The MSX Spacecraft System Design

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The Midcourse Space Experiment is an observatory-class spacecraft carrying 11 optical instruments and 5 contamination instruments. It also contains significant processing power to support these instruments. This article presents the mission, science, and instrument requirements that led to the spacecraft's present configuration, and also highlights the major system attributes.

INTRODUCTION

The Midcourse Space Experiment (MSX) is the 55th spacecraft, as well as the largest and most complex one, to have been built at APL.[1] The spacecraft has been a formidable challenge to the more than 500 people at APL who have worked on it with a myriad of partners from universities, government, and industry.

The MSX Program is sponsored by the Ballistic Missile Defense Organization (BMDO) and is a follow-on mission to the Delta series of experiments, which were launched in the mid to late 1980s.[2] The charter of the MSX mission is to go far beyond what was learned in the Delta series through use of a well equipped space platform, precisely calibrated sensors, and a well conceived, comprehensive set of experiments conducted over a long duration.

The information gathered by the MSX spacecraft will help fill significant spatial, spectral, and temporal gaps that currently exist in space environment models. This information will be needed by designers of future space defense operational systems. Although the MSX's primary mission is to provide the necessary data, another driving factor in the MSX Program is sensor and spacecraft technology improvement. The latest technology is used to provide the most up-to-date phenomenological information and to serve as a new-technology demonstrator.

In addition to meeting the needs of the BMDO, the MSX spacecraft provides a civilian benefit owing to its multispectral and hyperspectral capabilities.[3] Data collected from BMDO-related experiments can be used to perform environmental studies of the Earth. Special environmental monitoring experiments can also be conceived and performed.

MSX ORBIT

The mission design requires a circular orbit at an altitude of about 900 km and an inclination of 99.23°. The orbital plane is initially at about a 50° angle to the Earth–Sun line, and it drifts about 8° per year toward a full Sun orbit. The choice of orbit is a major factor in spacecraft design because it defines the Sun, Earth, and radiation environments that the spacecraft must both survive and use to operate. Sun angles and variations in eclipse time provide the power and thermal design criteria.

SPACECRAFT CONFIGURATION

The design of the MSX spacecraft was driven by a large set of interrelated mission, science, and instrument requirements. However, the fundamental configuration, shown in Fig. 1, was dictated by the size and thermal requirements of the Spatial Infrared Imaging Telescope III (SPIRIT III) instrument. The thermal constraints imposed by this cryogenic sensor forced a design that separates the warm electronics for both the instrument and spacecraft from the colder optical telescopes. Consequently, the system configuration was divided into three sections: the instrument section, truss structure, and electronics section.

The spacecraft stands about 5.2 m tall and 1.8 m wide, not counting the solar arrays. Figure 2 shows a breakdown of the power and weight allocation for the spacecraft bus and instruments. It is significant that almost 50% of both of these resources is allocated to instruments.

The primary objective of MSX is to provide simultaneous spatial, spectral, and temporal data from a scene over a wavelength range of 110 nm to 28 μm. Consequently, all 11 optical sensors are mounted with their lines of sight pointing along the $+x$ axis of the spacecraft. SPIRIT III is mounted inside the truss structure. The remaining 10 optical sensors surround SPIRIT III and are mounted on the instrument section. To enable simultaneous viewing of as much of a scene as possible, coalignment of all 11 optical instruments is maintained within 0.1°. To keep the focal plane detectors and optics as cold as possible and minimize heat loading on the SPIRIT III system, thereby conserving the expendable cryogen, most of the warm, power-consuming electronics associated with the instruments are remotely located on the electronics section at the bottom of the spacecraft. The thermal design of the instrument section incorporates heat pipes to isothermalize the structure independent of which combination of sensors is operating, to aid in maintaining coalignment.

