# EO-1 Advanced Land Imager

William E. Bicknell, Constantine J. Digenis, Steven E. Forman, and Donald E. Lencioni
MIT Lincoln Laboratory
244 Wood Street
Lexington, MA 02173

## ABSTRACT

The Advanced Land Imager (ALI), which will be flown on the NASA New Millennium Program's EO-1 mission, has been completed and is being integrated with the spacecraft. The motivation for the EO-1 mission is to flight-validate advanced technologies that are relevant to next generation satellites. The ALI telescope is a reflective triplet design having a 15-degree cross-track field-of-view that employs silicon carbide mirrors. It incorporates a multispectral detector and filter array with 10 spectral bands that cover a wavelength range from the visible to the short-wave infrared. The paper will describe the instrument and its operation, review test results, and suggest application to a future Landsat instrument.

**Keywords:** EO-1, multispectral imaging radiometer, visible to short-wave-infrared, push-broom scan

## 1. INTRODUCTION

The New Millennium Program (NMP) of the National Aeronautics and Space Administration (NASA) is an initiative to demonstrate advanced technologies and designs that show promise for reducing the cost and/or improving the quality of instruments and spacecraft for future space missions. Under this program, missions are intended to primarily validate such technologies and designs in flight by providing useful science data to the user community. The goal is to make future operational spacecraft "faster, cheaper and better," through incorporation of the technologies validated in the NMP. The Earth Observing (EO) missions will flight-validate advanced technologies for the next generation Earth Science Systems Program Office science needs. EO-1 is particularly aimed at future Landsat technology.

The primary instrument of the first Earth Observing satellite (EO-1) under the NMP is an Advanced Land Imager (ALI), with multispectral imaging capability. Overall direction of the EO-1 mission and acquisition of the spacecraft is being carried out by the Goddard Space Flight Center (GSFC) of NASA. MIT Lincoln Laboratory developed the Advanced Land Imager with NMP instrument team members Raytheon Systems Santa Barbara Remote Sensing (SBRS) for the focal plane system and SSG Inc. for the optical system. This instrument comprises an optical system, a focal plane system, a calibration system, and the structural, thermal, and electrical components required to form an integrated unit. Lincoln Laboratory was responsible for the design, fabrication, test and development of the instrument, the software and databases for calibration, and will be responsible for on-orbit performance assessment.

The EO-1 satellite is co-manifested with Argentina's SAC-C (Scientific Applications Satellite) and is scheduled for launch from the Western Test Range on a Delta 7320 in December 1999.[1,2]

## 2. DESCRIPTION AND OPERATION

The overall envelope and configuration of the instrument is depicted in Figure 1. The approximately 0.9m (X) x 0.9m (Y) x 0.7m (Z) size instrument sits on an aluminum pallet that attaches to the spacecraft. In orbit the instrument is wrapped in Multi-Layer Insulation (MLI). The instrument has a velocity vector in the +X direction with the base pallet mounted on the nadir deck of the spacecraft so that earth is in the +Z direction. The thermal radiators for the Focal Plane Electronics and the Focal Plane, itself, are outside the MLI wrap. The telescope is under the MLI surrounded by a thin (~1mm) aluminum housing that supports an aperture cover. The ALI Control Electronics and the Focal Plane Electronics (FPE) packages are supported on the pallet outside the telescope housing.

