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Aggressive Surveillance as a Key Application Area for Responsive Space

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Aggressive Surveillance as a Key Application Area for Responsive Space*

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Abstract

The fundamental goal of Aggressive Surveillance is to transform space surveillance from a long-term, strategic role to an immediate, responsive, tactical role by putting the desired on-orbit instrument where you want it, when you want it—anywhere, anytime, with 8 hours notice, at low cost (i.e., less than $20 million per mission including the payload, spacecraft bus, launch, and 1 year of operations). We want to actively pursue the enemy by acting or reacting quickly, at low cost, and in ways that cannot be predicted.

Initial systems can be developed and deployed within 2 years. After the process is initiated, the potential exists to truly change the way business is done in space— in defense, science, education, and commerce. In addition, the process and system are inherently scalable, such that savings in both cost and schedule can be rapidly extended to larger systems at a small fraction of the non-recurring cost and time normally associated with traditional, large space systems.

Introduction—The Utility of Aggressive Surveillance

Traditional space-based surveillance is fundamentally strategic. Systems are expensive and take a long time to develop. Thus, they are designed for global coverage and launched on a schedule largely unrelated to world events. Because coverage is global, any given location on Earth may have coverage only every few days from a single satellite. Opponents will often be aware of system parameters, such as the orbit, and can hide from the system when it is overhead.

The goal of Aggressive Surveillance is to actively and aggressively pursue the enemy by being able to act or react quickly, at low cost, and in ways that cannot be predicted or for which avoiding coverage significantly disrupts the enemy's mobility and activity. Specific parameters that we envision for such a system include:

- Being able to launch a payload or payloads of choice within 8 hours with no prior warning, potentially putting satellites into multiple orbits to provide coverage of more than one location or event.
- Responsive orbits that can provide coverage up to 5 or more times per day of a single location with one satellite to provide monitoring, tracking, and disruptive surveillance.
- Low altitude orbits that can provide high resolution images at dramatically lower cost than the high altitude LEO orbits that are traditionally used.
- Low cost surveillance payloads, such as visible observation systems, wind lidar, and other potential detection systems. Initial resolution can be in the range of 20 to 100 cm with substantially im-proved resolution as the system evolves.
- Responsive communications and operations that can make data rapidly available in multiple locations (i.e., in or near the area of interest and at command locations in CONUS).
- Autonomous, on-board orbit control for the construction of virtual constellations and coordinated observations among diverse spacecraft.

In addition, an aggressive surveillance program allows us to take advantage of technology advances in the shortest possible time, thus significantly magnifying technological superiority. Such advances include:

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- Plug-and-play spacecraft and payload systems for rapid changes or essentially immediate insertion of new technology.
- Reduced drag spacecraft that will allow both increased on-orbit life and substantially improved resolution at little or no added cost by enabling much lower orbits.
- Agile spacecraft to allow already on-orbit systems to respond to new or changing events or just-launched systems to extend their useful lives, track evolving events, or change their viewing parameters to avoid predictability.
- New or evolving payloads to provide better resolution, new sensor systems, or new approaches to data dissemination and utilization.

Key Elements of Aggressive Surveillance

This section addresses each of the key elements of Aggressive Surveillance defined above, along with the status of the technology and its potentially applicability in both the near term and longer range. While there are no set limits on the size of the spacecraft, keeping the cost low and system agile implies spacecraft with a dry mass of less than about 500 lbs, although this could certainly grow with increasing capability of low-cost, responsive launchers. There should be one, or at most two, payloads per spacecraft, and they should be at a low altitude of 150 to 300 km, such that good performance can be achieved from a small satellite. We anticipate a total mission cost (spacecraft bus, payload, launch, and operations) of less than $20 million per satellite.

Launch-on-Demand

The key characteristic of responsive launch-on-demand is that both satellites and launch vehicles must be built to inventory and available for launch when needed. If a cruise missile is needed, we don't expect to submit the order to multiple contractors for bids, negotiate a contract, build the system, integrate the payload, and send it to where it's needed for launch. Similarly, true launch-on-demand requires that the needed assets be built, in storage, and available within a few hours.

