feature articles

Chronicling the Landsat Legacy

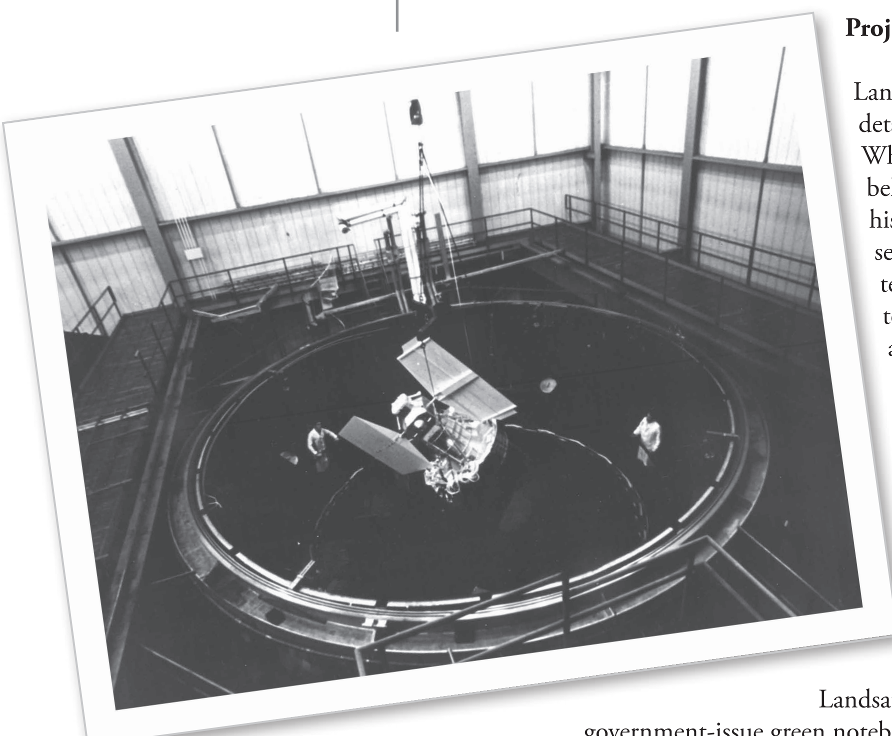
Laura Rocchio, SSAI, Laura.Rocchio@nasa.gov

In an era when receipt of images and data from low-Earth-orbiting satellites is more or less "routine," it's hard to remember that a few short decades ago this was not the case. As the first land-observing satellite program, Landsat laid foundations for modern space-based Earth observation. Today, Landsat offers the longest near-continuous data record of Earth's land surface.

Since the project's inception in 1966, Landsat has stood at the forefront of space-based Earth observation, and has been the trailblazer for land remote sensing as it is known today. Despite the program's prominence in Earth observation by a civilian program, the forty-five year history of Landsat has been organizationally tumultuous. Three government agencies and a private company have operated the Landsat satellites at various times over the course of four decades and eight Landsat missions. As a result, program records have become widely dispersed, risking the loss of historical details and the proliferation of misconceptions.

Birth of the Landsat Legacy Project

In 2004, an effort to accurately document Landsat's evolution began with the advent of the *Landsat Legacy* project. Since that time, NASA, together with the U.S. Geological Survey (USGS), has gathered over 800 pictures and documents related to the project. The library at NASA's Goddard Space Flight Center (GSFC) has assembled a digital archive to house these materials, focusing on technical papers and a series of 21 Landsat Legacy interviews conducted with 50 Landsat veterans. In 2007—with additional support from the NASA History Office—the Landsat Legacy team began writing a book-length history using these materials[1].



A mock-up of Landsat 1 at GE's Space Division in Valley Forge, PA. The mock-up (a Nimbus structural model) was brought to the GSFC High-capacity Centrifuge for testing. During the spin-up the satellite was completely destroyed due to improper structural strengthening.