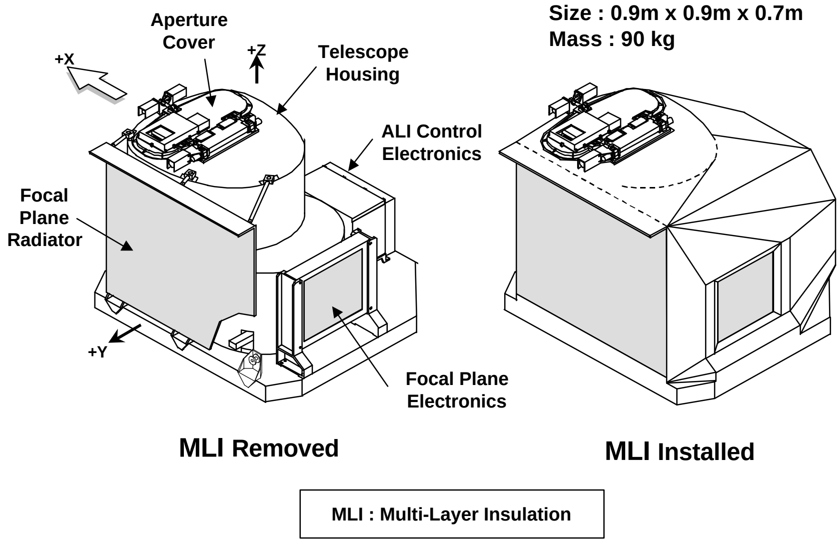



Figure 1. ALI instrument configuration showing the main thermal, mechanical, and electronic components.

Figure 2 shows a conceptual sketch of the wide field-of-view (FOV) optics and a top view of the Focal Plane Assembly (FPA). These are discussed in Sections 2.1 and 2.2. The telescope mirrors are mounted on an Invar truss that also supports the FPA as well as calibration lamps.

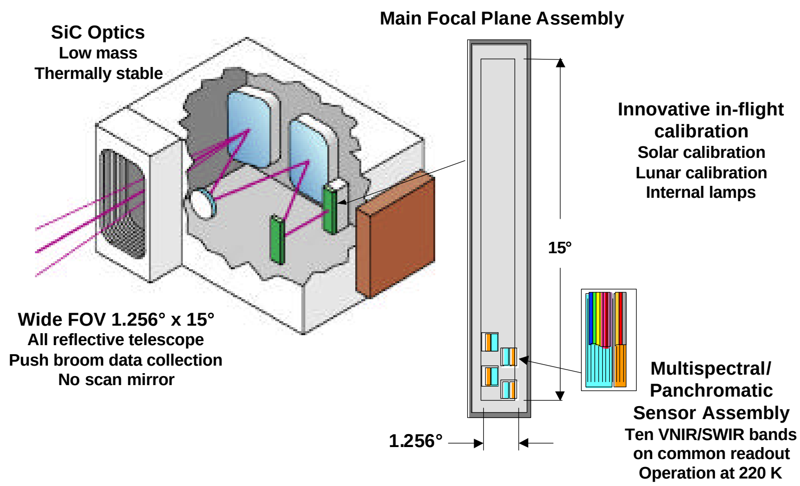



Figure 2. A conceptual sketch of the ALI telescope and Focal Plane Assembly.

### 2.1. Wide Field of View (15°) All-Reflective Optical System

The telescope is a f/7.5 reflective triplet design with a 12.5 cm unobscured entrance pupil and a FOV of 15° by 1.256°. It employs reflecting optics throughout, to cover the fullest possible spectral range. The design uses four mirrors; the primary is an off-axis asphere, the secondary is an ellipsoid, and the tertiary is a concave sphere; the fourth mirror is a flat folding mirror. This technology will enable the use of large arrays of detectors at the focal plane, for covering an entire 185 km swath equivalent to Landsat in a "push broom" mode. The optical design features a flat focal plane and telecentric performance, which greatly simplifies the placement of the filter and detector array assemblies.

The design incorporates silicon carbide mirrors and an Invar truss structure with appropriate mounting and attachment fittings. Silicon carbide has many favorable properties for space optical systems. It possesses high stiffness, high thermal conductivity, and low thermal expansion. Although it has been used for space optical elements previously, it has not been used for such large mirrors. A photograph of the silicon carbide mirrors that are held in place by the Invar metering truss is shown in Figure 3.

**Telescope features**

- **12.5 cm entrance pupil**
- **15° x 1.26° field-of-view**
- **Telecentric, f/7.5 design**
- **Unobscured, reflective optics**
- **Silicon carbide mirrors**
- **Wavefront error = 0.11 λ RMS @ 633 nm**

Figure 3. Photograph of the silicon carbide mirrors supported by the Invar metering truss.

## 2.2. Multispectral Panchromatic (MS/Pan) Focal Plane Array

Although the optical system supports a 15° wide FOV, only 3° was populated with detector arrays, as illustrated in Figure 4. The multispectral panchromatic (MS/Pan) array has 10 spectral bands in the visible, near infrared (VNIR), and short wave infrared (SWIR). The pan detectors subtend 10 m square pixels on the ground and are sampled every 10 m as the earth image moves across the array. The MS detectors subtend 30 m and are sampled every 30 m. The wavelength coverage and ground sampling distance (GSD) are summarized in Table 1. The wavelength intervals were chosen for comparison with Enhanced Thematic Mapper (ETM+) on Landsat 7 and for other science objectives.

