FRACTIONATED SPACE ARCHITECTURES: TRACING THE PATH TO REALITY

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ABSTRACT

In an effort to achieve responsiveness, increase effectiveness, and reduce the uncertainty involved in maintaining a space architecture dependent on a few high-capacity, high-cost satellites, the Defense Advanced Research Projects Agency (DARPA) has proposed the concept of fractionated spacecraft. DARPA plans to compress spacecraft development timelines, enable launch with smaller, more responsive vehicles, and make the spacecraft architecture fundamentally flexible and robust. DARPA’s System F6 (Future Fast, Flexible, Free-Flying, Fractionated Spacecraft united by Information eXchange) is a technological and paradigmatic demonstrator of this concept.

While fractionated architecture is likely to significantly transform the technology base, as well as the development and operational concept for delivering on-orbit capability, this disruptive concept arose from a substantial and rather distinguished pedigree of foundational thoughts, concepts, and demonstrators developed throughout the Space Age as designers have explored satellite constellations, cooperative spacecraft, distributed systems, and miniaturization. Concepts or programs ranging from pioneers like the Transit navigation and IDSCP/DSCS-I communications satellite efforts through the Air Force’s XSS series, NASA’s New Millennium, DART, and TPF programs, Orbcomm, ANTS, TechSat-21, GPS, and many others have contributed to the stream of innovation leading to the architectural paradigm shift of the F6 program.

It was not just the promise of new technologies and operational concepts that led to the genesis of F6, but also the deficiencies of the conventional, monolithic approach to space systems that largely pervades the industry today. This paper traces the development of the intellectual, technological, and policy foundations of the fractionated spacecraft concept throughout the preceding decades. We conclude with an assessment of future hurdles to its proliferation and make some projections about its likely applicability to various space missions in the years to come.

INTRODUCTION

DARPA formally initiated its System F6 fractionated architecture program in February 2008. System F6 – short for Future Fast, Flexible, Fractionated, Free-Flying Spacecraft united by Information eXchange - will mature the technological, architectural, and organizational advancements necessary for an on-orbit demonstration of a fractionated spacecraft. F6 will explore a rapid, multi-spiral design-build-test approach, relying on advances in four key technical fields and using design decisions guided by explicit quantitative system value models. The System F6 program, now preparing for contractor downselect and Phase II, will lead to an orbital demonstration of a microsatellite-scaled fractionated space system in late 2012.

OBJECTIVES

The first-generation microsatellite-based System F6 will provide all the manifestations described in the program's name, but the attribute that makes the system a breakthrough is flexibility: maintainability, scalability, and reconfigurability. Equivalent changes can be effected in a monolithic system (which, in this sense, may be a single craft or a constellation), but they can only be made during the initial design of the system. Thus, the key distinction between a monolithic and a fractionated system is that the latter
retains elements of design flexibility throughout the operational lifetime of the system. That flexibility allows for reconfiguration to meet new requirements, the ability to resist or respond to damage, affordable upgrades through the launch of new satellites, and other advantages of special interest to the Department of Defense (DoD) but applicable to a wide range of satellite types and applications.¹

F6 offers the post-design option of substituting a module, augmenting the system with an additional module, removing a module from the system, or porting a module from one system to another. These operations can provide the functionality of a large monolithic spacecraft, or a constellation thereof, with an architecture of microspacecraft.

**EVOLUTION TOWARDS F6**

Fundamental to development of the F6 concept was an examination of the entire spectrum of developments since the first artificial satellites.² With the earliest satellites, the active lifespan of each vehicle was on the order of months or days. Batteries and low-efficiency solar cells were the only technologies available to keep a satellite "alive." Single-string construction, with no redundancy, was common. Spacecraft could not maneuver, they could not support power-hungry payloads like imaging systems (which themselves were in a primitive state), and a satellite bus commonly housed only one payload and basic support functions.

