Multifunctional Structures Technology Demonstration on New Millennium Program (NMP) Deep Space 1 (DS1)
DS1 Technology Validation Report

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Acronyms

AFRL	AirForce Research Laboratory
BMDO	Ballistic Missile Defense Office
C&DH	Command and Data Handling
Cu/PI	Copper/Polyimide
DARPA	Defense Advanced Research Project Agency
DOD	Department of Defense
DS1	Deep Space 1
EDU	Engineering Development Unit
EMI/EMC	Electromagnetic Interference/Electromagnetic Compatibility
GFE	Government Furnished Equipment
HDI	High-Density Interconnect
HiLowPDM	High-side/Low-side Power Distribution Module
IC	Integrated Circuit
I/O	Input/Output
I&T	Integration and Test
LMA	Lockheed Martin Astronautics
LSB	Least Significant Bit
LTCC	Low-Temperature Co-fired Ceramic
MCM	Multi-chip Modules
MFS	Multifunctional Structures
NMP	New Millennium Program
PL	Phillips Laboratory
PWB	Printed Wiring Board
SIES	Spacecraft Integrated Electronics Systems

ABSTRACT

The future microspacecraft vision will only be realized through revolutionary changes in current spacecraft architecture coupled with the development of new technologies. This paradigm shift will bring a dramatic cultural change that can only be implemented using a truly concurrent-engineering approach that incorporates advances in structural, thermal, microelectronics, micro-instruments, sensor, power, and propulsion systems.

Addressing technology needs of future microspacecraft, Lockheed Martin Astronautics (LMA) has developed an innovative multifunctional structures (MFS) design that is a new approach to electronics packaging, interconnection, and data and power distribution. MFS integrates these functions with bearing-mechanical loads and provides thermal control.

In particular, the MFS concept involves embedding passive-electronic components within the actual volume of composite materials, new approaches to attaching active-electronic components directly to mechanical surfaces, and using surface areas for mounting sensors and transducers.

The ultimate goal for MFS technology is to maximize the ratio of the volume of the fundamental electronic parts to the total packaging volume. Multi-functional structure technology is a revolutionary design approach that will provide nearly an order-of-magnitude reduction in future spacecraft mass and volume. Significant cost savings are also expected through eliminating touch labor, reuse of flex-circuitry designs for multiple-spacecraft missions, and launch-cost reductions through reduced payload size. MFS is an enabling technology for future microspacecraft missions envisioned by the Department of Defense (DOD) and NASA.

The MFS design approach uniquely combines the advances in the area of electronics (e.g., 2-D/3-D multi-chip modules [MCM]) and flex-circuit interconnects), advanced composites (for structures), and thermal management. MFS eliminates the bulky components (chassis, cables, and connectors) of current spacecraft and enables the integration of electronic subsystems, such as the data-transmission and power-distribution networks, command and data handling (C&DH) subsystem, thermal management, and load handling.

The baseline MFS design consists of a structural-composite panel that has multi-layer copper/polyimide (Cu/PI) patches bonded to one side, heat-transferring devices embedded, and an outer surface acting as a radiator. Electrical interconnects are designed in the Cu/PI layers, circuitry is implemented in MCMs, and flex jumpers serve as electrical interconnects for power distribution and data transmission. The thermal management devices embedded in the MFS may include miniature heat pipes and various types of high-conductivity thermal doublers and straps.

In an Air Force Research Laboratory/Philips Laboratory (AFRL/PL), Ballistic Missile Defense Office (BMDO) and Defense Advanced Research Project Agency (DARPA)-sponsored program, LMA has successfully developed and demonstrated the design, integration, assembly, and functional performance of the MFS technology and its elements.

LMA has successfully integrated an MFS experiment on the NASA New Millennium Program (NMP) Deep Space 1 (DS1) spacecraft and validated key technology features of MFS design.

Technology and integration risks associated with the MFS-packaging system include:

- The electrical performance of the flex circuit, including the anisotropic electrical interconnects to the flex-circuit jumpers.
- The use of socketed MCMs in a flight environment.
- Connections between the flex circuitry and heritage connectors.
- Integration and test, rework, and repair issues associated with the direct installation of electronics on spacecraft structure without a chassis.

The validation objectives include the successful demonstration of the MFS technology elements (integrating flex interconnect, circuit patches, flex jumpers, thermal doublers, rad-hard composite spot shield, and structural substrate). In the electrical circuit performance area, conductivity measurements were taken during each experiment cycle to independently verify the nominal-trace conductivity, the performance of the anisotropic bonds in a jumper configured for multiple serpentined connections, and a set of daisy-chained connections to the thermal-simulator MCM through a socketed-lead system. A set of temperature measurements were collected to evaluate the thermal performance of the panel underneath the thermal-simulator MCM by using an array of sensors mounted on a flex-circuit tether. Finally, routine health- and status-data were collected to verify proper controller operation during the data collection.

