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# System F6: Progress to Date


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## ABSTRACT

The System F6 program has made progress over the past year, most notably with the F6 Developer's Kit (FDK). The FDK will provide open source and freely exportable standards and software from the physical wireless link layer through to the network protocol stack, including real-time resource-sharing middleware and a cluster flight application. The program is on track to complete integration, verification and validation of the FDK and begin development of the F6 Technology Package (F6TP). The F6TP will instantiate the FDK in modular, reliable, and affordable flight hardware platforms that can be readily integrated onto a wide variety of spacecraft. This paper summarizes the program's technical progress to date and previews upcoming activities including development and integration of spacecraft modules, shared resource and mission payloads, leading all the way to scheduled launch and on-orbit demonstrations in 2015.


## BACKGROUND

The goal of DARPA's System F6 program is to develop and demonstrate the enabling technologies for fractionated spacecraft architectures wherein the functionality provided by a single, large, "monolithic" satellite is delivered by a cluster of wirelessly-interconnected modules sharing a variety of software and hardware resources over a network. Such an architecture can significantly enhance the adaptability and survivability of space capabilities while shortening development timelines for complex space systems and reducing the barrier-to-entry for participation in the space industry. The benefits of fractionation are further detailed in the papers referenced[1,2,3].

## PROGRAM STRUCTURE

DARPA's Tactical Technology Office initiated the System F6 program in October of 2010 with the goal of developing three main products:

1. The F6 Developer's Kit (FDK) – the set of standards and software that enable fractionation, are released under an open-source license and are exportable without ITAR restrictions;
2. The F6 Technology Package (F6TP) – hardware platforms that instantiate the FDK standards, as well as the software enabling any spacecraft to participate in a fractionated cluster;
3. The F6 On-Orbit Demonstration Testbed – spacecraft buses, shared payload devices, and associated components and services to demonstrate the System F6 concepts on-orbit in 2015.

The structure of the program is a consequence of a novel acquisition strategy. Instead of a single large procurement contract, the program is disaggregated across multiple program tracks. These tracks and their relationships are shown in the figure below.

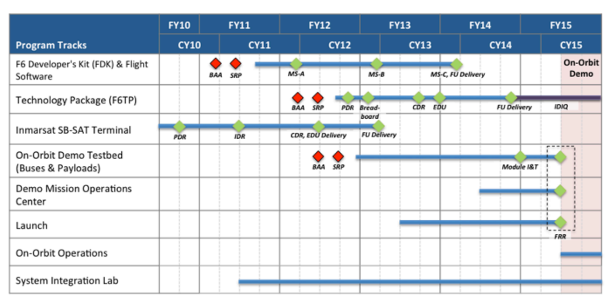


**Figure 1: System F6 Program Tracks**

This disaggregated acquisition strategy enables "best-in-class" performers from small research organizations to large prime contractors to propose directly to

DARPA. As a result, the program benefits from a larger proposer and performer base. This acquisition strategy also enables the program to focus on development of the more complex standards and software before soliciting and developing the hardware platforms and spacecraft systems needed for the on-orbit demonstration. By sequencing the order of development tracks, the program further ensures standards and software are developed with some inherent flexibility, as these elements must be designed and developed without a specific hardware platform or on-orbit mission as an immediate target. Fractionation may be applicable to a wide range of potential missions and cluster configurations and as such, the products developed in the program must be modular and adaptable to future stakeholder missions that are not necessarily represented by the on-orbit demonstration mission.

### *F6 Developer's Kit (FDK)*

System F6 is predicated on the development of open interface standards – from the physical wireless link layer, through the network protocol stack, and including the real-time resource sharing middleware and a cluster flight application – that can enable the emergence of a space "global commons" to enhance the mutual security posture of all participants through interdependence. A key program goal is the industry-wide promulgation of these open interface standards for the sustainment and development of future fractionated systems.

The FDK will encompass a wide-range of resources that includes the interface standards, protocols, software, behaviors, and reference implementations necessary for any party, without a contractual relationship with or assistance from any System F6 performer, to develop a clean-sheet module design to fully participate in a fractionated cluster. The FDK is modeled on a typical Software Development Kit (SDK), which nominally provides the resources necessary for a large number of developers to take part in contributing to the cyber-physical ecosystem of one or more computing platforms.