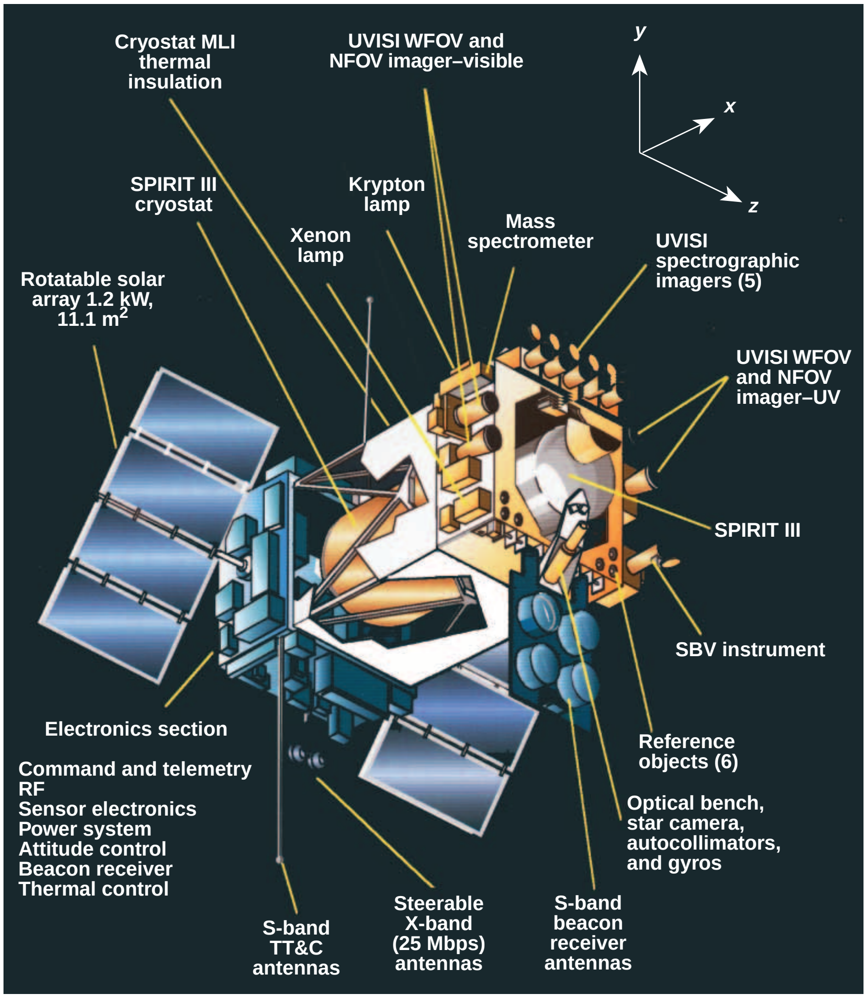

Figure 1. Orbital configuration of the MSX spacecraft, which is divided into three sections: the instrument section in yellow, the truss structure in white, and the electronics section in blue. The division of the spacecraft into these three sections is dictated by the size and thermal requirements of the Spatial Infrared Imaging Telescope III (SPIRIT III). MLI, multilayer insulation; NFOV, narrow field of view; OSDP, Onboard Signal and Data Processor; RF, radiofrequency; SBV, Space-Based Visible; TT&C, telemetry, tracking, and control; UVISI, Ultraviolet and Visible Imagers and Spectrographic Imagers; WFOV, wide field of view.

The truss structure provides the structural integrity to carry the instrument loads (about 1360 kg), and it has a very low coefficient of thermal expansion. These facts ensure that the SPIRIT III, which is mounted at the center points of the truss, and the rest of the instruments mounted on the instrument section atop the truss, remain coaligned to within the 0.1° specification. The truss also thermally isolates the instrument section from the electronics section. The instrument section is designed to operate at around −30°C, whereas the electronics section operates at about room temperature (20°C). To thermally isolate the sections from the SPIRIT III sensor inside, the truss is made of a graphite epoxy material with near-zero thermal conductivity. In addition, liberal use of multilayer insulation blanketing minimizes thermal radiative coupling.

A major design driver for the thermal team was to keep the average temperature of the SPIRIT III outside shell below 250 K, with

