Technologies for Future Landsat Missions

Stephen G. Ungar

Abstract

Advanced technologies are available that may potentially lower the cost and improve the quality of future Landsat systems. The NASA New Millennium Program (NMP) Earth Orbiter Mission (EO-1), serving as a technology pathfinder, is implementing several sensor and spacecraft technologies to further define the possibilities for Landsat 8 and beyond. The technologies involved include high spectral resolution grating and wedge imaging spectrometers; advanced multispectral chip assemblies; a Pulsed Plasma Thruster (PPT), included as a reaction wheel replacement for improved spacecraft attitude control; X-band phase array ground transmission antenna and high speed fiber optics data bus (FODB) for enhanced data transmission; a carbon-carbon radiator panel for power/heat dissipation; and a light-weight flexible solar array employing highly efficient photosensitive materials. In aggregate, these technologies and others not only offer considerable enhancements, but also the real possibility of implementing and operating future Landsat systems at substantially less cost.

Introduction

It was advances in technology that helped create the relatively high quality Landsat images that have become so familiar over the last 25 years (Mika, 1997). This paper will offer some ideas that may well be incorporated in future Landsat missions beyond Landsat 7. Near-term concepts are being explored and implemented through the NASA EO-1 technology mission. In this mission, new technologies for the observing instrument, including wedge and grating imaging spectrometers (WIS and GIS) and passively cooled (warm) focal plane detector chip technologies, are being developed. In addition, onboard data processing and storage technologies are under development along with advanced spacecraft systems. In total, these systems indicate that the Landsat capability can be improved while reducing overall mission costs. This paper will describe and discuss these technologies in terms of their impact in the near and longer term relative to their contributions to Landsat 8 and beyond.

Background: The New Millennium Program (NMP) Earth Orbiter Mission (EO-1)

NASA has embarked on a program to explore technologies that advance and enhance capabilities for both Earth and space science. The first Earth science mission selected was EO-1 because of the importance and impact of the Landsat program to the nation and the concurrent need to reduce cost and improve capability through the use of advanced technologies. The EO-1 satellite is presently scheduled for a launch in May 1999. It will be placed in a 705-km sun-synchronous orbit phased several minutes behind Landsat 7, in an orbit designed to capture the same ground track as Landsat.

The EO-1 mission has four overarching objectives which must be consistent with the major goal of reducing costs of future Landsat missions. The first objective is to evaluate selected technologies in the context of meeting science needs in the twenty-first century, as represented and included in the overall NASA Mission to Planet Earth (MTPE) program, with special emphasis on Landsat. In this context, technologies and techniques will be judged in terms of their potential for contributing to the realization of the appropriate Landsat data sets. Secondly, NASA will use EO-1 to evaluate "new ways of doing business" for conducting missions in the twenty-first century. This includes formation flying with other satellites, approaches to intersatellite calibration, evaluation of lunar calibration, and autonomous navigation/instrument operation. A third objective is to use the EO-1 mission to provide a technology infusion path for future NASA Earth Observation System (EOS) and other government agency (e.g., the National Oceanic and Atmospheric Administration—NOAA) satellite missions. The last objective is to provide information to facilitate commercialization of Landsat in the future.

EO-1 science validation efforts are focused on meeting the aforementioned objectives through close coordination with current and planned MTPE/Landsat activities. The ability of EO-1 to make Landsat-like measurements will be evaluated directly against concurrent Landsat 7 measurements. EO-1 will participate in EOS validation activities by acquiring data as appropriate over EOS test sites. Data will also be gathered in conjunction with major field campaigns, allowing for evaluation of derived parameters in terms of measured ground "proofs." In addition, data will be gathered in coordination with aircraft under-flights, helping researchers to characterize the atmosphere and assess the performance of onboard sensor components. Finally, it is intended to leverage MTPE's existing investment by reusing/replicating existing EOS/Landsat algorithms and processing facilities wherever possible.

The approach outlined above will be implemented through a set of science validation scenarios. The EO-1 *ad hoc* Science Advisory Team (SAT) is in the process of defining a framework and an initial set of scenarios. A NASA Research Announcement (NRA) is expected to be issued, inviting the Earth Sciences research community to participate in baseline validation scenarios and/or to propose alternative approaches to meet the validation objectives. Currently, baseline validation scenarios include: the generation of 200 test scenes to be obtained concurrently and compared against Landsat 7 data; the characterization of observing instrument components based on an ensemble of pre-flight, solar, lunar, onboard lamp, and vicarious calibrations; and formation flying with Landsat 7 and possibly the EOS AM-1 satellites.

