PART 4. SCIENCE VALIDATION

2. KEY ISSUES

2.1 Why was the science validation performed?

The EO-1 mission was undertaken to meet the needs of Landsat continuity in response to requirements stated in public law. It has demonstrated advanced technology in order to enhance the capabilities and reduce the cost of obtaining Landsat-like data in the future. Specifically, it has evaluated selected technologies in the context of meeting science needs for continuing Landsat-class observations at reduced cost and with enhanced capability; evaluated space-based imaging spectrometers for potential future Earth Science Enterprise scientific, applied, and commercial uses; and evaluated new ways of conducting missions. The science validation activities were the mechanism used to assess how well the mission has met its objectives by judging the effectiveness of the candidate technologies for a variety of scene-based applications. Further, these activities evaluated the quality and validity of derived data products produced with EO-1 data and also helped potential data users understand the extent to which EO-1 observations could be used to create both new data products and the same types of derived data products that are currently being created from Landsat observations.

The Advanced Land Imager (ALI) is the instrument on board EO-1 that focuses specifically on Landsat continuity. It was designed expressly to validate replacement technology for the multispectral Enhanced Thematic Mapper (ETM+) now flying on the current Landsat satellite. Scientific validation of the ALI assessed whether it performed as well as the ETM+ and evaluated its ability to produce calibrated, multispectral images of the Earth's surface.

The Hyperion hyperspectral imager was evaluated to determine the utility of spectral imaging for land-based remote sensing applications. The LEISA Atmospheric Corrector (LAC) was assessed for its ability to provide improved atmospheric correction of data.

NASA issued a research announcement in 1999 to carry out scientific investigations to validate EO-1 technologies and to assess EO-1 spectral imaging for science and applications research. The Principal Investigators (PIs) selected for these science validation activities have conducted a series of investigations relating to a variety of scientific applications in which coincident measurements were collected using both the EO-1 ALI and Landsat's ETM+. (The two satellites have been flying one minute apart and observe virtually identical landscapes.) The measurements obtained by the ALI and ETM+ were then inter-compared for the radiances in comparable bands to see whether the measurements were consistent.

In some investigations, scenes that were already well characterized were used. Derived attributes based on measurements obtained by the ALI were compared with these known characterizations. Overall, investigations focused on analyzing how well the ALI identified and distinguished the physical attributes of land surfaces based on the radiances when compared to (1) the ETM+, (2) well-known observations, or (3) measurements obtained by some other independent means. These investigations did not focus on characterizing new aspects of the Earth, i.e., conducting "new science," with the intention of making new discoveries.

The validation activity for the Hyperion hyperspectral imaging spectrometer included an additional focus. Investigators validating the Hyperion focused on gathering measurements for a variety of applications. They explored how well spectral imaging could address these applications and what kinds of applications could be better addressed with imaging spectrometers rather than with contemporary multispectral sensors. Some Hyperion scientific validation activities also compared Hyperion with airborne instruments such as AVIRIS and HyMap as well as with ground spectrometers. Still other validation investigations compared the ability of Hyperion to capture similar information as can be captured with multispectral instruments like the ALI or Landsat ETM+. For example, in one case, the PIs focused on identifying different species of trees and inter-comparing the ability to obtain this type of information with Hyperion with the ability to obtain similar information from a multispectral instrument. Finally, some PI's assessed Hyperion's ability to provide continuity with current multispectral observing systems by evaluating its ability to synthesize Landsat and ALI multispectral bands.

Scientific validation of the LAC is still underway. Its validation is to demonstrate that such an instrument can be used for atmospheric correction of data, particularly in relation to the water vapor content of the atmosphere. A secondary goal is to determine whether it can obtain information about aerosols. The LAC is also expected to detect thin cirrus clouds, which are not obvious in images and have the effect of subtly reducing the amount of light. In a future formation-flying scenario, use of a LAC-like instrument could fly in conjunction with a primary instrument. This instrument would facilitate the observations of the primary instrument by providing correction for atmospheric effects.

2.2 What has been learned?

In every case, the EO-1 ALI instrument has met or exceeded the performance of the ETM+. Stray light has been a problem on this mission primarily because of the excessive surface roughness of some of the ALI mirrors. Thus for purposes of validation, situations were avoided in which stray light would play a major role in the gathering of data.