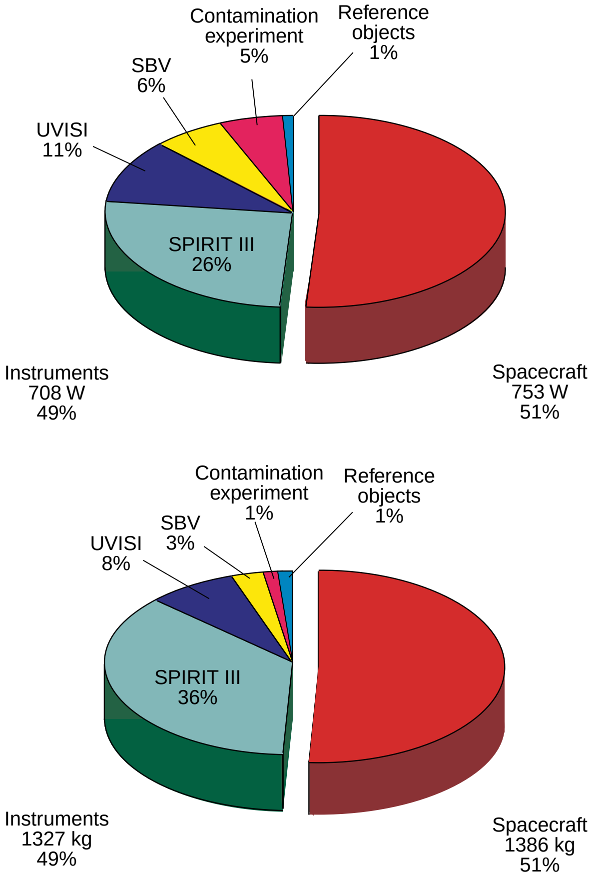

Figure 2. Power breakdown (top) and weight breakdown (bottom) of the MSX spacecraft. Nearly half of both the power and weight is allocated to instruments.

a goal of 225 K. Shell temperature is the major source of parasitic heat leakage into the SPIRIT III cryogenic system; therefore, minimizing this temperature can significantly increase cryogen lifetime. The open truss structure design allows for one side of the spacecraft to view cold space all the time while the other three sides are blanketed. Blanketing isolates the SPIRIT III shell from such heat sources as the Sun and Earth, and even from spacecraft heat sources such as solar arrays. Analytical models predict an average shell temperature of around 200 K, which exceeds the design goal and increases the SPIRIT III instrument lifetime by an estimated 2 months.

The mission requirement for the operational lifetime of SPIRIT III is 18 months. This period of time both satisfies target opportunities and allows the collection of statistically significant data during all seasons. Achieving an 18-month lifetime requires spacecraft operation to be episodic. The spacecraft spends most of its time in a rest state called “parked” mode. Here, it recovers from the last experiment by recharging its battery and allowing critical temperatures to cool in preparation for the next experiment. The parked mode keeps one side of the spacecraft pointed at the Sun, and the optical apertures and dewar radiator pointed to cold space. The SPIRIT III operational duty cycle limitation is set at 10% to achieve the 18-month lifetime. Other experiments may increase that duty cycle provided they have a negligible impact on the SPIRIT III cryogen depletion rate. To provide a margin, the spacecraft is designed to allow about a 20% duty cycle with respect to spacecraft resources, i.e., power, thermal, and data retrieval capabilities.

Several deployable devices are incorporated that enable the spacecraft to fit within the Delta II 3.0-m fairing. These devices are folded (or stowed) when the spacecraft is in its launch configuration. After they are deployed, the spacecraft is in the operational orbital configuration, which is depicted in Fig. 1. The following list gives the deployable items:

- *Solar arrays.* These standard solar arrays and associated deployment mechanisms are derived from the Global Positioning System satellites.
- *S-band antennas.* These are redundant antenna pairs mounted at the ends of two 1.5-m stalks, one on each side of the spacecraft. They are deployed away from the spacecraft body to keep it from significantly disturbing the hemispherical radiation patterns.
- *X-band antennas.* These redundant antennas are mounted on a 0.6-m stalk that is gimballed in two axes. The spacecraft attitude processor steers the two axes to point the antenna at the APL ground station while in parked mode.
- *Beacon receiver antenna bench.* This device is a 0.4-m^2 panel that houses a four-parabolic-dish, phased-array antenna. It is folded down to stow against the side of the instrument section during launch and is released and pinned in place so its antenna beams are pointed in the same direction as the optical instruments.

In addition, all of the optical instruments and one contamination instrument employ a deployable cover. Only the SPIRIT III cover is flyaway; all the rest are hinged and rotate out of the field of view. SPIRIT III also has two pyrotechnic actuated valves to open the cryostat orbit vent and vacuum vent to space after orbit insertion is achieved.

All deployment events are pyrotechnic initiated. The four stowed items and the SPIRIT III pyrotechnic actuated valves are autonomously initiated when separation from the Delta II second stage occurs. The covers are not released immediately, to give time for the contamination cloud around the spacecraft to dissipate. These deployment events are carefully planned and ground initiated, and happen within the first 7 days of orbit.

