

A Constellation of Three Micro Satellites Uses UV and Visible Sensors to Demonstrate Target Acquisition and Tracking

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ABSTRACT

The Distributed Sensing Experiment (DSE) program demonstrates the technology of using micro satellites to perform target acquisition, tracking, and three-dimensional track development using a visible camera payload. DSE is a concept demonstration to show how micro satellites, working singly and as a group, can perform a large part of the missile defense function at a much lower cost than traditional systems. A key design parameter of the program is incorporating commercial-off-the-shelf (COTS) hardware and software to reduce risk and cost, while maintaining performance. Having completed a successful Critical Design Review, the program is currently in fabrication, integration, and test phase. The constellation of satellites is scheduled for launch in CY2009. This paper describes the status and capabilities of the UV and visible sensor payloads, as well as algorithms and software being developed to achieve the DSE mission.

Keywords: COTS hardware, MDA, micro satellite, sensor, target tracking

THE MISSION

Microsat Program Purpose and Description

The DSE Microsat program is sponsored by the Missile Defense Agency's (MDA) Advanced Technology office. The mission of MDA is to develop and field systems to detect, track, and intercept enemy missile attacks on the US and its allies. A major constraint to development of a space-based tracking system has been the cost of fielding such a system. Concepts based on traditional spacecraft and payloads are cost prohibitive and have not progressed beyond the concept demonstration phase. The DSE Microsat program is a technology demonstration program whose purpose is to demonstrate and assess the viability of a constellation of micro satellites that will use COTS hardware to perform the target-tracking mission.

The program consists of three micro satellites flying in formation in a low earth orbit (LEO). During an engagement scenario, the satellites receive a cue from the ground which provides the constellation an initial estimate and trajectory of the target. The satellites use this data, along with current satellite attitude, position,

and ephemeris information, to compute the attitude required to point the payload sensor at the target. The spacecraft then slews to the derived attitude and the payload acquires the target. Once acquired, the spacecraft uses the position of the target reported by the payload to maintain pointing at the target. Each satellite computes the position of the target and reports this to the other satellites through an inter-satellite communication system. Each spacecraft uses the data from the other satellites along with the locally computed target state to compute a three-dimensional target state which is then sent to the ground.

Key functions to be demonstrated are the ability to autonomously acquire a target based on a cue from a ground system, cross-linking of target track data between spacecraft, and real-time data fusion and computation of the three-dimensional target state by on-board processors.

SPACECRAFT DESCRIPTION

While it is true that the payload makes the mission, it is also true that the mission is impossible without the bus. In the case of the DSE program, the use of a micro

satellite bus is an integral part of the overall purpose. It is through the use of micro satellites that major cost reductions are possible. SpaceDev Inc. is building the spacecraft for the DSE Microsat experiment. The DSE spacecraft is derived from SpaceDev's MBB-100 spacecraft design. DSE uses modular COTS electronics and fixed solar arrays. The bus communications system uses an S-band downlink and an inter-satellite crosslink in the VHF band.

The DSE bus is a deck and stringer design with components mounted to the decks (flat panels) as shown in Figure 1. The underside of the first panel comprises the communications deck, which houses the communication systems. Residing on the top side of the second panel is the power distribution system and the batteries. The command and data handling system is located on the bottom side of the second panel, along with the spacecraft computer and several other guidance, navigation and control system components. The third panel is an optical bench separating the payload bay from the remainder of the spacecraft. On the top side of the optical bench are the star tracker and the inertial measurement unit (IMU). Mounted to the bottom side of the optical bench is the instrument module which is within the payload bay. Payload electronics are mounted to the top side of the bottom deck of the spacecraft, also within the payload bay. Figure 1 illustrates the components and their relative position as described above. Specifications for the spacecraft, including its payload, are listed in Table 1.