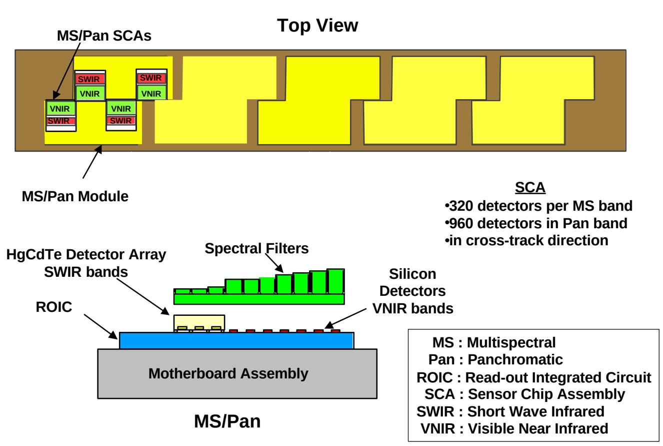



Figure 4. Focal Plane Assembly.

Four sensor chip assembles (SCA's) populate the 3° cross-track segment of the focal plane. Each MS band on each SCA contains 320 detectors in the cross-track direction, while each pan band contains 960 detectors. The total cross-track coverage from the single MS/Pan module is 37 km.

The MS/Pan arrays use Silicon-diode VNIR detectors fabricated on the Silicon substrate of a Readout Integrated Circuit (ROIC). The SWIR detectors are Mercury-Cadmium-Telluride (HgCdTe) photo-diodes that are Indium bump-bonded onto the ROIC that services the VNIR detectors. These SWIR detectors promise high performance over the 0.9 to 2.5 μm wavelength region at temperatures that can be reached by passive or thermoelectric cooling. The nominal focal plane temperature is 220K and is maintained by the use of a radiator and heater controls.

| **Band** | **Wavelength (μm)** | **GSD (m)** |
|---|---|---|
| Pan | 0.480-0.690 | 10 |
| MS-1' | 0.433-0.53 | 30 |
| MS-1 | 0.450-0.515 | 30 |
| MS-2 | 0.525-0.605 | 30 |
| MS-3 | 0.630-0.690 | 30 |
| MS-4 | 0.775-0.805 | 30 |
| MS-4' | 0.845-0.890 | 30 |
| MS-5' | 1.200-1.300 | 30 |
| MS-5 | 1.550-1.750 | 30 |
| MS-7 | 2.080-2.350 | 30 |

Table 1. Summary of the ALI Spectral Coverage and Ground Sample Distances

Application of detectors of different materials to a single readout integrated circuit (ROIC) enables a large number of arrays covering a broad spectral range to be placed closely together. This technology is extremely effective when combined with the wide cross-track FOV optical design being used on the ALI.

The FPE, also supplied by SBRS, provides necessary bias and clock voltages to operate and control the FPA. Both the array frame rate and the detector integration times can be set by commands to the FPE. The nominal frame rate is 226 frames/sec. The nominal integration time for the MS detectors is 4.05 msec while 1.35 msec for the Pan. The frame rate can be adjusted in 312.5 nsec increments to synchronize frame rate with ground scan velocity variations due to altitude and velocity variations during orbit. The FPE samples the output of each detector with a 12-bit converter. The samples are then multiplexed into a 32-bit parallel word (two detector samples plus an 8 bit header), RS-422 output channel that streams the data at a 102.4 Mbit/sec rate to a 44 Gbit capacity, Wideband Advanced Recorder-Processor (WARP) onboard the spacecraft.

### 2.3. ALI Control Electronics

The ALI Control Electronics (ALICE) commands the FPE. The FPE and ALICE operate coupled feedback control systems that maintain the radiator-cooled FPA temperature at a nominal 220K. The FPA operating temperature can be set in 5K increments between 205K and 225K.

