Design concepts for space-borne multi-mission sensors for tactical military needs

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ABSTRACT

A standard electro-optical sensor can perform several different surveillance missions to support tactical military users. The missions include environmental sensing, land and ocean remote sensing, tactical missile tracking, and space object surveillance. The key is that while the spacecraft is a standard configuration for all missions, its design is a compromise between the specific requirements for each mission; the orbit chosen and operations mode for each mission also vary. Although sub-optimal for any given mission, standard sensor systems have the advantage of achieving a higher benefit-to-cost ratio by realizing economies of scale in production and reduced development. Point designs of three different multi-mission sensors are presented, supported by design analysis, and encompassing several approaches to telescope design, focal plane design, scanning system design, data processing system design, and orbits/coverage and operations. The resulting sensor system designs are highly capable, compared to existing systems, meet the performance goals established, and yet fit within the tactical satellite class.

1. INTRODUCTION

The subject of increased support from space systems for tactical war-fighting military operators has received great attention in recent years. A new genre of satellites, known as tactical satellites (tacsats), which would be flown as complements to the existing large steady-state satellite programs but be dedicated to tactical users, have been proposed as one solution for providing more support to the tactical user. The tactical satellites generally have the characteristics of being smaller than existing larger satellites (about 1000 lb class) and are designed to support the end-product data needs of tactical users. A large part of the focus of tactical support from space and tactical satellites is in the area of electro-optical surveillance and imaging, covering the mission areas of environmental monitoring, land and ocean remote sensing, tactical missile tracking, and theater surveillance of the battlefield. Many organizations encompassing all three services are exploring the concept of tactical satellites and developing a number of designs of space-borne sensor payloads which are each optimally designed for the given sensing mission addressed.

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Space Systems Division (SSD/XRP) has taken a different approach to the problem. When considering the commonality in spectral requirements, resolution, and mode of integration into the existing tactical infrastructure between the missions, a common sensor system can be designed and deployed to meet the requirements of each mission, if approached innovatively. This paper begins with a description of the mission requirements and the thought process behind the various kinds of common module/standardized approaches which can be pursued. Then description of several different designs of common/multi-functional sensor payloads is presented. The designs are not believed to be optimal, but are felt to serve as validation of the technical feasibility of developing a multi-functional sensor system, and allow for quantitative prediction of the level of performance which can be expected for the relatively small satellites proposed.

Another mission area believed capable of being addressed by the same common sensor design is space control (of which space object surveillance is a part). Although not a terrestrial tactical mission, it requires a similar level of performance as other tactical surveillance missions. In this case CINCSPACE (commander of U.S. Space Command) is the tactical user and space is his theater of interest. The concept of tactical satellites is really based on a different mode of space operations and is not limited to supporting tactical military operators. A number of strategic mission areas have also been identified where, under certain conditions, a need exists for augmentation of the current space systems supporting these missions. If a tactical satellite system infrastructure (including launch, space, control, and terminal segments) is in place, it is suited to support these strategic missions also. Arms control verification and "confidence building," consistent with the Bush administration's policy of promoting "transparency," falls in this category.

2. DESCRIPTION OF MISSION REQUIREMENTS

Figure 1 presents a summary of the requirements for each mission. Tactical user needs differ from strategic needs in some fundamental ways. Tactical operations are very dynamic, but in almost all cases are very localized (an operation typically stays confined within a theater or some portion of the theater). So the two dominating principles of the architecture of tactical satellites are (1) near-continuous availability of timely data, and (2) focussed coverage. Data downlink needs are also different for tactical operations. Data must be reduced or be reducible by the end user in near real-time to be of value (this is especially true of tactical missile tracking and warning). So focus in designing the system needs to be placed on ensuring that the end output to the user is in a form that he can act on (e.g. location of targets, environmental data, state vector of missile).

2.1 Environmental monitoring

The primary tactical need in the environmental monitoring area is cloud imagery, with near-continuous refresh of the cloud map (the validated requirement for cloud imagery update is 15 minutes). Resolution between 0.5 km (resolution of DMSP) and 5 km (resolution of GOES) is required. Spectral regions of interest are primarily visible (0.4 - 1.1 microns) and long-wave infrared (10 - 11 microns). The latter is required for thermal cloud imaging. Intermediate spectral intervals (such as those recorded by the NOAA polar orbiting weather satellite) also are

MULTI-MISSION SENSOR PERFORMANCE GOALS

MISSION	SPECTRAL BANDS (MICRONS)	RESOLUTION	FIELD OF VIEW
LAND AND OCEAN SENSING	0.4 - 1.1 3.5 - 3.9 8 - 11	10M	0.15 - 1.0 DEG WITHIN +/- 50 FIELD OF REGARD
ENVIRONMENTAL MONITORING	VARIOUS BANDS .55 - 12.5	.5 - 5KM	1000KM APPROX.
MULTI-SPECTRAL SENSING	VARIOUS BANDS .55 - 11.0	5 - 30M	300KM
TACTICAL MISSILE WARNING	2 - 5	TRACK POINT SOURCES (REVISIT <3 SEC)	3 DEGREES FROM GEO
SPACE SURVEILLANCE	0.4 - 1.1	25 MICRORADIANS	1.8 DEGREES

Figure 1

useful for purposes such as creating accurate sea surface temperature profile maps. The rapid refresh rate is driven by the dynamic nature of tactical land/sea operations. To provide this with a small number of spacecraft, the spacecraft must be deployed in either geostationary or highly elliptical orbits (for example, an 8-hour elliptical orbit with apogee of 27,000 km captures a good compromise of high altitude for long dwell time over the area of interest and low enough altitude that good resolution can be provided from a small aperture telescope). Data must be downlinked directly to the military operators in the area of interest.

