A Constellation Architecture for National Security Space Systems

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The warfighter of the 21st century has become increasingly dependent on space. In geostationary Earth orbit there are multiple assets that provide multiple critical resources: surveillance, reconnaissance, weather information, and communications. The DoD is investigating a proposed constellation architecture called a Space Based Group consisting of multiple clusters of satellites in geosynchronous orbit. The distributed approach allows propellant and mission communications to be offloaded, enabling smaller, lighter, better performing, and cheaper mission satellites. This article presents the differences between a monolithic and distributed architecture and discusses the beneficial attributes of the distributed approach, e.g., how offloading mission communications from satellites in favor of a high-speed wireless local area network in space enables efficient use of both space and ground communications capabilities. Once instantiated, the architecture enables responsive operations, improves survivability, leverages technological advances, and better supports the industrial base.

INTRODUCTION

Militarily relevant needs supported by geostationary Earth orbit (GEO) satellites are becoming ever more complex and costly, driven by transportation costs, complexity of the individual sensors, integration complexity (e.g., interference from multiple sensors), and the need to process sensor data to get into a shared, relatively small downlink. One needs only to look at published accounts of recent acquisition programs (such as GOES, SBIRS, WGS, TSAT, and AEHF) to show that conventional GEO systems have negative trends over all programmatic measures of cost, schedule, and performance.

Specific negative issues driven by the architectural construct of monolithic spacecraft are engineering problems by nature and require only time and funds to resolve. The negative issues are easily summarized and lead to design questions that are answerable with a distributed architecture, as we presented at the 5th Responsive Space Conference in April of 2007.[1] In this

article, we summarize the major issues of the monolithic approach as well as discuss how the constellation architecture addresses each issue. The National Security Space Office (NSSO) has championed the early work to socialize the applicability and benefits of a distributed or constellation architecture called the Space Based Group (SBG). We were invited to review the early work and to participate in the socialization efforts. Since then, the SBG architecture has been embraced by major elements of the National Security Space community, and a program to demonstrate selected capabilities was to be planned (D. Borgeson, "The Space Based Group Enabling Demo Brief for SECAF Wynne," PowerPoint brief presented 31 Mar 2008). The benefits of a constellation architecture are covered qualitatively in this article and include increased survivability, responsiveness to warfighter needs, flexibility, leveraging of technology advances, increased orbital mass, reduced nonrecurring engineering and cost, and enhancement to the industrial base.

A *monolithic architecture* in the context of spaceborne systems describes a single spacecraft with all the requisite subsystems needed to perform its designated purpose. As a monolithic system, the spacecraft has a mission-specific payload (sometimes a single sensor, a large telescope, for example, or alternatively many sensors and instruments for a weather-sensing mission) and a bus with all the requisite capabilities to sustain the system for its intended lifespan. Integrated onto a mechanical structure, those capabilities are composed in subsystems such as power; communications; guidance, navigation, and control; propulsion; etc. NASA's Hubble spacecraft is an example of a monolithic system (Fig. 1).

Figure 1. NASA's Hubble spacecraft. (Image courtesy of NASA.)

ISSUES WITH MONOLITHIC SPACECRAFT

The uncompromising attributes and negative trends of GEO systems owe their misfortune to the architecture that up to now has proven capable with some economy of scale, namely, the monolithic satellite system. Before introducing an alternative, let us review the main attributes of the classical monolithic geosynchronous satellite architecture:

Single large spacecraft with multiple sensors

- High cost per spacecraft drives longer mission life
- Reliability for long life drives redundancy
- Bus redundancy and multiple sensors drive integration and testing (I&T) complexity and increased weight and power requirements, all contributing to higher cost and longer schedule

Nonserviceable design

- Subsystem capacities are designed to support full, fixed mission life (fuel, power, communications, etc.)
- Technology is frozen early in design
- Redundancy approach is limited
- Processing capacity is limited; it is always obsolete compared with ground processing
- Reliability drives parts screening (hence cost)
- Fuel often becomes a life-limiting factor

Launched with single space-lift vehicle

- Expensive, large space-lift boosters are required
- The vehicle must carry the propulsion stage to circularize orbit, or offload the stage with greater performance, or direct inject the launcher

Supported with stove-piped ground segment

- A separate, dedicated ground station is needed for each new system
- A dedicated backhaul network is needed

In summary, monolithic systems require integration of multiple missions on large, complex spacecraft; this, in turn, requires closely coupled interfaces, couples development risk, and results in I&T exercises in combinatorial complexity. Given that typical current large monolithic systems do not lend themselves to operational responsiveness (aside from certain systems' limited abilities to be retasked), what attributes of a system or architecture do lend themselves to operational responsiveness? First, we will define the potential solution space by asking a series of questions:

- Can individual sensor, subsystem, and system development efforts be decoupled from each other?
- Can overall program risk and system risk be reduced?
- Can complexity be reduced?
- Can I&T cost and effort be reduced?
- Can new technology be leveraged throughout the program?

