The EO-1 Advanced Land Imager: An Overview

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■ The Earth Observing 1 (EO-1) satellite, developed under NASA's New Millennium Program, was successfully launched on 21 November 2000 from Vandenberg Air Force Base, California. The primary land-sensing instrument for this mission is the Advanced Land Imager (ALI), designed and developed by Lincoln Laboratory. ALI collected its first image just five days after launch. Although EO-1 was intended to be a one-year technology-validation mission, ALI still continues to produce valuable science data after five years in orbit. Lincoln Laboratory personnel have evaluated in detail the technical performance of ALI. A team of experienced earth scientists assembled by NASA has also assessed the quality of the science products obtained from ALI and compared the results directly with those obtained from the Enhanced Thematic Mapper Plus sensor on Landsat 7. The results demonstrate that ALI has superior performance in resolution, sensitivity, and dynamic range. These investigations have provided critical input for the design and implementation of next-generation Landsat imagers. This article summarizes the initial ALI program development and Lincoln Laboratory's role in the mission formulation. We also give an overview of ALI instrument design and performance. Finally, we discuss the relevance of ALI to future land remote sensing instruments.

The missions of the New Millennium Program, sponsored by the National Aeronautics and Space Administration (NASA), are structured to accelerate the flight validation of advanced technologies and designs that show promise for dramatically reducing the cost and improving the quality of instruments and spacecraft for future space missions. These technology validations are accomplished in the context of science measurement objectives. The focus for the Earth Observing 1 (EO-1) satellite is the validation of those technologies relevant to future land imaging applications such as future Landsat missions. The Advanced Land Imager (ALI), developed at Lincoln Laboratory, has been designed to produce images directly comparable to those from the Enhanced Thematic Mapper Plus (ETM+) of Landsat 7.

Key technology features of the ALI include a 15° field-of-view push-broom instrument architecture with a 12.5 cm aperture diameter, compact multispectral detector arrays, a non-cryogenic HgCdTe detector array for the shortwave infrared (SWIR) bands, silicon-carbide optics, and a multilevel solar calibration technique. The focal-plane detector arrays cover ten spectral bands spanning the 0.4 to 2.5 micron wavelength region. A single panchromatic band has a 10 m ground sampling interval, while the nine multispectral bands have a 30 m ground sampling interval. The partially populated focal plane provides a 3° cross-track coverage corresponding to 37 km on the ground. The focal plane was designed in a modular fashion so that the full 15° coverage could be achieved by simply replicating the 3° ALI detector module four more times.

The detailed technology validation was conducted by Lincoln Laboratory. The validation of science products obtained from ALI was completed by the EO-1 Science Validation Team, a group of internationally renown scientists selected by NASA. The preflight and on-orbit results demonstrated superior performance in resolution, sensitivity, and dynamic range for ALI. These investigations are providing critical input for the design and implementation of the next-generation Landsat imager. An ALI with a fully populated focal-plane array would be smaller and less massive, and it would require less power and be less expensive than the ETM+ on Landsat 7.

The Historical Importance of Landsat

Landsat is the nation's oldest land-surface observation satellite program. It has collected images of the earth from space since 1972. The continuation of this work is an integral component of the U.S. Global Change Research Program. In October 1992 the Land Remote Sensing Policy Act was signed into law, identifying data continuity as the fundamental goal of the Landsat program. All Landsat imagers, however, including the most recent Landsat 7, have used essentially the same technology for the past three decades. A provision of the Land Remote Sensing Policy Act states that NASA should "provide for a technology demonstration program whose objective shall be the demonstration of advanced land remote sensing technologies that may potentially yield a system which is less expensive to build and operate, and more responsive to data users, than is the current Landsat system" [1].

EO-1 and the Advanced Land Imager

The genesis of the EO-1 mission, or at least Lincoln Laboratory's involvement in the mission, can be traced to a one-month Landsat study conducted by Lincoln Laboratory in January 1994 [2]. That study was requested by then–NASA Administrator Daniel Goldin shortly after the launch failure of Landsat 6 on 5 October 1993. The objective of the study was to develop a quick and inexpensive land remote sensing mission design, including sensor, spacecraft, and launcher, which would serve as a Landsat gap-filler and thus maintain data continuity. Although the study findings were not implemented immediately, they would ultimately prove to have significant influence on both the EO-1 sensor design and the overall mission concept.

During the spring of 1994, and again in late winter 1994–95, technical personnel at the Laboratory worked with their counterparts at NASA's Goddard Space Flight Center (GSFC) to further refine an advanced-technology Landsat follow-on mission [3]. The collaboration with GSFC resulted in the mission concept that was selected by NASA headquarters as the basis for the first New Millennium Program Earth Observing Mission. During the fall of 1995 Lincoln Laboratory personnel were chosen as members of the New Millennium Program Integrated Product and Development Team. Numerous technologies and mission concepts were explored. A collaboration of team members from SSG Inc., Santa Barbara Remote Sensing, and Lincoln Laboratory resulted in the Mission Concept Design Study, which led to the design concept and technologies for ALI [4] that were ultimately selected by NASA for the EO-1 mission.

After three years of intense development and testing, Lincoln Laboratory delivered ALI to NASA in early 1999, and EO-1 was launched into space on 21 November 2000. ALI recorded its first images of land areas from space five days later. Figure 1 summarizes the historical time line for the development of EO-1 and ALI.

ALI Design and Operation

The ALI performance requirements and basic design were developed from the bottom up by the instrument team in close collaboration with the earth science community. The key goals were to meet or exceed Landsat ETM+ performance (without the thermal band) at minimum size, weight, schedule, and cost. The spectral band suite was augmented for science reasons. The Landsat heritage band 4 was split into two subbands to eliminate the water-vapor absorption feature at about 824 nm. A band at 442 nm was added to obtain coastal and aerosol data. An additional SWIR band was added in the atmospheric window at 1244 nm. The upper cutoff of the panchromatic band was reduced to enhance the contrast between vegetation and non-vegetation regions. The ground sample distance (GSD) of the panchromatic band was reduced to 10 m. The dynamic range was increased to cover a