Given the novel nature of the MFS design, extensive development testing was performed prior to any DS1 design effort. This testing included vibe, thermal, x-ray, and electrical performance of a variety of test panels with different configurations of hardware. The technology was fairly well documented leading into the DS1 experiment design. The DS1 components were tested both individually and as a system. The controller board for the flight experiment was tested for

workmanship and the completed panel was tested with the full-up spacecraft assembly.

During the DS1 mission, the MFS experiment was powered up once every two weeks and two experiment cycles were carried out to ensure that a full set of data was collected. The experiment sequence provided a data set containing health and status information, the electrical-conductivity test data, and last (following a warming time period of the panel) thermal-gradient measurements. The experiment was an unqualified success based on the data returned. All health and status data was correct and within normal limits. The electrical-conductivity data never varied by more than one Least Significant Bit (LSB) from the preflight data set. The thermal-gradient data was appropriate for the position of the sensors versus the heat source in the MCM.

MFS technology is eminently suited to use in many missions for the following reasons:

- Offers significant mass (>50%) and volume (>2×) savings over traditional packaging systems.
- Takes full advantage of MCM devices without adding packaging mass due to printed wiring board (PWB) mounting.
- Frees up spacecraft design from traditional form factors.
- Flex circuitry is an enabling technology for wiring density in microspacecraft.
- The technology will readily support mass production of spacecraft for constellations.
- The techniques easily transfer to inflatable structures.

Overall, the NMP-DS1-MFS experiment has been very successful in demonstrating the majority of key features and showing that there are no major roadblocks. Even a minor rework was performed smoothly with the panel in place on the spacecraft bus. The MFS experiment was integrated quite easily on the spacecraft-bus panel and was the first technology experiment to be delivered to DS1.

Based on the successful technology-validation experiment, the MFS technology should be considered fairly mature.

FACT SHEET
MULTIFUNCTIONAL STRUCTURES

Strategic Vision

Establish modular multifunctional structures (MFS) technology, integrating electronic, thermal, and structural functions for Next-Generation, Cable-Free Spacecraft

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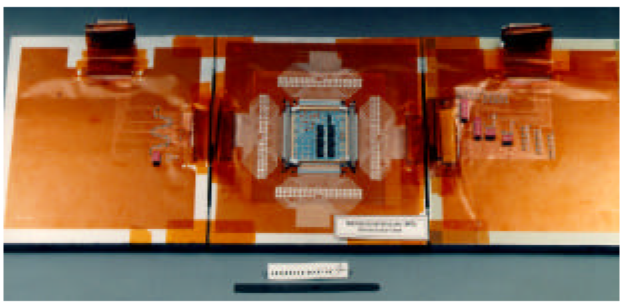
SATELLITE MANUFACTURING TODAY:

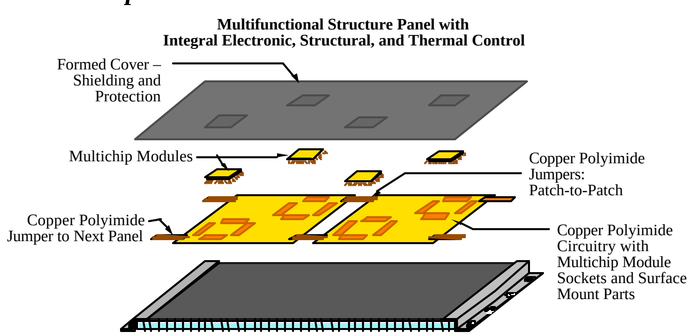
- 1000s of heavy individual cables
- Costly
- Complex
- Bulky electronic enclosures
- Wasted space



SATELLITE MANUFACTURING TOMORROW:

- Eliminate cables and connectors
- >10× reduction in mass and volume
- > 2× reduction in cost
- Enabling technology for satellites, launch vehicles, and missiles
- Revolutionary modular design

MFS Concept



Description

- Flex copper/polyimide circuit patch and interconnects for power and data distribution
- Flex material directly bonded to thermal-structural composite panel
- Applicable to intersubsystem cabling
- Revolutionary modular design

Who Needs It?

- All LEO platforms and GEO satellites
- High-density instruments, sensors, and microassemblies
- Nearly all rigid and inflatable structures

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1.0 INTRODUCTION

The MFS technology is a revolutionary development in spacecraft packaging that eliminates chassis and cabling by integrating the electronics, thermal control, and structure into a single element. A new system such as this carries the burden of proving itself before it can be considered as a viable design option for flight usage. During the early development of the MFS concept, extensive environmental and electrical testing was performed to demonstrate the robustness of this system. The next step was a flight demonstration; this was accomplished on the NMP DS1 spacecraft.

The following sections describe the MFS system, the validation objectives, potential risks and risk amelioration, the testing program and results, and the future use of MFS in spacecraft design. As a new system, it may take a little while for the design concept to "sink in"; however, the ramifications of this technology for future designs at all levels, but especially in microspacecraft, will be apparent in the description below.

