Preliminary Design and Concept of Operations for a Small Tactical Imaging Satellite

by

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INTRODUCTION

Tactical commanders could use a reconnaissance satellite which is survivable, flexible in operations, and able to provide real time direct data of high quality imagery. By design, the imaging satellite would be inexpensive and mutually beneficial to all the armed services.

The imaging satellite is solar powered and 3 axis stabilized. A constellation of satellites in sun synchronous orbits will provide near worldwide coverage with revisit times of 90 minutes. Command and control will come from a single field unit, although many units may have receive capability. The satellite could be used during times of crisis or stored for future use when reconstitution of forces may be necessary.

The satellite will use binary optics and charge coupled devices (CCD) in its imagery system. Data compression is necessary because of bandwidth constraints inherent in the Defense Satellite Communication System (DSCS III).

PERFORMANCE REQUIREMENTS

Providing timely and accurate intelligence to the tactical commander is always vital in warfare. The Tactical Exploitation of National Capabilities (TENCAP) was established by the services for this very reason.

Captain Lamb of the Naval Space Command has stated that, "One meter resolution is the answer" for tactical imagery intelligence.[1] Additionally, timeliness is even more critical than resolution in order for a proper decision to be made when necessary. The objective is to provide direct downlink of imagery to the user in the field rather than routing information within the intelligence community and then waiting for the dissemination of the information.

SYSTEM GOALS

Lt. General Casey, Commander of the Air Force Space Division, stated, "I believe we can, for a reasonable cost, put up satellites that could track aircraft and ships, which would be a great asset to tactical commanders. The system needs to be centrally managed, and should be adaptable to the requirements of all the services, in fact, all the theater commanders, to be useful. The potential exists of expanding surveillance around the world to the point where it is going to be impossible to mass a large military force without being able to track it."[2]

The following goals have been established for this type of satellite. It must:

(1) be an adjunct to existing systems
(2) have real time downlink to users
(3) be robust; provide for graceful degradation of capability
(4) be able to be launched from a variety of sites
(5) be relatively inexpensive
(6) be amenable to long term storage as a war reserve asset
(7) have a mission lifetime of approximately two months

LIGHTSATS

The principle of LIGHTSATS (also referred to as SPINSATS or CHEAPSATS) is that small satellites can be built to perform the same missions as larger ones. Naturally, tradeoffs must be made and the smaller satellite will have reduced capabilities. However, assuming the satellite is designed for a single purpose and the limitations are understood, it provides an economical alternative to larger, more costly satellites. It is essential to keep the design simple because added capabilities are costly and size constraints restrict hardware as well. Key elements of flexibility, simplicity and low cost are diminished as new capabilities are added.

The following describes the Defense Advanced Research Projects Agency's (DARPA) program: "Lightsat is our new DARPA program whose goal is to provide enduring spaceborne support to the battlefield commander in conflicts where the use of our national space assets would be denied due to Soviet attacks on our satellites, ground stations or both. Owing to the critical nature of this support, DARPA was directed by Congress to develop the technologies needed to reconstitute some fraction of our current national command, control, communications, and intelligence capabilities. DARPA expects to demonstrate satellite systems that will be responsive to the commander's needs, but which will be less complex and less technically capable than the satellites they would replace during war ...with a goal of limiting booster and payload costs to less than $20 million."[3]

Credit for revitalizing interest in "lightsats" can in part go to the Space Systems Academic Group at the Naval Postgraduate School (NPS).[4] Currently, NPS is designing

<u>ORION</u>, a small, general purpose satellite bus which can be launched from a variety of expendable vehicles. It can also be launched from the Space Transportation System (STS).

OPTICAL SYSTEM DESIGN

The design of the optical system is constrained by the type of launch vehicle used. The two options considered for this design study were the SCOUT expendable launch vehicle and the Space Shuttle which permits launching a small satellite from a Get-Away-Special canister in the cargo bay (see Table 1).

