constellation total cost because of re-launches. SMAD small satellite cost model is used to estimate cost of small satellites for this study. (Appendix A).

Altitude of 275 km is eliminated due to very short lifetime of space vehicles at that altitude (1:Back cover). Due to design and launch mass constraints of small satellites we can only design a small satellite with up to 2-meter resolution at 1666.219 km altitude.

Table 5-5 Final Small Satellite (FSS) Alternatives

	Period (min)	Eccentricity	Altitude (km)	Inclination (deg)	# sat
ALT FSS-1	119.6723	Circular sun-synchronous	1666.219	102.89	6
ALT FSS-2	119.6723	Circular sun-synchronous	1666.219	102.89	8
ALT FSS-3	119.6723	Circular sun-synchronous	1666.219	102.89	10
ALT FSS-4	119.6723	Circular sun-synchronous	1666.219	102.89	12

5.2.3 Unmanned Air Vehicles (UAV)

Two kinds of UAV designs are considered to accomplish the regional airborne imaging. First one is conventional UAVs; Global Hawk is taken as a baseline. Second one is solar powered UAVs; Helios is taken as a baseline. Due to security classification of detailed design and cost data on these UAVs, cost models are built with limited data available on mainly web and some published materials. (Appendix A)

Table 5-6 Helios and Global Hawk Cost Model

PARAMETERS	Helios cost(00$K)	Global Hawk cost(00$K)
unit cost	$15,000.00	$14,000.00
# UAV/Ground Station	10/2	10/2
learning curve	0.95	0.95
multiplier	17214.03202	17214.03202
fleet cost	$258,210,480.24	$240,996,448.22
rdte cost*	$50,000.00	$36,000.00
payload cost	$120,477.50	included in unit cost
operating cost*	$1.10	$1.10
ground station	$20,000.00	$20,000.00
cruise airspeed(mph)	22	350
risk	new technology risks	no risk(proven)
flight time	up to 6 months	up to 40 hours
TOTAL COST	**$258,902,757.74**	**$241,373,573.22**

*RDTE cost and operating cost are estimations based on general information about UAVs.

The Table 5-6 gives us cost information, cruise airspeed, risk and total cost for both kinds of UAVs. The resolution and coverage areas are approximately the same so they are assumed exactly same. Helios is representing the solar-powered UAVs and Global Hawk represents conventional tactical UAVs. Cost for both types are calculated for 10 UAVs and 2 ground stations. Helios costs a lot more than Global Hawk and since it is a new technology it has performance and schedule risk associated with it. Furthermore, Helios is approximately 15 times slower than Global Hawk which means that it will take 15 times more hours to reach a target than Global Hawk. So, Helios type solar-powered UAVs are more suitable for a very small area target imaging or regional communications applications. Hence, Global Hawk is chosen to be more satisfactory for our mission and it will be analyzed in detail.

5.2.4 Satellites &UAVs

In this category, due to airspace penetration regulations and limitations UAVs are primarily considered to be tasked over the primary region and satellites over second region with a lower resolution value for cost considerations. Design parameters and cost models mentioned above are used for both systems.

5.2.5 Small Satellites &UAVs

UAVs are primarily considered to be tasked over the primary region and small satellites over primarily second region with a lower resolution value for cost considerations for this group of alternatives. Design parameters and cost models mentioned above are used for both systems.

5.3 Analyze Alternative Mission Concepts

In the process of finding the best alternative we focus on two key parameters: altitude and resolution. The main reason for doing so is almost all of the MOEs are functions of altitude and resolution. Cost, risk, LOFOV, data downlink delay are functions of either altitude or resolution or both. Coverage and number of simultaneous customers are functions of number of air/space vehicles and orbit design and the differences among alternatives are evaluated for each alternative. Upgradeability and time to target are inherent characteristics of systems chosen. We again evaluated the differences in upgradeability and time to target in our value system design. So we first formed a table of varying altitudes for each group of alternatives wherever applicable then we found the optimum resolution for the system at optimum altitude for mission requirements.

5.3.1 Satellites

Here is the table of satellite alternative parameters for 5-meter resolution:

Table 5-7 Satellites Only Alternative Parameters and Scores

	Cost (Million $)	Risk	P. Resolution (m)	S. Resolution (m)	P. Coverage (Hr)	S. Coverage (Hr)	FOV	Dlink delay (Sec)	Upgradability	Time to Target	Simultaneous Customers	Scores
ALT FSO-1	**353.79641**	0	5	5	6.35	6.35	24.76	0	0	0	2	0.604848
ALT FSO-2	**398.34698**	0	5	5	7.22	7.22	24.76	0	0	0	2	0.616953
ALT FSO-3	**442.16326**	0	5	5	7.45	7.45	24.76	0	0	0	2	0.616771
ALT FSO-4	**485.40420**	0	5	5	7.67	7.67	24.76	0	0	0	2	0.616887
ALT FSO-5	**312.03670**	0	5	5	7.38	7.38	24.95	0	0	0	1	0.624975
ALT FSO-6	**345.89640**	0	5	5	10.95	10.95	24.95	0	0	0	1	0.692989
ALT FSO-7	**378.97186**	0	5	5	12	12	24.95	0	0	0	1	0.710681
ALT FSO-8	**351.57970**	0	5	5	8.08	8.08	24.88	0	0	0	1	0.637704
ALT FSO-9	**395.33365**	0	5	5	11.5	11.5	24.88	0	0	0	1	0.698968
ALT FSO-10	**438.13265**	0	5	5	12	12	24.88	0	0	0	1	0.704648
ALT FSO-11	**393.84500**	0	5	5	8.8	8.8	24.92	0	0	0	1	0.645544
ALT FSO-12	**446.52720**	0	5	5	11.8	11.8	24.92	0	0	0	1	0.699916
ALT FSO-13	**498.03543**	0	5	5	12	12	24.92	0	0	0	1	0.698725
ALT FSO-14	**454.48825**	0	5	5	9.3	9.3	25.03	0	0	0	1	0.649264
ALT FSO-15	**521.79678**	0	5	5	11.98	11.98	25.03	0	0	0	1	0.696173
ALT FSO-16	**587.63896**	0	5	5	12	12	25.03	0	0	0	1	0.689948
ALT FSO-17	**565.94238**	0	5	5	8.51	8.51	25.04	0	0	0	1	0.622295
ALT FSO-18	**658.75110**	0	5	5	11.76	11.76	25.04	0	0	0	1	0.675116
ALT FSO-19	**655.28378**	0	5	5	8.4	8.4	24.8	0	0	0	1	0.608035
ALT FSO-20	**815.64934**	0	5	5	9.938	9.938	24.8	0	0	0	1	0.6147
ALT FSO-21	**940.75485**	0	5	5	10.23	10.23	24.8	0	0	0	1	0.601815
ALT FSO-22	**939.02446**	0	5	5	8.96	8.96	25	0	0	0	1	0.576969

After applying value system design to this table we expect to determine the best altitude for satellite only alternatives for a fixed resolution. The most important parameters that will have the most important effect on the result are cost and coverage (primary & secondary). So the real trade-off is between these two parameters.

Figure 5-2 examines the utilities of two critical parameters that can play an important role on determining the best alternative. The winner should be one of the alternatives on the very right edge.

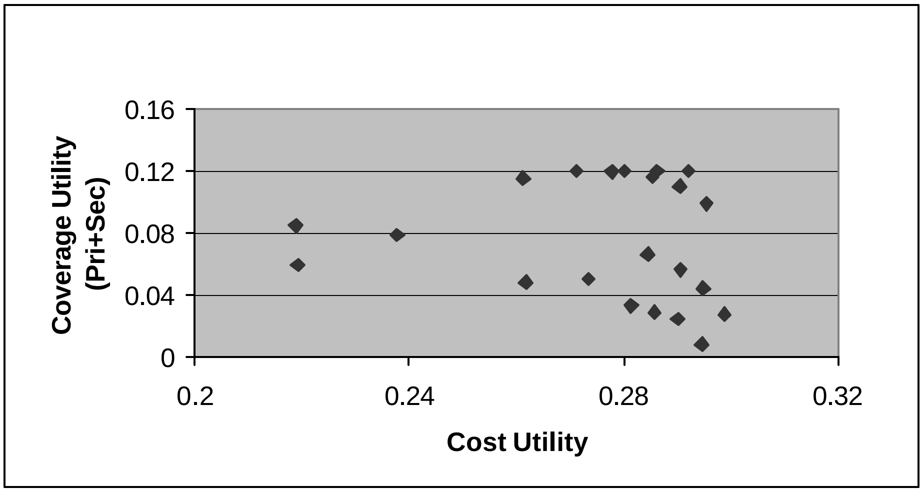

Figure 5-2 Pareto Analyses – Satellite Only

As seen from Table 5-7, Alternative 7 at 2705.881 km altitude with 4 satellites is the best satellite alternative.

The next thing we want to figure out is the best resolution design to proceed with. So, we are going to compare different resolutions at the best alternative's altitude, which is 2705.881 km for our case from Table 5-7. Our analysis showed that this altitude is the optimum for all resolutions ranging from 1 to 5 meters.

Table 5-8 Varying Resolution Alternatives for Constant Altitude of 2705.881 km

	Cost (Million $)	Risk	P. Resolution (m)	S. Resolution (m)	P. Coverage (Hr)	S. Coverage (Hr)	FOV	Dlink delay (Sec)	Upgradability	Time to Target	Simultaneous Customers
ALT FSO-7.1	2,695.9457	1	0.5	0.5	12	12	2.49	46.4	0	0	1
ALT FSO-7.2	1,504.5399	0	1	1	12	12	4.99	11.6	0	0	1
ALT FSO-7.3	679.4609	0	2	2	12	12	9.98	2.9	0	0	1
ALT FSO-7.4	500.0589	0	3	3	12	12	14.97	1.29	0	0	1
ALT FSO-7.5	422.5979	0	4	4	12	12	19.96	0	0	0	1
ALT FSO-7.6	378.97186	0	5	5	12	12	24.95	0	0	0	1
ALT FSO-7.7	462.50149	0	3.4	3.4	12	12	17	0	0	0	1

Here is a figure for utility functions of cost, resolution and FOV and the total scores of these utilities, which are the only changing parameters for the alternatives.

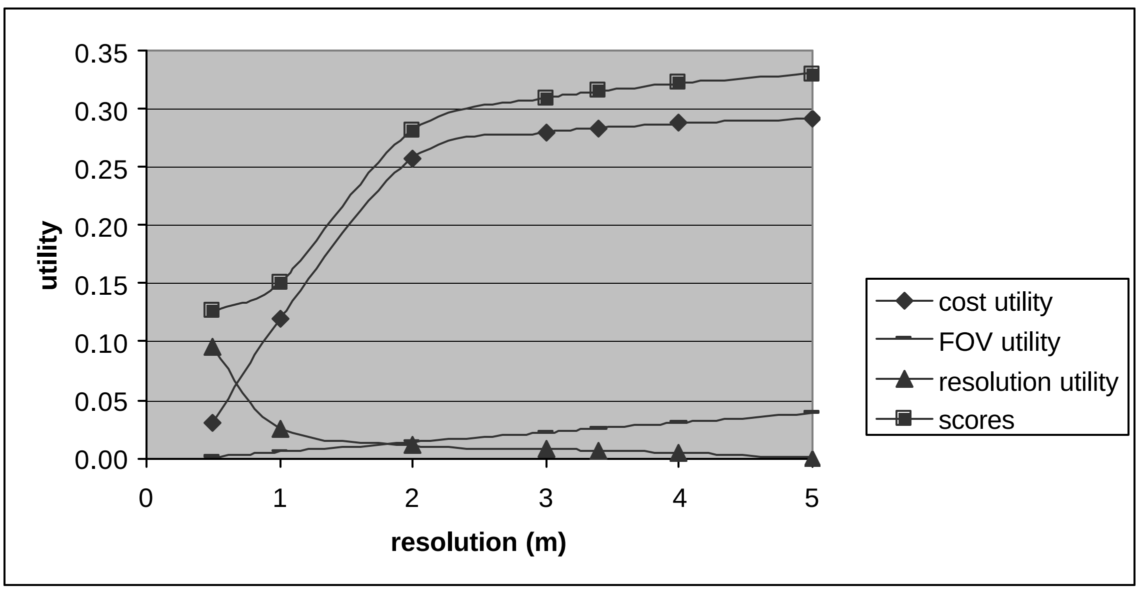

Figure 5-3 Utility Analyses-Conventional Satellites

Even though 5-meter resolution itself is zero utility to us, according to our value system design Alternative 7.6 has the highest total score. So, 4 satellites at 2705.881 km altitude with 12 hours coverage at 5-meter resolution is our best alternative among satellite only alternatives.