A major advantage of satellites relative to cruise missiles and similar assets is that satellites are inherently global and can be launched entirely from CONUS. Cruise missiles must be distributed in many locations and ultimately delivered to the area where they will be used. Satellites can be stored and brought to bear immediately from one or only a few locations far removed from the area of interest, such that relatively few of them are needed to provide effective worldwide utility.

Launch-on-demand is both a technical issue and an economic one. Economically, we must pay the cost of borrowing the money associated with having to buy satellites and launch vehicles and putting them in inventory. There is also a cost of maintenance, but it is likely to be less than the interest cost. Overall, launch-on-demand increases the cost of launch by 2% to 5%, if no surge capability is required and 5% to 10% with a modest surge requirement. [Wertz, 2004]

Technically, the problem is a matter of designing the system to be available for launch on short notice. Clearly, this is technically achievable since ICBMs have had this capability for many decades, but at a dramatically higher cost than is appropriate for responsive space missions. Some of the launch vehicles being developed to meet the launch-on-demand requirement are listed in Table 1. These are discussed in many papers at this and prior Responsive Space conferences. [Berry, et al., 2001; Chakroborty, et al., 2003, 2004; Conger, et al., 2002B, 2002C; Hudson, 2004, 2006; Shotwell, 2004; Wertz, et al., 2003]

Table 1. Potential Launch-on-Demand Small Launch Vehicles. Spacecraft-based techniques to increase the available on-orbit mass are given by Van Allen [2003] and Meissinger [1998].

Vehicle	Contractor	Lbs to LEO	Projected Cost	Launch Time from storage	Launch time when on alert
Falcon 1	SpaceX	1250 lbs	$6.7 M	TBD	24 hr
Liberty	Microcosm	3200 lbs	$7.8 M	8 hr	2 hr†
Quick Reach	AirLaunch	1000 lbs	$5.0 M*	TBD	24 hr
Sprite	Microcosm	810 lbs	$4.2 M	8 hr	2 hr†

* At a launch rate of 20/year

† 5 minutes, if fueled and on hold on the pad

In addition to the launch vehicle, the satellite will also need to be in storage and available for launch within a short period. Economic issues will be essentially the same as for launch vehicles, although in general we would expect more satellites to be in storage than launch vehicles in order to provide more options for specific on-orbit applications. Technical issues will depend on the particular satellite, but among the most common would be installation of a fresh battery, removing covers or lens caps, and possibly adding propellant. None of these should significantly impact the time to launch. In addition, launch ranges must move to a space-based range and develop and implement a rapid launch operations plan.

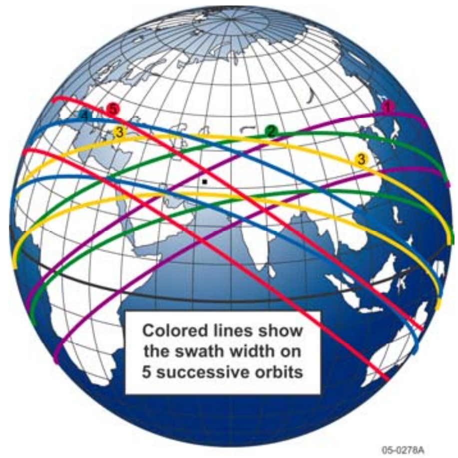
Responsive Orbits

The key issue for responsive orbits is to give up global coverage in exchange for much better coverage of a localized region at a well-defined time [Wertz, 2005]. Most responsive surveillance orbits also have a less-demanding launch requirement than traditional high-altitude, Sun synchronous surveillance orbits and, therefore, can either reduce launch costs or accommodate a larger payload. A detailed assessment of responsive orbits is given by Wertz [2005]. The two most important ones for Aggressive Surveillance are:

- **Fast Access Orbit** that provides coverage of the target of interest on the first or second orbit after launch (i.e., within 0.5 to 2.5 hours)
- **Repeat Coverage Orbit** that provides coverage of a particular area of interest on 5 or more successive orbits.

