SPACE TRAFFIC CONTROL
The Culmination of Improved Space Operations

Subject And Problem Statement

> Space is becoming unmistakably more multilateral in character. The number of satellites in GEO (high altitude) is likely to double in the next ten years... Continued growth in the number of spacecraft will amplify the risks of ambiguities and potential accidents and generate further requirements for effective cooperation in space surveillance... *The United States must improve our spacetracking and surveillance capabilities in space*.
>
> William J. Perry, Brent Scowcroft, Joseph Nye, Jr., and James Schear
> The Aspen Strategy Group, 1985[1]

> Any worthwhile change in launch philosophy will also dictate a fundamental shift in the existing satellite design mindset... We need to move away from one-of-a-kind satellites, satellites requiring unique control networks and extensive modifications to designated launch boosters, toward satellite payloads based on customer-defined mission requirements, launched with minimal modification on standard boosters and controlled through existing networks.
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> General Charles A. Horner,
> USAF, Commander in Chief, USSPACECOM
> Testimony to the Senate Armed Services Committee, 22 April 1993[2]

These two quotes seem unrelated, but in fact they are linked very strongly and provide the two anchors for this paper. The linkage is embodied in a concept called space traffic control, which is modeled in part on the air traffic control system. In addition to providing the space tracking and surveillance improvements urged by the Aspen Group, a properly designed space traffic control system requires an overarching operational concept (suggested by General Horner) affecting the way space vehicles are designed and employed. This connection between space object control and space operations is key to understanding the vision outlined in the pages that follow.

Leaping forward to the worlds envisioned by the SPACECAST 2020 Alternative Futures, you'll find significantly greater numbers of spacecraft competing for limited space and precious pieces of the electromagnetic spectrum. Motorola's IRIDIUM galaxy and Bill Gates' 800+ communication satellite constellation are only the opening gambits in a rush to space that may result in satellite proliferation orders of magnitude greater than anything foreseen by the Aspen Group in 1985. This explosion in the number of satellites will create increasing numbers of conflicts between the vehicles--and their Earth-bound owners. Assuming advancements in miniaturization, better lift capability, significant technology breakthroughs, or huge commercial demand, the rush to space could be overwhelming. Without a system for fused organization and deconfliction of space vehicles, conflicts caused by crowding will reach critical mass. In sum, space will likely become a very busy place (figure 1).

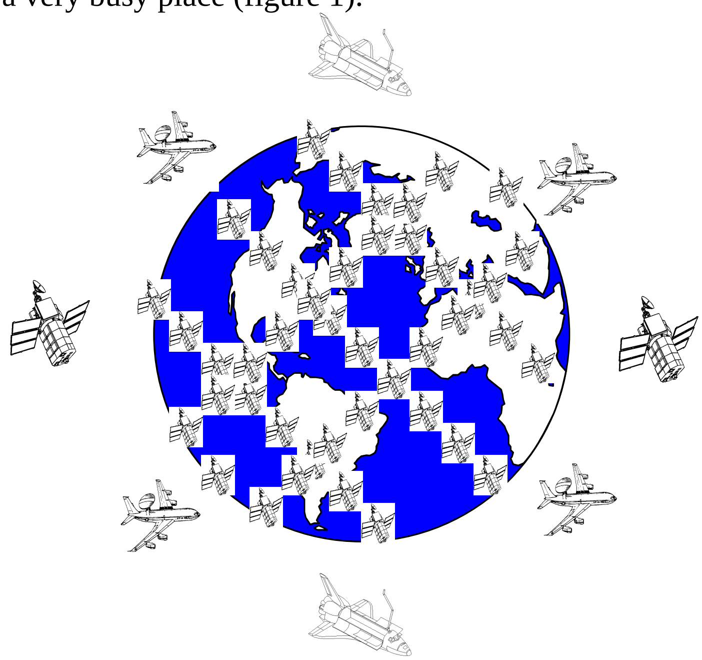

Figure 1. The Aerospace Environment in 2020: A Busy Place

Who will monitor, regulate, and provide stability for all these hurtling pieces of high technology? The US currently leads the world in the ability to track and monitor space objects, but the system is old, costly, Earth-based, and manpower-intensive. It holds too little potential for the situational awareness or operational agility required in the future. This paper proposes that we avoid the deer crossing syndrome, wherein government mandates the number of deer that must be killed on a given stretch of road before a sign is erected. Building a proper space traffic control system will put up the sign before satellite conflicts become a major issue.

Space vehicle control demands much more than a sign, however. This paper proposes the development of a comprehensive space traffic control system (hereafter called SPATRACS) integrating sensor information (on- and off-board), providing collision avoidance information, and also deconflicting flight planning. It is possible to envision not only control of space assets, but with some of the advances put forth in the SPACECAST 2020 papers on surveillance and reconnaissance, a seamless and sophisticated aerospace traffic control system as well. This strategic vision includes a system meeting the needs of the twenty-first century and allowing the US to continue to pursue a competitive advantage in space (at least in this area). By consciously building on the US lead in this area, and by taking advantage of emerging technology, the US will fill a vital niche in the information high ground of space. With the ideas outlined in this paper, SPATRACS will provide future space traffic control while simultaneously increasing the efficiency of space operations. The paper will further show that, in addition to providing many opportunities for the future, many of the pieces of SPATRACS make sense on their own--now.

Fiscal pressures on current systems and infrastructure are already stretching the fabric of the US space establishment uncomfortably tight. This paper suggests that it is in just such an environment that the pursuit of a SPATRACS system makes sense. An active, focused effort is needed to fully realize the possible benefits through the fiscally efficient control and exploitation of space. This can happen with fundamental changes in the way the US military designs, builds, and operates (e.g., task, monitor, control) space systems to take advantage of new technologies and operational processes. A significant benefit will be the creation of a world where operations in and transit through space become more routine, realistic, and affordable.