5.3.2 Small Satellites

Our small satellite alternatives are all at 1666.219 km altitude. However, the number of satellites being considered ranges from 6 to 12. Table 5-9 is the table of small satellite alternative parameters for 4-meter resolution (1-meter resolution payloads are too heavy to for small satellite bus and small satellite total mass are assumed to be less than 500kg). After applying value system design to this table we expect to determine the best small satellite alternative with the optimum number of satellites for a fixed resolution. The most important parameters that will have the most important effect on the result are cost and coverage (primary & secondary). So the real trade-off is between these two parameters.

Table 5-9 Small Satellite Alternatives & Parameters

	Cost	Risk	P. Resolution (m)	S. Resolution (m)	P. Coverage (Hr)	S. Coverage (Hr)	FOV	Dlink delay (Sec)	Upgradability	Time to Target	Simultaneous Customers
ALT FSS-1	$490,415.84	0	4	4	6.35	6.35	19.81	2.5	2	0	2
ALT FSS-2	$595,075.23	0	4	4	7.22	7.22	19.81	2.5	2	0	2
ALT FSS-3	$698,758.77	0	4	4	7.45	7.45	19.81	2.5	2	0	2
ALT FSS-4	$803,092.88	0	4	4	8.1	8.1	19.81	2.5	2	0	2

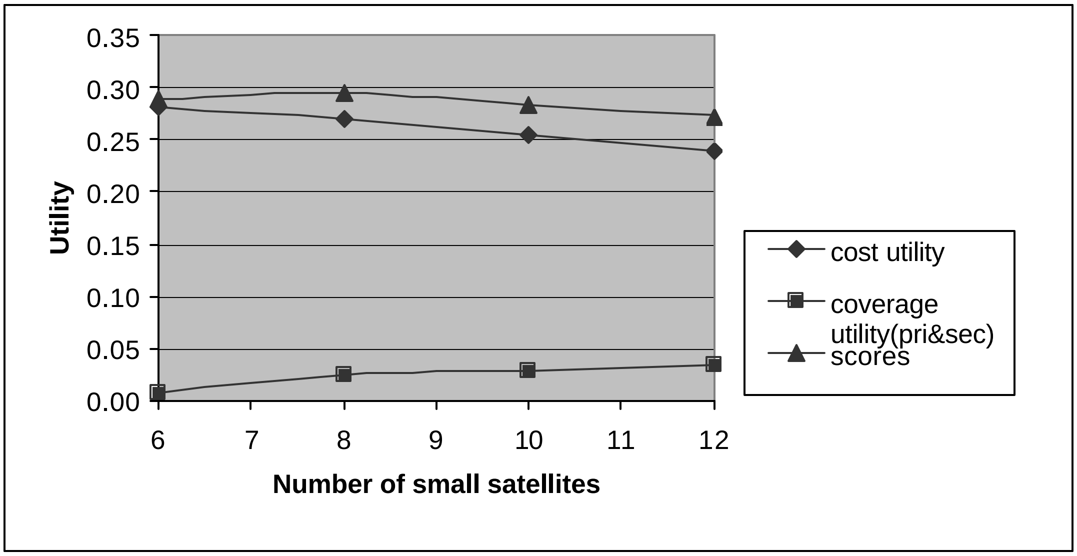

Figure 5-4 Utility Analyses – Small Satellites – 1

As seen from Figure 5-4, Alternative 2 with 8 satellites is the best small satellite alternative.

Next thing we want to figure out is the best resolution design to proceed with. So, we are going to compare different resolutions for the best alternative, which is Alternative 2 from Table 5-10.

Table 5-10 Varying Resolutions for Alternative 2

	Cost (Million $)	Risk	P. Resolution (m)	S. Resolution (m)	P. Coverage (Hr)	S. Coverage (Hr)	FOV	Dlink delay (Sec)	Upgradability	Time to Target	Simultaneous Customers
ALT FSS-2.1	722.92766	0	2	2	7.22	7.22	9.9	2.5	2	0	2
ALT FSS-2.2	642.17785	0	3	3	7.22	7.22	14.85	2.5	2	0	2
ALT FSS-2.3	633.09738	0	3.16	3.16	7.22	7.22	15.66	2.5	2	0	2
ALT FSS-2.4	595.07523	0	4	4	7.22	7.22	19.81	2.5	2	0	2

Here is a figure for utility functions of cost, resolution and FOV and the total scores of these utilities, which are the only changing parameters for the alternatives.

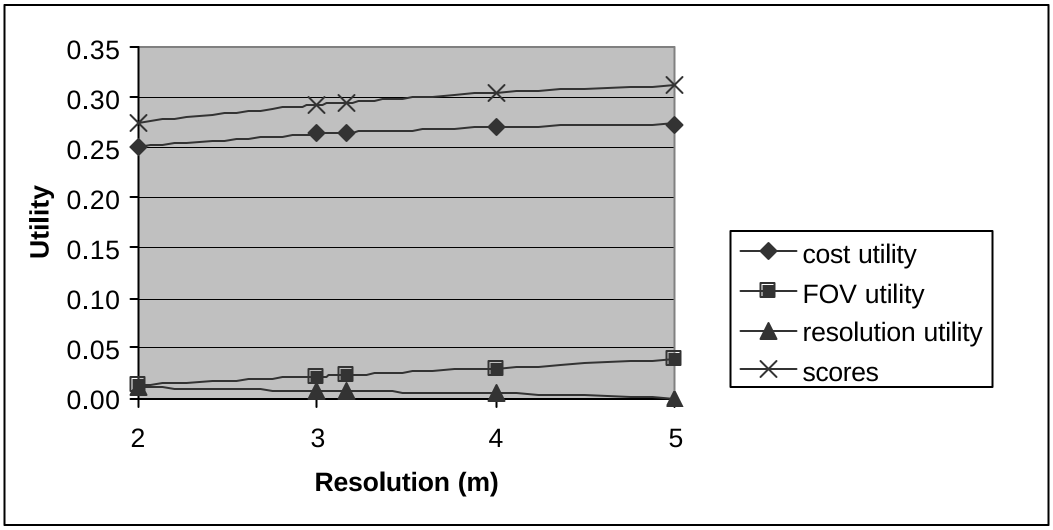

Figure 5-5 Utility Analyses – Small Satellites – 2

Even though 4-meter resolution itself is zero utility to us according to our value system design Alternative 2.4 has the highest total score. So, 8 satellites at 1666.219 km altitude with 7.22 hours coverage at 4-meter resolution is our best alternative among small satellite only alternatives.

5.3.3 Unmanned Air Vehicles (UAV)

Here are UAV alternatives with number of UAVs (implies the number of customers you can serve simultaneously) and cost being the parameters subject to trade-off.

Mission requirements indicate that the imaging system is intended to serve 5 customers in the primary region and 25 customers in whole target area. Number of UAVs is also the number of simultaneous customers that can be served. Figure 5-6 shows the relationship between cost and simultaneous customer utilities and gives the sums of these utilities for each alternative.

Table 5-11 UAV (U) Alternatives

	Cost (Million $)	Risk	P. Resolution (m)	P. Resolution (m)	P. Coverage (Hr)	S. Coverage (Hr)	FOV	Dlink delay (Sec)	Upgradability	Time to Target	Simultaneous Customers
ALT U-1	2,199.645	0	0.3	0.3	12	12	1.88	0	10	1.25	25
ALT U-2	1,546.625	0	0.3	0.3	12	12	1.88	0	10	1.25	17
ALT U-3	901.445	0	0.3	0.3	12	12	1.88	0	10	1.25	9
ALT U-4	738.799	0	0.3	0.3	12	12	1.88	0	10	1.25	7
ALT U-5	575.145	0	0.3	0.3	12	12	1.88	0	10	1.25	5
ALT U-6	410.231	0	0.3	0.3	12	12	1.88	0	10	1.25	3
ALT U-7	326.990	0	0.3	0.3	12	12	1.88	0	10	1.25	2
ALT U-8	242.825	0	0.3	0.3	12	12	1.88	0	10	1.25	1

As number simultaneous customer you want to serve increases, cost increases too. Alternative U-7, which is serving 2 customers simultaneously, is the best UAV alternative.

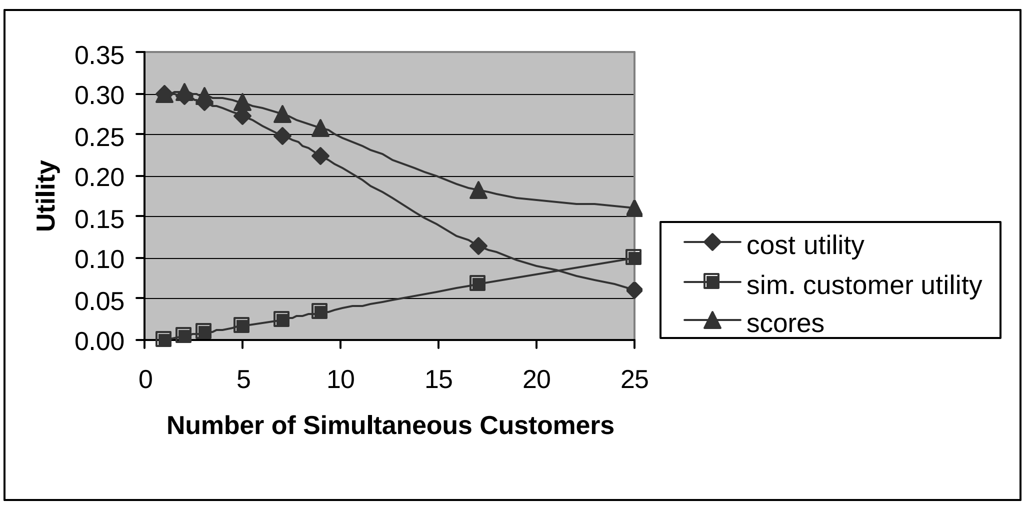

Figure 5-6 Utility Analyses – UAVs

5.3.4 Satellites & UAVs

Satellite & UAV alternatives consist of two different systems. Satellites are the same as the satellite only alternatives above and they are assigned to secondary region. UAVs consist of 5 UAVs and 2 ground stations and are assigned to primary area. Table 5-12 shows the satellite & UAV alternative parameters for 0.3-meter resolution for primary area and 5-meter resolution for secondary area.

After applying value system design to this table we expect to determine the best altitude for satellite & UAV alternatives for a fixed resolution. The most important parameters that will have the most important effect on the result are cost and coverage (sec). So the real trade-off is between these two parameters. There are also some other different parameters but they have relatively minor effect on alternatives. As seen from the table, Alternative SU-1 at 1666.219 km altitude, with 6 satellites and 5 UAVs, is the best satellite & UAV alternative.

Now we want to figure out the best resolution design. Figure 5-7 shows the utility functions of cost, resolution and FOV and the total scores of these utilities, which are the only changing parameters for the alternatives.