- Can smaller launch vehicles be used?
- Can experimentation or technology demonstrations be facilitated?
- Can ground segments be responsive to operations in the GEO belt?
- Can satellites be redeployed from their normal operating position to areas of higher need in a timely manner?

These questions make up the problem statement of how to architect a GEO system that is responsive to the military. The optimum solution, if these questions are being addressed, should also be cost beneficial, increase system survivability, and improve the industrial base.

THE CONSTELLATION ARCHITECTURE

When one examines in detail the attributes of monolithic systems in GEO, the concept of a distributed architecture becomes an obvious path to explore. In fact, since the early days of the space program the trade space between implementing one spacecraft or multiple spacecraft to perform a mission has been open and is examined as part of the mission systems engineering process. The Geostationary Operational Environmental Satellite R-Series (GOES-R) program and next-generation mobile communications systems explicitly looked at a distributed approach.[2–4] The constellation or clustered architecture (both used synonymously with SBG in this article) differs from the conventional distributed architecture in that instead of breaking the mission up into multiple monolithic spacecraft, each with its own specific mission or an "even" part of the general mission, specific enabling spacecraft functions are broken out and then provided as services to the remaining spacecraft within the cluster. By selecting specific functions that lend themselves to this approach, one can enable an architecture that is robust, flexible, and cost effective over the life cycle of the mission.

In the *Introduction*, a series of questions were posed. Let us revisit those questions and use them to define the constellation architecture.

Can Development Efforts Be Decoupled from Each Other?

The very nature of a distributed architecture in any form lends itself to resolving this issue. From a payload perspective, this leads us to dedicate individual spacecraft for each sensor modality. Also, the communications subsystem of a spacecraft can benefit from being decoupled from the payload's requirements and development schedule. This becomes even more important when the communications payloads move higher in bandwidth.

Can Overall Program Risk and System Risk Be Reduced?

Program and system risk are directly proportional to the complexity of the system. If we decompose a complex monolithic system into several less complex systems that work together, risk is obviously reduced, as long as one maintains diligence on the system interfaces. Also, by breaking the system into pieces, one can separate new technologies onto specific platforms that do not put the rest of the system at risk. Indeed, this can be viewed as a "system of systems" but without the lack of control of the systems development that is one of the trademarks of such an implementation.

Can Complexity Be Reduced?

As discussed in the previous section, reducing complexity is the key to reducing risk. By examining the interaction between subsystems in a monolithic system, one begins to see how the system complexity grows quickly as different requirements begin to become mutually exclusive. A good example would be a payload that requires precision pointing and low jitter but produces a large amount of valuable data. Getting the data to the ground requires high power, which drives the solar arrays to grow, which in turn disturbs the pointing and jitter control capability of the space vehicle, which then drives the design to complex solutions for pointing and jitter reduction. A simple way to resolve this issue, and to reduce complexity, is to view the communications to the ground as a resource that can be moved to another element of the cluster, which in turn allows a simpler communications solution for the sensor vehicle.

Can I&T Be Reduced?

An obvious result of reducing the complexity of the spacecraft is that system testing and verification activities have a similar reduction in complexity. Although a constellation architecture would require multiple I&T activities (for each element in the cluster), these activities can be decoupled (even between different organizations) and performed in parallel. A key advantage is the independence this allows for complex system integration efforts. If a single subsystem is holding up a monolithic satellite system, the entire program is subject to overruns. A decomposed constellation architecture allows individual troublesome elements to be worked intensely without necessarily forcing testing, integration, and launch delays on the overall system. In the worst case, partial capability can be deployed while the remaining portions of the system complete development and fabrication, to be launched at a later time to join the already on-orbit constellation. Finally, it is a well established fact that repetitive builds of the same spacecraft bus result in a lowering of overall effort in I&T as a result of the assembly-line nature of the process.

Can Technology Be Leveraged Throughout the Program?

A major drawback to today's approach to acquiring and deploying large, monolithic systems is the risk associated with implementing a technology refresh, which in turn stifles innovation and results in old, lower-performance technology being the only acceptable solution. Creating an architecture that allows newer, proven technology to be infused into the system without replacing all elements of the system can provide an enormous benefit. In fact, one of the most significant attributes of this architecture is that new technology insertions do not threaten the entire system, as any resulting failure is constrained to the one portion of the system into which it was inserted.

Can Smaller Launch Vehicles Be Used?

The breaking apart of a large monolithic system will result in spacecraft of various sizes. To facilitate cost and responsive launch, minimization of both size and mass is a desirable feature. One of the main drivers of GEO spacecraft size and mass is the propulsion system, which, because of station-keeping requirements, also becomes one of the life-limiting components of the system. Creating an architecture that reduces the size of the propulsion system would facilitate the use of many different types of launch vehicles and offer the capability to extend the life of the spacecraft by refueling as needed. The capability of the current Evolved Expendable Launch Vehicle system to manifest multiple satellites and perform direct-inject missions should allow cost-effective use of the standard launch infrastructure. In addition, multiple low-cost launch vehicles are under development, many of which promise the opportunity for low-cost GEO launches of smaller vehicles.