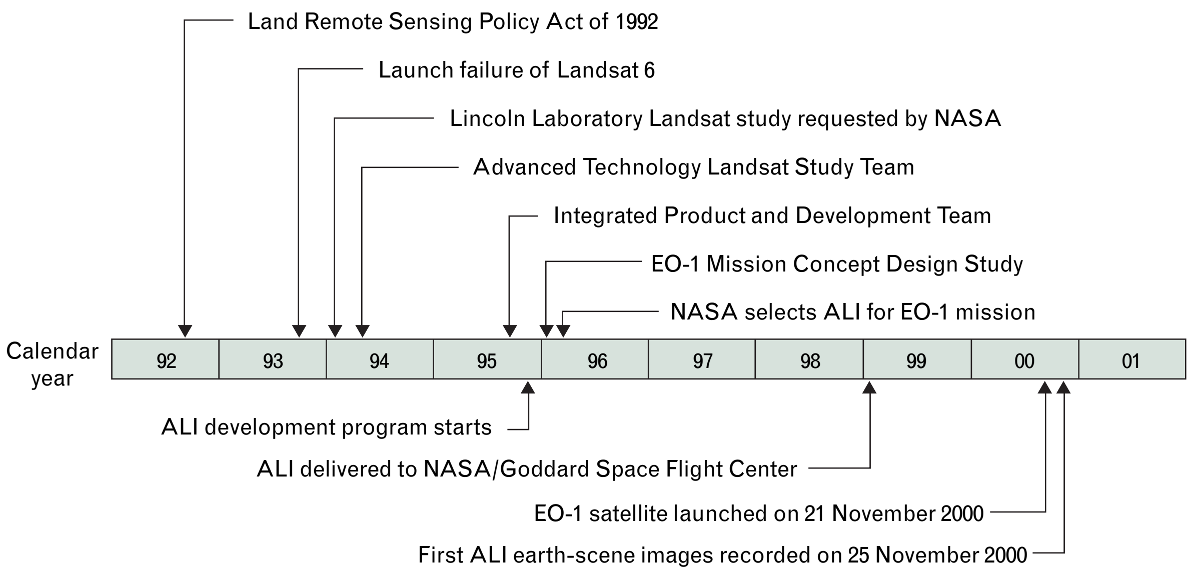


FIGURE 1. The historical time line for the development of the Earth-Observing 1 (EO-1) satellite and the Advanced Land Imager (ALI). Lincoln Laboratory's involvement began with a one-month Landsat study requested by NASA in 1994, and culminated in the launch of ALI onboard EO-1 in November 2000. Although ALI was initially designed as a one-year Landsat technology-validation study, it has continued to supply land imagery to the earth science community for five years.

100% albedo with one gain state. The signal-to-noise ratio (SNR) was increased by four to ten times the ETM+ values. Additional technical goals included the demonstration of spatial, spectral, and radiometric calibration for large detector arrays. Other performance goals were guided by the Landsat 7 specifications [5].

Basic Architecture of the Imaging Sensor

The design approach for the sensor was to reduce the optical diameter, and therefore the weight, by increasing the number of detectors in the focal-plane array. The payoff can be quantified with a simple performance scaling law for a background-limited sensor. For each spectral band

$$\frac{\mathrm{SW} \times \mathrm{SNR}^2}{L \times \mathrm{GSD}} \propto D^2 \times N ,$$

where SW is the swath width, SNR is the signal-to-noise ratio, L is the in-band radiance being measured, GSD is the ground sample distance, D is the pupil diameter of the optical system, and N is the number of detectors. The left side of the equation contains the system performance requirements, while the right side contains the key design trade-off parameters.

Increasing the number of detectors allows an improvement in system performance as well as a reduction in optical diameter and therefore a reduction in sensor size and weight. The minimum acceptable optical diameter is in general constrained by matching the GSD to the diffraction limit. When the number of detectors in the cross-track direction times the GSD is made equal to the swath width, then push-broom imaging can be employed. The push-broom system represents a significant design simplification compared to the whisk-broom approach employed in the previous Landsat sensors.

The cross-track field of view required for the Landsat mission is 15°. High-quality image performance over such a large field of view can be achieved with an off-axis three-mirror anastigmat optical design form. The field of view achievable in the in-track direction is considerably smaller than the cross-track field of view, and thus restricts the physical size of the focal plane in that dimension. Application of detectors of different materials to a single read-out integrated circuit enables a large number of spectral bands covering a broad spectral range to be placed close together. This close proximity of the spectral bands was achieved with a

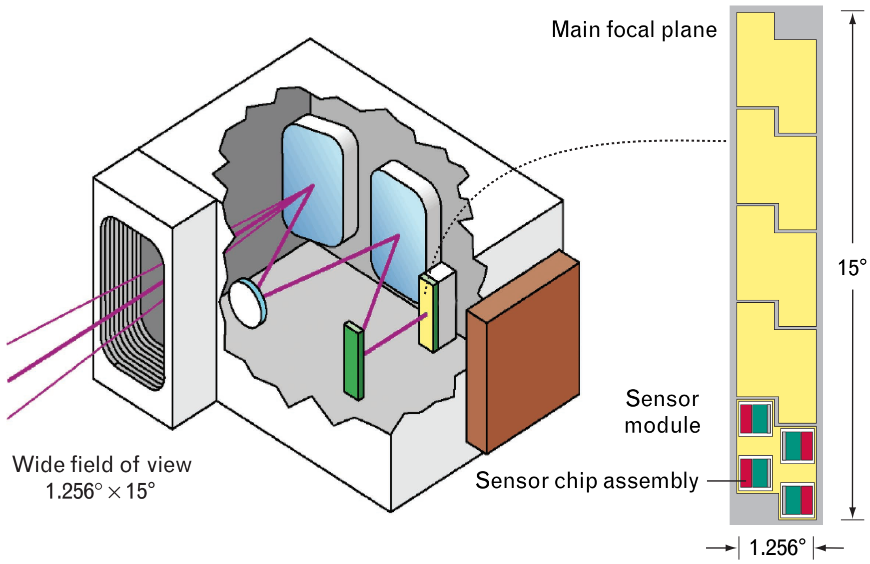


FIGURE 2. Conceptual sketch of the optical design of the ALI telescope, and an illustration of the main focal plane. The optical design enables a 15° cross-track field of view, which translates to a 185 km swath width when imaging the earth, identical to the swath width of the Landsat satellites. The main focal-plane assembly, shown in yellow in the ALI telescope sketch, can contain up to five sensor modules. Each sensor module consists of four panchromatic/multispectral sensor chip assemblies, containing a panchromatic sensor and nine multispectral channels. The panchromatic channel has a ground resolution of 10 m, and the multispectral channels have a ground resolution of 30 m.

novel hybrid consisting of a visible and near infrared (VNIR) detector and a SWIR detector on a common readout chip. This technology is a perfect complement to the wide field-of-view optical design used on ALI.

Instrument Description

The conceptual sketch shown in Figure 2 illustrates the major design features of the ALI telescope. The telescope is an *f*/7.5 reflective Cooke triplet design with a 12.5 cm unobscured entrance pupil, with a field of view 15° cross-track by 1.256° in-track. The ALI design 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, the tertiary is a concave sphere, and the fourth is a flat folding mirror. This technology enables the use of large arrays of detectors at the focal plane, allowing coverage of an entire 185 km imaging swath width, which is equivalent to the Landsat swath width in a push-broom imaging mode.

The optical design features a flat focal plane and near telecentric performance, which greatly simplifies the placement of the detector array assemblies and

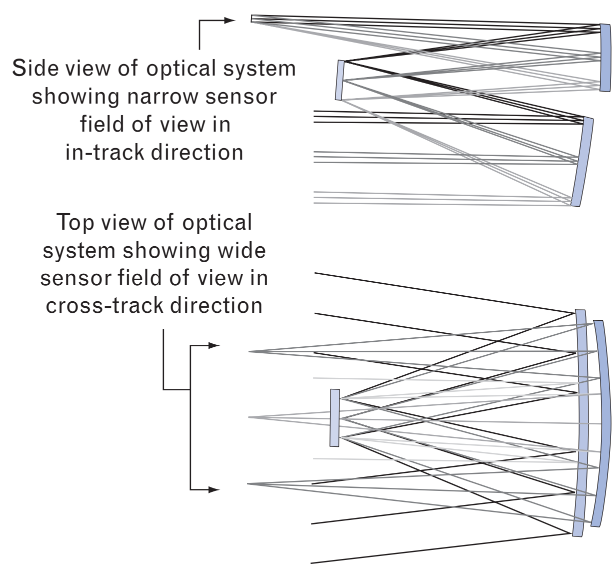


FIGURE 3. Optical design form for the ALI. This design is a reflective version of a Cooke triplet, consisting of an aspheric primary mirror, an ellipsoidal secondary mirror, a spherical tertiary mirror, and a flat folding mirror. This design supports a large field of view in one dimension and is ideal for a push-broom sensor with a large cross-track field of view. The telecentric performance of this mirror assembly simplifies the placement of the detector modules and the design of the spectral filters.