Table 5-12 Satellite & UAV (SU) Alternative Parameters

	Cost (Million $)	Risk	P. Resolution (m)	S. Resolution (m)	P. Coverage (Hr)	S. Coverage (Hr)	FOV	Dlink delay (Sec)	Upgradability	Time to Target	Simultaneous Customers	Scores
ALT SU-1	848.94141	0	0.3	5	12	6.35	8.42	90	5	0.893	7	0.6165
ALT SU-2	893.49198	0	0.3	5	12	7.22	8.42	90	5	0.893	7	0.6139
ALT SU-3	937.30826	0	0.3	5	12	7.45	8.42	90	5	0.893	7	0.6084
ALT SU-4	980.54920	0	0.3	5	12	7.67	8.42	90	5	0.893	7	0.6030
ALT SU-5	807.18170	0	0.3	5	12	7.38	5.73	105	5	1.042	6	0.6000
ALT SU-6	841.04140	0	0.3	5	12	10.95	5.73	105	5	1.042	6	0.6127
ALT SU-7	874.11686	0	0.3	5	12	12	5.73	105	5	1.042	6	0.6130
ALT SU-8	846.72470	0	0.3	5	12	8.08	5.71	105	5	1.042	6	0.5982
ALT SU-9	890.47865	0	0.3	5	12	11.5	5.71	105	5	1.042	6	0.6081
ALT SU-10	933.27765	0	0.3	5	12	12	5.71	105	5	1.042	6	0.6041
ALT SU-11	888.99000	0	0.3	5	12	8.8	5.72	105	5	1.042	6	0.5949
ALT SU-12	941.67220	0	0.3	5	12	11.8	5.72	105	5	1.042	6	0.6019
ALT SU-13	993.18043	0	0.3	5	12	12	5.72	105	5	1.042	6	0.5952
ALT SU-14	949.63325	0	0.3	5	12	9.3	5.74	105	5	1.042	6	0.5882
ALT SU-15	1,016.94178	0	0.3	5	12	11.98	5.74	105	5	1.042	6	0.5890
ALT SU-16	1,082.78396	0	0.3	5	12	12	5.74	105	5	1.042	6	0.5693
ALT SU-17	1,061.08738	0	0.3	5	12	8.51	5.74	105	5	1.042	6	0.5584
ALT SU-18	1,153.89610	0	0.3	5	12	11.76	5.74	105	5	1.042	6	0.5549
ALT SU-19	1,183.19297	0	0.3	5	12	8.4	5.70	105	5	1.042	6	0.5336
ALT SU-20	1,310.79434	0	0.3	5	12	9.938	5.70	105	5	1.042	6	0.5222
ALT SU-21	1,435.89985	0	0.3	5	12	10.23	5.70	105	5	1.042	6	0.5049
ALT SU-22	1,434.16946	0	0.3	5	12	8.96	5.73	105	5	1.042	6	0.4988

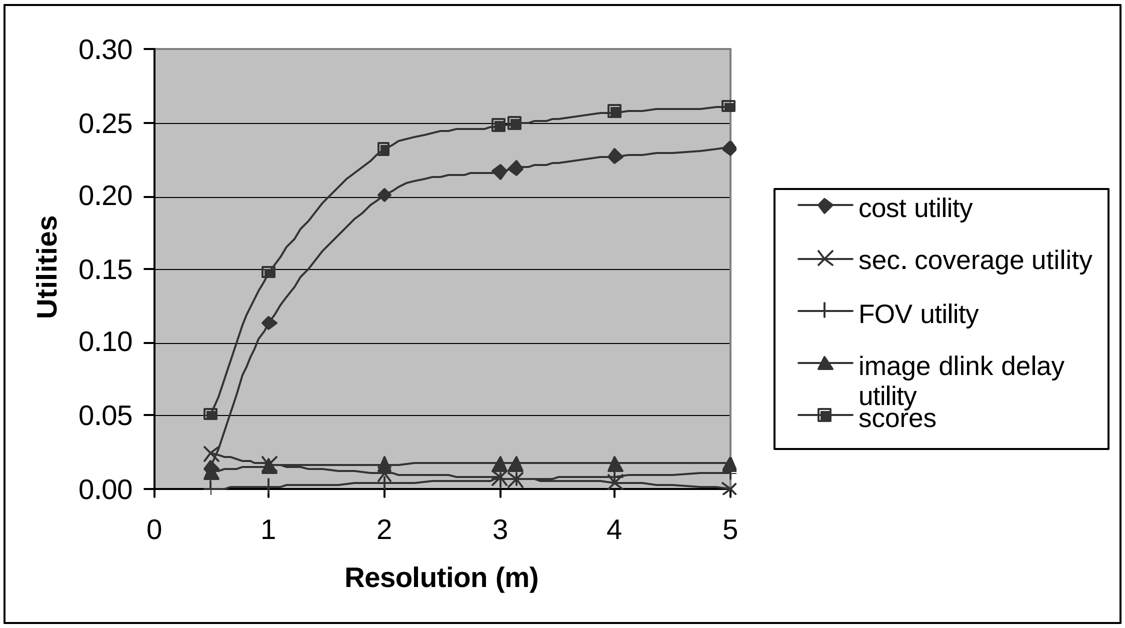

Figure 5-7 Utility Analyses – Satellites & UAVs

Even though 5-meter resolution itself is zero utility to us according to our value system design it has the highest total score. So, Alternative 7D which consists of 4 satellites at 2705.881 km altitude with 5-meter resolution and 5 UAVs is our best alternative among satellite & UAV alternatives.

5.3.5 Small Satellites & UAVs

Small Satellite & UAV alternatives consist of two different systems. Small Satellites are the same as the small satellite alternatives above and they are assigned to secondary region. UAVs consist of 5 UAVs and 2 ground stations and are assigned to primary area. Here is the table of small satellite & UAV alternative parameters for 5-meter resolution:

Table 5-13 Small Satellite & UAV (SSU) Alternative Parameters

	Cost (Million $)	Risk	P. Resolution (m)	P. Resolution (m)	P. Coverage (Hr)	S. Coverage (Hr)	FOV	Dlink delay (Sec)	Upgradability	Time to Target	Simultaneous Customers	Scores
ALT SSU-1	960.13085	0	0.3	5	12	6.35	8.42	0	6	0.893	7	0.648
ALT SSU-2	1,058.58371	0	0.3	5	12	7.22	8.42	0	6	0.893	7	0.629
ALT SSU-3	1,156.17573	0	0.3	5	12	7.45	8.42	0	6	0.893	7	0.609
ALT SSU-4	1,253.09328	0	0.3	5	12	7.67	8.42	0	6	0.893	7	0.596

For a fixed resolution, the most important parameters that will have the most important effect on the result are cost and coverage (sec). So the real trade-off is between these two parameters. There are also some other different parameters but they have relatively minor effect on alternatives.

As seen from the table, Alternative SSU-1 at 1666.219 km altitude with 6 small satellites and 5 UAVs is the best small satellite & UAV alternative.

Now, we are going to compare different resolutions at the best alternative's altitude, which is 1666.219 km for our case from Table 5-13.

Here is a figure for utility functions of cost, resolution and FOV and the total scores of these utilities, which are the only changing parameters for the alternatives.

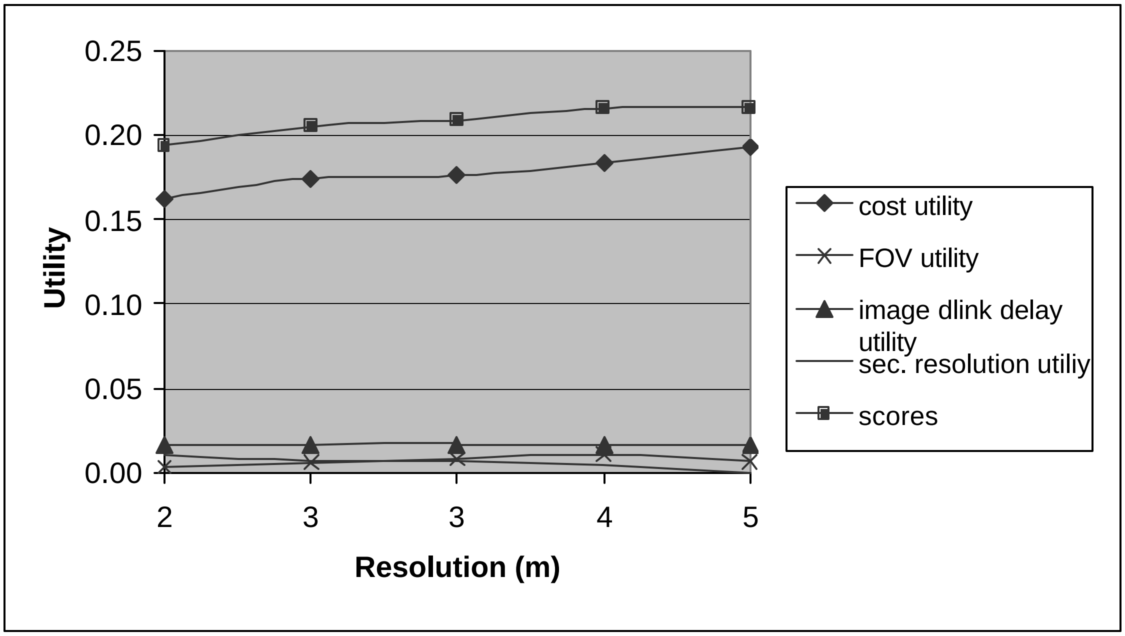

Figure 5-8 Utility Analyses – Small Satellites & UAVs

Cost utility has the biggest impact on final scores. Other parameters have relatively small effect. Alternative with 5-meter resolution has the highest score. So, 6 small satellites at 1666.219 km altitude with 5-meter resolution and 5 UAVs is our best alternative among small satellite & UAV alternatives.

5.3.6 Best Of All Alternatives

In this chapter, we had 5 categories of alternatives: satellite only, small satellite only, UAV only, satellite&UAV, small satellite&UAV. We applied our VSD to each group and chose the best one out of each. Table 5-14 shows the best alternatives of all categories.

Table 5-14 Best of all alternatives

	DEFINITION	ORBIT	ALTITUDE (km)	NUMBER OF VEHICLES	SIMULTANEOUS CUSTOMERS
ALT BEST-1	SATELLITES	CIRCULAR SUN-SYNCHRONOUS	2705.881	4 SAT	1
ALT BEST-2	SMALL SATELLITES	CIRCULAR SUN-SYNCHRONOUS	1666.219	8 SMALL SAT	2
ALT BEST-3	SATELLITES &UAVs	CIRCULAR SUN-SYNCHRONOUS	2705.881	4 SAT & 5 UAV	6
ALT BEST-4	SMALL SATELLITES & UAVs	CIRCULAR SUN-SYNCHRONOUS	1666.219	6 SMALL SAT & 5UAV	7
ALT BEST-5	UAVs	-	20	2 UAV	2

Chapter 6 - Results and Sensitivity Analysis

6.1 Chapter Overview

This chapter consists results of analysis of alternatives, interpretation of results, decision-making, sensitivity analysis, and comparison of our system with existing technologies.

6.2 Results

Table 6-1 Best Alternatives and Parameters

	Cost (Million $)	Risk	P. Resolution (m)	P. Resolution (m)	P. Coverage (Hr)	S. Coverage (Hr)	FOV	Dlink delay (Sec)	Upgradability	Time to Target	Simultaneous Customers	Scores
ALT BEST-1	378.97186	0	5	5	12	12	24.95	0	0	0.00	1	0.711
ALT BEST-2	563.43871	0	5	5	7.22	7.22	24.76	0	2	0.00	2	0.612
ALT BEST-3	874.11686	0	0.3	5	12	12	5.725	0	5	0.89	6	0.663
ALT BEST-4	1,058.58371	0	0.3	5	12	7.22	5.82	0	6	0.89	7	0.629
ALT BEST-5	326.99000	0	0.3	0.3	12	12	1.88	0	10	1.25	2	0.749

After applying value system design to this table we expect to determine the best alternative among the best of all 5 alternative categories. As seen from Table 6-1 Alternative BEST-5, which is a UAV only alternative with 2 UAVs has the highest score. Alternative BEST-1, which is a satellite only alternative with 4 satellites, is in the second place. In our value system design we have 11 parameters of the alternatives that we analyze.

Between Alternative BEST-1 and Alternative BEST-5, there are 5 parameters that have close values: cost, risk, coverage primary, coverage secondary and number of simultaneous customers. So, we will be able to serve approximately the same number of simultaneous customers, with an acceptable risk, during same coverage hours. However, the service quality is quite different between the two alternatives. Most importantly, resolutions are quite different. UAVs can provide 0.3-meter resolution where satellites can only handle 5-meter resolution. Satellites are far from being competitive with the existing systems. If we recall from requirements document, our resolution requirement is 1-meter resolution. So, resolution has become an issue to re-discuss with the sponsor. Length of field-of-view and image downlink delay are also quite different however since they are functions of resolution they will vary with resolution and will be decided upon solving the resolution issue. Time to target depends on which system we select. If we consider satellite alternatives, they will be flying in the space all the time and will be able to reach target area in no time during coverage hours. On the other hand, UAVs need to take-off from a runway and fly for a while to reach the target area. However, this issue of time to reach target area can be solved by setting a prior notification standard and precise planning.