Biosphere Sciences Branch, Code 923, NASA/Goddard Space Flight Center, Greenbelt, MD 20771 (ungar@highwire.gsfc.nasa.gov).

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Overall, the EO-1 is exploring these technologies in three main areas: (1) the observing instrument, consisting of imaging optics and sensor system; (2) the spacecraft, consisting of observing platform and onboard data handling system; and (3) the ground receiving and processing systems. These technologies are described in the following sections of the paper.

Observing Instrument

The primary payload on the EO-1 mission, the Advanced Land Imager (ALI), is expected to weigh 74 kg, operate on 90 W, and fit into a volume of 0.75 cubic metres. The ALI is a hybrid multisensor instrument, as schematically shown in Plate 1. The field of view (FOV) for this observing system is determined by the Wide Field Telescope (WFT). The WFT has a 15° by 1.26° field of view, capable of imaging a swath on the ground 185 km wide, nominally centered along the nadir ground-track of the satellite. This telescope is advanced in terms of both its design and construction material. Silicon carbide is used for all the optical (reflective) components. Silicon carbide approaches the rigidity and athermal characteristics of beryllium, but at a cost only marginally greater than that of aluminum. The structural components of the telescope are made out of Invar, an iron/nickel alloy whose low coefficient of thermal expansion closely matches that of silicon carbide. Manufacturing difficulties prohibited the construction of silicon carbide structural components within the cost and launch date constraints for the current EO-1 mission. It is anticipated that silicon carbide will be used for both structural and optical components in future designs to provide a thermally monolithic structure.

The focal plane of the ALI telescope will contain a variety of sensor chips as indicated in Plate 1. Although the full 185-km ground swath is imaged on the focal plane, the focal plane is only partially populated with a variety of sensor chip assemblies to allow ALI to serve as a multi-technology test bed, while containing costs and meeting a tight launch date constraint. The fact that the focal plane is only partially populated with chip assemblies results in only partial coverage by the various sensor systems, as follows:

- Four multispectral chip assemblies, subtending a total of 3° (1/5 of the Landsat swath), will result in a 37-km swath at one edge of the FOV at the wavelengths and ground resolutions indicated in Table 1. Each chip assembly will contain nine rows consisting of 320 square multispectral detector cells. Multispectral detector cells measure 39.6 by 39.6 μm, resulting in a ground resolution of 30 metres;
- The panchromatic detector cells will be integrated directly into each multispectral chip as a 760-element row and will provide overlapping coverage with the multispectral bands, but at a 10-metre ground resolution;
- The Wedge Imaging Spectrometer (WIS) chips, placed at the center of the focal plane, will provide a 9.6-km nadir swath with a 30-metre pixel size. The WIS will provide spectral coverage between 0.4 to 2.5 μm using 309 variable bandwidth "samples." This is accomplished by overlaying Visible/Near-Infrared (VNIR) and Short-Wave-Infrared (SWIR) detector chips with variable interference filters (Elerding *et al.*, 1991); and
- The Grating Imaging Spectrometer (GIS) assembly, also to be placed at the center of the focal plane to provide coincident ground-track coverage with the WIS, will provide 233 spectral

TABLE 1. ADVANCED LAND IMAGER MULTISPECTRAL SENSOR CONFIGURATION

Band Designation	Band Width (mm)	Ground Sample Distance (m)
Pan	0.480 - 0.680	10
1'	0.433 - 0.453	30
1	0.450 - 0.515	30
2	0.525 - 0.605	30
3	0.630 - 0.690	30
4	0.775 - 0.805	30
4'	0.845 - 0.890	30
5'	1.200 - 1.300	30
5	1.550 - 1.750	30
7	2.080 - 2.350	30