Jitter on the imaging sensors was a major concern in spacecraft design because any vibrations at sensor focal planes smear the image. Almost all of the optical sensors on the MSX have individual pixels whose instantaneous field of view is around 90 μrad. It was deemed, for science reasons, that the allowable jitter at instrument focal planes should be ±10% of the pixel size, or ±9 μrad. This value is also consistent with the optical designer's point spread function.

To address the issue of jitter, any moving part on the spacecraft had to be carefully designed to minimize its vibrational excitation of the structure. Some large components of particular concern were the four reaction wheels and the two tape recorders; special requirements were invoked that forced their designs to minimize vibration. A flexible body structural model was developed to analyze and verify that these moving parts would not excite significant jitter at any of the instruments. The ring laser gyro, which is part of the attitude determination system, is mounted on the instrument section and can measure jitter at frequencies of up to 100 Hz. Measurements of jitter, obtained while the spacecraft is in orbit, will be used to validate the analytical model.

SUBSYSTEM ELECTRICAL DESIGN

The target tracking experiments are the primary mission of the MSX and the main driver of spacecraft design. These experiments last about 30 min, with all sensors powered and collecting data and the spacecraft slewing at high rates to follow ballistic missile targets. The target tracking experiments constituted the original stressing design case. Secondary and more routine background experiments were originally supposed to be bounded, from the point-of-view of spacecraft resources, by the design of the target tracking mission. As the design matured, however, the repetitive background modes became the driver for optimal thermal system design, and target tracking became an infrequent transient from the background design.

The tracking experiments sized the spacecraft power, attitude, and data handling systems. There is a requirement that the spacecraft be capable of performing a full target tracking experiment without solar input, to permit experiments to be done in eclipse or with the solar panels in an unfavorable solar attitude. A 50-A·h, nickel–hydrogen battery was therefore chosen to supply all of the power for a target tracking event. After an event, the spacecraft returns to a favorable solar attitude, allowing the battery to be recharged. Furthermore, to maintain power balance and allow recovery from a tracking event, the solar arrays are sized to provide about 1200 W of power while in direct sunlight at the beginning of their life.

The kinematics of the target tracking experiment led to the sizing of the attitude control system. Attitude rates of up to 1.6°/s, with accelerations of $0.03°/s^2$, were required for the spacecraft to follow the ballistic missile target through the point of closest approach. The "postprocessing" attitude accuracy of ±9 μrad led to the combination of the star camera and ring laser gyro attitude sensors. Control system design was a trade-off between jitter, high slew rate, and fine pointing requirements. Predicted pointing accuracy varies from 20 μrad (0.001°) for slow maneuvers and inertial stares to 130 μrad (0.0075°) for maximum-rate maneuvers.

The 30-min duration of the target events sized the storage capacity of the onboard tape recorders. The full combination of instruments at their maximum sampling rates requires a spacecraft data gathering rate of 25 megabits per second (Mbps). This figure, combined with event length, led to tape recorders with a 54-Gbit capacity. Routine background experiments do not require the high sampling rate, so another, lower rate mode was added at 5 Mbps. This arrangement allows both longer duration experiments and several successive experiments to be conducted before a downlink is required.

The MSX incorporates another function not normally seen in spacecraft: closed loop tracking on targets other than stars. As seen in Fig. 3, a tracking processor (TP) can take sensor information from several sensors to acquire and closed-loop-track a target. These sensors are identified in the following list:

1. Beacon receiver. This S-band passive radar tracker tracks telemetry transmitters on target vehicles. It has a much wider field of view than the optical instruments, and it guides spacecraft attitude, through the TP and attitude system, to point the target to well within the smaller field of view of the optical sensors.
2. Ultraviolet and Visible Imagers and Spectrographic Imagers (UVISI) narrow field-of-view visible imager, a 1.3° × 1.6° visible band imager.
3. UVISI narrow field-of-view ultraviolet imager, a 1.3° × 1.6° ultraviolet imager.
4. UVISI wide field-of-view visible imager, a 10.5° × 13.1° visible band imager.
5. UVISI wide field-of-view ultraviolet imager, a 10.5° × 13.1° ultraviolet imager.
6. SPIRIT III radiometer. Band A or D can route images to an experimental target processor called the Onboard Signal and Data Processor, which routes target tracking information to the spacecraft TP.

Sensors 2 through 5 can send images to the UVISI image processor. The image processor finds targets and passes tracking information to the TP.