The ALICE utilizes surface mount technology and employs a Essential Services Node (ESN) multi-chip module controller developed by NASA and Honeywell for operation and control of spacecraft instruments. ALICE conditions power from the spacecraft for the ALI from a nominal $28\pm7$ V supply. ALICE provides 960 bits of housekeeping data per second for tracking ALI operational state and status. The housekeeping includes 34 temperature sensor readings per second. ALICE receives commands over a 1773 fiber optic cable from the spacecraft Command and Data Handling (C&DH) system and transmits these commands to the FPE and ALI mechanisms.

The nominal standby power required by the ALI is 40 watts. During data collection events, the power increases to about 58 watts. Operation of the calibration lamps and opening and closing the telescope cover (both requiring about a 16 second duration) the power draw increases to 73 watts and 83 watts, respectively. For a typical data collect, the 100-minute average orbital power requirement is 41 watts.

### 2.4. Mechanisms

Figure 5 illustrates several motor-driven mechanisms employed by the ALI. The aperture cover opens for a data collection event and closes after data collection. There is an aperture cover throwback spring that is enabled by firing a High Output Paraffin Actuator (HOPA). The throwback spring would be used in case of motor failure; however, shutting the aperture cover would not be possible after invoking this option.

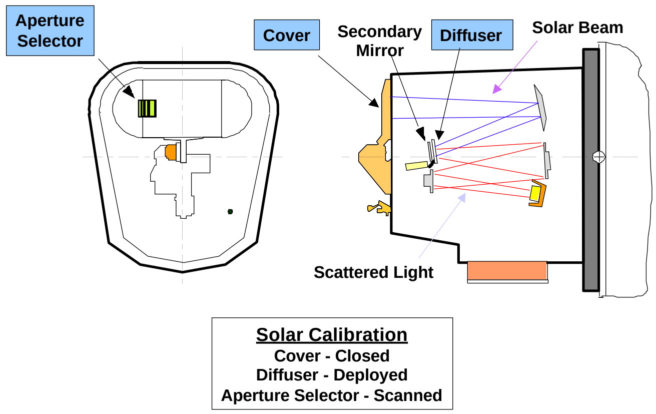



Figure 5. Mechanisms used in ALI.

For solar calibration there is motor-driven Aperture Selector in the Aperture Cover assembly itself. The Aperture Selector moves an opaque slide over a row of small to increasingly larger slit openings and then reverses the slide motion to block all light. Just prior to solar calibration, a Spectralon diffuser plate is swung over the secondary mirror by a motor-driven mechanism. The diffuser reflectively scatters the sunlight that would otherwise impinge on the secondary. During solar calibration the reflectively scattered sunlight exposes the FPA to an irradiance that is equivalent to earth-reflected sunlight for an earth albedo ranging from 0 to 100%. Like the Aperture Selector, the diffuser plate has a HOPA enabled throwback spring to clear it out of the optical path in case the motor fails.

### 2.5. In-Flight Calibration and Operation

The Advanced Land Imager will demonstrate an innovative approach toward accurate radiometric calibration on orbit, using precisely controlled amounts of the incident solar irradiance. The goals are to achieve 5% absolute and 2% relative radiometric calibration accuracy. Solar calibration will be the basis of maintaining absolute accuracy. The instrument also uses internal calibration lamps to routinely monitor status and to provide a reference for each data collection event.

The ALI will produce images that will be directly compared to those from the ETM+. The goal is to demonstrate that the ALI technology will provide data continuity with previous and current Landsat data. The EO-1 satellite will fly “in formation” with the Landsat 7 satellite in a sun-synchronous, 705 km, approximately 100 minute period orbit with a 10:01 am descending node. That is, it will be in an orbit that covers the same ground track as Landsat 7, approximately one minute later. The objective is to obtain images of the same ground areas at nearly the same time, so that scenes may be directly compared. It is planned that this can be done up to 4 scenes per day. Accordingly, the basic field of view, angular resolution, and spectral bands are matched to be as good or better than those of the ETM+.

## 3. GROUND TEST RESULTS

The flight telescope was delivered by SSG to MIT Lincoln Laboratory in April 1998. The Focal Plane System was delivered by SBRS in June 1998. ALI sub-systems were assembled, integrated, and tested over a 9-month period in preparation for delivery to the spacecraft integrator (Swales Aerospace) in March 1999. The integration and assembly followed a set of NASA processes specially tailored for the program quality control, documentation, and cleanliness of space-qualified components and sub-systems. During this time period testing was undertaken for subsystem alignment, for space flight qualification, and for performance measurement.