2.2 Land and ocean remote sensing

Data from LANDSAT and other land and ocean remote sensing systems is used routinely by the tactical military community. Remote sensing satellites which provide topographical and oceanographic imagery in a number of spectral intervals in the visible and infrared wavebands may be useful. The systems need to be task-oriented so that individual tactical users may command the satellite to provide only the phenomenology data they need for their operations.

An additional requirement in this mission area is to provide moderately high resolution surveillance in the visible spectrum which can be used to locate targets of interest to the theater military operators, consistent with the Air/Land Battle 2000 doctrine. A low altitude orbit is required. The sensor field of view may be very narrow (approximately 1-3 degrees) but the system should be task-oriented so that the sensor may point transverse off-nadir within a field of regard of +/- 50 degrees. The altitude and inclination of deployment should permit the fields of regard of adjacent orbit passes to meet at the equator, so that one satellite can be guaranteed to provide 12 hour refresh globally (once per day on the ascending node and once on the descending node).

2.3 Tactical missile tracking

Tactical missile tracking involves detecting and establishing a state vector for small, short-burn intra-theater missiles, e.g. SS-21 Soviet missiles. Due to the short burn times of these missiles, and considering that cloud cover up to 30,000 feet is often present in areas such as Europe and that three separate detection points ("hits") on a missile trajectory are required to obtain an accurate velocity state vector, the sensing system must have a re-visit capability of

2-3 seconds over the entire area of interest. A 3 x 3 degree field of view from geostationary is sufficient to cover the area of interest, which helps to make the rapid re-visit requirement achievable.

2.4 Space object surveillance

The purpose of this mission is to detect point sources (space objects) to augment the existing ground-based space surveillance system.

3. MULTI-MISSION SENSOR APPROACHES

Referring to Figure 1, there is a large degree of overlap between the requirements of the five missions described. While it is possible to design a separate sensor system for each mission, with each sensor's design optimized to perform that mission, the large degree of commonality invites one to attempt to design one system to meet all of the requirements.

Many different approaches exist for addressing multi-mission systems. One is to build one system skeleton, with as many elements of the system common as possible (among optics, focal plane, and data processing and downlink), but have some unique elements for each mission. This would be a "modular" system; one example of such an approach is the Common-Module FLIR system, where a user chooses from a small assortment of optics modules, focal plane modules, and processing modules to suit his application. In the case of a tactical satellite sensor, different satellites would be assembled from the common elements and each satellite would be flown in a different orbit, depending on its mission. Hence it may be possible to use one set of optics for both low and high altitude missions so that high ground resolution and narrow field of view are achieved from low altitude deployment while coarse ground resolution and wide field of view are achieved from high altitude deployment.

Another approach is to develop one standard sensor payload (hence one satellite) which could be deployed in different orbits to perform the various missions. This approach is an extension of the common-module approach described above. A third approach is to deploy one system which, depending on how it is operated, performs different functions. This system would be a "multi-functional" satellite.

What follows are descriptions of the designs of three different examples of multi-mission sensor systems. The first is a standard satellite which, depending on the orbit chosen, performs either environmental surveillance, land and ocean remote sensing, or theater missile tracking. The second sensor (multi-wavelength) performs both environmental sensing and missile tracking when deployed in geostationary orbit, or land/ocean imaging if deployed in a low altitude orbit. The third sensor (visible only) is deployed in a low altitude orbit and performs space object surveillance if pointed into deep space, or land sensing if pointed at the earth.

4. DESCRIPTION OF MULTI-FUNCTIONAL SENSOR DESIGNS

4.1 Multi-mission sensor one

The first approach (developed by A.H. Sarrafian) for a multi-functional sensor which was explored was to design an entire sensor system (optics, focal plane, data processing) which performs different missions when deployed in different orbits without requiring any changes to the sensor system for each mission. Figure 2 presents a summary of the design parameters of the system. The three missions addressed are weather surveillance from a highly elliptical 8 hour orbit, tactical missile tracking from geostationary orbit, and land sensing from 500 km circular orbit.

