

**Earth Orbiter-1, Incorporating New Technology  
Advanced Sensors and Instruments**

Mark E. Perry, PhD.  
Swales Aerospace  
5050 Powder Mill Road  
Beltsville, MD, 20705  
301-902-4341  
mperry@swales.com

Michael McCullough  
Swales Aerospace  
5050 Powder Mill Road  
Beltsville, MD, 20705  
301-902-4533  
mmccullough@swales.com

Wayne Roher  
Litton Amecom  
5115 Calvert Road  
College Park, MD, 20740  
301-454-9146  
wayne\_roher@amecom.com

Matthew M. Jurotich, PhD.  
NASA/GSFC  
Greenbelt Road  
Greenbelt, MD, 20707  
301-286-5919  
matthew.m.jurotich.1@gsfc.nasa.gov

Earth Orbiter-1 (EO-1) is a flight segment of the New Millennium Program, which evaluates new technologies for future space missions. Although EO-1's most important new technologies are part of the Advanced Land Imager (ALI) instrument—which contains several technologies that will be evaluated for use in the follow-on to Landsat 7—many un-proven technologies are incorporated into the spacecraft. Systems engineers are challenged to incorporate as many new and innovative technologies as possible, but still minimize the risk to the primary goal of the mission: to evaluate the ALI performance.

Following a short overview of the EO-1 mission, this paper describes the EO-1 spacecraft bus with an emphasis on the technical solutions required to minimize the risk of incorporating new technologies. New spacecraft technologies are separated into two categories: those that replace a spacecraft component, and those that are stand-alone and treated like a separate payload.

EO-1 weighs 529 kg and will launch in late 1999 into an orbit near Landsat-7: 705 km, sun-synchronized, with a 10:00 AM descending node. The spacecraft is three-axis stabilized, nadir pointing, with advanced avionics, articulating 600-watt Silicon solar arrays, passive thermal control, and a hydrazine propulsion system for correcting insertion errors and orbit maintenance.

## Introduction

Due to the expense of putting satellites in orbit, and the inability to repair them if problems arise, NASA prefers to minimize risk by using proven technology where possible. This slows the introduction of many beneficial technologies, and reduces performance of satellites compared to what would be possible using technology that is more current.

In an effort to speed the incorporation of new technology for space use, NASA created the New Millennium Program (NMP). Led by the Jet Propulsion Laboratory, the NMP has several phases that involve government, academic, and industry partners. The final phase is to validate the technologies with on-orbit demonstrations.

The goal of Earth Orbiter-1 (EO-1) is to perform an on-orbit evaluation of several instrument and spacecraft technologies. The most important of these technologies are sensor technologies that, if proven, will be used in later Landsat and Earth Science Enterprise missions. These technologies will greatly reduce mass, power, cost and development time, while simultaneously increasing performance by several orders of magnitude.

Incorporating several new technologies without incurring unacceptable risk is one of the challenges of EO-1. After describing the mission and the major technologies, we discuss the new technologies and the strategies used to limit risk. We focus on the role of systems engineering in mitigating risk and maximizing performance.

## Mission Overview and Goals

The Earth Orbiter-1 Mission is the first of the NMP Earth-orbiting missions. The Advanced Land Imager (ALI) instrument, built by a team under the leadership of MIT/Lincoln Laboratory, is the primary payload. The ALI is a reflective triplet telescope with multispectral detectors producing the Landsat bands plus four other spectral bands. SSG Inc. designed and manufactured the telescope, and Santa Barbara Research Center (SBRC) manufactured the focal planes.

As prime contractor for the spacecraft bus and mission integration, Swales Aerospace leads the spacecraft team, which includes Litton Amecom, the Hammers Corporation, and Welch Engineering. GSFC is responsible for mission operations. Integration tests and mission operations will both use the same electrical and software support system: the Advanced System for Integration and Spacecraft Test (ASIST). Spitzbergen, Norway, is the primary ground station for both S-Band and X-Band communications.

To compare images with Landsat 7 and EOS-AM-1, EO-1's orbit differs from those missions only in descending node and phase. The orbit is circular, sun-synchronous, at an altitude of 705 km and an inclination of 98.2. The descending nodal crossing time is 10:01 a.m., following Landsat-7 by a minute and preceding EOS AM-1 by about 15 minutes. Figure 1 shows the relative position of each of these satellites. Orbit insertion will be a safe distance from Landsat-7, with an along-track maneuver used to put EO-1 into its final position.

NASA is in the process of performing a feasibility study of adding Hyperion, a hyperspectral imager, to the EO-1 mission. Built by TRW, Hyperion is similar to, and has the same performance as, the Hyperspectral Imaging Spectrometer (HIS) flown on Lewis. (The Lewis mission was lost before collecting any HIS data.) The grating spectrometer is one of the options for future Landsat-like instruments. This potential change will delay launch from May 1999 to late 1999.

As a technology-development mission, EO-1's goals are distinctly different from a science or commercial mission. Images are gathered and evaluated by the science team only to the extent required to assess instrument performance. Most of the technologies do not require continuous operation. Consequently, EO-1 will be in a stand-by mode approximately 90 percent of the time. The one-year mission length permits evaluation of lifetime radiation effects. Except for early orbit, calibration slews, delta-V maneuvers, and emergencies, the mission will be nadir pointing throughout the orbit.

