The EO-1 Mission and the Advanced Land Imager

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The Advanced Land Imager (ALI) was developed at Lincoln Laboratory under the sponsorship of the National Aeronautics and Space Administration (NASA). The purpose of ALI was to validate in space new technologies that could be utilized in future Landsat satellites, resulting in significant economies of mass, size, power consumption, and cost, and in improved instrument sensitivity and image resolution. The sensor performance on orbit was verified through the collection of high-quality imagery of the earth as seen from space. ALI was launched onboard the Earth Observing 1 (EO-1) satellite in November 2000 and inserted into a 705 km circular, sun-synchronous orbit, flying in formation with Landsat 7. Since then, ALI has met all its performance objectives and continues to provide good science data long after completing its original mission duration of one year. This article serves as a brief introduction to ALI and to six companion articles on ALI in this issue of the *Journal*.

Under the Landsat program, a series of satellites have provided an archive of multispectral images of the earth. The first Landsat satellite was launched in 1972 in a move to explore the earth from space as the manned exploration of the moon was ending. There have been six more Landsat satellites since then, the most recent one—Landsat 7—launched in 1999. The data acquired by the Landsat satellites are a unique resource for global-change research, with applications in agriculture (e.g., crop discrimination and assessment), geology (e.g., volcanic eruption monitoring), forestry (e.g., canopy water-content estimation and species composition), regional planning (e.g., monitoring land use and urbanization), hydrology (e.g., monitoring snow accumulation and melt), and national security. Landsat data provide an extraordinary image resource that has been used for years to meet the many important needs of business, government, science, and education.

Landsat satellites fly in a polar orbit at about 700 km altitude. The Landsat imagers have relatively few detectors in a linear array that is mechanically scanned in the cross-track direction, covering a ground swath width of 185 km. The typical image is also 185 km long along the flight path.

The Advanced Land Imager (ALI) was developed at Lincoln Laboratory under the sponsorship of the National Aeronautics and Space Administration (NASA) and their New Millennium Program. The purpose of ALI was to validate in space new technologies that could be utilized in future Landsat satellites, resulting in significant economies of mass, size, power consumption and cost, and in improved instrument sensitivity and image resolution. The resolution improvement applies only to the panchromatic band (10 m), while all other bands are at the standard Landsat imager resolution of 30 m to provide data continuity. ALI has been designed to produce images directly comparable to those from the imager on Landsat 7.

ALI achieves a reduction in size by employing a fixed planar array of more than fifteen thousand detectors operating in push-broom mode, replacing the mechanically scanned linear array of earlier imagers. The planar detector array is coupled to a wide field-of-view

