



NanoEye — Military Relevant Surveillance for Less Than \$5 Million Total Recurring Mission Cost

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Less Than \$5 Million Total Recurring Mission Cost**

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ABSTRACT

NanoEye is a near-term space system capable of providing better than 0.5 m resolution at nadir for a total recurring mission cost of less than \$5 million — including payload, spacecraft, launch, and 3 years of mission operations. NanoEye is based on a unique, light-weight telescope built and tested on IR&D by ITT, a unique structural design, also created on IR&D, by Microcosm, and existing proven CubeSat components from Pumpkin. The system has a dry mass of less than 10 kg without propulsion and less than 15 kg for an advanced system with enhanced bus capability and a propulsion system. (Cost and performance numbers are for the advanced system.) Because the advanced system can carry up to twice its dry mass in propellant, it is exceptionally agile with on the order of 2 km/sec of delta V available. This allows the spacecraft to fly low for extended periods and change its orbit as needed to adjust coverage, viewing times and angles, and provide drag compensation, thus giving the system unique capabilities that are not practical with larger, heavier, more traditional (and much more expensive) surveillance systems.

By the end of Phase II in late 2010, all the components for the Tech Demo mission (no propulsion) will be qualified and ready for integration and test, which could be completed within an additional 6 months. The biggest impediment to an operational system is the lack of a dedicated, low-cost NanoLauncher, so launch options will also be discussed.

The paper will describe the current status of NanoEye and the expected results of the present development phase. It will describe the reasons for the very low non-recurring and recurring costs, potential follow-on missions, and the implications of this approach to creating dramatically more affordable, more responsive space missions with high mission utility that provide an excellent complement to more conventional large space systems. Participants in Phase II are Microcosm, ITT Geospatial Systems, Pumpkin, General Dynamics C4 Systems, NASA Goddard Space Flight Center, and NASA Ames Research Center.

Acronyms

CMOS	Complementary Metal Oxide Semi-conductor	LEO	Low Earth Orbit
DRAM	Dynamic Random Access Memory	MSM	Multi-Stage Missile
EAV	Exo-Atmospheric Vehicle	NRE	Nonrecurring Engineering
EO	Electro-optical	OBA	Outer Barrel Assembly
EELV	Evolved Expendable Launch Vehicle	ORS	Operationally Responsive Space
FOV	Field-of-View	PL	Payload
GEO	Geosynchronous Earth Orbit	RCO	Repeat Coverage Orbit
GSD	Ground Sample Distance	RPDP	Reconfigurable Payload Data Processor
HEO	Highly Elliptical Orbit	SSO	Sun Synchronous Orbit
IR	Infrared	TRL	Technology Readiness Level
IR&D	Internal Research and Development	TT&C	Telemetry, Tracking, and Commanding
JPEG	Joint Photographic Experts Group	UAV	Unmanned Aerial Vehicle

INTRODUCTION

The Phase I SBIR program verified that it was feasible in the near-term to develop a low-cost, low-risk, low-mass (<10 kg), compact, but capable electro-optical/infrared (EO/IR) sensor payload and supporting spacecraft for use in low Earth orbit (LEO) to directly support the tactical Joint Land Warfighter. Much of the technology necessary to achieve this capability is at a Technology Readiness Level (TRL) of ≥ 4 , can reach TRL 5 by the end of Phase II, and achieve TRL 6 or 7 with subsequent testing. In addition, in order to provide military utility, the payload has been coupled with bus and mission concepts and hardware that can also be brought to bear in the near term, and these technologies are also available. Specifically:

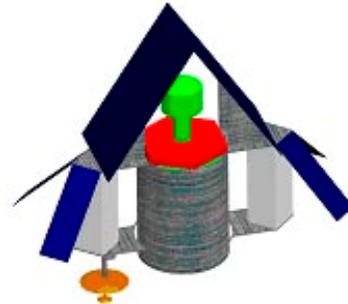
- ITT has completed the fabrication of an ultra-light-weight telescope for space applications with a 10-inch aperture, that is currently at a TRL of 5.
- The ITT telescope is designed initially to accommodate a low-noise CMOS image sensor featuring high resolution and high frame rate operation at low light levels. Shortly, ITT will have both IR and hyperspectral options that can be adapted to its telescope.
- Microcosm’s extensive background in Operationally Responsive Space (ORS) mission analysis and design (See, for example, Wertz [*Responsive Space Mission Analysis and Design*, 5-day short course, 2007].) has led it to create a variety of ORS surveillance missions that have been provided to the Army for consideration [Wertz, Van Allen, and Shelner, “Aggressive Surveillance as a Key Application Area for Responsive Space,” 2006], ORS Surveillance Orbits [Wertz, “Coverage, Responsiveness, and Accessibility for Various ‘Responsive Orbits’”, 2004], and Mission Utility [Wertz, “ORS Mission Utility and Measures of Effectiveness,” 2008].
- Microcosm has created a number of the enabling bus technologies relevant to the nano/microsatellite surveillance mission implementation, which led to a range of NanoEye bus/payload configurations that are shown in Figures 1 and 2.
 - Exo-Atmospheric Vehicle (EAV) for very low altitude flight [Microcosm White Paper submitted to various government agencies, available upon request — MIC06-1078-11]
 - MicroMak™ ultra light weight precision star sensor [US Patent No. 6,060,702]

- Miniature components for attitude control
- Autonomous orbit control [US Patent Nos. 5528502, 5687084]

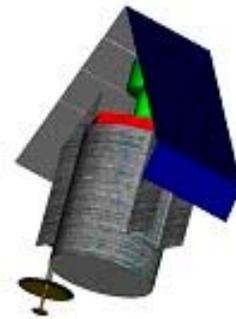
The overall goal of Phase I, which was achieved, was to clearly establish the technical feasibility of obtaining militarily significant EO/IR surveillance data (better than 1.5 m ground sample distance [GSD]) in an overall package for space or airborne use with a total mass (payload plus bus) of less than 10 kg. In addition, we defined an approach that will bring this technology to TRL 5 by the end of Phase II and TRL 6 or 7 with subsequent testing. Finally, we did some preliminary non-recurring and recurring costing for various configurations. Representative recurring cost information for the Advanced ED/OR version of NanoEye is provided in Table 1.

Table 1. Advanced EO/IR Cost Summary for Lots of 10 (FY\$09).

Bus/ Payload	Launch (Scorpius® mini-Sprite)	Operations (Includes launch)	Total
\$1.4M	\$2.4M	\$1.2M	\$5M



Option A: Two 3U CubeSats attached to telescope



Option B: Integrated spacecraft/telescope structure

Figure 1. Basic EO Bus/Payload Configurations Developed — No Propulsion.

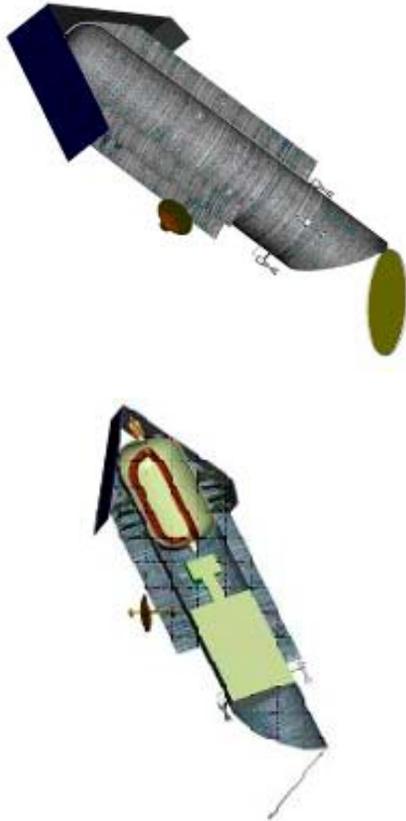


Figure 2. Option B Advanced EO and EO/IR Bus/Payload Configuration Developed — With Propulsion.