# Constellation Flying

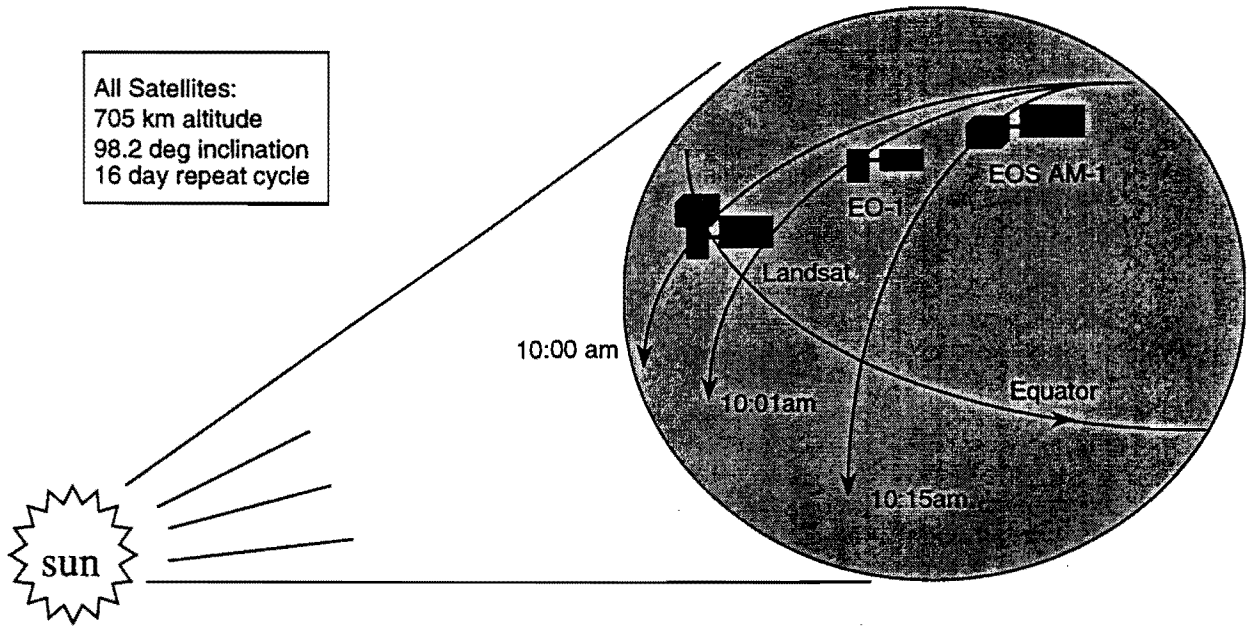


Figure 1 Satellite Relative Positioning

In addition to the technical aspects of the mission, the management of EO-1 incorporates several organizational and teaming policies aimed to reduce cost and shorten the schedule. The streamlined management process reduces formal reviews, formal documentation requirements, and extensive travel to provider sites. For more information, see "Small Spacecraft Bus Development in the New Millennium" by Michael J. Cully in this conference.

## Architecture of the EO-1 Spacecraft Bus

The satellite mass is 529 kg, but may increase to 590 kg if Hyperion is added to the mission. The spacecraft bus provides more than 300 watts of orbit-average power, has 3-axis control to 0.02 degrees, and uses hydrazine propulsion for orbit maintenance. EO-1 design life is one year, with sufficient propellant for an additional year of operation.

EO-1 has a closed, hexagonal primary structure with aluminum-honeycomb equipment panels on each side of the hexagon (see Figure 2). The nadir and zenith decks are machined aluminum, a design that reduces cost and takes advantage of some available mass reserves. Electronics are mounted on the inside of each

equipment panel, and the thermal properties of the outside of the panel are adjusted to reject the correct amount of heat (Figure 3a and 3b). The ALI telescope and its electronics and focal-plane radiator, are mounted and aligned to a pallet that is the single mechanical interface with the spacecraft.

The C&DH and attitude control system (ACS) software resides in the Attitude Control and Data System (ACDS), which contains a 12 MHz Mongoose V processor with 1.8 Gbits of storage. Figure 4 shows the electronics architecture. The C&DH software functions include directing all traffic on the 1773 data bus; storing, executing, and routing commands; formatting and filtering telemetry; failure detection; and safing the spacecraft in event of an anomaly. Most subsystems contain a Remote Services Node (RSN), which is a R000 processor for both 1773 interface and subsystem control.

The ACS is three-axis stabilized and is capable of inertial pointing, sun pointing, and nadir pointing. The ACS uses an autonomous star tracker and a low-noise gyro to provide accurate attitude knowledge. Reaction wheels control the spacecraft, with magnetic torque bars for momentum management. Course sun sensors

are the primary sensors in the sun-acquisition mode (safe-hold) and a magnetometer provides input for momentum management. GPS provides position and accurate time information at 1 Hz.