Table 1
PHYSICAL LIMITS

	Basis	Total Length	Diameter	Payload Length	Total Mass	Payload Mass
Scout Launch	Large Fairing	1.558 m	0.965 m	0.75 m	190 kg	35 - 70 kg
GAS Launch	NPS ORION	0.89 m	0.48 m	0.33 m	120 kg	23 - 45 kg

The resolving power of a lens is estimated by the Rayleigh Criterion and the autocorrelation method. The angular resolution is then determined from the resolving power. Knowing these lens parameters, the ground resolution (smallest discernable object seen) is then calculated. From similar triangles (see Figure 1), F/r = H/R

F -- focal length
r -- resolving power (focal plane resolution)
H -- altitude
R -- ground resolution

R = 1 meter.

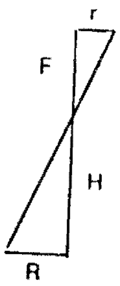

Figure 1 Ground Resolution Geometry

At this point, the design has neglected atmospheric effects (attenuation and scintillation) and detector resolution, which influence integration time for the sensor or limits swath width.

The system scan rate is usually limited by the detector. Either line or area charge coupled devices (CCD) will be used as the image detector. Exposure equals the product of the time the area is viewed and its intensity at the detector. In other words, the lower the object intensity, the longer the integration time must be for a detector of a given responsivity.

As the spacecraft orbits, its sensor scans across the track and relays data to the user (Figure 2). A similar technique using line detectors was successfully used by Landsat Thematic Mapper sensors.,[5,6]

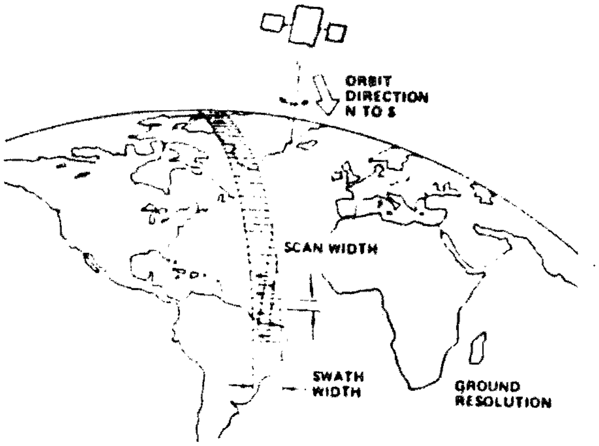

Figure 2 Concept of Collection Operations
(from Lansing, et al., 1979)

The design objective is to match the detector and optics to give approximately one meter ground sample distance (GSD) at nadir. An altitude of 300 km was selected as the starting point for this spacecraft, which is roughly the altitude for most Shuttle missions. 300 km is low enough for resolution requirements yet high enough to minimize propulsion requirements. Based on this altitude, telescope angular resolution must be arctan (1/300E+3) = 0.19 milliradians. If the detector pixel size is 10 microns, the focal length would have to be about 3 meters.

An important formula for the design is:

GSD = (h*r)/f
h -- height
r -- focal plane resolution
f -- focal length

For a given h, the objective is to keep r small while having f large. However r is directly proportional to f and inversely proportional to the lens diameter. Therefore, the only way to minimize GSD is to maximize the lens diameter and then find the best design within that constraint.

The emergence of a new technology called binary, or diffractive, optics makes an entirely new class of telescopes possible. Structures etched into the reflective or refractive surface alter the incident wavefront. This technology may well revolutionize the design of optical systems. A single diffractive element can be used to correct aberrations which once required a triple lens system.[7] Diffractive optics may be used in the visible and infrared spectrum resulting in potential weight and cost savings.

An indispensable tool is one of the ray trace and optical system design computer programs. The particular program used at the Naval Postgraduate School was "Super Oslo" by Sinclair Optics which is an interactive program that runs on Hewlett-Packard 9000/217 machines.

