The Landsat Program: Its Origins, Evolution, and Impacts

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Abstract

Landsat 1 began an era of space-based resource data collection that changed the way science, industry, governments, and the general public view the Earth. For the last 25 years, the Landsat program — despite being hampered by institutional problems and budget uncertainties — has successfully provided a continuous supply of synoptic, repetitive, multispectral data of the Earth's land areas. These data have profoundly affected programs for mapping resources, monitoring environmental changes, and assessing global habitability. The societal applications this program generated are so compelling that international systems have proliferated to carry on the tasks initiated with Landsat data.

Introduction

Civilian land remote sensing satellite systems are currently being operated by the United States, France, India, Japan, Canada, Russia, and the European Space Agency. On command, all of them make measurements of the land surface, transmitting data to a global network of strategically located ground receiving stations. Data from these Earth-observing satellites are used to map, monitor, and manage Earth's natural and cultural resources.

The United States pioneered land remote sensing from space and has been the unquestioned leader of this unique technology. Americans take pride in having developed the Landsat program and other, more recent, civilian programs. The evolution of Landsat, however, has been neither linear nor predictable. This paper provides an overview of its conception, genesis, and growth; its accomplishments and current status; and its uncertain future.

The Road to Landsat

Perhaps the first person who believed that not only machines but humans, too, could venture into space was Jules Verne, a French provincial lawyer with no scientific or technical training (Mark, 1984). Verne, in 1865, made the extraordinary prediction that a rocket would be launched from Florida by means of chemical propulsion and that the crew would include three people (and a dog). First they would only circle the Moon and return to Earth, as did Apollo 8. This would be followed by a trip to the Moon's surface, returning to Earth with a "splash down" in the Pacific Ocean and recovery by a warship. Perhaps Verne's most remarkable prediction was that this first journey would be made by Americans. What he did *not* predict was that astronauts would be awed by "the blue marble," or that their photographs would so sensitize the world, that subsequent human scientific interest would shift toward space as a means for studying the Earth. The United States was not only the first to land a spacecraft on the Moon, but, beyond Verne's vision, it also developed the first remote sensing satellites whose profound importance in today's sense of a global village cannot be overstated.

In 1946, the United States Army Air Corps requested that RAND Corporation consider how objects might be inserted into orbit (Mark, 1988). The study resulted in a report, *Preliminary Design of an Experimental World-Circling Spaceship* (Burrows, 1986). The proposed midget moon, or "satellite," would provide "...an observation aircraft *[sic]* which cannot be brought down by an enemy who has not mastered similar techniques." After many aborted lift-offs and system failures, the military successfully launched its first Earth-observing satellite in August 1960. It was called Discoverer and was expected to be an unclassified system to support biomedical research and Earth observations (Tsipis, 1987; Whelan, 1985). A few months after launch, however, a Presidential Directive classified the Discoverer program and plunged it into deep secrecy. Only recently have images collected by its successor, the Corona program, been declassified for public use (McDonald, 1995).

Parallel to the early military/intelligence programs in space, the scientific and industrial communities in America were awakening to the potential of space for providing a new world perspective. In 1951, six years before Sputnik 1, Arthur Clarke, a science fiction writer and prophet of technology, proposed that a satellite could be inserted into orbit over the North and South Poles while the Earth revolved beneath it, and that this satellite would permit humans to view the planet in its entirety (Fink, 1980). In April 1960, the National Aeronautics and Space Administration (NASA) and the Department of Defense (DoD) launched the Television and Infrared Observational Satellite (TIROS-1) into such an orbit, inaugurating the first experimental weather satellite (U.S. Dept. of Commerce and Nat'l. Aero. and Space Admin., 1987). This system generated the first television-like pictures of the entire globe in a systematic and repetitive manner. This ongoing series of TIROS satellites became operational in 1966 as the TIROS Operational Satellites (TOS), and in 1970 were renamed by the National Oceanic and Atmospheric Administration (NOAA) the Polar Orbiting Environmental Satellites (POES) (Morain and Budge, 1995).

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Growing the Science Community

The Environmental Research Institute of Michigan (ERIM), formerly the Institute of Science and Technology at the University of Michigan, is credited with organizing in February 1962 the first technical conference on remote sensing in the United States, perhaps the world. Its *First Symposium on Remote Sensing of Environment*, sponsored by the Navy's Office of Naval Research (ONR) had 15 presenters and 71 participants (Environ. Res. Instit. of Michigan, 1962). One of the presenters, who represented the U.S. Department of the Interior (DOI), was the U.S. Geological Survey's (USGS) Dr. William Fischer, an early advocate of an Earth-observing system. The field was so new that Dana Parker, an organizer of the Symposium, focused his inaugural address on fundamentals of the electromagnetic spectrum. In October 1962, the second symposium drew 162 participants to hear 35 technical papers (Environ. Res. Instit. of Michigan, 1963). It was sponsored by the Geography Branch of ONR, the Air Force Cambridge Research Laboratory, and the Army Research Office.