Can Experimentation or Technology Demonstrations Be Facilitated?

By breaking the mission into multiple spacecraft with different roles, a technology infusion will put at risk only the spacecraft it is on, not the entire constellation. New sensor technology can be demonstrated without designing and manufacturing a large system, but rather by using just a vehicle that provides the sensor's core needs. Obviously this does not directly apply to a vehicle providing a service to the cluster. However, if multiple clusters are deployed, even a problem with a service vehicle suffering from issues related to new technology could be mitigated by redeploying another service vehicle from another cluster.

Can Ground Segments Be Responsive to Operations in the GEO Belt?

The most obvious way to make something more responsive is to make it simpler, standardized, and lower in cost. Current ground segments are each unique, dedicated to the monolithic systems they control. By standardizing the space segment's interface to the ground (such as the current initiative to incorporate standards) and reducing the number of such interfaces, true responsiveness can be achieved in the ground segment.

We can summarize the desired top-level attributes of a constellation architecture in GEO in the following way:

- Distributed system of systems (multiple spacecraft)
- Serviceable design
- Launch using smaller launch vehicles or multiple spacecraft on one launch vehicle
- Simplified interface with the ground segment

Delving one level deeper, more detailed attributes are revealed:

- Different sensors are implemented on dedicated spacecraft.
- An infrastructure is implemented that provides key resources to the cluster.

Note that, within a constellation architecture, spacecraft with and across multiple clusters do not need to be functionally identical. Specialized functions would be implemented with the spacecraft that required it, enabling the cluster to take whatever form is required to implement the potential multiple missions that exist within its domain. In this way specialized infrastructure spacecraft can effectively support multiple missions, amortizing the cost of the infrastructure investment among many "customers." In many ways this model is analogous to cell phone towers providing the infrastructure for many types of terrestrial wireless services (voice, data, location, etc.). One of the desired outcomes of this structure is that mission satellites would be smaller (and therefore cheaper) than the monoliths they replace. Total mass to orbit is greater by 30% (estimated) but is highly dependent on the implementation approach.

THE CONSTELLATION INFRASTRUCTURE

The next step in architecting the cluster is to identify the services that should be made available as an infrastructure. An appropriate filter to apply to the process would take the form of identifying those services that are economical when provided in bulk to multiple missions. One would also consider particularly appealing those services that can enable new capabilities or capacities. It is also critical to consider those services that do not lend themselves to being made available as a service because of either a mission-specific functionality or a function that is simply not currently economical or feasible to institute.

The two functions to which all GEO systems need to be truly responsive, regardless of the specific mission, are communications and longevity. When viewed from the

perspective of an infrastructure, these two items manifest themselves as the ability to relay large amounts of data to the ground and the ability to replenish fuel as needed. Instead of separate, dedicated, unique downlinks and ground stations, a single, consolidated downlink and ground station is implemented. The members of the cluster would use a wireless Internet Protocol (IP) local area network (LAN) to relay data locally to a dedicated communications satellite, which would then relay the data to the ground segment. Instead of a restricted amount of life-limiting fuel, the cluster would have a servicing vehicle with the capability of transferring fuel to other members as needed.[5] The entire cluster would now have the ability to change orbits without being concerned about the life-limiting effects, as more fuel could be launched as needed, taking advantage of the unused, wasted mass to orbit that exists on every GEO launch.

In truth, providing the data-relay function and the refueling function can be viewed as a service provided to constituents of the cluster, essentially changing the paradigm of how complex GEO missions can be implemented. Once the architecture infrastructure is in place, all one needs to do is add a simple, sensor-accommodation-driven spacecraft to the orbital slot to achieve an entirely new capability. Fuel and communications would become a given once a constituent arrives on station with the cluster, allowing enhanced capability in a responsive fashion at a lower cost.

Enabling Technologies

The fundamental communications technologies that enable constellation satellite architectures are actually terrestrial telecommunications based. The two key technologies are high-data-rate, low-power wireless networks and IP routing. A separate, complementary technology that enables responsiveness in the GEO orbit is spacecraft servicing, consisting of rendezvous, docking, refueling, and propulsion.[6]

Wireless networking experiments have been conducted in space several times. NASA's early wireless networking experiments focused on operations in Mir and the International Space Station (ISS).[5] Since then, wireless networks have been deployed on shuttles and the ISS, and experiments have flown communicating between free-flying satellites. Several of NASA's research teams have explored intersatellite networking technologies.[7] The physics are straightforward; commercial protocols can be adapted to provide a starting point, and NASA has performed research on COTS router hardware to determine its feasibility for use in space.[8] The range of these systems in free space is hundreds to thousands of meters, depending on the frequency bands, antennas, and power levels chosen.