4.1.1 System design

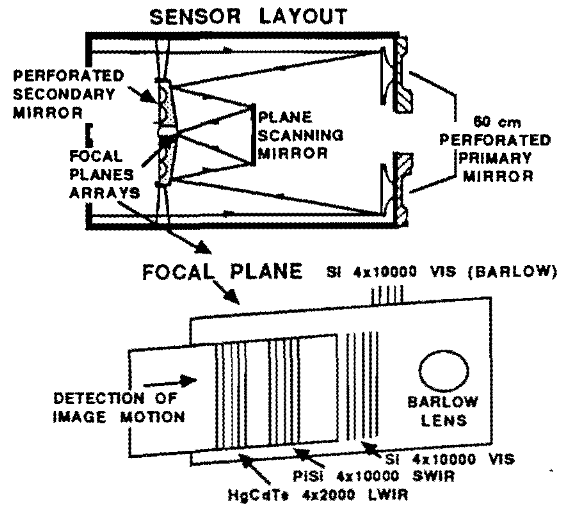
The optical element uses an f/3.33 Ritchey-Chretien telescope having an aperture of 0.6 m and an effective focal length of 2.0 m. To effect a compromise between the large diameter aperture required for adequate resolution performance in a low altitude and small aperture (i.e. low sensor weight) required for missile tracking in geostationary orbit, a 60 cm diameter was selected. An all-reflecting telescope is a necessity so that the same optical system can be used at all wavelengths. The Ritchey-Chretien design, a modification of the standard Cassegrain, employs hyperbolic primary and secondary mirrors in order to correct for the aberration known as coma which is present in most all-reflecting telescopes. Elimination of this defect greatly increases the field of view and permits imaging over the 3 degree area.

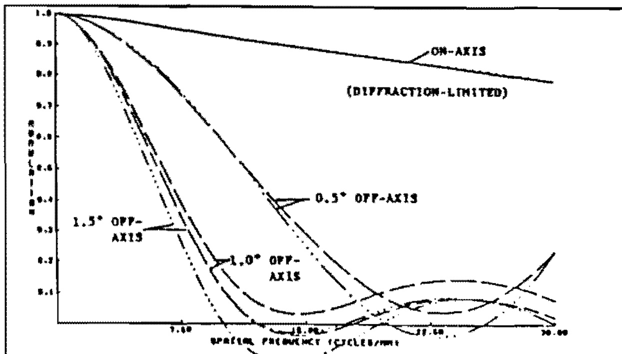
A constraint imposed by the speed of this system (f/3.3) is that the back focal length must be kept short in order to prevent the secondary mirror from becoming excessively large. This precludes the common practice of locating the scanning mirror and focal plane behind the primary mirror. A clean solution to this dilemma was found in folding the light back toward the secondary mirror and placing the focal plane inside a central perforation in the secondary mirror and can be achieved without introducing any additional on-axis light losses or any serious vignetting. Although fast systems have a greater sensitivity to defocusing, restricting the range of satellite altitude over which acceptable focus is maintained, calculations show that focus can be maintained within the Rayleigh tolerance of a quarter wavelength wavefront error over a range of 180 km to infinity.

The complete focal plane module contains a total of four detector strips. For each mission, the operation of the sensor would be adjusted so that only the detectors providing the wavebands of interest for the mission are read out. Three of the arrays are located in the main focal plane and subtend the width of the 3 degree FOV: Si CCD 4 x 10,000 (visible), Pt:Si 4 x 10,000 (SWIR), and HgCdTe 4 x 2,000 (LWIR). For each detector material, the pixel sizes chosen match the state of technology for arrays which have been fabricated. In order to accomodate curvature of field, it will be necessary either to segment the detector arrays or to introduce field flattening optics over each array.

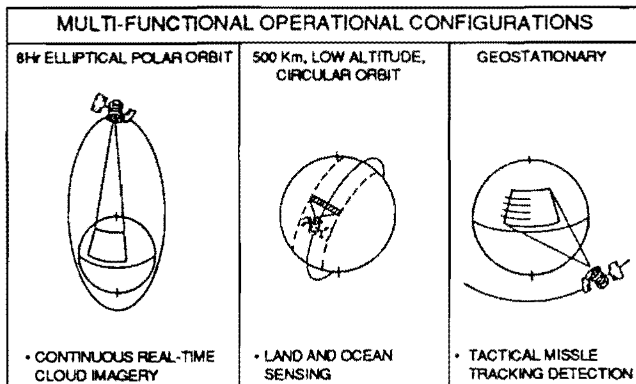
The system was designed to match diffraction-limited resolution with detector cell size in the LWIR band. In order to exploit more fully the resolution

SPECIFICATIONS SUMMARY	
FEATURE	VALUE
OPTICS:	
APERTURE DIAMETER:	60 cm
TYPE:	RITCHEY-CHRETIEN-ALL REFLECTIVE
FOCAL LENGTH:	200 cm
F.O.V.	3 DEGREES
BARLOW LENS	5x MAGNIFICATION
FOCAL PLANE:	
Si CCD:	4x10,000 PIXELS
Pt : Si:	4x10,000 PIXELS
HgCdTe:	4x2,000 PIXELS
LAYOUT:	THREE PARALLEL STRIPS
MODE OF OPERATION:	INTERNAL PLANE SCANNING MIRROR (3 DEGREE ROCKING SCAN)
COOLING SYSTEM:	STIRING CYCLE COOLER (PROVIDES 77 K FOR SWIR & LWIR) PLUS RADIATOR
TOTAL WEIGHT:	300 lbs