The remainder of the paper will describe the primary elements of a new space traffic control concept. First, the paper will describe a framework for the future of military operations in space. Second, it will discuss the design changes needed to eliminate stovepiped[3] systems in favor of systems that can be unique yet conform to interface standards. Third will be a description of how space system design must change to support this philosophy, as well as the implications these design changes will have for space operations.

The key theme of each of these changes is increased satellite autonomy (to include on-board navigation and housekeeping functions), which implies the need to think about an entirely new way of tracking and controlling space systems (and those transiting space)--in other words, a space traffic control system. Many of the improvements proposed in this paper, when viewed in isolation, have the potential, on their own, for cost saving and increasing operational effectiveness. When combined, these proposals constitute a novel approach to space operations and a pivotal and dynamic space role for this country.

The Capability and Its Relevance

Historical Background

From 1958 to 1994, computers advanced from room-sized machines to hand-held personal digital assistants, fighter aircraft from the F-100 to the F-22, and arcade entertainment went from pinball machines to virtual reality. In the same period of time, however, US space operations made progress similar to the B-52--missions changed dramatically, technology charged ahead, but the same old shell, power plant and control systems remained in place. The B-52 remains an effective weapon system, and the US space operations system still performs adequately, however, both have outlived their design lifetimes.[4] The pace of innovation requires changes in military space operations--changes in approach, equipment, and manning. This paper advocates incorporation of technological advances merging the historically separate functions of satellite control and space surveillance into a much more capable and flexible scheme.

Assumptions

In the year 2020, an ever-increasing number of satellites will be orbiting the globe. Access to space is assumed to be much more affordable and responsive. Satellites will be smaller and last much longer than the satellites of today; while some might be deliberately designed for short life and early replacement to take advantage of continually emerging technology. Satellite missions will be more varied, but the underlying spacecraft capabilities will enable a more routine approach to space operations. Human involvement with each satellite will be greatly reduced and more closely resemble the current air traffic control interaction with aircraft. The controlling function of this space environment will be the SPATRACS.

The space segment of SPATRACS itself will consist of a few (<20) small, simple satellites composed of passive sensors and on-board processing responsible for tracking all objects in space. The crowds in space and the need for comprehensive collision avoidance and satellite deconfliction will be compelling, and as a result, both civilian and military satellites will be designed to work interactively with SPATRACS.

What is Space Traffic?

To outline how this paper envisions the future, a more complete understanding of the environment will help bring the concept into focus. Three kinds of objects will exist that must be accurately tracked in order to accomplish true space traffic control: debris, uncooperative space systems, and SPATRACS-capable space systems. The debris problem is growing, and will likely increase in the coming decades. In SPATRACS, debris will be identified by space sensors and once identified, will be tracked easily due to its deterministic flight path degradation. With improvements in sensor technology, identification and tracking of increasingly smaller pieces of space debris will be possible.

The second category of space objects, uncooperative space systems, are non-interactive members of the SPATRACS family which include any pre-SPATRACS satellites still operating after system implementation. Since dumb satellites will maneuver without continuous on-board position reporting, they will require more SPATRACS asset allocation and attention. As with debris, space-based surveillance technology will provide track information of these objects. The number of objects requiring external sensing as the primary means of tracking will decrease as the SPATRACS standard on-board navigation and reporting systems are included in future space platforms.

The third category, SPATRACS-capable space systems (with transponder-like gear) provide constant, crosslinked position updates to the interlocked brain on board controlling satellites.[5] Satellites on orbit, as well as new launches in the twenty-first century, can and should be designed to effectively interface with SPATRACS. Every SPATRACS-capable system will carry internal navigation and housekeeping packages and perform (and report) routine station-keeping maneuvers on their own. Multiple phenomenology sensing will allow the position and navigation systems to be updated (much like the way inertial navigation systems are "zeroed" at a known location). This affords more accurate telemetry and allows satellite tracking like aircraft in the current air traffic control system. Aircraft position is constantly tracked by transmitted (IFF) and external (radar) sensing, and analogous systems will apply in space. The satellite will report to the SPATRACS constellation and passive sensors will provide additional position checks.

The design and integration of SPATRACS capability into satellite design is critical if the system is to be adopted. User participation will grow as the system evolves and proves its worth. Early generation SPATRACS could perform the bulk of its mission using its own sensor information. Additionally, SPATRACS satellites should be designed to incorporate off-board information.[6] As satellites become increasingly autonomous, ever increasing accuracy can be realized.

Operations Under SPATRACS: Merger of Satellite Control and Surveillance

For the most part, sensors for this system will be space-based. Due to the elimination of atmospheric interference, these sensors will be able to detect and track very dim targets (visible magnitude 15 or 16 is possible).[7] Although they will mainly be passive sensors, given sufficient numbers and on-board processing and crosslinking of data, they will be able to generate accurate orbital elements for the objects being tracked.[8] Low to medium (spatial) resolution visible spectrum sensors will conduct the bulk of the space surveillance. These will be augmented by similar resolution IR sensors to track high priority targets in Earth’s shadow, detect new launches, and track maneuvering targets. Space object identification will be conducted through one or more of the following methods: spectral signature analysis using low to medium (spatial, but high multi/hyper/ultra/omni-spectral) resolution sensors, deployment of higher spatial resolution sensors, or use of medium resolution sensors to produce interferometric images.

Having generated track files, tentative object identification and catalog updates on orbit, the system will then downlink the information to a central facility providing fusion with other data (e.g., from ground based sensors which are advantageous for gathering some types of data), validation, and additional analysis. In addition, the facility will develop tasking for the space surveillance network (which will have capacity for specific observations beyond orbital catalog maintenance, e.g., to focus efforts in anticipation of the launch of a new threat country space asset). This facility will be directly linked to a main satellite control facility, so collision warnings will be immediately available for action, to customers interested in space object track data.