2.0 TECHNOLOGY DESCRIPTION

2.1 MFS Functionality and DS1 Demonstration

The multifunctional structure technology is a new method for constructing spacecraft. An MFS demonstration was proposed for the DS1 spacecraft to incorporate the key design features. Eventually, it is envisioned that entire spacecraft will be fabricated using the MFS system; the DS1 mission provided a starting point. The experiment was designed to demonstrate several features of the technology, including design methods, integration and test (I&T) impacts, functional routing of signals and power, use of flex circuitry in novel ways, and the elimination of chassis and cabling.

The experiment was designed with a spacecraft-interface card to support data gathering, formatting, and transmittal to the main spacecraft computer. The interface card followed an experiment sequence in collecting health and status data (voltages, check sums, initial temperatures, and a subset of electrical conductivity measurements), a full set of conductivity data on a variety of circuit conductors in multiple configurations, and a temperature-gradient measurement following a 30-minute panel-heating operation. The data set was collected twice in succession to increase the odds of obtaining full data sets. This was in lieu of having any spacecraft data checking to look for dropouts.

The high-level goals for the experiment included successful installation, proper operation of the circuitry over the life of the mission, good thermal performance of the thermal-simulator multi-chip module (MCM) mounting system, and minimal problems dealing with the unique features of the packaging.

2.2 Key Technology-Validation Objectives at Launch

The primary validation objectives included:

- Demonstrate proper electrical performance for the flex-circuitry conductors.
- Monitor the anisotropic flex-to-flex sample bonds for any sign of degradation.
- Verify the stability of MCM electrical connections made using a separable connector attached to the device leads.
- Collect thermal-gradient data that demonstrates proper heat removal from the thermal-simulator MCM.

Given the novel nature of this technology, a variety of intrinsic objectives were also indicated as follows:

- Demonstrate a concurrent engineering effort on the experiment layout and design.
- Demonstrate successful installation of the hardware on another subcontractor's flight panel.
- Show that rework/repair operations are straight forward even if performed with the panel on the bus.
- Verify the flightworthiness of a new MCM socket that permits rapid removal and replacement of MCMs.
- Demonstrate an instrumentation tether by collecting data from the opposite side of the panel using a flex-circuit element with a linear array of temperature sensors.
- Demonstrate a cover that provides mechanical protection, EMI/EMC shielding, and radiation shielding.
- Demonstrate the use of filled-composite materials for localized radiation shielding of the printed-wiring board (PWB).

2.3 Expected Performance Envelope

The conductivity measurements of the flex circuitry and MCM socket system follow standard analytical techniques for resistance in copper conductors. The criteria for the returned flight measurements primarily centers on the repeatability from ground-to-flight measurements within a specified tolerance: i.e., the launch and flight environment do not cause any degradation that would either increase the resistance or result in a completely open circuit. The allowable tolerance was 20% from ground to flight. A variety of circuit-trace and socket configurations were created to permit testing of traces, anisotropic bonds, and the MCM socket interconnects. Each configuration permitted independently testing for a single type of interface, thereby avoiding contamination between different interconnect systems.

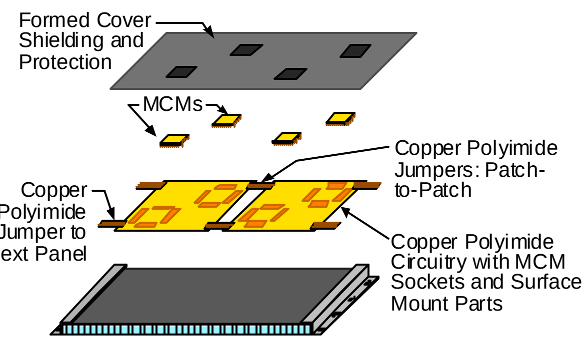
The thermal-gradient part of the experiment measured the temperature distribution over a small area of the spacecraft panel before and after a 30-minute heating cycle. The predicted-maximum rise for safety purposes was approximately 5º C regardless of total heating time. The heat source was a thick-film resistor screen printed in the thermal-simulator MCM package. The resistor footprint was sized to simulate the dissipation from an integrated circuit. The expected performance of the thermal-bonding system from the MCM to the panel was to produce a maximum rise of about 5º C directly under the MCM "hot spot" with an appropriate falling off over near distance from the hot spot.

Secondary performance expectations included no significant degradation in the performance of the spacecraft-interface electronics, no loss of measurements or measurement data, and successful power-up and communication sequences with the spacecraft interface. Also, the survival of the packaging system through the launch phase was obviously a strict criterion given the focus of multifunctional structures.

2.4 Detailed Description

Driven by a spacecraft requirement on a flight program to incorporate a reworkable MCM stack processor on a composite panel, the Spacecraft Integrated Electronics Systems (SIES) program was funded by Air Force Research Laboratory (AFRL)/Phillips Laboratory (PL) to develop methods for efficiently incorporating MCMs into spacecraft without losing the volumetric and mass advantages. The MFS efforts have produced a system that incorporates structure, thermal control, and electronics into a single packaging system while permitting efficient rework and test. Chassis, PWBs, connectors, and cabling have all been eliminated in this system.

