A Microsatellite "Space Guard" Force

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Abstract

The microsatellites now under development will be capable of a variety of inspection, surveillance, servicing, and propulsion services. As the military and commercial importance of space increases, a practical near-term use of this technology will be to provide the kind of services in space that the U.S. Coast Guard provides on Earth. The Coast Guard provides the U.S. coastal waters with law enforcement, search and rescue, safety inspection, and a myriad of other services. All these services are needed in the near-Earth region as well, and will become more critical as thousands of additional satellites are launched. A "Space Guard" constellation of microsatellites would use the technology being developed under the XSS-10, Mightysat, and other programs to provide similar services, beginning with low Earth orbit (LEO). Space Guard satellites could evaluate damaged satellites, enforce treaties by inspection, monitor traffic in key orbits, and report collision hazards, If needed, microsats could attach thrusters or tether packages to move or deorbit a disabled satellite. While an independent agency or international consortium could eventually operate the Guard, its initial deployment would most likely be under U.S. Space Command. This paper assesses the requirements and technology involved in the Space Guard proposal, along with possible operational structures and initial cost estimates. The Space Guard concept is a vital one. Microsatellites are the most affordable and effective way to put it into practice.

Introduction

As the explosion in use of space, especially the increasingly crowded LEO belt, continues, space planners are faced with a situation analogous to what the U.S. government dealt with in the early years of the Nation's existence. Coastal water traffic was increasing rapidly and haphazardly. This trade was important for the new nation's economic well-being and a vital source of revenue. But it had to be regulated, required taxes and fees collected, and the safety of the vessels involved had to be ensured. This led to the creation in 1789 of the Revenue Marine and the Lighthouse Service. These two organizations were later combined into the U.S. Coast Guard (USCG).

Today, most nations with sea coasts have similar services. Some are military, some civilian, and some, like the USCG, have dual identities. Their functions vary, but most have responsibilities which include the inspection of ships, maintenance of navigational aids, enforcement of laws, collection of revenue, and search and rescue.

Billions of dollars' worth of satellites are now in orbit, providing services so vital that space is referred to as a new economic center of gravity. A 1999 forecast by the Teal Group estimated that 1,447 additional satellites, valued at $126.8 billion, will be orbited from 2000-2009.[1]

There are only a few international treaties in place to regulate this traffic, and there is no enforcement, rescue, or centralized traffic-deconfliction body. As space's importance to Earth commerce will only increase, it is time to examine the options for a "Space Guard" – a Coast Guard in space.[2]

This requirement arises at the same time a promising technology is becoming mature. That technology is microsatellites. Microsats, offering low-cost, rapid-response spacecraft able to perform a variety of functions, can be the "Coast Guard cutters" of the new space service.

Background

Since 1957, thousands of satellites have been launched into orbit, along with countless upper stages, shrouds, and other hardware. The North American Aerospace Defense Command (NORAD) Space Surveillance Network (SSN) today maintains orbital element sets for some 8,000 objects, and many more are too small or too eccentric in their orbits to be catalogued. The debris now in orbit totals an estimated 4,000 metric tons, with 175 metric tons added every year.[3]

With the launching of major constellations of commercial satellites, the economic importance of space and its relative crowding will increase once more. Iridium has 77 satellites in orbit (not all functional), ORBCOMM 36, and Teledesic alone will add 288. Many of these are concentrated along particular inclination "belts," such as the 56-degree inclination, which will become very busy as construction and operation of the International Space Station (ISS) proceeds.

The Air University study *Spacecast 2020* put the problem this way: "The explosion in the number of satellites will create increasing numbers of conflicts between the vehicles – and their Earth-bound owners…space will become a very busy place. Who will monitor, regulate, and provide stability for all these hurtling pieces of high technology?"[4]

Complications will inevitably arise from the ever-increasing use of space. Nonfunctioning satellites, from microsats to a giant $800M Milstar launched in 1999, are in orbit without power or command capability. While slots in the geosynchronous orbit (GEO) belt are governed by international agreement, there are no enforcement mechanisms for this arrangement, and no analogous governing regimes for satellites in other orbits.