The beacon receiver is the main tracking sensor for target experiments. Targets will have S-band transmitters on board that enable the beacon receiver to acquire and track them using an alpha–beta tracker. The TP receives these data, along with attitude and ephemeris information from the attitude processor (AP) and time from the data handling system, to process in a Kalman

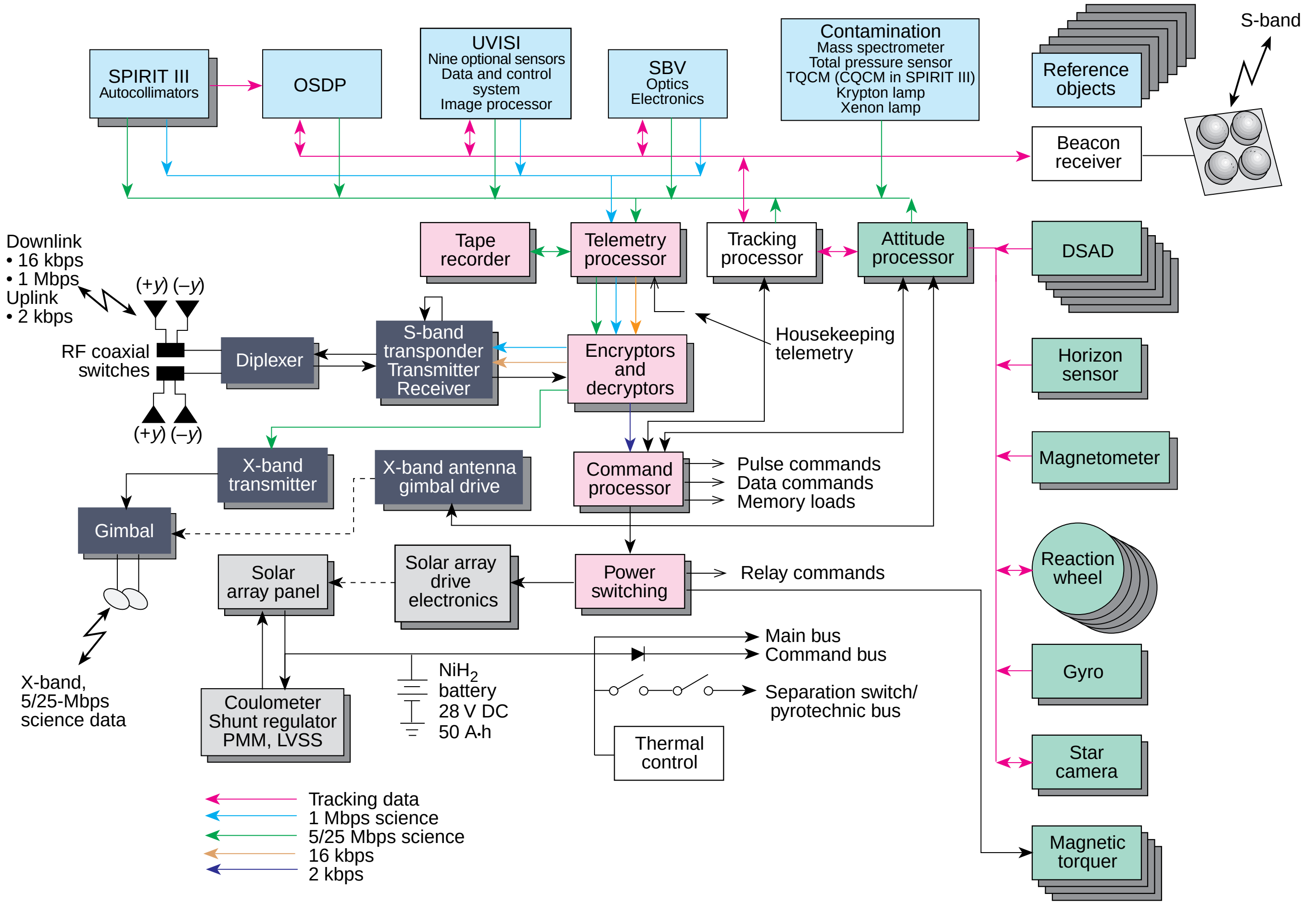

Figure 3. Functional block diagram for the spacecraft. Blocks are color coded by subsystem. Light blue blocks, instruments; green blocks, attitude system; gray blocks, power system; pink blocks, command and data handling system; dark blue blocks, RF system. Shaded boxes behind blocks indicate system redundancy. DSAD, digital solar attitude detector; PMM, power management module; LVSS, low-voltage sensing switch.

filter and output attitude quaternions and rates to the AP. The AP then implements the appropriate control torques to position the spacecraft attitude as directed.