The FDK Broad Agency Announcement[4] and subsequent contract awards separated the development activities into four technical areas. Technical areas 2, 3, and 4 are organized largely around the Open Systems Interconnection (OSI) model; with technical area 2 developing the wireless intermodule communications (WIC) at Layers 1 and 2; technical area 3 developing the information architecture platform (IAP) that encompasses the real-time middleware, networking, and multi-level security architecture (Layers 3-7); and technical area 4 developing a cluster flight application (CF App) that executes on top of the information architecture platform (Layer 7). Technical area 1 is a separate effort focused on the development of a value-centric architecture and design (VCAD) methodology and user-friendly toolset that will enable decision makers to make appropriate architectural and systems engineering design decisions incorporating new value metrics such as adaptability and survivability into the tradespace of satellite system alternatives.

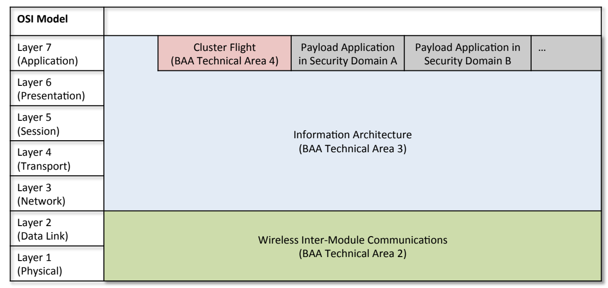


**Figure 2: FDK on OSI Model**

The FDK development effort is structured with a 6-month base period and two consecutive 1-year option periods. DARPA awarded twenty-one FDK performer contracts in May of 2011 to pursue exploration and development activities in the initial 6-month base period. The program held a series of Principal Investigator (PI) meetings during which all performers participated in open and collaborative sessions structured around a series of use-cases. The following four functional capabilities, essential to demonstrating the fractionation concept, drove systems design:

1. Semi-autonomous long-duration maintenance of a cluster and cluster network, and the addition and removal of spacecraft modules to/from the cluster and cluster network.
2. Secure resource sharing across the cluster network with real time guarantees and among payloads or users in multiple security domains.
3. Autonomous cluster reconfiguration to retain safety- and mission- critical functionality in the face of network degradation or component failures.
4. Defensive cluster scatter and re-gather maneuver to rapidly evade a debris-like threat.

Performers analyzed and discussed their solutions vis-à-vis each use-case for various cluster configurations. In order to ensure the broad applicability of the developed solutions to a range of potential missions and stakeholders, performers analyzed their designs under a number of cluster configurations and parameters, including the number of modules (4 to 20), orbital altitudes (300 km to 1500 km) and average inter-module distances (100 m to 100 km). Performers also examined varying network traffic loading, interference environments, and fault conditions to analyze the designs under stressing conditions. Similarly, they analyzed use-cases for each cluster event, including module ingress, module egress, station keeping, cluster reconfiguration and scatter/re-gather.

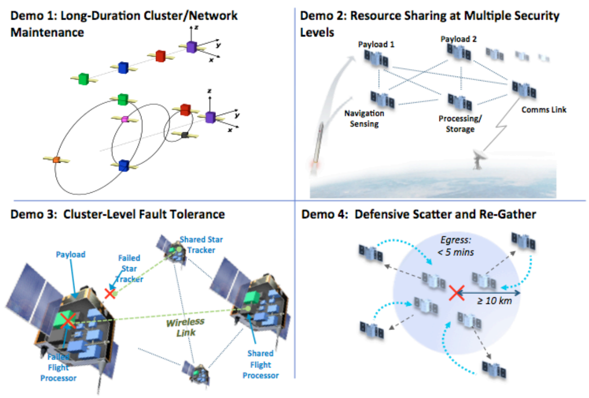


**Figure 3: Four Key Functional Capabilities**

The results of the PI meetings during the base period and subsequent draft FDK inputs enabled DARPA to synthesize an architecture that best met the vision of the program while also demonstrating a clear path towards successful development and verification and validation for flight demonstration. In total, DARPA selected six performers to continue with their 1-year option period starting in November of last year. Their solutions are summarized here.

*WIC:* Southwest Research Institute and Aeronix are each responsible for developing a set of wireless inter-module standards and protocols and an accompanying set of flight-qualified transceivers for the on-orbit demonstration mission. Southwest Research Institute's solution will utilize a wideband direct sequence spread spectrum (DSSS) waveform operating in K-Band at Layer 1 and a distributed time-division multiple access (TDMA) protocol at Layer 2. Two sets of radome antennas mounted on opposite sides of the spacecraft will enable omni-directional coverage and full mesh connectivity with all modules in the cluster. Aeronix's solution will include two separate transceivers: 1) a low-data rate solution operating in S-Band at Layer 1 using a pair of 5-patch antenna enclosures mounted on opposite sides of a spacecraft, and 2) a high-data rate solution operating in V-Band using highly directional optically steered antennas. Both low and high data rate solutions will utilize the 802.11 carrier sense multiple access (CSMA) protocol at Layer 2.