To achieve the above overall goal, we achieved the following specific objectives in Phase I:

- Used Government input on mission objectives and operational scenarios to create strawman mission concepts (mission and bus design) for NanoEye missions in LEO.
- Used the strawman mission concepts and the ORS Payload Developers Guide to define the payload requirements for the NanoEye EO/IR payload.
- Using the existing ITT design and hardware as a baseline, developed, analyzed, and sized the design of a NanoEye payload sensor.
- Developed a Phase II implementation and test strategy to allow development and initial testing of a NanoEye prototype in Phase II in order to bring the technology to TRL 5 by the end of Phase II.

Summary

The results of the Phase I effort by task are summarized in the lower right quadrant of Figure 3. In addition, the figure also provides an overview of both the Phase I goals (successfully achieved) and the plan for Phase II (upper left quadrant). Further, it lists the benefits that a NanoEye surveillance system will provide to the warfighter (lower left quadrant), including a representative picture, and 2 representative NanoEye configurations that span a basic EO system with no propulsion to a more capable EO/IR system with propulsion (upper right quadrant).

Conclusions

As a result of the work done on the Phase I NanoEye program, it is clear that an extremely capable imaging sensor can be fabricated in 18 months with existing technology. Further, an enhanced imaging sensor that includes substantial maneuvering capability, building on the basic imaging sensor, can be fabricated in 2 years (an additional 6 months).

Table 2 provides basic parameter information for the various NanoEye configurations that have been conceived under this contract. Included in the various mass, power, and cost budgets are margins to account for possible growth. In spite of the margin, the Tech Demo version can be fabricated for just over \$1M (sum of the nonrecurring and first unit cost in the first column), with much more capable versions for between \$1.2M and \$1.4M in quantities of only 10.

Imaging Payload

An engineering test version of the imaging sensor, built with IR&D funds by ITT, was completed in May 2009 and initial testing was completed in November 2009. It has been designed to accommodate EO, IR, or a combination of the 2, to provide day/night capabilities. This sensor can achieve sub-meter nadir GSD from 175 km, which is sufficient to differentiate people and achieve a visible National Image Interpretability Rating Scale (NIIRS) level of 6.

Bus Subsystems

Virtually all the bus subsystems can be purchased from a variety of CubeSat component vendors and have already been space qualified for the LEO environment. As a result, they are low cost, low risk, and can easily be delivered in a timeframe to support a completed Tech Demo version of NanoEye in 18 months.

Phase 1

- Developed an EO/IR payload for satellites in LEO based on ITT's light weight telescope (nadir resolution of 1.5 m at 600 km) and Microcosm's extensive experience in space mission design
- The team developed a conceptual payload design, and strawman bus and mission concepts

Phase 2

- Demonstrate the technical feasibility by building a prototype camera system and define a low-cost test program to verify space environment performance
- At the end of Phase 2 the unit will be at TRL 5 and ready for advancement to TRL 6 or 7, depending on the choice of follow-on tests and possible supplemental funding

The low cost/low risk system can be operational in 18 – 24 months

NanoEye Program Goals/Benefits

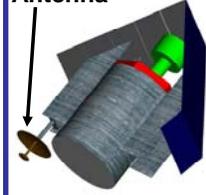
- Give the warfighters on the ground
 - The images they need when needed
 - The ability to control what they get, when, and anywhere on Earth within hours of need
 - This capability in 18 months of ATP - total recurring cost (spacecraft/ payload) of \$0.9M - \$1.4M, depending on payload configuration and propulsion capability
- Uses existing, proven, low risk hardware and systems
- Initial payoff in surveillance/ reconnaissance applications in direct support for the tactical Joint Land Warfighter



Sub-meter resolution from 175 km

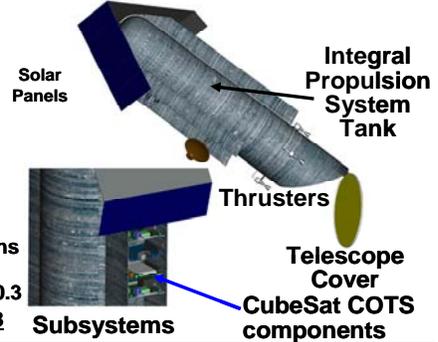
NanoEye Configurations

Communications Antenna



Basic EO No Propulsion
 Maximum Dimensions (m)
 L = 0.8 W = 0.6 D = 0.3
 Dry Mass (kg) = 9.8

EO/IR With Propulsion
 Maximum Dimensions (m)
 L = 1.8 W = 0.7 D = 0.3
 Dry Mass (kg) = 15.6



Phase 1 Tasks

- Task 1 - Mission concepts developed
- Task 2 - Payload requirements defined; at COTR direction, concentrated on LEO system
- Task 3 - Payload has been designed - Tech Demo payload built on ITT IR&D and now in testing
- Task 4 - Implementation and test strategy completed - making use of existing CubeSat components for essentially all bus functions
- Task 5 - Have moved program forward more rapidly than planned – all CDRLs completed and delivered

MIC09-1148h

Figure 3. Program Summary.

Table 2. NanoEye Basic Parameters.

Parameter	Tech Demo	Basic EO	Advanced EO	EO/IR
Basic Parameters				
Dry Mass	9.2 kg	9.8 kg	13.5 kg	15.6 kg
Max Power (all systems)	24 W	27 W	42 W	50 W
Non-Recurring Eng (NRE) Cost ¹	\$160K	\$140K	\$160K	\$120K
First Unit Recurring Cost	\$910K	\$980K	\$1.3M	\$1.5M
Recurring Cost, lots of 10 ²	N/A	\$900K	\$1.2M	\$1.4M
On-Board Propulsion	No	No	Yes	Yes
Max available delta V ³	0	0	>~ 2,500 m/s	>~ 2,500 m/s
Comm Bandwidth	TBD (low)	TBD (low)	TBD (high)	TBD (high)
Altitude	400 - 500 km	400 - 500 km	175 - 500 km	175 - 500 km
Min working elevation angle	20 deg	20 deg	20 deg	20 deg
Max resolution	~1.0 m	~1.0 m	Sub-meter	Sub-meter
Min resolution (visible)	~2.8 m	~2.8 m	~2.8 m	~2.8 m
Min FOV at nadir (0.27 deg)	1.9 x 1.9 km	1.9 x 1.9 km	0.8 x 0.8 km	0.8 x 0.8 km
Swath width at min altitude	> 1,500 km	> 1,500 km	> 500 km	> 500 km
Swath width at max altitude	> 2,000 km	> 2,000 km	> 2,000 km	> 2,000 km

¹ Assumes development of next lesser model has been done (\$FY09)

² Recurring Cost in lots of 10, excluding launch cost (\$FY09)

³ Specific delta V depends on launch vehicle capability to the selected orbit

Launch

With an envelope of only 0.8 m X 0.6 m X 0.3 m, and masses ranging from only 13.8 kg to 14.7 kg, the Tech Demo and Basic EO versions of the NanoEye can fit into the shroud of a wide range of available and future launch vehicles. Also, the design is naturally stiff, and there are no deployable structures, so there are no major issues associated with launch loads. The Advanced EO and EO/IR versions have dimensions of 1.8 m X 0.7 m X 0.3 m, and depending on propellant loading, the Advanced EO and EO/IR versions could have masses up to about 80 kg. In all cases, existing launch vehicles, such as the Minotaur 1, the Falcon 1, and planned launch vehicles, such as the Scorpius® Multi-Stage Missile (MSM) and the Mini-Sprite, could be used.

Responsive Orbits

We examined 5 orbit types: Sun synchronous, LEO Fast Access, Repeat Coverage, Low Highly Elliptical Orbit (HEO), and Prograde Circular (Medium Earth Orbit). Microcosm has developed specialized orbits for ORS missions to maximize the coverage of a particular geographic area. The NanoEye can be placed into any of the specialized ORS orbits by a wide range of launch vehicles that will be covered later.