Two designs were analyzed. One was optimized for launch in a SCOUT and the other for launch from the shuttle. One is composed strictly of reflective elements (Ritchey-Chretien), and the other is catadioptric -- Maksutov (refer to Figures 3 and 4). The Ritchey-Chretien design eliminates coma and was used in the Landsat Thematic Mapper. The Maksutov was chosen because, "For a given aperture, the Maksutov outclasses all kinds of telescope in almost every respect. An expertly designed instrument is practically free from spherical aberration, coma and astigmatism, and may be arranged to produce a bright image on a wide flat field from a telescope of which the tube length may be as short as one fifth of the equivalent focal length of the system."[9]

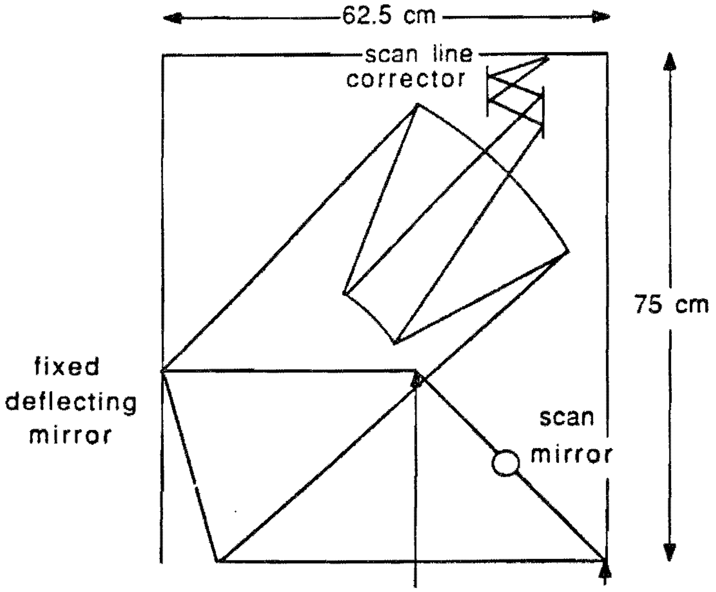

Figure 3 Scout Telescope Layout

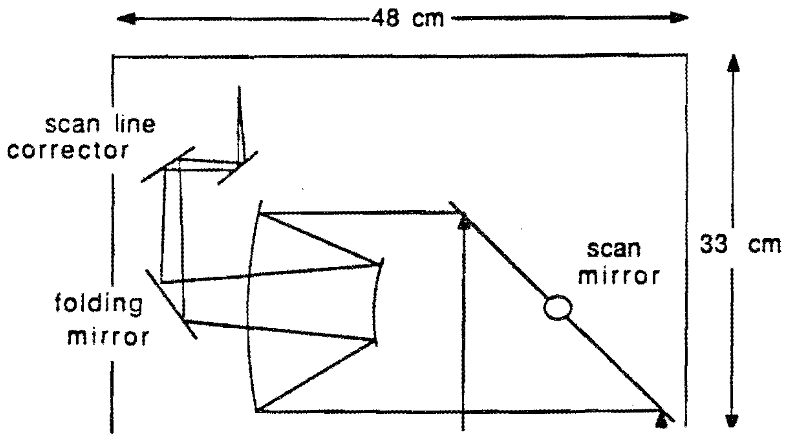

Figure 4 ORION Telescope Layout

Super Oslo was used to perform the design and optimization. In each case, location of the mirrors was determined by allowing for clearance of the rotating scan mirror. Table 2 provides a system comparison for the candidate systems. Note that the table does not tell the whole story. The modulation transfer functions for each system must be studied as well. From these, a feel can be gained regarding the degree of resolution lost at lower than the limiting spatial frequency.

Each system offers about the same ground sample distance (see Figure 5). From a qualitative point of view, no significant difference appears among the various designs.

