Advanced Land Imager Summary

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This abstract document outlines the technology performance of the Earth Observing-1 (EO-1) Advanced Land Imager (ALI). Discussed are the instrument architecture, characteristics, preflight calibration, and performance assessment on orbit.

The ALI multispectral (MS) instrument is the primary instrument on the first EO-1 satellite under the New Millennium Program (NMP). MIT Lincoln Laboratory developed the ALI with NMP instrument team members Raytheon Systems Santa Barbara Remote Sensing (focal plane) and SSG Inc. (optical system). This instrument includes 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 is responsible for on-orbit performance assessment.

The key attributes of ALI are that it is smaller in both size and weight than the Enhanced Thematic Mapper (ETM+) of Landsat 7 by a factor of four and requires less power to operate by a factor of five. It has nine MS bands plus a Panchromatic (Pan) band, three more than ETM+, but does not have the thermal band. It has increased sensitivity by a factor varying from four to ten depending upon the band. The spatial resolution of the MS bands is the same as that of ETM+ (30 m) but it is better in the Pan band (10 m versus 15 m).

The overall envelope and configuration of the ALI are depicted in Figure 1 on the next page.

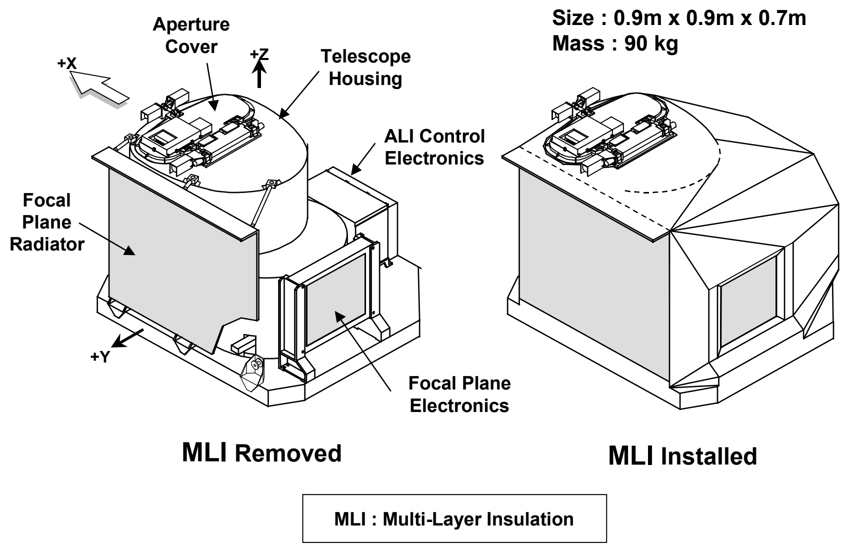

Figure 1. ALI instrument configuration showing the main thermal, mechanical, and electronic components.

The telescope is a f/7.5 reflective triplet design with a 12.5-cm unobscured entrance pupil and a field-of-view (FOV) of 15° cross-track by 1.256° in-track. The telescope design incorporates silicon carbide mirrors and an Invar truss structure with appropriate mounting and attachment fittings. 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, the tertiary is a concave sphere, and the fourth is a flat folding mirror. The optical design features a flat focal plane and telecentric performance, which greatly simplifies the placement of the filter and detector array assemblies. The focal plane consists of five modules, only one of which is populated with detectors (for cost reasons). When the focal plane is fully populated, the detector arrays will cover an entire 185-km swath on the ground, equivalent to Landsat, in a “push-broom” mode.

The wavelength coverage and ground sampling distance (GSD) are summarized in Table 1. Six of the nine MS bands are the same as those of the ETM+ on Landsat 7, enabling direct comparison. The additional bands, indicated with primes (’), were chosen for other science objectives.

Table 1. ALI spectral coverage and ground sample distances.

Band	Wavelength (μm)	GSD (m)
Pan	0.480-0.690	10
MS-1’	0.433-0.453	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

Four sensor chip assemblies (SCAs) populate the 3° cross-track segment of the focal plane to form the focal plane array (FPA). 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.

Three key ALI instrument performance characteristics are dark current, noise, and anomalous detectors. The dark current and noise of the ALI are closely coupled. The dark current defines the background level for each detector, and frame-to-frame fluctuations of this current are a major contributor to the noise of the instrument.