For the TP to adequately use the Kalman filter technique, *a priori* information must be available about target trajectory, or a significant amount of time must be spent in building trajectory information to establish an accurate track. For our experiments, this information is known, and it is loaded into the TP to allow accurate tracks throughout target flight. Other experiments are nonballistic targets and do not lend themselves to use of the Kalman filter. An example is the Auroral Hot Spot Tracking background experiment using the UVISI wide field-of-view ultraviolet imager as the tracking sensor.

The TP also incorporates a wide variety of open loop pointing modes. Open loop pointing is employed for two reasons. First, it facilitates positioning the spacecraft attitude to the initial acquisition point in preparation for going into the closed loop, target tracking events. A preprogrammed target trajectory is stored in the TP for use as a backup in case of loss of track. Second, open loop pointing eases the pointing task of all of the background experiments. The capabilities of open loop pointing are given in the following list:

1. *Polynomial curve fit.* This mode is used where the trajectory can be defined by up to an *n*th-order polynomial. The polynomial coefficients need only be entered; the TP software handles the rest.
2. *Sinusoidal curve fit.* This mode is similar to the polynomial curve fit, but the curve is defined by a sinusoidal equation of up to *n*th-order.
3. *Latitude, longitude, altitude.* This mode makes it easy to point at a certain spot on or above the Earth that is required for both Earth-limb and terrestrial experiments.
4. *Azimuth, tangent height.* This mode is used for Earth-limb pointing experiments. Azimuth is measured relative to the orbit vector, and tangent height is measured as a height above the Earth's surface.
5. *Azimuth, elevation.* This mode is also used for Earth-limb experiments, with elevation measured relative to the orbit vector.
6. *Earth-Centered Inertial unit vector.* This mode is used for celestial experiments.

7. *Earth-Centered Inertial vector with length*. This mode is the same as the unit vector mode but is used for targets closer than infinity.
8. *Satellite trajectory*. This mode allows the MSX to point at any orbital or suborbital target whose trajectory can be defined by a state vector with drag. This open loop pointing method is used to back up the closed loop tracking of missile targets. It cannot, however, be used for missiles that are still thrusting.
9. *Quaternion*. This method can be used to point at any single inertial attitude.
10. *Offset*. A constant offset from any other pointing mode can be programmed. Offset is useful in compensating for mechanical misalignments between the instrument line of sight and the attitude control system line of sight.
11. *Scans*. Scans can be overlaid on any pointing mode to ensure that the target is seen by all sensors. *Geometric scans* specify spacecraft body rates around the axes, while the *time reference mode* controls the scans relative to time.

The TP is used to define pointing for all events that move out of parked mode. The TP sends the information to the AP, which tells it where to point and at what rates. The AP determines spacecraft attitude from its star camera, ring laser gyros, digital solar attitude detectors, horizon sensors, and magnetometer sensors, and it computes reaction wheel control torques needed to achieve that attitude.

The telecommunications system consists of the radiofrequency (RF) communications subsystem and the command and data handling subsystem. The RF subsystem can be divided into two separate systems, the S-band and X-band systems. The S-band system is compatible with all Air Force Satellite Control Network (AFSCN) Remote Tracking Stations around the globe as well as the APL Satellite Communications Facility in Building 36. These links provide standard telemetry, tracking, and control functions as well as a low rate, real time, quick-look science downlink at 1 Mbps. The AFSCN provides the orbit tracking function, keeping both the ground systems and the spacecraft updated on spacecraft ephemeris. Spacecraft updates are scheduled for every 6 h to keep within the accuracy requirement of 200 m. More frequent updates are conducted to accommodate special experiments requiring greater accuracy.

The X-band system is used to downlink the science data recorded on board. All experiments are conducted out of ground contact or do not require ground contact, so the science data are always recorded on the tape recorder for later downlinking. Data from the tape recorders are dumped to the APL ground station at a rate of 25 Mbps, independent of the record rate. A high power, solid state transmitter and steerable high gain antenna are used to downlink the data at that high rate.