Project Revelations

Landsat Legacy research has uncovered lost details about the storied Landsat project. While untangling a web of long-held beliefs and objective reality, a fascinating history has emerged. The complex intersections of personalities, agency cultures, technological advances, and policy have touched everything from the conceptualization of Landsat's first multispectral sensor to the recent emancipation of the Landsat data archive. Some relevant stories are summarized here.

Breakneck Speed

During an early oral history interview, Landsat 1[2] Spacecraft Manager, **Gil Branchflower** reminisced about the astounding pace of the Landsat 1 development. He brought along his government-issue green notebooks, the content of which revealed that the first meeting between GSFC representatives and the spacecraft contractor, General Electric (GE), took place on July 20, 1970. Just two years later, on July 23, 1972, the spacecraft was launched carrying two sensors—a Return Beam Vidicon (RBV) and the Multispectral Scanner System (MSS). This remarkably short time from blueprint to orbit was achieved despite major mission complexities, integration problems with both instruments, and the complete destruction of the spacecraft structural model in GSFC's High-capacity Centrifuge.

[1] The book is expected to be published in 2013.

[2] Landsat was initially called the Earth Resources Technology Satellite (ERTS) until it was changed to Landsat after the launch of the second satellite in 1975. For simplicity's sake, the name Landsat is used throughout this article.

MSS Heritage

The MSS concept came as an unsolicited proposal from Hughes Aerospace Corporation engineer **Virginia Norwood**. The MSS was flown on Landsat 1 as an experimental instrument. However, it immediately eclipsed the relatively noisy and short-lived RBV camera system due to its better radiometric and geometric fidelity. The MSS was limited to ~60 lbs because the majority of the budgeted mass was designated for the RBV cameras that were expected to have the higher geometric fidelity essential to the mapping community, but the MSS geometry turned out to be remarkably good for its time. Well-known USGS cartographer, **Alden Colvocoresses**, had been highly cynical about the MSS's ability to collect cartographically accurate data with "a little mirror in space," but upon seeing the first MSS image he turned to his colleagues and exclaimed "Gentlemen, that's a map." He later wrote to Norwood and told her "it has become obvious to me and others, that the MSS is a real mapping instrument."

John DeNoyer and MSS Lead Engineer **Virginia Norwood** reflect on the history of Landsat.

Many longtime Landsat associates have always assumed that technology for the MSS came out of the defense world, but the converse is the reality. The MSS digital scanning technology and spectral detectors were brand new and were later adopted by military missions. The only military-to-civilian sensor technology used by Landsat was the thermal band mercury-cadmium-telluride (HgCdTe) detectors on Landsats 3–7.

Rocking the Spacecraft—The Demise of RBV

After the launch of Landsat 1 there was an on-orbit checkout period when various modules were turned on sequentially. On August 3, 1972, a power surge caused by an improperly functioning tape recorder forced ground controllers to turn the recorder off. Then, on August 6, 1972, a second massive power surge associated with the RBV instrument occurred. According to the Landsat 1 project and spacecraft managers, this huge second electrical transient physically rocked the spacecraft, causing it to lose attitude control and point away from Earth. Ground controllers quickly turned off the RBV. The spacecraft recovered, and the MSS instrument operation resumed. After a few months[3] of working together, NASA and RCA engineers confirmed—by using a bench-test model—that a faulty inductor in the power-switching unit that fed the RBV was to blame for the major electrical short. The recognized superiority of the MSS data made it unnecessary to turn the RBV back on, and caused interest in RBV data to wane on succeeding missions[4].

The Massive Landsat Science Team

Prior to 1972, the idea of using satellite data for land monitoring, mapping, or exploration was a foreign concept. For Landsat 1, scientists from a wide array of

[3] Some readers may note this is imprecise; these details were supplied via oral histories—as opposed to precise timelines. According to spacecraft manager **Gil Branchflower,** "I think it took three or four months" to conduct the bench test that figured out the problem.
[4] There is one noteworthy exception. A cadre of USGS glaciologists found the 38-meter resolution of the Landsat 3 RBV essential for distinguishing individual large crevasses in Antarctica where MSS resolution and band saturation caused problems.