The Repeat Coverage Orbit is illustrated in Fig. 1. A single satellite will provide 2 to 3 minutes of coverage every 90 minutes for 6 to 7.5 hours, and two satellites can provide coverage for 15 hours per day. The coverage can be matched to the time of day such that two satellites provide coverage every 90 minutes for essentially all daylight hours. Because of orbit precession, the coverage will move earlier 20 to 30 minutes per day in mid-latitude regions. Thus, a single satellite biased late in the day, would provide good coverage for about two weeks (and then again about a month later). A set of 3 satellites in a repeat coverage orbit will provide 24 hour/day coverage for the life of the satellites and precession will not be an issue.

Fig. 1. A Repeat Coverage Orbit Provides a Short Span of Coverage of a Defined Region on 5 or More Successive Orbits. 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 be disruptive to enemy operations if an attempt were made to avoid surveillance. [Wertz, 2005]



Low Altitude Orbits

In some respects the most important issue for low-cost surveillance systems is the orbit altitude. In traditional reconnaissance missions a large payload is flown in a high LEO orbit (typically 800 to 900 km) to provide a combination of wide coverage and long lifetime. Because we do not know where the need for surveillance will arise, the system must provide global coverage, which drives us to a high altitude and large aperture instruments. If we narrow our focus to a specific, identified region, comparable or even better resolution can be obtained with instruments that are dramatically lower cost. For example, the Hubble Space Telescope flying at 800 km would have a ground resolution at nadir of 0.22 m in the visible region of the spectrum. (See Table 2.) At 2.4 m diameter, Hubble's initial cost was $2.5 billion in $FY06 [Apgar, et al., 1999]. Essentially the same resolution can be achieved with a 1 m instrument flying at 300 km. If either the reduced drag spacecraft or spacecraft agility are implemented as described below, then flying at 150 to 200 km is reasonable and the Hubble resolution can be achieved with only an 0.5 m aperture. At this low altitude, the 1 m aperture would provide twice the resolution of Hubble at 800 km. Most importantly, instruments in the range of 0.5 to 1.0 m diameter can be obtained in a short time at a cost of millions, rather than billions of dollars.

Table 2. Ground Resolution, R, at Nadir for Varying Altitudes and Apertures for a wavelength of 0.55 microns in the visible region of the spectrum. (Based on $R = 1.22\ h\lambda/D$)

Altitude (km)	Resolution (m)		
	2.4 m Aperture	1.0 m Aperture	0.5 m Aperture
800	0.22	0.54	1.07
600	0.17	0.40	0.81
300	0.08	0.20	0.40
200	0.06	0.13	0.27
150	0.04	0.10	0.20

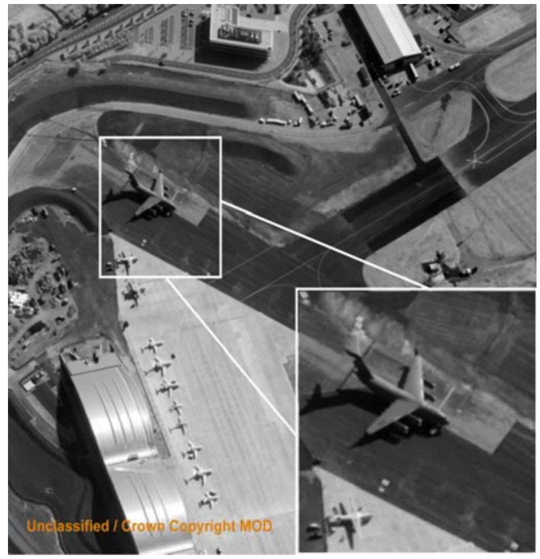
It is often argued that flying at a higher altitude provides better access, but that is only partially true. Smaller instruments often have a larger field-of-view and, therefore, may achieve a similar area coverage rate as the larger, higher instrument. The higher altitude has the advantage of being able to see more of the Earth and, therefore, has greater utility if we don't know the area of interest. If we have a defined region that we wish to cover, then the lower altitude can provide a similar area coverage rate as the higher altitude with a much more frequent revisit rate and comparable or better resolution at a small fraction of the cost.