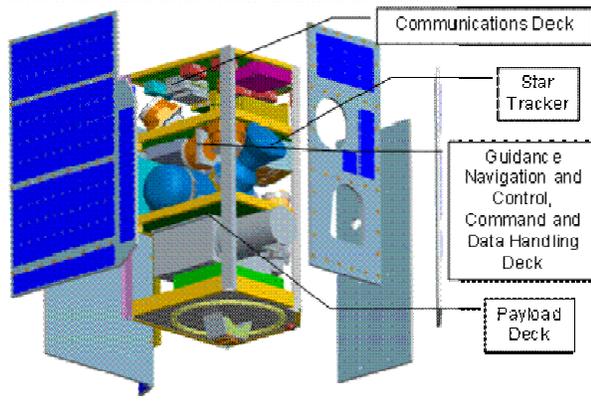


Figure 1: DSE Microsat spacecraft decks
(used by permission from SpaceDev. Inc.)

Table 1: Spacecraft specifications (with payload)

Description	Value	Units
Mass	<100	kg
Power (nominal operational)	<120	Watts
Power (during engagement)	<275	Watts

PAYLOAD DESCRIPTION

is housed in the lowest (payload) bay of the spacecraft. The instrument module is mounted to the bottom side of the optical bench to provide good alignment with the spacecraft star tracker and the IMU. The electronics module is mounted on the opposite side of the bay on the top side of the bottom spacecraft deck (Figure 1).

The instrument module contains an alternate-three-mirror-anastigmat (ATMA) telescope with an additional fold mirror, a mechanical shutter assembly, a camera, and a filter mechanism with two movable filter sets – one for visible and one for UV. The payload camera is derived from a COTS Hamamatsu camera and focal plane. The camera was repackaged and modifications were required for operation in a vacuum environment. The Hamamatsu focal plane is unique in that it has a spectral response throughout the visible spectrum and also has a strong spectral response in the UV. The camera's capabilities in the UV allow observation of rocket plumes below the horizon.

A number of commercially available focal planes and cameras were considered during the preliminary design stage of the program. The Hamamatsu focal plane was selected for its excellent quantum efficiency, an individual pixel size that meets the requirements for the optics, cost, and ability to detect in the UV band. A drawback of the selected focal plane is that it requires a mechanical shutter to control the integration time, and to block light from the focal plane during the read-out of the charge coupled device. Compromise is a necessary condition when adapting commercial components to novel uses such as those of DSE and the pros of the focal plane outweighed the necessity of a shutter and associated control electronics. Both the shutter and shutter control electronics are COTS and are part of the instrument module (Figure 2).

Resulting from initial trade studies, a decision was made to use a custom telescope for the optics. This decision was driven by several factors. Commercial telescopes are not designed for the launch environment and require extensive modifications to ensure alignment after the launch event. A compact telescope design was required in order to fit within the allowable envelope, but with maximum light transmission for maximum range performance. A design driver was the ability to observe faint objects near the earth's horizon which

necessitates good off-axis rejection. These factors drove the choice of a custom ATMA telescope.