At the third symposium in October 1964, 280 participants heard 54 technical papers (Environ. Res. Instit. of Michigan, 1965). By this time, all of the principal government, academic, and private-sector motivators for an orbiting resource satellite system were represented. Among the papers in the *Proceedings* was one by Dr. Robert Alexander of *ONR*. He announced what evolved into Landsat 1. His abstract read:

> *The National Aeronautics and Space Administration is sponsoring a study of the geographic potential of observations and experiments which might be carried out from the remote vantage of earth-orbiting spacecraft. The investigation will involve both the value of the science of geography and the expected practical applications of an earth-viewing-orbiting laboratory and other possible geographic satellite systems. Early emphasis will be on problems of systematizing and managing the flow of geographic information which would result from such a program* (p. 453).

The eighth symposium (Environ. Res. Instit. of Michigan, 1972), held eight years after Alexander's announcement and only a few weeks after the first Landsat 1 images were released, included 14 presentations describing the utility and quality of these data. By that time, the broader field of remote sensing attracted more than 700 participants who selected from a program of 116 papers on topics including theoretical and applied engineering, natural and cultural resources monitoring, state and local government applications, and even subjects addressing environmental and public health issues.

NASA became an official sponsor of the ERIM symposia in 1971. In 1973, NASA's Administrator inaugurated its decade-long program of University Research Grants to stimulate cooperative research at the local level. In some cases, it assisted construction of laboratory facilities and supplied the equipment to train the 1970's generation of Ph.D. remote sensing specialists. By the mid- to late-1970s, many of these young professionals were employed on collaborative Federal Government research projects for "proof-of-concept" applications embracing the whole range of natural and cultural resources. The Large Area Crop Inventory Experiment (LACIE) and the subsequent AgriSTARS are examples of these. The Application System Verification Tests (ASVTs) are others.

While these were not the only applications development programs under way, they were symptomatic of a massive, spontaneous adaptation to fundamentally new ways of studying the Earth. Within little more than a decade of ERIM's first symposium, the core remote sensing community increased its numbers by several orders of magnitude. Their efforts brought about major changes in organizational structures, became the basis for a new international research agenda, and germinated the seeds of thought for global habitability studies.

Stimuli for an Earth-Orbiting Resource Satellite

The forces that emanated from the science community, private sector, and government and stimulated today's Landsat program were numerous and complex. Five of the most compelling were (1) the need for better information about Earth features, (2) national security, (3) commercial opportunities, (4) international cooperation, and (5) international law.

Need for Better Information. *Society requires better information about the geographic distribution of Earth resources, and satellites will help obtain this information.* The Earth now supports more than five billion people, and human populations are growing at 1.5 percent per year, or three people per second. By the year 2000, the number will exceed six billion. Nobody knows how many people the Earth can sustain; some guess eight billion, but others say nearly double that (McRae, 1990; Ashford and Noble, 1996). No matter how many people can be squeezed onto the planet, however, there are limits to the renewable and nonrenewable resources needed to support them. Efficient management of renewable resources and judicious use of nonrenewable ones, as well as improved conservation and protection of fragile and endangered environments, depend upon timely information about, and accurate analysis of, those resources. In the late 1960s, there was a convergence of thought that the best means for acquiring needed data rested on Earth-orbiting satellites that could provide continuous and nearly synoptic coverage of terrestrial resources. Such coverage would be especially useful for understanding and measuring Earth-system processes at regional, continental, or global scales. Human numbers and human impacts on resources thus became an early and globally compelling argument to study the Earth.

National Security. *The United States Government maintains national security, which includes using data from civilian satellites to protect and defend the Nation against aggressors.* It is no secret that defense/intelligence satellites are assets for maintaining national security. It is not as widely known, however, that the defense/intelligence community has always employed data from civilian satellite systems to carry out its security mission (National Space Council, 1989). While there were, and still are, many security limitations imposed on the first generation of civilian Earth-observing systems, there was nevertheless a defensible argument that such a system should be developed. Timely information about the global distribution of critical natural resources, and the factors that affect global environmental conditions, are integral to national security and would be augmented by civilian systems. Indeed, the decision to build and launch Landsat 7 was partly driven by requirements of the defense/intelligence community (White House, 1992).