Low-Cost Surveillance Payloads

At an altitude of 150 to 300 km, a much smaller instrument can obtain comparable or better resolution than that from a larger instrument at a higher altitude. These instruments will be both lighter weight and dramatically lower cost than their larger counterparts.

An example of a low-cost, near-term surveillance payload is the derivative of the Goodrich SYERS sensor used for airborne surveillance and described at RS3 and RS4 [Cox, et al., 2005, 2006]. This would provide a resolution of 0.67 m at an altitude of 200 km and could be built in the near term at a mass and cost compatible with our ~500 lb, $20 million overall system objective. An example of the image quality is shown in Fig. 2.

Fig. 2. Image quality expected from the Goodrich SYERS-derived payload flying at an altitude of 200 km.



Responsive Communications and Operations

Responsive communications and operations is a substantial problem area for Aggressive Surveillance. (See, for example, Knight [2006].) If we are trying to observe a newly defined area of interest within a few hours, then it is unlikely that there will be a ground station conveniently located to collect data from a low-flying spacecraft. In principal, we could use a real-time geosynchronous relay link, but this solution is typically too expensive for our low-cost system goals because of the need for an articulating communications antenna.

While challenging, there are a number of possible solutions that could be adopted, such as:

- Delayed GEO relay such that the spacecraft stores the data on board and sends it via a geosynchronous relay after the target region has gone out of view by moving the entire spacecraft to track the GEO relay satellite.
- Iridium modem link using the Iridium communications constellation. The supported data rates would be comparable to a commercial modem (i.e., very low) such that substantial on-board pre-processing would be required.

- Distributed ground station network located, for example, at embassies and consulates around the world. Within a relatively short period of time any satellite will fly over one or more of these stations and could return high bandwidth data.
- Ground stations fixed relative to the launch site at longitudes 22.5 deg and 45 deg west of the launch site. Irrespective of the launch inclination, satellites will pass over these locations 1 and 2 orbits after launch, providing a rapid data return for the Fast Access Orbit.

Autonomous On-Board Orbit Control

Particularly in a high drag environment, it will be very difficult to predict or control the ground track of the satellite due to the widely varying levels of atmospheric drag, particularly on the critical first few orbits. (See, for example, Wertz [1999].) This difficulty can be overcome by making use of absolute autonomous orbit control on board the spacecraft that both reduces the propellant required for orbit control and provides a well-defined, predictable orbit [Conger, et al., 2002A; Gurevich, et al., 2001; Wertz, et al., 1996, 2001]. The parameters can, of course, be changed to make the orbit unpredictable to the enemy.

Because the orbit is controlled and can be predicted well in advance, coverage can be coordinated among different satellites in very different orbits with different flight parameters, thus creating a "virtual constellation" with whatever satellites happen to be on orbit at any given time. For example, we may be able to adjust the parameters of a satellite already on orbit to provide coverage after the time that precession has started to move the Repeat Coverage Orbit into the pre-dawn period, several weeks after launch.

Other Supporting Technologies

One of the major advantages of an Aggressive Surveillance program is that it allows us to take maximum advantage of the development of new technologies. With the current approach to surveillance systems, the development and insertion of new technologies can take decades — i.e., long past the time at which they are needed. Our goal should be to develop technologies in a short period and to use them to solve today's problems. There are a great many technologies that will allow this goal to be achieved or which will contribute substantially to Aggressive Surveillance. Among the most important are the following.