The size, weight, and power requirements of wireless networks with a range of kilometers are orders of magnitude lower than conventional space–ground links. A 50-Mb/s wireless link based on 802.11a weighs tens of pounds, requires tens of watts, and fits into the form factor of a small briefcase, including a small 12-dB antenna for the client satellite systems. The equivalent ground link approaches 100 lb and requires hundreds of watts of power and a large jitter-producing pointing antenna.

Complementing this are standard routing and concentrating technologies. Satellite routing has been proven experimentally, and systems like Spaceway perform low-level routing onboard. Cisco Systems has worked with the U.S. Strategic Command on a technology demonstration project called IRIS (Internet Router in Space) to demonstrate IP routing on an Intelsat platform, after previous successful tests on a U.K. satellite in low-Earth orbit.[9] This combines with standard communications satellite technologies to form a concentrator hub, a high-bandwidth up-and-down link that can route data to other satellites in the cluster through the wireless network. This enables a natural hub-and-spoke configuration for which the communications concentrator satellite serves as the core router for the satellite clusters.

The final enabling technology for this architecture is on-orbit servicing. Responsive operations require the ability to redeploy orbital assets to areas of need. Ordinarily, this would involve a lengthy decision process to justify the sacrifice of years' worth of station-keeping fuel, with the speed of the reposition being traded off against the lost lifespan. If we are able to refuel satellites on orbit, fuel consumption becomes a recoverable event; satellites can be repositioned within the geosynchronous belt quickly and efficiently, on the order of days instead of weeks.

These technologies have been developed over decades, beginning with the Gemini missions, the Soviet Salyut missions, and the Mir space station resupply missions. The ISS has repeatedly demonstrated the value of the Progress system, with which an unmanned robotic spacecraft performs automated docking with a manned platform.

Fully autonomous servicing has been proven on orbit with the Defense Advanced Research Projects Agency (DARPA) Orbital Express mission. Orbital Express successfully demonstrated autonomous rendezvous, cooperative and uncooperative docking, fuel transfer, and replacement of individual packaged components. The key elements required to enable responsiveness are docking and refueling. The ability to maneuver while docked is an additional potential bonus, allowing the "tanker" to provide initial boosts for fast transfers, leaving the client vehicle with full tanks to end the drift and assume its assigned station. Orbital Express also demonstrated noncooperative docking using a robotic arm, replacement of orbital replacement units, and autonomous rendezvous from tens of kilometers.