While evolution from these beginning was mainly toward more capable monolithic spacecraft, there was an interesting early example of a fractionated approach. This was the Apollo lunar exploration vehicle. After the Saturn booster was discarded, Apollo had two major segments: the Command and Service Module (CSM) and the Lunar Module (LM). These could be, and were, separated into two units connected by radio transmissions, and then rejoined into the single "stack." The components themselves could each separate into two spacecraft (the CSM into the CM and SM, the LM into the ascent and descent stages), although these could not recombine. The functionality of all four units combined to enable

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**Figure 1. DARPA's Concept of Transition from a Monolithic Spacecraft (top) to a Fractionated Cluster. (DARPA)**

The technological advances behind F6 also add up to greater resiliency. To give one example of the concerns related to the current paradigm, when a new generation of intelligence satellites was approved by President Obama's administration in April 2009, one of the objections raised in Congress was that the individual satellites were both very costly and vulnerable: their life expectancy was diminished due to the debris clouds in low orbit.² An F6 system is robust and able to respond to the loss of nodes the way a monolithic satellite can't.

**F6 AND MICROSPACECRAFT**

While fractionated systems can exist across all sizes of satellites, it is on the microspacecraft level that the concept will be proven in space and where the greatest savings in terms of launch costs will be found.

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**Figure 2. The 1.5-kg Vanguard 1, the Second U.S. Satellite and the First with Solar Cells. (NRL)**
a single mission, a human voyage to and from the Moon. (Apollo 15 and 16 had one more component, as they ejected scientific subsatellites into lunar orbit.)

Advances in technology, including miniaturization, solar cells, thermal management, and structural materials and design, have enabled a quantum leap beyond the early generations of spacecraft. Today, a satellite's active lifespan may be measured in decades, leading to significant redundancy and reliability advances but also to increased requirements for these attributes. These requirements must be met in each individual satellite because the cost of satellites and launch systems within a constrained budget limits the effectiveness of the military's favored "spiral development" approach to modernization. Spiral development works well on aircraft, where each production batch or "spiral" is more capable than the last and the improvements can be retrofitted to older planes. With satellites, each spacecraft or small group of them is made more capable in terms of hardware as well as software, but the ability to upgrade older satellites to match is limited to software uploads.

While the capabilities of individual satellites have continued to grow impressively, there are limitations of large satellites which cannot be designed away, absent a costly on-orbit servicing infrastructure so far funded only to the stage of experiments like Orbital Express (see below). Even this approach is impractical because the large satellites to be fielded over the next decade are in production or advanced development now, and the capability to be serviced on orbit must be designed in. (This is why experiments like Orbital Express have more ready applicability in the rapid-spiral world of System F6.)

Gradually, in fits and starts (and with some reversals) over the last two decades, the beginnings of a revolution against the monolithic concept have unfolded. With the advent of micro-electronics, micro-electromechanical structures, and multi-functional structures, users including DoD agencies have been open to reexamining the large-spacecraft paradigm. That paradigm is still dominant, but experiments aimed at reducing the size and mass of spacecraft are in progress, and new ideas are nibbling at the edges of the old monolith. Adding impetus to the consideration of smaller satellites is that, simply put, gravity remains an intractable and expensive force to overcome. There have been no major strides in reducing the cost of a kilogram to orbit, and none are on the near-term horizon.

On-orbit sparing or the building and launching of satellites to update a constellation like the Air Force's MILSTAR, where individual satellites weigh 4500 kg and cost in the billion-dollar range, is prohibitively expensive and takes years. Accordingly, current military constellations must be designed to a static set of requirements, a snapshot of ever-changing needs, and can meet only those requirements for the many years they are in service.

DoD's Operationally Responsive Space (ORS) office has taken a first step toward solving this conundrum by sponsoring the TacSat series of lighter, less expensive spacecraft for some applications. Fractionation offers the possibility of going a step further, breaking spacecraft into nodes that can use still smaller launch vehicles and secondary payload opportunities, along with faster updating and a more resilient architecture to allay the always-present military concern of having critical on-orbit capabilities taken out by accident, malfunction, or enemy action. The ORS staff points out the office and the concept are not just about smaller satellites: they're about faster, more affordable, and more efficient services for the warfighter, from whatever architecture can provide that.

F6 ENABLING TECHNOLOGIES

The four key technologies identified for System F6 include Networking, Wireless Communication, Cluster Flight, and Distributed Computing.