MODULATION TRANSFER FUNCTION



MISSION			SPATIAL				TEMPORAL		SYSTEM
COVERAGE	SPECTRAL BANDS (MICRONS)	RE-VISIT	F.O.V. (DEG)	RANGE (KM)	DETECTOR FOOTPRINT (M)	F.P.A. (PIXELS/ MICRONS)	INTEG TIME (SEC)	RAW DATA RATE Mbps	S.N.R.
WEATHER SURVEILL (8 HOUR ELLIPTICAL)	0.4 - 1.1 10 - 11	CONTINUOUS NATO (2 SATS)	3 x 3	27,000	143 717	10,000 x 4/10 2,000 x 4/50	90 E-3 450 E-3	50.9 2.03	4,333
LAND AND OCEAN SENSING	0.4 - 1.1 1.0 - 5.0 8.0 - 11.0 0.4 - 1.1 (BARLOW)	2 - 3 DAYS (1 SAT)	3 x 3	500	2.1 2.1 10.4 0.6	10,000 x 4/10 10,000 x 4/10 2,000 x 4/50 10,000 x 4/10	272 E-3 272 E-3 136 E-5 78 E-5	208 208 8.24 823	13.5
TACTICAL MISSILE TRACKING (GEO)	1.0 - 5.0	3 SEC	3 x 3	42,000	187	10,000 x 4/10	300 E-6	266	10

▒ = INDICATES COMMON SYSTEM ELEMENT

FIGURE 2: SENSOR ONE DESIGN SUMMARY

capability of the system in the visible spectrum, a negative element or Barlow lens, is mounted adjacent to the silicon detector strips and slightly above the main focal plane (i.e. toward the primary mirror). A fourth array, identical to the silicon array described above, is mounted at the focus of the Barlow lens just beyond the plane of the first three detectors. This Barlow lens provides an expanded view of the center of the FOV magnified four times, providing higher resolution visible spectrum imagery near boresight. The scan rate is also amplified by the Barlow lens; the integration time allowable (75 E-5 sec) may not be sufficient. Replacement of the linear array with a small mosaic Si focal plane and operating the Barlow lens scan in a staring mode would allow for a longer integration time and overcome this difficulty.

Both the Pt:Si and HgCdTe detector arrays require cooling; for this reason the focal plane is cooled to a temperature of 77 K. A Stirling Engine is designed as a tentative cooling device; it is able to cool the focal plane rapidly and is lightweight. For the low altitude land sensing mission, a simpler system such as a dewar or a blowdown-before-operation system may be sufficient. Vibration of the cooling system is a potential problem, causing smear of the image on the focal plane. It can be overcome by operating the coolers prior to a set of observations and then turning the cooler off during observation. Spectral bandpass filters (not shown in Figure 2) can be used in conjunction with each detector array to restrict the spectral passband(s) to those required for each mission. These filters either can be permanently mounted in the system or made to be retrofitted in the field prior to launch.

In both the weather and missile warning missions, the scanning mirror oscillates, slewing the image back and forth across the focal plane arrays. In the land sensing mission, the scanning mirror remains fixed and the orbital motion of the spacecraft allows the sensor to scan in a "pushbroom" fashion. For the Barlow lens and its associated detector array, the image remains in focus on the array but is scanned four times as rapidly because of the magnification of the Barlow lens. In the land sensing operation mode, the system is task-oriented to the extent that the spacecraft can be rolled to align the boresight of the sensor with the location on the ground of interest. Hence on a given orbit pass, data collection can be conducted on any 3 degree swath within a +/- 57 degree transverse from nadir field of regard of the satellite. Rapid slewing of the spacecraft to collect data of a number of locations on a given orbit pass is not possible. This trade-off was considered carefully, in view of the fundamental principle that tactical satellites are designed from the user's point of view. But to conserve weight (which is critical for a sensor which will be flown in a geostationary orbit) and relax the performance requirements imposed by the sensor on the spacecraft, the addition of a one- or two-axis gimbal assembly and the associated momentum compensation hardware for a 60 cm telescope, which would allow rapid and accurate slewing of the sensor for imaging, was not felt to be cost-effective. Moderate slewing of the entire spacecraft will provide some user control.

Results of radiometric calculations to determine S/N ratios which can be expected for representative targets in each of the missions are shown. Calculations are based upon actual radiance data, and assume conservative performance values within the current state of the art. Noise levels are due to detector D-star noise, with detectors operating in the photovoltaic mode. Contrast is the critical parameter for verifying performance of the sensors in all imaging missions; Optical attenuations both in the telescope and bandpass filters have been conservatively modeled. In the last column S/N ratios are calculated (as a rule of thumb, a value of 6 is the minimum acceptable value). Stray light shielding has been designed to minimize the amount of stray light reaching the focal plane.