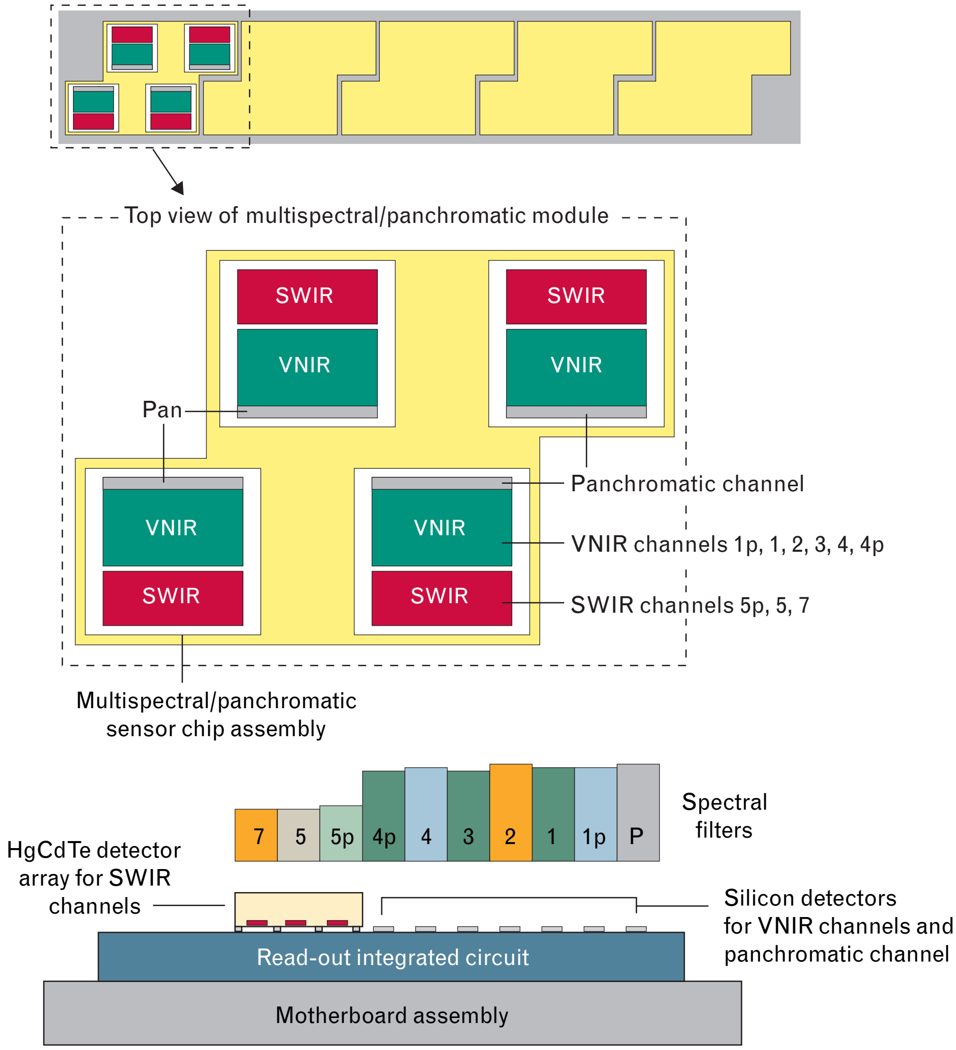


FIGURE 4. The ALI focal plane and the layout of the sensor chip assembly, showing the location of the three shortwave infrared (SWIR) channels, the seven visible and near infrared (VNIR) channels, and the panchromatic channel on the read-out integrated circuit.

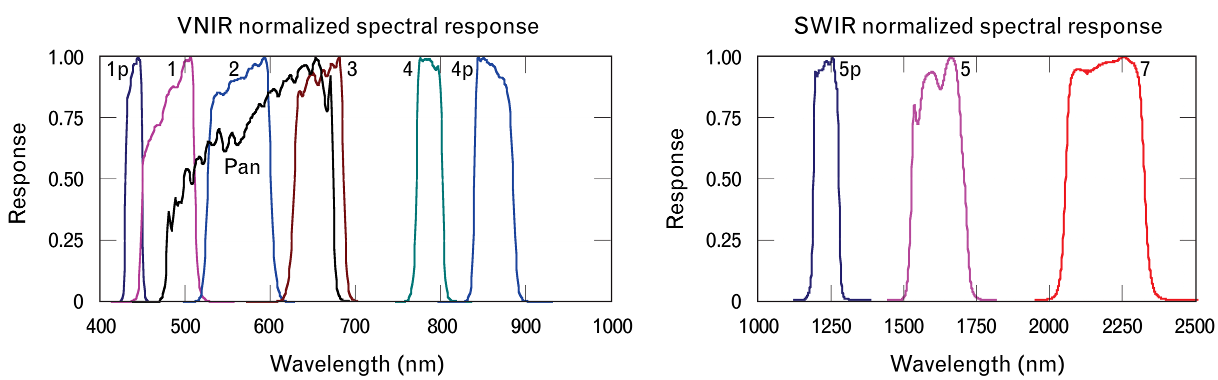
the designs of the spectral filters. The optical design incorporates silicon-carbide mirrors and an Invar truss structure with appropriate mounting and attachment fittings. Silicon carbide has many favorable properties for space optical systems. It possesses a high stiffness-to-weight ratio, a high thermal conductivity, and a low coefficient of thermal expansion. Figure 3 illustrates a ray trace summary of this design form.

Although the optical system supports a 15° wide field of view, only 3° of this field of view was populated with detector arrays, as illustrated in Figure 2 and Figure 4. The focal-plane assembly is designed to hold up to five sensor modules. For this technology-validation study, however, only one sensor module was used in the ALI focal plane, limiting the field of view to 3°. Four sensor chip assembles populate the 3° cross-track segment of the focal plane. Each multispectral band on each sensor chip assembly contains 320 detectors in the cross-track direction, while each panchromatic band contains 960 detectors. The total cross-track coverage from the single multispectral/panchromatic module is 37 km. The multispectral detectors subtend 30 m square pixels on the ground and are sampled every 30 m. The panchromatic detectors subtend 10 m and are sampled every 10 m as the earth image moves across the array.

The multispectral/panchromatic arrays use silicon-diode VNIR detectors fabricated on the silicon substrate of a read-out integrated circuit. The SWIR detectors are mercury-cadmium-telluride (HgCdTe) photodiodes that are indium bump-bonded onto the read-out integrated circuit that services the VNIR detectors. These SWIR detectors promise high performance over the 0.9 to 2.5 micron 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. Application of detectors of different materials to a single read-out integrated circuit enables a large number of arrays covering a broad spectral range to be placed close together. This technology is extremely effective when combined with the wide cross-track field-of-view optical design used on ALI.