The MFS assembly concept is shown in Figure 1. A composite panel with embedded or laminated thermal-control elements forms the basis for the MFS. For typical-spacecraft construction, clips will be used on the edge of the panel for mechanical attachment to adjacent panels. Flex-circuit patches are then installed on the panel using adhesive. These circuit patches provide local interconnects and can accommodate surface-mount devices. MCM sockets developed in this effort are also installed at this time. Flex-circuit jumpers are added for patch-to-patch and panel-to-panel interconnection and are connected using an in-place bonding system. These jumpers provide signal paths and shielding as required. In the MFS system, it should be noted that traditional chassis, mother boards, cabling, and connectors have all been replaced with the flex-interconnect system. The PWB electronics are reduced to MCMs.



Spacecraft Structural Panel with Integral Thermal Control

Figure 1. Exploded Assembly View of a Multi-functional Structure Panel Incorporating Structure, Thermal and Electrical Elements

The next step is the installation of leaded MCMs into the sockets with a clamping assembly to secure the part and the leads. The clamp also ensures that adequate thermal circuit would normally have functional testing. Test jumpers can be added for testing and then removed or stowed. Finally, a cover is installed that can provide the following protection: physical protection during assembly, electromagnetic interference/electromagnetic-compatibility (EMI / EMC) shielding, and radiation shielding. The entire MFS system is designed to readily support repair/rework with a fundamental requirement that in all cases the MCMs shall be easily removed for reuse with no risk of damage.

The SIES contract provided for several demonstrations, including a flight demonstration on NASA's NMP DS1 mission. This provided an ideal opportunity to validate the technology in terms of produceability and long-term flight worthiness during a multi-year mission. An experiment was designed to apply and test the following features of the MFS system: Circuit patches, in-place jumpers, socketed MCM, soldered MCM, flex tether with embedded sensors, and flex interfaces to traditional connectors. The MFS DS1 experiment is shown in Figure 2.

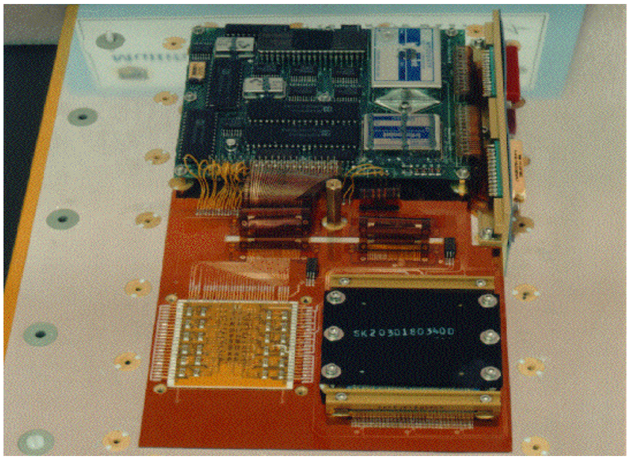


Figure 2. Multifunctional Structures Experiment Installed on a NMP DS1 Flight Panel. The PWB carries the spacecraft interface circuitry and contains the controller for managing the experiment.

The MCMs used in the experiment require close attention to detail in terms of electrical interconnections, thermal and structural interfaces, and compatibility with the remainder of the MFS concepts. The remainder of the paper will discuss these aspects of MCM usage in the system in greater detail and outline the development, limitations, and hardware testing.

2.4.1 Interconnect Systems—In their most basic form, interconnects provide an insulated electrical path from a source circuit to a destination. Enhancements include shielding and connectors or, in the case of local circuitry, circuit traces, and electrical joints, such as solder.

Flexible circuitry was selected for the MFS concept for a variety of reasons:

- Replaces both PWBs and cabling.
- Local electrical-bonding systems can eliminate all connectors.
- Lightweight/low volume.
- Standard product.
- Conductors can be sized/added to meet voltage-drop, shielding, and isolation requirements.

It is very desirable to eliminate connectors for several reasons. They are bulky compared to the conductors and add significant weight. They are usually labor intensive between assembly, calibration of assembly tools, inspections, and test. They can be the source of many additional failure modes.

In a pure implementation of the MFS design, all connectors are eliminated. In situ flex-to-flex bonding is performed to link circuit patches and flex cabling. The only routine connector left is a prototype MCM socket that has been qualified in extreme vibration environments and is being demonstrated on NMP DS1. The MCM leads are clamped into the connector; the MCM package is then clamped to the panel. This approach supports the easy removal and reinstallation of MCMs during re-work and minimizes the loss of expensive parts.

2.4.2 Multi-chip Module Interface Characteristics—Primary interface considerations for the use of MCMs with MFS are the electrical interconnects and the thermal interface. These are linked in various MCM packages because some lead styles are in the normal-thermal path through the base of the package. Electrical interconnects fall into four categories: leaded packages, pin grids, ball grids (and column grids), and flex-circuit extensions. The best performance is obtained from the leaded and flex-extension packages since they can have the base of the package in good thermal contact with the panel when mounted. The package can either be directly in contact with the panel facesheet or additional heat spreaders/doublers can be used for higher dissipation levels. Ball-grid-array attachment presents greater challenges in thermal-dissipation management.