Relatively small crews (by today's standards) will man SPATRACS ground stations. These ground stations (primary and backup) will be responsible for handling anomalous situations, authorizing, coordinating and reporting collision avoidance maneuvers with satellite owners, and coordinating space object identification (particularly threat identification). Overseas ground sites, with their cost and vulnerability, will be eliminated. All the data gathered can be augmented by ground site data collected from continental US (CONUS) bases, but the system can remain autonomous.

The long-term integration of SPATRACS with all space satellites could be planned for later in the twenty-first century. The initial SPATRACS, as described above, could perform the bulk of its mission using its own sensor information. SPATRACS satellites should be designed to allow for the incorporation of off-board information available from other satellites as well. As other satellites become increasingly autonomous, increasing accuracy can be obtained from SPATRACS. Satellites after the year 2010 should all be designed to effectively interface with SPATRACS. More specific information about the technologies required by SPATRACS are in subsequent sections of this paper.

The SPATRACS system will have some degree of on-board intelligence, and won't depend entirely on any central facility. SPATRACS could, for example, automatically track and provide information on enemy space assets directly to a theater commander in chief (CINC). The degree of automation in the process and the location of human decision makers in the system are architectural issues that need to be addressed.

Atmospheric Traffic Control

When space travel or space transit (using a transatmospheric vehicle) becomes routine, a system like this is essential. A fully capable "aero" space traffic control system, (seamlessly integrated with the air traffic control system) will allow for conflict-free transit of multiple simultaneous events.

Advantages

If the US is able to provide a space traffic control system many advantages will be possible:

First, financial advantages abound. If the US adopts the proposed new vision for space operations, the savings over time will be considerable. Much of these savings will be realized through the elimination of stovepiping and over-reliance on manned ground systems. Selected information can be sold to commercial operators or foreign governments, helping pay for the acquisition and maintenance of a system in a time of declining budgets. It will need to be available at a price encouraging its use, and not so expensive to use that other nations will be tempted to develop their own system. A national, long-term strategy to underwrite entry into the business may be required to provide this kind of early, low cost service and will lead to substantial downstream savings.

Second, space operations will be streamlined. The significant US presence and influence in space will remain intact precisely because the nation moved quickly to a more consistent, efficient approach to space operations to insure competitive advantage. This vision sees space operations as more regular and affordable, expanding the bounds of what is doable from space. This philosophy implies basic changes in the way space systems are designed and built, provides for a more efficient and effective means of operating space systems, greatly increases US awareness of and ability to respond to changing situations in space, and ties all these things together under the umbrella of SPATRACS. Such changes make sense: even at the existing level of space operations, savings of hundreds of millions of dollars per year are possible.[9]

Third, such a system is a prerequisite for space control. If the US has a system that can provide current, accurate, and precise information on satellite position and movement, it then becomes feasible to deny that information to potential enemies--and use it for the nation's advantage. Such information is required for intelligence as well as for space control purposes in time of conflict. By possessing dominance in this area, the US might be able to deny potential adversaries many space control options. It also comprises a platform for developing space tracking and detection that will be a force multiplier in a future that might include space-to-space force employment.

Issues

Some potential problems will arise with a system like SPATRACS. Those problems include the international agreements that will have to be negotiated to allow this system to be world-wide in scope. Given a world where there are enough actors to make it feasible, aerospace traffic control becomes a security issue for satellite owners and a significant source of leverage for the controller. In the history of international agreements, where the subject of discussion is of relatively minor interest (e.g., the Antarctica Treaty), the agreement enjoys success. Once vital national interests come into play (like they will if space traffic control became vital to space use), there is both trouble achieving agreement and more trouble enforcing compliance. Another problem is that the US will in some sense become a space insurance agency, thereby potentially incurring liability. If a space operator is told that their planned or current track is debris-free, and they take a lethal or debilitating impact from space junk, is the US responsible? If it happens to an unfriendly (from a US point of view) international actor, did the US set them up for failure on purpose, and what will be the international implications of such an incident?

Also, a technical vulnerability issue of standard systems that must be addressed. There is the chance for introduction of a Trojan Horse that could disable all your systems, and since that chance exists, how should it be countered? Is there a requirement for multi-level security when you have certain users that only need certain information? None of these are easy questions, but they do not detract from the general desirability of the SPATRACS concept, and some (e.g., multi-level security) are already being worked.

Space Operations: Design and Philosophy

A truly effective military space capability must be responsive, resilient, flexible and cost-effective. Perhaps one of the greatest leaps needed to reach the SPATRACS vision is a change both in the design of space systems and the philosophy of operating them. Current stovepiped, manpower-intensive systems have none of these characteristics and look increasingly anachronistic under the budgetary heat lamp. This paper will identify additional actions sharpening the aim toward a more efficient mode of space operations synergistic with this concept of aerospace traffic control.

The operator of every satellite system, be they military or civil/commercial, defines the interfaces that satellite designers must satisfy to support ground operations. Ground operations themselves are defined by satellite owners. Historically, there has been very little commonality in any of these areas. The result is a series of stovepiped satellite operations where no two systems are exactly alike. An operator trained to support one satellite system must be retrained before crossing over to another system. The development of better standards for space operations will eliminate these inefficiencies and will create savings in satellite operations and development.

Interfaces

Interfaces concerning satellite navigation, housekeeping, and telemetry, tracking, and control (TT&C) must be defined (see "Standardized Space Systems Design" below). This effort should take its cue from the computer world and focus on enabling an open system architecture based on standardized protocols or languages rather than inflexible, mandatory hardware and software standards. Since interfaces have to be defined for system designers anyway, and if intelligent standardization is recognized as a goal that will result in significant savings, standard interfaces should be defined supporting space traffic control. Satellite design requirements must include on-board processing to accomplish many of these functions currently performed on the ground.[10] Such standard interfaces (hardware, software, data, etc.) will be phased in as technology, particularly improved on-board processing, becomes available. An aggressive technology program should be pursued while a joint working group of civil/commercial/military satellite operators work at the development of a roadmap to implement standards for integrated operations. As these standards are worked out, the next logical step is to begin to apply them in practice, namely in improving standardization in the design of new space systems.