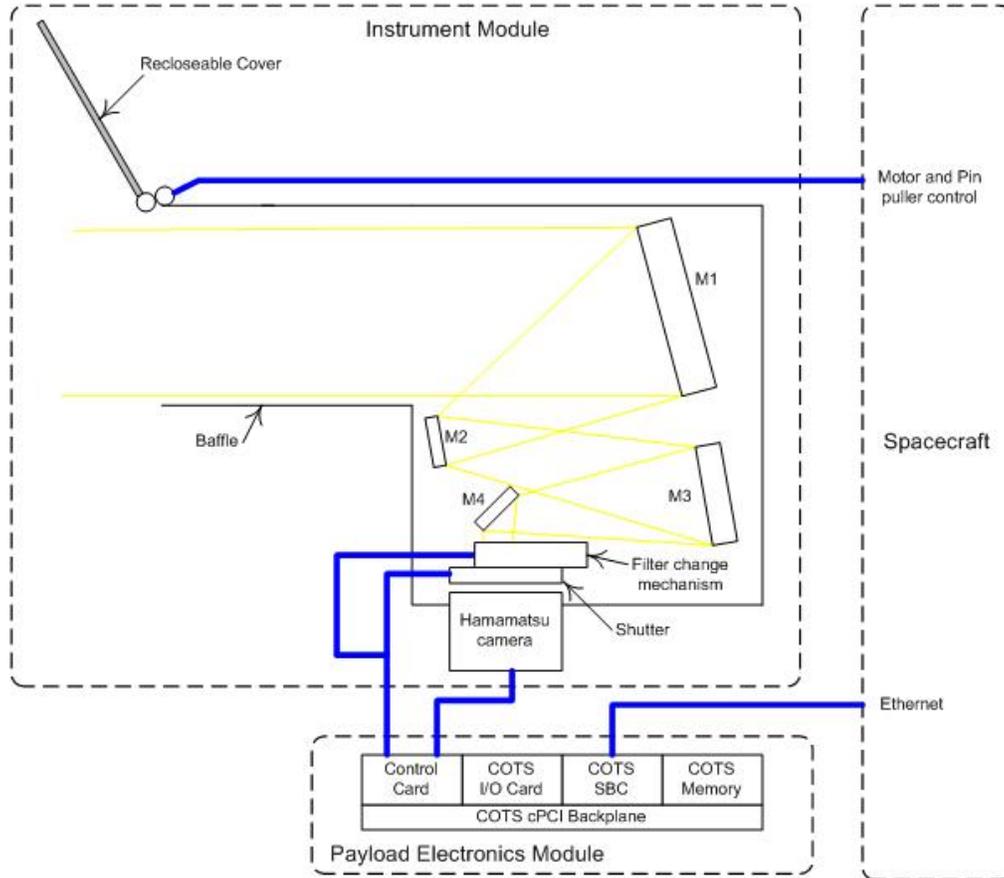


Figure 2: Block diagram of DSE payload and spacecraft interface

The custom filter changer assembly (Figure 3) is required to allow the camera to block visible light from reaching the focal plane when operating in the UV mode. Several filter designs were considered before selecting a novel filter set consisting of low cost commercial UV filters with a custom blocking filter coating applied to an inner surface of the filter elements. The simple mechanical design uses the same electric motor as the aperture cover with a pin puller to put the camera in the visible mode should the motor fail.

As discussed previously, one of the program objectives is to use COTS components wherever feasible. The payload support electronics (PSE) module makes extensive use of COTS components. SDL and SpaceDev looked at several different commercial single board computers before selecting a PowerPC based board. The 3U form factor computer uses the compact

Peripheral Component Interconnect (cPCI) standard backplane. The computer provides high performance at relatively low power, is available in a ruggedized version, and has passed radiation testing that was performed by SpaceDev. This computer is used by both the spacecraft as the main spacecraft computer and the payload thus taking advantage of shared development and reduced cost through volume purchasing. A layout of the components of the payload support electronics (PSE) module is shown in Figure 4. In addition to the commercial single board computer, the PSE uses a commercial programmable I/O card for acquiring the image data from the camera. The PSE also uses a cPCI non-volatile memory card for storage of application files and data files. This card is a commercially available radiation-tolerant card designed for space applications. This card was chosen to ensure reliable storage of application data.