While F6 is genuinely a new paradigm for Earth satellites, like all breakthroughs it builds on past achievements. For F6, these include satellites and ground demonstrations which have validated all these capabilities.
Technological underpinnings of the F6 system come from many sources. DoD has supported spacecraft R&D for over 50 years, and agencies including Air Force Space Command's Space and Missile Systems Center (SMC), the Air Force Research Laboratory (AFRL), the Naval Research Laboratory (NRL), and DARPA have made major contributions to the F6 technology base.

The National Aeronautics and Space Administration (NASA) has developed systems through the X2000 program to enable smaller and smarter spacecraft, as well as carrying out the broader New Millennium program and the associated Space Technology demonstration missions. Purely commercial missions, like Iridium and Orbcomm, have also developed relevant technologies and expertise. A host of contractors and subcontractors, from giants like Boeing and Lockheed Martin down through smaller firms like a.i. solutions and MicroSat Systems (now part of Sierra Nevada Corporation), have developed components, systems, and spacecraft in response to all these projects. Other technical contributions come from foreign and international programs.

**Networking**

Networking of satellites has its origin in ground-based computers, specifically with ARPANET, the product of DARPA's predecessor ARPA (the Advanced Research Projects Agency). This network went live in 1969. The idea moved into space on internal networks (that is, networks within a single spacecraft) with the Space Shuttle in 1981. The Shuttle's General Purpose Computers (GPCs) talked to each other and with 18 data buses. Networked laptop computers using Ethernet made it on board in the 1990s. The International Space Station (ISS) took this a step further with a built-in Local Area Network (LAN).5

While these examples concerned networks on a single spacecraft, the principle remains the same for a spacecraft group, only using radio frequency (RF) or laser links rather than wires.

Another step forward in networking is the use of Internet protocols (IP) in spacecraft. IP use enables the plug-and-play addition of new modules to a spacecraft, or new spacecraft to a network.

Experimentation along these lines was done beginning in 1997 by NASA's Operating Missions as Nodes on the Internet (OMNI) project. Surrey's UoSAT-12, launched in 1999, demonstrated the use of IP on a relatively small (325 kg) satellite. The 120-kg UK-DMC satellite, part of the Disaster Monitoring Constellation of small satellites, carried an internet router built by Cisco Systems when it launched in 2003. Such spacecraft have resolved, at least in Low Earth Orbit (LEO), the time lag and other problems involved in tying satellites to Earth-based networks and each other via IP. The enabling of IP for space systems, as demonstrated on UK-DMC, was named by *TIME* magazine as one of the ten best inventions of 2008.6

In April 2007, Intelsat won a contract under DoD's Joint Capability Technology Demonstration (JCTD) program for an effort titled Internet Routing In Space (IRIS). This project will validate the carrying of military communications through an orbiting Internet router via a payload carried on satellite IS-14, due to launch in August 2009. Intelsat Vice President Don Brown explains, "The IRIS architecture allows direct IP routing over satellite, eliminating the need for routing via a ground-based teleport, thereby dramatically increasing the efficiency and flexibility of the satellite communications link."7 This experiment, which will feature automatic switching of data traffic through the Cisco router on board the satellite, is one step short of System F6, which will route both data and command traffic the same way.

As a step toward smarter space networks, NASA's ANTS (Autonomous Nano-Technology Swarm) program for planetary surface rovers has patented a conceptual model called a neural basis function, which "combines the capability of autonomous and collective interaction, or bi-level intelligence, for each component, subsystem, or agent."8 Given that ANTS is expected to function on celestial bodies where time lags will make real-time control from Earth impossible, NASA engineers at Langley and Goddard Space Flight Centers have been working to make the nodes rely on collective intelligence, a concept which can further increase the networked capabilities of System F6.

**Wireless Communication**

Science writer Willy Ley once observed that the invention of the transistor radio made the artificial satellite practical. While there have been non-communicating satellites, their applications were very limited. Wireless communication in spacecraft has gotten increasingly sophisticated, to the point where the kind of seamless networking needed and used in System F6 cluster is now practical.