*IAP:* Vanderbilt University is charged with developing the information architecture platform. Its solution will utilize a model-driven application development approach to capture and formally verify mission user specifications. Vanderbilt is developing the F6OS – a new operating system that will provide secure multi-level security (MLS) features and is adaptable to changing resource constraints as cluster configurations change over time. In F6OS, all mission user applications and privileged system actors will communicate through a secure transport abstraction. All messages will be labeled and only forwarded to the network if multi-level security rules are satisfied. Vanderbilt is adapting existing CORBA and OpenDDS middleware services to enable standard communication patterns across the cluster network. Under F6OS, all system resources including computation, memory, and network access will be partitioned among mission users. The operating system will strictly enforce temporal and physical partitioning at run-time. This strategy has the benefit of enabling resource management, fault containment, and security containment.

*CF App:* The ultimate goal of the FDK is to create and foster a vibrant application development community that continuously contributes new cyber-physical applications and improvements. The first instantiation of an FDK application will be the cluster flight application, developed by Emergent Space Technologies. Emergent is developing a service-oriented navigation and cluster control solution that encapsulates generalized, robust algorithms for maneuver planning, fault detection, collision probability, and relative navigation. These services will be distributed over the cluster network so that capabilities such as station-keeping, scatter and re-gather maneuvering, and cluster ingress and egress can be performed reliably and efficiently with fault tolerance and failover features built in. The software architecture will be modular, enabling different control algorithms to be developed, tested, and executed on the cluster platform. Similarly, the navigation filter software will take inputs from multiple sources of varying accuracies such as ranging information from the wireless inter-module transceivers, ground-based location fixes, and onboard GPS pseudo range measurements. This will be one of the first true "apps" developed for spacecraft (NASA Ames is also creating an app-centric architecture on other small satellites). This is somewhat profound; the utility of this approach is manifest in the performer's ability to write and test the application with no current knowledge of the specific spacecraft bus(es) on which the application will run.

*VCAD:* Lastly, the Jet Propulsion Laboratory (JPL) and Stevens Institute of Technology are charged with developing VCAD tools and decision support techniques. The JPL-developed toolset will provide stakeholders with the capability to autonomously develop SysML-based spacecraft models that enable a variety of space system designs to be evaluated for overall cost and value over their lifecycle. This ModelCenter-based tool will include the introduction of a variety of dynamic external stimuli that provide measures of cost, risk and reward when introducing adaptability into system design. The toolset will also enable users to traverse and inspect the tradespace through various visualization, exploration, and optimization techniques. Stevens Institute of Technology is developing the theoretical underpinnings of measures of resiliency and adaptability of space systems in the context of environmental uncertainty and design complexity. These findings will be abstracted into decision support tools to provide design "rules of thumb" for fractionated and other adaptable systems.

### *F6TP*

The FDK standards and software will be instantiated in a size, weight, and power optimized computing platform, nominally referred to as the F6 Technology Package (F6TP). The F6TP will be essentially a network-computing device that enables a standard spacecraft to become part of a fractionated cluster. The F6TP will provide all the interfaces necessary to communicate with other modules in the cluster and enable F6 payload devices to be shared across the cluster network.

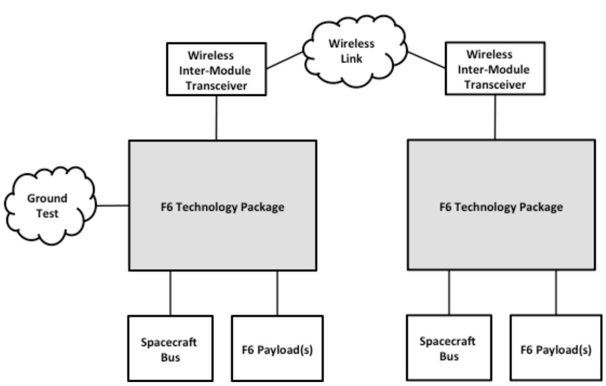


**Figure 4: F6TP Interfaces**

The System F6 program envisions a market of low-cost, commercially available F6TPs that can readily be purchased and installed on any spacecraft, thus enabling the advantages of fractionation at marginal cost and complexity. To facilitate that goal, subsequent to the program an indefinite delivery indefinite quantity (IDIQ) contract will be established to provide any Government stakeholder the ability to quickly procure F6TPs for integration onto their spacecraft. The F6TP broad agency announcement[5] was released in December last year and multiple selectees are currently in contract negotiations to begin work. The duration of the development effort is scheduled for 27 months.