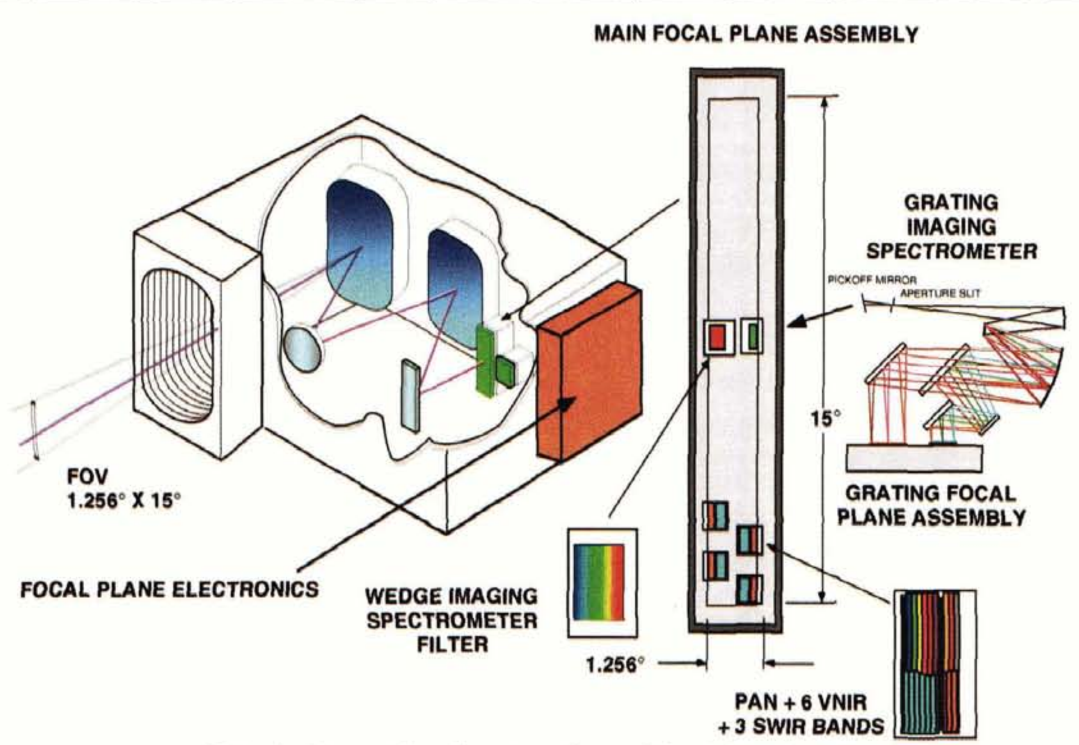

Plate 1. Advanced land imager optics and focal plane layouts.

samples at a spatial resolution of 30 metres. The GIS effective bandwidth will be 6 nm in the VNIR and 12 nm in the SWIR.

In addition to ALI, a second instrument, referred to as the LEISA (Linear Etalon Imaging Spectral Array) Atmospheric Corrector (LAC), is expected to be included on EO-1 to provide atmospheric correction data. The LAC will be a totally independent instrument which will be coaligned with the WFT assembly in order to cover the full 185-km swath of the WFT. The LAC is based on a Wedge Imaging Spectrometer, covering the spectral region from 0.85 to 1.6 μm, with a separate channel at 0.76 μm to aid in determining atmospheric aerosol content. The LAC will have a spatial resolution of 250 metres.

Supporting Spacecraft Systems

Advanced technologies being tested on EO-1 include a Pulsed Plasma Thruster (PPT) reaction wheel replacement, X-band phase array ground transmission antenna, high speed fiber optics data bus (FODB), carbon-carbon radiator panel, and light weight flexible solar array.

The Pulse Plasma Thruster (PPT) will be used on EO-1 as a candidate replacement for one of the reaction wheels which is used to stabilize and "lock in" the spacecraft attitude. The PPT is able to increment it's moment of inertia at very low levels of quantization. A traditional reaction wheel is a potential source of jitter because of bearing pressure, etc. Inclusion of the PPT on future missions is likely to result in the more stable spacecraft operations needed to support pushbroom sensor technology.

Carbon-carbon radiator panels are composed of a very light-weight composite material with extremely high thermal conductivity. This provides a very efficient method for dissipating heat by conducting the heat efficiently to the surface of the radiator panel. In addition, the mass-to-surface ratio is smaller than conventional panels. This technology addresses passive cooling requirements for successfully exploiting "warm" focal plane technology on future missions.