Wireless communication from satellites to Earth began with the very first spacecraft, Sputnik and
Explorer, and today is used to shift huge amounts of data between continents. America's first satellite, the 14-kg Explorer 1, was considered a superb example of small, lightweight communications technology in 1958. It carried a receiver, a 10-milliwatt (mw) transmitter weighing 907 grams (of which 680 grams was batteries), and a 60mw transmitter. These transmitters were independent systems, using a total of eight channels simultaneously.9

The first ground-to-space to ground communications satellite, a one-time experiment using a single radio channel, was ARPA's Project Score in 1958. It was a precursor to the communications networks that, just a few years later, would circle the Earth and connect the continents.

Wireless communication between spacecraft was demonstrated by manned spacecraft before unmanned ones: it began with the shortwave chat between cosmonauts in Vostoks 3 and 4, which passed several kilometers apart in 1962.

The next step was a data-carrying crosslink between satellites. This was demonstrated at a low bandwidth (10-100 kbps) by the Lincoln Experimental Satellites 8 and 9, launched in 1976.10 The idea went operational in the 1980s with NASA's Tracking and Data Relay Satellite System (TDRSS), which allowed spacecraft in any orbit to exchange communications with other spacecraft or the Earth. TDRSS was strictly a repeater, performing no processing or other alteration of the signals involved. The U.S. Air Force's MILSTAR system used a V-band system and did process crosslinked data. The high-capacity 60-GHz MILSTAR crosslink payload weighs 360kg.11

The largest constellation to crosslink its satellites by RF transmissions was the $7 billion Iridium global commercial mobile communications system, launched in 1997. Iridium's innovative system of 66 active 690-kg satellites proved a solid technical success (although a commercial failure thanks to advances in cellular communication on Earth). Each Iridium satellite had dynamic control of routing and channel selection and could link to four other spacecraft: two neighbors ahead of and behind it in the same orbital plane, and two satellites in neighboring planes.12

The field of RF communications continues to evolve, along with its space-based aspects. New RF systems use ever-advancing software, techniques, and hardware to shrink weight and size while increasing efficiency. Gaussian Minimum Shift Keying (GMSK), a form of modulation used widely for cellular telephone networks because of its efficient use of power and bandwidth, got its first use in space in 2009, when the European Space Agency (ESA)'s Herschel Space Observatory established a 1.5Mbps link to Earth at a distance of 280,000 kilometers (km).13

As a complement or alternative to RF systems, laser communication between spacecraft is rapidly maturing. Lasers, while requiring a line of sight, offer high data rates with a low probability of intercept. An early example was ESA's Artemis satellite. In 2001, imaging data from the CNES SPOT-4 Earth observation satellite was sent by laser to the geostationary Artemis and from there by RF to a ground station.14 In an example of international cooperation from 2008, the U.S. Missile Defense Agency (MDA)'s NFIRE satellite used a German-built Laser Communication Terminal to crosslink with the German Terra SAR-X satellite at a high data rate of 5.6 Gbps at a range of 5,000 km.15

Cluster flight

Cluster flight is the next step in an evolution that led from constellations to formation flying and then to System F6.

The idea of launching a group of satellites to form a constellation goes back a long ways. The 45-kg satellites of the Initial Defense Satellite Communications Program (IDSCP), later renamed the Defense Satellite Communications System I, provide an early instance. Twenty-six satellites of the basic design were launched in groups up to eight per booster from 1966-68.

The commercial 34-satellite Orbcomm constellation, using 42-kg microsatellites and launched in 1997, was a more modern demonstration of this approach. The Orbcomms, launched in groups of eight for each of three orbital planes in the main constellation, were not crosslinked.

The above-mentioned Iridium project showed the feasibility of manufacturing large numbers of identical satellites. (The largest satellites, usually launched years apart, are essentially handbuilt. They are always modified from one vehicle to the next as lessons are learned or new requirements come in. No two MILSTAR satellites, for example, are identical.) IDSCP had used batch production, as did Orbcomm, but the sophistication of the Iridium satellites showed that even complex spacecraft can be built this way.
Cluster flight requires that each spacecraft know the position of itself and the others in the cluster. This is a capability initially demonstrated in automated docking arrangements. A system of radar and radio telemetry called IGLA ("Needle") was used on Soyuz capsules beginning in 1967 to guide an actively maneuvering craft docking with a passive one, with the latter carrying a transponder to exchange radio signals with the active craft, providing range, range rate, and attitude data.