Stan Freden with a Landsat 1 model in 1972.

disciplines and organizations were invited to submit proposals to become Landsat principal investigators (PIs). NASA hoped that exposure to this new Earth-observation technology would erase uncertainty about Landsat and entice scientists to examine how its data could be applied in their respective research fields. The Landsat PI request for proposals (RFP) went out in the 1970–'71 timeframe and; over 600 proposals were received in response. This was an unprecedented number of proposals to an RFP (the typical number at the time was closer to 25), and it demonstrates how Landsat democratized the scope of who could propose to and receive funding from NASA. Over a grueling two-week period, NASA reviewers whittled the 600 proposals down to 300 from universities, federal and state agencies, private industry, and approximately 100 foreign organizations representing 38 countries. The proposals that were selected and funded typically got $150,000—a sizable sum in the early 1970s.

Stan Freden at GSFC was responsible for coordinating the research. Freden conducted four symposia to document and distribute the PI results. Landsat had quickly changed the view of Earth's land surface—a traditionally myopic view that had instantaneously become synoptic. As an early Landsat researcher remarked, it took the Landsat MSS instrument 28.5 seconds to collect an image; it took 2.5 days flying around in a Cessna to photograph that same area.

How Landsat 3 Almost Never Came to Be

The original Landsat program included two satellites. Later, plans were adopted for a more-advanced sensor—the Thematic Mapper (TM)—to fly on two additional satellites (ultimately, Landsats 4 and 5). While work was well underway for the TM, Landsat 2 exceeded its design lifetime. "We had a growing user community, and there was concern that if we stopped data, the whole program would end," Freden explained. An intermediary was needed, but NASA—an R&D agency—thought that a third, unplanned copy satellite was too operational. As a salve, improvements were included in the Landsat 3 design: a thermal band was added to the MSS and the RBV spatial resolution was increased. With these improvements, NASA got behind Landsat 3 as an incremental technology-expanding satellite, but the Office of Management and Budget (OMB) did not support the concept. Fortunately, **Robert Allnutt**, the NASA Assistant Administrator for Legislative Affairs, thought the public good that would derive from continuing Landsat was indispensable. When the NASA budget came to the Hill with no Landsat 3 funding, Allnutt recommended that authorization for funding be reinstated. "I recommended both in 1973 and 1974, that we add back authorization for new satellites in the series—and the Committee did so, the Senate passed the bill, and we prevailed in conference with the House (which really did not fight us on the issue)," Allnutt explained. With funding authorized, the Appropriations Committees followed suit and added funds for Landsat 3 to the NASA appropriations for two years, allowing Landsat 3 to be built and then launched in March 1978[5].

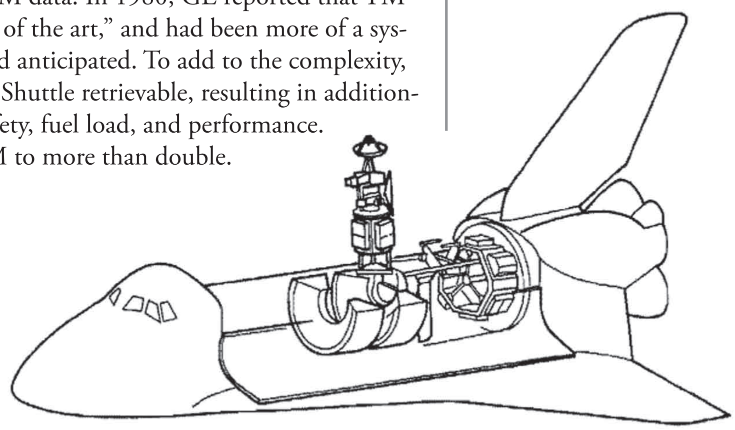
[5] Unfortunately, the Landsat 3 MSS was largely built using spare parts from the Landsat 1 and 2 MSS instruments. The instrument experienced problems after launch, including line-start issues that caused the loss of 30% of each image. This problem began six months after launch and plagued the sensor intermittently throughout its lifetime. Additionally, there were troubles with the thermal band and satellite tape recorders.