The X-band phase array antenna is an electronically steerable array with the ability to effectively steer the array by introducing appropriate phase delays in each element, thereby giving directional properties to transmitted signals. This technology eliminates the need for complex antenna tracking mechanisms and offers the potential for significant savings in mass.

The Fiber Optics Data Bus (FODB) will permit transfer rates on EO-1 of up to one gigabit per second. FODB architecture offers the ability to intermix instrument and processor nodes on a single ring structure. In fact, multiple interchanges at one gigabit can be sustained on the ring by expeditiously placing the nodes. That is, if specific processor nodes are paired with corresponding instrument nodes, one can sustain multiple transfers at 1 gigabit rates. The FODB associated electronics support standard Asynchronous Transfer Mode (ATM) protocol, simplifying the task of encoding the instrument and processor inputs and outputs.

The light-weight solar array is made of a highly efficient photosensitive material and has a very low mass-to-electrical-power-generation ratio. This has obvious benefits in terms of both launch costs and orbital maneuvering/maintenance fuel reserve requirements.

Discussion: Landsat 8 and Beyond

Although Landsat 8 has yet to be designed, external constraints impose many of its characteristics. It will have to be less expensive to build, launch, and operate while providing continuity with data from earlier Landsat missions. It will have to be more flexible and capable than the current Landsat system in terms of capturing surface reflectance information from sites of interest at opportunistic times.

Cost containment dictates a major departure from the scanning systems that have formed the basis for the Landsat series to date (Mika, 1997; pages 839-852 in this issue). The likely Landsat 8 candidate would include a wide field optical telescope and a single focal plane populated by Sensor Chip Assemblies (SCAs) with appropriate spectral response. This system would operate as a simple pushbroom scanner. The elimination of a complex scanning mechanism improves the stability and lightens the mass of the observing system substantially. However, insuring high performance of such systems makes significant demands on the relative alignment of detectors in the focal plane and the ability to control spacecraft attitude precisely. There are two candidate technologies which may be employed to ensure inherent detector alignment for Landsat 8 and beyond.

A single hybridized Multispectral/Panchromatic (MS/Pan) SCA is an evolutionary step from detector arrays employed in current pushbroom systems such as SPOT. Because the hybridized SCA is monolithically fabricated at the foundry, a higher degree of precision in detector-to-detector alignment within the chip to is assured. The single SCA would contain detectors responsive to a variety of wavelengths in the VNIR/SWIR (0.4- to 2.4-μm) spectral regions, as well as multiple size detectors resulting in multiple ground pixel resolutions. A single Landsat 8 SCA is likely to have 512 detectors in each of nine VNIR/SWIR MS bands and 1536 Pan band (0.48- to 0.68-μm) detectors, corresponding to a 30-m multispectral and 10-m panchromatic resolution on the ground. Four SCAs would be coaligned in a single module which would subtend 5° (a 60-kilometre ground track at a 700-kilometre altitude) of the wide-angle telescope focal plane. Therefore, only three modules would be required to construct a multispectral sensor system equivalent to the current Landsat. A prototype module, subtending 3° and consisting of four 320-detector-wide hybridized MS/Pan SCAs, is being developed for evaluation on EO-1.

An alternate approach, which is more revolutionary than evolutionary, is based on an SCA which allows for sampling the spectral response of a ground target at several hundred points in the spectral interval 0.4 to 2.4 μm. This technology offers the possibility of constructing customized sets of Landsat-like bands, measuring and correcting for atmospheric water vapor and thin cirrus contamination on a pixel-by-pixel basis, and, finally, conducting advanced analyses based on the availability of the complete spectral distribution of the pixels being observed. The spectral sampling scheme will generate almost two orders of magnitude more data than the MS/Pan approach, adding the complexity of transmitting this volume down to the ground or processing much of it onboard. The EO-1 validation activity will provide an opportunity to compare the performance of synthesized Landsat bands (Ahn *et al.*, 1996), based on WIS and GIS observations, against contemporaneously obtained Landsat 7 observations for a variety of applications. Furthermore, the WIS/GIS ability to resolve atmospheric spectral features, at Landsat ground resolution (30 metres), will be used to correct the synthesized bands for the presence of atmospheric water vapor (Green *et al.*, 1995; Green *et al.*, 1991) and high cirrus cloud obscuration (Gao *et al.*, 1993) on a pixel-by-pixel basis. The coarser spatial resolution (250 metres) EO-1 LAC will be used to correct contemporaneously obtained full Landsat 7 scenes for the presence of atmospheric water vapor and cirrus cloud obscuration. The impact of these corrections will be evaluated for a variety of applications as part of the EO-1 validation activities.