Cluster flying has benefited greatly from the Air Force's Global Positioning System (GPS). GPS has made it unnecessary for spacecraft to use active sensors, like radar, to find the position of other satellites in its cluster. Satellites can now self-report their positions to all other members of the cluster.

GPS combined with active sensing has been used to support increasingly sophisticated rendezvous and docking missions. Two successful single-satellite missions were the Air Force's XSS-10 and XSS-11 microsatellites. The XSS-10, a 28-kg spacecraft launched as a secondary payload with a GPS mission in 2003, demonstrated autonomous navigation, proximity operations, and inspection of a Resident Space Object (RSO) (in this case, a spent booster stage). The larger (138 kg) XSS-11, launched in 2005, performed similar operations, but had a longer lifespan and, according to AFRL, had as part of its rationale, "increasing the level of autonomy, maneuverability, and complexity of mission operations that can be planned and safely executed."

The most sophisticated such mission to date was DARPA's 2007 Orbital Express. Orbital Express demonstrated repeated rendezvous, soft docking, fluid transfer, and exchange of components to validate the feasibility of robotic, autonomous on-orbit refueling and reconfiguration.

Whereas NASA's less ambitious Demonstration of Autonomous Rendezvous Technology (DART) in 2005 had succeeded in rendezvousing with a target but suffered navigation and sensor problems leading to a collision, Orbital Express succeeded in all its objectives. In an important demonstration of autonomy, the servicing spacecraft, ASTRO, was closing on the target spacecraft, NextSat, when a navigational computer problem emerged. The ASTRO computer automatically stepped in and backed off 120 meters (m) from NextSat to preclude collision while staying close.
According to MIT's David Miller, the next generation of SPHERES is intended to operate in space, with the craft positioning themselves to an accuracy of one centimeter (cm) while performing tasks as EVA assistants, resupply, or repair craft. Advanced versions could also, via radio links, form linked constellations. One idea of the spacecraft's developers is to use more advanced SPHERES to form telescope apertures much larger than the Hubble Space Telescope.  

ESA's Cluster mission, launched in 2000, marked the first time four spacecraft were put in formation. By making simultaneous measurements and sometimes flying in a lopsided pyramid or tetrahedron formation, these large (1200 kg) satellites have made the first detailed, three-dimensional study of near-Earth space. It was, for example, Cluster data that first showed large quantities of hydrogen escaping from the Earth's atmosphere. Cluster data has also been combined with the two satellites of China's Double Star mission for increased scientific capability, although none of the satellites involved communicate directly with one another. The above-mentioned radar satellite TerraSAR-X will soon be joined by a formation-flying partner of its own, TanDEM-X, with the two together providing extremely precise digital elevation measurements of Earth.

NASA's GRACE mission, launched in 2003, includes a K-band Ranging System which measures the distance between two spacecraft in the same orbit (nominally 220 km apart) within 10 micrometers (µm) to study perturbations in Earth's gravity.

DARPA was involved in an earlier effort that overlapped with some F6 technologies, most notably formation flying of clustered satellites. This was TechSat-21 (Technology Satellite of the 21st Century), an Air Force Research Laboratory (AFRL) idea to demonstrate how multiple satellites could form a "virtual aperture" for missions like radar imaging that might be most effective if the size of the "antenna" could be adjusted on command.

One proposal was for a TechSat-21 cluster to include eight microspacecraft separated by a distance of 250 m or less. While the technically ambitious program was eventually canceled, some relevant work was done in areas including an automated planning assistance system for mission planning (SpaceCAPS) and work at NASA's Jet Propulsion Laboratory (JPL) on the Autonomous Sciencecraft Constellation demonstration meant for the first TechSat-21 mission. NASA did fly the Autonomous Sciencecraft Experiment on a single spacecraft, Earth Observation 1, in which the spacecraft spotted an infrared anomaly and on its own focused other instruments on this target (a volcanic eruption).

The EO-1 mission also contributed to the technology of formation flying. NASA put EO-1 into formation with another spacecraft, Landsat-7. Using an algorithm developed at NASA's Goddard Space Flight Center and a program called FreeFlyer® from a. i. solutions, EO-1 flies 60 seconds (450 km) behind Landsat-7, a separation it maintains within two seconds (15 km). The spacecraft adjust autonomously to maintain the distance.