The dark current for each detector of every band was calculated as the mean of 450 MS and 1350 Pan frames (2 seconds). Nine ALI detectors have been identified as having excessive dark current (>1.25 times the mean dark current for that band and SCA). The observed large dark current offsets between odd and even detectors on SCA 4 Band 2 and SCA 3 Band 3 are the result of two "leaky" detectors. Detector 1149 on Band 2 and detector 864 on Band 3 have significant cross-talk with neighboring odd and even detectors respectively. When illuminated, these detectors leak or induce signal onto detectors of the same band and row. Additionally, when the leaky detector is not illuminated, residual cross-talk remains but is effectively removed by dark-current subtraction. As a result, an empirical correction method has been developed to effectively eliminate the addition of optical or electrical cross-talk induced by leaky detectors. Finally, Bands 5p, 5, and 7 exhibit large increases in dark current centered on detector 1200. These regions of enhanced dark current, otherwise referred to as "hot spots," are stable and repeatable, and may be accounted for by using normal dark current subtraction techniques.

The random or white noise of the ALI has been calculated for each detector as the standard deviation of ground calibration dark current data. The mean of white noise values is ≤ 1.2 digital numbers for all bands and all SCAs. Detectors with white noise values greater than three times the mean noise value for each SCA or detectors with zero white noise have been flagged as unusual. Fifteen ALI detectors have more than three times the average white noise values for all three focal plane operating temperatures. All but one of these detectors are shortwave infrared (SWIR) detectors.

Focal planes with highly repeatable dark current and noise properties are very desirable. The dark current was found to be repeatable to within ±2 digital numbers for all visible and near infrared (VNIR) and Pan detectors. SWIR detectors are repeatable to within -20/+100 digital numbers. The mean noise levels were found to be repeatable to within 0.1 digital numbers for all bands. Six inoperable detectors were identified indicating that 99.96% of the ALI focal plane is functional.

A major functional verification test of the ALI was the End-to-End Imaging test, performed at Lincoln Laboratory. The resulting digital images from all of the VNIR bands were examined, and the instrument was found to be working correctly. A final imaging test was also performed in a clean room at Goddard Space Flight Center (GSFC) after integration with the spacecraft and thermal vacuum testing. There was no perceptible difference between the original images and the final image.

Extensive preflight calibration of the instrument was performed at Lincoln Laboratory. Areas of investigation included spatial, spectral, and radiometric calibration.

The spatial response of the ALI instrument was calibrated in the laboratory prior to its integration with the spacecraft. Spatial response is fully characterized by a spatial transfer function (STF), which is a two-dimensional complex function. For the ALI, the conventional modulation transfer function (MTF) looks like the absolute value of Re(STF). For simplicity, therefore, the STF is worked with, which is referred to as the "complex MTF" or simply the MTF while discussing the ALI calibration.

Figure 2 shows the MTF curves derived from scans of the four Pan arrays, along with the average, modeled MTF curve.

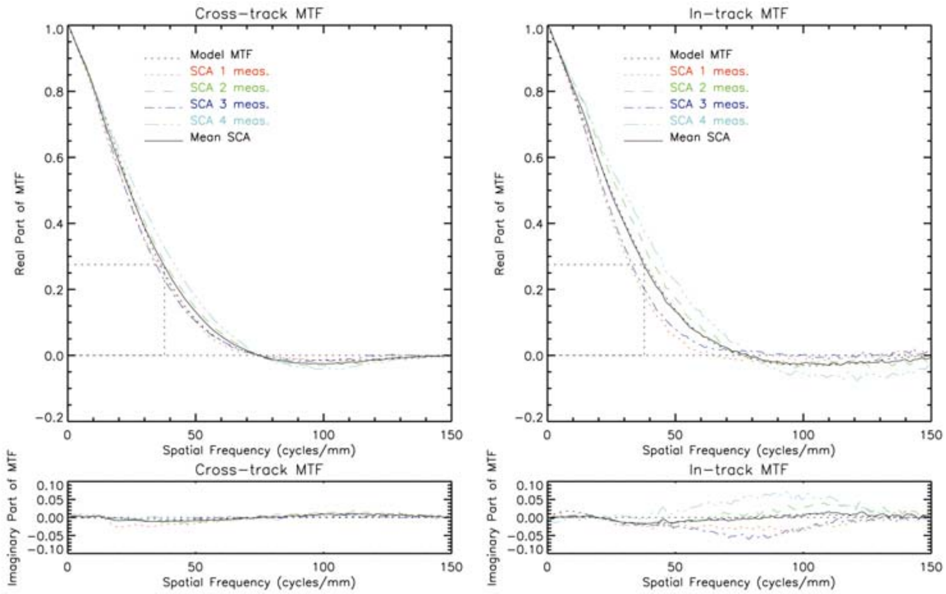

Figure 2. Measured and modeled average MTFs for the Pan band and measured MTFs for the individual SCAs.