There is also a significant difference in Length of FOV of these two alternatives. As seen in the table, Alternative BEST-1 serves the largest picture size with 5 m resolution and no delay. This feature would be preferred if the customer needs a picture of a large area continuously. Also the resolution can be improved by narrowing the picture size or using a higher capacity downlink to prevent the possible delay, which might be a problem due to better resolution and large size picture.

Alternative BEST-3 would be chosen by a customer who may want moderate Length of FOV and an acceptable downlink delay but a good resolution of 0.3 m in primary region. Therefore, there will be a chance to upgrade the system in 10 year life cycle time.

The customers who give the most importance to the best resolution in all regions in spite of a small sized picture with a low-cost system will choose the last alternative where the system includes only UAVs. Hence there will have a big capability to upgrade the system according to technological and functional needs. However, this system can be improved to have a large size of picture with a small or no downlink delay if the downlink capacity can be improved. This is another issue of technology and system budget.

Finally, upgradeability is an inherent property of which system we select. In other words, we will either be able to upgrade or we will be stuck with what we launch depending on the alternative chosen to be the best for our application.

Our initial intentions were to design a cost competitive system which will provide 1-meter resolution or less for 12 hours and serve at least 5 simultaneous customers. As one notices, we could not come close to our resolution and simultaneous customer requirements, which are directly related to quality of service, with satellite alternatives. Resolution is 5 meters and we can only serve one simultaneous customers with our best satellite only alternative, which is the only alternative that competes with UAV alternatives. As we stated in Chapter 4 it is not possible to design a low-cost, high-resolution system that will cover a target area for 12 hours and simultaneously serve 5 customers which defines our baseline design parameters. Especially coverage and simultaneous customer requirements are contradicting parameters for satellites. One should either serve fewer customers for 12 hours of coverage or serve more customers for 2 –3 hours of coverage during daylight hours. Requiring high numbers for both parameters drives up the cost simply because of the need to increase the number of satellites.

Since we could not come close to our baseline design parameters with satellite alternatives, we wanted to look at inflatable technologies again to see if they will allow a system that will satisfy our baseline design parameters. We disregarded the risks associated with inflatables and chose low heritage numbers in cost model. Basically we assumed inflatables to be an existing and operationally proven technology and analyzed the alternatives accordingly. Best inflatable alternative has 1- meter resolution, 12-hour coverage, relatively low-cost ($809904 million) and serves only one simultaneous customer. It had 0.64 points out of 1 as final score, which is still well below best UAV alternative's score of 0.74 points.

As a result, according to the requirements and constraints the best alternatives are UAVs. This conceptual study narrows the solution field and recommends more emphasis to the conventional UAVs like Global Hawk for regional high-resolution image missions.

6.3 Design Verification For The Best Alternative (UAV Alternative)

Table 6-2 Design Verification

Requirement	***Description***	***Design Verification***
Coverage frequency	Continuous coverage (6am-6pm) Daily revisit	Yes Yes
Resolution	1 m panchromatic 5 m multi-spectral	Yes Yes
Location accuracy	10 m	*****See below
Simultaneous Customers	5 customers in primary region 25 customers in whole region	Yes Yes
Image Quality	Sun elevation Image elevation	> 15^0 > 20^0
Availability	98%(excluding cloud cover)	Yes
Refueling frequency	1 year or electric propulsion or solar	N/A
Survivability	Space radiation hardening	N/A
Cost	Cost competitive	******See below
Design Life	10 Years	Yes
Launch system	<10 vehicles	N/A

***** Since the imaging system will be serving in the local area, we assume that we can easily compensate for location inaccuracies using our knowledge about the area.

****** There is no other existing system providing high-resolution imagery with our coverage frequency so we were not able to compare our system with a similar existing system. User is satisfied that with service quality our design is providing, total cost is reasonable. Decreasing the number of UAVs can decrease cost of the system.

6.4 Sensitivity Analysis

Sensitivity analysis is accomplished by changing the weights of the VSD parameters (one at a time) and recalculating the percentages of each parameter. New percentages are multiplied by utilities to find score for each parameter. Then, the score of each parameter is added together to find out the total score for each alternative.

Table 6-3 Sensitivity Analysis Results

	Weight	Best Alternative	Weight	Best Alternative	Weight	Sensitivity
	Range-1	**Range-1**	**Range-2**	**Range-2**	**In study**	**To weight change**
Cost	0-30	5	30+	5	30	**Not sensitive**
Risk	0-10	5	10+	5	10	**Not sensitive**
Primary Resolution	0-5	1	5+	5	9	Highly sensitive
S. Resolution	0-3	5	3+	5	3	**Not sensitive**
P. Coverage	0-9	5	9+	5	9	**Not sensitive**
S. Coverage	0-3	5	3+	5	3	**Not sensitive**
Length of FOV	0-8	5	8+	1	4	Highly sensitive
Image Downlink Delay	0-6	5	6+	5	6	**Not sensitive**
Upgradeability	0-2	1	2+	5	6	Highly sensitive
Time to target	0-13	5	13+	1	10	Highly sensitive
Simultaneous Customers	0-10	5	10+	5	10	**Not sensitive**

Table 6-3 shows the results of the sensitivity analysis on 5 best alternatives. If there is no change in the winning alternative along the whole range that parameter is labeled as “Not sensitive”. If there is a change in the range, that parameter is labeled as

“Sensitive” and if this change in the winning alternative occurs close to the actual weight of the parameter, the parameter is labeled as “Highly Sensitive”.

Cost, Risk, Secondary Resolution, Primary Coverage, Secondary Coverage, Image Downlink Delay, Simultaneous Customers are not sensitive parameters. Cost is not sensitive because the winning alternative has already the lowest cost. Risk is not a sensitive parameter, because there is no difference in risk among these five alternatives. Recall that, there is no requirement on risk but there is a requirement on coverage hours however that requirement has already been satisfied at the maximum level possible. Primary and secondary coverage hours are also non-sensitive parameters, because winning alternative already has the highest possible coverage hours during daylight hours, which is 12 hours. So Cost, Risk, Secondary Resolution, Primary Coverage, Secondary Coverage, Image Downlink Delay, Simultaneous Customers have no effect on the winning alternative.

Primary Resolution, LOFOV, Upgradeability, and Time To Target are highly sensitive parameters. Recall from requirements document that Resolution is the only parameter that has a requirement stated among 4 highly sensitive parameters. The requirement is 1-meter resolution. Alternative BEST-1 provides 5-meter resolution and Alternative BEST-5 provides 0.3-meter resolution. The other highly sensitive parameters are either functions of resolution (LOFOV) or inherent property of the system (Upgradeability, and Time To Target). So, looking at the quality difference between the services provided by each system in terms of resolution and reconsidering the importance of that quality for the sponsor and customers highly affect the results. Even a change of couple points out of 100 is sufficient to re–define the winning alternative.

Overall, there are 7 non-sensitive, 4 highly sensitive parameters. So we conclude that our system is a sensitive system although it seems like the competition is really between Alternative 1 and Alternative 5 all the time.

6.4.1 Sensitivity Analysis On Number Of Simultaneous Customers

Recall from the requirements document that we are required to serve 5 simultaneous customers initially in the primary region and total of 25 simultaneous customers in the whole area finally. From Table 6-4 and Table 6-5, the best two alternatives can only serve 1 or 2 simultaneous customers. If we look at our value system design parameters, first 10 parameters are most like system parameters but number of simultaneous customers will indeed determine the commercial performance and success.

So we decided to make a sensitivity analysis on number of simultaneous customers. We did the analysis in two ways. First, we designated a number of simultaneous customers to be served and evaluated 5 alternatives accordingly. Second, we took Alternative BEST-1 and Alternative BEST-5, which were the best two alternatives, and increased number of simultaneous customers from 1 to 25.

Table 6-4 Best alternatives serving 7 simultaneous customers

	Cost (Million $)	Risk	P. Resolution (m)	P. Resolution (m)	P. Coverage (Hr)	S. Coverage (Hr)	FOV	Dlink delay (Sec)	Upgradeability	Time to Target	Simultaneous Customers	Scores
ALT BEST-1	1,132.41089	0	5	5	12	12	24.95	0	0	0.00	7	0.619
ALT BEST-2	1,330.17688	0	5	5	7.22	7.22	24.76	0	6	0.00	7	0.529
ALT BEST-3	874.11686	0	0.3	5	12	12	5.725	0	5	0.89	7	0.683
ALT BEST-4	1,058.58371	0	0.3	5	12	7.22	5.82	0	6	0.89	7	0.629
ALT BEST-5	738.799	0	0.3	0.3	12	12	1.88	0	10	1.25	7	0.728

Note that the only changing parameter by changing number of simultanteous customers is the total cost of the system. From Table 6-4, Alternative BEST-5 is the best alternative if we wanted to serve 7 simultaneous customers. Alternative BEST-3, which is a satellite & UAV alternative, has the second place. Alternative BEST-1, which was the best alternative before, is now in the third place. Overall, there is a big difference between Alternative BEST-5 and other 4 alternatives. So, we conclude that as the number of simultaneous customers to be served increases UAV only alternatives become more attractive.

Now, we will increase the number of simultaneous customers from 1 to 25 and evaluate the results to further analyze the conclusion we made in previous paragraph. Table 6-5 is depicting the final scores of UAV alternatives as number of simultaneous customers increase.

Table 6-5 Satellite vs. UAV alternatives for varying number of simultaneous customers

	Cost (Million $)	Risk	P. Resolution (m)	P. Resolution (m)	P. Coverage (Hr)	S. Coverage (Hr)	FOV	Dlink delay (Sec)	Upgradability	Time to Target	Simultaneous Customers	Scores
ALT BEST-5.1	242.825	0	0.3	0.3	12	12	1.88	0	10	1.25	1	0.747
ALT BEST-5.2	326.99	0	0.3	0.3	12	12	1.88	0	10	1.25	2	0.749
ALT BEST-5.3	410.231	0	0.3	0.3	12	12	1.88	0	10	1.25	3	0.745
ALT BEST-5.4	495.145	0	0.3	0.3	12	12	1.88	0	10	1.25	5	0.744
ALT BEST-5.5	738.799	0	0.3	0.3	12	12	1.88	0	10	1.25	7	0.728
ALT BEST-5.6	982.53	0	0.3	0.3	12	12	1.88	0	10	1.25	10	0.697
ALT BEST-5.7	1,042.755	0	0.3	0.3	12	12	1.88	0	10	1.25	11	0.686
ALT BEST-5.8	1,233.345	0	0.3	0.3	12	12	1.88	0	10	1.25	13	0.657
ALT BEST-5.9	1,546.625	0	0.3	0.3	12	12	1.88	0	10	1.25	17	0.629
ALT BEST-5.10	1,706.695	0	0.3	0.3	12	12	1.88	0	10	1.25	19	0.621
ALT BEST-5.11	1,866.625	0	0.3	0.3	12	12	1.88	0	10	1.25	21	0.615
ALT BEST-5.12	2,199.645	0	0.3	0.3	12	12	1.88	0	10	1.25	25	0.607

6.4.2 Comparison Of Our System With Existing Systems

Table 6-6 Comparison Of Our System With Existing Systems

	WORLDWIDE CONSTELLATION	REGIONAL (Our System)	WORLDWIDE/SINGLE SATELLITE/LEO
Cost (FY00$K)	***$5,000,000***	$2,000,000	$250,000
Continuous coverage	Yes	Yes	***15 min***
Daily revisit	Yes	Yes	***2.9 days***
# Ground stations	***High***	Low	Medium
# Vehicles	***High (66 sat)***	Medium (25UAV)	1 sat
Launch vehicle cost	High	N/A	Low
Resolution	Same	Same	Same
Upgradeability	None	Yes	None
Time to Target	***%98 (Excluding weather)***	All weather UAV's	***%98 (Excluding weather)***
Lifetime	***10 years***	>10 years	***10 years***
Image type	***Visual, IR***	Visual, IR, SAR	***Visual, IR***

** Italic fonts indicate the worst alternative in specified category*

We are comparing three kinds of systems. First one is a constellation of 66 satellites (like Iridium) that provides worldwide coverage. Second one is our system, which is intended to serve as regional continuous coverage during daylight hours providing high-resolution imagery. Third one is Ikonos-type one imaging satellite at LEO, which travels around the whole earth, downlinks the data to certain ground stations in different locations with high resolution.