### *On-Orbit Demonstration Testbed*

The program has initiated the next set of procurement activities related to the spacecraft bus and shared payload devices for the on-orbit demonstration mission. A broad agency announcement[6] was recently released, which calls for the development of four cost-effective, ESPA-compatible spacecraft buses and associated integration and operational support activities. The broad agency announcement is divided into four technical areas corresponding to the four shared payload devices to be hosted and demonstrated in the demonstration cluster: 1) host a Government-furnished Inmarsat SB-SAT terminal (to be described later in this paper), 2) host and provide a high-speed space-to-ground transmitter, 3) host and provide a high-performance computing element, and 4) host a Government-furnished mission payload. The notional on-orbit demo cluster is shown below.

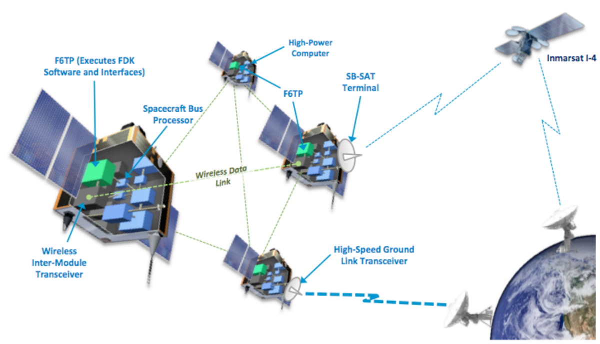


**Figure 5: Notional On-Orbit Demonstration Cluster**

The on-orbit demonstration will take place in LEO over a 6-month duration. The exact orbit has not been determined, but the program is targeting a launch date in mid 2015 pending final launch manifest. The on-orbit demonstration will prove out the technologies and concepts developed under the System F6 program but will otherwise remain mission agnostic.

### *Inmarsat SB-SAT*

DARPA contracted Inmarsat Navigation Ventures Ltd. for the development of the SB-SAT terminal in August of 2010. The SB-SAT terminal will provide near 24/7 connectivity (492 kbps full duplex) anywhere in LEO through the Inmarsat I-4 GEO constellation and associated ground network. Broad Reach Engineering and ComDev Europe provide the majority of the technical development effort under subcontract to Inmarsat.

The SB-SAT terminal will enable ground operators and application users to communicate with the System F6 on-orbit demonstration cluster for near continuous commanding and telemetry monitoring. Similar to other F6 shared resources, the space-to-ground communication link provided by the SB-SAT terminal will be shared between multiple applications, each operating at a different security domain. The Inmarsat ground network provides a gateway to the Internet that will enable instantaneous access to the SB-SAT terminal in orbit from any network-connected computing node on the ground. The SB-SAT terminal recently completed a critical design review and is currently on track for flight unit delivery in 2013.

### *Systems Integration Lab*

The System F6 program recently initiated development of a Systems Integration Lab at the NASA Ames Research Center for the purpose of providing independent verification and validation and hardware integration. During the initial phase, the focus of the lab is centered on maintaining a repository for FDK software and other performer-developed deliverables. In the future, the Systems Integration Lab will provide independent assessment and testing of all performer-developed software products. Since all FDK materials are being developed with an open-source license, the FDK repository can be transitioned to an open-source community in the future.

As hardware development matures, the Systems Integration Lab will take on additional responsibilities for hardware integration and hardware-in-the-loop verification and validation activities. Integration of breadboards and engineering development units (EDU) in the lab will enable the program to demonstrate system-level interfaces between all F6 devices and components. The lab will also perform extended simulations of the system in order to characterize system-level performance metrics for varying orbital configurations. As the program transitions to flight and on-orbit operations, the hardware-in-the-loop capability will also enable ground controllers to simulate on-orbit events and diagnose anomalies.

### *Mission Operations Center*

Once in orbit, it is envisioned that ground operators will interface with the demonstration cluster through the F6 mission operations center (MOC). The exact location of the F6 MOC is to be determined, but it is envisioned to require minimal infrastructure or personnel resources. As the program extends the concept of the Internet Protocol (IP) architecture across the space-to-space and space-to-ground network, it envisions a time when all mission data, as well as command and data handling messages, will be delivered over a secure virtual private network to any connected node on the Internet. This architecture takes advantage of ubiquitous and robust terrestrial networks, maximizes the flexibility for infrastructure deployment and re-deployment, and minimizes overall system complexity. Development of the MOC will begin once all principal space segment development efforts have matured past the initial design phases.