The data handling system collects, formats, and stores all data for later downlink. All links, both up and down, are encrypted to prevent unauthorized access to the data. The data handling system also maintains the clock used by all the spacecraft systems and instruments to within 10 ms of Universal Time. Spacecraft clock drift is monitored and corrected by the ground system on a routine basis. The spacecraft's command system receives commands from the ground station, including stored commands to execute experiments when not in sight of a ground station.

Figure 3 shows a functional block diagram of the spacecraft. The subsystems are color coded in the figure.

SOFTWARE

Software is becoming an increasingly important part of spacecraft design. The major role that software plays in the MSX satellite can be seen in Table 1. A distributed processing philosophy is used, so there are as many different types of processors as there are organizations building instruments and spacecraft components. However, one common processor built at APL for multiple subsystem use is a 1750A processor using the radiation-hardened Performance Semiconductor CMOS SOS chip-set. The AP incorporates two such processors, one as an input–output processor and one as a number crunching coprocessor, whereas the command processor, TP, and UVISI image processor each utilize a single one.

The critical attitude control and target tracking software was subjected to extensive, and completely independent, verification and validation by Batelle. In addition, APL's separate attitude processor and tracking processor (AP/TP) test-bed simulator was built to continue the same kind of software testing as the program progresses through launch.

A copy of the AP/TP test-bed simulator has become a valuable part of spacecraft ground support equipment. It provides the only way for the spacecraft test team to conduct realistic testing of the spacecraft attitude and tracking systems. Furthermore, the simulator allows control of solar array simulations, which has improved spacecraft power and thermal performance evaluation during thermal vacuum testing.

The simulator also became a much used tool for the Flight Operations Team as it developed data collection events. Accurate pointing simulations are essential to better event design, given the complex maneuvers that principal investigators request. The simulator will be maintained throughout the mission lifetime in case future software changes are proposed. Changes can be adequately tested before the Configuration Control Board approves them for loading onto the spacecraft.

Table 1. Processors and software used in the MSX spacecraft. The different processors and the variety of software testify to the distributed processing philosophy of the spacecraft design.

Subsystem	Component	Hardware supplier	Processor	MIPS	Function	Language	Software supplier	Lines of code
Attitude	Star camera	Ball Aerospace	RTX 2000	2	Star ID	Assembly	Ball	1,000
	Ring laser gyro	Honeywell	(2) GVSC 1750	2.4	Attitude quaternions	Jovial, Assembly	Honeywell	2,500
	Attitude processor	APL S2F/S3G	(4) PACE 1750A	4	General purpose	ADA	APL S3G	39,842
						Math utilities	APL S3G	7,887
						Assembly	APL S3G	16,157
			(4) 8085	0.2	Serial I/O controller	Assembly	APL S2F	2,200
Power	Power management module	APL S3S	(2) 8085	0.1	General purpose	Assembly	APL S2F	1,354
Command and data handling	Data handling system	APL S2F	(2) 8085	0.1	Data handling system controller	8085 Assembly	APL S2F	4,000
			(2) 8085		Serial I/O controller	8085 Assembly	APL S2F	2,200
	Command processor	APL S2F	(2) PACE 1750A	1	General purpose	ADA	APL S2F	6,188
						1750 Assembly	APL S2F	2,929
Tracking	Tracking processor	APL S2F	(2) PACE 1750A	2	General purpose	ADA	APL S1A	11,689
						Assembly	APL S1A	10,760
			(2) 8085	0.1	Serial I/O controller	Assembly	APL S2F	2,200
Beacon receiver	Data processing unit	APL S2R	Harris 80C86RH	0.5	CPU	C	APL S2R	2,139
						Assembly	APL S2R	72
			(3) ADSP 2100	30	Digital signal processor	C	APL S2R	1,043
						Assembly	APL S2R	806
UVISI	Data control system	APL S1I	(2) 8085	0.3	Sensor control processor	C	APL S1I	2,832
						Assembly	APL S1I	6,132
			(2) 8085	0.3	Instrument control processor	C	APL S1I	3,631
						Assembly	APL S1I	5,151
	Image processor	APL S2F	PACE 1750A	1	General purpose	ADA	APL S1A	3,357
						Assembly	APL S1A	7,946
			ADSP 2100	10	Digital signal processor	Assembly	APL S1A	5,120
			(1) 8085	0.1	Serial I/O controller	Assembly	APL S2F	2,200
	Sensor electronics units	APL S1I	(9) 8085	0.9	Controller	C	APL S2F	2,500
Contamination experiment	Quartz crystal microbalance	QCM Research	Z80	0.1	Controller	Assembly	QCM Research	1,000
OSDP	Object-dependent processor	Hughes	(2) GVSC 1750	3	Object tracking	ADA, Assembly	Hughes	20,000
	Microcontroller	Hughes	(2) 80C31	0.1	Microcontroller	Assembly	Hughes	8,000
SPIRIT III	Command control box	SDL/USU	Harris 80C85	0.1	Controller	Assembly	SDL/USU	1,000
	Downlink telemetry encoder	SDL/USU	Harris 80C85	0.1	Data compression upload	Assembly	SDL/USU	1,000
	Interferometer control electronics	SDL/USU	Harris 80C85	0.1	Interferometer alignment	Assembly	SDL/USU	500
SBV	Experiment controller	SCI, Huntsville	Harris 80C86RH	0.3	Experiment coordination	Forth, Assembly	MIT/LL	39,000
	Signal processor	MIT/LL	Motorola DSP56001	10	Object detection	C, Assembly	MIT/LL	41,100
	Camera	MIT/LL	UTMC 1750	4	Camera control	Native RISC	MIT/LL	4,100
			Totals	**72.8**				**278,535**