Several concerns with this approach must be addressed. First, haphazard application of standards can drive up costs and reduce flexibility, exactly opposite the desired effect. Second, implementation of common systems must always guard against vulnerabilities (e.g., if only one common set of code controls all satellites, every one of the satellites is vulnerable to an error in the code or to software sabotage). Third, for the foreseeable future, space systems will continue to include highly classified payloads, so any system of interfaces must address the need for multi-level security capability. None of these are show-stoppers; in fact, they are problems that are being dealt with for command and control and for other systems already, but they must be addressed.

Space System Design

What design elements must change to prepare for space operations in the next century? Virtually all aspects of space system design need to be addressed, including: interfaces, launch concepts, orbital insertion and checkout, spacecraft "housekeeping", navigation, telemetry, tracking and control, mission payload management, space system ground segments.

How should the US redesign space systems to provide more effective traffic control, and what effect will this have? The first element of the redesign is to get away from detailed system design specifications and concentrate on interface specifications. This means not only the on-board hardware interfaces (physical, electrical, thermal), but even more critically on the data interfaces for the payload to communications system, inputs and outputs for spacecraft housekeeping, navigation and control functions, and ground segment hardware. This idea specifically addresses the problem of stovepiped systems--rather than a unique design of everything from the launch vehicle interface to the mission data ground workstation. A focus on interface specification allows an increased degree of commonality among space systems, both in hardware and software, and has the potential to greatly reduce training and operations costs. This interface requirement is analogous to the personal computer video bus standard (e.g., VESA), which enormously improves system integration, but allows for competing systems to forge their way to market when other system capabilities outpace bus limitations. The key is to develop standards that do not overly restrict innovation and still allow upgrade to new integration standards when technology drives expanded capabilities.

For launch systems, an improved space operations concept requires that payloads be less complex and fragile, and less dependent on specific expertise. Given an inexpensive, rapid, flexible, and reliable way to get to space,[11] payloads can be designed either to fit whatever volume is available, or to be assembled on orbit from segments fitting the launcher envelope. Again, interfaces from the satellite to the launch platform should be standardized so that whatever on-orbit capability is required can be launched on demand.

Satellite designers should take full advantage of miniaturization, modularity, and standardization to design systems that can be rapidly upgraded or tailored to a particular mission and delivered for launch with minimal test and check-out. Where on-orbit upgrading is desirable, maximum use should be made of designs allowing software upgrading to improve performance (there are lessons to be learned from NASA's deep-space probes in this area). Design philosophies must emphasize rapid, flexible design and manufacturing of satellites, even if they come at the expense of satellite endurance. Given the right launch system, it is economically and militarily preferable to possess surge capability with *competent* spacecraft than to orbit a few exquisitely capable but irreplaceable battlestars.

Moving to the area of on-orbit operations, spacecraft must be designed to allow more rapid check-out and activation. It does no good to put a satellite on orbit within hours of a request if it takes weeks or months to make it fully operational.[12] Modularity, standardization of interfaces, and a reduction in complexity of individual satellites will help reach the doctrinal design goal. There is the possibility of on-orbit servicing and design for upgrading or tailoring.[13]

Once a spacecraft is operational, an inordinate amount of manpower and contact time is currently devoted to routine functions such as housekeeping and navigation. Today's satellite control system is archaic and should be replaced with a three-tiered approach: 1) On-board systems will perform routine housekeeping and navigation chores (this is well within current technology) and update the ground segment periodically. These on-board systems will have sufficient intelligence to alert ground operators if any parameter was diverging unacceptably from nominal values. 2) The second tier will be an austere ground segment with a standardized human-machine interface and expert system support to handle most likely satellite emergencies. 3) Finally, there will be an available technical troubleshooting staff if a problem requires expertise beyond that built into expert systems (this staff will constantly update the expert systems too.) The work of these troubleshooters will be diminished significantly by the increased commonality in space system design. One group conceivably could perform depot-like support for all space systems, whereas costly technical staffs currently are employed for each individual system. This environment will greatly reduce training requirements, and as a result, smaller numbers of spacecraft operators will qualify more rapidly, move from system to system with minimal difficulty, and handle surge requirements during expanded and crisis operations.

With spacecraft functions and interfaces standardized, the only specialization among satellite systems will be in mission payloads. Here also, interface specification and careful satellite design will reduce or even eliminate differences in routine operations among systems. In terms of the ground segment, only the mission element (tasking system, data displays, and analytical support) will be different from system to system, and this element need not be collocated with the spacecraft control element. This will allow mission terminals (of relatively small size and weight) to be deployed in support of theater or other warfighters, while the routine operations functions are kept separate and at the most convenient location.

The above improvements will greatly reduce the need for many current satellite control practices. Satellites will be able to handle many functions on their own; for example, knowing their own position, monitoring their own health and status, discharging and recharging batteries as necessary (perhaps even performing some self-repair), and carrying out theater CINC mission tasking autonomously (i.e., the mission payload ground segment will task a satellite to perform certain functions--with the aid of software to ensure these functions are possible--and the satellite will carry them out on its own, pointing, tracking, and perhaps even maneuvering as necessary). A control site will monitor regular reports from the satellite, allocate priorities to various users of the system (e.g., for multi-theater support) and intervene in an emergency. This does not imply a single geographic location (which might become a critical node) for all space system control. Functions can be redundant or physically dispersed, yet linked electronically. The key is that the space segment will be far less dependent on any ground support than current systems. Under normal conditions, the system will require little direct control. Power, weight, bandwidth, and ground segment assets currently used for TT&C could be allocated to more mission oriented tasks.