In order to reconstruct the ALI image data in reference to the geographic coordinates of the land scene, the lines-of-sight (LOS) of the many detectors relative to the satellite body axes must be known. That information is contained in the LOS map. The LOS map is a tabulation of the sight direction of each detector on the ALI focal plane, relative to a set of reference axes. A parameterized model was developed to describe the apparent position of each detector on the focal plane, as seen through the telescope. The end product of the LOS calibrations is a data file to be used for the reconstruction of ALI images.

Spectral calibration of the ALI was conducted on both the subsystem and the system level with comparisons being made between system and component-level values. The system-level spectral response function for each ALI VNIR, SWIR, and Pan band was measured for SCA 3. The Pan band in particular revealed good agreement between system and component-level measurements despite intricate variability across this band’s spectral bandpass. It was also found that the cut-on and cut-off wavelengths agreed with subsystem-level measurements to within 1 nm for VNIR bands and 2 nm for SWIR bands. In summary, it was found that the system-level ALI VNIR, SWIR, and Pan spectral response measurements are in excellent agreement with theoretical models generated from component measurements.

The technique adopted for the measurement of the radiometric response of each ALI detector consisted of flooding the entrance aperture with a diffuse source of stable, broadband emission at various radiance levels and recording the output of the focal plane at each level. Analysis of the radiometric response was divided into three categories: VNIR, SWIR, and “leaky.” The “leaky” detector category refers to Band 2 of SCA 4 and Band 3 of SCA 3. The results obtained in the analysis, along with results from the “leaky” detector analysis, have been incorporated into the calibration pipeline and are being used to radiometrically calibrate ALI flight data.

After a successful launch of the EO-1 into a descending polar orbit, 1 minute behind Landsat 7, the ALI was calibrated spatially and radiometrically on-orbit using a variety of techniques.

Objectives of the on-orbit test validation were to show that the technology performed on-orbit as well as it did before launch and to verify that the conditions of the launch or the orbital environment did not significantly degrade the performance. The on-orbit test validation was divided into spatial and radiometric performance categories. Spatial validation of the ALI technology consisted of demonstrating that the instrument yielded clear, sharp images that may be accurately registered with features on the ground. The major aspects of spatial validation were to verify the MTF and the detector LOS. Radiometric validation was to show that the in-band radiances reported in the radiometrically calibrated (Level 1R) data accurately represented the top-of-the-atmosphere radiances of the scene imaged.

The approach to MTF validation on-orbit was to use the ground spatial calibration data to simulate the instrument response to simple models of certain well-defined objects imaged from space. Objects that were used for MTF validation were bridges and the moon.

An image of the Bronx Whitestone Bridge was used for spatial validation. A comparison of the bridge's radiance profile for modeled data and image pixel data showed close agreement, thereby validating the calibrated MTF. As a further check, the apparent width of the bridge was compared to the actual width with a resulting comparison of 22.15 m vs. 23.5 m respectively. A Pan image of a lunar calibration scan also showed good agreement with the Pan edge spread function computed from the MTF calibration data.

To date, the best indication of the validity of the detector LOS map is the clarity of MS images reconstructed from radiometrically calibrated data. An example of these images is seen in Figure 3. Close inspection revealed no fringes of color that would indicate a misregistration of the spectral bands. There was also no sign of the boundaries of the individual SCAs. Thus the detector LOS map is valid, at least down to the sub-pixel level.