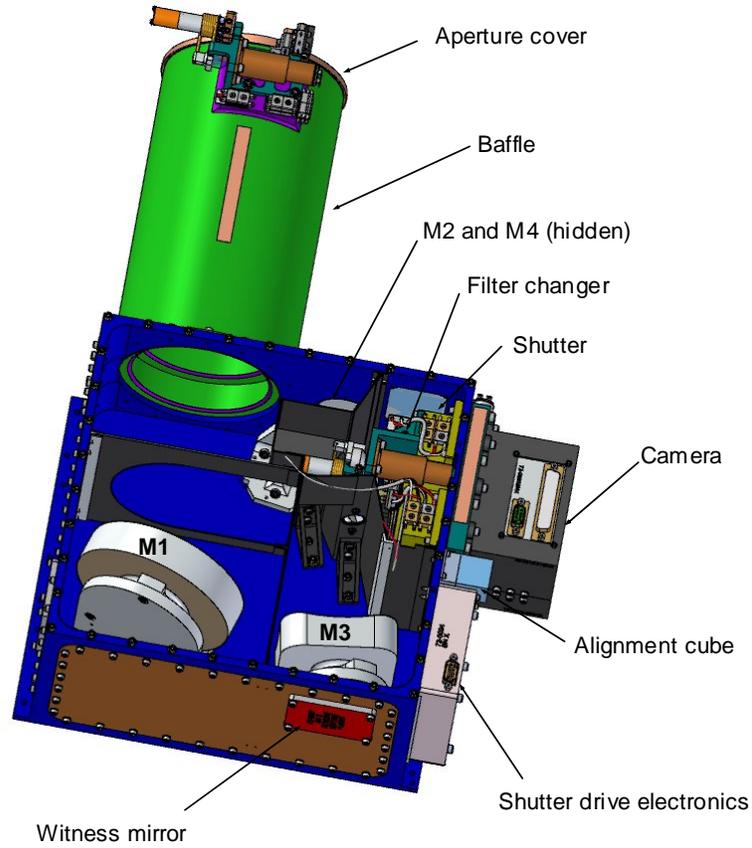


Figure 3: Payload instrument module

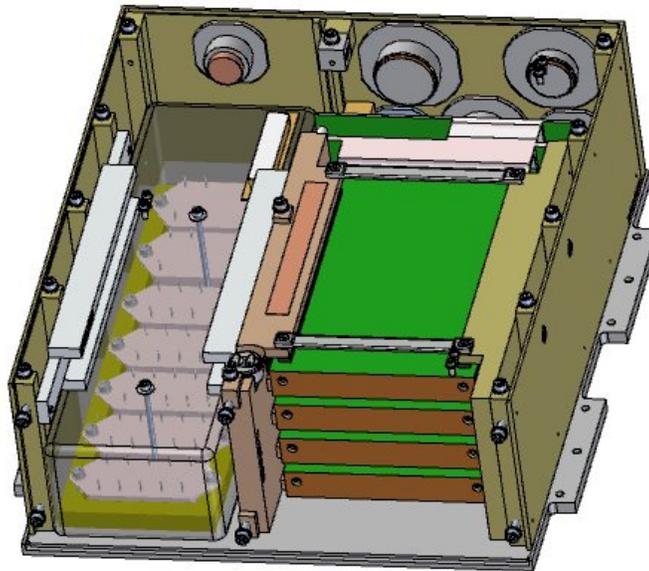


Figure 4: Payload support electronics (PSE) module

The PSE module performs power isolation and conversion, control of the camera, control of the filter mechanism, processing of camera data, and individual and fused three-dimensional, target-state formation. Communications between the payload and the spacecraft is accomplished through an Ethernet connection between systems. In addition to power and Ethernet interfaces between the payload and the spacecraft, there are also discrete lines for temperature monitors and some control functions. Specifications for the PSE module including nominal and maximum operating power for the payload are given in Table 2.

Table 2: Payload specifications

Description	Value	Units
Mass	<32	kg
Power (nominal operational)	<50	Watts
Power (during engagement)	<80	Watts
Entrance pupil size	100	mm
F number	3.5	