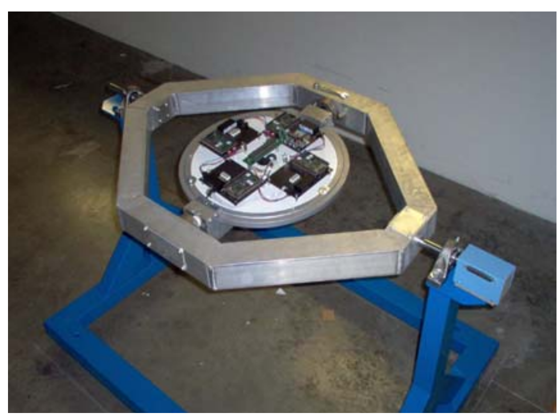
Plug-and-Play Spacecraft

Traditional spacecraft take months, and sometimes years, in the integration and test process. In contrast the modern plug-and-play peripherals in a desktop computer are integrated nearly instantaneously. Changing printers or exchanging a printer for a memory stick is truly a matter of exchanging hardware and possibly installing a driver. This same plug-and-play functionality is now being developed and demonstrated for spacecraft systems [Avery, 2006; Collins, et al., 2003; Graven and Hansen, 2006; Morphopoulos, et al., 2004; Orogo, 2006]. A plug-and-play spacecraft attitude control system is shown in Fig. 3. In terms of Aggressive Surveillance, plug-and-play technology enables a variety of important functions:

- Rapid integration of a new spacecraft.
- Rapid insertion of new technology into spacecraft already built and in storage.
- Common spacecraft components or payloads that can be built, stored, and used as needed (the "6-day spacecraft").

The key issue here is to give up absolutely minimum weight in order to accommodate flexibility and responsiveness.

Fig. 3. Microcosm demonstration of a plug-and-play spacecraft attitude control system on a 3-axis rate table. The system is self-reconfiguring to proceed with the best available information.



Scalable Launch Systems

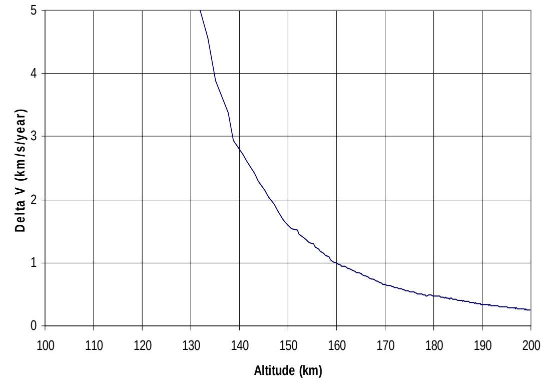
Although not directly related to responsive launch, one of the central elements of an Aggressive Surveillance program is a scalable launch system. As low-cost systems become more competent, they will also get more massive, particularly as propellant is added to provide spacecraft agility or low-altitude, high-resolution missions. Unless low-cost, responsive launch systems are scalable, we will be in the position of having to optimize the system for minimum weight, which returns us to the "death spiral" that has caused much of the current optimized, high cost missions that we are trying to circumvent. As discussed in other Responsive Space Conference papers and elsewhere, Microcosm's Scorpius® family of launch vehicles is specifically designed for scalability [Bauer, 2006; Conger, et al., 2002B, 2002C; Wertz, et al., 2003].

Reduced Drag Spacecraft

Below approximately 500 km altitude, drag will impact the satellite lifetime and make orbit prediction more difficult. (See, for example, Walterscheid [1999].) Below 300 km, the problem becomes severe, and traditional spacecraft will have a lifetime of a few months or less without substantial orbit maintenance. However, as described above, flying at altitudes of 150 to 300 km can provide very high resolution imagery at a mass and cost far less than what would be needed at higher altitudes.

One approach to achieving low altitude missions is to reduce the drag on the spacecraft. Microcosm has been working on a proprietary approach that can reduce satellite drag by a factor of 5 to 10, or equivalently, create an "Effective Ballistic Coefficient" of 1000 kg/m2 or higher. The resulting delta V needed to maintain a given altitude is shown in Fig. 4. The net effect of creating a reduced drag spacecraft is to allow satellites to fly at altitudes as low as 200 km for an extended period and as low as 150 km for short periods, such as dropping perigee to a low altitude and then raising it for long term observations or on-orbit storage.