Responsive Orbits are those intended to meet the needs of responsive missions. The most important characteristics of these orbits are:

- **Responsiveness** — Data returned within a few hours of launch
- **Low Cost** — Reasonable payload available from a small launch vehicle
- **Good Coverage** — Mixture of speed, persistence, and repetitiveness are key
- **Tactical Applications** — Provide data for a specific, defined location on Earth

Long-term stability and global coverage were not principal issues, as they are for more traditional missions. Traditional Earth observation orbits — such as GEO, Molniya, or high altitude Sun synchronous orbits (SSO) — do not work well for responsive missions. However, the use of non-traditional orbits will inevitably impact the launch system, spacecraft, communications, and operations used for responsive missions.

The Sun synchronous orbit is the traditional surveillance orbit that provides global coverage at the expense of revisiting a given location only every 2 to 3 days — these orbits typically range in altitude from 600–800 km, with periods roughly between 96–100 minute, and inclinations of around 98 degrees. Due to the long time between revisits of a particular location, it

is not a good choice for NanoEye, with its focus on tactical surveillance.

The LEO Fast Access Orbit, shown in Figure 4, is one in which the spacecraft is [Wertz, 2005] launched into an orbit that flies over the target on the first revolution. The figure shows a range of possible inclinations, all of which intersect at a location 22.5 degrees further west after 1 orbit. It provides 5 minutes of coverage within 90 minutes after launch and once or twice per day thereafter for any identified location on Earth. The range of working altitudes is 200 to 400 km.

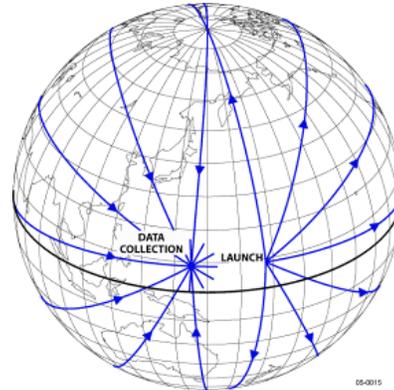


Figure 4. Representative Fast Access Orbit.

The LEO Repeat Coverage Orbit (RCO) [Wertz, 2005; Wertz, 2006] is a good candidate for the NanoEye as a responsive orbit intended to provide persistent periodic surveillance of an identified Earth target. This type of responsive orbit provides a high level of utility for monitoring or tracking ground activity at a specific time in a specific region and would also be disruptive to enemy operations if an attempt were made to avoid surveillance. Precession moves coverage 15 – 30 minutes earlier each day, depending on latitude. Autonomous orbit control, developed by Microcosm and validated on UoSat-12 [Koenigsmann, et al, 2000; Wertz, et al, 2000; Conger, et al, 2002] in 1999 and on TacSat-2 [Plam, et al, 2008] in 2007, makes the revisit time predictable and controllable, but can be changed to confuse the enemy. The spacecraft is launched into an orbit with an inclination 3 to 5 degrees higher than the latitude of the target, in effect “tuning” the orbit such that it revisits a predefined location for 4–6 successive orbits. This type of moderate inclination, prograde orbit reduces the launch energy, which leads to 30% more mass to orbit than to a Sun synchronous orbit with most launch vehicles. For the example shown in Figure 5, this implementation provides 3 to 5 minutes of coverage per orbit for 4 or 5 successive orbits, i.e., 6 to 8 hours. If additional surveillance is needed, a constellation of 3 or 4 satellites could provide coverage every 90 minutes indefinitely, and 6 or 8 satellites could provide coverage every 45 minutes indefinitely. Adding additional satel-

lites in additional planes will further cut down the time between revisits. The later satellites in the constellation could be launched after the results of the initial surveillance showed that additional coverage was appropriate, which makes this an extremely flexible option. As with the other low altitude responsive orbits, we assume a circular orbit between 175 km and 300 km, which provides a resolution of 0.45 m to 0.75 m at nadir for a representative 0.25 m diameter instrument working in visible wavelengths. Thus, this scenario would be particularly appropriate for visible or IR or low-light visible sensors, if observations at night were also critical.

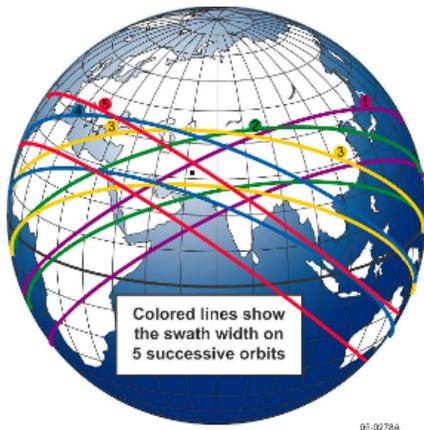


Figure 5. Single Satellite Repeat Coverage Orbit.

Figure 6 shows the coverage comparison between an RCO and an SSO, for varying swath widths of the payload sensor. [Wertz, 2008] RCO coverage requires selecting the orbit to provide coverage of the latitude of interest. For RCOs with moderate inclinations, a prograde orbit reduces launch energy, yielding 30% more mass compared to SSO with most launch vehicles. The RCO can provide 3 to 10 times better mid- and low-latitude coverage, at the expense of global coverage, by adjusting the orbit to the latitude of interest. If only daytime passes were included, SSO coverage would be half that shown.

A representative Low HEO Orbit with a 500 km altitude perigee and a 4,000 km provides lower resolution, but much greater persistence. The orbit rotates rapidly unless it is at the critical inclination of 63.4 degrees. Satellites in this orbit have the major complication of operating in the Van Allen radiation belts, which is technically feasible, but adds complexity, mass, and cost to the spacecraft that make it a poor choice as a low cost tactical option.

The final orbit considered was the Prograde Circular Orbit at 4,000 km. This orbit provides longer dwell than the Low HEO Orbit, and can be at any inclination, but it has the same negative impacts as the Low HEO Orbit because of the Van Allen belts. In fact, any altitude above about 1,000 km will be in the Van Allen belts and require radiation hardening.

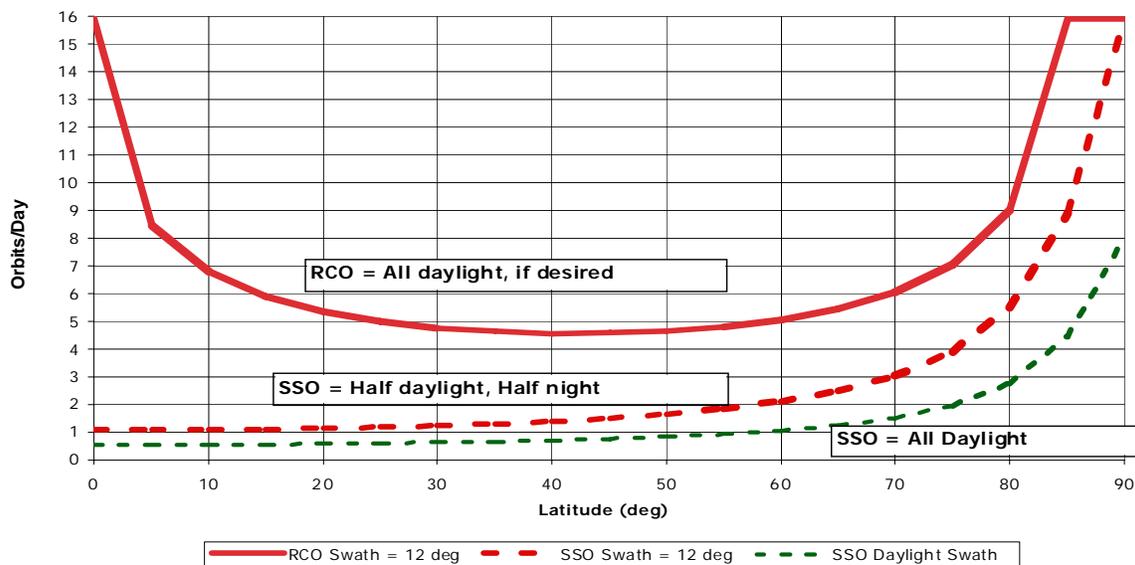


Figure 6. Coverage for Single Satellite Sun Synchronous vs. Repeat Coverage Orbits.