The combination of technologies, design practices and procedures mentioned above will have the effect of reducing the frequency and duration of contacts a satellite (or an entire constellation) must make with the ground.[14] This will not only reduce the number of personnel required, but will greatly reduce space system vulnerability through decreased dependence on ground sites, to include elimination of overseas ground sites via data crosslinking. Not only is the system less vulnerable because the ground sites are removed as targets, but spacecraft are less dependent on ground contact in general, and can operate autonomously if there is a communications outage, destruction or degradation of Consolidated Space Test Center (CSTC) or Consolidated Space Operations Center (CSOC), or other conceivable degraded conditions.

A further step needed to operationalize space is improvement of space surveillance, tracking and identification (SSTI) capabilities. Since the spacecraft described above will be more autonomous, the concept of a SPATRACS gains validity and more closely approximates air traffic control. Eventually, the two systems could even overlap and merge when true aerospace vehicles come on line.

Future Evolution of SPATRACS

Spaceways

As an interim step to full satellite autonomy, "spaceways" may have to be created. Like today's airways or jet routes for domestic and international aviation traffic, which fulfill the need for traffic deconfliction and sequencing as a means of ensuring safe air operations, tomorrow's spaceways could fulfill similar functions. The determining factors will be: (a) the actual risks of collision; (b) the degree of legal, financial or political liability should collisions occur; and, (c) the degree of international cooperation on the issue of safe operations in space. If there is high risk of collision, clear liability and heavy, enforceable restitution, and increased international cooperation regarding travel through the region of near-earth space, spaceways could provide an interim solution.

Spaceways, like airways or jet routes, have a set of minimum requirements. There are at least five of these. First, there must be an authoritative definition of what constitutes a route. On the earth, these are straight lines between two fixed terrestrial points. Since the earth rotates beneath orbiting spacecraft, the definition of spaceways would be more complicated. Second, traffic on the route must remain on or within whatever defines the route, and both the spacecraft and the controlling agency must have some way of knowing this. Aviation operations in Positive Control Airspace (PCA), for example, require both a two-way radio for instructions and position reporting and a transponder which electronically indicates aircraft position and, in most cases, altitude. Third, there must be some kind of controlling agency responsible for route assignment and route monitoring. Fourth, re-routing or off-route operations must either be sanctioned by the controlling agency as "conflict-free" or the maneuvering spacecraft (and its owning controlling agency) must accept that the spacecraft is moving with "due regard" (in the case of military air operations today, some are authorized only after the military declares "MARSA," or "Military Assumes Responsibility for the Separation of Aircraft) for other potentially conflicting traffic. Fifth, there must some kind of penalty or sanction should a collision occur. Each of these minimum requirements deserves elaboration.

Orbital positions are defined by an element set. Once established in orbit, and unless it is maneuverable, the spacecraft will remain in that orbit. For very low orbiting spacecraft, atmospheric drag and the force of gravity have the effect of decreasing the spacecraft's height above the planet over time. A spaceway, then, would be defined by the satellite ephemeris or element set once established in orbit. Three-dimensional separation requirements would define the spaceway.

Some nations have very sophisticated spacecraft and multiple means of space surveillance and space object identification and tracking--radar, optical, and others. Other nations rely on interferometer or radio, only able to confirm where their spacecraft actually is during part of its orbit. If there are to be spaceways, all spacefaring nations or non-state groups need to know that their spacecraft is on the spaceway. If they lack the indigenous capability of knowing this, they must acquire the information from somewhere and it must be accurate. The United States, today through the United States Space Command and its Air Force Component, has superior space surveillance capability compared with other nations. Spaceways, then, cannot be created without the active cooperation of the United States.

Depending on the degree of international cooperation in space, an entity of or in the United States might become the foundation for the controlling agency. It is arguable on the one hand that the other users would accept United States' control, or that on the other hand the United States would relinquish the control it presently has. It is not inconceivable, however, that at some point the United Nations might become the controlling agency for spaceways subscribed to by spacefaring nations. Services provided by other nations would be provided for some sort of compensation. Since an agreed-upon controlling agency is one of the minimum requirements for spaceways, absent such an agency deconfliction will be done at the election of the user. Unless there is a controlling agency, off-route or maneuvering operations in space will all be like MARSA is today. The same nations that have the most sophisticated surveillance capability would logically have the most sophisticated spacecraft, including manned spacecraft and trans-atmospheric vehicles. Obviously, these would not be moved or maneuvered without assessing the risk of collision.

Should collisions occur, liability would have to be fixed and some type of penalty assessed. These provisions already exist. The problem with having a controlling agency, is that the agency itself could be liable for causing a collision. An international entity like the United Nations would probably be as unwilling to waive immunity as a national entity would be. All things considered, it appears clear that spaceways are no more than an interim solution. The goal must remain to have the highest value spacecraft the most able to avoid collision with other space objects autonomously.

Aerospace Traffic Control

Space operators in the future could enter a flight plan and automatically receive preliminary deconflicted clearance. In addition, ongoing, in-flight deconfliction will also be available without operator manipulation. It could integrate information from even more sophisticated sensors of the future, such as electro-magnetic, chemical, visible, and omni-spectral. Hand-offs from one sector to another will occur, but only in the on-orbit SPATRACS brain, which is transparent to the operator. This is envisioned as a next generation, smart system integrating volumes of data into information in a format giving the operators what they need to know on a timely basis.

Integration of atmospheric flight with SPATRACS will be a natural outgrowth when the learning curve with space operations merges with advanced sensor systems and transatmospheric flight. Even though much of the technology exists today for making space traffic control more robust and cost-effective, integrating air traffic control, to include flight planning, conflict avoidance, and sensing of anything transiting the air is far off, but well within a conceivable evolutionary chain. The computing and information handling ability required to take inputs from the wide variety of sensors and make accurate decisions increases dramatically when atmospheric flight is introduced. When that computational capability exists, air traffic control could be enhanced by fusing sensors and data to comprise a whole new way of doing business. As an example, a post-

2020 air vehicle will have a navigation system which files and checks the flight plan, offers fuel saving tracks (through integration of weather and jet stream data), provides constant in-flight collision avoidance, and stacks it into busy airports automatically. Transcontinental, oceanic, global flight will be free of air sector hand-offs because the transitions will occur in the brains of SPATRACS and will be transparent to the operator. This vision for seamless, total air and space awareness is a natural stepping stone to more brilliant sensors and information synthesis as envisioned in the white paper on "Surveillance and Reconnaissance in 2020."