The power system consists of a 600-Watt silicon array, a 50 Amp-hour NiCd battery, and Power System Electronics (PSE) to manage power, generation, storage and distribution. The power system is modular, with additional services easily accommodated. The solar array articulates about a single-axis to track the sun and is canted at 28 degrees to the orbit plane. The bus voltage is 28+/-7 volts, unregulated. The PSE contains re-settable circuit breakers for each power service. The orbit-average power is over 300 watts. The release mechanisms are paraffin to reduce shock levels and safety concerns. These mechanisms are easily resettable reducing I&T effort.

The blow down hydrazine propulsion system provides delta-V to correct launch vehicle insertion errors, to maintain the orbit, to fly in formation with Landsat 7, and to de-boost at the end of the mission. The propellant tank is a titanium sphere with an elastomer diaphragm and a capacity of 22.3 kg. The thrusters each provide 0.2 pounds of force and contain redundant valves. The four thrusters mount on the zenith-facing deck of the spacecraft and are canted at 15 degrees to provide attitude control in all three axes during delta-V. The propulsion system is built onto the deck of the

spacecraft, which is then integrated as a unit into the rest of the spacecraft.

Image data from all three sensors—the ALI, Atmospheric Corrector (AC), and Hyperion (if flown)—are gathered by the Wideband Advanced Recorder Processor (WARP). The WARP is a solid-state recorder build by GSFC and capable of ingesting data at nearly one Gb/s. The EO-1 WARP stores more than 40 Gbits of data.

EO-1 uses S-band for command and telemetry, and X-band for downlinking image data. The S-band system has two S-band omni antennas and will use TDRSS at 2 kb/s for early-orbit monitoring, but nominal operations for downlink are with the ground at 1 Mb/s. An additional, higher rate of 4 Mb/s is available as a backup, if the X-band fails. The Solid State Recorder (WARP) contains a RF exciter connected directly to the X-band phased-array antenna.

The spacecraft is cold-biased, with redundant heaters to supply make-up heater power in cold conditions. Electronics are mounted to external equipment panels, which act as radiators for excess heat. The spacecraft is tightly coupled, thermally, to reduce thermal gradients. Nominal operating temperature is 0° to 40° Celsius. Special requirements such as 0-20° Celsius for the battery and 5-32° Celsius for the propellant are also accommodated.