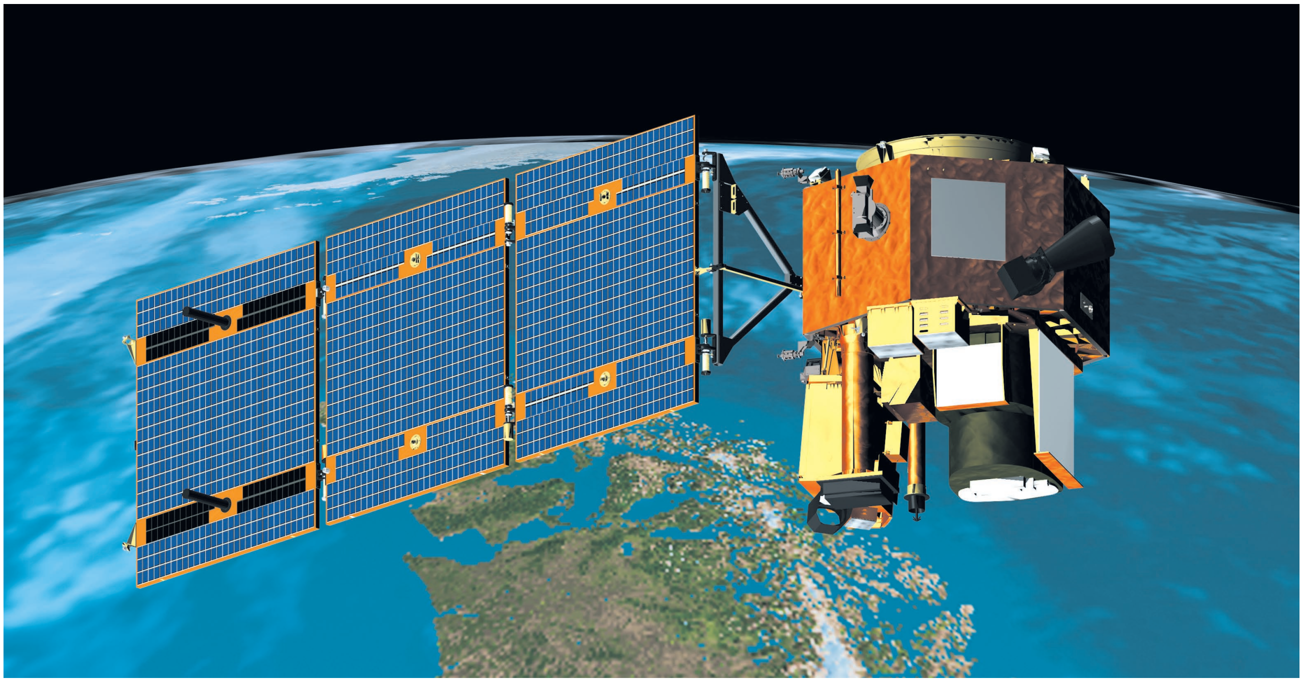

FIGURE 1. Artist's rendering of the Earth Observing 1 (EO-1) satellite in flight, shown without the protective space cloth for a better view of the instruments. The Advanced Land Imager (ALI) is on the lower right with the white cover and two radiators (the light-color rectangles). Two other imagers—the Linear Etalon Imaging Spectrometer Array (LEISA) atmospheric corrector and the hyperspectral Hyperion sensor—are also onboard EO-1. (Image courtesy of NASA Goddard Space Flight Center.)

optical system (15°) that covers the full swath width of a typical Landsat image (185 km). Lightweight silicon carbide mirrors are used in ALI to reduce weight. In addition, the HgCdTe detectors are formulated for operation at a higher temperature (220 K) than earlier detectors, making possible passive radiator cooling that also saves weight and power. The focal-plane detector arrays cover a total of ten spectral bands spanning the 0.4 μm to 2.5 μm wavelength region. To reduce cost, the focal plane was partially populated, providing 3° cross-track coverage that corresponds to 37 km on the ground. The focal-plane detector array was designed in a modular fashion so that the full 15° coverage could be achieved by simply replicating the current module four more times.

The Earth Observing 1 (EO-1) satellite is the first of the earth-orbiting missions under the New Millennium Program that was conceived as a series of lean, less-expensive missions to validate new instrument and spacecraft technologies in flight. The NASA Goddard Space Flight Center (GSFC) has overall responsibility for the EO-1 mission. ALI was selected as the main instrument on EO-1. Other imagers on EO-1 are the Linear Etalon Imaging Spectrometer Array (LEISA) atmospheric corrector developed by GSFC; and Hyperion, a hyperspectral imager with 220 spectral channels and a 7.6 km swath width, developed by TRW for GSFC*. Figure 1 shows an artist's rendering of EO-1 in flight, with its protective space cloth removed for illustration. The history of the development of the ALI concept and an overview of the instrument design and performance are recounted in this issue by Donald E. Lencioni et al. in the article entitled "The EO-1 Advanced Land Imager: An Overview."

Lincoln Laboratory developed ALI with New Millennium Program instrument team members from Raytheon Santa Barbara Remote Sensing (SBRS), who developed the focal-plane system; and with team members from SSG, Inc., of Wilmington, Massachu-

* In addition to six articles on the development and performance of ALI, this issue of the *Journal* has a companion article on the Hyperion hyperspectral imager and its use for surface feature discrimination and coastal characterization. For more information, please see "Examples of EO-1 Hyperion Data Analysis," by Michael K. Griffin et al.

setts, who developed the optical system. Lincoln Laboratory was responsible for the design, fabrication, test, and calibration of ALI; the development of the instrument control and calibration software and databases; and the initial on-orbit performance assessment.

Under the motto "faster, cheaper, better," NASA allowed some shortcuts in documentation and in the review process, and a reduction in hardware prototype models, in exchange for an increased emphasis on schedule, cost, and performance. The engineering development unit was eliminated, and the qualification and flight units were combined into one, known as the protoflight unit. Single-point failure modes were allowed in non-critical components. NASA established strict schedules and budgets, which were enforced under penalty of mission cancellation.

The development of ALI began in this environment. A small team of unit engineers and scientists was assembled at the Laboratory to carry out the instrument development and testing. To stay within schedule, it was often necessary to work long hours on weekdays and weekends. The project organization within the Laboratory was as follows: program manager Costas Digenis; instrument scientist Don Lencioni; system engineers Dave Harrison (1996–1997), Ed Bicknell (1997–1999), and Jeff Mendenhall (1999–2001); and payload engineering manager Steve Forman.

Some of the lead engineers on the project are represented as authors of the following articles in this issue. Others are acknowledged in the article by Steven E. Forman entitled "Advanced Land Imager: Mechanical Design, Integration, and Testing."