- In terms of cost, constellation is the most expensive among three kinds of systems. Regional image provider system is about 40% and one-satellite system is about 5% of the constellation.

- Constellation and regional systems provide continuous coverage with daily re-visitation. One-satellite system provides 15 min coverage of a location every 2.9 days.

- Since constellation and one-satellite systems are intended to serve worldwide they require many ground stations throughout the world. Regional system requires only a few ground stations in the region of interest.

- Number of vehicles is highest in the constellation. Regional imaging system is in second place and one-satellite system has the lowest number of vehicles. The difference stems from the type service required from each system. The constellation is required to serve worldwide customers simultaneously. Although Ikonos is also intended to serve worldwide customers, it cannot provide simultaneous service to different customers in different locations. Regional system is intended to serve 25 customers simultaneously in the specified region. That is also true that you cannot provide worldwide service effectively with UAVs.

- We can provide imagery with same resolution with each system.
- Constellation and one-satellite systems do not allow upgrading. But UAVs can be upgraded anytime.
- Satellite systems (constellation and one-satellite systems) can provide imagery as long as there is no cloud coverage over the area. UAVs, however, are all weather and can provide service by flying under the clouds or above the clouds with radar or in spectrums other than visual. Global Hawk, for example, can provide visual, IR and SAR images.
- Satellite lifetimes are usually 10-12 years, but UAVs can be upgraded and used many more than 10 years.

6.5 Summary and Conclusions

Mission requires to provide daily, high-resolution imagery for 12-hours during daylight over a relatively small target area in a cost competitive to at least 5 simultaneous customers.

UAV alternative is the optimum solution for our problem according to our value system design.

Regardless of the technology used, it is really expensive to try to satisfy mission requirements with satellites. (12-hour daily coverage versus simultaneous customers)

Inflatable technology enables us to launch larger diameters in less volume, however there are risks associated with inflatables since they are not operational yet.

If inflatables are proven to be effective, they might satisfy mission requirements. But we still need to decide whether to serve less simultaneous customers or require less coverage hours or both.

Small satellites cannot satisfy most of the mission requirements due to limited orbit altitude (high number of satellites), limited mass (smaller diameters), shorter design life (re-launch issues).

UAVS cannot potentially see the whole target area. They are assigned to each target. In almost all other areas they are superior to satellites for small target areas.

6.6 Recommendations and Future implementation

This system was designed according to our user's requirements. As we could see in the sensitivity analyses, when preferences of user change, the best alternative will also change. So, we may use this design for building another system design with similar requirements. SEP may be tailored for future studies with different requirements.

While progressing in our system design project some data were missing, actual cost models were unavailable for student use and some data had little impact in this project. Because of these reasons we made assumptions. These assumptions would affect our validity. In the conceptual design these assumptions helped us look at all aspects of the problem and be able to complete the conceptual SEP on time. However, for later phases of systems engineering life cycle these assumptions would affect the system's validity negatively. In the detailed design process or other future studies, using more accurate data and cost models should solve this problem.

Conventional UAV is a high altitude, high endurance unmanned aircraft and integrated sensor system to provide intelligence, surveillance, and reconnaissance. Although they have some air space constraints and risks associated with their short history, UAVs offer some outstanding advantages when compared with satellites for regional imaging missions. UAVs are cost effective, can provide high-resolution images, and have higher upgradeability. Because of their cost effectiveness even countries with small defense budgets or private businesses can afford these systems.

Satellites can only use the payload the are launched with however, UAVs are compatible with different systems such as optical sensors, SAR, moving target indicator radar, electro optical and infrared sensor systems and these systems can be added to UAVs whenever requested. This capability gives UAV users to be able to achieve wide range of missions. Some of these potential applications include commercial operations such as mapping, city planning, weather, telecommunications and natural disaster awareness and military operations such as Targeting and Precision Strike Support, Battle Damage Assessment, Enemy Order of Battle Information, Intelligence Preparation of the Battlefield, and Sensitive Reconnaissance Operations.

During the design process we referred UAV as a general, conventional type UAV for which we accepted Global Hawk as the baseline UAV. Another study might be towards determining the optimum UAV design to satisfy specific mission requirements.

Inflatable technology is also promising for future space imaging missions. In this study because of high risks and high heritage factors alternatives using inflatable technology weren't considered among the best alternatives. However technological improvements in this area may affect future studies. The risks associated with new technologies should be reconsidered at every stage of the studies because the knowledge we have about the new technologies changes daily.

The costs are calculated for the same reliability for all alternatives and the reliabilities of alternatives are assumed to be same. For future implementation a detailed reliability study should be made.

Ground station design might also be a subject to a future study. Optimum ground station design and an effective way to distribute images to customers and end-users should be analyzed.

Mission computer system was out of the scope of this study however it is important in many aspects as data processing (on-board or ground) and data transfer rates, which directly improves service speed and quality and shall be analyzed in detail.

APPENDIX A: Cost Models

CERs for Estimating Subsystem RDT&E Cost (FY00$K)

Cost Component	Parameter, X (Unit)	Input Data Range	RDT&E CER* (FY00$K)	SE (%)
1. Payload				
1.1 IR Sensor	aperture dia. (m)	0.2–1.2	$356{,}851\ X^{0.562}$	53,559†
1.2 Visible Light Sensor	aperture dia. (m)	0.2–1.2	$128{,}827\ X^{0.562}$	19,336†
1.3 Communications	comm. subsystem wt. (kg)	65–395	353.3 X	51
2. Spacecraft	spacecraft dry wt. (kg)	235-1,153	101 X	33
2.1 Structure	structure wt. (kg)	54–392	$157\ X^{0.83}$	38
2.2 Thermal	X_1 = thermal wt. (kg) X_2 = spacecraft wt. + payload wt. (kg)	3–48 210–404	$394\ X_1^{0.635}$ $1.1\ X_1^{0.610}\ X_2^{0.943}$	45 32
2.3 Electrical Power System (EPS)	X_1 = EPS wt. (kg) X_2 = BOL power (W)	31–491 100–2,400	$62.7\ X_1$ $2.63\ (X_1\ X_2)^{0.712}$	57 36
2.4 Telemetry, Tracking & Command (TT&C)/DH‡	TT&C/DH wt. (kg)	12–65	$545\ X^{0.761}$	57
2.5 Attitude Determination & Control Sys. (ADCS)	ADCS wt. (kg)	20–160	$464\ X^{0.867}$	48
2.6 Apogee Kick Motor (AKM)	AKM wt. (kg)	81–966	$17.8\ X^{0.75}$	—
3. Integration, Assembly & Test (IA&T)	spacecraft bus + payload total RDT&E cost (FY00$K)	2,703 – 395,529	989 + 0.215 X	46
4. Program Level	spacecraft bus + payload total RDT&E cost (FY00$K)	4,607 – 523,757	$1.963\ X^{0.841}$	36
5. Ground Support Equipment (GSE)	spacecraft bus + payload total RDT&E cost (FY00$K)	24,465 – 581,637	$9.262\ X^{0.642}$	34
6. Launch & Orbital Operations Support (LOOS)	N/A			

* Taken from USCM, 7th edition (1994) using minimum, unbiased percentage error CERs.
† Absolute error (in FY00$K), not percentage error.
‡ Includes spacecraft computer. If separate CERs for TT&C and C&DH are desired, use a 0.45/0.55 split.

CERs for Estimating Subsystem Theoretical First Unit (TFU) Cost

Cost Component	Parameter, X (Unit)	Input Data Range	TFU CER* (FY00$K)	SE (%)
1. Payload				
1.1 IR Sensor	aperture dia. (m)	0.2–1.2	$142,742\ X^{0.562}$	21,424†
1.2 Visible Light Sensor	aperture dia. (m)	0.2–1.2	$51,469\ X^{0.562}$	7,734†
1.3 Communications	comm. subsystem wt. (kg)	65–395	140 X	43
2. Spacecraft	spacecraft dry wt. (kg)	154–1,389	43 X	36
2.1 Structure	structure wt. (kg)	54–560	13.1 X	39
2.2 Thermal	thermal wt. (kg)	3–87	$50.6\ X^{0.707}$	61
2.3 Electrical Power System (EPS)	EPS wt. (kg)	31–573	$112\ X^{0.763}$	44
2.4 Telemetry, Tracking & Command (TT&C)/DH‡	TT&C/DH wt. (kg)	13–79	$635\ X^{0.568}$	41
2.5 Attitude Determination & Control Sys. (ADCS)	ADCS wt. (kg)	20–192	$293\ X^{0.777}$	34
2.6 Apogee Kick Motor (AKM)	AKM wt. (kg)	81–966	$4.97\ X^{0.823}$	20
3. Integration, Assembly & Test (IA&T)	spacecraft bus wt. payload wt. (kg)	155–1,390	10.4 X	44
4. Program Level	spacecraft + payload total recurring cost (FY00$K)	15,929 – 1,148,084	0.341 X	39
5. Ground Support Equipment (GSE)	N/A			
6. Launch & Orbital Operations Support (LOOS)	spacecraft bus + payload wt. (kg)	348–1,537	4.9 X	42

* Taken from USCM, 7th edition (1994) using minimum, unbiased percentage error CERs.

† Absolute error (FY00$K), not percentage error.

‡ Includes spacecraft computer. If separate CERs for TT&C and C&DH are desired, use a 0.45/0.55 split.

Cost-Estimating Relationships for Earth-orbiting Small Satellites including RDT&E and Theoretical First Unit

Cost Component	Parameter, X (Unit)	Input Data Range	Subsystem Cost CER* (FY00$K)	SE (FY00$K)
1. Payload	Spacecraft Total Cost (FY00$K)	1,922–50,651	0.4 X	$0.4 \times SE_{bus}$
2. Spacecraft	Satellite bus dry wt. (kg)	20–400	$781 + 26.1\ X^{1.261}$	3,696
2.1 Structure†	Structures wt. (kg)	5–100	299 + 14.2 X ln(X)	1,097
2.2 Thermal‡	Thermal control wt. (kg)	5–12	$246 + 4.2\ X^2$	119
	Average power (W)	5–410	$-183 + 181\ X^{0.22}$	127
2.3 Electrical Power System (EPS)	Power system wt. (kg)	7–70	$-926 + 396\ X^{0.72}$	910
	Solar array area (m^2)	0.3–11	$-210{,}631 + 213{,}527X^{0.0066}$	1,647
	Battery capacity (A-hr)	5–32	$375 + 494\ X^{0.754}$	1,554
	BOL Power (W)	20–480	$-5{,}850 + 4{,}629\ X^{0.15}$	1,585
	EOL Power (W)	5–440	$131 + 401\ X^{0.452}$	1,603
2.4a Telemetry Tracking & Command (TT&C)**	TT&C/DH wt. (kg)	3–30	$357 + 40.6\ X^{1.35}$	629
	Downlink data rate (Kbps)	1–1,000	$3{,}636 - 3{,}057\ X^{-0.23}$	1,246
2.4b Command & Data Handling (C&DH)	TT&C + DH wt. (kg)	3–30	$484 + 55\ X^{1.35}$	854
	Data Storage Capacity (MB)	0.02–100	$-27{,}235 + 29{,}388X^{0.0079}$	1,606
2.5 Attitude Determination & Control Sys. (ADCS)	ADCS dry wt. (kg)	1–25	$1{,}358 + 8.58\ X^2$	1,113
	Pointing accuracy (deg)	0.25–12	$341 + 2651\ X^{-0.5}$	1,505
	Pointing knowledge (deg)	0.1–3	2,643 – 1,364 ln(X)	1,795
2.6 Propulsion††	Satellite Bus dry wt. (kg)	20–400	$65.6 + 2.19\ X^{1.261}$	310
	Satellite volume (m^3)	0.03–1.3	1539 + 434 ln(X)	398
	Number of Thrusters	1–8	$4{,}303 - 3{,}903X^{-0.5}$	834
3. Integration, Assembly & Test (IA&T)	Spacecraft total cost (FY00$K)	1,922 – 50,651‡‡	0.139 X	$0.139 \times SE_{bus}$
4. Program Level	Spacecraft total cost (FY00$K)	1,922 – 50,651‡‡	0.229 X	$0.229 \times SE_{bus}$
5. Ground Support Equipment (GSE)	Spacecraft total cost (FY00$K)	1,922 – 50,651‡‡	0.066 X	$0.066 \times SE_{bus}$
6. Launch & Orbital Operations Support (LOOS)	Spacecraft total cost (FY00$K)	1,922 – 50,651‡‡	0.061 X	$0.061 \times SE_{bus}$

* CERs based on the Small Satellite Cost Model [Bearden, Boudreault, and Wertz, 1996], adjusted for inflation as shown in Table 20-1, and broken into subsystem cost using the percentages from Table 20-9.
† Aluminum materials primarily with selected use of advanced materials (e.g. composites, magnesium).
‡ Thermal CER appropriate for passive systems only.
** CER applies to UHF/VHF and S-band LEO systems
†† Hydrazine monopropellant and cold-gas stationkeeping systems only. CER not appropriate for bipropellant or dual-mode systems. Costs of AKM are not included.
‡‡ Input data range for items 3–6 calculated using min and max values of input data range for spacecraft bus cost CER in item 2.