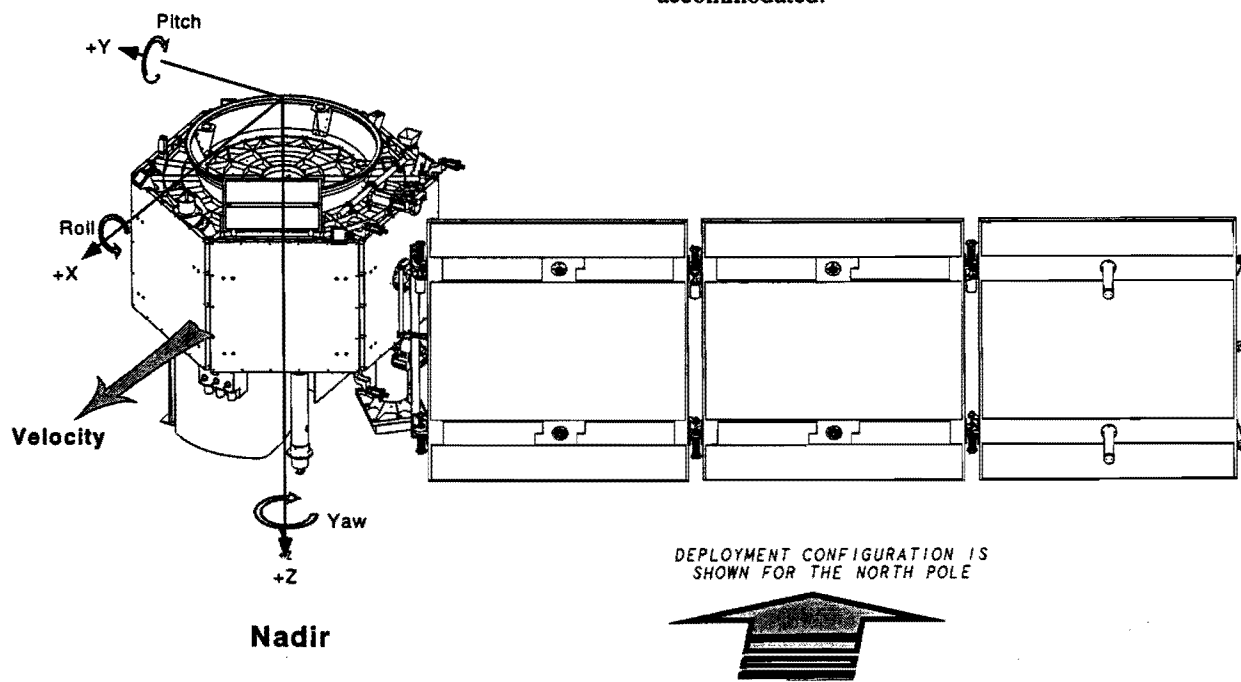


Figure 2

EO-1 Spacecraft Deployed Configuration

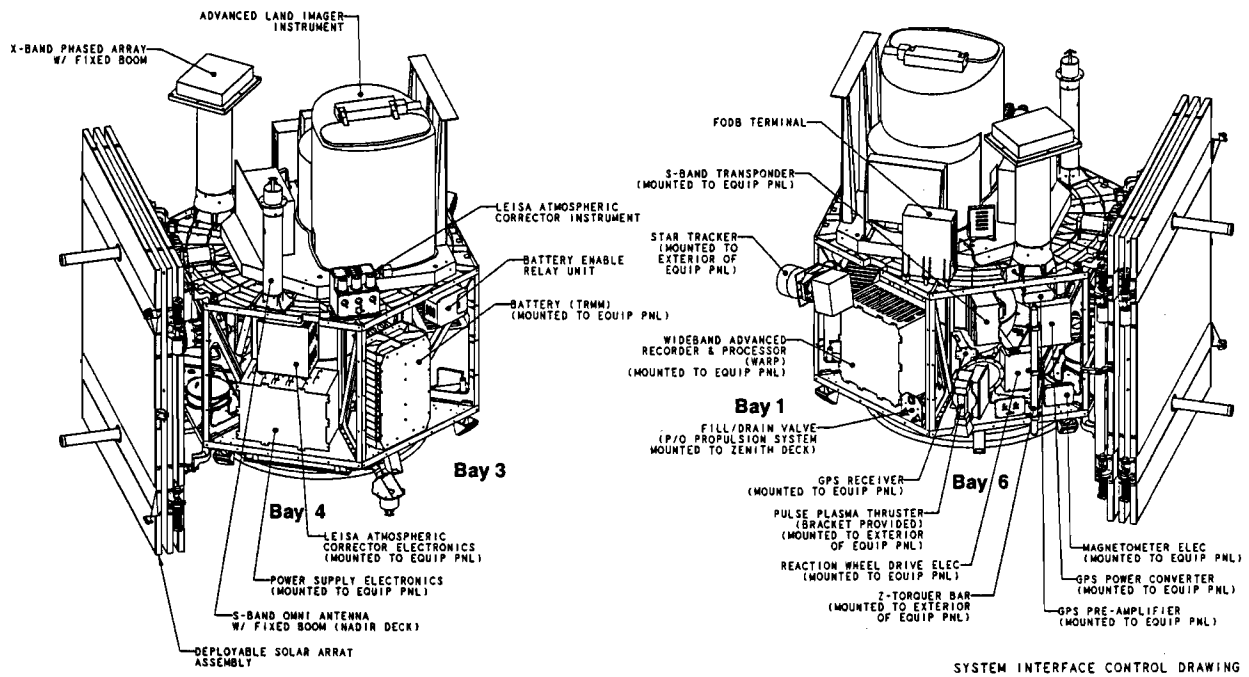


Figure 3a EO-1 Stowed Configuration Mechanical Layout (Nadir View)

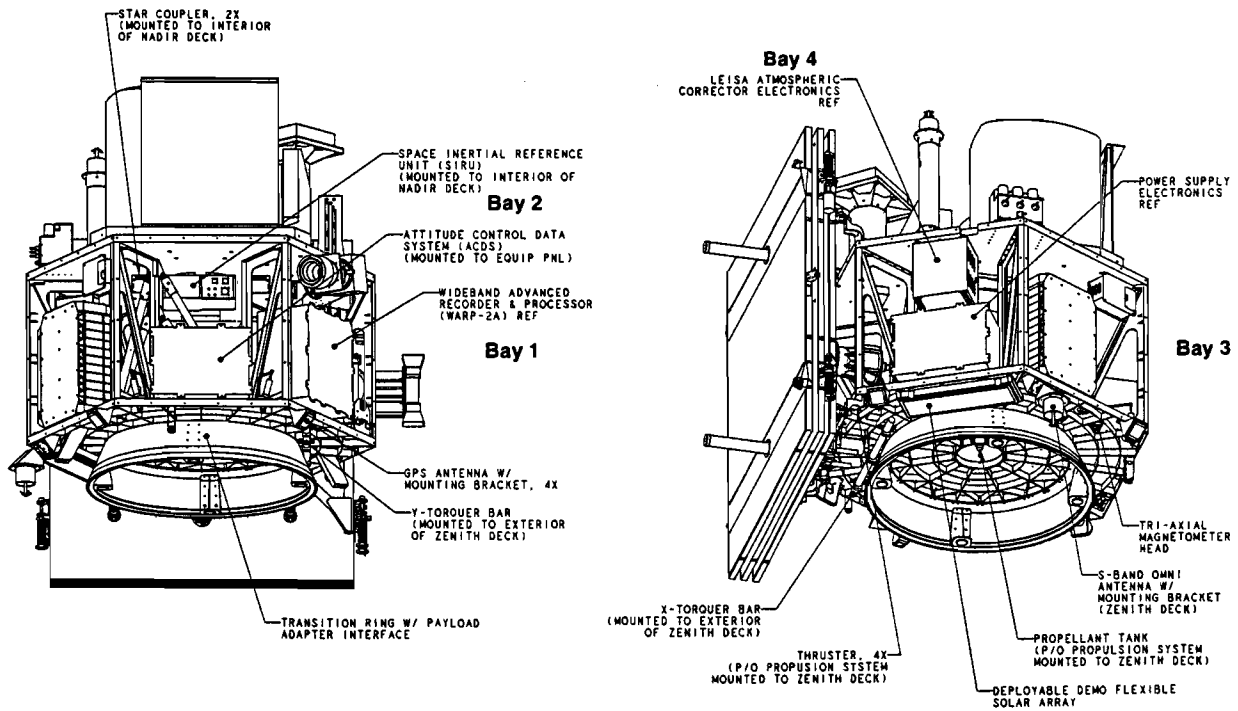


Figure 3b EO-1 Stowed Configuration Mechanical Layout (Zenith View)