Thematic Mapper Challenges

In the late 1970s the TM was considered "…the most complex and pioneering Earth-viewing instrument ever proposed for a NASA program." [6] The optical technology of the sensor was innovative, and its cold-focal-plane technology presented many fabrication problems. Additionally, GE, the contractor for the flight and ground segments, was dealing with many new communication requirements, including a Tracking and Data Relay Satellite System (TDRSS) antenna, a global positioning system (GPS), and high-data-rate download capability for TM data. In 1980, GE reported that TM integration was "pushing minicomputer state of the art," and had been more of a system driver for their segments than anyone had anticipated. To add to the complexity, Landsats 4 and 5 were mandated to be Space Shuttle retrievable, resulting in additional requirements on the satellite's structure, safety, fuel load, and performance. All these challenges caused the cost of the TM to more than double.

Commercialization

Mired in an economic stagflation, the Carter Administration commissioned studies to assess which elements of government programs could be successfully spun off into private industry.



A drawing of a proposed Space Shuttle - Landsat rendezvous. While shuttle launches to polar orbit were actively pursued during the early- and mid-1980s, in the end no such rendezvous ever occurred.

After extensive studies in 1978 and 1979, the November 1979 Presidential Directive NSC-54, *Civil Operational Remote Sensing*, directed the National Oceanic and Atmospheric Administration (NOAA) to take over operations of the Landsat program and to investigate how to increase private-sector involvement in the program. President Reagan's campaign promises of smaller government left his team of advisors looking for ways to tighten the government's belt after his 1980 election. They converged on Landsat. The push to commercialize Landsat accelerated so that government funding could end as soon as possible. By 1981, NOAA was ordered to recover full operating cost from the sale of data. New prices went into effect in October 1982 and climbed to a staggering $4400 per scene over the next three years causing data sales to drop precipitously. By January 1984, NOAA had solicited bids for commercialization. Of the seven bids offered, five were rejected for technical shortcomings, leaving only Kodak and EOSAT in the running. Kodak later withdrew its bid due to imprecise OMB financial terms. In a stinging commentary, a *Science* editorial opined that "…in the name of economy, the Administration has managed to narrow the free and open competition for Landsat down to a single bidder by changing the rules in mid-game." A decade and a half of unsustainably high data prices ensued.

Understanding Earth as a System

The notion of Earth as a connected system of environmental cycles that could influence human wellbeing (via storms, drought, famine, etc.) garnered strong scientific attention during the 1980s. The concept of using space-based remote sensing to study Earth as a system had been around since the 1960s; NASA developed a number of Earth-observing satellites through the '60s and '70s—including Landsat—with this systems approach in mind. By the latter half of the 1980s Landsat's contribution to Earth system science studies and to the mitigation of environmental stressors was developing considerable appreciation, but under the commercialization requirements the Landsat historical data archive suffered, and data prices and copyright restrictions kept its data out of many researchers' hands.

During the same period, Landsat's use by the Pentagon grew because its broad spectral range proved a strategic asset during the first Gulf War. While other satellite data of-

[6] Quote taken from a job description put out by NASA GSFC for a System Engineer to oversee Hughes SBRC TM/MSS sensor design.

fered better spatial resolution, the TM's seven spectral bands enabled military analysts to tease more information out of the data by evaluating ground reflectances from the blue wavelengths through the thermal. With military and government-funded researchers as major Landsat data users, Congress—and the public, via a spate of newspaper articles—realized it was "paying twice" for Landsat data, in that tax dollars had built the satellites and then by paying a government-subsidized company for its data. As a result, after many Congressional hearings the decade-long commercialization experiment was ended, and the Landsat program returned to the government fold.