Payload Algorithms/Software

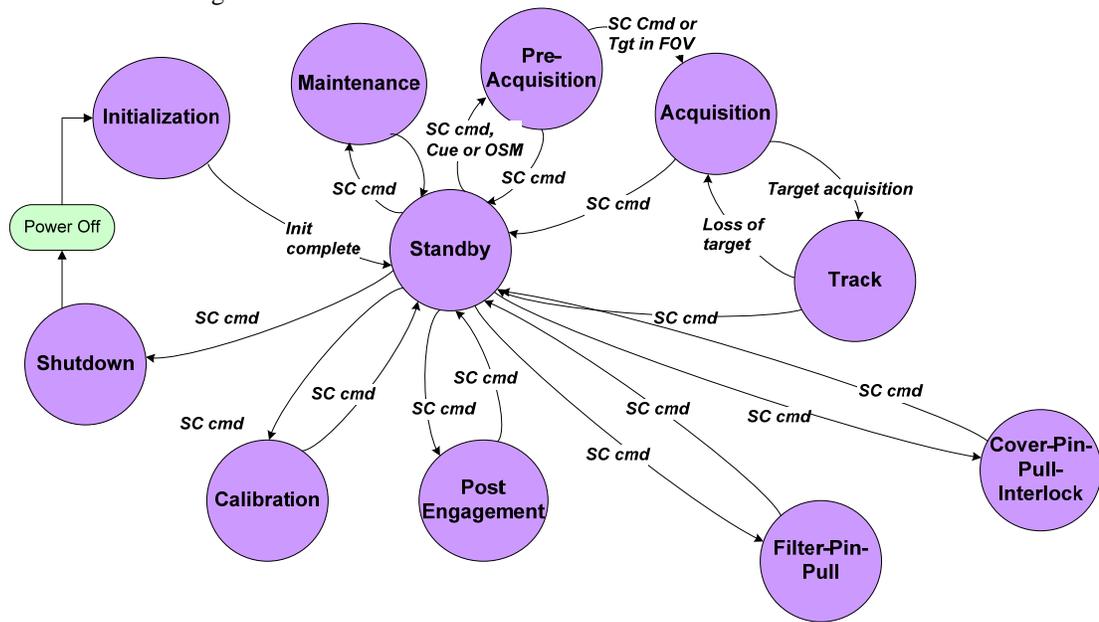
The primary objective of this program is to compute the three-dimensional state of a target of interest in real-

time using target state data from each (at least two) of the micro satellites. Each satellite separately acquires and tracks the target starting with an estimated target state cue provided by the ground system. This data is then transmitted to the other satellites for computation of the three-dimensional target state which is transmitted to a ground station within communication range of the satellite. The various operational states required for accomplishing the goals of the mission are detailed in Figure 5.

PSE Software

The Payload software provides the following key functions:

1. Command and control of the payload including transition between the different operational states as depicted in Figure 5.
2. Autonomous execution of the target acquisition and tracking algorithms after receipt of an external cue.
3. Camera system configuration and control.
4. Command and messaging interface with spacecraft.
5. Provide support for on-orbit software and instrument calibration updates.



*All states have implicit fault transition to Standby and Initialization state (depending on fault)

Figure 5: PSE operational states

Another area of commonality between the spacecraft and payload is the use of Linux as the operating system for the spacecraft and payload computers. Linux is not a traditional choice for space applications, but is rapidly gaining support and acceptance for real-time and embedded applications in aerospace systems. When using a commercially supported Linux distribution, the costs for the platform, tools, and support are not zero, but do compare favorably to more traditional real-time operating system support costs. Linux is supported by a comprehensive set of commonly used development tools and cross-compilers, lowering the program's development effort and associated costs for the class of custom applications required for the payload executive. Linux also supports a variety of file systems suitable for use with the flash memory systems on the DSE payload.

Key to the use of Linux for this space application was the availability of a board support package and kernel for the single board computers as well as device drivers for the other boards. Resolving issues related to the implementation of the operating system and the device drivers has been the most time consuming of the COTS modifications. Variations in the Linux distributions, the rapid Linux update schedule, and the non-backward compatibility of some updates have made integration of the hardware devices more difficult compared to implementation of a dedicated real-time operating system such as VxWorks. The difficulties encountered have not been insurmountable but care needs to be taken when selecting components, and additional time and resources need to be allocated to the project to account for these issues.