CPU, central processing unit
DSP, digital signal processor
MIPS, million instructions per second
SDL/USU, Space Dynamics Laboratory/Utah State University

CONTAMINATION

The optical instruments can be permanently degraded if their mirrors or lenses are contaminated, so the spacecraft design minimizes sources of contamination. All designs use special approved low-outgassing materials, which are thermal vacuum baked to get most of the volatile materials out before spacecraft integration and launch. In addition to outgassing contaminants, particulate contamination is a significant problem, especially for the SPIRIT III infrared sensor. All components are therefore precision cleaned before being assembled onto the spacecraft, and the spacecraft is kept in a class 10,000 clean room where particulate contamination rates are controlled. Four contamination control plans were developed to cover the various phases of the MSX Program:

1. *Contamination Control Plan, Phase 1.* This plan covered spacecraft hardware design to ensure that only approved, low-outgassing materials were used. A nonmetallic material bookkeeping system was kept so that information could be employed by the contamination principal investigator team. In certain cases, where use of approved materials was not possible, an approval and tracking system was implemented.
2. *Contamination Control Plan, Phase 2.* This plan covers the fabrication and spacecraft integration phase of the MSX Program, including component bakeouts, cleaning procedures, and clean-room requirements for buildup of the spacecraft.
3. *Contamination Control Plan, Phase 3.* This plan covers contamination control requirements and activities during system environmental testing of the completed spacecraft at Goddard Space Flight Center.
4. *Contamination Control Plan, Phase 4.* This plan covers launch preparation activities at Vandenberg Air Force Base.

A manifold system was built onto the instrument section to prevent contaminants from entering the optical cavities of instruments. This system flows high purity, dry nitrogen purge gas through the optical cavities at a small pressure above atmospheric. Flow starts when an instrument is integrated onto the spacecraft and continues until the Delta II launch vehicle lifts off and the umbilical is ejected. Contamination monitoring and spacecraft and ground facility cleaning are ongoing efforts during the entire ground operations phase.

CONCLUSION

The MSX spacecraft provides capabilities for pointing, tracking, and data processing in support of 11 optical sensors. The spacecraft also has 5 contamination instruments. The size and complexity of the MSX have made it a formidable spacecraft to design, build, and operate.

REFERENCES

[1] Huebschman, R. K., and Pardoe, C. T., "The Midcourse Space Experiment Spacecraft," in *Proc. AIAA 1992 Aerospace Design Conf.*, Irvine, CA (1992).

[2] Coughlin, T. B., Crawford, L. J., Dassoulas, J., Griffin, M. D., Partridge, P. E., and Peterson, M. R., "Strategic Defense Initiative," *Johns Hopkins APL Tech. Dig.* **13**(1), 200–217 (1992).

[3] Mill, J. D., O'Neil, R. R., Price, S., Romick, G. J., Uy, O. M. et al., "Midcourse Space Experiment: Introduction to the Spacecraft, Instruments, and Scientific Objectives," *AIAA J. Spacecraft and Rockets* **31**(5), 900–907 (1994).

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