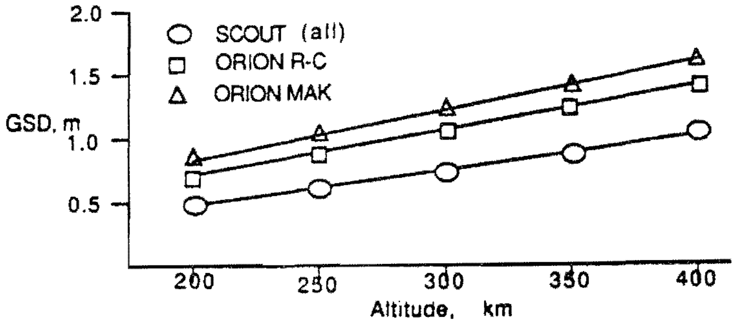

Figure 5 GSD vs Altitude by System

Table 2
COMPARISON OF CANDIDATE SYSTEMS
(distances in cm unless otherwise noted)

	SCOUT1 (.33)	SCOUT1 (.5)	SCOUT2 (.33)	SCOUT2 (.5)	SCOUT MAK	ORION (.33)	ORION (.5)	ORION MAK
Primary Diameter	28	28	28	28	28	20	20	20
EFL	175.1	120.7	108.8	72.0	120.6	156.0	72	93.9
Nadir GSD (300 km)	77	77	77	77	77	108	108	120
Spherical Aberration	.00061	.0072	.0338	-.558	.0047	-.144	.502	.046
Coma (xE-5)	-5.8	-48	-.48	-3000	-20	-120	290	50
Astigmatism (xE-5)	-13.6	-10	-14	-150	-1.8	4.6	-12	1.2
Distortion (xE-5)	44	-1.3	-.044	-3.3	-.48	1.5	-.28	.48
Cutoff Freq (lpmm)	272	395	450	662	395	218	473	326
Airy Radius (μm)	4.48	3.09	2.71	1.84	3.09	5.59	2.58	3.74

SYSTEM INTEGRATION

Detector pixel size must be reconciled with the optical system's designed resolution limit (including effects of atmospheric degradation). A problem arises from the size of the CCD pixels, which are three to five times larger than the focal plane resolution limited by optics. In other designs, tapered fiber optics were used to form a cone to enlarge the detector area. The base of the cone was used as the detector. In this application, the cones would have to be inverted in order for the base of the fibers to match the CCD pixel size. The tapered end of the fibers would act as the detector. Furthermore, the shape of the image can also be adjusted if it is necessary to correct for curvature of the field.

The spacecraft is three axis stabilized with its long axis pointing directly at nadir. A tilting scan mirror is required to scan the field of view. The scan must be corrected to avoid a zig zag pattern across the earth's surface; a scan line corrector similar to Landsat Thematic Mapper must be included in the design (see Figure 6).

Use of a four chip, 4096 by 4096 pixel detector results in a ground frame size of approximately four square km. To cover the ground track, the scan mirror must complete one cycle across the track and back per second. The required integration time for a shuttle-launched satellite at 15