Communications between the spacecraft bus and the payload are layered on TCP/IP over 100 Mbps Ethernet. The use of Linux provides ready access to all major protocols layered on IP, including FTP, Telnet, Network time protocol, ICMP, and NFS. Since the payload and bus computers appear as IP addressable nodes on the local network, transfer of collected payload data or software updates, is implemented as file-based transfers using FTP between the resident flash file systems on each end. This greatly simplifies the development required for this segment of spacecraft to payload communications. The combination of IP over Ethernet, Linux, and NFS also significantly eases the embedded software development, allowing maintenance of a 'virtual' target processor file system which the target remotely mounts from the embedded development host, avoiding time-consuming downlink and power-cycles of the target between software updates.

Acquisition Algorithm

The acquisition algorithm demands the most resources from the CPU and memory, and therefore must be very efficient to stay within resource availability. Targets must be distinguished and extracted from a background of stars and noise spikes. The typical approach would be to use match filters to separate targets from stars. However this approach is throughput intensive. The algorithms used for DSE make use of the distinguishing feature that the objects of interest will be moving relative to the celestial background. As the overarching goal of the program is to track dim objects, our approach is to follow the expected motion of the object provided by the cue. If the sensor is tracking properly, the object image should appear nearly motionless in consecutive images while the stars stream away. Depending upon the attitude slew rate of the spacecraft, star images may appear as streaks that are many pixels long.

The acquisition algorithms consist of several tasks. These include pixel-level processing for the formation of objects and the acquisition algorithm that uses the object lists for several frames of image data. The pixel-level processing functions are compensating for individual pixel response differences (non-uniformity compensation), thresholding of the pixel outputs to minimize false detections, and clustering of the pixels that exceed the threshold. The resulting clustered pixels are kept as a list of objects for that image frame.

A valid object follows a predictable path across the celestial background. The acquisition algorithm makes use of this characteristic by searching a region around the predicted location of a valid object in each of several frames. Each object in the current frame is backward propagated to a region in a previous frame. If the object is a target being tracked, the region in previous frames is likely to contain the object. If the object is a star or a noise spike, it is transient and will not appear in the predicted region in previous frames.

The acquisition algorithms are both memory and throughput efficient. The memory required for each frame is reduced from 2 megabytes to less than 100 kbytes. Instead of multiple passes through each frame of pixel data, the passes are made through the object location index containing only the locations of each valid object. Throughput analysis of the algorithms currently shows significant margin with all processes (acquisition, track, control, communications, monitoring, data storage) taken into account.

A simulation of the star background, targets, and spacecraft motion has been developed to aid in the development of the algorithms. Simulation runs of the

acquisition algorithm are performed to fine tune and obtain effective values for these parameters.

Track Algorithm

Each micro satellite in the constellation provides a good two-dimensional state vector for the object. With more than one micro satellite imaging the same object, it is possible to extract a three-dimensional target state vector of the same object via triangulation. The objective of the track algorithm is to fuse asynchronous object state measurements from the sensors on each of the micro satellites into a composite three-dimensional track that performs target position and velocity tracking, trending, and prediction. The primary challenge of the track algorithm is to generate object state measurements with accuracy comparable to those estimates generated from traditional satellites, while doing so at a much lower cost.

A Kalman filter is a set of mathematical equations that provides an efficient computational (recursive) means to estimate the state of a process, in a way that minimizes the mean of the squared error. The filter is very powerful in several aspects: it supports estimations of past, present, and even future states, and it can do so even when the precise nature of the modeled system is unknown. The track algorithm is a six-state standard Kalman filter that produces a position and velocity estimate. Like the acquisition algorithm, the track algorithm must be fast and efficient. Prior to acquisition of the target by the payload, the target state will be predicted using an initial target state estimate (provided from the ground).

The Kalman filter estimates a process by using a form of feedback control: the filter estimates the process state at some point in time, and then obtains feedback in the form of (noisy) measurements. As such, the equations for the Kalman filters fall into two groups: process model (time update) equations and measurement update equations. Simplifications were made to the process model equations that allowed the noise associated with the process model to be considered negligible while still maintaining sufficient accuracy in the computation of the target state.