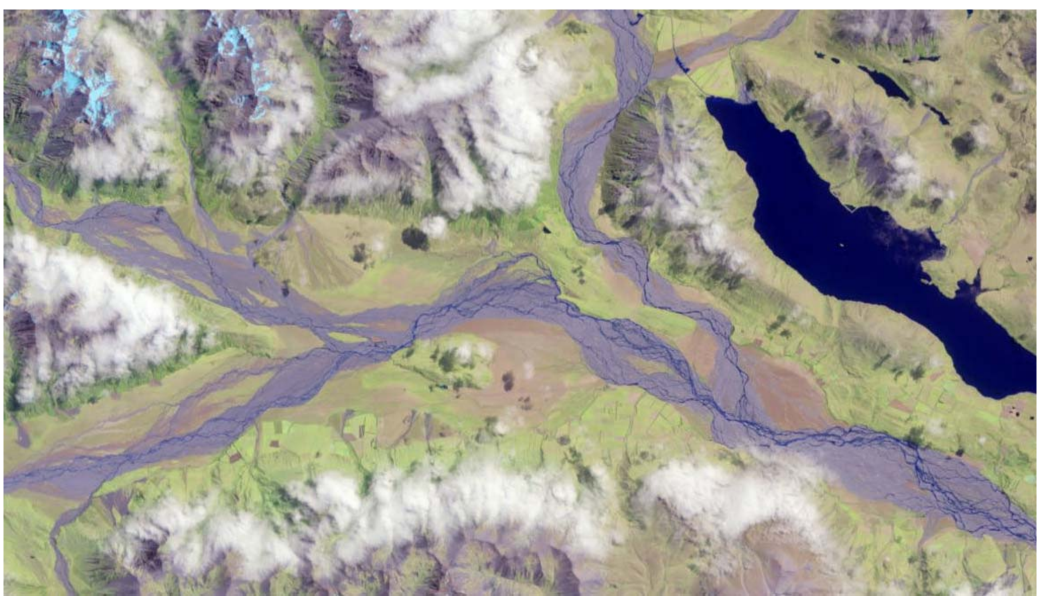

Figure 3. False-color multispectral image of part of the South Island of New Zealand. Seen here are parts of the Rolleston Range, Lake Coleridge, and the Rakaia River. The red, green, and blue components represent Bands 7, 4, and 2, respectively. In this presentation, snow on the mountain peaks appears light blue, while clouds near the peaks are white.

The on-orbit radiometric performance assessment of the ALI consisted of deriving radiometric performance characteristics of the instrument and comparing them to measured pre-flight or expected values.

The focal plane of the ALI has been designed to provide a signal-to-noise ratio for each band between four and ten times that of the Landsat ETM+. To check signal-to-noise ratios on-orbit, three regions of a data set were selected and collected as a part of the on-orbit solar calibration sequence, representing low, medium, and high albedo scenes. Table 2 lists the derived signal-to-noise ratios for all bands.

Table 2. Signal-to-noise ratio for varying radiances.

Band	Radiance*	SNR	Radiance*	SNR	Radiance*	SNR
1p	4.78	151	14.79	339	34.92	520
1	5.55	245	17.08	572	41.1	1263
2	5.11	310	16.10	1001	38.28	1536
3	4.29	343	13.37	1039	31.99	1933
4	3.34	358	10.44	722	25.03	1123
4p	2.80	350	8.73	710	20.93	1145
5p	1.40	263	4.42	662	10.66	1258
5	0.68	341	2.15	1040	5.13	1606
7	0.22	274	0.68	912	1.63	1636
Pan	4.82	215	15.04	348	36.01	703

* mW/cm^2 sr μ

The absolute radiometric accuracy of the ALI defines the ability to make accurate, quantifiable measurements of a scene's radiance in each of the instrument's ten spectral bands. On-orbit, the absolute radiometric accuracy of any mission is challenged by stray light, instrument aging, and the space environment. The absolute radiometry of the ALI was extensively examined during the first year the instrument was on-orbit, using solar, lunar, and ground truth calibration techniques. Results from each method agreed within experimental errors and indicated an 18% drop in the Band 1p response of the instrument since pre-flight characterization. The on-orbit calibration data also revealed a small drooping of the VNIR band responses (other than Band 1p) toward the blue. The highest of these was a 5% decrease in radiometric response for Band 1. Finally, the on-orbit Band 5 response was consistently 5%-12% higher than the response measured during pre-flight calibration.

The ALI stability measurements using solar, lunar, ground truth, and internal lamp data were in good agreement. All methods indicated excellent stability (<1% per year) for Bands 1p, 1, 2, 5p, 5, 7, and Pan. However, solar and lunar data indicated a 2%-3% change per year for Bands 3, 4, and 4p. The Bands 3, 4, and 4p linear decrease in response should be monitored and correction factors applied to these data as a function of mission day number in order to preserve the absolute radiometric accuracy of ALI data for these bands. Stability measurements also revealed 1% per year long-term intra-SCA variations for Bands 3, 4, and 4p (and Bands 5p, 5, and 7 to a lesser degree). These effects can be mitigated by correcting the intra-SCA radiometric calibration coefficients every six months.