Where satellites are concentrated, so is space junk. In June 1999, NASA attempted to move the ISS because of a collision hazard posed by Russian space debris. The object missed the ISS – which was fortunate, since the ISS' thrusters could not be fired due to human error.[5]
So far, there has been one confirmed instance where a satellite was damaged by collision. This was in 1996, when a spent booster stage collided with the Cerise microsatellite. It is logical to assume that increased use of space will bring more such instances.

For the Space Guard to have maximum effectiveness, the capability to track space objects will also need upgrading. The SSN, which is the world's most capable tracking system today, can track only objects over 10 centimeters (cm) in diameter, and it cannot track objects continuously. Space objects are monitored each time they break "fences" erected by ground-based radar. There is no way to follow an object with an eccentric path – for example, a malfunctioning satellite firing its thrusters in an unpredictable pattern – to see if a hazard is being posed at any given moment. A 1997 report by the General Accounting Office concluded the U.S. needed to add the capability to track smaller objects – down to 1 cm, if possible – and the ability to precisely locate tracked objects in space.[6]

One solution is to put space surveillance capability into orbit, where the field of view would exceed that of any terrestrial sensor and the obscuring effects of Earth's atmosphere are not present. The feasibility of this is being demonstrated now using the Space-Based Visible (SBV) sensor on the Midcourse Space Experiment (MSX) satellite.[7] Air Force Space Command (AFSPC) plans to develop a Space-Based Electro-Optical Network (SBEON) using three satellites in GEO. Another approach is to have tracking spacecraft which can follow (physically or by sensors) a threatening object.

The optimum approach may be a mix of ground- and space-based capabilities, with something like the current SSN (which could include the current ground-based sensors plus SBEON) providing global monitoring while Space Guard microsats add space object identification (SOI) capabilities for heavily-used orbits or conduct special searches to more precisely locate possibly-threatening objects detected by the SSN.

Finally, there is currently no way to perform a close inspection of a satellite. Ground-based and aircraft-based telescopes can provide some data on the status of a malfunctioning object in low orbit, but these sensors are limited both in field of view and in resolution.

Why Microsatellites ?

The need for a Space Guard would be irrelevant if there were no affordable means for deploying the needed capabilities. Until recently, this was the case. Fortunately, while space launch remains expensive, technology now exists to develop microsatellites which can track debris, inspect space objects, deorbit dead satellites, and perform the other functions required. Microsats (defined here as satellites under 100 kilograms (kg) wet mass) are also cheaper to launch. A smaller satellite needs a smaller launch vehicle, and microsats can also take advantage of the secondary payload opportunities that exist on large expendable launch vehicles (ELVs) and the Space Shuttle.

Twenty years from now, the Space Guard role may be filled by crewed or uncrewed reusable launch vehicles (RLVs), which will operate much in the way aircraft do today. The development of RLVs, however, is an extremely expensive enterprise, and it is impossible to predict when space access via RLV will become truly routine. If we want to create a Space Guard in the near term, microsats are the only affordable way to do it.

Policy and Requirements

The cornerstone of space law is the 1967 Outer Space Treaty, which declares space is not subject to appropriation, establishes the right of free transit of space, and forbids the stationing of weapons of mass destruction in space. Other agreements worth mentioning include the Liability Convention, which establishes that each nation is responsible for damage done by its space objects, and the Registration Convention, which requires all nations to release basic information on each satellite placed in orbit.

While there is no legal regime in place specifically providing for a function like the Space Guard, there is also none prohibiting it. If, for example, U.S. Space Command deployed Space Guard microsatellites to support U.S.-owned satellites, no treaty problems would arise. As one space law authority, Professor Joanne Gabrynowicz, points out, problems may arise when conflicts with other nations' satellites appear. Satellites are the sovereign property of the launching nation, and any contact with a satellite may be construed as a violation of national sovereignty.[8] (Passive inspection which does not interfere with the operation of the target satellite is permissible.)