Of course, there are significant differences between air and space traffic, and potential aerospace vehicles will further complicate the picture. Some of those differences are summarized in table 1. This figure illustrates some of the factors requiring a change from current air traffic control and space control systems and procedures to accommodate true aerospace vehicles.

	Air	**Space**	**Aerospace**
Flight Path	Variable	Mainly deterministic	Mixed (dep. on phase of flight)
Speed	100s kph	~10,000 kph	From air to space speeds
Control Type	Hand on stick	Machine	Both
On-board system management	Fully autonomous	Little autonomy (now)	A mix
Comm Method	Voice	Telemetry	A mix
Nav inputs	INS, GPS, altimeters, etc.	INS, GPS? star/horizon trackers, ground	All
Maneuvers	Unpredictable	Constrained	Both

Table 1. Differences in Air and Space Traffic

Planetary Warning

SPATRACS will also be a logical tool for a planetary warning system (described in the white paper Preparing for Planetary Defense) tying together Earth, Moon and other space-based deep space sensors to detect potentially dangerous Earth-orbit crossing objects sufficiently early to take action. If it can accurately track and fuse satellites at great distances, focusing and tracking other space objects will not be a great leap.

Summary of the Capability and Its Relevance

An integrated effort to create a new methodology for designing and operating satellites will clearly have a high payoff. If such an effort is pursued, it is feasible that by the year 2020, all on-orbit systems could be integrated and controlled by a SPATRACS that will significantly improve US operational military capability, and yield tremendous savings in space system design and development costs.

SPATRACS is more than an interesting mission in space. It defines a future for US space operations in line with the nation's traditional aerospace leadership role and avoids a quagmire where institutional inertia cannot be overcome. The benefits that could be derived through the focused integration of doctrine, policy, and operational systems is nearly limitless--and should be pursued. Having outlined the basic thrust of SPATRACS, this paper now zooms in on a more in-depth discussion of required technologies and programs.

Potential Technologies

This section will describe a roadmap for integrating near-term and far-term efforts and changes in technologies and doctrine necessary to fully meet the vision of space operations in 2020 described in this paper. The next section (Near-term Technologies and Operational Exploitation Opportunities) will reiterate some of the critical near term activities recommended for immediate action or continuation. Overlap between these two sections is intended.

Most of the component technologies needed for implementing the new space operations, monitoring, and traffic control architecture described above are either already available or are rapidly emerging. This does not mean that the sum of the parts is either obvious or easily implemented; however, test and demonstration at the system level is absolutely essential. Practically speaking, wholesale changes cannot and will not happen overnight. Risk aversion, institutional inertia, presently programmed acquisitions, and funding limitations will encourage a gradual pace of change. In the near term, measures to prove key technologies in operationally realistic environments, reduce system-level risks, and demonstrate operational and cost advantages are necessary. All of these, in aggregate, will sow the seeds for future generations of space systems that achieve the vision described above.

Direction

To some extent, the long lead indicators of change are present in documents such as US Space Command's "Space Logistics Master Plan"[15] and "Sustaining Space Systems for Strategic and Theater Operations."[16] Senior military space leaders are calling for new satellite systems to incorporate modularity, standardized interfaces, and ground segments requiring less manpower. There is general recognition of the need for more flexible, responsive and cost-effective operations. This paper recommends the military services turn the attention of their space doctrinal development organizations to assessing the impact of emerging technologies as described herein, with the goal of building a joint doctrine driving coordinated space system development instead of merely adapting to the limits of current systems.

Technologies

<u>Space-Based Space Surveillance</u>

Sensors/detectors. For the most part, detector technology is sufficiently advanced to build the kind of capability required for satisfactory identification of space objects. It is fully expected, that by the year 2020, sensor technology will be advanced far beyond the requirements for the system described in this paper, to include the first glimmers of next-generation atmospheric transit sensors.

Optics. Light weight and thermal compatibility (with detectors and host satellites) are the primary features needed here. New approaches, like silicon carbide optical elements, may be preferable to traditional multi-metal telescope designs. The

Phillips Lab Space Surveillance, Tracking and Autonomous Repositioning (SSTAR) experiment has proposed demonstrating such a device.

Position determination. A space-based system must be able to accurately determine its own and the track's position. Current position can be gained from global positioning system (GPS) or other autonomous navigation techniques, while accurate determination of the track's position will require correlation of data from more than one passive sensor (a single passive sensor suffers from an inability to get unambiguous range data, even against fairly deterministic tracks such as satellites).

Brains/software. New algorithms and data handling routines will be needed to incorporate space-based data into the space surveillance system (which is ground-based today). Some of this work has already been done for the Space-Based Visible (SBV) experiment on board the ballistic missile defense office MSX satellite.

Deployment. The sensor/position determination/brains/communications package can be deployed on light, dedicated satellites, and probably can also be deployed as a piggyback package on satellites with other primary missions. A modular design will greatly aid in this, as the SPATRACS system could easily be distributed on the host.

Tasking and analysis/ground segment capabilities and requirements. These should be developed in conjunction with the demonstration of space-based space surveillance hardware and software. This will take full advantage of new capabilities and maintain parity with advances in other space systems in the areas of flexibility, modularity, reduced manning requirements, etc.

System-level demonstration. This is vital to the acceptance of the space-based space surveillance concept. SBV will be a first step in this direction. The SSTAR demonstration will be significantly more comprehensive and allow for true operational utility demonstrations.

Launch Systems

Reducing launch costs and making access to space more reliable and flexible is essential to any efforts at improving space operations. The SPACECAST 2020 white paper on spacelift addresses this problem in more detail.