## INTEGRATION PLAN

The integration plan for the System F6 program is influenced by several factors: 1) the software-focused complexity of the development effort, 2) the disaggregated program structure resulting from no single performer being responsible for overall integration, 3) a varied and non-traditional set of performers, and 4) as with most DARPA programs, a compressed development timeline. Due to these constraints, the program's integration plan utilizes a non-traditional approach largely informed by the agile software development process successfully proven across a broad range of complex software development efforts in industry.

### *Integrated Demonstrations*

The System F6 program drives development efforts using two-month build-demo cycles. The end of each cycle coincides with a PI meeting focused on a set of related features (a theme) and nominally including an associated set of functional capabilities, tests and documentation, as well as the software and hardware deliverables needed to demonstrate these features. The goal of the overall effort is to arrive at an integrated demonstration exercising the four primary functional capabilities of the system from which all system and subsystem objectives and performer requirements are derived. As the fidelity of these features and their representative hardware platforms and simulated environments improve, demonstrations of these functional capabilities are repeated to gain confidence for flight.

DARPA defines the set of themes in yearly increments and refines the expectations for each interval every two months in consultation with performer teams. This process enables the program to react and adapt to challenges and opportunities as the development effort progresses.

A key output of this strategy is an evolving simulation and emulation capability, from prototype software executing on low-fidelity emulation environments to flight-qualified software executing on flight-equivalent engineering development units (EDU) and flight hardware. This integrated demonstration provides evidence of the successful and continuous integration effort between performer teams and their respective solutions. In addition, it enables the testing and analysis of the integrated solution in representative orbital configurations and scenarios. More importantly, it provides a common deliverable that ties all teams to a shared responsibility and accountability for mission success. As the integration effort progresses, the program gains significant confidence at each step towards eventual flight qualification. The development and evolution of the integrated demonstration enables the program to measure progress and track risks in a substantiated manner.

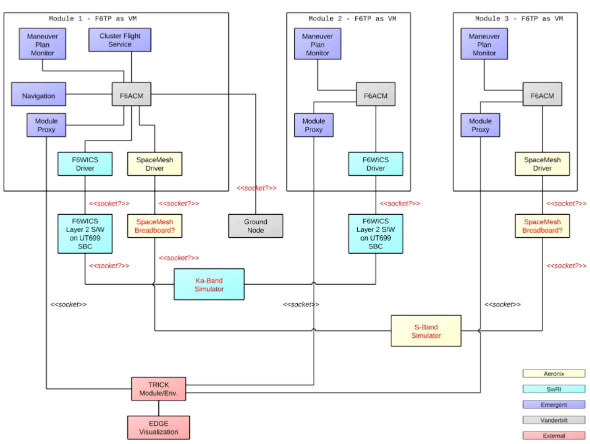


**Figure 6: Integrated Demonstration**

In addition to the integrated demonstration, the F6 community conducts a thorough review of the progress made towards the refinement of the FDK (to include documentation, analyses, source code, and other artifacts) at each PI meeting. Design reviews are held for capabilities and architectural features that do not lend themselves readily to a functional demonstration. These include security features, fault management, networking, and quality of service architecture. Performer-developed solutions rapidly incorporate the recommendations emerging from these reviews.

### *Objective Evaluations*

While sufficient confidence can be gained through integrated demonstrations of functional capabilities, the program also intends to perform a series of activities needed to ensure that the long-term objective system goals are met. These goals include ensuring the soundness of FDK products, the ability to adapt the FDK for a wide range of potential missions and stakeholder requirements, and the promotion of the FDK as a space "global commons." The program intends to carry out a thorough performance evaluation of the developed FDK products spanning a range of potential cluster configurations, orbits, and environments. The program also plans to conduct a thorough review and assessment of the FDK as a suitable platform for potential stakeholders. A more immediate test of the FDK's suitability will be exercised when a mission payload is integrated onto the on-orbit testbed. Finally, a security assessment of the FDK and overall security architecture will be performed to facilitate eventual certification by stakeholders' security organizations and the National Security Agency (NSA).

## SUMMARY

The System F6 program in on-track to complete development of the FDK by the end of 2013. Subsequent development of the F6TP and on-orbit testbed will commence in the upcoming months. We are currently implementing a series of integration activities to enable the program to make continuous and rapid progress towards demonstrating the integrated capability from multiple performer-developed products. We plan to build on these integrated demonstrations to gain sufficient confidence necessary for flight. Future activities include development of a hardware-in-the-loop capability, complete integration and verification of the on-orbit testbed, development of an F6 mission operations center, launch, and on-orbit demonstrations in 2015.

### *Disclaimer*

The views expressed are those of the author and do not reflect the official policy or position of the Department of Defense or the U.S. Government.

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