For example, assume a nonfunctional Russian satellite presents a hazard to an American satellite. The U.S. would need to contact Russia and request permission to have the Space Guard move or deorbit the Russian satellite. In this case, since Russia would be liable for the damage its satellite causes, the Russians should be amenable to allowing such action. They might even share the costs of the operation, a subject discussed later in this paper.

If the Russian and American satellites in this example were both operational, and therefore valuable, the negotiations would be more complex. It would certainly be in both countries' interests to solve the problem, and so it's reasonable to assume a solution would be worked out.

The alternative to a U.S.-directed Space Guard would be to begin broad negotiations now to establish an international legal regime. While there are definite advantages to having such a regime in place, such as being able to take action without negotiating with each government involved every time there was a problem, it would probably take years to establish the required agreements. A middle ground might be for the U.S. to move simultaneously along parallel paths: establishing a Space Guard for support of U.S. satellites while sponsoring an international working group to broaden the use of the Space Guard in the future.

Hazards of Space Commerce

Many of the hazards involved in space commerce are analogous to those in maritime commerce. They include collisions with derelicts and debris: collision with other vessels: dangers posed by vessels operating without proper regard for the "rules of the road:" natural hazards (in space, solar flares and meteors): and the rare but genuine possibility of outright “piracy” or other hostile acts.

While NORAD maintains a relatively complete catalog of space objects within the detectable size range, the agency has no capacity to take any action to mitigate any hazards that may be detected. Neither the U.S. nor any other nation has a capability to eliminate or redirect space debris. The U.S. Space Shuttle offers a limited capability to retrieve or fix dead satellites, but only in certain orbits and with months of lead time.

Where will inspection requirements and collision hazards arise? The two LEO orbits most in need of assistance will probably be the 56.1-dgree inclination, where the ISS and all its support flights will operate, and the sun-synchronous orbit around 98 degrees, where many imaging and scientific missions are placed. The Clarke belt (GEO) offers a unique case, since its limited numbers of slots are doled out by international agreement and can be blocked by malfunctioning or illegally placed satellites (both of which have happened). While technology and costs make it simpler to deploy the first wave of Space Guard microsats into LEO, a GEO follow-on should receive serious consideration.

Another hazard, paradoxically, is created by efforts to mitigate the orbital debris problem. Many launch vehicle upper stages, like the Delta 2, are maneuvered after payload delivery to lower their orbits so they will re-enter within two years. However, only Russia's Proton actually makes a de-orbit burn. Other stages enter randomly, with some chance that debris will survive re-entry and impact populated areas.[9] If Space Guard microsats could closely monitor such re-entries, the ability to predict impact times and locations would be greatly improved. A step beyond this would be to use Guard microsats to intercept particularly threatening stages and impart a corrective force to ensure they come down over ocean areas.

Options for Space Guard Organization

The first-generation Space Guard, if deployed within the next five years, would almost certainly have to be operated by U.S. Space Command. No other agency currently in existence has a comparable network of tracking systems, command capability, etc.

In the long run, an international agency could be created, but duplication of existing facilities would not be cost-effective. The NORAD-run SSN, for example, would probably continue to be part of such an effort. Whether the effort is national or international, the existing Space Control Center (SCC) in NORAD's Cheyenne Mountain installation in Colorado is a logical place to collate the sensor data, while operating the Microsats from existing AFSCN installations at Schriever Air Force Base in Colorado also seems logical. Personnel from civilian agencies or international partners could be part of the teams involved.

There are many precedents for military involvement in functions which are in part civilian or international. The U.S. Coast Guard is a part of the Department of Transportation in peacetime, but has military responsibilities and is placed under the U.S. Navy in time of war. The U.S. Air Force runs the GPS satellite system, which provides services worldwide to all types of users.

Microsatellite Capabilities Required

A Space Guard capable of mitigating all the hazards described for far would need certain capabilities, including the ability to:

1. Inspect a satellite
2. Deorbit a satellite
3. Alter the orbit of a satellite
4. Deorbit or deflect space debris

It may be that not all these capabilities are deployed, or that they are deployed gradually. For example, an XSS-10-type microsat, capable of locating and inspecting a target satellite, might be the first "cutter" in the Space Guard's inventory. As technology is developed and made affordable, other types of satellites could be added.