Additional Mission Related Factors Evaluated

SmallSat Altitude Issues

The major benefit of low altitude is high resolution with a small payload and spacecraft, as shown in Figure 7. This effect can be demonstrated further by referring to Figure 7 that shows the increase in GSD for altitudes ranging from 175 km to 500 km, nadir pointing.

There is also a small increase in launch capability relative to mass to orbit, but the effect is minor. Operating at low altitude means doing without deployable solar arrays that have excessive drag. However, there typically is much less of a requirement for deployable arrays on small spacecraft due to the larger

surface area/unit volume, and solar arrays are becoming far more efficient. In addition, responsive mission duty cycles tend to be low, which further helps out relative to simpler solar arrays. There is a benefit to keeping the spacecraft symmetric about the velocity vector to minimize aerodynamic torque. On the downside, both payload and communications coverage will be less, but there are multiple ways to solve the communications problem. All of these factors need to be balanced for a specific payload and system design. The bottom line is that low altitude is dramatically cheaper than large aperture. So long as we are willing to give up global coverage and 5 to 10 year lifetimes, we can achieve major benefits in terms of cost.

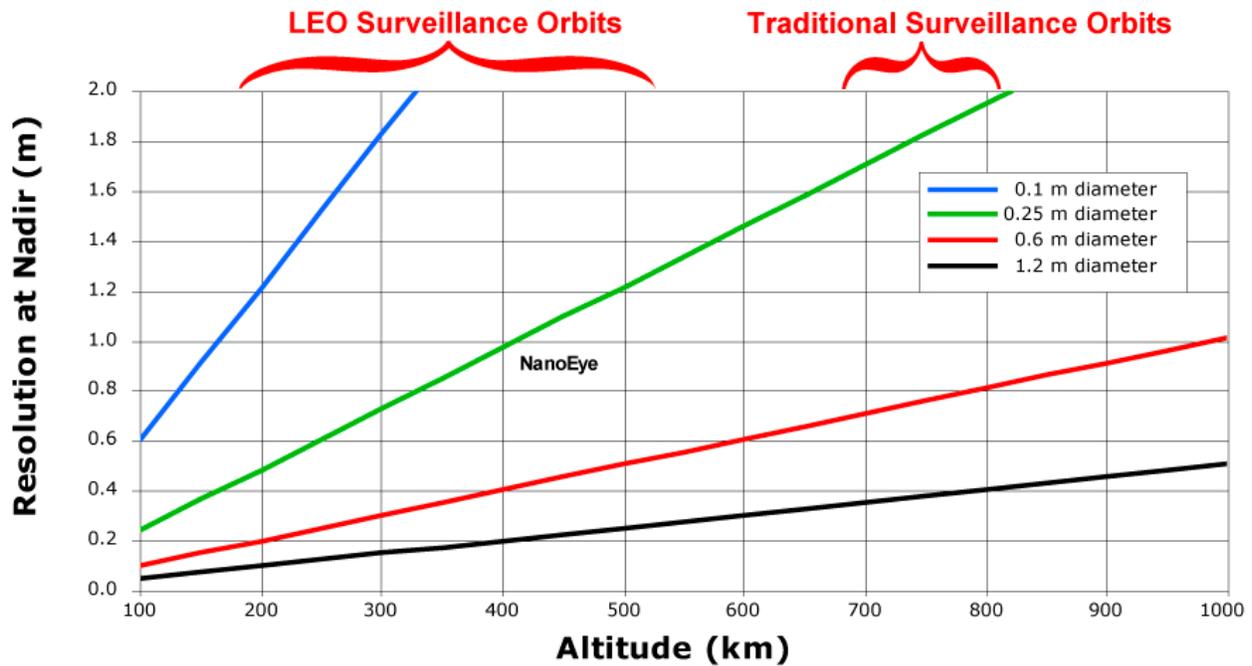


Figure 7. Resolution vs. Altitude.

In order to fly low, in the 175–300 km altitude ranges we are considering, there are a number of ways to operate. More propellant can be carried to help offset the effects of increased drag at the low altitudes. There are several spacecraft modifications that have been identified that can reduce the momentum transfer from atomic oxygen that would normally significantly reduce orbit lifetime. Increasing the ballistic coefficient is another way to offset the effects of atmospheric drag (See Figure 8 for a plot of delta V required as a function of altitude for various ballistic coefficients.). Putting the spacecraft into a slightly elliptical orbit will reduce the time the spacecraft operates at the very low altitude, but complicates constellation management. Finally, the

orbit can be raised when the higher resolution is not needed and lowered when tensions rise. Also, all of the above can be used together.

Agile Spacecraft

The basic agile spacecraft concept is to use a total delta V on the spacecraft of 1 – 2 km/sec to maneuver on-orbit satellites and make them responsive in ways not otherwise possible. The concept also ties into the ability to offset atmospheric drag discussed above. The NanoEye has delta V of up to 2.6 km/sec, with the propellant loading adjustable as a function of the mission and launch vehicle capability. Examples of agile spacecraft capabilities include:

1. Changing the look-angle or arrival time of an imaging pass so that it cannot be predicted by the adversary
2. Maintaining a pair of satellites in elliptical orbits with one at a higher altitude for mapping followed by the other at a lower altitude for better imaging
3. Changing the orbit to provide coverage of unanticipated events
4. Improving viewing angles
5. Using a maneuver sequence so that adversary can no longer identify the satellite

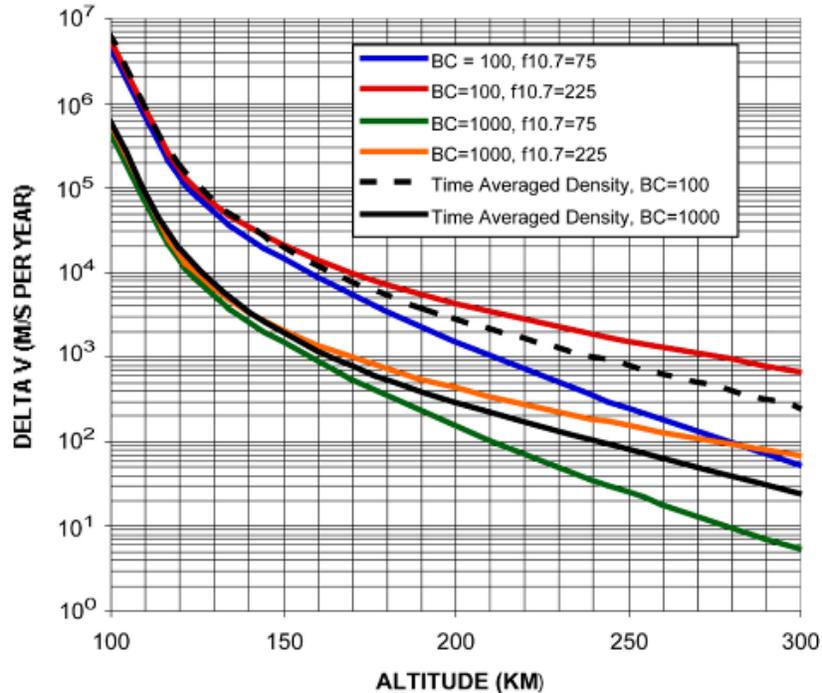


Figure 8. Delta V vs. Altitude for Orbit Maintenance.