Two examples of reconstructed ALI images are presented below. They have been system-corrected, using the radiometric and LOS calibrations of the detectors; however the images are not geo-referenced. A Pan image presented in Figure 4 shows the downtown portion of Washington, D.C., and Figure 5 shows a true-color image of Cape Canaveral, Florida.

Figure 4. Panchromatic image of Washington, D.C.

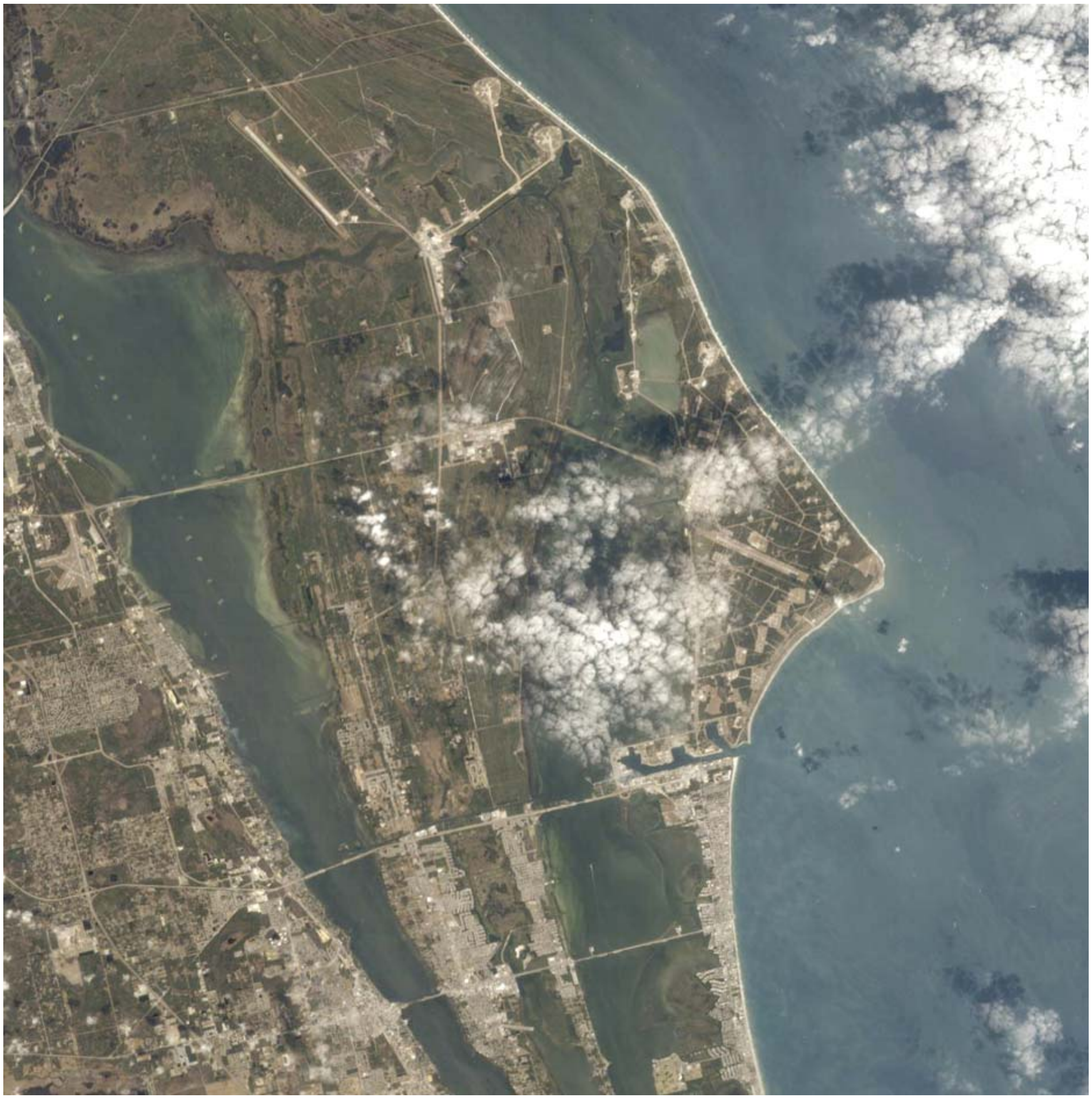

Figure 5. True-color image of Cape Canaveral.

Also discussed in the full ALI Technology Validation Report are the technology transfer model adopted for this instrument and the lessons learned during this program.