Allocation of Program-Level Cost

Program Level Component	RDT&E	Theoretical First Unit
Program Management	20%	30%
Systems Engineering	40%	20%
Product Assurance	20%	30%
System Evaluation	20%	20%

Heritage Cost Factors

Multiplicative Factors for Development Heritage (Apply to RDT&E Costs Only)	
New design with advanced development	> 1.1
Nominal new design—some heritage	1.0
Major modification to existing design	0.7 – 0.9
Moderate modifications	0.4 – 0.6
Basically existing design	0.1 – 0.3

Our Heritage Assumptions (34)

- Heritage factor for conventional satellites is 0.3.
- Heritage factor for inflatable-structure space vehicles is between 1-1.5 depending on the diameter. The statements below are also taken into consideration.
- The inflatable antenna has a range of 10 to 50 meters in size will have the following advantage over current technology (advantages increase with size).
- Lower cost by 1 to 2 orders of magnitude.
- Lower stored volume 1 to 2 orders of magnitude.
- Lower mass by factors of 2 to 8.

Breakdown of Small Satellites Costs

Subsystem/Activity	Fraction of Spacecraft Bus Cost (%)	Non-Recurring Percentage (%)	Recurring Percentage (%)
1.0 Payload	40.0%	60%	40%
Bus Total	**100.0%**	**60%**	**40%**
2.1 Structure	18.3%	70%	30%
2.2 Thermal	2.0%	50%	50%
2.3 EPS	23.3%	62%	38%
2.4a TT&C	12.6%	71%	29%
2.4b C&DH	17.1%	71%	29%
2.5 ADCS	18.4%	37%	63%
*2.6 Propulsion**	8.4%	50%	50%
Wraps			
3.0 IA&T	13.9%	0%	100%
4.0 Program Level	22.9%	50%	50%
5.0 GSE	6.6%	100%	0%
6.0 LOOS	6.1%	0%	100%
Total	**189.5%**	**92.0%**	**97.5%**

* Propulsion costs may be excluded if, as is the case with many small satellites, the spacecraft doesn't have a propulsion system.

Software Development Cost

Flight Software	435 X KLOC
Ground Software	220 X KLOC
KLOC = Thousand of Lines of Code; cost without fee	
FACTORS FOR OTHER LANGUAGES	
Language	**Factor**
Ada	1.00
UNIX-C	1.67
PASCAL	1.25
FORTRAN	0.91

Ground Segment Development Cost Model

Ground Station Element	Development Cost Cost Distribution (%)	Development Cost as Percent pf Software Cost (%)
Facilities (FAC)	6	18
Equipment (EQ)	27	81
Software (SW)	33	100
Logistics	5	15
Systems Level Management	6	18
Systems Engineering	10	30
Product Assurance	5	15
Integration and Test	8	24

Earth Terminals, Antennas, and Communication Electronics

Maintanence	0.1 X (SW+EQ+FAC)/year
Contractor Labor	$160K/Staff Year
Government Labor	$110K/Staff Year

Operations and Support Cost in FY00$

Frequency	Cost (FY00$K)
SHF	(50 X D)+(400 X P) + 1,800
K,C Band	640
Ku Band	750
D = antenna diameter in m	P = RF power in Kw

Launch Vehicle Costs in FY00$M

Launch Vehicles	Maximum Payload-to-Orbit (kg)			Unit Cost (FY00$M)	Cost per kg to LEO (FY00$K/kg)
	LEO	GTO	GEO		
USA					
Atlas II	6,580	2,810		80–90	12.2—13.7
Atlas II A	7,280	3,039		85–95	11.7–13.0
Atlas II AS	8,640	3,606		100–110	11.6–12.7
Athena 1	800			18	22.5
Athena 2	1,950			26	13.3
Athena 3	3,650			31	8.5
Delta II (7920, 7925)	5,089	1,840		50–55	9.8–10.8
Pegasus XL	460			13	28.3
Saturn V	127,000			820	6.5
Shuttle* (IUS or TOS)	24,400	5,900	2,360	400	16.4
Titan II	1,905			37	19.4
Titan IV	21,640	8,620	5,760 (Centaur)	214 (270)	9.9
Taurus	1,400	450		20–22	14.3–15.7
ESA					
Ariane 4 (AR40)	4,900	2,050		50–65	10.2–13.3
Ariane 4 (AR42P)	6,100	2,840		65–80	10.7–13.1
Ariane 4 (AR44L)	9,600	4,520		95–120	9.9–12.5
Ariane 5 (550 km)	18,000	6,800		130	7.2
CHINA					
Long March C23B	13,600	4,500	2,250	75	5.5
RUSSIA					
Proton SL-13	20,900			55–75	2.6–3.6
Kosmos C-1	1,400			11	7.9
Soyuz	7,000			13–27	1.9–3.9
Tsyklon	3,600			11–16	3.1–4.4
Zenit 2	13,740			38–50	2.8–3.6
JAPAN					
H-2	10,500	4,000	2,200	160–205	15.2–19.5
J-1	900			55–60	61.1–66.7
GTO = Geosynchronous Transfer Orbit; GEO = Geostationary Orbit; LEO = Low-Earth Orbit					

* There is no official price for a Space Shuttle launch. Following the Challenger loss, only government payloads have been allowed. The GAO has assigned a price of $400 million per flight, but the actual cost depends strongly on the flight rate.

COST ESTIMATING FOR RDT&E (FY00$K)

Cost Component	Parameter, X (units)	Input range	Value	Cost (FY00$K)	SE (%)	SE (FY00$K)	Heritage Factor
1. Payload							
1.1 IR Sensor	aperture dia (m)	0.2-1.2	0.00E+00	0		0	0.3
1.2 Optical Sensor	aperture dia (m)	0.2-1.2	1.19E+00	42,586		19,336	0.3
1.3 Communications	subsystem wt (kg)	65-395	14	1,484	51%	757	0.3
Payload Total				**44,069**		**20,093**	
2. Spacecraft	s/c dryweight (kg)	235-1153	0	0	33%	0	0.3
2.1 Structure	structure weight (kg)	54-392	106.691858	2,272	38%	863	0.3
2.2 Thermal	x1=thermal wt (kg)	3-48	22.9031854	863	45%	388	0.3
	x2=s/c wt+payload wt (kg)	210-404	0	0	32%	0	
2.3 Electrical (EPS)	x1=EPS wt (kg)	31-491	152.355973	2,866	57%	1,634	0.3
	x2=BOL power (W)	100-2400	0	0	36%	0	
2.4 TT&C/DH	TT&C/DH wt (kg)	12-65	22.9031854	1,772	57%	1,010	0.3
2.5 Attitude Det(ADCS)	ADSC wt (kg)	20-160	30.4427434	2,690	48%	1,291	0.3
2.6 Apogee kick motor	AKM wt (kg)	81-966	0	0	0%	0	0.3
S/C Bus Total				**10,463**		**5,187**	
3. Integration Assembly and test (IA&T)	S/C bus + payload total RDT&E cost (FY00$K)	2703-395,529	54532.4167	**12,713**	46%	**5,848**	
4.Program Level	S/C bus + payload total RDT&E cost (FY00$K)	4607-523,757	54532.4167	**18,899**	36%	**6,804**	
5.Ground Support Equipment (GSE)	S/C bus + payload total RDT&E cost (FY00$K)	24,465-581,637	54532.4167	**10,177**	34%	**3,460**	
		TOTAL RDT&E (FY00$K)		**96,323**		**41,392**	

Multiplicative Factors for Development Heritage:

New design with advanced development	>1.1
Nominal new design-some heritage	1.0
Major modification to existing design	0.7-0.9
Moderate modifications	0.4-0.6
Basically existing design	0.1-0.3

COST ESTIMATING FOR THEORETICAL FIRST UNIT (TFU) (FY00$K)

Cost Component	Parameter, X (units)	Input range	Value	Cost (FY00$K)	SE (%)	SE (FY00$K)	Heritage Factor
1. Payload							
1.1 IR Sensor	aperture dia (m)	0.2-1.2	0	0		0	0.3
1.2 Optical Sensor	aperture dia (m)	0.2-1.2	1.188422935	17,014		7,734	0.3
1.3 Communications	subsystem wt (kg)	65-395	14	588	43%	253	0.3
Payload Total				**17,602**		**7,987**	
2. Spacecraft	s/c dryweight (kg)	154-1389	0	0	36%	0	0.3
2.1 Structure	structure weight (kg)	54-560	106.6918575	419	39%	164	0.3
2.2 Thermal	thermal wt (kg)	3-87	22.90318542	139	61%	85	0.3
2.3 Electrical (EPS)	EPS wt (kg)	31-573	152.3559726	1,555	44%	684	0.3
2.4 TT&C/DH	TT&C/DH wt (kg)	13-79	22.90318542	1,128	41%	462	0.3
2.5 Attitude Det(ADCS)	ADSC wt (kg)	20-192	30.44274335	1,249	34%	425	0.3
2.6 Apogee kick motor	AKM wt (kg)	81-966	0	0	20%	0	0.3
S/C Bus Total				**4,491**		**1,820**	
3. Integration Assembly and test (IA&T)	S/C bus wt. + payload wt. (kg)	348-1537	229.6089565	**2,388**	44%	**1,051**	
4.Program Level	S/C bus + payload total recurring cost (FY00$K)	15,929-1,148,084	22,093	**7,534**	39%	**2,938**	
5.Ground Support Equipment (GSE)	N/A						
6. Launch & Orbit Operations Support (LOOS)	S/C bus wt. + payload wt. (kg)	348-1537	229.6089565	**1,125**	42%	**473**	
		TOTAL RDT&E (FY00$K)		**33,139**		**14,268**	

COST ESTIMATING FOR SOFTWARE DEVELOPMENT COSTS (FY00$K)

Cost Component	Parameter, X (units)	Value	Cost (FY00$K)	Language	Language Factor	Heritage Factor
Flight Software	KLOC	26	5,655	ADA	1	0.5
Ground Software	KLOC	100	22,000	ADA	1	1

COST ESTIMATING FOR SPACE AND LAUNCH SEGMENT COSTS (FY00$K)