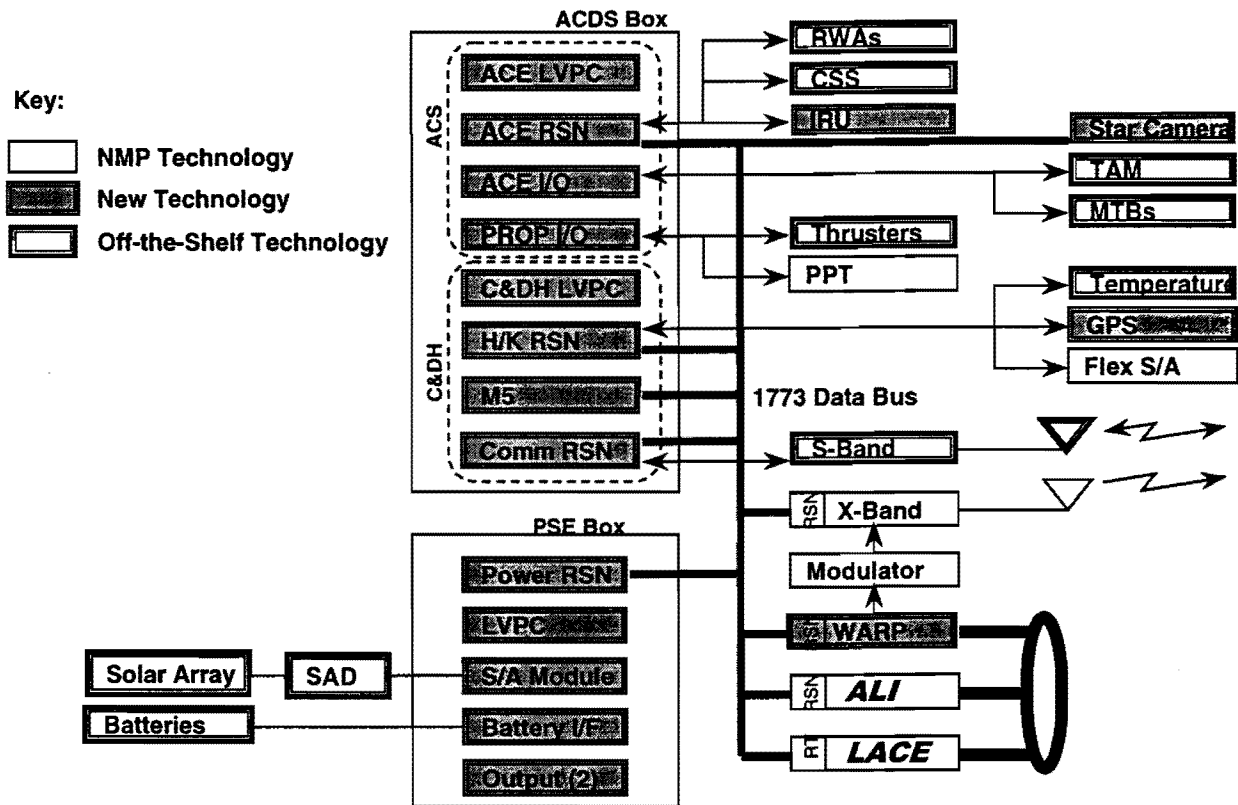


Figure 4 EO-1 Electronic Architecture Implementation

**Payloads and Advanced Technology on EO-1**

To address risk at the top level, the NMP separates new technologies into three categories:

- Category 1 is a defining technology for the mission and is necessary for mission success. On EO-1, the sensor technologies are category 1.
- Category 2 technologies replace an existing subsystem or component that was performing a critical function. These technologies require a backup or alternate approach available in the event that the NMP technology development is unsuccessful or fails on-orbit. There are several category 2 technologies on EO-1, including the X-Band Phased Array.

- Category 3 technologies receive a flight demonstration without interfering with normal operations or higher-category technologies. Category 3 technologies can be secondary payloads such as the lightweight solar array demonstration, which operates and is tested without connection to the spacecraft power system. Or, category 3 technologies can be devices that are functionally switched into the spacecraft when they are evaluated. The pulsed plasma thrusters are an example of this type of technology.

Table 1 lists the new or advanced technologies incorporated into EO-1.