In addition to the tight schedule and budget, another challenge was the calibration of more than fifteen thousand detectors in the focal plane. The necessary hardware and software for this calibration phase of the project were developed at Lincoln Laboratory. All the detectors were individually calibrated in a thermal vacuum prior to the launch of EO-1, and their performance has been periodically verified since the launch. The instrument calibration is described in two articles, the first by Jeffrey A. Mendenhall et al. entitled "Spectral and Radiometric Calibration of the Advanced Land Imager," and the second by David R. Hearn entitled "Spatial Calibration and Imaging Performance Assessment of the Advanced Land Imager."

Concurrent with the development of ALI, the necessary ground instrumentation was assembled and software was written to acquire and process the ALI data. This ground-based system was utilized extensively during the ground testing of ALI and also to process the subsequent flight data. The system is described in the article by Herbert E.M. Viggh et al. entitled "An Automated Ground Data Acquisition and Processing System for the Advanced Land Imager."

The unfortunate coincidence of several mission failures from 1997 to 1999 led NASA to a marked change of approach to mission assurance. EO-1 was subjected to a rigorous "Red Team" review by a panel of experts in March 2000, about a year after ALI had been delivered to NASA. Additional technical resources were made available, and the schedule was allowed to slip to solve certain challenging engineering problems. A thorough risk analysis was conducted and guidelines were established for the acceptable overall mission risk. While the revised approach primarily benefited other elements of EO-1, it also contributed to the thoroughness of the preparation and the overall mission success.

The EO-1 satellite was launched on 21 November 2000, on a Delta II rocket from Vandenberg Air Force Base, California, and inserted into a 705 km circular, sun-synchronous orbit. Within a month, after a series of orbital maneuvers, EO-1 achieved its intended position in formation with Landsat 7. In this position, EO-1 covers the same ground track one minute later than Landsat 7. Images of the same ground areas, at nearly the same time, have been collected by the two satellites for direct comparison.

EO-1 had a primary mission duration of one year but was designed to operate for an additional year. It carried enough consumables for five years. The current plans are to fly EO-1 through fiscal year 2007 (by judicious use of on-board consumables) but at a much reduced level of operational cost. The orbit of EO-1 will be lowered gradually and sufficiently such that the spacecraft will reenter the atmosphere within twenty-five years, as mandated by NASA. Thus EO-1 will be able to provide good science data for at least two more years, barring any problems in the interim.

As of this writing (November 2005), EO-1 and ALI are still functioning nominally and collecting about fifteen images per day. The total number of ALI scenes currently exceeds 24,000, a twelvefold increase over the original plan for 2000 images. A small sample of the impressive imagery collected by ALI is shown in the article entitled "A Gallery of Images from the Advanced Land Imager," by David R. Hearn.

The most serious problem encountered by ALI is the gradual build-up of contaminants on the cold surface of the focal plane. The likely source of the contamination is conjectured to be outgassing products from the black paint on the telescope, caused by insufficient duration of the paint bake-out during ground processing. We first diagnosed the problem during the initial thermal vacuum tests on the ground. We found that raising the temperature of the focal plane to 0°C for several hours was effective in boiling off the contaminants. As a result, we performed a bake-out for several days before shipping the instrument from the Laboratory, and we verified in subsequent testing that there was no evidence of contamination. For good measure, we added a heater to the focal-plane radiator so we can bring the focal-plane temperature to 0°C while the ALI is on orbit. This heater turned out to be a good feature to implement because contamination reappeared on the focal plane after launch.

We have found it necessary to conduct periodic bake-outs on orbit to remove the contaminant build-up. Each bake-out cycle lasts about twenty hours. The interval between bake-outs was initially five days, but a gradual decrease in the contaminant build-up rate after the second year on orbit has allowed us to lengthen the bake-out interval to one month. The cumulative bake-out time over the first year, when most of the reduction in the rate of contamination was observed, is roughly equivalent to a continuous outgassing period of one month. Since focal-plane contamination is not a problem unique to EO-1, a lesson learned is to allow sufficient time after launch for instrument outgassing. For more information on this topic, see the previously mentioned article by Jeffrey A. Mendenhall entitled "Spectral and Radiometric Calibration of the Advanced Land Imager."

The scientific community has embraced the ALI data; researchers are excited about the greater resolution of the panchromatic band, the greater sensitivity of the multispectral bands, and the overall increased band selection, compared to the imager on Landsat 7. More than three hundred scientific publications, based on EO-1 data, have been generated and many of these are about ALI. An extensive technology-transfer effort has been carried out by NASA and Lincoln Laboratory. This effort consisted of several publications, a number of presentations and workshops in open forums, and many one-on-one interactions with interested instrument vendors. Many of the activities were in support of the Landsat Data Continuity Mission. As of this writing, NASA is pursuing procurement of the Operational Land Imager (OLI), which is expected to bear a strong resemblance to ALI. That event will mark the successful fruition of the EO-1 mission and the continuing contribution of ALI to the science and art of imaging the earth.

Acknowledgments

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