In the DS1 experiment, two MCMs are used. One MCM is a high-density interconnect (HDI) type of device; the other unit is fabricated in low-temperature, co-fired ceramic (LTCC). The HDI device is fabricated using integrated circuit (IC) dice mounted in a ceramic carrier, with the local interconnects made using multiple layers of flex circuit that is repeatedly laser drilled to the IC die-bonding pads, metallized, and then etched to leave traces. External connections can be made with a flex interposer or conventional lead frames (used in the DS1 part). The HDI device functions as a high-side/low-side switching power-distribution module (HiLoPDM).

The LTCC device has a number of thick-film resistors of different geometries simulating the dissipation from different IC dice. The interconnects are formed with a conventional lead frame whose pitch matches the MCM socket strips. The HiLoPDM device is soldered in using conventional methods. Both of these devices are shown in Figure 2 (although the LTCC device is concealed under a clamping plate).

2.4.3 MFS Flight Experiment and Data–Collection Descriptions—The MFS experiment on NMP DS1 is the first flight demonstration of the MFS technology. The experiment met several guidelines, including: not flight critical, minimal data set collected once per two-week cycle, basic RS232 interface, basic command protocol, low power, and no failure modes that could either cause excessive thermal dissipation or cause electrical-bus faults. The electronics block diagram is shown in Figure 3.

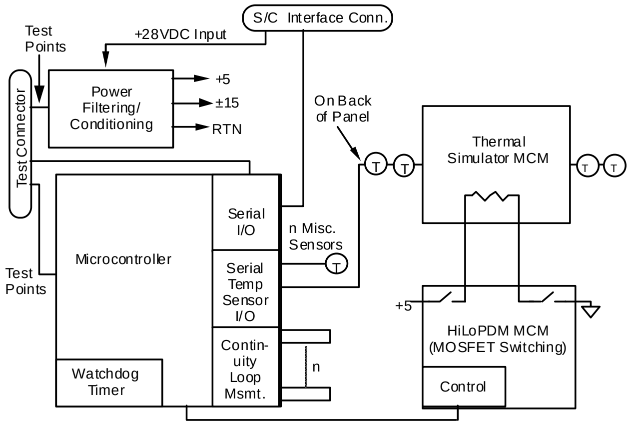


Figure 3. Block Diagram of the MFS Experiment Electronics on the NMP DS1 Flight. The basic experiment verifies the electrical performance of the various interconnect systems used in MFS and demonstrates distributed sensors measuring an induced-thermal gradient in the panel.

2.4.4 Circuit Description—A microcontroller PWB was provided for the spacecraft and test interfaces. The interface board provides the Input/Output (I/O) for the experiment operations, including conductivity measurements of flex-circuit traces and MCM–socket contacts, control of the HiLoPDM power switch for the thermal-gradient experiment, and the temperature sensors that measure the gradient.

The conductivity measurements cover the following: copper "control" traces for nominal conductor performance, traces through the flex jumpers, which includes the anisotropic bonds at each end, and the socket contacts, which are daisy chained in and out of the thermal-simulator MCM contacts. The original design only included an open/connected determination; however, this was modified to a regular measurement with a high and low range to determine if the conductors are degrading. The three types of conductors have been designed to keep the types of connections independent: i.e., there are no anisotropic bonds in the MCM socket-pin path, etc. This avoids confusion in data interpretation if there is a systematic failure in one type of interconnect.

In the diagram, a series of temperature sensors are shown passing beneath the thermal-simulator MCM. There are 12 sensors in a 4 × 3 array on the back of the panel under the footprint of the MCM. These devices use a three-wire interface with serial communications and unique addressing. They are mounted on a serpentine-flex circuit that passes from the front of the panel to the rear and is then attached with film adhesive. Several sensors are also used for other measurements on the front of the panel, including the PWB.

2.4.5 Data Collection—Data collection is initiated by the spacecraft through the following sequence: Power on, command #1 to MFS, response with health-and-status information including software version and checksums, command #2 to MFS, response with conductance measurements and 30-minute heating cycle when the thermal simulator MCM is started, pause approximately 30 minutes, command #3 to MFS, response with thermal-gradient data, power is turned off. This cycle is repeated twice in succession to ensure a complete data set. The sequence will be repeated every two weeks during the mission until the link efficiency starts to fall off; thereafter, the sequence will be repeated at larger time intervals.

2.5 Technology Interdependencies

There are no interdependencies between MFS and other spacecraft subsystems.

2.6 Test Program

2.6.1 Ground Test—

2.6.1.1 Development and Protoflight Testing—Thermal and vibration testing was performed during the MFS development efforts to verify performance and electrical integrity. The MCM socket was felt to be especially critical to the value of the MFS system and was therefore subjected to extreme levels of vibration while being monitored by "chatter" detectors for intermittents on the connections. Basically, the MCMs and socket assembly satisfied the typical vibration environment. Subsequently, the vibration levels were increased to test to failure. While the imposed vibration levels generated localized delamination in the panel, the MCM's socketing approach was robust, with no indication of degradation.