Fig. 4. Delta V needed to maintain altitude for 1 year with an "Effective Ballistics Coefficient" of 1000 kg/m2.



Agile Spacecraft

Substantial work has been done at the Air Force Space and Missile Center on what they have called Agile Spacecraft, that is, spacecraft with 0.5 to 1.5 km/sec of delta V capability such that the spacecraft can make substantial orbit maneuvers many times during their life [Pollock, 2005]. The basic idea is to allow on-orbit spacecraft to be more responsive in terms of meeting changing needs or accommodating orbit maneuvers, such as perigee lowering to improve resolution. Many of the applications of Agile Spacecraft are directly applicable to Aggressive Surveillance:

- Lowering perigee to allow high resolution, low altitude imaging for a two-week period of interest.
- Raising apogee to provide wide area, lower resolution coverage.
- Maintenance of satellites in a 200 km or lower orbit.
- Changing the orbit inclination or node to accommodate a changing area of interest on the ground or extend the time period over which good coverage is available.
- Changing the time or viewing angle of a coverage pass in ways that cannot be predicted by the enemy (surprise flyovers).

Agile spacecraft do not represent a new technology per se because this capability already exists. Space qualified, long duration, thrusters of a wide variety of sizes appropriate for agile spacecraft are readily available. It is far more a matter of changing the way space operations are done and how missions are accomplished.

New and Evolving Payloads

In the proposed approach, both launch vehicles and satellites are built to inventory and stored until needed or launched for test or evaluation purposes. At less than $20 million/mission, it is reasonable to have at least some launches that are intended simply as tests of new spacecraft or payload technology. This process is intended to facilitate the rapid insertion of new technology and use of new and evolving payloads. Thus, as a new payload is completed, it could be mated with an existing bus already in inventory and launched immediately as a test mission or held until an appropriate "mission of opportunity" arises. For example, new imaging payloads could be launched in response to a natural disaster (such as the southeast Asia tsunami or the gulf coast hurricanes) to both provide assistance and test the capability and limits of the new payloads.

Because the mission duration is short and new payloads can be inserted into the process as they become available, it isn't necessary or appropriate to develop the "gold-plated" version of a payload prior to the first launch. Initial payloads may be space-qualified versions of existing airborne or ground payloads. For example, the Goodrich optical payload sensor described above is a space-qualified version of the SYERS airborne payload [Cox, 2005; Kishner 2006]. This payload can be upgraded as newer, lighter weight or larger aperture systems become available, much like today's aircraft systems are upgraded. Using the plug-and-play technology also described above, many sensors may be "line-replaceable-units" that are changed out in systems that are in storage awaiting launch.

Another example of near term evolving payloads is the TacSat-3 hyperspectral imaging payload, ARTEMIS (Advanced Responsive Tactically Effective Military Imaging Spectrometer), developed by Raytheon and scheduled to be built in 15 months [Cooley, et al., 2006]. At an initial cost of $14 million, ARTEMIS likely falls outside of our $20 million/mission objective, but costs far less than would normally be the case for payloads of this size and complexity. In addition, economies of scale could easily bring the cost of subsequent units to well below the payload cost target. Other examples of TacSat and SmallSat payloads and their military utility were described by Space et al. [2004] at RS2. Their conclusion is fully consistent with the objectives and approach of an Aggressive Surveillance program: "An agile, responsive, commander-oriented vision for space systems development and operation, focused primarily at the tactical and operational level of war, will result in revolutionary capabilities through and from space. Focus on small- and micro-spacecraft (with concurrent launch programs), in the near-term, will allow the acquisitions and procurement process to accept higher risk and to drastically lower costs ensuring that critical, niche capabilities can be delivered in tactically-meaningful timelines." [Space et al., 2004]

A design for low-cost, responsive communications systems under development by Surrey Satellite Technology Limited (SSTL) has been described by Davies, et al. [2004]. While specifically intended for GEO, these payloads could potentially be adopted to one or more of the communications-oriented responsive orbits [Wertz, 2005].