Raw PCM data rates for sensor video signals have been calculated based upon one sample per dwell and eight bits per sample. Dwell times for the land sensing mission are based on satellite ground motion for a 500 km circular orbit. Weather mission dwell times are based on a 15 minute frame time and missile tracking dwell times are based on a 3 second scan of one entire frame. The data rate values in Figure 2 greatly exceed the receive capability of existing ground terminals available for each mission. Several options exist for reducing the data rate of the downlink. Weather data can be buffered and downlinked at a much lower data rate. On-board processing can be used to reduce downlink data rates for missile tracking, as the Defense Support Program (DSP) does. For land sensing, the military operators in the theater will have some command authority of payload operations and will be able to select specific spectral bands and regions for data collection and downlink. Also, real-time data compression techniques exist which can dramatically reduce the data rate with negligible degradation of data quality.

The major limitation to the Ritchey-Chretien design is off-axis aberration; resolution degrades progressively off-axis. At the edge of the field or 1.5 degrees off axis, 50 % contrast occurs at about 7 line pairs/mm. From an altitude of 500 km, for 50 % contrast, pixel footprint size in the visible drops off from 2.1 m on axis to about 18 m at the edge of the field. (Recall that on-axis diffraction-limited performance is about 0.5 m).

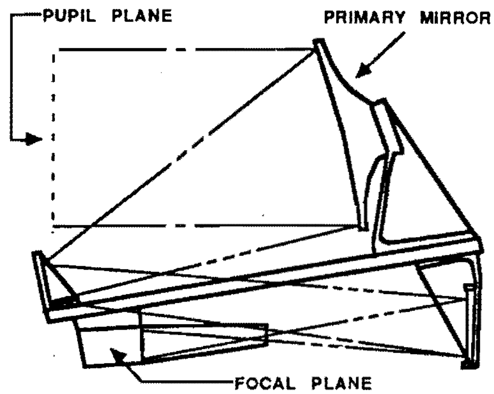
This case study shows that the concept of a single sensor which can be used, with little or no hardware modification, in any of three missions is very ambitious but achievable. Some sub-optimization in system design must be allowable.

4.2 Multi-mission sensor two

We now present a different approach to designing a multi-mission sensor. Considering the difficulties of designing a wide field of view system which also achieves high resolution, another possible approach for multi-mission design is to use separate systems for general surveillance and for narrower field of view higher resolution imaging. Hence Sensor Two (Figure 3) is designed for multispectral and infrared surveillance and topographical imaging (LANDSAT-type) from either LEO or GEO while Sensor Three (Figure 4) performs higher resolution visible-only surviellance and imaging. (Both sensors were developed by S. Kilston.)

Sensor Two is a multi-wavelength, multi-orbit, and multi-functional sensor system. The system uses a two-axis gimballed telescope which can be commanded to scan a field of view up to 18 x 18 degrees, with a 20 second revisit time, or as small as a 3 x 3 degree field of view, with a 2 second revisit time. When deployed in geostationary orbit, operation of this sensor would involve continuous full-earth-disk scanning for strategic warning, periodic weather map storage, and rapid-repeat theater scanning (about a 2-second cycle) in times of local crisis.

The key is to incorporate versatility in how the sensor collects data. The scan pattern and field of view size are tailored to be commensurate with the



MISSION/TARGET/PRODUCT

1. TOPOGRAPHICAL SENSING/GEOGRAPHIC FEATURES, LARGE TARGETS/LANDMARK & TARGET I.D.s AND LOCATIONS (LEO)
2. IR MAPPING/INDUSTRIAL, MILITARY INSTALLATIONS/IR BACKGROUND MAPS AND POSITIONS OF HOT SOURCES (LEO)
3. OCEANOGRAPHIC/OCEANS, SEAS, SHORELINES, WAVES AND TIDES/REAL-TIME DATA ON EXTENTS AND HEIGHTS (LEO)

1. THEATER & STRATEGIC WARNING/STRATEGIC & SHORT-RANGE MISSILES/MISSILE LOCATION & VELOCITY VECTORS (GEO)
2. AUGMENT DMSP/CLOUDS/WEATHER MAPS (GEO)

SENSOR/OPTICS

VISUAL & INFRARED SCANNER, OFF-AXIS RELAYED, ASPHERICS, APERATURE 35 cm, FOV 3° x 0.5°, GEOM. ABERR. < 10 μRAD

FOCAL PLANE ARRAY

HgCdTe DETECTORS, 50 AND 100 μm SQUARE, 8 x 4028 & 8 x 2014, SI CCD DETECTORS, 18 μm SQUARE, 2 x7172

SCAN & COVERAGE RATES

4°/s DATA, 10°/s RETURN / ≥ 16° SWATH / ≥ 4 s UPDATE (LEO)

8°/s SCAN RATE / 18° x 18° TOTAL AREA / 20 s REVISIT TIME (GEO)

TEMPERATURE CONTROL

LUCAS COOLER + RADIATOR, FPA AT 80 K+ COOL OPTICS

DATA RATE

SURV.: ~ 500 MHz READOUTS, ~ 500 MEGABITS/s DOWNLINK (LEO)

1.8 GHz READOUT; DOWNLINKS: 20 Kb/s (WARN.), 70 Mb/s (DMSP)

WEIGHT ESTIMATION	
TELESCOPE	81 lb
PROCESSORS	30
COOLERS[2]	11
RADIATORS	10
COUNTERLOADS	35
INTERFACE BOX	20
CMD. & TELEM. EL.	25
CALIBRATION UNIT	5
CABLES	10
SUM	227
CONTINGENCY (40%)	91
GRAND TOTAL	318 lb