The multispectral/panchromatic array has seven spectral bands in the VNIR (labeled Pan, 1p, 1, 2, 3, 4, and 4p), and three spectral bands in the SWIR (labeled 5p, 5, and 7), as illustrated in Figure 4. The ten spectral filter wavelength intervals were chosen for comparison with the ETM+ sensor on Landsat 7 and for purposes dictated by the other science objectives summarized previously. We used two methods to determine the normalized spectral response functions in our calibration plan. The first method relied on combining the individual component measurements—the spectral reflectance of the four mirrors, the transmissions of the filters, and the detector responses. The product of these terms when normalized to the peak is expected to give an accurate estimate of the system response. Note that errors in this function are of second order, since the magnitude of the transmission is carried in the calibration response coefficients. The second method used measurements made at the full sensor system level with the ALI under simulated flight conditions in the thermal vacuum test chamber. This method not only provided measurements through the full optical path but also detected any vacuum- or thermal-induced effects such as contamination, outgassing, or dimension changes of the optical coatings The two methods were in excellent agreement.

Figure 5 summarizes the wavelengths and bandwidths of the ten spectral response functions that were implemented on ALI. The details of these spectral measurements are described elsewhere in this issue in an article entitled "Spectral and Radiometric Calibration of the Advanced Land Imager," by Jeffrey A. Mendenhall, Donald E. Lencioni, and Jenifer Evans.



ALI spectral bands	1p	1	2	Pan	3	4	4p	5p	5	7
Wavelength (nm)	442	485	567	592	660	790	866	1244	1640	2226
Bandwidth (nm)	19	53	70	144	56	31	44	88	171	272

FIGURE 5. The ten ALI spectral response functions, with associated center wavelength and bandwidth. The seven VNIR functions are labeled Pan, 1p, 1, 2, 3, 4, and 4p. The three SWIR functions are labeled 5p, 5, and 7.

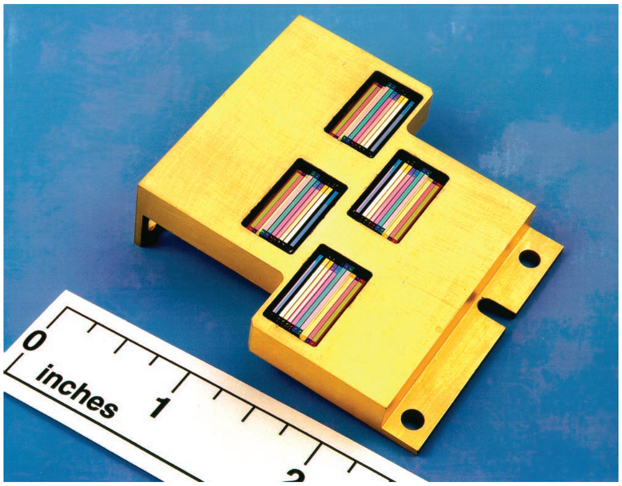


FIGURE 6. The multispectral/panchromatic flight module, showing the four sensor chip assemblies covered by the ten spectral filters.

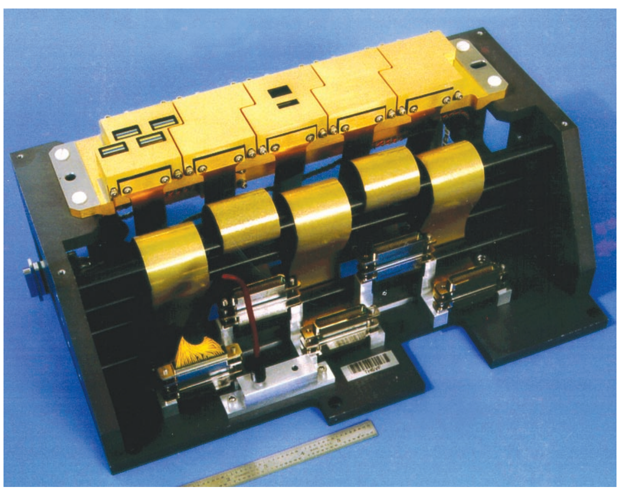


FIGURE 7. Photograph of the flight focal-plane array assembly, which can hold up to five multispectral/panchromatic modules. Each module covers a 1.256° by 3° field of view.

Both the array frame rate and the detector integration time can be set by commands to the focal-plane electronics. The nominal frame rate is 226 frames/sec for the multispectral detectors and 678 frames/sec for the panchromatic detector. The nominal integration times are 4.05 msec for the multispectral detectors and 1.35 msec for the panchromatic detector. The frame rate can be adjusted in 312.5 nsec increments to synchronize frame rate with ground-track velocity variations due to altitude and velocity variations during orbit. The integration times can also be selected over a range from 0.81 msec to 4.86 msec in steps of 0.27 msec for the multispectral detectors. The corresponding values of the integration times for the panchromatic band are one third of those for the multispectral bands. The focal-plane electronics samples the output of each detector with a 12-bit converter. The digitized data are then sent to the solid state recorder on board the spacecraft.

Figures 6 and 7 show photographs of the flight multispectral/panchromatic module and flight focal-plane array assembly. Figure 8 shows a photograph of the integrated flight telescope and focal-plane assembly, but without the external housing. Note the external calibration source mounted on the left side of the metering truss.

Calibration and Characterization

The calibration and characterization plan for the ALI had both pre-launch and in-flight components. The objectives were to characterize the overall instrument performance and to determine all instrument parameters required to generate accurate estimates of spatial, spectral, and radiometric image quantities. The ALI performance requirements were guided by the Landsat

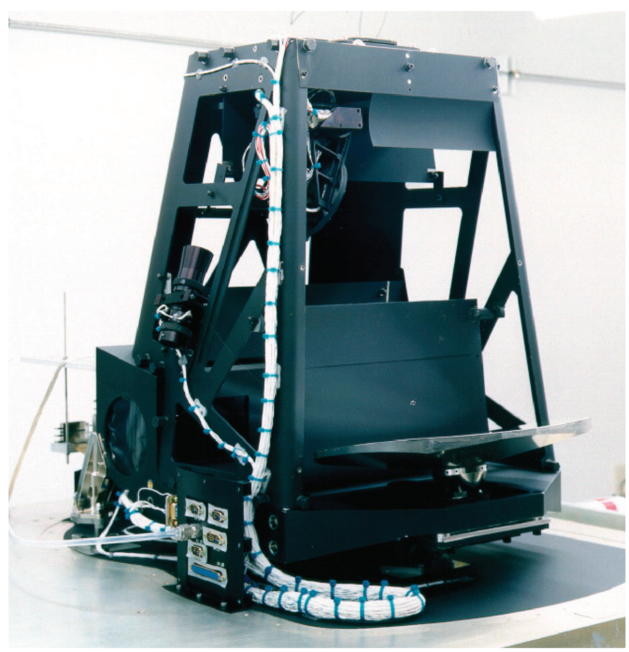


FIGURE 8. Flight ALI mounted on the aluminum flight pallet prior to the housing installation. The internal calibration source is mounted on the left side of the metering truss.

7 specification [5] and were generated in concert with Landsat, Earth Observing System (EOS), and EO-1 calibration scientists. The scope of the calibration effort was consistent with the primary New Millennium Program mission objective, which was the validation of enabling technologies in flight.