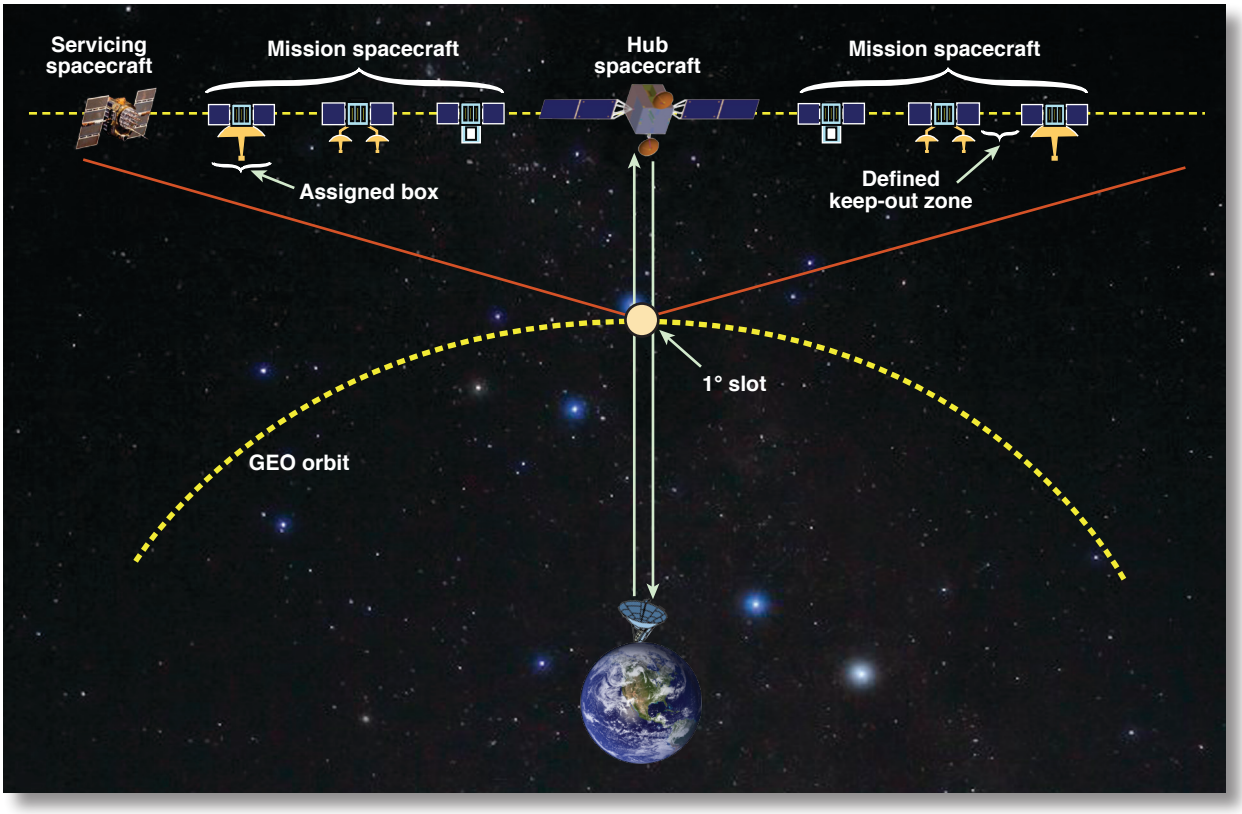

Figure 2. Several spacecraft form a constellation in a single slot of the geostationary orbit.

Implementing the Constellation Architecture

We have developed a constellation architecture concept that splits functionality among mission satellites while concentrating common utility functions in infrastructure satellites. The architecture and associated on-orbit geometry is shown in Fig. 2.

The core satellite of the cluster is a communications satellite. It has a high-bandwidth, dedicated ground link several times larger than the typical mission satellite ground link, scaling to hundreds of megabits or even gigabits. This communications satellite serves as the hub, or access point, for one or more kilometer-distance wireless networks. The hub satellite provides routing and control services for the overall cluster. The corresponding ground infrastructure is scaled to serve the full amount of data available from the satellite and to provide a medium-bandwidth packet-addressed command and control link; the hub will route the signals to the client satellite(s) through the local wireless network. A conceptual hub satellite could easily be built around one of the smaller commercial communications satellites as shown in Fig. 3.

A set of three ground stations with multiple antennas at each provides a worldwide infrastructure. Similar in concept to the NASA Deep Space Network, three evenly spaced ground stations allow missions to operate anywhere in the GEO belt (Fig. 4). Each ground station will have sufficient bandwidth to backhaul the full data feed from the clusters back to control centers in the continental United States.

Individual client satellites should be designed to accommodate one class of mission, simplifying the engineering and integration efforts. Notional examples are shown in Fig. 5. A single-sensor model for Earth-observation systems is logical. Other missions, such as space weather missions, may desire a suite of similar or related instruments on a single platform or multiple instances

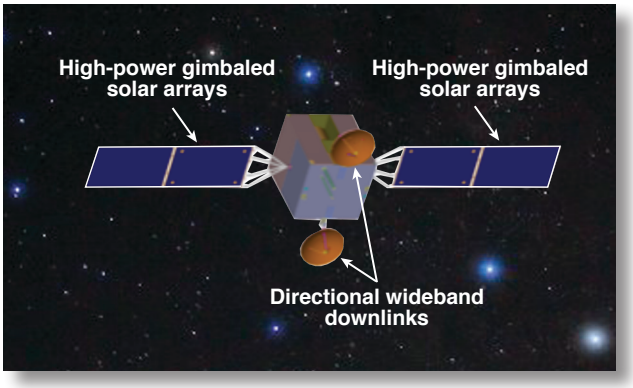

Figure 3. The conceptual hub satellite for the constellation architecture is a simple commercial communications satellite in common use today.