Autonomous Navigation

GPS receivers that can provide navigational inputs for spacecraft are currently available. One is being flown on the Technology for Autonomous Operational Survivability (TAOS) experimental spacecraft launched recently. TAOS also incorporates on-board sensors and a flight computer providing a truly autonomous (as opposed to a GPS-based system, which naturally depends on GPS signals) navigation capability. TAOS incorporates other features desirable for autonomous operations, including a new electronic architecture with the first use of a MIL-STD 1553B data bus connecting the various subsystems. Perhaps most importantly, its planned experiments will provide the first chance for space system operators to become familiar with a satellite with some autonomous capability. Many other experimental satellite proposals in recent years included autonomous navigation capabilities, but most of these foundered for lack of money. The next key step is to tie autonomous navigation to other elements of autonomy, such as housekeeping, on-board mission data processing, expert systems in both the space and ground segments, and to put these together with mission-oriented experiments (e.g., surveillance) to convincingly demonstrate the positive cost and operational impacts to warfighting CINCs and space system operators. The SSTAR demonstration incorporates several of these elements with a space-based space surveillance mission payload.

A further goal of SSTAR is to show that elements of the modular system can be attached to any satellite with minimal impact. The following elements are demonstrated on SSTAR: space object tracking optics and detectors that can double as high-precision star trackers for attitude determination, an autonomous position determination system including a GPS receiver, and a communications package. In other words, these modular capabilities will not only make a space-based space observation platform out of any satellite, but will also give that satellite a precise autonomous navigation and attitude determination capability.

Standardization and Interfaces

TAOS is also an important first step in this area, with its Space Test Experiments Platform (STEP) spacecraft bus and the 1553B data bus. A more significant program, since it addresses on-board interface standardization and the ability to design spacecraft modularity to a greater extent than STEP can, is the ARPA-sponsored Advanced Technology Standard Satellite Bus (ATSSB) program, which has suffered from funding cutbacks. Although the contractor proposals received for this system indicate a high degree of confidence that they can design and build multi-mission, modular spacecraft buses, a full-up demonstration is almost certainly an essential risk-reduction element before the government specifies features for operational satellite systems.

Modularity

TAOS and ATSSB both incorporate key elements in proving the concept of modularity; the next step is to prove the flexibility of the basic spacecraft design by flying different missions using the same platform. In addition, there are few technological obstacles to design a satellite for remote (as opposed to human, which has already been proven with the Hubble space telescope) on-orbit servicing, repair, and upgrading. The key obstacles are the cost of getting to orbit combined with the penalties of designing a system for servicing. In the past, this made servicing unattractive compared to replacement. With new technologies available, however, it is worth revisiting this concept as a hedge against increasingly expensive large booster costs or to take advantage in a breakthrough that dramatically lowers launch costs for small payloads. An application of modularity will be the design of systems for assembly on orbit.

Expert Systems

There appears to be no great obstacle to concurrent design of an on-board, rule-based expert system for a spacecraft incorporating the design techniques mentioned above. For experimental (initially) and operational (later) purposes, the satellite will have sufficient on-board processing power, memory and a suitable operating system to execute such software, then the expert system can be developed over time from ground operations and regularly updated and uploaded to the spacecraft. This system will eventually take over routine housekeeping functions, subsequently expand its capabilities to deal with minor anomalies, and perhaps (again assuming appropriate satellite design) progress to managing emergency situations (non-fatal impact, subsystem failure) and perform self-repair (e.g., by reconfiguring subsystems to compensate for some kind of failure). The design can be sufficiently flexible to allow for gradual testing and implementation as the expert system gets smarter and the human operators gain confidence.

Operating System Software

There currently is no software operating system (analogous to DOS for personal computers) for spacecraft. Each military space system is custom designed and coded, with corresponding extra cost and incompatibility. This paper strongly supports initiatives such as Phillips Lab's Reusable Operating System Software (ROSS) that will attempt to correct this deficiency.

Electronics

The primary elements for this new space operations concept are sufficiently powerful (but not power-hungry) processors and on-board memory. A thorough study of processor design choices is needed. Should the US continue with customized MIL SPEC designs such as the Advanced Spaceborne Computer Module (ASCM) which, though offering impressive radiation hardness and other design capabilities, is already generationally obsolete, or can the military now accept some system design compromises (shielding, redundancy) to make use of the latest commercial technology in satellite design? For on-board storage, pursuit of solid-state memory devices to replace tape recorders as standard mass storage on board spacecraft is necessary.

Communications

Independence of satellite constellation to ground stations and improved space surveillance capability depend on high capacity, secure crosslinks. Laser crosslinks are preferable to radio frequency systems because of size and weight considerations,. Although the laser crosslink program for the Defense Support Program (DSP) system has a checkered history, alternative approaches (such as Phillips Lab/MIT Lincoln Lab's LITE program) may be ready to provide the required capability. Up and down link requirements will be reduced by performing more routine functions in space (e.g., it will be simpler to downlink orbital elements from the space-based space surveillance system than to dump all the raw observation data to the ground), but this will require confidence building demonstrations before it can become widely used.

Ground Segment

In parallel with satellite design and development, the ground segment must be completely restructured. There is no technical reason why a satellite or even a constellation incorporating a degree of autonomy cannot be controlled by a very small number of personnel using software-reconfigurable workstations.[17] As with most of the other issues, this is not as much a matter of new technology as it is of smart design and a change in operational philosophy. Particularly, this requires separating satellite and constellation control functions from payload tasking and mission data receipt, analysis, and dissemination. With suitable demonstrations and testing, the concept of a warfighting CINC's staff directly tasking and receiving data from a mission payload without compromising centralized control of the satellite itself could be realized.

Near Term Technologies and Operational Exploitation Opportunities (Including Commercial Opportunities)

The following paragraphs comprise a list of existing initiatives pointing toward the new system architectures required by SPATRACS.

The TAOS experimental spacecraft is essential for demonstrating many of the critical technologies needed to fulfill the vision described above. Its planned experiments will provide the first chance for space system operators to become familiar with a satellite with some autonomous capability.