The major sensor calibration data consisted of five measurement categories and were established for each detector channel. These were the normalized spectral response functions, pixel angular directions in object space, modulation transfer functions, radiometric response coefficients, and zero signal offsets. These five calibration parameter files were built up from all the pre- and post-launch measurements. Several measurement approaches, including both ground and on-orbit, were used for each of the five parameters. Only for the spectral response functions were there no useful on-orbit calibration techniques. The instrument performance and verification tests also included measurements of noise, repeatability, polarization dependencies, temperature transient response, saturation recovery, image artifacts, and stray light rejection.

Pre-Launch Calibration and Characterization

The pre-launch calibration began with testing and analysis at the component level. This process continued through subsystem-level and system-level testing. The objective was to generate initial estimates of the sensor's spatial, spectral, and radiometric characteristics and then track the performance throughout the development phases of the instrument. This process provided an early indication of any test setup errors, analysis errors, or performance anomalies. Moreover, since this process employed a number of independent and complementary calibration methods, consistency in projected performance increased the confidence of the final calibration parameters.

Pre-launch testing and calibration were conducted under mission-like conditions, including appropriate environmental conditions, and the full range of signal levels, wavelengths, and spatial frequencies. The internal calibration source was used throughout ground testing as a health check and a measure of stability of performance. This internal calibration was especially useful during environmental testing as a means of verifying satisfactory performance.

The definitive ground calibration and characterization measurements on the ALI were performed while the instrument was in the thermal vacuum chamber that contained a liquid-nitrogen-cooled shroud, and with ALI operated at flight temperature. Three major optical test configurations were used for most of the key measurements. These consisted of a Schmidt sphere imaging collimator, an off-axis parabolic collimator, and a 30 inch integrating sphere with a spectro-radiometer. With the ALI in the vacuum chamber,

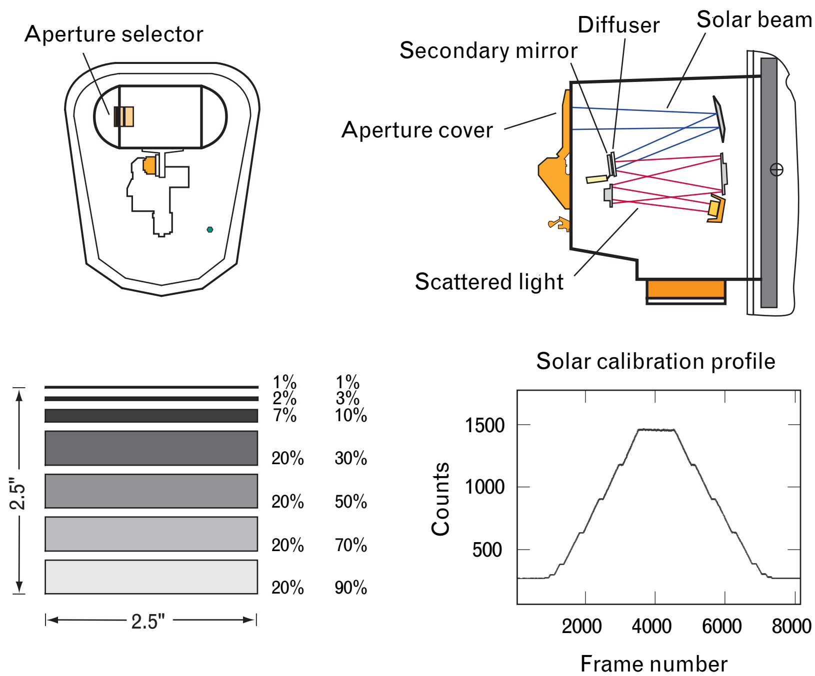


FIGURE 9. The solar calibration mode. The upper left figure illustrates the location of the aperture selector slide on the ALI aperture cover. The lower left figure illustrates the set of seven slit openings that are uncovered as the slide opens. The upper right figure shows the location of the Spectralon diffuser when it is placed in front of the secondary mirror. The lower right figure shows the detector response as the slide opens and then closes. These data were obtained from the laboratory functional test with a solar simulator.

optical measurements were made through a 12 inch diameter fused-silica window. This window was well characterized for both wavefront error and spectral transmission.

In-Flight Calibration

The on-orbit absolute calibration relied primarily on solar calibration. The solar calibration procedure, illustrated in Figure 9, involves pointing the ALI at the sun with the aperture cover closed. A motor-driven aperture selector in the aperture cover assembly moves an opaque slide over a row of small to increasingly larger slit openings to allow an increasing amount of sunlight to enter the system. The cover then reverses the slide motion, decreasing and eventually blocking all sunlight. A series of seven discrete aperture areas are obtained.

Just prior to solar calibration, a space-grade 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 mirror. During solar calibration the reflectively scattered sunlight exposes the focal-plane array to an irradiance that is equivalent to what the ALI would see from earth-reflected sunlight for an earth albedo ranging from 0 to 100%.

Other on-orbit techniques used for both image quality assessment and radiometry included lunar scans, imaging well-characterized ground scenes, direct comparison with common scenes imaged by Landsat, and measurement of stars. Detector stability and contamination buildup on the filters was monitored with internal source measurements. The on-orbit calibration plan contained adequate capabilities for cross checks and diagnostic tests.

On-Orbit Performance

EO-1 was launched on 21 November 2000 from Vandenberg Air Force Base in California. Figure 10 shows a photograph of the satellite mounted on the Delta-2 launch vehicle, and a photograph of the liftoff. Early operations of ALI began November 25, the fifth day