CONOPS

The NanoEye will be designed to communicate with and operate within the existing protocols currently in use and planned for use by the Army. As such, it will be able to communicate directly with a range of assets available to the Theater Warfighter and to other assets that currently are being developed. A critical advantage of NanoEye and other Army tasked space-based assets is their ability to operate over territory that is denied to more conventional assets, such as UAVs and manned aircraft.

From a low 175 km altitude, the representative 0.25 m aperture telescope can achieve sub-meter nadir resolution, which is sufficient for identifying a wide range of objects. Although 175 km is very low by any standard, as discussed above, Microcosm has developed several spacecraft modifications and a Concept of Operations (CONOPS) that will allow operations at this low altitude for an extended period of time measured in at least months, and possibly 1–2 years. Besides modifying the spacecraft, by adding a large (multiple

km/sec) delta V capability, the NanoEye can operate at very low altitudes during a crisis that might last several weeks to several months, and then boost itself to a higher orbit to extend its lifetime (Even at a representative 400 km altitude, NanoEye nadir resolution will still be at an approximate and respectable meter level).

Launch

The Tech Demo configuration can be launched on any low-cost launch of opportunity or as a secondary payload (typically lower cost). It has no on-board propulsion so it will decay naturally from whatever orbit it is placed in, which should be below ~600 km to ensure reentry within the 25 year guideline for spacecraft disposal. A 500 km altitude would ensure a lifetime of no more than ~5 years so that the Tech Demo does not contribute significantly to the debris population.

Operational NanoEyes will largely require a dedicated launch, both for responsiveness and for insertion into

the desired orbit, although 2/launch vehicle may be possible for some orbits. Most operational missions will require propulsion (i.e., Advanced EO or EO/IR) because without propulsion, the satellite orbit cannot be adjusted or maintained, constellations would not be an option; and view parameters would be determined by natural decay.

The Advanced EO and EO/IR systems offer exceptional launch flexibility and allow propellant to be offloaded to meet launch vehicle capability. The propulsion capability also means the NanoEye can fly

itself to the operational end orbit. For example, an Advanced EO system can raise its orbit by 300 km for a delta V of 170 m/s, which corresponds to 3.6 kg of propellant, only about 7% of the maximum available delta V. Having a propulsion capability means that the NanoEye is essentially insensitive to launch insertion accuracy.

Launch system requirements are shown in Table 3 below for the 4 different configurations examined. Depending on the orbit and propellant load, NanoEye requires an equivalent due East launch mass of 14–75 kg (30–165 lbs) for LEO missions.

Table 3. Launch System Requirements.

	Tech Demo	Basic EO	Advanced EO	EO/IR
Size	30x61x85 cm	30x61x85 cm	30x61x130 cm	30x61x130 cm
Min Shroud Dia	68 cm	68 cm	68 cm	68 cm
Min Shroud Dia	27 in	27 in	27 in	27 in
Min Shroud Dia, 2 spacecraft	34 in	34 in	34 in	34 in
Dry Mass	9.2 kg	9.8 kg	13.5 kg	15.6 kg
Max Propellant	N/A	N/A	33.5 kg	33.5 kg
Max Wet Mass	N/A	N/A	47.0 kg	49.1 kg
Orbit Cost Function, LEO	1.5	1.5	1.5	1.5
Orbit Cost Function, 4000 km	3.85	3.85	3.85	3.85
DEEM 100*, LEO, min	13.8 kg	14.7 kg	20.3 kg	23.4 kg
DEEM 100, LEO, max	13.8 kg	14.7 kg	71 kg	74 kg
DEEM 100, 4000 km, min	35 kg	38 kg	52 kg	61 kg
DEEM 100, 4000 km, 5 kg prop†	N/A	N/A	71 kg	79 kg

* DEEM 100 = Due East Equivalent Mass at 100 NMi

† Assuming 5 kg of propellant which can provide approximately 600 m/s delta V

Representative launch vehicle options are listed below. There are no strong, low-cost launch options at present, but many that can be developed in the near term at low to moderate cost.

- SpaceX Falcon 1/1e (185 km circular orbit due East from Kwajelein)
 - ~925 lbs (420 kg), \$8.9M/ ~ 2,220 lbs (1,010 kg), \$10.5M (12/31/09) (http://www.spacex.com/falcon1.php#pricing_and_performance)
 - Has flown twice successfully
 - Will be used by SMDC for CubeSat communications satellite launch
- Scorpius® MSM
 - 105 lbs (48 kg) to LEO due East for \$1.7M at 10 per year
 - Launch from inventory within 8 hours of unanticipated demand (2 hrs if on alert)
 - Based on existing SR-M suborbital with 2 upper stages
- NRE = \$9.7M over 18 months
- Scorpius® mini-Sprite
 - 240 lbs (110 kg) to LEO due East for \$2.4M at 10 per year
 - Launch from inventory within 8 hours of unanticipated demand (2 hrs if on alert)
 - Based on Sprite Small Launch Vehicle
 - Extensive review by SMC/XR in Oct., 2008
 - Mini-Sprite uses existing 25 inch tanks and 5 klb engines
 - NRE = \$10.4M over 18 months
- Others
 - Mini-launcher being developed by SMDC
 - Mini-launcher being developed by NASA Ames
 - Mini-launcher being developed by ESA
 - Very few parameters have been released on these launch systems

Potential NanoEye launch vehicles are shown in Figure 9.



- Full-scale model of mini-Sprite (left)
- SR-M = 1st stage of MSM (below)
- SpaceX Falcon 1 (right) <http://www.spacex.com/>

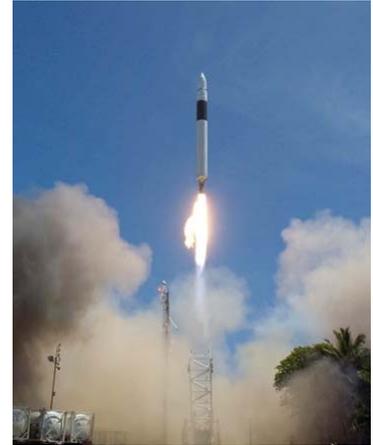


Figure 9. Potential NanoEye Launch Vehicles.

Spacecraft Bus Design

We completed a preliminary mass and power budget for 4 variations on the complete NanoEye spacecraft, including the sensor itself, as well as all spacecraft bus supporting hardware (See Figure 1 Option B, Figure 2, and Figure 10). The solar cells are mounted to provide power across a wide range of Sun angles (Figures 11 and 12). The Tech Demo and Basic EO configurations of the spacecraft are essentially nadir-pointed. They do have 3-axis control via a set of reaction wheels to allow

off-nadir pointing, with magnetic torquers for wheel momentum desaturation. With 3-axis control, the solar panels can be oriented appropriately to reduce drag when not in the data gathering mode. The Advanced EO and Advanced EO/IR configurations align the spacecraft appropriately all the time, with the sensor cover closing during orbit correction maneuvers. A star sensor provides high accuracy attitude determination for excellent geolocation accuracy for imaging.

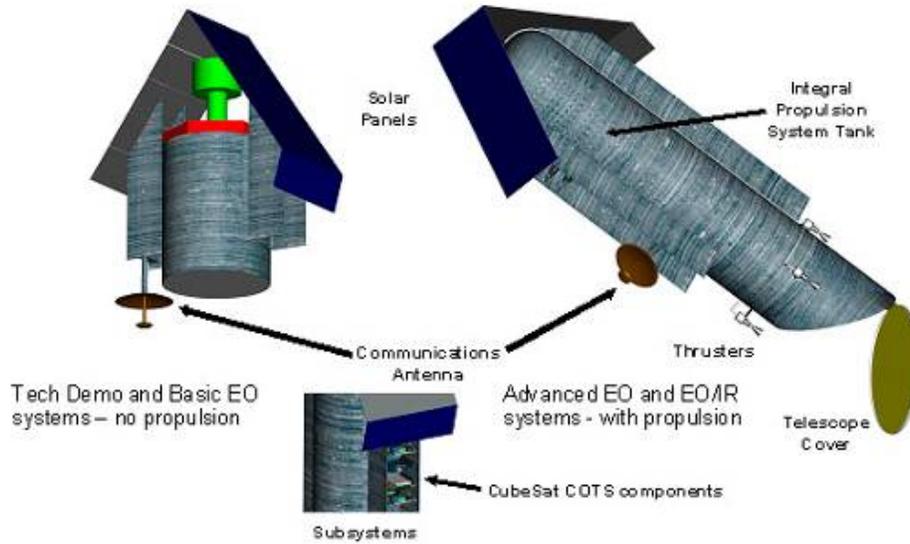


Figure 10. NanoEye Configurations.