MISSION			SPATIAL				TEMPORAL		SYSTEM	
COVERAGE	SPECTRAL BANDS (MICRONS)	RE-VISIT	F.O.V. (DEG)	RANGE KM	DETECTOR FOOTPRINT (m)	F.P.A. (PIXELS/ MICRONS)	INTEG TIME (SEC)	RAW DATA RATE Mbps	INTRINSIC TARGET CONTRAST	S.N.R.
MISSILE TRACKING (GEO)	1.0 - 5.0	2 SEC	3.0 x 0.5 SCANNED OVER 3.0 x 3.0	42,000	1,449	1518 x 2/85	247 E-6	96	N/A	10
ENVIRON SENSING (GEO)	0.55 - 0.7 0.7 - 1.1 3.8 - 4.0 10.6 - 11 12 - 12.5	30 MIN	3.0 x 0.5 SCANNED OVER 18 x 18	40,000	1,640	7172 x 1/18 7172 x 1/18 2554 x 1/50 1277 x 1/100 1277 x 1/100	105 E-6 105 E-6 294 E-6 294 E-6 294 E-6	552 552 696 34.4 34.4	0.20 0.14 0.38 0.01 0.01	10
TOPOGRAPH SENSING (LEO)	0.45 - 0. 1.0 - 1.3 1.55 - 1.	2-3 DAYS	3.0 x 0.5 PUSH-BROOM	700	5.1 5.1 5.1	7172 x 1/18 7172 x 1/18 7172 x 1/18	105 E-6 105 E-6 105 E-6	552 552 552	0.10 0.08 0.14	10
IR MAPPING (LEO)	3.4 - 4.2 4.6 - 4.8 8 - 9	2 - 3 DAYS	3.0 x 0.5 PUSH-BROOM	700	14.4 14.4 28.6	2554 x 1/50 2554 x 1/50 1277 x 2/100	294 E-6 294 E-6 294 E-6	69.6 69.6 35.2	0.13 0.14 0.01	10
OCEAN SURVEILL (LEO)	0.5 - 0.5 0.7 - 1.1 4.6 - 4.8 8 - 9.5 10.6 - 11	2 - 3 DAYS	3.0 x 0.5 PUSH-BROOM	700	5.1 5.1 14.4 28.6 28.6	7172 x 1/18 7172 x 1/18 2554 x 1/50 1277 x 2/100 1277 x 2/100	105 E-6 105 E-6 294 E-6 586 E-6 586 E-6	552 552 69.6 35.2 35.2	0.65 0.20 0.14 0.004 0.002	10 10 10 10 10

[ ] = INDICATES MULTI-FUNCTIONALITY [shaded] = INDICATES COMMON SYSTEM ELEMENT

FIGURE 3: SENSOR TWO DESIGN SUMMARY

revisit time desired. While performing the theater missile tracking mission continuously, the scan pattern can be altered for about 20 seconds every 15 or 30 minutes so that a weather map can be generated and downlinked. By designing in commandable filtering and operation of either or both the infrared and visible detector arrays, the user can tailor the downlink data stream to his needs of the moment. The focal plane is designed to allow data collection in two visible and three infrared spectral intervals and therefore actually surpasses the capability of DMSP and provides as much information as the NOAA polar orbiting weather satellites, but with continuous refresh and higher resolution.

In a 700 km low earth orbit, the same sensor system, or one with slight changes in filtering and data processing, provides multi-spectral topographical sensing, infrared mapping, and oceanographic sensing with resolution in the visible spectrum of about 5 m and in the LWIR of about 30 m. It uses a bidirectional whisk-broom scan covering a swath centered at up to 37 degrees transverse from nadir. Commandable operational modes and readouts allow tailoring of the downlink data stream for individual users (e.g. different spectral bands would be downlinked while covering ocean areas than when covering land areas). Further data compression or time-sharing of spectral band data may be needed due to the high resolutions and large downlink data rate. This system, with its spectral collection flexibility and resolving power, surpasses the capabilities of LANDSAT, SPOT, and the Soviet land and ocean remote sensing satellite systems, while weighing only 320 lb.

4.2.1 System design

The optical system is a visual and infrared off-axis scanner with aspherical mirrors. Diameter of the primary mirror is 35 cm. The field of view of the sensor is 3 x 0.5 degrees which is scanned in a number of different ways, as described above, to perform different missions. Off-axis aberrations are less than 10 microradians, allowing imaging at constant resolution across the entire 3 degree field. A cutaway drawing of the sensor design, centered on the main scan axis, is shown in Figure 3. The plane of the drawing represents the narrow (0.5 degrees) field of view dimension. The 3 degree field is normal to the drawing. The three mirror design allows for a cold-stop to minimize warm optics noise hitting the infrared focal plane and helps to minimize all stray light. Reaction wheels (not shown) are part of the sensor itself to allow for scanning with complete momentum compensation within the sensor; no feedback torque is transferred to the spacecraft bus. Current wheel concepts require no added power and less than 20 % additional weight in the pointing and control subsystem.