**Table 1 New Millennium Technologies on EO-1**

Technology	NMP Cat.	Description
SiC optics	1	The optics are made of SiC, a high thermal conductivity, low CTE material.
Wide FOV, high-resolution, reflective optics	1	Telecentric optics are compact, high-resolution, and contain no moving parts; ideal for push-broom instrumentation.
Non-cryogenic detectors	1	Detectors at approximately 220 K use Thermal Electronic Control (TEC) and passive radiators rather than cryogenes.
Calibration methodologies	1	Use the sun and moon to demonstrate techniques to get 5% absolute & 2% pixel-to-pixel relative radiometric calibration.
X-band phased array antenna	2	Use electronic pointing to achieve high gain without gimbals. Replaces earth-coverage antenna.
Carbon-carbon thermal radiators	2	Uses high-conductance composite materials as structural elements (composite facesheets).
Linear Etalon Imaging Spectral Array/Atmospheric Corrector	3	Measures water vapor and aerosols to correct ground images for absorbance by the atmosphere.
Pulsed plasma thrusters as attitude-control actuators	3	Low cost, low mass, high Isp propulsion system to demonstrate attitude control. ACS commands will go to PPTs instead of a wheel to demonstrate feasibility.
Lightweight Flexible Solar Array	3	Small secondary payload to test copper indium diselenide/CuInSe2 (CIS) solar cells & ultra-thin mylar substrate & shaped-alloy hinges & release mechanisms.
Formation flying	3	Maintain orbit with high precision relative to another satellite. Ideally, performed autonomously without ground support. Enables coordinated, stereo, & near-simultaneous imaging.
Hyperion	3	Proposed imaging spectrometer, similar to that flown on the Lewis Mission.

• **Category 1 Technologies**

The Advanced Land Imager (ALI) is a wide field of view (FOV) imager that provides Landsat-like images with a higher signal-to-noise ratio and several additional spectral bands. In addition to higher performance than Landsat, ALI is smaller and less expensive. The low-cost, stable optics are a pushbroom design that does not require a scan mirror.

Figure 5 is a schematic of the instrument and the focal plane. Since EO-1 is not a science mission, the multispectral/panchromatic detectors only populate enough of the focal plane to prove the technology. Four Sensor Chip Assemblies (SCAs) occupy one side of the 15-degree FOV, covering about 3 degrees or 35 kilometers on the ground.

Figure 5 also shows two types of imaging spectrometers originally incorporated into the focal plan. The EO-1 Project Office removed both of these spectrometers from the mission when they could not be developed with sufficient performance in time to meet the launch schedule. This is an example of some of the difficult decisions that are required frequently in technology-development missions.

The NMP technologies on ALI also include the optics, which are made of Silicon Carbide, a low-CTE and high thermal-conductivity material that reduces distortion. The detectors operate at 220 Kelvin, eliminating the need for active cooling. Finally, the calibration technologies are considered NMP development items in that new approaches will be tested and assessed.

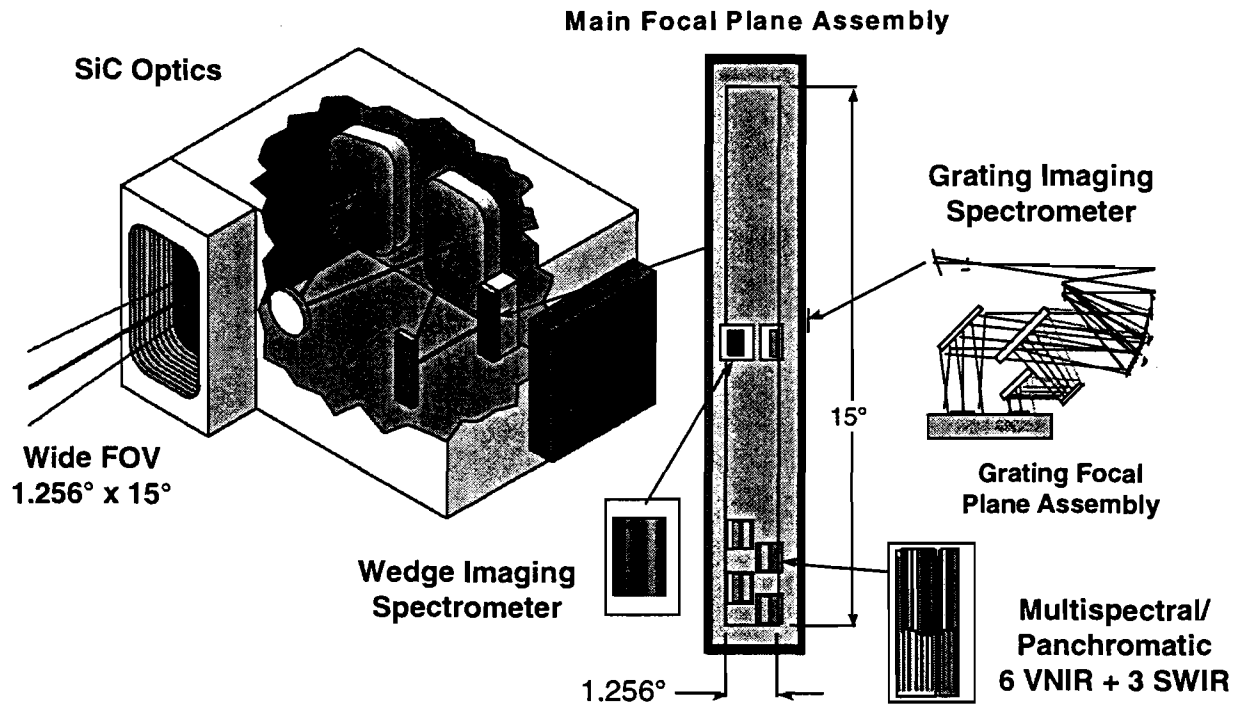


Figure 5 Advanced Land Imager (ALI)