The NMP DS1 engineering development unit (EDU) panel was subjected to much lower levels since there was a PWB mounted on standoffs with potential resonances. During the design phase, the board was analyzed against the flight requirements and the design was adjusted to ensure survival. Figure 4 is a graph of the flight-environment envelope for the protoflight vibration testing. The panel did not have any failures.

Thermal testing was performed during the development phases of the MFS designs. The primary goal was to determine if there were anticipated MCM-dissipation levels that exceeded the capability of a well-designed composite panel with associated thermal controls. The conclusion was that there is probably not a heat load for which design techniques cannot keep the baseplate temperature within the limits necessary to meet junction-temperature requirements. The ultimate limitation is the capability of the spacecraft to dissipate the total heat load.

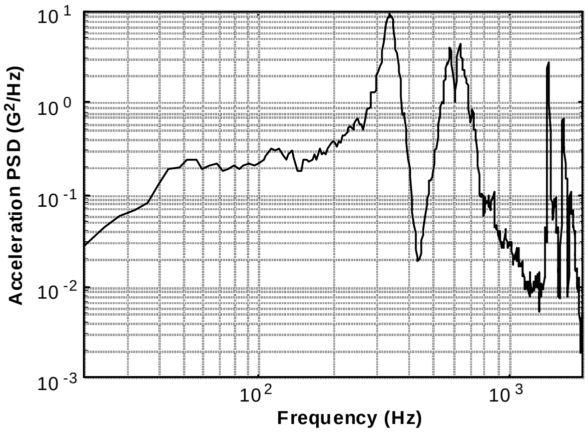


Figure 4. Vibration Levels Used in the Testing of the NMP DS1 MFS Engineering Development Unit.

2.6.1.2 Continuity and Thermal Gradient Measurements—The continuity measurements were the primary measurements for meeting the MFS demonstration goals. During ground tests, measurements were taken and were found to comply with the analytical predictions listed in Table 1. It should be noted that digitized measurements have a built-in error of ±1/2 LSB; therefore, there are cases in the flight data where a change in one LSB will be seen between different samples. In addition, every measurement was taken on both a unity-gain scale and a ×10 scale. Given the low values of the resistances measured, the ×10 scale is more representative of the measurements. The continuity measurement is non-linear due to the electronics; therefore, the corresponding resistance ranges are also listed for reference. There are three types of continuity measurement: flex-circuit trace only, anisotropic bond, and MCM socket. These are also distinguished below. Layout variations on the flex-circuit patch are responsible for the variations in similar measurements.

The temperature sensors were commercial devices that are designed for a resolution of 0.01° C. The devices were attached to the flex-circuit tether and placed in a temperature chamber to obtain linearity curves. The part-to-part variation was on the order of ±0.2° C. The original intent was to fabricate the panel in house. However, the panel ended up being Government Furnished Equipment

Table 1. Description of the Continuity-Measurement Collection-System Output

BYTE	NAME	DESCRIPTION	VALUE (DEC)	NOTES
1	LOOPCAL1	CALIBRATION MSMT	17+/-3	Rcal = 49.9 OHM
2	LOOP1	GAIN = 1 RESISTANCE MSMT	0+3-0	FLEX TEST
3	LOOP2	GAIN = 1 RESISTANCE MSMT	0+3-0	JUMPER/BONDING
4	LOOP3	GAIN = 1 RESISTANCE MSMT	0+3-0	JUMPER/BONDING
5	LOOP4	GAIN = 1 RESISTANCE MSMT	0+3-0	JUMPER/BONDING
6	LOOP5	GAIN = 1 RESISTANCE MSMT	0+3-0	JUMPER/BONDING
7	LOOP6	GAIN = 1 RESISTANCE MSMT	0+3-0	JUMPER/BONDING
8	LOOP7	GAIN = 1 RESISTANCE MSMT	0+3-0	MCM SOCKET
9	LOOP8	GAIN = 1 RESISTANCE MSMT	0+3-0	MCM SOCKET
10	LOOP9	GAIN = 1 RESISTANCE MSMT	1+3-1	MCM SOCKET
11	LOOP10	GAIN = 1 RESISTANCE MSMT	1+3-1	MCM SOCKET
12	LOOP11	GAIN = 1 RESISTANCE MSMT	1+3-1	MCM SOCKET
13	LOOP12	GAIN = 1 RESISTANCE MSMT	1+3-1	MCM SOCKET
14	LOOP13	GAIN = 1 RESISTANCE MSMT	0+3-0	FLEX TEST
15	LOOP14	GAIN = 1 RESISTANCE MSMT	0+3-0	FLEX TEST
16	LOOPCAL2	NOT USED	0	
17	LOOPCAL1	NOT USED	0	
18	VER1	GAIN = 10 RESISTANCE MSMT	2+/-2	FLEX TEST
19	VER2	GAIN = 10 RESISTANCE MSMT	3+/-2	JUMPER/BONDING
20	VER3	GAIN = 10 RESISTANCE MSMT	3+/-2	JUMPER/BONDING
21	VER4	GAIN = 10 RESISTANCE MSMT	3+/-2	JUMPER/BONDING
22	VER5	GAIN = 10 RESISTANCE MSMT	4+/-2	JUMPER/BONDING
23	VER6	GAIN = 10 RESISTANCE MSMT	4+/-2	JUMPER/BONDING
24	VER7	GAIN = 10 RESISTANCE MSMT	4+/-2	MCM SOCKET
25	VER8	GAIN = 10 RESISTANCE MSMT	4+/-2	MCM SOCKET
26	VER9	GAIN = 10 RESISTANCE MSMT	6+/-2	MCM SOCKET
27	VER10	GAIN = 10 RESISTANCE MSMT	6+/-2	MCM SOCKET
28	VER11	GAIN = 10 RESISTANCE MSMT	7+/-2	MCM SOCKET
29	VER12	GAIN = 10 RESISTANCE MSMT	9+/-2	MCM SOCKET
30	VER13	GAIN = 10 RESISTANCE MSMT	3+/-2	FLEX TEST
31	VER14	GAIN = 10 RESISTANCE MSMT	3+/-2	FLEX TEST
32	LOOPCAL2	GAIN = 10 RESISTANCE MSMT	169+/-5	Rcal = 49.9 OHM