Total Units Produced: 4

Learning Curve Slope: 95% **Production Cost:** 3.61

Cost Component	Parameter, X (units)	Value	RDT&E Cost (FY00$K)	1st Unit Cost (FY00$K)	2nd - Final Total Unit Cost (FY00$K)	Total Cost (FY00$K)	SE (FY00$K)
1. Payload							
1.1 IR Sensor	aperture dia (m)	0	0	0	0	0	0
1.2 Optical Sensor	aperture dia (m)	1.188422935	42,586	17,014	44,406	104,005	47,256
1.3 Communications	subsystem wt (kg)	14	1,484	588	1,535	3,607	1,670
Payload Total			**44,069**	**17,602**	**45,941**	**107,612**	**48,105**
2. Spacecraft	s/c dryweight (kg)	0	0	0	0	0	0
2.1 Structure	structure weight (kg)	106.6918575	2,272	419	1,094	3,785	1,454
2.2 Thermal	thermal wt (kg)	22.90318542	863	139	363	1,365	694
2.3 Electrical (EPS)	EPS wt (kg)	152.3559726	2,866	1,555	4,060	8,481	4,104
2.4 TT&C/DH	TT&C/DH wt (kg)	22.90318542	1,772	1,128	2,944	5,844	2,679
2.5 Attitude Det(ADCS)	ADSC wt (kg)	30.44274335	2,690	1,249	3,261	7,200	2,825
2.6 Apogee kick motor	AKM wt (kg)	0	0	0	0	0	0
S/C Bus Total			**10,463**	**4,491**	**11,721**	**26,675**	**8,819**
3. Integration Assembly and test (IA&T)	S/C bus + payload total RDT&E cost (FY00$K)	54532.41667	**12,713**	**2,388**	**6,233**	**21,334**	**9,641**
4.Program Level	Same as previous	54,532	**18,899**	**7,534**	**19,663**	**46,096**	**17,410**
5.Ground Support Equipment (GSE)	S/C bus + payload total RDT&E cost (FY00$K)	54532.41667	**10,177**	**N/A**	**N/A**	**10,177**	**3,460**
6. Launch & Orbit Operations Support (LOOS)	S/C bus wt. + payload wt. (kg)	229.6089565	**N/A**	**1,125**	**2,936**	**4,062**	**1,706**
7. Flight Software	Kilo Lines of Code	26	**5,655**	**0**	**0**	**5,655**	**N/A**
Total Space Segment Cost to Contractor			**101,978**	**33,139**	**86,494**	**221,611**	
10% Contractor Fee			**10,198**	**3,314**	**8,649**	**22,161**	
Total Space Segment Cost to Government			**112,175**	**36,453**	**95,143**	**243,772**	
8. Launch Segment				**13,000**	**39,000**	**52,000**	
Total Cost of Deployment						**295,772**	**71,042**

GROUND STATION DEVELOPMENT COST MODEL (FY00$K)

Cost Component	Development Cost wrt Software Cost (%)	Cost(FY00$K)
Software	100	22,000
Equipment	81	17,820
Facilities	18	3,960
Logistics	15	3,300
Systems Level		
Management	18	3,960
Systems Engineering	30	6,600
Product Assurance	15	3,300
Integration and Test	24	5,280
Total		**66,220**

ANNUAL OPERATIONS AND MAINTENANCE COST (FY00$K)

Cost Component	Number of Personnel	Cost(FY00$K)
Contractor Labor	10	1,600
Government Labor	0	0
Maintenance		4,378
Total Annual Cost		**5,978**

Life-Cycle Cost Estimate (FY00$K)

Years Spacecraft Life: *10*

Cost Component	Cost(FY00$K)
Initial Deployment	
Space Segment	243,772
Launch Segment	52,000
Ground Segment	66,220
Subtotal	361,992
Operations and Maintenance	
Annual Ops and MNX	5,978
Total for System Life	59,780

COST UNCERTAINTY

Element	TFU Cost ($M)	System Technology Level	System Tech. Std. Dev. ($M)	Cost Estimate Std. Dev. ($M)	Combined Std. Dev. ($M)
S/C Bus	4.49	6 (10%)	0.45	0.67	0.81
Payload	17.60	5 (15%)	2.64	2.64	3.73
Total	22.09				
		Step 1: Sum			4.54
		Step 2: RSS			3.82
		Step 3: **Average**			4.18

For Small Satellite Cost Model

Similar Satellite

IKONOS		**NEW SATELLITE**	
h0(km)	681	**hi(km)**	1666.219
landa0(m-6)	9.00E-07	**landai(m-6)**	9.00E-07
res0(m)	0.95	**resi(m)**	5
height0(inch)	31	**heighti(m)**	3.66E-01
width0(inch)	31	**widthi(m)**	3.66E-01
length0(inch)	61	**lengthi(m)**	7.20E-01
mass0(kg)	109	**massi(kg)**	23.55611365
power0(w)	350	**poweri(w)**	75.63889703
aperture0(cm)	1.57E+02	**aperturei(cm)**	7.32E+01
ratio	4.65E-01		

Similar Satellite Costs

COST (00$K)	**tfu**	**rdte**
payload cost	17013.77562	42585.51111
spacecraft cost	20016.20661	50100.60131
total spacecraft cost	70116.80792	
software	27655	
ground station	66000	
maintenance	2500	
life time	5	10
relaunches	2	
launch cost	208000	
# of satellites	*8*	*16*
learning curve	*0.95*	*0.95*
production cost mutliplie	6.859	13.0321
	total life cycle-cost	**637608.8074**

RDTE and TFU payload costs are estimated
from table of satellite only cost

UAV Costs

PARAMETERS	Helios cost(00$K)	Global Hawk cost(00$K)
unit cost	$15,000.00	$14,000.00
# UAVs	10	10
learning curve	0.95	0.95
multiplier	8.43	8.43
fleet cost	$126,450.00	$118,020.00
rdte cost	$50,000.00	$36,000.00
payload cost	$120,477.50	included in unit cost
operating cost	$1.10	$1.10
ground station	$20,000.00	$20,000.00
cruise airspeed(mph)	22	350
risk	new technology risks	no risk(proven)
fligh time	up to 6 months	up to 40 hours
TOTAL COST	**$818,727.50**	**$495,145.00**

APPENDIX B: Resolution Requirements

Ground Resolution Requirements for Object Identification (in meters) (9)

TARGET	DETECTION	GENERAL ID	PRECISE ID	DESCRIPTION	TECHNICAL ANALYSIS
Bridges	6	4.5	1.5	1	0.3
Communications					
Radar	3	1	0.3	0.15	0.015
Radio	3	1.5	0.3	0.15	0.015
Supply Dumps	1.5	0.6	0.3	0.03	0.03
Troop Units	6	2	1.2	0.3	0.15
Airfield facilities	6	4.5	3	0.3	0.15
Rockets/Artillery	1	0.6	0.15	0.05	0.045
Aircraft	4.5	1.5	1	0.15	0.045
C2 Headquarters	3	1.5	1	0.15	0.09
SSM/SAM Sites	3	1.5	0.6	0.3	0.045
Surface Ships	7.5	4.5	0.6	0.3	0.045
Vehicles	1.5	0.6	0.3	0.06	0.045
Land Mines	9	6	1	0.03	0.09
Ports and Harbors	30	15	6	3	0.3
Coasts/Beaches	30	4.5	3	1.5	0.15
Rail Yards & Shops	30	15	6	1.5	0.4
Roads	6-9	6	1.8	0.6	0.4
Urban Areas	60	30	3	3	0.75
Terrain		90	4.5	1.5	0.75
Surfaced Submarines	30	6	1.5	1	0.03

APPENDIX C: Design of Coverage Hours by Using STK

STK Coverage

Access	Start Time (LCLG)	Stop Time (LCLG)	Duration (sec)
1	19:00:00	19:37:58	2278.266
2	20:07:10	20:44:39	2249.601
3	21:22:10	21:59:39	2249.557
4	2:20:08	2:28:53	524.829
5	3:35:08	3:43:53	524.891
6	4:23:35	5:07:03	2607.915
7	5:38:35	6:22:03	2607.908
8	6:47:02	7:35:23	2900.281
9	8:02:02	8:50:23	2900.279
10	9:09:56	9:55:37	2740.966
11	10:24:56	11:10:37	2740.968
12	11:30:47	12:12:48	2521.033
13	12:45:47	13:27:48	2521.043
14	13:47:58	14:33:41	2742.921
15	15:02:58	15:48:41	2742.932
16	16:08:15	16:56:35	2900.103
17	17:23:14	18:11:35	2900.1
18	18:36:36	19:20:02	2605.512
total duration (sec)			**28238.534**
total duration(hr)			**7.84**

APPENDIX D: Utilities of MOEs

	Weights	MIN 0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	MAX
COST	**30**	3.3	2.7	2.2	1.8	1.5	1.3	1.1	1	0.8	0.6	0.3
RISK	**10**	Existing	-	-	-	-	One new	-	-	-	-	Two new
PRIMARY RESOLUTION	**9**	1	1	1	0.9	0.8	0.8	0.7	0.6	0.4	0.2	0
SECONDARY RESOLUTION	**3**	5	4.5	3.5	2.5	1.5	1.1	0.9	0.8	0.5	0.3	0
PRIMARY COVERAGE	**9**	6	6.6	7.2	7.8	8.4	9	9.6	10	11	11	12
SECONDARY COVERAGE	**3**	6	6.6	7.2	7.8	8.4	9	9.6	10	11	11	12
LENGTH OF FOV	**4**	1.9	5	8	11	14	17	20	23	26	30	33
IMAGE DLINK DELAY	**6**	126	113	101	88	76	63	50	38	25	13	0
UPGRADEABILITY	**6**	0	1	2	3	4	5	6	7	8	9	10
TIME TO TARGET	**10**	1.3	1.1	1	0.9	0.8	0.6	0.5	0.4	0.3	0.1	0
NUMBEROF SIMULTANEOUS CUSTOMERS	**10**	1	3.4	5.8	8.2	11	13	15	18	20	23	25
TOTAL	**100**	-	-	-	-	-	-	-	-	-	-	-

APPENDIX E: Design Parameters for Satellites

Orbit Parameters

2705 KM ALTITUDE		
PERIOD	P(min)	143.6068
S.MAJ.AXIS	a(km)	9083.881081
ECCENTRICITY	e	0
RADIUS PERIGEE	Rp(km)	9083.881081
RADIUS APOGEE	Ra(km)	9083.881081
HEIGHT PERIGEE	Hp(km)	2705.881081
HEIGHT APOGEE	Ha(km)	2705.881081
MEAN MOTION	n(rad/s)	0.000729225
TRUE ANOMALY	v(rad)	1.57075
MEAN ANOMALY	M(rad)	1.57075
TIME OF FLIGHT	delta t(sec/min)	2153.998066
GRAVITATIONAL CONS.	mu(km^3/s^2)	398600.5
ECCENTRIC ANOMALY	E	4.63268E-05
INCLINATION	I(deg)	109.96

[SMAD TABLES 6-2, 6-3;137,140]

2705 KM ALTITUDE		
J2	0.00108263	
mean motion(deg/day)	3609.809072	
Radius Earth(km)	6378	
a(km)	9083.881081	
e	0	
inclination(deg)	109.96	
capomegadot(deg/day)	0.986351628	[SMAD EQ 6-19, 143]
littleomegadot(deg/day)	-0.603315053	[SMAD EQ 6-20, 143]

?V

[SMAD Table 6-5, 149]

CONSTANTS	
EARTH GRAVITATIONAL CONSTANT(KM^3/S^2)	398600.5
EARTH RADIUS(KM)	6378
GIVEN	
PARKING ORBIT ALTITUDE(KM)	200
TRANSFER ORBIT ALTITUDE(KM)	2705
STEPS(PAGE 147-EQUATIONS FOR HOHMANN)	
1. TRANSFER ORBIT SEMI MAJOR AXIS(KM)	1452.5
2. PARKING ORBIT VELOCITY(KM/S)	44.64305657
3. TRANSFER ORBIT VELOCITY(KM/S)	12.13906634
4. PARKING TO TRANSFER VELOCITY(KM/S)	60.9227482
5. TRANSFER TO FINAL ORBIT VELOCITY(KM/S)	4.50445458
6. PARKING ORBIT DELTA-V(KM/S)	16.27969163
7. TRANSFER ORBIT DELTA-V(KM/S)	7.63461176
8. TOTAL DELTA-V(KM/S)	**23.91430339**