Nearly Flawless: Landsat 7 Triumphs and Tribulations

On April 15, 1999, fifteen years after Landsat 5's launch and six years after EOSAT's failed Landsat 6 launch, the government-owned Landsat 7 was orbited. Once on orbit, the excellent data quality, the consistent global archiving scheme, and reduced pricing (then $600 per scene) led to a large increase in data users—many of them migrating back from low-cost coarse-resolution data obtained from other resources.

Today the 27-year old Landsat 5 satellite continues to collect data. The serendipitous surfeit of fuel from the unrealized Shuttle-retrievable plans has enabled the massively extended life of the mission, but hydrazine fuel alone has not kept the satellite alive: Landsat 5 operations engineers have overcome myriad age-related challenges.

A new image collection method called the *long-term acquisition plan* (LTAP) was established to enable the realization of Landsat's mission—to provide systematic, seasonal, global coverage.

LTAP is a preplanned imaging scheme that enables systematic worldwide coverage. Using vegetation greenness as measured by the *normalized distribution vegetation index* (NDVI), cloud cover climatology, and cloud predictions, the optimal acquisition times for land and coastal waters of interest are dynamically determined during the daily scheduling process. More scenes are collected during vegetation green-up and senescence than during peak greenness and dormancy. Extensive modeling was used to evaluate the efficacy of the scheduling process. Earth is on average 63% cloud-covered each day, but LTAP has reduced the average cloud cover across all archived Landsat 7 scenes to 32.5%—nearly half of the global average. Applying the LTAP to the Landsat 7 scheduling system has resulted in robust worldwide coverage; inclusion of a similar plan is in the specifications for the next Landsat, planned for launch by the end of 2012 as the Landsat Data Continuity Mission (LDCM).

With the triumph of LTAP and highly accurate data calibration, the Landsat 7 mission went flawlessly until May 2003, when a hardware component failure left wedge-shaped gaps of missing data on either side of Landsat 7's images. Six weeks after suffering the loss of its scan line corrector (SLC), Landsat 7's Enhanced Thematic Mapper-plus (ETM+) instrument resumed its global land survey mission resulting in only a short hiatus in its imagery acquisition for the U.S. archive. However, the malfunction impacted the imagery of Landsat 7, essentially cutting out 22% of each scene. Fortunately for the Landsat community, the venerable Landsat 5 is still collecting data in concert with the handicapped Landsat 7.

A Marvel of Engineering: Landsat 5 Lives On

Today, the 27-year old Landsat 5 satellite continues to collect data. The serendipitous surfeit of fuel from the unrealized Shuttle-retrievable plans[7] has enabled the massively extended life of the mission, but hydrazine fuel alone has not kept the satellite alive: Landsat 5 operations engineers have overcome myriad age-related challenges.

As an example, as Landsat 5 approached its 100,000th orbit on December 19, 2002, engineers had to find a way to incorporate a six-digit orbit number into the flight control and data processing software because the original software allowed for only a

[7] NASA came very close to implementing these plans for shuttle launches into polar orbit. To learn more see "The Earth Observing Legacy of the Space Shuttle Program" in the September–October 2011 issue of *The Earth Observer* [**Volume 23, Issue 5**, pp. 4-17.].

five-digit orbit number, as no one imagined that the satellite would still be flying 18 years—and 99,999 orbits—after its launch. And absolutely no one imagined that after extensive software updates to address perceived problems that could have been caused by the turn of a new century ("Y2K") that more than a ten-year extension of the star catalog would be needed, but it was.

On January 1, 2010, the star map for January 1, 1910 was inadvertently uploaded, making Landsat 5's attitude stray as it attempted to locate stars where they had been 100 years ago; fortunately, the satellite easily recovered.

Over the years, serious anomalies have struck the Landsat 5 solar array, batteries, communications system, and attitude system, and virtually none of the redundant systems are still available. Despite this, the flight operations team has successfully dealt with all of these anomalies by adapting ground control procedures, modifying orbital operations, and—in some cases—resurrecting onboard equipment previously thought to be unrecoverable. Their efforts to recover the satellite from these potentially mission-ending anomalies were recognized by the American Institute of Aeronautics and Astronautics in 2006 with receipt of the *International SpaceOps 2006 Award for Outstanding Achievement*.