(GFE); this impacted the analytical accuracy of the thermal-gradient predictions. The normal experiment sequence for the thermal gradient was as follows: collect a subset of five temperatures during initialization, energize the resistance heater in the thermal simulator MCM for 30 minutes, collect all temperature measurements, power down the experiment for several minutes, power up the experiment, and repeat the data-collection sequence. The flight data clearly reflects the soak temperature, the first rise, the cool down, and the second heat rise. The data also supported the analytical prediction that the maximum heat rise under any condition including faults was <10° C.

2.6.2 Flight Test—Flight data collected during two experiment sequences on 26 February 1999 are shown in Table 2. Data was similarly collected approximately every two weeks from February through September and the results never varied by more than one LSB.

Thermal-gradient temperature measurements are shown from the same date in Table 3. The first column is the pre-heating set of measurements as described earlier. The larger temperature variations in the post-heating data sets reflect the effect of having a concentrated heat source placed in the middle of a field of temperature sensors with varying horizontal distances from the heating source on the reverse side of the panel.

2.7 Comparison Between Ground Test and Flight Test

First, it should be noted that the health and status data collected in each measurement cycle was within normal limits, with power-supply outputs always coming in within tolerance and the check sum for the first data set being correct. The conductivity flight data in Table 1 is representative of all further data sets collected. The data did not vary by more than one least significant bit (LSB); this would be a good indication of the stability of the interconnect system used in MFS for this flight.

The thermal data was well within normal limits and varied appropriately in such a fashion to show all temperature sensors working correctly. Varying ambient conditions due

Table 2. Flight-Continuity Measurement Data

BYTE	NAME	DESCRIPTION	VALUE (DEC)	DATA SET 1	DATA SET 2
1	LOOPCAL1	CALIBRATION MSMT	17+/-3	17	17
2	LOOP1	GAIN = 1 RESISTANCE MSMT	0+3-0	0	0
3	LOOP2	GAIN = 1 RESISTANCE MSMT	0+3-0	1	0
4	LOOP3	GAIN = 1 RESISTANCE MSMT	0+3-0	0	0
5	LOOP4	GAIN = 1 RESISTANCE MSMT	0+3-0	0	0
6	LOOP5	GAIN = 1 RESISTANCE MSMT	0+3-0	0	0
7	LOOP6	GAIN = 1 RESISTANCE MSMT	0+3-0	0	0
8	LOOP7	GAIN = 1 RESISTANCE MSMT	0+3-0	0	0
9	LOOP8	GAIN = 1 RESISTANCE MSMT	0+3-0	1	0
10	LOOP9	GAIN = 1 RESISTANCE MSMT	1+3-1	1	1
11	LOOP10	GAIN = 1 RESISTANCE MSMT	1+3-1	1	0
12	LOOP11	GAIN = 1 RESISTANCE MSMT	1+3-1	1	1
13	LOOP12	GAIN = 1 RESISTANCE MSMT	1+3-1	1	1
14	LOOP13	GAIN = 1 RESISTANCE MSMT	0+3-0	0	0
15	LOOP14	GAIN = 1 RESISTANCE MSMT	0+3-0	0	0
16	LOOPCAL2	NOT USED	0	0	0
17	LOOPCAL1	NOT USED	0	0	0
18	VER1	GAIN = 10 RESISTANCE MSMT	2+/-2	1	1
19	VER2	GAIN = 10 RESISTANCE MSMT	3+/-2	3	3
20	VER3	GAIN = 10 RESISTANCE MSMT	3+/-2	3	3
21	VER4	GAIN = 10 RESISTANCE MSMT	3+/-2	3	3
22	VER5	GAIN = 10 RESISTANCE MSMT	4+/-2	3	3
23	VER6	GAIN = 10 RESISTANCE MSMT	4+/-2	3	3
24	VER7	GAIN = 10 RESISTANCE MSMT	4+/-2	3	3
25	VER8	GAIN = 10 RESISTANCE MSMT	4+/-2	3	3
26	VER9	GAIN = 10 RESISTANCE MSMT	6+/-2	5	5
27	VER10	GAIN = 10 RESISTANCE MSMT	6+/-2	5	5
28	VER11	GAIN = 10 RESISTANCE MSMT	7+/-2	5	5
29	VER12	GAIN = 10 RESISTANCE MSMT	9+/-2	7	7
30	VER13	GAIN = 10 RESISTANCE MSMT	3+/-2	2	2
31	VER14	GAIN = 10 RESISTANCE MSMT	3+/-2	2	2
32	LOOPCAL2	GAIN = 10 RESISTANCE MSMT	169+/-5	176	174