- **Category 2 Technologies**

The X-band system is a phased-array antenna (PAA), one of the NMP technologies. By varying the phase of its 64 antennas, the antenna steers the antenna electronically instead of mechanically. Built by Boeing, the PAA transmits at 105 Mb/s, has a gain of 23 dBi and a 3dB-beam width of 7 degrees. It weighs 5 kg, uses 45 watts of power when transmitting, and is 10x14x3 inches in size. It can scan 360 degrees to an elevation of 65 degrees.

The carbon-carbon radiator (CCR) is a lightweight structural member with high thermal conductivity, in contrast to conventional composites, which are poor conductors of heat. A consortium of industry partners manufactured the CCR. On EO-1, one equipment panel will be CCR, aluminum honeycomb with carbon-carbon face sheets. Swales Aerospace is building a spare equipment panel to use in the event of a problem with the CCR panel. Due to the thermal-expansion mismatch between the CCR and the aluminum spacecraft, the attachment holes are oversized to reduce stress.

- **Category 3 Technologies**

The Pulsed Plasma Thruster (PPT) is a single module propulsion system using an electric arc to generate a high-efficiency ( $I_{sp}=900$  to 1000) pulse of Teflon plasma. On EO-1, the PPT is mounted and used to provide pitch-axis control. During the mission, the operations team will inhibit the pitch-axis reaction wheel, and the PPT will provide the required changes in angular momentum. On future missions, a set of PPTs could replace the reaction wheels, torque bars, and the delta-V propulsion system, with significant savings in cost and mass. The EO-1 dual-axis PPT weighs about 6 kg, and provides up to 1 mN of thrust.

The Linear Etalon Imaging Spectral Array (LEISA)/Atmospheric Corrector (AC) provides high-spectral (30  $cm^{-1}$ ) and low-spatial (250 meters) resolution to measure aerosols and water vapor in the atmosphere. Atmospheric water and aerosol provide the largest degree of uncertainty in ground image spectra. The EO-1 AC is less than 6 kg, including optics and support electronics, and generates about 80 Mb/s of data. Built by GSFC, this instrument has a 15-degree field of view (185-kilometer swath width) and covers 0.85 to 1.6 microns.



The Lightweight, Flexible Solar Array (LFSA) incorporates three new technologies:

- The copper indium diselenide/CuInSe<sub>2</sub> (CIS) flexible photovoltaic cell and its interconnection into a solar array, mounted on a flexible substrate.
- A retention and deployment system of shaped-memory alloy.
- Hinges of shaped memory alloy.

Made by Lockheed Martin, and weighing less than 2 kg (including all interface electronics and housing), the technology can substantially reduce power-system mass. The shaped-memory alloy mechanisms are safe, light and easily reset, also reducing cost and mass. The two demonstration arrays are about 7 by 18 inches, each. To remove risk to EO-1, the power generated by the LFSA is independent of the EO-1 power system.

Enhanced formation flying (EFF) developed by GSFC with industry partners that include the Hammers Corporation, will demonstrate the capability of EO-1 to fly autonomously over the Landsat-7 ground track to within 3 km with 1-minute separation. EFF is a set of on-board software that calculates EO-1's position relative to Landsat 7, and then commands an appropriate delta-V maneuver if necessary to maintain a specified distance or formation. EO-1 will test two EFF algorithms, one developed by GSFC and one developed by JPL. By replacing a large multi-instrument satellite with several smaller and cheaper satellites that can fly in formation, EFF reduces risk and enables additional data such as stereo imaging.

To mitigate the risk to the mission, EFF commands initially are disabled. However, EFF continues to perform maneuver planning, and transmits the calculations to the ground. Only after the operations team verifies that the on-board EFF is planning correct maneuvers will the on-board EFF commands be permitted to actually initiate a delta-V maneuver. Although future EFF implementation will include direct spacecraft-to-spacecraft communications, EO-1 will receive Landsat position via ground communications.

In addition to NMP technology demonstrations, EO-1 incorporates other advanced components and systems. Some of these advanced components are necessary to meet constraints such as the cost cap and the mass limits. Other advanced technology only recently became available, and is compatible with the EO-1 technology-oriented mission goals. Some of the state-

of-the-art technologies incorporated into the EO-1 spacecraft are:

- Resettable, paraffin, non-pyrotechnic release mechanisms. Reduced safety concern and faster reset during testing compared to pyrotechnic-based mechanisms.
- 40 Gbit, 840 Mb/s solid-state recorder. Developed by GSFC. 25 kg.
- Mongoose 5, a 12 MIPs processor, developed under a Space Act Agreement between GSFC and Litton.
- Distributed power architecture, also developed under a Space Act Agreement, will also be flown on GSFC's Microwave Anisotropy Probe Explorer mission.
- Lockheed-Martin autonomous star tracker, providing a quaternion with 20 arcseconds, three sigma accuracy in two axes, and about 50 arcseconds in the third.
- ASIST: component-to-ground system EGSE. By building on box-level test procedures, reduces work and mitigates risk of converting procedures from one test setup to another.
- Loral GPS for constant, accurate position and time information.
- Hemispherical Resonating Gyro supplied by Litton Amecom GN&C Division.