Free Landsat data, paired with today's powerful computer processing capabilities, have enabled large-scale, global-change studies that in the past were too costly to be conducted by all but a few institutions. These policies have heralded what some are calling a "democratization of satellite mapping."

Free Data—A World of Influence

In April 2008, the USGS (with a strong push from then-Associate Director of Geography, **Barb Ryan**) announced that all archived Landsat data would be made available for free.

USGS Director **Mark Myers** explained that by opening the Landsat archive for free electronic access, the USGS sought to promote "…a common global understanding of land conditions—historical and contemporary—for users worldwide." The USGS made Landsat data available for no cost starting in October 2008 (with free Landsat 7 data); in January 2009, Landsat 1–5 data were also made available at no cost. Since then, the USGS has experienced a 60-fold increase in daily data downloads. In August 2009, the millionth free scene was downloaded; the following August downloads hit three million; and in August 2011, free downloads surpassed six million. The success of the new Landsat data policy is encouraging other international projects to follow suit. Free Landsat data, paired with today's powerful computer processing capabilities, have enabled large-scale, global-change studies that in the past were too costly to be conducted by all but a few institutions. These policies have heralded what some are calling a "democratization of satellite mapping."

Continuing the Legacy

The eighth Landsat satellite—the LDCM—is currently under development and scheduled to launch in December 2012[8]. Plans for an operational Landsat program run by the Department of the Interior (and starting with Landsat 9) have been developed, but face congressional vetting before being funded. LDCM and an operational Landsat program will continue the legacy of Landsat's rich, global, medium-resolution data archive.

Understanding the Historical Archive

The benefit of the Landsat archive is its depth. Looking back into the archive many coverage "holes" are found prior to the implementation of LTAP. Many areas of missing data were perplexing, but the Legacy project has cast light on this. Early collection priorities for the original 300 principal investigators, large-scale projects with the U.S. Department of Agriculture, work with **Jacques Cousteau**, and a coastal bathymetry campaign coupled with downlink limitations, frequent onboard recorder failures, and no prompt way to visually inventory the spatial coverage of the global data archive have been found to be the main reasons behind the strange global coverage patterns that appear in the early archive.

[8] LDCM will be renamed Landsat 8 when it reaches orbit.

Strong Personalities Behind Landsat

Throughout the Landsat history, a number of spirited personalities have emerged to shape the project. A few notable names among the early Landsat pioneers were Secretary of the Interior **Stewart Udall**, USGS Director **William Pecora**, NASA scientist **Bill Nordberg**, MSS engineer **Virginia Norwood**, USGS cartographer **Alden Colvocoresses**, Berkeley professor **Robert Colwell**, and Purdue professor **David Landgrebe**. Some had magnetic personalities, some imposing, but all were influential on the Landsat program. Much as Pecora replied to a congressional review prior to Landsat 1's launch when asked if he preferred the RBV or the MSS, "Well, it's like beer. There's good beer and there's better beer, but there's no bad beer."

Filming of a Landsat Legacy oral history, November 2008 Pecora Conference in Denver, CO, featuring **John DeNoyer** and **Virginia Norwood**.

Acknowledgment: The Landsat Legacy Team members are: **Terry Arvidson** [Lockheed Martin]; **Sam Goward** [University of Maryland, College Park]; **Jim Irons** [GSFC—*LDCM Project Scientist*]; **Shaida Johnston** [Global Science & Technology, Inc.], **Laura Rocchio** [GSFC/Science Systems and Applications, Inc.]; and **Darrel Williams**. [GST].

Additional Resources

Landsat Resources
landsat.gsfc.nasa.gov
landsat.usgs.gov

Landsat Legacy Project
library.gsfc.nasa.gov/landsat