### 3.1. Thermal and Mechanical Testing

During the past year a number of tests were conducted to establish the qualification of the ALI for launch and space operation. Table 2 summarizes these tests.

| Test | Test Conditions |
|---|---|
| Sine burst acceleration along each axis<br>• ALI Structural Thermal Model | 12.2 g along launch axis, 9.6 g transverse to axis (Qualification Level loads) |
| Random vibration along each axis, one minute per axis<br>• Electronic's Engineering Development Unit<br>• ALI Flight Unit<br><br>Note: Acceleration spectrum was notched as necessary to insure 3 $\sigma$ acceleration loads did not exceed Qualification Level loads at any frequency. | Shaped 20 Hz – 2000Hz acceleration spectrum, $S(f)$<br>• Electronics: $\sqrt{\int_{20}^{2000} S(f)df}$ = 10.6 g RMS<br>• ALI: $\sqrt{\int_{20}^{2000} S(f)df}$ = 5.8 g RMS |
| Mechanism Life Testing<br>• Mechanism's Engineering Development Unit | 1.5 times design life<br>Aperture Selector and Calibration Diffuser: 240 cycles<br>Aperture Cover: 2900 cycles<br>Survive 50°C to -10°C thermal cycle before and after test |
| Thermal Cycle Testing<br>• ALI Flight Unit | 50°C to –30°C survival hot-to-cold soak cycle<br>Four thermal cycles 40°C to –10°C<br>Checked operation before, during, and after each cycle. |

Table 2. Thermal and Mechanical Tests During Development

As indicated in Table 2, an ALI Structural Thermal Model (STM) and an Engineering Development Unit (EDU) of the electronics and mechanisms were developed during the course of fabrication and assembly of the instrument. The STM and EDUs were used for test purposes. The ALI Flight Unit was subjected to vibration and thermal cycle testing. Figure 6 shows the ALI being placed into the thermal vacuum test chamber. The STM, EDUs, and Flight Unit successfully passed all tests.

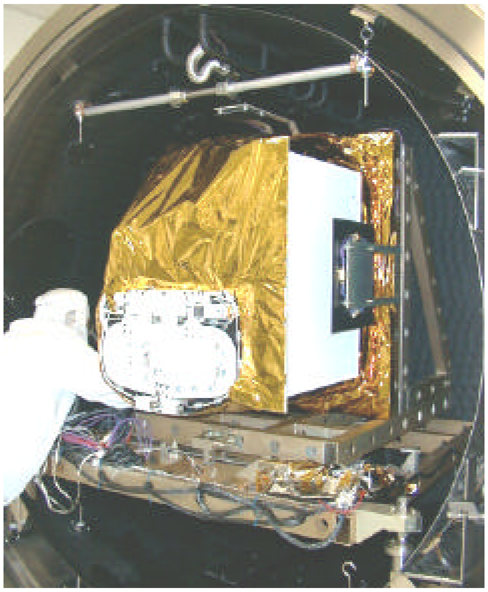


Figure 6. ALI being placed into thermal-vacuum test chamber.

### 3.2. Spatial, Spectral, and Radiometric Testing

Testing during the integration period included a significant number of measurements that characterized the ALI spatial, spectral, and radiometric performance. These will be discussed in subsequent papers of these proceedings.[3-6]

## 4. INSTRUMENT DELIVERY

The culmination of the integration and test effort led to delivery of the instrument to NASA in March 1999. Figure 7 shows the instrument on the spacecraft at Swales Aerospace, Beltsville, MD. Since its installation on the spacecraft the instrument has been successfully operated with the spacecraft C&DH electronics and data has been recorded and faithfully replayed from the WARP.