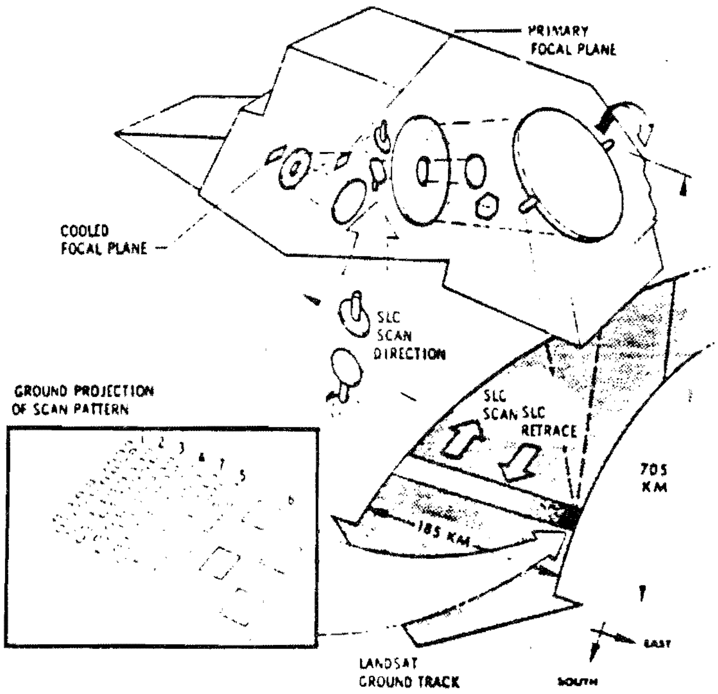

Figure 6 Landsat Scan Pattern Correction
(from Lansing, et al, 1979)

degrees turns out to be 5 milliseconds and for a SCOUT-launched satellite at 50 degrees is about 10 msec. (Refer to Table 3.) These calculations took into account atmospheric effects and noise. Landsat Thematic Mapper used 30 dB signal to noise ratio. A SNR of 30 dB was used as a baseline for required integration times.

LOWTRAN is an Air Force computer program which calculates transmission of radiant energy through the atmosphere. A variety of climatic and aerosol models are included, the U.S. standard atmosphere was used for this design.* Assuming readout time equals integration time (a conservative estimate), the corresponding frames/sec are 50 for a SCOUT launch and 100 for a shuttle launch. Unfortunately, the SCOUT can only image about one third of the area it will sweep (SW = 370 km) due to limitations of the time for the scan mirror to sweep. However, ORION is able to cover all of its area (SW = 160 km) due to its higher frame rate and smaller viewing area.

*Kneizys, F., et al., "Atmospheric Transmittance/Radiance: Computer Code LOWTRAN 6, Air Force Geophysical Laboratory, report number AFGL-TR-83-0817, 1 August 1983.

Table 3
INTEGRATION TIME CALCULATIONS

	NADIR VIEWING		MAXIMUM VIEWING ANGLE	
	SCOUT	ORION	SCOUT (50)	ORION (15)
Power, top of Atmosphere	1340 W/sq m			
Power in Visible (40%)	536			
Times transmittance	t = .8451 453	t = .8451 453	t = .7577 406	t = .8391 450
Times reflectance	95.1	r = 0.21 95.1	85.3	94.5
Lambertian Io (It/pi)	30	30	27	30
Reflected Into Angle	30	30	17.4	29
Times transmittance	25.6	25.6	13.2	24.3
Solid Angle Subtended	6.8E-13	3.5E-13	2.7E-13	3.2E-13
Times Solid Angle	1.75E-11	8.9E-12	3.6E-12	7.9E-12
Times Photons per sec per Watt	4.8E+7	2.5E+7	9.9E+6	2.2E+7
Times Quantum Eff. (50%)	2.4E+7	1.2E+7	5.0E+6	1.1E+7
Peak to Peak Noise	50	50	50	50
Signal for 30 dB S/N	50,000	50,000	50,000	50,000
Required Integration	2 msec	4.2 msec	10 msec	4.5 msec

DATA TRANSMISSION VOLUME

The DSCS III was chosen as the communication system with channel 6 providing 10 Watts transmit power and 50 MHz bandwidth employing an earth coverage antenna. Data will be encrypted using established formats. The 50 Mhz bandwidth should easily support a data rate of 6.0 Mbps.[2] Each frame is 4000 by 4000 pixels. Using two bits per pixel (allowing 4 grey shades), 32 Mbps are required per frame. Data compression is essential. A vector quantization algorithm allows a 16:1 data compression. This would permit approximately three 4 km by 4 km frames to be transmitted per second with no onboard image storage necessary. The tactical commander is limited to three frames per scan of the satellite's field of view.

SUMMARY

It is physically possible to put an optical system into a small satellite which can meet a ground sample distance of 1.0 meter. The ORION design can scan 160 km swath width and the SCOUT design can scan 370 km swath width.

ACKNOWLEDGEMENT

This paper is a brief overview of LT Neal Miller's thesis (unclassified version, June 1988).

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