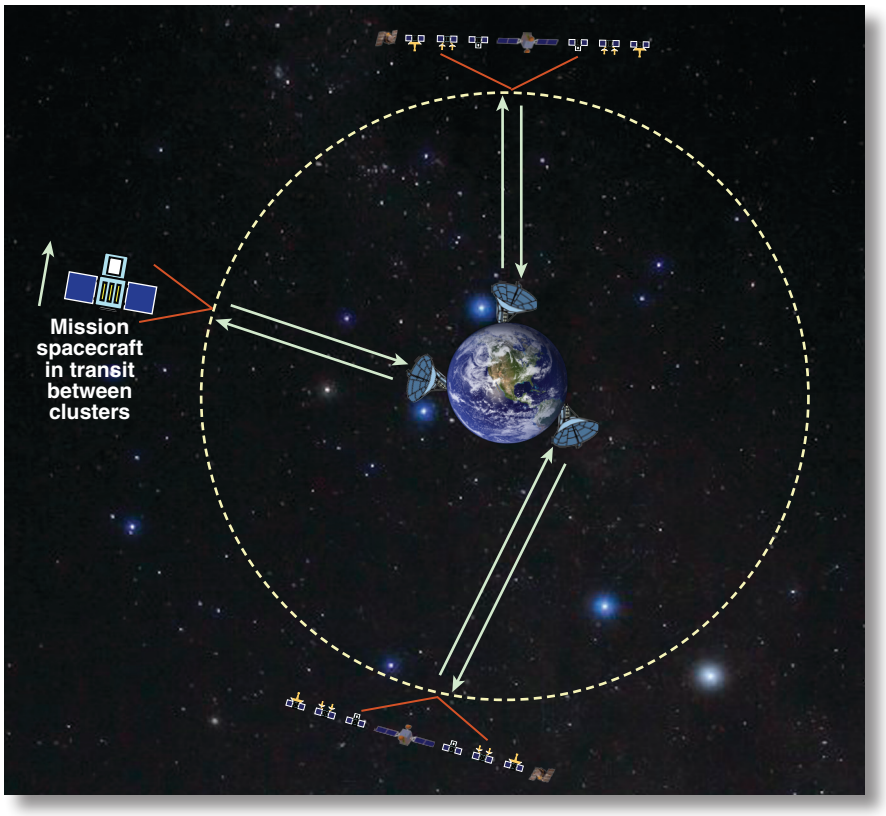

Figure 4. Worldwide coverage can be provided by three ground stations.

A common trade-off in mission satellites today occurs between the downlink bandwidth and the amount of data generated by the sensor suite. Ideally, every bit generated by the sensors is of value and should be transmitted to the ground. However, modern instruments are capable of generating megabits' and gigabits' worth of data; mission designers must therefore perform processing and compression of the raw data to fit it into the ground links currently in use. When using this constellation architecture, bandwidth becomes a crosslink and downlink network optimization consideration and may be billed as a service rather than built into the system and flown statically. In cases in which bandwidth use is dynamic, the system should allow multiple data rates and deconflict based on priority and quality of service guarantees.

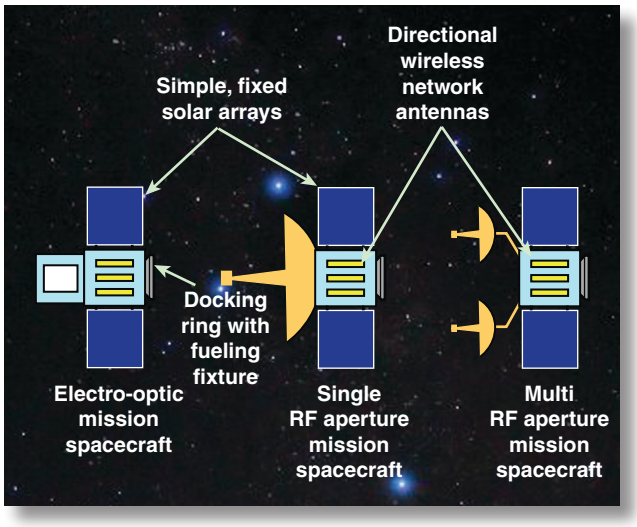

Figure 5. Modular spacecraft buses support different types and classes of mission satellites, operating independently in each constellation.

of the platform within the cluster for diversity and increased resolution. Each of these satellites performs all mission communications through a lightweight, low-power wireless network connection. Removal of the ground link's weight and power requirements should be a significant improvement in the mission mass fraction for cluster client satellites.

A Conceptual Heterogeneous Constellation of Spacecraft Deployed at GEO

Heterogeneous satellite missions sharing the communications infrastructure allow dissimilar missions to be flown in the same cluster. Environmental monitoring, space situational awareness, and deep-space communications can operate independently of each other; conversely, multiple instances of similar instruments within a cluster may be tasked to operate cooperatively, without affecting the operations of any other elements in the cluster.

Satellites within the cluster will be assigned stations and frequencies through the standard low-band telemetry and command links required of all GEO satellites (i.e., Space-Ground Link System or Universal Serial Bus) for launch and anomaly situations. During normal operations, the communications hub satellite would be used for the primary command and telemetry path. Each satellite should have a capability to derive its own location, whether derived from Global Positioning System or star and horizon trackers. The cluster is strung out through tens of kilometers of space; the station-keeping tolerances have been shown to be well within the state of the art.

The servicing capability combines with establishment of the ground station infrastructure to allow responsive operations around the world. Take the instance in which a high-value satellite suffers a failure and the only

comparable capability currently on orbit is deployed to a cluster halfway around the world. Relocating the active satellite to meet the need would be a complex decision if using conventional satellites; the satellite could be slowly drifted around the world, with a small cost in fuel but a loss of mission for many days, or it could be boosted quickly into a higher-speed drift orbit, at the price of years' worth of station-keeping fuel and mission life.

A servicing satellite turns this into a cost issue. How much does each day out of operations cost versus how much will the fuel and delta-V of the servicing node cost? The servicing satellite docks with and refuels the client satellite and then performs the boost maneuver to place them both in the high-speed drift. It then breaks free and returns to its station at its leisure, while the client satellite has full tanks to stop its drift and assume station in the destination cluster. Upon arrival it is already configured with a station assignment and network access configuration; it goes into mission operations as soon as it is stable and logged into the local wireless network.