For the measurements update part of the filter, the following uncertainties are incorporated:

1. Attitude Control System (ACS) pointing knowledge uncertainty.
2. Pixel resolution (target centroiding knowledge uncertainty on each FPA pixel).
3. Spacecraft state uncertainties (GPS accuracy).
4. Radiometric parameters.

Figure 6 below shows the fusion architecture of the track algorithm. The track algorithm is implemented as three layers of Kalman filters. This architecture was chosen to improve track accuracy while staying within the constraint of very limited micro satellite cross-communication bandwidth. In particular:

1. KF1: Generates object state messages at FPA frame rate. Filter re-initializes (with very large target state and covariance) at KF2 output rate.
2. KF2: Generates composite fused 3-D target state at 1 Hz. Filter initializes with a target state cue and target covariance provided from the ground.
3. KF3: Generates composite two-dimensional target state at FPA frame rate to the spacecraft ACS. Filter initializes with a target state cue, and target covariance provided from the ground.

Each KF1 generates object state messages which are transmitted to the other micro satellites. The object state message is used by KF2 in each of the other satellites to generate a three-dimensional composite track. In addition to the layered Kalman filter implementation, a data compression scheme was developed and implemented. The novel approach for transmission of the covariance matrix fits within the data rate restrictions of the inter-satellite communication bandwidth, yet minimizes the track accuracy degradation. The scheme uses the Cholesky decomposition scheme on the state covariance, and transmits the log of the entries instead of the whole entry. The Cholesky decomposition guarantees filter stability by retaining positive definiteness of the matrix.

Comprehensive stand-alone simulations are performed to assess the performance of the track algorithm. Results to date have been very satisfactory and meet the requirements.

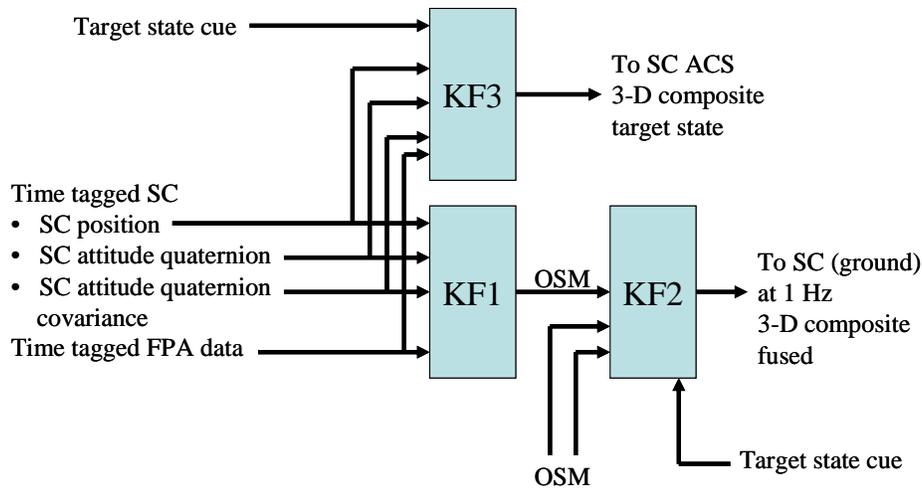


Figure 6: Filter fusion architecture per satellite

SUMMARY

The DSE program was conceived as a demonstration of the performance possible with a low-cost missile tracking system that provides fused real-time, three-dimensional target track state data using micro satellites and an optical payload composed of several COTS components. Several novel approaches for solving the problems associated with providing sufficient accuracy

while maintaining the size, weight, and power constraints of such a system have been implemented in the payload. Difficulties with integrating COTS products have been encountered and work-arounds have been developed. Work continues on the buildup of the flight hardware and software, and DSE is on track for launch in FY2010.