A fractionated system may or may not use a tight formation, but it will require some capability to move both individual nodes and the system as a whole. System F6 modules could carry individual propulsion capabilities or make use of a "tug" module to move them, a concept proven first by the Gemini-Agena flights of the 1960s.

Another approach, one demonstrated in the laboratory by MIT engineers, is called electromagnetic formation flight (EMFF). With EMFF, magnetic fields are created around modules using specifically designed wire bundles. By controlling the direction and strength of the magnetic field, modules can be attracted, repelled, and/or rotated relative to one another. Using either the tug or EMFF approach, it may be possible for a centralized propulsion module to move an entire cluster "glued" together by docking mechanisms or magnetic forces.

Improvements in tightly controlled, autonomous formation flying are of great interest to NASA, given its uses in such scientific functions as the search for Earthlike planets. A NASA-led team has worked out some of the technical issues. The agency's now-canceled Terrestrial Planet Finder Interferometer (TPF-I) needed very precise interval-keeping to provide interferometric study of distant solar systems using a technique in which one collector "nulls out" the light of the target star while others collect images of planets. Such an interferometer array must be rotated around the line of sight to a star to search the whole region around the star. In 2007, the team demonstrated this precision on Earth using the Formation Control Testbed (FCT), on which two robots demonstrated formation flying with autonomous maneuvering and operation while controlling their relative position within 5 cm. The FCT is being used now in support of the F6 program.
**Distributed Computing**

Distributed computing is a concept developed to a high degree in terrestrial networks, in which a program can be split up over interconnected computers to provide increased computing power for a particular function or task. A distributed system can be designed to be scalable and to work without a damaged node, both important considerations in the F6 architecture. There are several different computing architectures, including peer-to-peer and three-tier architecture, demonstrated in Earth-based distributed computing systems.

The first step toward such sophisticated computing was to add increasingly sophisticated electronics to the simple radio systems and sensors of the initial satellites. For example, the first electronic memory (as opposed to tape) on a satellite was in the 112-kg navigation satellite Transit 3-B in 1961. Power and weight requirements on the first weather satellites, the 119-kg TIROS series first launched in 1960, were reduced by enabling cameras and recorders to be programmed remotely from Earth stations. Performing computations on the ground was a common approach, used as well on the early piloted missions of America's Mercury and Russia's Vostok capsules.

The next step was to put some computational power on the spacecraft themselves. NASA credits the Gemini Digital Computer as the first computer on orbit, a status achieved in 1964. This manually operated machine, based on a magnetic ring core memory holding 159,744 bits, weighed 27 kg and performed the calculations for several flight control situations. On-board processors rapidly became exponentially more powerful and took on more functions, and are indispensable in the age of giant satellites.

An example of current technology, used on many spacecraft including NASA's Mars rovers and the Air Force's Advanced EHF communications satellites, is BAE Systems' radiation-hardened RAD6000® 32-bit microprocessor, a CPU packing 1.1 million transistors (the newest RAD750®, used on the XSS-11 satellite, has ten times that) and packaged with 128MB of random access memory (RAM).

Advances in computing concepts such as expert systems, artificial intelligence and neural networks have led to "smart" spacecraft capable of managing themselves, even in difficult situations. In concert with "smart" ground systems, operator intervention is reduced to non-routine or anomalous activities.

Distributed computing on board a single spacecraft has been well demonstrated. NASA's Voyager probes, launched in 1977, used three computers in what the agency described as a distributed system. On the Galileo probe, launched toward Jupiter in 1989, 19 networked microprocessors handled computing for specific instruments and the integration and processing of the resulting data. This provided reliability and redundancy as well as eliminating the tiny but crucial delay that would have been caused by sending traffic from a monolithic computer between the spun and despun sections of the craft. The system included microprocessors controlling the six instruments on the atmospheric entry probe, which separated five months before it entered the Jovian atmosphere and relayed data to Earth through the main spacecraft.