Responsiveness of the GEO Concept

The capability of the constellation architecture to reposition satellites among clusters addresses Operationally Responsive Space Tier-2 responsiveness, meaning meeting a need in hours or days.[10] The replacement capability can now be launched as soon as it is available and placed into operations in the original cluster or as a backfill to the client satellite that was relocated to meet the need, addressing Tier-3 requirements. The cluster concept is a natural fit for Tier-3 responsiveness, allowing experiments, technology demonstrators, and iterations on technologies to fly independently of each another, in an existing infrastructure.

The Value of Fuel for the GEO Concept

The value of fuel, in and of itself, can be a sufficient driver for a major architecture change. The value concept can be immediately broken down into two categories: life expectancy and performance enhancement (relocation without concern about life-limiting issues). The ability to reposition an asset on orbit in a timely fashion is the key to responsive operations, and the ability to do so without concern for the impact on the system's life expectancy would have great impact on how responsive operations are performed. Both communications systems and Earth-viewing systems would benefit immensely from the ability to relocate on demand.

The current model for fuel use in monolithic systems in GEO revolves around station keeping for the life of the mission, with margin for potential repositioning of the asset. The constellation architecture concept changes the model for fuel consumption from this forecast/lifetime-based approach to a demand-based approach, which allows responsive operations across the entire GEO belt. The architecture benefits from life extension as a result of a reduction in fuel limitations. "Orphaned" fuel in a spacecraft that is no longer in service would no longer be an issue because the service vehicle could dock with the spacecraft and remove the unneeded fuel to be transferred to another asset. The new architecture sends vehicles to the graveyard orbit with minimal wasted fuel. Recently, DARPA's Orbital Express program demonstrated the feasibility of on-orbit servicing to include fuel transfer between vehicles and, hence, can be viewed as an example of the enabling technology base.

In the context of today's monolithic systems, one can postulate that if other life-limiting issues are dealt with appropriately (radiation, mechanisms, etc.), a system's lifetime could be significantly extended through on-orbit servicing. Doubling of the system's lifetime can be construed as saving the entire cost of the original system's replacement, providing a significant money pool to draw upon to implement the constellation architecture. In turn, over the life cycle of the architecture a significant cost savings would be achieved and would provide an infrastructure of on-orbit services that would provide savings to systems that followed.

Survivability of the GEO Concept

Survivability is an attribute the military has been interested in since the first conflict during which warfighting assets were destroyed. The successful antisatellite demonstration by China in 2007 has brought to the forefront the need to think about survivability. In fact, the intercept of a decaying satellite by the U.S. Navy in 2008 using a Standard Missile demonstrated the United States' inherent capability in this area, which can only serve to increase other nations' desire to match this ability. The head of Air Force Space Command at Peterson Air Force Base is on public record identifying the need for survivability of space assets.[11] Intuitively, a distributed system as instantiated by a constellation architecture is more survivable because of the number of targets needing engagement. Should a communications node be targeted, a replacement can be moved from another constellation or an interim capability via a mission spacecraft for reduced communications placed on orbit, if not already on station.

THE CIVIL RESERVE AIR FLEET AND F6

The introduction of the constellation architecture would not be complete without mentioning two related endeavors, one old and one new. The old one takes us out of the space domain and recognizes another model by which the U.S. Air Force (USAF) used out-of-the-box thinking to improve military responsiveness at reduced cost. The Civil Reserve Air Fleet is made up of U.S. civil air carriers that are committed by contract to provide air-

craft for personnel and cargo airlift by the USAF.[12] The Civil Reserve Air Fleet program is designed to quickly mobilize our nation's civil airlift resources to meet USAF force projection requirements. This allows the USAF to reduce the total number of military airlift acquired. The USAF provides a yearly remittance to each of the participating airlines to fly the cargo-configured aircraft meeting their specifications. One possible implementation of the SBG uses a similar model by which the civil communications satellite operators are reimbursed for flying a capability to support colocated mission spacecraft.

During the time that the NSSO was investigating the SBG, DARPA notified the community of its new interest in investigating the viability of clusters of small, individually launched satellites that can operate as a network in space to demonstrate that large traditional satellites can be replaced with smaller "fractionated" satellites that would fly in clusters and would be linked through wireless networks. The first phase of a program dubbed "F6," which stands for "Future, Fast, Flexible, Fractionated, Free-Flying," was intended to push the technology envelope across several of the subsystems, such as power distribution between the cluster so that individual spacecraft did not need power generation and storage (O. C. Brown, "Industry Day Briefing, System F6," PowerPoint brief, presented 24 Jul 2007). APL's National Security Space Business Area was tracking this program for a possible bid and made the introduction between the DARPA program manager and NSSO's SBG architecture lead. Since that introduction, the program has commenced. DARPA has made multiple contract awards for the first phase of the F6 project. Which parts of the system each contractor will fractionize and the approach to the space-based LAN have yet to be identified; each is in the proprietary, conceptual development phase.

WHAT'S NEXT?