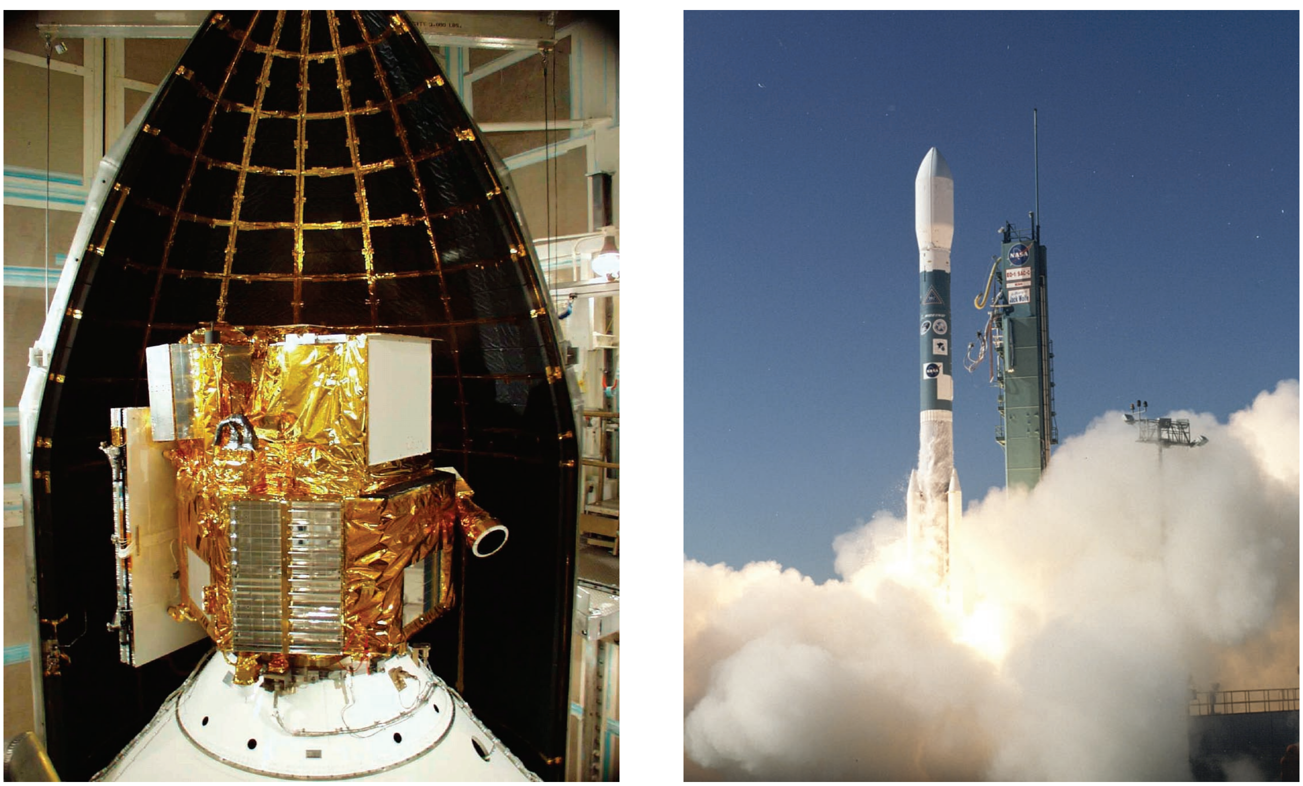


FIGURE 10. (left) EO-1 spacecraft on the Delta-2 launcher, and (right) liftoff on 21 November 2000 from Vandenberg Air Force Base, California.

FIGURE 11. "First Light"; the first ALI image was taken five days after launch. The frame on left shows a true color image of the Matanuska range and valley in Alaska. The frame on right shows a blowup image in the panchromatic band of the town of Sutton, Alaska.

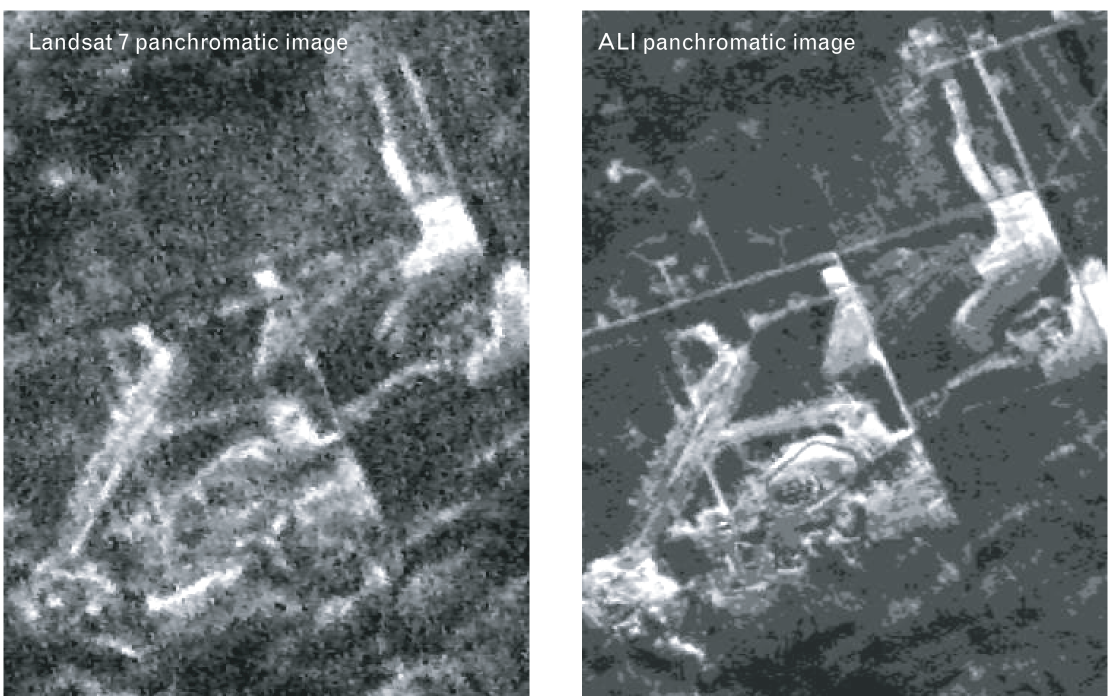


FIGURE 12. Comparison of panchromatic images from the Enhanced Thematic Mapper Plus (ETM+) sensor on Landsat 7 (left) and ALI on EO-1 (right), taken on 25 November 2000 over Sutton, Alaska, five days after the launch of EO-1. This comparison was provided courtesy of Dr. Stephen G. Ungar, the NASA EO-1 mission scientist. (Landsat image courtesy of NASA.)

after launch. Initial comprehensive performance tests were conducted to check the general health of the instrument. Following these tests, four earth scenes were collected, and then the instrument was placed in outgassing mode for five days.

The first image collection was planned well before either the EO-1 orbit or spacecraft attitude knowledge were finalized. Our first earth imaging opportunity was over a region thought to be near Fairbanks, Alaska, which we believed was heavily clouded. Nevertheless NASA management had a strong interest in getting data from ALI as quickly as possible. The preliminary analysis of the image data confirmed our fears of a high cloud cover. After additional data processing, an incredibly sharp image of a cloud-free mountain range and valley emerged. Figure 11 shows these initial ALI images, made five days after the launch of EO-1.

A blowup of the image reveals a small town, Sutton Alaska, hidden in the dark valley. The sun angle at that time of day and year was less than 5° above the horizon. Nevertheless, the image shows remarkable detail and sensitivity. Figure 12 compares this blowup image from ALI with a similar image taken by the ETM+ of Landsat 7 nearly to the day but a year earlier. The superior image quality of ALI is apparent. Recall that one mission objective was to compare images from the two sensors taken one minute apart. This was not possible for the first ALI images because EO-1 had not been maneuvered into its final orbit behind Landsat 7. Three other image collections were made on that first day: east Antarctica, the island of Roi-Namur in the Marshall Islands, and north-central Australia.

The very first ALI image illustrated both the superior image quality and SNR of ALI. In particular, the improved SNR is significant, given the relatively small optical aperture (12.5 cm). Figure 13 summarizes the average SNR of all the ALI spectral bands for a 5% earth surface reflectance, and compares these results to the SNR of similar channels in the ETM+. In the bands that are common to both instruments, the expected ALI SNR ranges from 4 to 10 times greater than ETM+. This enhanced SNR is a direct result of the larger number of detectors.

After a series of bus maneuvers, the EO-1 satellite was placed into its desired orbit, which follows a repetitive, circular, sun-synchronous, near-polar orbit with a nominal altitude of 705 km at the equator. The spacecraft travels from north to south on the descending (daytime) orbital node, maintaining a mean equatorial crossing time between 10:00 a.m. and 10:15 a.m. for each daytime pass. The satellite circles the earth at 7.5 km/sec, with an orbit inclination of 98.2° and an orbital period of 98.9 minutes. The velocity of the EO-1 nadir point is 6.74 km/sec. EO-1 completes just over 14 orbits per day, with a repeat cycle of 16 days, trailing Landsat by one minute. This orbit has allowed us to perform cross comparisons of instrument performance from the two satellites over the same region of the earth. Figure 14 shows the 37 km ALI measurement swath width over the earth, com-

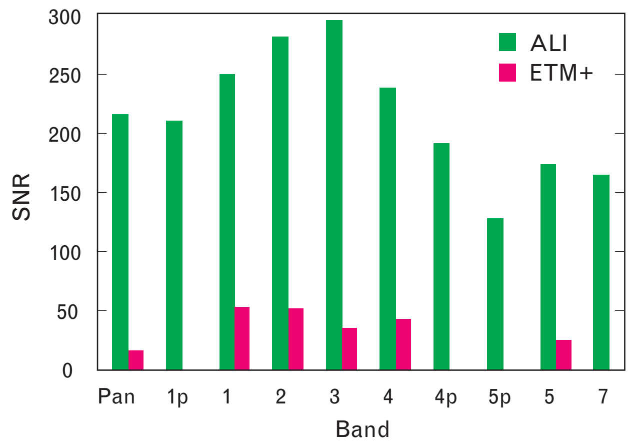


FIGURE 13. Average signal-to-noise ratio performance for a 5% earth surface reflectance for the ten spectral bands of ALI and six spectral bands of ETM+.