There is always a balancing act between buying a single system capable of many missions (meaning the individual satellites will be heavier and more expensive) vs. buying several types of specialized satellites (which creates logistical and operational challenges).

One way to approach this problem is to deploy first what is available "on the shelf" (in this case, microsats like the XSS-10) and make the tradeoffs as microsatellite technology matures. Miniaturization might advance to the point where the replacements for these first satellites could be multipurpose. Another approach is to take a bus like that of the XSS-10 and develop a variety of front ends with "plug and play" replaceability.

Alternatively, it might be more cost-effective to keep buying XSS-10 derivatives for the track-and-inspect missions and have specialized repositioning and repair microsats. The alternatives will have to be analyzed before the initial satellite buy and then revisited each time acquisition of a new block of spacecraft is planned. The notional Space Guard plan (below) includes three block purchases over a 15-year life span.

Technology Required

The critical technology - some of it on the shelf and some still in development - can be broken down by capabilities.

General

All microsat functions, even those already space-proven, can benefit from further improvements in basic areas such as lightweight buses, high-efficiency solar arrays, and more efficient propulsion. Promising efforts along these lines include the composite buses, like the all-composite structure of the FORTE satellite for Los Alamos national Laboratory, flexible thin-film solar arrays built by AFRL, integrated tank/line/thruster designs such as the XSS-10's, and "subsystemless" design principles, which have been pursued by Ball Aerospace with the concept of basing design on functions rather than traditional subsystems.[10]

Other general features desirable in Space Guard microsats include:

- Autonomy: Future satellites will need to possess a high degree of autonomy, both on board and with ground command and control systems. This can reduce operational costs and risks associated with their missions.

- Sleep Modes: This technology could extend on-orbit lifetimes by allowing the satellite to essentially hibernate between missions. All nonessential subsystems and components are shut down to the maximum extent possible. This includes payload, attitude control, and thermal. The satellite can be reactivated via ground command.

- Man-in-the-loop Control: This feature allows for positive human control during inspection and/or repositioning activities. The command and telemetry system will need to possess adequate bandwidth to support this. Also, the inertial environment of space requires in-depth training and familiarization for the operator.

Added Requirements for Specific Missions

Inspection: Inspection of a satellite for damage or for illegal payloads (such as weapons of mass destruction) requires the capability to move in close, inspect from all sides, and provide video and other data of sufficient resolution to obtain the desired knowledge. All this has to be done without interfering with the target satellite's trajectory or its function. Such interference could be viewed, justifiably, as an unfriendly act, similar to impeding the passage of a ship on this high seas.

This requires extremely precise maneuvering capability and small, high-resolution sensors. The sensor question may be resolved by the Active Pixel Sensors (APS) developed at JPL. These "cameras on a chip" require only a fraction of the weight and power of current CCD imagers.

Repositioning: Moving satellites, especially satellites larger than the Space Guard microsat, between orbits will require robotic grappling devices to attach the microsat or a thruster package for the time required and sufficient delta-V on the part of the microsat to achieve the changes in speed and direction required. High-efficiency storable propulsion systems should result in simpler, more reliable, and more efficient propulsion.

Microsats might also be used in conjunction with larger vehicles the Air Force Space Command's planned Solar Orbital Transfer Vehicle (SOTV). A microsat might become the front end of an SOTV and provide the "brains" needed for a mission, or a microsat could direct an orbiting satellite onto an orbit where the more powerful SOTV could dock with it and take over the task of orbit-changing.

If the microsat is to be capable of actually docking to the target satellite and moving it, repositioning capability will also require adaptable guidance and control algorithms capable of sensing and adjusting immediately to the changed center of gravity and other characteristics of the combined spacecraft.

Deorbiting: Deorbiting a satellite (either a nonfunctioning spacecraft or a hazardous piece of debris, like a spent upper stage) is a similar problem. One solution in this case is for the microsat to carry miniature tether packages, like the "Remora Retriever" proposed by Tethers Unlimited.[11] These would weigh about 25 kg and could allow the microsat to perform another function while the tether slowly brought down the offending space object.