Three detector strips comprise the focal plane: HgCdTe 8 x 4028 (50 micron pixel size), HgCdTe 8 x 2014 (100 micron pixel size), and Si CCD 2 x 7172 (18 microns pixel size). An elaborate filtering system, which has not been fully designed yet, is also required. A Lucas cooler (a type of Stirling engine) and a passive radiator cool the focal plane to 77 K and cool the optics. Figure 3 presents system performance parameters of S/N and intrinsic target contrast. Mapping observations with these sensors are generally limited by background noise rather than internal sensor noise, since the earth itself is a bright background in most wavebands, especially the sunlit half. Intrinsic target contrast, the key parameter used to ensure that enough signal is received to make identification of target features possible in the sensor output, is shown for each mission. In general, very low contrast levels are discernible with the proposed design, except in the case of the visual-band ocean-sensing mission, where photon count is extremely low at the scan rate suitable for the other missions. The sensor achieves the minimum S/N goal of 6 in all cases.

Processing of the high raw data rates in the geostationary configuration allows for the downlink data rate to be compatible with existing ground terminals in the case of weather information. For theater missile tracking, where instantaneous transmission of warning and missile vector information to the end user is paramount, the data rate can be reduced to a 20 Kbps link. This allows for a UHF "duck" message to be broadcast down to users when tactical missiles are detected; small walkie-talkie type receivers carried on the belts of all personnel in the area can receive the duck message and will give the users enough time to take active and passive defensive measures. Due to the resolution and volume of data collected in the low altitude orbit, data compression is required.

4.3 Multi-mission sensor three

Because of the limitation of achieving good resolution from a small wide field of view optical system, Sensor Three was designed as a complement to Sensor Two for performing the higher resolution surveillance visible waveband missions: space object surveillance, and land sensing. The system is multi-functional; when pointed into deep space, the system performs space object surveillance. When rotated to look at the earth, the system performs land sensing with pixel footprint size of 1 m.

The optical system uses a 50 cm diameter dual-focal length system for the wide coverage space surveillance and high resolution (narrow field of view) land sensing modes. For maximum range the CCD focal plane array is cooled, as operation is detector noise limited, which is most important for the long-range surveillance mission. Figure 4 shows a cutaway view of the three-mirror sensor design. The design allows for excellent resolution with a comparatively wide field of view for an essentially all reflecting design. The last reflecting surface and zero-power refractive elements near the focal plane are present solely to provide a partially reflecting surface (partially silvered), allowing 80 % of the incident light to pass through, forming the f/3.6 optical path shown for the surveillance mode (bottom diagram - Si CCD 2048 x 2048 focal plane at the right). 20 % of the light is reflected back, forming the f/14.4 optical path for the imaging mode (top diagram - Si CCD 1024 x 1024 focal plane to the right of the small lenses in the center of the drawing). There is no S/N problem with imaging, even though the last reflecting surface reflects only 20 % of the incident light.

The sensor is also mounted in a two-axis gimbal which gives very wide field of regard. A Lucas cooler and radiator are used to cool the optics and focal plane to 77 K. The downlink data rate for the surveillance mission is very low (20 Kbps), whereas the data rate for land sensing is much higher, requiring data compression. The system is designed with the same commandable pointing and readout features as Sensor Two to optimize support to users and provide end-product data directly to them. Sensor design gives an estimate of 300 lb for the total system weight (including a 40 % contingency).

MISSION/TARGET/PRODUCT

1. SPACE SURVEILLANCE/SPACECRAFT IN ORBIT/ SATELLITE MAPS, COUNTS, AND CATALOGUES
2. LAND AND OCEAN VISIBLE SENSING

ORBIT

LEO, 700 km ALTITUDE, 4000 km RANGE (SURVEILLANCE)

SENSOR/OPTICS

VISUAL STARER, DUAL-FOCUS 3-MIRROR ANASTIGMAT, APERTURE 50 cm, FOV 1.8° (SURV.) & 0.15° (THEATER SURV)

STEP AND COVERAGE

1.8° PER 1.8s (SURVEILLANCE) / 360° SWATH IN 360s (4 LOOKS PER FRAME, FOR MOVING TARGET ID)