### Problems and Solutions to Incorporating New Technology

There are two main differences between a technology-development mission and a traditional science mission. First, many of the normal systems-engineering challenges of building a satellite are magnified. For example, there are multiple payloads, interfaces, and institutional partners; risk is higher than normally acceptable for space programs; and due to the fast pace and developing technologies, there are many changes during development. These are discussed, below.

The second main difference is that cost and schedule are at least as important as performance. Since the basic spacecraft bus is augmented with multiple technologies—and all contribute to mission success—no single technology is permitted to compromise the mission cost or schedule. Performance is not considered inviolate. If cost or schedule is threatened, performance trades are considered. The technologies do not have a specific science goal, so there is flexibility in how the technology is incorporated into the mission, increasing the available trade space. As

technology is developed, the systems engineers make changes either to improve the probability of a successful test or to remove the technology from the mission, as required by programmatic constraints. To maximize return from the mission, scope-reductions are common, and the early design must be realistically evaluated with respect to program constraints: "buy-ins" will not work.

- **Multiple Payloads**

Multiple payloads make the systems tasks more complex. Because new technologies have not flown before, they often have unexpected features that generate broad-ranging systems effects that only become apparent during development. This is one of the primary benefits of performing a flight demonstration: the complete systems effects are identified and addressed. An EO-1 example is the CCR, which does not attenuate particle radiation as well as aluminum. Using the CCR required additional radiation analysis and some alternate parts.

With multiple payloads, there are more interfaces and there is a greater potential for conflicting requirements. Systems engineers collect the thermal, mechanical, FOV, telemetry, pointing, and data requirements for each payload. The systems engineers must understand the underlying drivers for each requirement. To reduce the number of iterations leading to the final design and to shorten the overall schedule, the systems engineers propose solutions for conflicting requirements. On EO-1, interfaces were established early, along with requirements. All ICDs were developed as part of feasibility studies.

- **Risk Management**

If too much risk is in series with other risks, then overall mission success is threatened. Where possible, new technologies are in parallel with another approach. New technologies are phased during development, with decision points identified. Each technology is categorized (as described above); and mitigation and backup plans put in place. From the initial mission design, work-arounds, graceful degradation, and contingency plans are designed into the mission. On EO-1, there is a backup to the X-band PAA and to the 1 Gb/s fiber-optic data bus. The FODB is currently being considered for removal in order to accommodate the Hyperion Instrument.

There are insufficient funds and schedule for full redundancy, so only mission-critical systems are redundant, and then, only when the redundancy is affordable. The EO-1 redundant systems include the release mechanisms for the solar arrays, the power bus, the 1773 data bus, heaters for the propulsion system, and a backup attitude controller installed on a separate—but already existing—processor.

- **Mission Changes**

The spacecraft team must anticipate change and be able to react quickly, even to major changes. By definition, the new technologies are development projects and may not meet schedule. Even scope reductions affect spacecraft interfaces. To manage change, the overall design is flexible, so that it can easily accommodate additional components mechanically and thermally. EO-1 uses distributed power and communications systems to ease the addition or deletion of payloads.

As soon as a potential change is identified, the systems lead conducts a feasibility assessment within one or two days. Searching for a minimal cost and schedule approach, the lead engineers quickly reviews several options to determine risk, feasibility, and top-level technical and programmatic trades. On EO-1, several new technologies were added after the initial design was complete. These technologies were incorporated with minimal additional cost and limited delays. The spacecraft team is now in the process of assessing adding Hyperion, a second major instrument, less than one year from planned launch.

- **Distributed Responsibilities**

There is another key to successful low-cost, technology missions: the managers and systems engineers must identify and empower lead engineers who have the initiative, capability, and dedication to take full responsibility for their system. Full responsibility includes not just design and manufacture, but also performance, cost, schedule, and interfaces. This empowering distributes the systems-engineering responsibility and ensures several checks on each interface. The EO-1 engineer responsible for the structure also acts as the mechanical systems engineer, confirming interfaces and doing the system layout. This approach minimizes the number of dedicated systems engineers and reduces overall cost.

**Conclusion**

The EO-1 spacecraft, under construction by the Swales-led industry team, is an excellent example of NASA's faster-better-cheaper programs. EO-1 will demonstrate more than ten revolutionary technologies for the new millennium, technologies that will reduce cost and increase performance of future missions. The

spacecraft team is building the spacecraft on a short schedule, and within a cost cap that is a factor of two to three less than a spacecraft with similar capabilities. The engineering challenges inherent in a technology-development mission are met through anticipation of problems, attention to system risks, and flexibility in design and management. Efficient systems engineering is one key to the successful development.