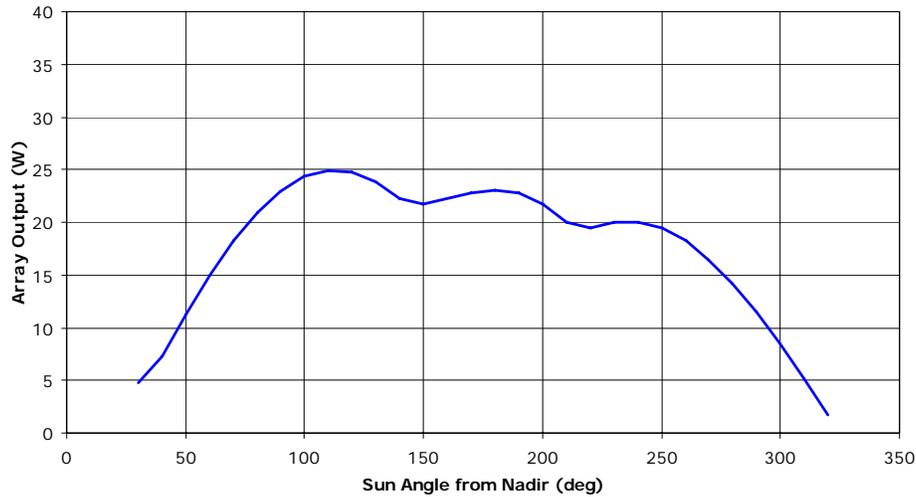


Figure 11. Solar Array Output — Basic EO.

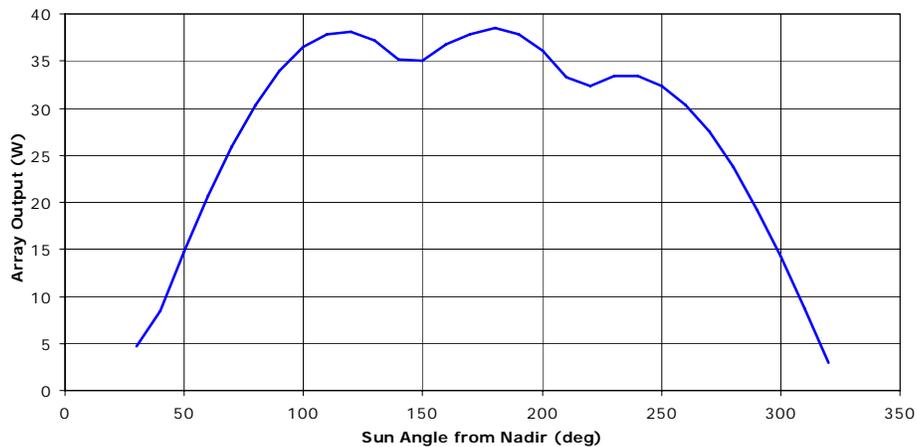


Figure 12. Solar Array Output — Advanced EO and EO/IR.

Table 4 shows an updated mass breakdown for the NanoEye Tech Demo configuration. These are estimates based on actual hardware that has either flown or is near flight-ready development status. Examples of actual attitude control actuators and an attitude determination

sensor are shown in Figure 13 below, demonstrating a very small magnetic torquer built by Microcosm/ZARM and a very small star sensor that is under development at Microcosm as well.

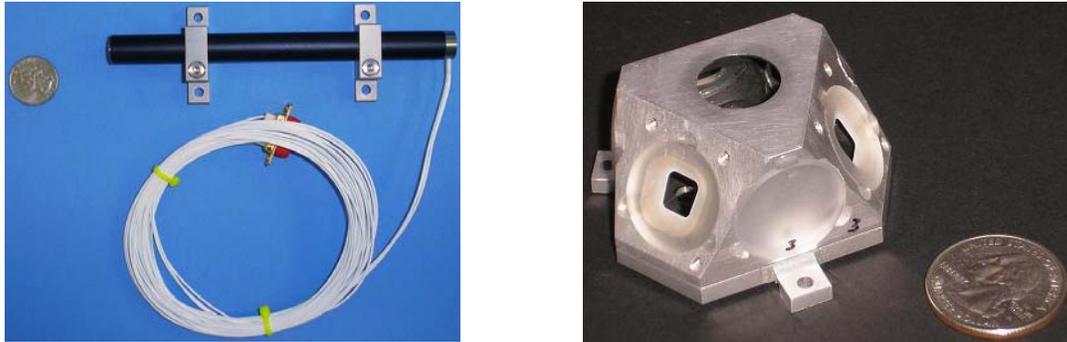


Figure 13. Miniature magnetic torquer (MT2 model) built by ZARM/Microcosm (left) and MicroMak™ miniature star sensor optical head (right) built by Microcosm.

Table 4. NanoEye Tech Demo Mass Budget.

<u>Component</u>	<u>Mass (kg)</u>		<u>Options/Comments</u>	
Payload**	4.5*	4.725*	5% margin	
Power		1.102	1.322	Total power = 22 W
Array	0.91			Solar cells on primary structure, 200W/m ²
Battery	0.062			
Elect. Power Sys. (EPS)	0.08			
Harness/Misc.	0.05			
Attitude Determination/Control/Navigation		1.014	1.217	
ADACS	0.91			IMI-100
Magnetometer	0.02			
GPS Receiver/Antennas	0.044			
Harness	0.04			
Propulsion		0.00	0.00	Baseline = no propulsion; could be added
Structure		0.94	1.128	
Primary	0.74			Examine making telescope the primary structure
Secondary	0.20			
Thermal		0.13	0.156	Temp range = -60 deg C to +30 deg C
TT&C/Processing		0.524	0.629	
S/C Computer	0.17			
Transceiver/C&DH/Antenna/Harness	0.354			
Bus Total		3.71	4.452	20% margin
Spacecraft Total		8.21	9.177	

* Actual masses from the actual telescope final assembly varied little from this number that at this point it will not be changed.

Key System Design Trades

Key spacecraft system design trades were identified and evaluated to first order in this task and have been discussed above:

1. The bus design to accommodate candidate sensors (Figures 1, 2, and 11) can vary between a no propulsion version and one with propulsion that can have its propellant loading be a function of the mission and/or the launch vehicle capability.
2. The number of spacecraft to accomplish the observation mission can be varied from 1 to multiples of 3–4 to achieve periodic persistence from every 90 minutes, 24 hours/day, down to every 45 minutes, and so on.
3. Whether to create a combined EO/IR sensor or develop distinct sensors for EO and IR and fly them on separate spacecraft.
4. The use of air coil vs. solid core magnetic torquers is another option. The configurations evaluated for this study focused on COTS air coil torquers that are available for CubeSats, but Figure 14 provides an example of a solid core magnetic torquer.
5. Relative to the level of onboard data processing and image compression, more work is required, but the downlinks will currently be limited to S-band, which corresponds to about 3 Mbps, and will still permit images to be downloaded, even without compression.
6. For the very low 175–300 km orbit altitudes being considered, the number of NanoEye spacecraft to achieve specific tactical or reconnaissance goals will not be impacted.
7. When it comes to trades on orbital implementation vs. high altitude aircraft for various mission objectives, it is more a matter of the CONOPS, where they will actually work together, as shown in Figure 9.
8. Cost vs. performance trade results are shown in summary fashion in Table 2, from the Tech Demo configuration of NanoEye to the Advanced EO/IR configuration.