In order to operate a sequentially sampled pushbroom system successfully, the spacecraft must be able to maintain highly stable attitude in a jitter-free environment. Eliminating the complex scanning mechanism certainly does help to eliminate a major source of jitter. The basic design for the proposed Landsat follow-on instruments will have few moving parts. Recent developments in star camera technology have resulted in moderately priced instruments, such as the one being employed on EO-1, with the ability for determining three-axes orientation of the spacecraft to accuracies approaching 1 arcsecond. Furthermore, plans are underway to exploit the science data itself to generate input for the onboard navigation systems to correct the alignment of the SCAs such that travel of the image across the focal plane is registered across all wavelengths. In this scenario, data from a row of spectrally redundant detectors at both ends of an SCA may be analyzed, using correlation algorithms running on the onboard computer, to generate a fine sensor error signal. This error signal is fed into the Attitude Control System (ACS) to generate an alignment correction for ensuring correct alignment of the SCA in question. The idea of using the science data itself as a basis for a fine sensor correction is appealing from both an alignment accuracy and cost containment perspective. It is intended to develop and test a science data correlation algorithm, running on the onboard computer, to generate an ACS error signal, during the extended operations phase of the EO-1 mission. The source data will come from the WIS SWIR chip, which contains two spectrally redundant rows, separated by approximately half the chip long-track length. This redundancy is due to the fact that each WIS chip is overlaid by two adjacent filter segments, enabling some degree of overlapping spectral coverage.

The spacecraft will have the capability of pointing into adjacent ground tracks to increase the revisit capability for time-critical events. Furthermore, the spacecraft will have the capability of periodically performing a controlled scan over the surface of the moon to provide a calibration across different observing platforms, and throughout time periods corresponding to the entire lifetime of an observing platform. Lunar calibration planned for EO-1 will be used both to monitor instrument stability and to demonstrate the efficacy of using the lunar surface for intersatellite calibration through coincident lunar observation with MODIS.

The onboard data system must have the capacity and capability to support both observing instrument and spacecraft demands. Light-weight fiber optic data buses with data transfer rates exceeding 1 GB per second will be used to shuttle data between instrument and processing nodes using a standard ATM (Asynchronous Transfer Mode) protocol. The data bus architecture will allow multiple exchanges between instrument and processing nodes, at full data rate, to occur simultaneously over the same bus by appropriately pairing the instrument and processor nodes. Onboard solid-state storage will permit the staging of hundreds of gigabits of processed and unprocessed data for later downlink, or further processing. Onboard processing will accomplish several varieties of tasks. The scene acquisition tasks will enable orbit and attitude adjustment based on the onboard Global Positioning System (GPS), ACS sensors, fine sensor related science data, and ground-based scheduling priorities. Pre- and post-acquisition screening software will rely on the science data stream to determine if environmental conditions (e.g., cloud cover) are suitable for acquiring or relaying the science data back to the ground. Finally, the science data processing algorithms will be used to aggregate spectral data into the appropriate customized Landsat bands, or trade-off an increased number of spectral channels against the number of digitization levels. This software will also be able to bundle and arrange the science data to facilitate a quick turnaround on the ground. Atmospheric corrections may either be generated and applied to the appropriate science data onboard, or data needed to generate these corrections may be bundled with the appropriate science data and transmitted back to the ground.

The downlink transmission rate is probably the limiting factor in terms of the amount of data to be economically transmitted to the ground from each observing platform. We will be employing new transmission mechanisms which allow for flexibility and simplicity at a cost and weight savings. A likely candidate transmission technology for Landsat 8 is a K-band phase array antenna. This electronically steerable antenna, containing no moving parts, will be capable of sustaining highly reliable transmission with rates in excess of 150 megabits per second. An X-band version of this antenna, capable of transmitting 105 megabits per second, is being constructed for use on EO-1.