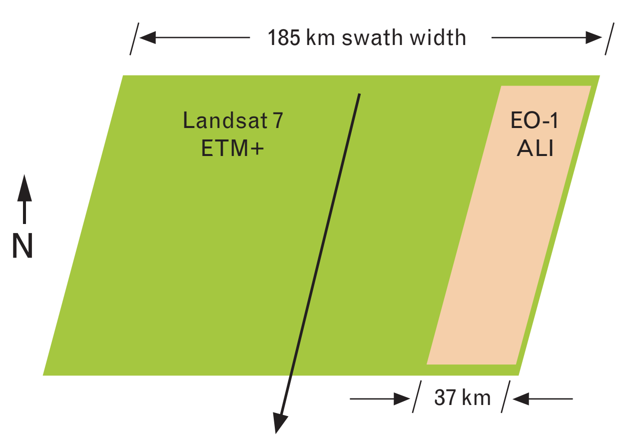


FIGURE 14. EO-1 and Landsat 7 descending orbit ground tracks.

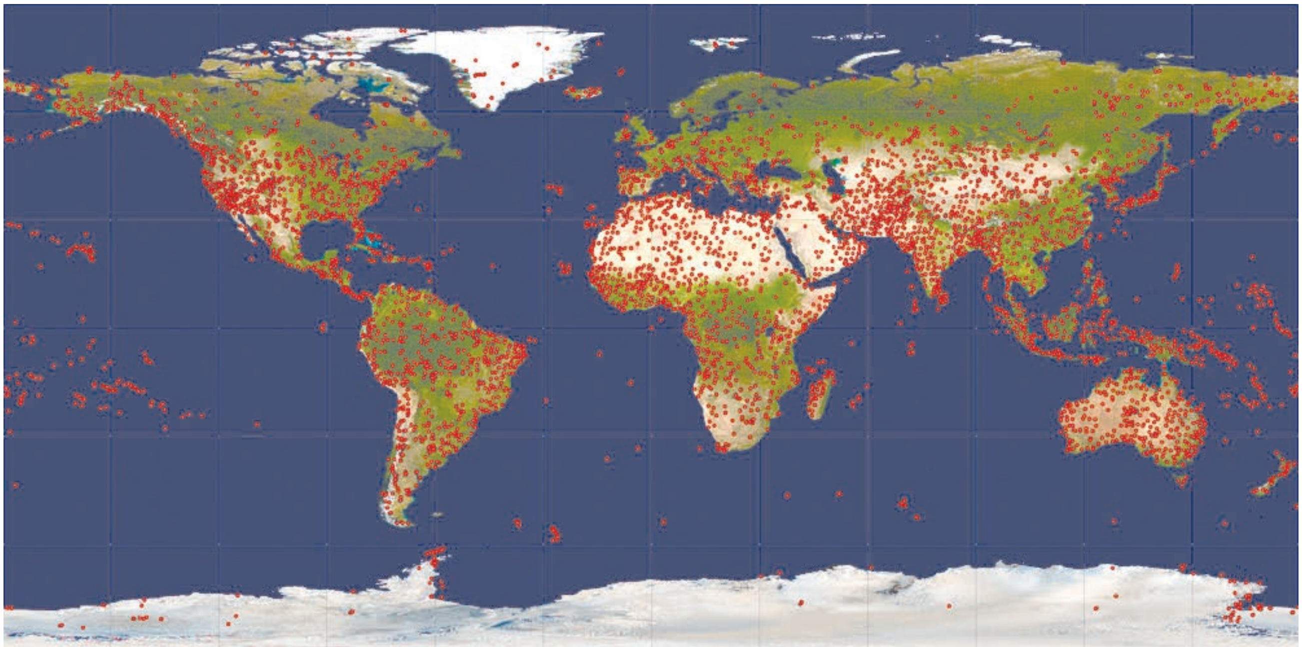


FIGURE 15. ALI imagery (indicated in red) in the U.S. Geological Survey National Center for Earth Resources Observation and Science (EROS) archives from 1 January 2001 through 21 April 2005.

pared to the 185 km swath width of Landsat. Note that the narrower overlap region of ALI is due to its partially populated focal-plane array.

All of the technology and science validation objectives of ALI have been met. ALI image data from over 22,000 data collections are now available to the worldwide user community through the U.S. Geological Survey National Center for Earth Resources Observation and Science (EROS). Figure 15, taken from the EROS web site [6], illustrates the worldwide coverage of ALI imagery.

Application to Future Landsat Instruments

One key element of the New Millennium Program technology-validation study for ALI is a demonstration of the ability to scale up to a full 185 km field-of-view Landsat instrument. Several design features and tests have accomplished this result. The focal-plane array was designed in a modular fashion so that the full 15° coverage could be achieved by simply replicating the ALI detector module four more times. Figure 16 illustrates this capability. With five modules in the fo-

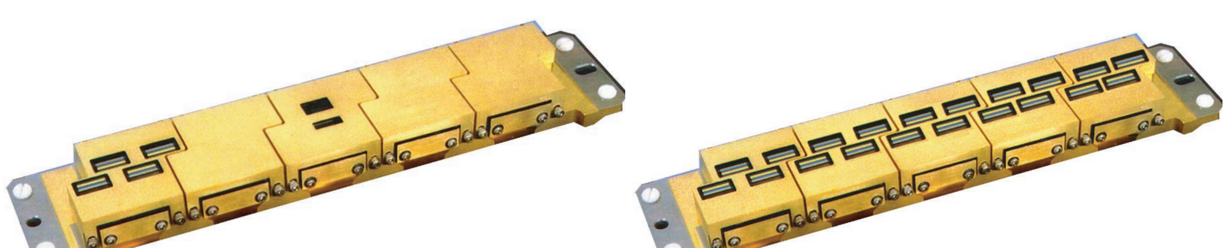
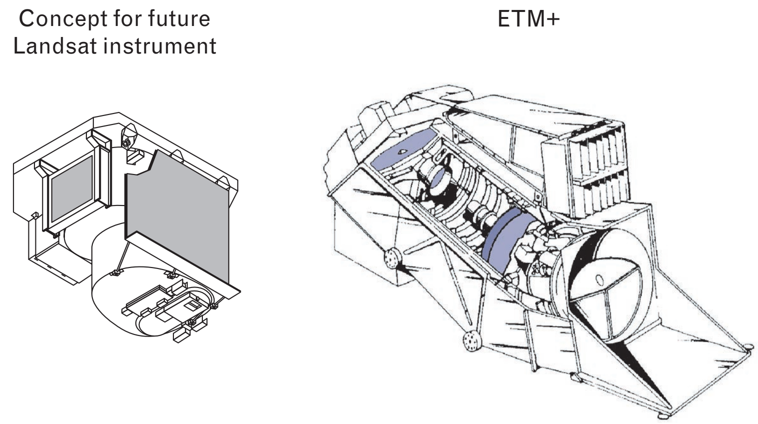


FIGURE 16. Growth path from a single-module ALI assembly to an advanced Landsat sensor. Populating the focal-plane array with five multispectral/panchromatic modules will allow future Landsat sensors to achieve the full 185 km field of view with sensor chip assemblies that have higher sensitivity and faster data rates, at a lower cost and volume, with reduced power consumption, than current ETM+ sensors.