The stray light issue with ALI was identified early in the mission and a decision made to not delay launch because of it. Researchers conducted an independent study to address the concern and decided to separately pursue validating that an instrument could be built that meets all stray light requirements. The ALI-type mirrors were rebuilt and successfully demonstrated that they could be polished to the degree that performance was consistent with the ALI stray light specification and therefore confirmed that the ALI can be the basis for developing future Landsat-type instruments. Thus, in situations where stray light is not an issue, EO-1 outperforms Landsat, allowing subtle differences in contrast to be discerned. Stray light, though, will still remain an issue on some future missions, particularly when looking at subtle changes from time to time and when near cloud edges because stray light limits the ability to determine absolute radiance.

Many studies have shown that greater precision can be achieved with ALI than with ETM+. The additional shortwave infrared (SWIR) band and improved signal-to-noise have been helpful in vegetation analysis, as demonstrated in a Canadian forest survey where species identification and differentiation with 85% accuracy were obtained as opposed to 75% accuracy with ETM+.

The blue band has been identified as potentially useful in determining aerosols and for capturing scattering properties for bathymetry applications. Although initial investigations are promising, research activities for both of these investigations are still ongoing.

The performance of the ALI Pan band exceeds that of the ETM+ on Landsat. The ALI Pan band has finer spatial resolution (10 meters) than the ETM+ Pan band (18 meters effectively). The ETM+ Pan band spans the infrared plateau. The Pan band on ALI, on the other hand, is contained entirely within the visible portion of the spectrum. This results in more reliable Pan sharpening of the ALI band in the visible portion of the spectrum.

Since ALI is a sequentially sampled push-broom array instrument, the inherent band-to-band registration critically depends on both the array alignment and the instrument sampling rate. The array can be accurately oriented and maintained to enable satisfactory band-to-band registration in the cross-track direction. The ALI sampling rate can also be varied on board to keep the bands co-aligned in the along-track direction. The sampling rate, however, is sensitive to the height of the land surface. Therefore, along-track misregistration of bands cannot be avoided in areas of rapidly changing topography. For an instrument going across a full 185-km swath, there would often be considerable variability in height, and one sampling rate would not maintain the desired band-to-band registration across an entire row of pixels. Resampling of data, although not the preferable option in many cases because some information would be lost, would be a possible approach to addressing the problem if there were good knowledge of the topography. However, topographic information at sufficient resolution is not yet available on a worldwide basis. The problem of along-track band-to-band misregistration must be addressed to successfully employ sequentially sampled push-broom array technology on future Earth observation missions.

For the Hyperion, the preflight characterization of the instrument has proven to be fairly accurate. Its level of signal to noise has proven to be somewhat better than that projected from preflight measurements, roughly 25 to 50% better, and in spite of the existing signal-to-noise restrictions, the instrument has performed far better than originally anticipated. As an example, in a forestry study discussed earlier in which there was 75% identification accuracy with ETM+ and 85% accuracy with ALI, there was 94% accuracy with Hyperion. Although the instrument is limited in performance, Hyperion has allowed characterizations of a variety of landscapes not possible with the ETM+ or ALI. It has provided good results in areas of vegetative cover and in semi-arid regions.

2.3 Where do the results lead us?

For the ALI, the results lead us to believe that we can do considerably better than Landsat with the new technology at a lower price. The bonus is that not only can we do it "cheaper and faster," but using the new technology allows us to do it better as well.

The problem with co-registration is endemic to push-broom sequential sampling. It will be necessary to come up with a combination of a sampling scheme and an on-board recording/processing scheme that will allow co-registration. Such a system could support on-board image-aided navigation.

It may also be worthwhile to turn attention away from multispectral imaging and toward hyperspectral imaging as a continuation to Landsat. It may be possible to use the new technology developed for multispectral imaging for hyperspectral applications. This technology could also be extrapolated to instruments with much finer spatial resolution, perhaps 10 meters, and the Pan band at perhaps 5 meters or 1 meter. A problem, however, with going to hyperspectral imaging or increased spatial resolution is the great increase in the amount of data that would need to be handled, perhaps on the level of one to two orders of magnitude, and transmitted to the ground. There may be ways to streamline the data and selectively choose what is needed. Further, it may be possible to adaptively combine spectra into bands and selectively transmit data from a combination of bands.

2.4 What contributions have spacecraft technologies made to science validation?

The spacecraft technologies complement the instrument technologies and enhance their overall usefulness in remote sensing applications. All of the spacecraft technologies were chosen based on their ability to enable the spacecraft to do a better job in support of the instruments than they could with current technologies. The project was integrated in a way so as to provide the strongest validation package that could be devised within the existing budget. This was done by first picking the instruments and then selecting the spacecraft technologies that would best complement those instruments.