Getting From Here to There—Implementing Aggressive Surveillance

This being the modern space era, it is highly likely that we will spend more time and possibly even more money discussing what can be done than it will take to do it. While not precise, the general recurring cost breakdown which we envision is as follows:

Launch	$5 million
Spacecraft bus	$5 million
Payload	$9 million
Operations (1 year)	$1 million

More specifically, as shown in Table 3, we estimate that a demonstration mission with 0.3 to 1.0 m resolution at nadir can be developed in 24 months for a recurring flight cost (in small quantities) of approximately $16.2 million. Final costs will depend, of course, on the selected payload(s), bus, and launch vehicle and the requirements that are levied on the system.

Table 3. Estimated Cost for an Aggressive Surveillance Demonstration Mission.

Element	Recurring	Source
Payload	$7.0 M	Goodrich SYERS derivative
Spc Bus	$4.4 M	TacSat-3 derivative
Launch	$4.2 M	Microcosm Sprite
Operations	$0.6 M	TacSat-3 derivative
Totals	$16.2 M	Meets Objective of <$20 M

The demonstration mission can include a variety of technologies and capabilities depending on the timing of the mission and selected objectives. A conservative baseline would be a 300 km circular Fast Access or Repeat Coverage orbit, depending on the identified needs and mission objectives [Wertz, 2005]. Some spacecraft agility could be demonstrated by reducing perigee to 200 km or lower for demonstrating higher resolution imaging. Testing some level of drag reduction would also be appropriate.

The demonstration payload could be the SYERS derived optical surveillance system based on existing airborne systems [Cox, 2005; Kishner, 2006]. The spacecraft bus and operations can be based on the TacSat-3 system currently under development. This bus can meet the performance and cost objectives and is currently scheduled for delivery in 2007. For on-demand, all-weather launch, we propose using the Microcosm Sprite launch vehicle [Wertz, 2003; Bauer et al., 2006].

An important part of the demonstration program is the development of a **Transition Plan** for showing clearly how the system will move from a demonstration system to one that is operational and achieves the desired cost objectives. Microcosm developed a launch vehicle Transition Plan during the DARPA FALCON program on the basis that the FALCON model of 20 launches/year for 10 years was not a realistic follow-on to a single initial demonstration flight. Similarly, there must be an **Evolution Plan** for bringing in other payloads, system growth, and technology insertion. The goal of the demonstration system is not to create a single isolated mission, but to have a well-defined and fiscally realistic approach for evolving the initial demonstration into a truly transformational system.

Conclusions

The proposed Aggressive Surveillance program is not the result or implementation of a single, specific technology, but rather an aggregate of the work on Responsive Space that has been done over the last several years, much of which has been reported at this and previous Responsive Space conferences. The results, however, do represent a dramatic change in the utility, cost, and timeliness of space missions. We can implement an Aggressive Surveillance program within 2 years such that operational missions can be launched in less than 8 hours from a previously unidentified demand, or minutes if the system is on alert and fueled on the launch pad. Such operational missions can and should have a cost of less than $20 million per mission and should be used to put payloads on-orbit when and where they are needed to meet the needs of the warfighter or the need for natural or man-made disaster assistance.

The nature of our enemies has changed dramatically since the collapse of the former Soviet Union. They are substantially more elusive and more difficult to find. While sophisticated in some respects, they do not have and will not easily acquire the space assets available to the United States (although this does not mean that they are not capable of attacking our space systems). Therefore, we should take maximum advantage of our space resources and of technological advances in space. We should be able to respond appropriately and immediately to attacks anywhere in the world or in space and provide sufficiently aggressive surveillance to be able to disrupt the enemy's planning and operations whenever possible. Waiting a decade or more for technology insertion in the space arena is no longer acceptable and no longer needed. The potential exists to do not only better, but dramatically better.

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