Current ground station acquisition and command strategies will be entirely inadequate in the Landsat 8 era. As we fly constellations of satellites to provide for a Land Observing Network beyond Landsat 8, the ability to receive the data on the ground will become the sole limiting factor. Autonomous operation, including onboard algorithms for enhanced formation flying, currently under development, will greatly reduce the number of contacts required to control the operation of the satellites. Up-link command strings specifying acquisition scenarios will be greatly reduced in length by the ability to store a variety of pre-determined acquisition strategies onboard. Ground reception of the science data is another matter. Ground stations will have to be equipped with X- and K-band antennas capable of receiving data at rates in excess of 150 megabits per second. Greater reliance will be placed on NASA polar ground stations such as those at McMurdo Sound in Antarctica, Poker Flats in Alaska, and Spitsbergen in Norway, because these stations will provide more frequent (almost every orbit) and longer (up to 20-minute) contacts with polar orbiting spacecraft than will the mid-latitude stations currently planned for Landsat 7. Communication satellite links to move data from the McMurdo ground station at rates in excess of 300 megabits to a receiving station in White Sands, New Mexico, are technically feasible even at this point in time. Use of the high-speed data links being developed by NASA's Ames Research Center as part of the next generation Internet capability is currently under investigation. EO-1 will rely on the polar ground stations as it's primary telemetry acquisition sites. Onboard autonomous navigation (i.e., enhanced formation flying), to keep EO-1 within 1 minute ± 10 seconds of Landsat 7, is planned for implementation during the extended operations phase of the mission.

Conclusions

As a "pathfinder," the EO-1 mission will substantively explore several technologies that have high potential not only to maintain the observing capabilities represented by Landsat 7 and its predecessors, but also, in several instances, to considerably improve upon those capabilities. In addition, the general approach should demonstrate that future Landsat missions can be accomplished at lower cost. The Earth science and related applications communities should expect to see improvements in the following specific areas as Landsat 8 and later Landsat missions are developed: (1) instrument performance, including spatial resolution, radiometry (e.g., calibration, signal to noise, quantization, stability over time, spectral resolution) and concomitant geometric properties (e.g., band-to-band registration, pixel geographic registration); (2) spacecraft position knowledge, stability, and attitude control to facilitate improved band-to-band registration and pixel geographic registration; and (3) onboard data systems and data transmission, along with improved ground data reception and processing systems. All these factors indicate that the future is bright for continuing Landsat-type observations that will be provide information of considerable value to the broad user community at considerable cost savings to the U.S. taxpayer.

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References

Ahn, C-W, M.F. Baumgardner, and L.L Biehl, 1996. Performance of AVIRIS, Adjusted AVIRIS, and Simulated TM Data for Classifying Crop Residue, *PECORA 13 Symposium*, Sioux Falls, South Dakota, 20-22 August (in press).

Elerding, G.T., J.G. Thunen, and L.M. Woody, 1991. Wedge Imaging Spectrometer: Application to Drug Pollution Law Enforcement, *Surveillance Technologies, Proceedings of SPIE*, 1479:380–392.

Gao, B.-C., A. Goetz, and W.J. Wiscombe, 1993. Cirrus Cloud Detection from Airborne Imaging Spectrometer Date Using the 1.38 micrometer Water Vapor Band, *Geophysical Research Letters*, 20(4):301–304.

Green, R.O., J.E. Conel, J. Margolis, C. Bruegge, and G. Hoover, 1991. An Inversion Algorithm for Retrieval of Atmospheric and Leaf Water Absorption from AVIRIS Radiance with Compensation for Atmospheric Scattering, *Proceedings of the Third AVIRIS Workshop* (R.O. Green, editor), JPL Publication, pp. 51–61.

Green, R.O., D.A Roberts, J.E. Conel, and J. Dozier, 1995. Imaging Spectrometer Measurement of Water Vapor in the 400 to 2500 nm Spectral Region, *Optical Remote Sensing of the Atmosphere*, Optical Society of America, Salt Lake City, 5-9 February, Vol. 2.

Mica, A.M., 1997. Three Decades of Landsat Instruments, *Photogrammetric Engineering & Remote Sensing*, 63(7):839–852.