**Figure 6. Galileo, Showing the Spun and Despun Sections and the Atmospheric Probe (NASA)**

One of the leading companies in smallsat technology, SSTL, describes the connections between satellites in a modern constellation as allowing "a loosely coupled form of distributed computing." One of SSTL's development efforts is the creation of middleware which sits "on top of" the existing real-time operating system (RTOS) and allows "tighter coupling between the nodes in the distributed system." SSTL's development efforts is the creation of middleware which sits "on top of" the existing real-time operating system (RTOS) and allows "tighter coupling between the nodes in the distributed system." SSTL's development efforts is the creation of middleware which sits "on top of" the existing real-time operating system (RTOS) and allows "tighter coupling between the nodes in the distributed system." SSTL's development efforts is the creation of middleware which sits "on top of" the existing real-time operating system (RTOS) and allows "tighter coupling between the nodes in the distributed system." SSTL's development efforts is the creation of middleware which sits "on top of" the existing real-time operating system (RTOS) and allows "tighter coupling between the nodes in the distributed system." SSTL's development efforts is the creation of middleware which sits "on top of" the existing real-time operating system (RTOS) and allows "tighter coupling between the nodes in the distributed system." SSTL's development efforts is the creation of middleware which sits "on top of" the existing real-time operating system (RTOS) and allows "tighter coupling between the nodes in the distributed system." SSTL's development efforts is the creation of middleware which sits "on top of" the existing real-time operating system (RTOS) and allows "tighter coupling between the nodes in the distributed system." SSTL's development efforts is the creation of middleware which sits "on top of" the existing real-time operating system (RTOS) and allows "tighter coupling between the nodes in the distributed system." SSTL's development efforts is the creation of middleware which sits "on top of" the existing real-time operating system (RTOS) and allows "tighter coupling between the nodes in the distributed system." SSTL's development efforts is the creation of middleware which sits "on top of" the existing real-time operating system (RTOS) and allows "tighter coupling between the nodes in the distributed system." SSTL's development efforts is the creation of middleware which sits "on top of" the existing real-time operating system (RTOS) and allows "tighter coupling between the nodes in the distributed system." SSTL's development efforts is the creation of middleware which sits "on top of" the existing real-time operating system (RTOS) and allows "tighter coupling between the nodes in the distributed system."
PUTTING IT ALL TOGETHER

DARPA’s microspacecraft demo may not be the optimal result of these technologies. Issues such as LEO vs. GEO systems, fully heterogeneous vs. mixed architectures, and single payloads vs. multiple payloads need to be worked out, but the information from the first on-orbit demonstration will be invaluable in charting the future course of fractionation.

It’s not possible to say with certainty what satellite applications will benefit most from using the System F6 concept to complement existing approaches. Applications which have been demonstrated as practical using conventional constellations of small-to-medium spacecraft, such as communications (Orbcomm) and medium-resolution imaging (DMC), are likely near-term examples of interest. TechSat-21’s signature application, radar imaging using a virtual aperture, is another possibility. Any scientific or military application requiring simultaneous data gathering from multiple points, such as electronic intelligence (ELINT), can potentially be enhanced using fractionation.

The fractionated approach does have limitations. Compared to conventional satellites with huge capacities, a fractionated architecture incurs some penalty for duplicating overhead functions on each spacecraft. Some applications, such as high-resolution imagery, may be better done by conventional approaches for many years to come.

DARPA engineers believe, however, that the penalties will be more than offset by the opportunity to build space architectures with greater responsiveness and resiliency. If the System F6 demonstration is successful, future constellations may well use smaller and smaller spacecraft, all the way down to "pixie dust" nanosatellites of computer-chip size. There is no reason such a fractionated architecture could not be global in its reach, effectively encasing the Earth in a scaffolding of flexible satellite capabilities.

CONCLUSION

Bringing together the heritage of predecessor systems and concepts into the F6 paradigm offers many advantages compared to current systems. System F6 is a logical next step, well supported by technology proven over the first half-century of space system development. The F6 demonstration mission will culminate 52 years of space hardware experience in a way that will give us important new capabilities with improvements in cost and value as well as flexibility and the other attributes discussed earlier. The F6 experience may, and hopefully will, point us to the dominant paradigm of the next half-century of the Space Age.

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3 Shah and Brown, Ibid.
20 "SPHERES," http://ssl.mit.edu/spheres/