The Wideband Advanced Recorder and Processor (WARP) provides a capable solid-state memory with an unusually large ingest rate and a microprocessor to process data prior to its downlink. It also, in the case of EO-1, provides an RF exciter that connects directly to the X-band phased array antenna. Future missions using phased array antenna should consider utilizing the WARP's architecture in this regard.

Although digital electronics has advanced so rapidly that there now are solid state recorders on-orbit that exceed the WARP's specifications, this EO-1 technology paved the way for their development.

The X-band Phased Array Antenna (XPAA) is a high data rate, low mass system that can support simultaneous imaging and downlinking of data with minimum jitter. It is agile, being electronically steerable with no moving parts, is a very reliable system, and offers a viable alternative to gimbaled systems for future missions. In addition, the EO-1 XPAA is considered a stepping-stone to Ka-band phased array antennas for extremely high data rate applications (> 300 Mbps) although X-band will remain the "workhorse" frequency band.

The Enhanced Formation Flying (EFF) capability has enabled us to safely fly sufficiently close to Landsat 7 in an autonomous manner so as to permit paired-scene comparisons with the ETM+ on Landsat 7. This is an essential capability that was sought in order to validate the imagers, particularly the ALI. The underlying concept is the requirement to be able to take two images of the same ground scene near enough in time so that the atmospheric region is the same for both cases. The desired autonomous formation flying operation was accomplished quite readily and it is believed that this technology is ready for operational use. The Goddard EFF algorithm was demonstrated first since it was the most mature. Later in the flight, the JPL algorithm was demonstrated. For the EO-1 application, both performed equally well although the GSFC algorithm is more general and can be applied to any orbit about any celestial body.

In terms of precision pointing, this feature is important in that it allows the spacecraft to have a "point and shoot" capability that substantially enhances the flexibility of the system. Typically, the images from the ALI or Hyperion are within 100 meters of the exact longitude and latitude requested of the spacecraft.

The EO-1 mission was the first time a Pulsed Plasma Thruster (PPT) was used to serve as a precision attitude control actuator for a spacecraft. It has operated successfully for a number of demonstration cases. Initially, there was some concern the PPT might interfere with the image taking process. But, in fact, it has been demonstrated that no interference occurs. The PPT has operated flawlessly and has maintained satisfactory pitch control during all operational phases. By providing significant mass savings over conventional systems in conjunction with the small disturbance inducing impulses, the PPT is an attractive candidate for being an active part of the precision pointing capability in future missions.

For the Lightweight Flexible Solar Array (LFSA), the goal was to demonstrate that, by the use of solar cells on a flexible substrate in conjunction with the use of shape memory alloys for the hinge and deployment system, the specific power output could be increased considerably above the current range of 20-40 Watts/kg. An inherent part of this goal was to assess the performance degradation in the space environment. Unfortunately, an unexpected major degradation in power output occurred shortly after launch. The cause was traced to a progressive fracture of solder joints between the solar cell modules and the power harness. Fortunately, as the result of an investigative study of the problem, the contact metallurgy practice for this application has been revised so as to preclude this problem. Notwithstanding the early failure, the initial power output of the LFSA corresponded to the design objective and therefore validates the potential use of thin-film solar array technology and shape memory alloys to produce significantly greater specific power output than current technologies.

The Carbon-Carbon Radiator (CCR) performed well throughout the mission. The objective of this technology is to demonstrate that Carbon-Carbon (C-C) can be a cost effective facesheet material for honeycomb-core radiator panels that can also function as primary structure. As a material, C-C has a higher stiffness and a higher thermal conductivity than aluminum and consequently a markedly higher specific thermal efficiency. Consequently, a CCR offers improved performance for a lower mass. Because C-C is a composite, an opportunity is provided to tailor its strength and its functionality to serve both functions. In this regard, C-C facesheet honeycomb panels offer a viable option to future missions wherein radiators can also be used as structural components.

The goal of the LA-II thermal coating technology was to demonstrate the improved thermal performance of a new low absorptance inorganic white paint when compared with a known white paint in current use (Z93). The expected improved performance will allow space radiators to run cooler. The results of on-orbit measurements show that the LA-II coating runs about 5 °C cooler during the sunlit portion the orbit. Therefore, where use of a thermal coating is appropriate on future missions, the LA-II coating will permit a reduction in radiator size or the accommodation of higher power equipment or instruments.