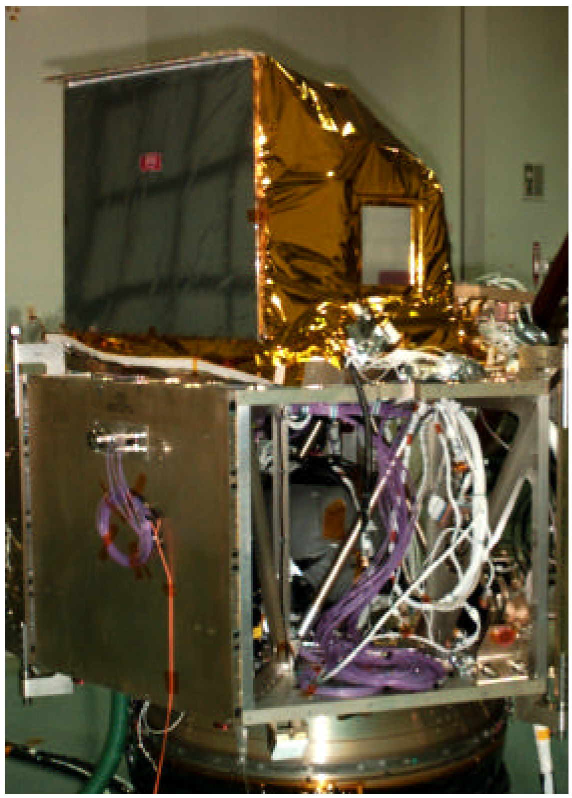


Figure 7. ALI installed on spacecraft at Swales Aerospace.

## 5. APPLICATION TO FUTURE LANDSAT INSTRUMENT

Figure 8 shows the estimated signal-to-noise ratio (SNR) of the ALI for 5% earth surface reflectance as compared to the ETM+. The ALI SNR values are based on measurements during integration and test. In the bands that are common to both instruments, it is seen that the expected ALI SNR ranges from 4 to 10 times greater than ETM+. It is then of interest to consider what is required to fully populate the ALI focal plane.

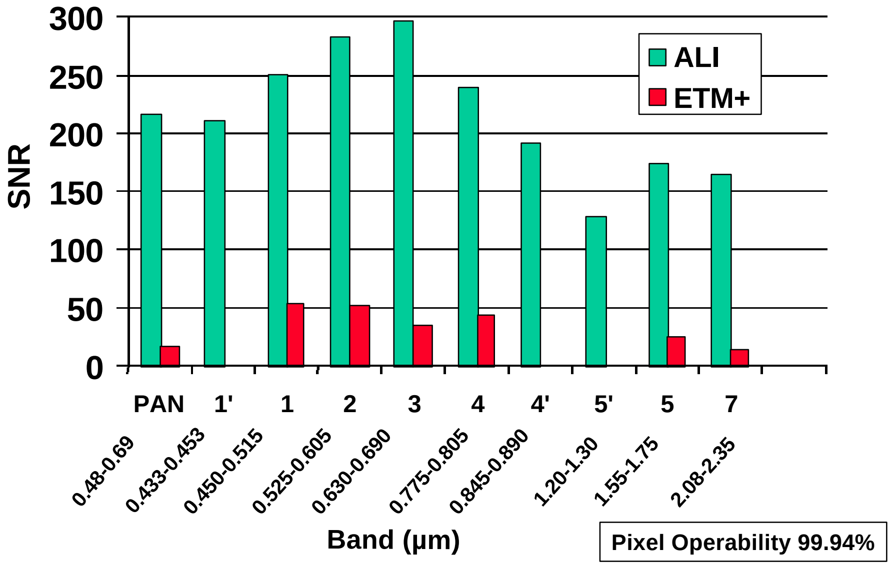



Figure 8. MS/Pan signal to noise ratios at 5% earth reflectance compared with those for ETM+.

Figure 9 addresses the changes needed to fully populate the ALI FPA bench with 5 modules to achieve full 185 km push-broom swath width. The data rate increases by a factor of 5 while it is estimated that the electrical power the FPA would increase about a factor of 3. There would be no physical changes in the instrument design to accommodate this upgrade.