The Secretary of the Air Force has tasked the Space and Missile Systems Center to plan a demonstration to show the viability of the space-based LAN to support the SBG architecture. To reduce the cost of the demonstration, the Space and Missile Systems Center is considering several options that leverage near-term space system efforts. The intent is to fly early LAN hardware technology on an already planned mission and "visit" it with a surrogate mission spacecraft. In parallel, APL's National Security Space Business Area is looking at starting an advanced concept initiative using personnel from the Applied Information Sciences and Space Departments to develop a hardware and software approach to the LAN communications that enable the constellation architecture.

CONCLUSIONS

The constellation architecture presents a new approach to fielding space-based capabilities in GEO that takes advantage of current and developing technology by distributing the typical spacecraft functions across several spacecraft. This approach provides the fundamental infrastructure for truly operationally responsive operations at GEO. Early in this article we posed a series of questions. We now provide answers to highlight the conclusions:

- Decoupled development of the service elements (communications, fuel) of the constellation and the sensor elements enables accelerated program schedules and should allow early fielding of missions even in the event of issues with one element.
- Program risk is reduced as a function of reduced complexity of the individual elements.
- Complexity is reduced by decomposing the complex system into less complex elements that do not compete for resources.
- I&T efforts are reduced as a result of reducing complexity, and parallel I&T efforts are facilitated, which, in turn, shortens schedules.
- The ability to insert new spacecraft without replacing the entire constellation fosters technology refresh at an incremental, virtually risk-free pace.
- The resulting multiplicity of different-size spacecraft allows the use of multiple, different-size launchers and allows the users to take advantage of shared launch opportunities and use the full throw weight of the launch vehicle.
- Experimentation and demonstrations are supported without risk to the entire system, because the only interface with the rest of the constellation is via a wireless LAN.
- Reducing the current number of ground segments to a small number of standardized portals tied to the Global Information Grid enables operations around the world, independent of the physical location of the mission processing and control centers.

Although changing to a distributed architecture has numerous qualitative benefits, the U.S. government's space system acquisition organizations will have to quantitatively address, and hence place value on, attributes such as survivability, responsiveness, and technology refresh. A distributed infrastructure will cost more to implement but should prove to have benefits beyond this initial expenditure.

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REFERENCES

[1]Orndorff, G. A., Zink, B. F., and Cosby, J. D., "Clustered Architecture for Responsive Space," in *Proc. AIAA 5th Responsive Space Conf.*, Los Angeles, CA, paper RS5-2007-1002 (2007).

[2]Gelderloos, C., Atkins, B., and Gail, W., "Benefits of Distributed Architecture Solutions for GOES-R," in *Enabling Sensor and Platform Technologies for Spaceborne Remote Sensing*, G. J. Komar, J. Wang, and T. Kimura (eds.), Proc. of SPIE, Vol. 5659, SPIE, Bellingham, WA, pp. 272–283 (2005).

[3]Crison, M., Nelson, B., Soukup, J., Madden, M., and Scott, W., "NOAA's GOES-R Series: Selectable and Programmable Operations of a Distributed Geostationary Constellation," in *Proc. AIAA Space Conf.*, Long Beach, CA, paper 2003-6249 (2003).

[4]Stuart, J. R., and Stuart, J. G., "Next Generation Mobile Satellite Communications Architectures, Networks and Systems," in *Proc. Fifth International Mobile Satellite Conf.*, Pasadena, CA (1997).

[5]Mir Wireless Network Experiment website, http://spaceflight.nasa.gov/history/shuttle-mir/science/iss/sc-iss-mwne.htm (accessed 30 Apr 2010).

[6]Galabova, K., Bounova, G., de Week, O., and Hastings, D., "Architecting a Family of Space Tugs Based on Orbital Transfer Mission Scenarios," in *Proc. AIAA Space Conf.*, Long Beach, CA, paper 2003-6368 (2003).

[7]Schnurr, R., Rash, J., Hogie, K., Parise, R., and Criscuolo, E., "NASA/GSFC Space Internet: Extending Internet Technology into Space," http://ses.gsfc.nasa.gov/ses_data_2001/011018_Rash.ppt (2001).

[8]Mobile Router Technology Investigated for Space Radiation Efforts, http://www.grc.nasa.gov/WWW/RT/2005/RC/RCN-carek1.html (accessed 14 Apr 2008).

[9]Carless, J., *Cisco Systems is at the Forefront of Extending the Internet into Space*, http://newsroom.cisco.com/dlls/2004/hd_063004.html (accessed 14 Apr 2008).

[10]Kneller, E., and Popejoy, P., "National Security Space Office Responsive Space Operations Architecture Study Final Results," in *Proc. AIAA Space Conf.*, San Jose, CA, paper 2006-7496 (2006).

[11]Kehler, C. R., "The Next Space Age," Remarks to the National Space Symp., Colorado Springs, CO (30 Mar–2 Apr 2009), http://www.af.mil/information/speeches/speech.asp?id=464.

[12]Air Mobility Command, *Civil Reserve Air Fleet*, Fact Sheet, http://www.amc.af.mil/library/factsheets/factsheet.asp?id=234 (accessed 14 Apr 2008).

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