Existing Programs to Leverage

The U.S. is developing a number of microsatellite programs with Space Guard applicability. Most notable is the XSS series being developed by the Air Force Research Laboratory. These will have space surveillance and space object identification capabilities, augmented later with the ability to refuel and reposition other satellites.

Other programs of note include the Daimler-Chrysler Aerospace development of the second-generation Inspektor satellite for the ISS. This satellite weighs only 8 kg and is designed for close inspection. It is powered by a cold-gas propellant system, and can be recovered and re-used.

Cost Estimates

If we assume that, for a first-generation Space Guard, the existing U.S.- owned tracking and command facilities, augmented when needed by those of other nations, would be adequate, then the major costs involve microsatellites and their launch vehicles.

The XSS-10 microsatellite, with space tracking and close inspection capabilities, was estimated by Boeing to cost about $3.5M for the first spacecraft or about $1.8M (hardware costs alone) for a block of 20.[12] Other costs include storage facilities on the ground, launch, and control of the microsats on orbit. The control function could be assumed largely by existing Air Force Space Command and USSPACECOM units.

To offer some sample cost projections for the “base case” (lowest cost), we here make the following assumptions:

1. The microsats used are XSS-10 derivatives. There are two types: Imagers (with wide-angle surveillance and close-range inspection capabilities) and Mechanics (able to dock, transfer fluids, or reposition satellites). Both are assumed to cost $3.5M each (all costs in Base Year 00 dollars) and have one-year life spans on orbit.[13] (The $3.5M cost is used here to be very conservative, since Boeing's $1.8M block estimate did not include any costs other than hardware. Using $3.5M as a fleet average cost also allows for the presumably higher price per satellite of the Mechanic type.)

2. Agencies already pursuing XSS-type microsats, including AFSPC and AFRL, have paid the research and development costs of these satellites.

3. The Space Guard uses existing command and control facilities, but a 12-person branch (which may be a mix of military, civilian, and/or international personnel) is added to one of the space operations squadrons at Schriever AFB.[14]

4. In keeping with current USAF plans, launch services are purchased, not launch vehicles.

5. From 2002 through 2026, two Imagers are continually on orbit in the 56.1-degree the 98-degree inclinations. Imagers are replaced on an annual schedule using secondary payload slots costing approximately $500,000 each.

6. An average of one Mechanic a year is launched on a dedicated small launcher (Minuteman derivative or equivalent) costing an average of $9M.[15]

Keeping in mind these assumptions represent a single, simplified case out of many possibilities, the top-level Work Breakdown Structure looks like this:

Space Guard System	Costs ($M)
TOTAL	372.80
EMD PHASE (EMD provided by AFRL, others)	
PRODUCTION PHASE	201.00
PRIME MISSION EQUIPMENT	178.50
SPACE VEHICLE SUBSYSTEM	178.50
SPACE VEHICLE PME	178.50
Microsat Imager Satellite	115.50
Microsat Mechanic Satellite	63.00
SYSTEM-LEVEL NON-PME ELEMENTS	12.75
Spare Satellites under Space Vehicles	
SYSTEM DATA	0.02
SYSTEMS ENGINEERING/PROGRAM MGT	3.61
OTHER GOVERNMENT COSTS	9.12
Contractor Support	9.12
ENGINEERING CHANGE ORDERS (ECO)	9.74
OPERATIONS & SUPPORT PHASE	171.80
MISSION PERSONNEL	11.80
Launch Services (Vehicle, range costs, etc.)	160.00

This total could be reduced if the Microcosm Sprite launch vehicle becomes available. Now in development with AFRL support, the Sprite is intended to provide rapid launch of a microsat for under $2M. This would shave $70M off the base year cost estimate for launch services.[16] Costs would also be cut if low-cost, rapid-response service is established by one of the companies, such as Kistler or Rotary Rocket, now pursuing reusable launch vehicles.

Factors which could raise this estimate include:

- Additional failures (a total of 6 spare satellites, three of each type, are included in the above estimate.)
- Adding more capable microsats with other missions.
- Insertion of additional technology, especially if the Space Guard has to provide its own research and development.
- Adding GEO-capable microsats and their launch services.
- Failure to obtain secondary payload space suited to all Imager requirements.