**Populate focal plane with 5 MS/PAN modules**

- Full 185 km wide field-of-view
- Main Focal Plane bench designed for 5 modules

**Changes required to accommodate full MS/PAN coverage**

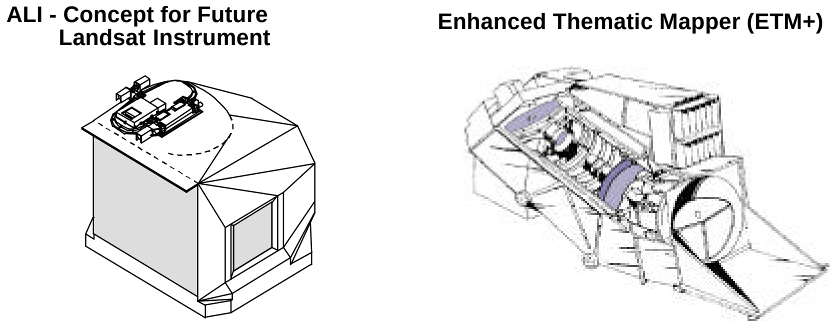
| Resource | ALI | Advanced Landsat |
|---|---|---|
| ❑ Data Ports | 1 | 5 |
| ❑ Data Rate | 102.4 Mb/s | 512 Mb/s |
| ❑ FPE Power | ~ 15 Watts | ~ 50 Watts |
| ❑ FPA Size | 30.7 x 6.6 x 5.2 cm | 30.7 x 6.6 x 5.2 cm |

**Summary**

- No significant physical changes for full Landsat coverage focal plane

Figure 9. Upgrade to full MS/PAN FPA coverage.

Figure 10 compares an ALI with an upgraded FPA to the ETM+. It is seen that the ALI exhibits about one-fourth the mass, one-fifth the power, and about one-third the volume. This along with the improved SNR makes it a very attractive option.




| ALI | | ETM+ |
|---|---|---|
| 100 | Mass (kg) | 425 |
| 100 | Power (W) | 545 |
| 90 × 90 × 70 | Size (cm) | 196 × 114 × 66 |
| 7, 3, 0 | VNIR, SWIR, LWIR Bands | 5, 2, 1 |
| 10, 30 | Pan, MS Resolution (m) | 15, 30 |
| 4-10 | Relative SNR | 1 |

Figure 10. Comparison to Enhanced Thematic Mapper Plus.

## 6. SUMMARY

The ALI has demonstrated breakthrough technologies in the large non-cryogenic MS/Pan FPA, Wide FOV telescope, and silicon carbide optics. It has been thoroughly tested, characterized, and calibrated. It is expected with high confidence that flight tests will validate data continuity with Landsat 7. It provides a pathfinder for an attractive follow-on Landsat and, with technology transfer, would significantly lower follow-on costs.

## ACKNOWLEDGEMENT

The authors acknowledge contributions from Dr. Bryant Cramer, Dale Schulz and Ralph Welsh, Jr. of NASA GSFC; and Dr. Charles Bruce and William M. Brown, Jr. of MIT Lincoln Laboratory to this effort.

## REFERENCES

1. Lencioni, D. E. and Hearn, D. R., “New Millennium EO-1 Advanced Land Imager”, *International Symposium on Spectral Sensing Research,* San Diego, Dec. 13-19, 1997.
2. Constantine J. Digenis, Donald, E. Lencioni, and William E. Bicknell, “New Millennium EO-1 Advanced Land Imager”, *SPIE Conference on Earth Observing Systems III*, San Diego California, July 1998*, SPIE Volume 3439,* pp. 49-55.
3. D. E. Lencioni, D. R. Hearn, J. A. Mendenhall, W. E. Bicknell, "EO-1 Advanced Land Imager calibration and performance," *SPIE Conference on Earth Observing Systems IV*, Denver, Colorado, 18 July 1999.
4. D. R. Hearn, J. A. Mendenhall, B. C. Willard, "Spatial calibration of the EO-1 Advanced Land Imager," *SPIE Conference on Earth Observing Systems IV*, Denver, Colorado, 18 July 1999.
5. J. A. Mendenhall, A. C. Parker, "Spectral calibration of the EO-1 Advanced Land Imager, "*SPIE Conference on Earth Observing Systems IV*, Denver, Colorado, 18 July 1999.
6. J. A. Mendenhall, d. E. Lencioni, A. C. Parker, "Radiometric calibration of the EO-1 Advanced Land Imager," *SPIE Conference on Earth Observing Systems IV*, Denver, Colorado, 18 July 1999.

---

This work was sponsored by NASA/Goddard Space Flight Center under U.S. Air Force, Contract F19628-95-C-0002.

Opinions, interpretations, conclusions, and recommendations are those of the authors and are not necessarily endorsed by the United States Air Force.