Breakdowns for the payloads and major subsystems for the various NanoEye configurations that have been conceived under the contract have been provided to the

Army as a part of the Phase I effort. Included in the various mass, power, and cost budgets are margins to account for possible growth. Candidate suppliers for the various subsystems have also been provided to the Army. Even including the margin, the Tech Demo version can be fabricated for about \$1M, with much more capable versions for between \$1.2M and \$1.4M in quantities of only 10.

NanoEye Payload Requirements

Based on the key strawman mission concepts (mission and spacecraft bus design) developed with the assistance of the customer, and the ORS Payload Developer’s Guide, Microcosm derived requirements for the NanoEye EO/IR payload. This activity included defining performance requirements such as ground resolution, sensor lifetime, duty cycle, operational temperature limits, and other environmental survival specifications. Table 5 lists some fundamental considerations that will be incorporated into the EO/IR sensor design, as a function of operating environment. These environmental and operational considerations will be defined in greater detail and will feed into the formal requirements for the NanoEye sensor.

Table 5. EO/IR Sensor Operating Considerations for Various Environments.

	Duty Cycle	Launch Loads	External Temp. Variation	Atms. Pressure	Drag
LEO	~ 10%	Yes (See Tables 6 – 8 and Figures 15 – 17)	± 121 deg C	~ 0	High

Launch loads need to cover the range of possible launch vehicles that includes the Atlas V, Delta IV, Minotaur I, Minotaur IV, Falcon 1, and Falcon 9, although none of these has a truly responsive capability. Representative launch data extracted from the Evolved Expendable Launch Vehicle Standard Interface Specification, Version 6, 5 September 2000 is reproduced in Tables 6–7 and Figure 14. Similar information for the Minotaur IV is shown in Table 8 and in Figures 15–16. ITT has determined that launch loads are essentially a non-issue.

Table 6. Payload Maximum Acoustic Levels.

1/3 Octave Band Center Frequency (Hz)	MPC PL Sound Pressure Level (dB re 20 micropascal)	4m IPC PL Sound Pressure Level (dB re 20 micropascal)	5m IPC/HPC PL Sound Pressure Level (dB re 20 micropascal)
32	118.0	122.0	129.0
40	123.4	123.7	130.5
50	123.0	125.2	131.0
63	124.5	126.3	132.0
80	126.0	128.0	132.5
100	128.2	131.0	133.0
125	129.1	132.2	133.0
160	130.0	133.4	132.7
200	131.1	131.9	131.8
250	130.5	130.5	131.0
315	130.0	130.0	130.2
400	130.0	130.0	128.8
500	129.8	129.8	127.5
630	128.3	128.3	126.2
800	126.9	126.9	124.3
1000	123.9	123.9	122.5
1250	122.0	122.0	120.7
1600	120.4	120.4	118.3
2000	120.9	120.9	116.5
2500	117.9	117.9	115.0
3150	117.2	117.2	113.0
4000	115.5	115.5	111.5
5000	114.5	114.5	109.5
6300	113.7	113.7	107.5
8000	113.9	113.9	106.0
10000	114.8	114.8	104.0
OASPL	140.4	141.6	142.7

Table 7. EELV Maximum Shock Levels.

Shock Spectrum from EELV to PL (G's)				Shock Spectrum from PL to EELV Interface (G's) (due to SV separation)	
Freq-Hz	HPC	5m IPC	4m IPC/MPC	Freq-Hz	All Payload Classes
100	70	70	40	100	150
125	-	-	-	125	175
160	-	-	-	160	220
200	80	-	-	200	260
250	-	-	-	250	320
315	-	-	-	315	400
400	-	-	-	400	500
500	-	-	-	500	725
630	-	-	-	630	1100
800	-	-	-	800	2000
1600	-	-	-	1600	5000
2000	3000	3000	-	2000	5000
5000	3000	3000	3000	5000	5000
10000	3000	3000	3000	10000	5000

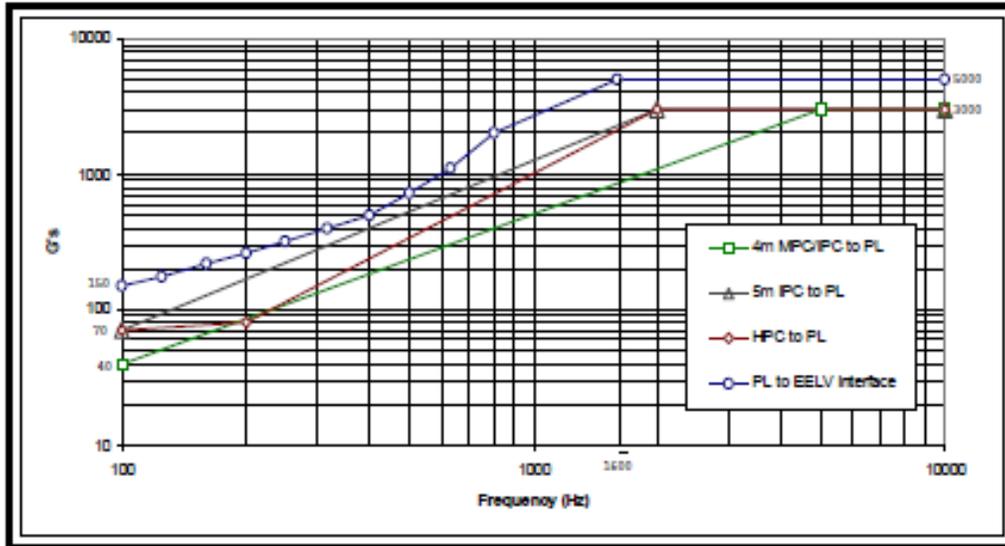


Figure 14. EELV Maximum Shock Levels — Intermediate Frequencies.

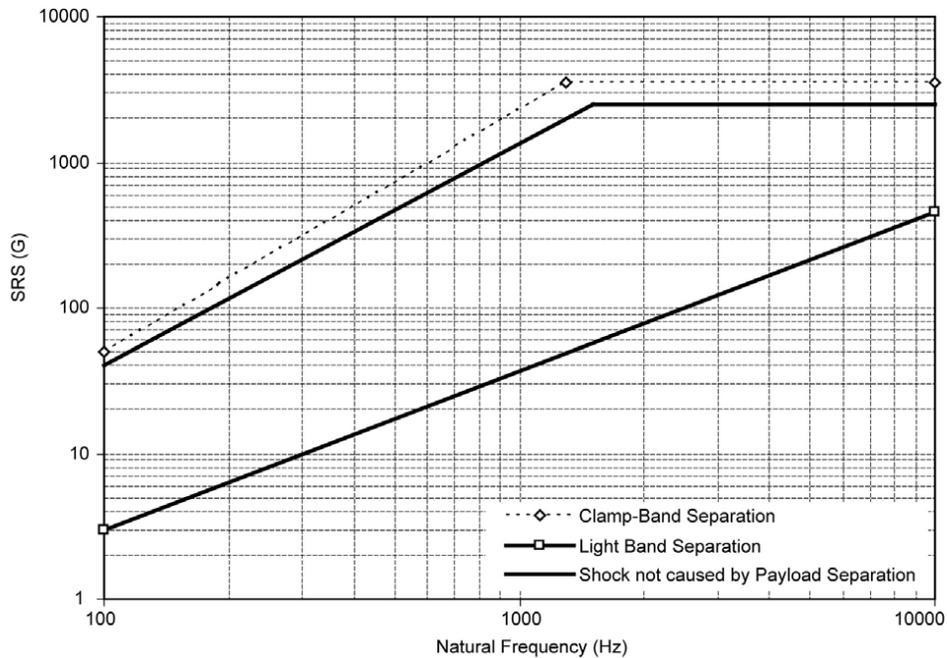
NanoEye Payload Design

This task was the responsibility of ITT and involved evaluating its current telescope design against the EO/IR sensor requirements derived earlier in the program as a result of the strawman mission and bus concepts that were developed. ITT evaluated whether or not modifications needed to be made to the existing

telescope design to transform it into an instrument that satisfied the requirements. This effort involved sensor performance modeling and analysis activities. The end result was that there was no need to refine the design, and ITT has fabricated and tested a functioning engineering version of the optical payload.