An annual budget averaging under $25M is a small price to pay to safeguard billions of dollars in LEO assets. If one collision with the $60-billion ISS is avoided, the Space Guard will have paid for itself many times over. The same is true if Space Guard microsats can rescue one high-cost satellite, such as Milstar, stranded in the wrong orbit. Finally, a demonstrated capability to protect and/or rescue satellites should result in lower insurance costs, benefiting the entire space industry.

Options for Funding

The U.S. Coast Guard is funded by a mix of direct tax support and fees collected for services, such as boat registration. The Space Guard could be funded similarly. A fee could be charged to the launching nation for each satellite placed in an orbit serviced by the Space Guard. It could also charge fees (if approved in advance by treaty) to nations whose spacecraft are helped in time of distress.

The Teal Group forecast assumed 1,447 satellites over 8 years, an annual rate of about 180. A $25M budget divided by 180 would give a fee of $138,888. This seems unpalatable, especially since GEO satellites would receive little direct benefit (although all satellites benefit indirectly by the enforcement of space treaties), so some level of funding by participating governments would be needed to keep this down. Since the Space Guard would also serve the higher purposes of treaty enforcement and protect the gigantic international investment in the ISS, such funding seems appropriate.

Funding the Space Guard may turn out to be the cheapest way for satellite owners to meet future requirements preventing orbital debris. The Inter-Agency Space Debris Coordination Committee is discussing guidelines requiring satellite owners to remove satellites (either by orbit-raising or de-orbiting) from heavily used orbits. An official with the French space agency, CNES, has objected this is a very expensive proposition, requiring perhaps 150kg of fuel.[17]

Leaving aside the cost of designing and installing larger fuel tanks (or using existing tanks and accepting a shorter useful lifespan, which is even less appealing), just placing an extra 150kg into orbit, using a common rule of $10K per kilogram, adds up to $1.5M per satellite. There is no mandatory rule so far requiring this capability, but it's an issue to keep in mind. Paying fees to support the Space Guard or paying the Guard directly each time a satellite is removed would be attractive options compared to building such capability into every satellite launched.

Issues

That a Space Guard is desirable does not mean there are no issues to resolve. There are many. For example:

If the U.S. leads in deploying the Guard, would Guard microsats be used to interfere with enemy satellites in wartime? The inability to perform counterspace activities is a major deficiency in AFSPC plans, but whether the Guard can have this function must be decided before its is created, especially if the Guard will have international aspects. A possibility, perhaps more palatable to potential partners, would be to use the Guard for counterspace only if the conflict is supported by a United Nations resolution, as in the Persian Gulf War.

A related question is: If the Guard detects unlawful activity, such as a weapon of mass destruction on a satellite, what happens then? Does the Guard have jurisdiction to act? Again, this type of situation should be decided in advance and covered in any international agreements involved.

How should the Guard deal with overlapping jurisdiction? Satellite ownership may be shared between nations. One owner might be willing to cooperate with a Guard action, such as moving their satellite to avoid a hazard, while its partner may not.

Finally, there is the question of liability. If satellite-owning companies or spacefaring nations come to rely on the Space Guard, do they have a claim if the Guard fails to respond to, for example, a debris threat to a satellite? Space treaties require that nations provide each other with "all possible assistance" in space. Having a Space Guard would raise considerably the standard of what is "possible" and therefore expected.[18]

Conclusion

The concept of a microsatellite-based Space Guard appears both feasible and desirable. The exact shape and functions of such a system need to be worked out over the next few years as the technology matures. This system is affordable and highly cost-effective, since it would maintain safe and orderly commerce worth many billions of dollars. It is not logical to wait for more collisions, liability arguments, and space policy disputes before beginning work on the Space Guard. A proactive approach will smooth the way for orbital business development and science for the next generation and head off many problems before they become serious. An international working group, with the U.S. Space Command and NASA as key players, should begin now to shape the Guard and put this concept into action.

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NOTE: All cost estimating used the DoD-approved ACEIT software program.

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