Table 3. Flight-Temperature Measurement Data (all in °C)

TEMP SENSOR NO.	MSMT 1	MSMT 2 POST-HEATING	MSMT 3	MSMT 4 POST-HEATING
TEMP1	13.21	16.51	15.79	17.18
TEMP2		16.54		17.66
TEMP3	12.82	16.50	15.58	17.66
TEMP4		17.11		18.25
TEMP5	13.18	17.02	15.95	18.09
TEMP6		17.16		18.23
TEMP7	13.11	17.52	16.06	18.66
TEMP8		17.66		18.83
TEMP9	12.96	17.57	16.06	18.75
TEMP10		17.44		18.53
TEMP11		17.13		18.19
TEMP12		17.38		18.53
TEMP13		17.46		18.65
TEMP14		16.39		17.72
TEMP15		17.17		18.53

to different spacecraft attitudes and flight away from the Sun were reflected in the data with a general trend towards a colder ambient condition. There was no indication of any failed or degraded sensors.

3.0 TECHNOLOGY–VALIDATION SUMMARY

The following risks were retired with the DS1 MFS demo experiment:

- Use of flex-circuit patches and interconnecting jumpers applied directly to spacecraft panels as an electrical-interconnect system.
- Use of sockets for flight MCMs without risk of opens, shorts, or degradation with time.
- Use of distributed sensors interconnected with flex circuitry to collect data from remote parts of the spacecraft.
- Use of a protective cover that provides an optimum mix of EMI/EMC shielding, radiation shielding and physical protection.

All identified risks that were addressed in the DS1 demonstration were retired. At the time of the experiment conception, the MFS approach was a distinct-paradigm shift from traditional packaging methods to a new system that eliminated the majority of secondary and tertiary packaging to take advantage of the advances in MCM usage. The flight data returned from the experiment did not identify any anomalies and readily met all analytical predictions.

This technology continues to evolve and several organizations are pursuing and/or supporting further improvements and enhancements. Lockheed Martin Corporation (LMA) would be pleased to enter into further efforts to use the MFS packaging system with any interested parties. This would involve the following concerns:

- The design, fabrication, rework/repair, and test of spacecraft panels built without chassis and cabling.
- Hybrid approaches that mix traditional spacecraft chassis/cabling with the MFS design approach.

4.0 TECHNOLOGY APPLICATION FOR FUTURE MISSIONS

In the few short years since the MFS experiment was conceived, a number of applications and further demonstrations of the MFS technology have been produced. Hardware using the MFS concepts and "lessons learned" has been supplied to NMP Deep Space Two (flex-circuit interconnects and the tether system), MightySat II Sindri (solar-array interconnect), Space Test Research Vehicle (STRV) IIc, d (experiment and radiation sensor interconnects and entire top panel), Advanced Technology Demonstration Satellite (ATDS) (AFRL/PL demonstration spacecraft), NMP ST5 (in planning), and a variety of further applications in large inflatable structures and nanosats.

LMA is pursuing several enhancements in the MFS technology. These include: demonstration of radio-frequency (RF) pathways in the flex circuitry using alternative dielectrics, optical pathways, production-optimized flex-bonding systems, and integration with inflatable elements.

5.0 ACKNOWLEDGMENTS

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Appendix A. DS1 Technology Validation Telemetry Channels

MULTI-FUNCTIONAL STRUCTURE

Channel	Mnemonic
O-0051	MFS_mgr_stat
O-0052	MFS_last_cmd
O-0053	MFS_wrds_snt
O-0054	strt_cmd_cnt
D-0192	last_pkt_12
D-0193	buf_typ_12
D-0194	buf_min_12
D-0195	buf_max_12
D-0196	pkt_age_12
D-0197	buf_pkt_12
D-0198	sent_pkt_12
D-0199	spac_used_12
D-0200	bytes_ack_12
D-0201	byte_dump_12

Appendix B. DS1 Technology Validation Power On Times

MULTI-FUNCTIONAL STRUCTURE

MFS initial turn-on was 02/25/99.
Experiment was then conducted bi-weekly from power-off.
Experiment was also conducted weekly with LPE/PASM starting 05/26/99.