Table 8. Minotaur IV Payload Acoustic Maximum Predicted Environment (MPE).

1/3 Octave Band Center Freq (Hz)	SPL (dB) Re: 20 mPa	1/3 Octave Band Center Freq (Hz)	SPL (dB) Re: 20 mPa
20	114.5	630	120.9
25	115.7	800	118.5
31.5	116.8	1000	114.9
40	118.9	1250	110.9
50	119.6	1600	109.5
63	120.1	2000	108.7
80	121.5	2500	109.3
100	122.4	3150	108.7
125	122.9	4000	107.3
160	126.5	5000	109.2
200	127.2	6300	103.9
250	127.5	8000	100.1
315	127.4	10000	99.5
400	127.1		
500	125.4		
		Overall Level(dB)=	136.2



**Figure 15. Minotaur IV Payload Shock Maximum Predicted Environment (MPE)
— Launch Vehicle to Payload.**

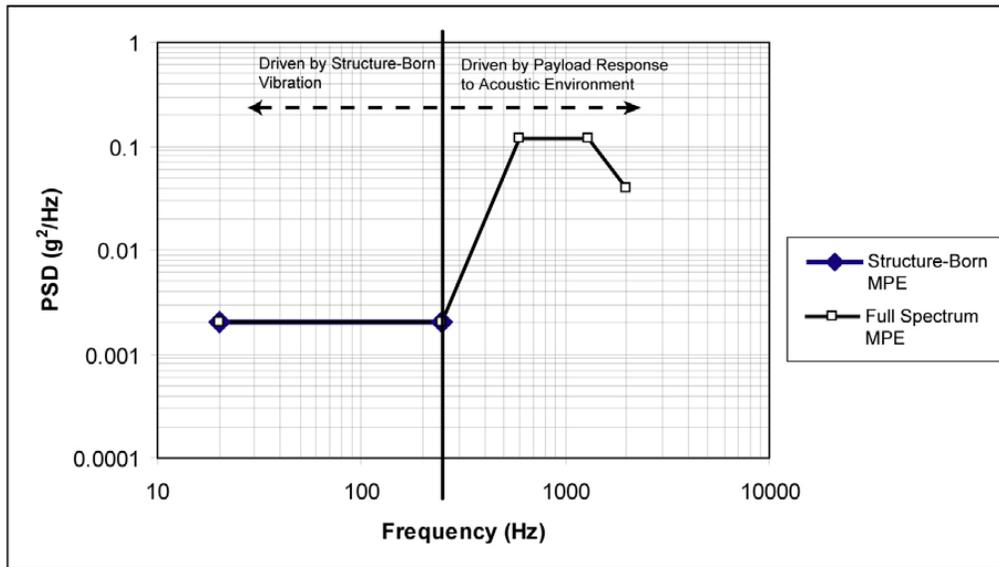


Figure 16. Minotaur IV Payload Random Vibration Environment.

ITT has decided to stay with its initial choice of a Fairchild camera as the one that initially will integrate with the telescope. Another camera was deemed probably too “commercial” to use for space, and ITT is continuing to evaluate other alternatives for the visible camera. Additionally, ITT is looking at sensor types for other mission possibilities, specifically an IR camera and a hyperspectral imager, but has not made any choices yet.

ITT reviewed and reconfigured the packaging concepts of the electronics. Mass reduction was accomplished by using several of its existing patents for Electronics Packaging to improve thermal conductivity, grounding and EMI shielding directly in the circuit board to facilitate removing the electronics housing, and mounting the electronics directly to the telescope support structure (currently the outer barrel assembly [OBA]). Use of flexible circuit board materials to

physically allow the circuit board to have a radius that would better mount to the cylinder geometry of the OBA is another option that was examined. In addition, mission parameters were reviewed in order to optimize a low-mass data processor for the specific LEO mission being evaluated. As a result of these efforts, ITT reduced the mass for the Reconfigurable Payload Data Processor (RPDP) by over 4 kg baseline such that it beat its mass goal). The mass of the power supply for the RPDP is estimated to be about the same as the reduced mass for the RPDP. To avoid noise from the power supply interfering with the operation of the RPDP, they will have to be packaged separately and mounted on opposite sides of the telescope.

The NanoEye ITT RPDP concept is a scalable and re-useable (not required for the space application) processing architecture. One processing channel or pipeline within the architecture is called an “Element”. For NanoEye — only “One Element” is required and represents a simplification of a design ITT developed for more complex and higher performance imaging systems. One Element is what is on ITT’s prototype board that has been laid out in a schematic, but not yet fabricated.

The output interface is 16 frames/sec and could easily store 100 pictures on the DRAM on board. It will be possible to transfer (downlink) with a little as 1 bit/pixel for a visually lossless JPEG 2000 image and to reduce the bandwidth down as needed — there is no extra complication to the board to get smaller thumbnail images or smaller bandwidth.

Implementation and Test Strategy

This task involved creating a plan for integrating and testing the NanoEye sensor in Phase II to reach TRL 5 by the completion of Phase II. The focus was on integration of the NanoEye sensor with the spacecraft bus and creating a test plan for the integrated system to validate it to TRL 5.

ITT reviewed the integration of the payload to the Microcosm designed spacecraft bus and communications system (See Figures 1, 2, 11). Two options are being carried forward:

1. Integrate 2 3U CubeSats with the ITT telescope such that loads from the CubeSats are not transmitted to the OBA, utilizing available space-qualified CubeSat subsystems, including such subsystems as solar arrays, electrical power system, and the attitude control system (Figure 1, Option A).
2. Microcosm fabricates an integral spacecraft bus/OBA designed to accommodate the same

space-qualified CubeSat subsystems, with ITT integrating its telescope components into the integral spacecraft/OBA (Figure 1, Option B).

ITT also investigated the range of data flow that was thought to be a key definitizing parameter of this system. In fact, ITT’s processing architecture is sufficiently flexible that it can be adjusted according to frame rate and downlink capability.

An imaging analysis and performance characterization for the concept system was performed by ITT based on specific mission needs, which demonstrated that its telescope could meet the 1.5 m GSD capability from 600 km that was specified in the SBIR topic description.

Key integration parameters were provided by ITT in various formats. In addition, ITT reviewed and investigated modalities appropriate to the mission opportunities that included other EO, IR, and hyper-spectral imagers.

SUMMARY

The fundamental implementation strategy is to use the sensor payload currently developed by ITT for which a functioning prototype has been built and tested. Further, CubeSat components that have been built, tested, and, to the extent possible, flown, will be incorporated into the NanoEye system. Fundamental to the spacecraft design will be its ability to be launched on any of multiple existing or planned vehicles appropriate for putting a 45 kg class payload into LEO. Relative to CONOPS, also to the extent possible, the operation of NanoEye will be compatible with current Army UAVs and any Army satellites that may have been launched prior to the launch of NanoEye. Finally, missions will be designed such that operational NanoEye systems will be put into the most appropriate Responsive Orbit with tasking from the ground user and data provided directly to the ground user.

Plans have been created or are in work for integrating and testing the NanoEye sensor in Phase II to reach TRL 5 by the completion of Phase II. Testing will result in a sensor TRL of 5 well before the end of Phase II. Since most CubeSat components have been tested to appropriate levels and most have flown in space, they are therefore currently at or beyond TRL 5.

Acknowledgements

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