	Future Landsat	*ETM+*
Mass (kg)	100	425
Power (W)	100	545
Size (cm)	70 × 75 × 75	196 × 114 × 66
VNIR bands	7	5
SWIR bands	3	2
Longwave infrared bands	0	1
Panchromatic resolution (m)	10	15
Multispectral resolution (m)	30	30
Relative SNR	4–10	1

FIGURE 17. Comparison of the current Landsat ETM+ with a future Landsat instrument based on the ALI architecture. The table lists the reduced physical dimensions and the expected improvement in performance.

cal-plane array, the data rate would increase by a factor of five while the electrical power of the focal-plane array would increase by about a factor of three, according to estimates.

There would be no significant physical changes in the instrument design to accommodate this upgrade. Moreover, the optical subsystem performance was verified over the full 15° field of view. The placement of the populated detector module on the outer 3° of the available field was done deliberately to validate the most stressing portion of the field of view. An ALI with a fully populated focal-plane array would exhibit about one-fourth the mass, one-fifth the power consumption, and one-third the volume, and it could be constructed at a lower cost, compared to the ETM+ of Landsat 7. These attributes, along with the significantly improved performance, make the EO-1 ALI design and technologies very attractive for use in future missions. Figure 17 compares the current Landsat ETM+ with the reduced physical dimensions and expected improvement in performance of a future Landsat instrument based on the ALI architecture.

Summary and Conclusions

The development, testing, and launch of the EO-1 Advanced Land Imager has been a successful collaboration between Lincoln Laboratory and NASA. ALI is the primary instrument on the EO-1 mission of NASA's New Millennium Program and has undergone extensive pre-launch and on-orbit testing, characterization, and calibration. The results indicated superior performance in resolution, image quality, SNR, dynamic range, radiometric accuracy, and repeatability. The EO-1 mission has successfully flight-validated the New Millennium Program technology and science objectives. The EO-1 mission Science Validation Team concluded that "ALI has been shown to be a significant improvement over Landsat ETM+." This performance has been achieved in a sensor of considerably smaller size, lower weight, and power consumption than in previous instruments with similar earth observing objectives. It has provided a clear developmental path for a lower cost, higher performance, next-generation Landsat sensor. Lincoln Laboratory has been working with NASA to transfer ALI technologies to industry for use in future missions, in particular the Landsat Data Continuity Mission.

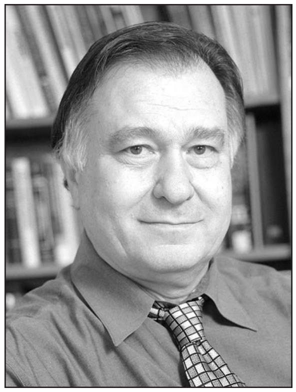
Additional information on the EO-1 mission can be found on the NASA EO-1 web site [7].

Acknowledgments

Many individuals made major contributions during various phases of the ALI program. One is uniquely noteworthy. The late Dr. Herbert Kottler was then head of the Aerospace division at Lincoln Laboratory. He had a close working relationship with the highest levels of NASA management and was enthusiastic about developing this collaborative flight program. His strong interest, support, and guidance were critical to the initiation and success of both the EO-1 mission and the ALI development. We also express our appreciation to Charles Bruce and William Brown for their support and contributions throughout the program.

REFERENCES

1. "Land Remote Sensing Policy Act of 1992," Public law 102-555-Oct. 28, 1992.
2. A.E. Filip, private communication, 1994.
3. "Advanced Technologies Landsat Program, Mission Concept Review, Pre-Phase A Study," NASA, Goddard Space Flight Center, ATLaST #001, 15 June, 1994.
4. D.E. Lencioni and D.R. Hearn, "New Millennium EO-1 Advanced Land Imager," *Int. Symposium on Spectral Sensing Research, San Diego, 13–19 Dec. 1997.*
5. "Landsat 7 System Specification," revision K, NASA/Goddard Space Flight Center, 430-L-0002-K (July 1997).
6. <http://eo1.usgs.gov/aliAcq.php>
7. <http://eo1.gsfc.nasa.gov>



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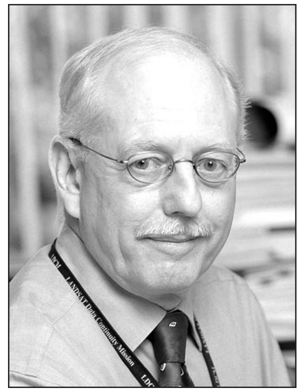
joined Lincoln Laboratory in 1971 after receiving a B.S. degree in physics from DePaul University and M.S. and Ph.D. degrees in physics from the University of Wisconsin–Madison. His initial research on the propagation of high-power laser beams included atmospheric breakdown, thermal blooming, and atmospheric turbulence. He became assistant leader in 1981 and then leader of the Advanced Techniques and Systems group in 1983, where he served until 1994. The focus of the group during this period was on development of passive longwave infrared sensors. He was the associate project leader of the Optical Aircraft Measurements Program from 1983 to 1994, during which time the Cobra Eye Sensor System was developed and deployed. In 1994 he joined the Aerospace division as associate leader of the Sensor Technology and Systems group, where he initiated work on the Advanced Land Imager that was developed by Lincoln Laboratory for NASA. Currently, he is a senior staff member of the Advanced Space Systems and Concepts group, where he works on optical systems for remote sensing applications.



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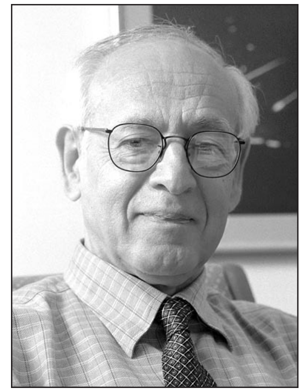

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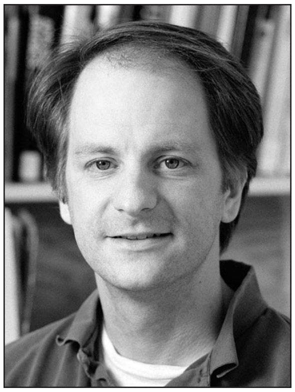

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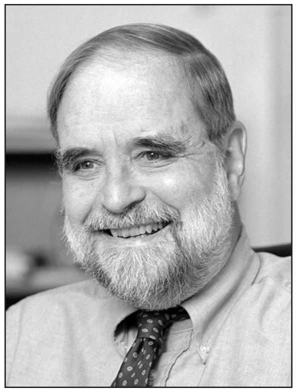

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