Even though the ARPA-sponsored ATSSB program has been suffering from funding cutbacks, such a system is essential to meeting the desire for standard satellite modules in the future. If the ATSSB is not pursued, another effort will need to take its place. The commercial sector (e.g., Motorola's IRIDIUM) is also pursuing standard buses. A joint government and commercial effort could be beneficial in this area.

Phillips Laboratory's ROSS is an important critical program that should be continued. It is also a program that could be worked jointly with commercial industry.

Bill Gates, founder of Microsoft and father of DOS, recently announced plans to build an 840 communication satellite constellation. If DOS and Windows are any indication, he will clearly be developing a standard operating system. Joining forces early could be a tremendous advantage.

Laser crosslink is an essential capability that is not being aggressively pursued. Increased efforts are recommended in this area. This will free SPATRACS compatible satellites from RF spectrum squabbles (a major problem) and provide information control.

In the BMDO programs, the SBV experiment is an important demonstration of many critical technologies. Continued support of SBV is recommended.

Also, the Air Force's Brilliant Eyes program implements many of the same concepts this paper proposes. This paper does not compare specific technical merits of one program to others (e.g., DSP), but recognizes that some of the elements of Brilliant Eyes pertain directly to the kind of satellite that will likely be developed in the next century (smaller, more autonomous).

In the commercial sector, the development of expert systems along with powerful computer processors with large on-board memory is an area in which the government will have continuing interest. Yet, it is in precisely these areas where the commercial sector is proceeding faster. Therefore, the government should closely monitor the commercial sector and take advantage of their efforts. Large government programs are not required, but a significant commitment to developing effective interfaces (people to people) is in the government's best interests to ensure that any military-unique requirements are adequately addressed. The SPACECAST 2020 white papers on "Global View: An Integrated Joint Warfighters Command, Control, Communications, and Intelligence Systems Architecture" and "Surveillance and Reconnaissance in 2020" go into greater detail in this vital area.

Conclusion

SPATRACS--a design for space traffic control--is also a vision for the future of the US space operations. Risks to both new and existing space assets are increasing, and within the answer to that problem lies improved opportunities for operational effectiveness across the board. The creation of an integrated space traffic control system will head off serious problems that result from space tracks becoming increasingly conflicted. If the system goes beyond space-based sensors and becomes a part of satellite design, deconfliction could be highly accurate and would improve the usability of space. By freeing up spaceways, it would provide enormous benefits not only for the military, but for the civil and commercial space sectors as well. The systems proposed in this paper each have value on their own merits and, when combined in SPATRACS, result in many and compelling benefits.

In the years following World War I, US aviators' ability to see the air dimension as much more than a land support arm paved the way for a legacy of air superiority that this nation enjoys today--but only after a great deal of effort was focused on gaining the support of senior military and political leaders. That same opportunity exists today in space, and this paper brings the vision into sharper focus by laying out the path to US space domination in the next century.

NOTES

[1]Nye, Joseph P., Jr., Perry, William J. Schear, James A., Scowcroft, Brent, and others. Seeking Stability in Space. Aspen Strategy Group and University Press of America: 1985. p. 4 and p. 26.
[2]Horner, Charles A. Testimony to the Senate Armed Services Committee, 22 Apr 93.
[3]Stovepiped, as used here and elsewhere in this paper, refers to the tendency for all military space systems to develop on their own, without interfacing with other satellite systems--much like a pipe on an old stove that would do its job in total isolation from the other pipes.
[4]In some ways, this analogy is even deeper than it appears. Like many of our space systems, the B-52 was initially over-designed. As a result, each has been upgraded and used for missions never originally intended. Perhaps, in a way, each was too good initially and thus inhibited development of even more effective (and more efficient) follow-on systems.
[5]The brain is contained on the 20 SPATRACS system satellites. SPATRACS-capable satellites will be crosslinked to the 20 satellite brain. In sum, the system contains 20 controlling satellites and is supported by information from other satellites that can communicate with them.
[6]To clarify, the sensors would be able to handle the entire load without incorporation of sensors located elsewhere. For instance, a ground-based radar could uplink to the controlling satellites and the on-board brain would incorporate the information into the tracking algorithm.
[7]Based on MIT Lincoln Laboratory Space Based Visible (SBV) experiment studies.
[8]This can be done with passive sensors using stereo viewing, similar to missile tracking. Augmentation with active sensors is an option.
[9]For example, Space and Missile Systems Center (SMC) studies showed replacing GEODDS with a space-based system could save $300M per year. This would be just a small part of the cost-saving changes envisioned by this paper.
[10]This was once a major limitation: the size, weight, power requirements and limited capability of microprocessors seldom justified their inclusion on board spacecraft, hence our historical emphasis on ground control. This changed with the emergence of ever-more capable electronics. Shorter satellite acquisition and deployment times (as well as deliberately shorter design lifetimes) would make the argument that "it's always easier to upgrade the ground segment" irrelevant.
[11]See SPACECAST 2020 White Paper "Spacelift Suborbital, Earth to Orbit, and On Orbit," June 1994.
[12]MILSTAR, admittedly an extreme example, will require about a year to complete its initial check out. (Space News report - 1 week after launch).
[13]See SPACECAST 2020 White Paper "Space Modular Systems", June 1994
[14]The cost of a contact can be as high as $10,000 per minute, depending on the system. (Conversations regarding SSTAR at Phillips Lab, April 1994.)
[15]Space Logistics Master Plan, HQ USSPACECOM, J4-J6 Directorate, DRAFT, April 1994.
[16]Sustaining Space Systems for Strategic and Theater Operations, USSPACECOM/J4L, 17 Sep 93.
[17]For cost reasons, universities in Europe used this approach for the small research satellites. Phillips Laboratory is using the same principles for its "Payload Operations Center." (Discussions with Phillips Laboratory Space Experiments personnel, 1992-1993)