FOCAL PLANE ARRAY

SI CCD, 27 & 18 μm SQUARE PIXELS, 2048 x 2048 & 1024 x 1024

TEMPERATURE CONTROL

LUCAS COOLER + RADIATOR, FPA AT 80 K + COOL OPTICS

DATA RATE

SURVEILLANCE:
10 MHz READOUT, 20 Kb/s DOWNLINK

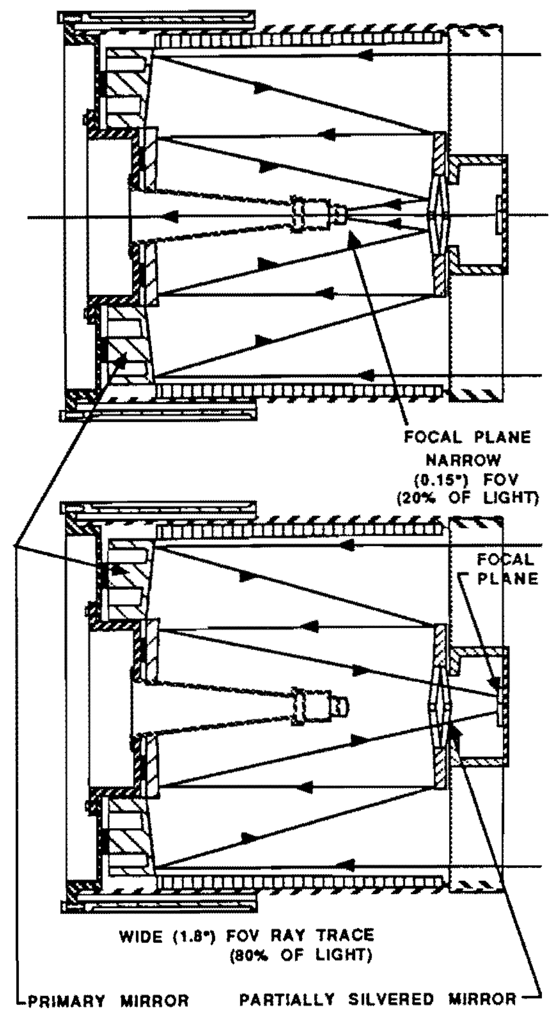
THEATER SURVEILLANCE:
62 MHz READOUT, 248 Mb/s DOWNLINK

ENVELOPE/WT./POWER

34 x 38 x 40 in. / 300 lb. / 240 W

OPTICAL CONFIGURATIONS:

NARROW F.O.V. RAY TRACE



MISSION			SPATIAL				TEMPORAL		SYSTEM	
COVERAGE	SPECTRAL BANDS (MICRONS)	RE-VISIT	F.O.V. (DEG)	RANGE (Km)	DETECTOR FOOTPRINT (M)	F.P.A. (PIXELS/ MICRONS)	INTEG TIME (SEC)	RAW DATA RATE Mbps	INTRINSIC TARGET CONTRAST	S.N.R
SPACE OBJECT SURVEILL (LEO)	0.4-1.0	NEAR-CONTINUOUS	1.76 x 1.76	4,000	60.0	2,048 x 2,048/27	800 E-6	76	N/A	10.0
LAND AND OCEAN SENSING (LEO)	0.4-1.0	12 HRS FOR ONE SATELLITE	0.15 x 0.15	700	1.75	1,024 x 1,024/18	8,000 E-6	248	0.05	10.0

☐ = INDICATES MULTI-FUNCTIONALITY ▒ = INDICATES COMMON SYSTEM ELEMENT

FIGURE 4: SENSOR THREE DESIGN SUMMARY

5. CONCLUSIONS

Three different designs have been presented for multi-mission and multi-functional electro-optical sensors for tactical satellites. One uses a standard satellite to perform three different missions (tactical missile tracking, environmental surveillance, and land and ocean remote sensing) when deployed in three different orbits (geostationary, highly elliptical, and 500 km circular). A second uses one system to perform two missions simultaneously (missile tracking and environmental sensing) from geostationary orbit and flexible, commandable multi-spectral imaging from a 700 km circular orbit. The third uses one system to perform several missions from a 700 km circular orbit: space object surveillance when pointed into space, and land sensing when pointed at the earth. From the design work performed to date, the systems appear to meet the performance goals of Figure 1. Their payload sizes are all about 300 pounds, which implies a spacecraft which falls squarely within the realm of tactical satellites (under 1000 pounds).

The focus on multi-mission and common system design for tactical sensing systems is based on the approach of achieving a high ratio of benefit-to-cost by realizing economies of scale in production and reduced development. The versatility demanded of such sensors implies that a single optical system and focal plane must satisfy the needs of a variety of missions. Commandable readout and processing options tailor the data stream to individual user needs. This approach would offer especially great savings for focal plane arrays, signal processing systems, and optical components.

Adaptation of a Barlow lens focal plane concept similar to Sensor One to Sensor Two is being explored. This would allow Sensor Two to more fully exploit diffraction-limited performance in the visible waveband. Use of a staring array at the focus of the Barlow lens to increase the integration time and meet the required contrast level and signal-to-noise ratio may be required. This concept appears feasible at the moment, although no design data is available yet. If successful, the resulting sensor system would be able to meet the requirements of all five missions, further improving the system's benefit-to-cost ratio.

The technical feasibility of the approach of multi-mission tactical sensors appears very promising. No technical issues which would make the concept infeasible have been found. Some sub-optimization in the design of the systems exists, but the resulting sensor system designs are highly capable, compared with existing systems, meet the performance goals established, and yet fit within the tactical satellite class. The results of the work completed are very positive; further exploration needs be conducted.

6. ACKNOWLEDGEMENT

The authors wish to recognize and thank Mr. Robert Weber of the Aerospace Corporation for his innovation in originally conceiving the concept of multi-mission tactical sensing satellites.

This paper was originally published in the Proceedings of the Society of Photo-optical Instrumentation Engineers, Infrared Technology XVI, Vol 1341, July 1990.