Optic Scale

IKONOS		NEW SATELLITE	
h0(km)	681	***hi(km)***	2705.881
landa0(m-6)	9.00E-07	***landai(m-6)***	9.00E-07
res0(m)	0.95	***resi(m)***	5
height0(inch)	31	***heighti(m)***	5.94E-01
width0(inch)	31	***widthi(m)***	5.94E-01
length0(inch)	61	***lengthi(m)***	1.17E+00
mass0(kg)	109	***massi(kg)***	62.12364
power0(w)	350	***poweri(w)***	199.4796
aperture0(cm)	1.57E+02	**aperturei(cm)**	1.19E+02
ratio	7.55E-01		

Bus Design

ELECTRO-OPTICAL SENSOR		
MASS(KG)	62.123635	
POWER(W)	199.47956	
COMMUNICATIONS		
MASS(KG)	14	
POWER(W)	200	
TOTAL		
MASS(KG)	7.61E+01	
POWER(W)	3.99E+02	
DRY MASS(KG)	3.64E+02	[SMAD TABLE 10-5, 312]
AVERAGE POWER(W)	5.71E+02	[SMAD TABLE 10-9, 316]
PROPELLANT MASS(KG)	4.15E+02	[SMAD TABLE 10-6, 312]

Weight Budget

ELEMENT OF WEIGHT BUDGET	**ESTIMATE % OF PAYLOAD MASS (KG)**	**ESTIMATED MASS (KG)**
PAYLOAD	100	98.373
STRUCTURES	75	73.779
THERMAL	16.1	15.838
POWER	107.1	105.357
TT$C	16.1	15.838
ATT. CONTROL	21.4	21.052
PROP(DRY)	21.4	21.052
MARGIN(KG)	12.5	12.297
SPACECRAFT DRY MASS(KG)		**363.585**
PROPELLANT MASS(KG)		415.214
SPACECRAFT LOADED MASS(KG)		778.799

Volume
[SMAD Table 10-28,337]

AVERAGE DENSITY(KG/M^3)	79
SPACECRAFT LOADED WEIGHT(KG)	7.79E+02
SPACECRAFT VOLUME(M^3)	9.86E+00
LINEAR DIMENSION(M)	2.30E+00
BODY AREA(M^2)	5.29E+00
MOMENT OF INERTIA(KG*M^2)	9.55E+11
HEIGHT(M)	3.58817

Solar Array

AVERAGE POWER(KM)	5.71E+02		ASSUME	
ORBIT ALTITUDE(KM)	2705		**Xd**	0.8
ECLIPSE DURATION(MIN)	35.63	BACK OF TEXT	**Xe**	0.6
DESIGN LIFETIME(YR)	10			
ORBIT PERIOD	143.6068			
DARK TIME(MIN)	107.9768			
POWER REQUIRED(W)	1027.213	EQ. 11-5		
POWER OUTPUT(W/M^2)	301	MULTIJUNCTION SOLAR CELLS		
INHERENT DEGRADATION	0.77			
POWER-BOL(W/M^2)	231.77			
DEGRADATION PER YEAR	0.005			
LIFETIME DEGRADATION	0.95111	EQ. 11-7		
POWER-EOL(W/M^2)	220.4388			
AREA REQUIRED(M^2)	4.659854	EQ. 11-9		
MASS OF SOLAR ARRAY(KG)	41.0885			

Moments of Inertia
[SMAD Table 10-29]

SOLAR AREA OFFSET(M)-La	7.509235591
SOLAR ARRAY MOMENT OF INERTIA(KG*M^2)	
PERPENDICULAR TO ARRAY FACE	2324.315187
PERPENDICULAR TO ARRAY AXIS	2320.619499
ABOUT ARRAY AXIS	3.695687053
BODY MOMENT OF INERTIA(KG*M^2)	
PERPENDICULAR TO ARRAY FACE	9.55E+11
PERPENDICULAR TO ARRAY AXIS	9.55E+11
ABOUT ARRAY AXIS	9.55E+11
TOTAL	
PERPENDICULAR TO ARRAY FACE	9.55E+11
PERPENDICULAR TO ARRAY AXIS	9.55E+11
ABOUT ARRAY AXIS	9.55E+11

APPENDIX F: Design Parameters for Small Satellites

Orbit Parameters

1666 KM ALTITUDE		
PERIOD	P(min)	119.6723097
S.MAJ.AXIS	a(km)	8044.219
ECCENTRICITY	e	0
RADIUS PERIGEE	Rp(km)	8044.219
RADIUS APOGEE	Ra(km)	8044.219
HEIGHT PERIGEE	Hp(km)	1666.219
HEIGHT APOGEE	Ha(km)	1666.219
MEAN MOTION	n(rad/s)	0.000875071
TRUE ANOMALY	v(rad)	1.57075
MEAN ANOMALY	M(rad)	1.57075
TIME OF FLIGHT	delta_t(sec/min)	1794.998034
GRAVITATIONAL CONS.	mu(km^3/s^2)	398600.5
ECCENTRIC ANOMALY	E	4.63268E-05
INCLINATION	I(deg)	102.89
[SMAD TABLES 6-2, 6-3;137,140]		

1666 KM ALTITUDE		
J2	0.00108263	
mean motion(deg/day)	4331.771743	
Radius Earth(km)	6378	
a(km)	8044.219	
e	0	
inclination(deg)	102.89	
capomegadot(deg/day)	0.986275454	[SMAD EQ 6-19, 143]
littleomegadot(deg/day)	-1.661180287	[SMAD EQ 6-20, 143]

Optic Scales

IKONOS		NEW SATELLITE	
h0(km)	681	***hi(km)***	1666.219
landa0(m-6)	9.00E-07	***landai(m-6)***	9.00E-07
res0(m)	0.95	***resi(m)***	5
height0(inch)	31	***heighti(m)***	3.66E-01
width0(inch)	31	***widthi(m)***	3.66E-01
length0(inch)	61	***lengthi(m)***	7.20E-01
mass0(kg)	109	***massi(kg)***	23.55611365
power0(w)	350	***poweri(w)***	75.63889703
aperture0(cm)	1.57E+02	**aperturei(cm)**	7.32E+01
ratio	4.65E-01		

Bus Power

PAYLOAD POWER(W)	7.56E+01
AVERAGE POWER(W)	1.08E+02

Weight Budget

ELEMENT OF WEIGHT BUDGET	EST. % OF PAYLOAD MASS (KG)	ESTIMATED MASS(KG)
PAYLOAD	100	23.55611365
STRUCTURES	75	17.66708524
THERMAL	16.1	3.792534297
POWER	107.1	25.22859772
TT$C	16.1	3.792534297
ATT. CONTROL	21.4	5.04100832
PROP(DRY)	21.4	5.04100832
MARGIN(KG)	12.5	2.944514206
SPACECRAFT DRY MASS(KG)		**87.06339604**
PROPELLANT MASS(KG)		4.97E+01
SPACECRAFT LOADED MASS(KG)		1.37E+02
MARGIN AS % OF DRY MASS		25%

Volume

[SMAD Table 10-28,337]

AVERAGE DENSITY(KG/M^3)	79
SPACECRAFT LOADED WEIGHT(KG)	1.37E+02
SPACECRAFT VOLUME(M^3)	1.73E+00
LINEAR DIMENSION(M)	1.29E+00
BODY AREA(M^2)	1.66E+00
MOMENT OF INERTIA(KG*M^2)	1.60E+08
HEIGHT(M)	2.00941

Solar Array

AVERAGE POWER(KM)	1.08E+02		ASSUME	
ORBIT ALTITUDE(KM)	1666.219		**Xd**	0.8
ECLIPSE DURATION(MIN)	35.63	BACK OF TEXT	**Xe**	0.6
DESIGN LIFETIME(YR)	10			
ORBIT PERIOD	119.6723			
DARK TIME(MIN)	84.04231			
POWER REQUIRED(W)	211.4203	EQ. 11-5		
POWER OUTPUT(W/M^2)	301	MULTIJUNCTION SOLAR CELLS		
INHERENT DEGRADATION	0.77			
POWER-BOL(W/M^2)	231.77			
DEGRADATION PER YEAR	0.005			
LIFETIME DEGRADATION	0.95111	EQ. 11-7		
POWER-EOL(W/M^2)	220.4388			
AREA REQUIRED(M^2)	0.959088	EQ. 11-9		
MASS OF SOLAR ARRAY(KG)	8.456811			

APPENDIX G: Design Parameters for UAVs

Optic Scale

IKONOS		NEW SATELLITE(UAV)	
h0(km)	681	***hi(km)***	20
landa0(m-6)	9.00E-07	***landai(m-6)***	9.00E-07
res0(m)	0.95	***resi(m)***	0.3
height0(inch)	31	***heighti(m)***	7.32E-02
width0(inch)	31	***widthi(m)***	7.32E-02
length0(inch)	61	***lengthi(m)***	1.44E-01
mass0(kg)	109	***massi(kg)***	0.942750924
power0(w)	350	***poweri(w)***	3.027181865
aperture0(cm)	1.57E+02	**aperturei(cm)**	1.46E+01
ratio	9.30E-02		

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VITA

First Lieutenant Arif ARIN graduated from Isiklar Military High School in Bursa, Turkey. He entered undergraduate studies at the Air Force Academy in Istanbul, Turkey where he graduated as a 2nd Lieutenant with a Bachelor of Science degree in Industrial Engineering on 30 August 1995. His first assignment was at the Cigli AFB, Izmir, Turkey as a student in Undergraduate Pilot Training in July 1995. In July 1996, he was assigned to Air Education Command, Izmir, Turkey. In February 1997 he attended Personnel Officer Course in Gaziemir, Izmir. After graduating from Personnel Officer Course, he was commissioned as a personal manager in Canakkale Radar Site. In August 2000, he entered the Graduate School of Engineering and Management, Aeronautics and Astronautics Department, Systems Engineering Program, AFIT.

First Lieutenant Ali DURMUS graduated from Besiktas Ataturk Anatolia High School in Istanbul, Turkey. He attended undergraduate studies at the Air Force Academy in Istanbul, Turkey where he graduated as a 2nd Lieutenant with a Bachelor of Science degree in Electronical Engineering on 30 August 1997. His first assignment was at the Çigli Air Force Base, Izmir for undergraduate pilot training (UPT). After graduating from UPT in April 1999, he was assigned to 9th Main Jet Base, Balikesir, Turkey as a F-16 pilot. In August 2000, he entered the Graduate School of Engineering and Management, Aeronautics and Astronautics Department, Systems Engineering Program, AFIT. After graduation he will return to his previous assignment, as a fighter pilot.

VITA-2

First Lieutenant Birce Boga BAKIRLI graduated from Bursa Anatolian High School in Bursa, Turkey. She entered undergraduate studies at the Air Force Academy in Istanbul, Turkey where she graduated as a 2nd Lieutenant with a Bachelor of Science degree in Industrial Engineering on 30 August 1998. Her first assignment was at the Cigli AFB, Izmir, Turkey as a student in Undergraduate Pilot Training in July 1998. In July 1999, she was assigned to Air Education Command, Izmir, Turkey. In February 2000 she attended Personnel Officer Course in Gaziemir, Izmir. After graduating from Personnel Officer Course she entered the Graduate School of Engineering and Management, Aeronautics and Astronautics Department, Systems Engineering Program, AFIT.

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14. ABSTRACT

In most recent years, both high-resolution imagery systems and images were only available to military and national security organizations. Distinctive changes within the commercial image industry allowed space-borne pioneers to provide high-resolution images. Space-borne Image Company's Ikonos satellite provides a 1-meter resolution for the past 3 years. Current development of 0.5-meter resolution will be offered in the near future. Access of these images is available in ground stations located worldwide in different regions. Studies have shown that these high quality images are eye-catching and may serve a purpose through its design; on contrary high cost and accessibility does not meet all the requirements of a nation or a region. A nation certainly cannot rely on a every 2.9 days on an average with high resolution.

This study seeks a commercial imaging solution foreign commercial company for reconnaissance needs in times of crisis. The best frequency of coverage for a single point on earth is available once for regional applications. Mission requirements are set well above the existing commercial imaging systems including; continuous coverage during daylight hours, and daily re-visitation; service 5 to 25 'simultaneous' customers in addition to competitive resolution and cost. Alternatives considered include satellites, small satellites, UAVs and mixed systems. Inflatable technologies that permit higher orbit attitude and solar-powered UAVs with extended on-station times are also evaluated in this study.

15. SUBJECT TERMS

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