Commercial Opportunities. *To benefit from the powers of the free enterprise system, the United States Government encourages private-sector investment in the Nation's space program, including civilian Earth-observing satellites.* Remote sensing technology was developed by aerospace industries under contract to Federal Government agencies to satisfy both government and public needs. Commercializing this know-how is fundamental to American ideals and has been a stimulus for continued industry investment. By the early 1970s, several industries had already proven the commercial value of the space environment. These included communications satellites and booster launch services. The prospects for similar financial gain from Earth resources data seemed evident, but a successful experimental system would be a necessary first step. Commercial space-based remote sensing products and services finally will be tested in 1997 when several privately owned satellites are scheduled for launch. The assumption that Earth resources data would have commercial value beyond those for the public good was thus a powerful argument for developing the Landsat program. Full commercialization of both the space and ground segments might yet prove to be intractable, but there is clearly a viable and profitable role for industry to build launch vehicles, space platforms, sensor systems, and ground processing facilities, and to provide value-added data processing services.

International Cooperation. *The United States Government seeks international cooperation in civilian Earth-observing satellites to better understand, manage, share, and protect Earth resources.*
The United States is committed to using space for peaceful as well as defense purposes. Toward this end, Americans want to share benefits from space technology with other nations, but they also want to protect their commercial interests. Earth observations from space have never been the sole domain of the United States, and several nations now participate in this activity with competing spacecraft and sensor systems. The argument for promoting cooperation among nations is based on the apparent redundancy between different national programs, the obvious savings to be gained in joining programs through the sharing of costs, and the opportunity for the United States to promote its foreign policy objectives (White House, 1996).

International Law. *Societies are governed by laws, rules, and regulations to maintain organization and order — not only on Earth, but also in space.*
Societies establish laws by which they govern against chaos and anarchy. Space law is relatively new to jurisprudence, but it is a central force because it sets the rules by which all nations, not just the spacefaring ones, have a voice in how to participate in space technology. Legal aspects of civilian space-based remote sensing are complicated and sometimes controversial, especially regarding the issues of national sovereignty, rights of privacy, and, most recently, commercial gain. The United States has always argued strongly for an open skies and nondiscriminatory data distribution policy for civilian space data, believing that the greatest good for the greatest number can come from free and open exchanges of data and information (Stowe, 1976; White House, 1988). When the United States undertook the Landsat program, it made an extraordinary effort to ensure that every nation had access to these data, even to the extent that foreign ground receiving stations were installed.

Evolution of the Program

The Landsat Concept

The concept of a dedicated, unmanned land-observing satellite emerged in the mid-1960s from this complex milieu of synergy and conflicting interests. It arose primarily in the ONR and NASA, and in the USGS under its late director, Dr. William T. Pecora (Waldrop, 1982). In fact, scientists within the USGS, working in cooperation with Dr. Archibald Park and others in the United States Department of Agriculture (USDA), originally proposed to the Bureau of the Budget (now Office of Management and Budget) to build, launch, and operate an Earth Resources Observation Satellite (EROS). The Under Secretary of the Interior announced the objectives of EROS in a memorandum dated 12 July 1967, and addressed to the DOI's Assistant Secretaries and Bureau heads (Luce, 1967). These objectives were to (1) construct and fly an Earth-observing system by the end of 1969 and to follow with improved systems as required by operational needs of resources programs; (2) provide unclassified remotely sensed data to facilitate assessment of land and water resources of the United States and other nations; and (3) design specific systems on the basis of data user requirements, distribute such data to users, and make operational use of the data in resource studies and planning. The overall goal of the proposed EROS program was to acquire remotely sensed data from satellites in the simplest possible way, deliver these data to the user in an uncomplicated form, and ensure their easy use (Pecora, 1972).

Because development of space technology was NASA's responsibility, the DOI proposal was rejected by NASA Administrator James Webb, who met with President Johnson to discuss DOI's announcement. Webb succeeded in exercising NASA's control of what was to become an "experimental" program (Covert, 1989). In cooperation with DOI, USDA, and other agencies, NASA designed an Earth-observing satellite, obtained funding for the project, and successfully launched in July 1972 the first Earth Resources Technology Satellite (ERTS-1), which was later called Landsat 1.

Although unsuccessful with its own "operational" satellite system, the Department of the Interior continued with an Earth Resources Observation Satellite[1] (EROS) program under the direction of USGS. The EROS mission was to archive and distribute remotely sensed data, and to support remote sensing research and applications development within the DOI. To carry out the EROS responsibilities, the USGS built the EROS Data Center in Sioux Falls, South Dakota, in 1972.

Conflicts in agency roles began to appear even as the first Landsat was being prepared for launch. NASA's charter was to engage in space research and technology development. It did not include Earth resource data handling, processing, archiving, or distribution to a large and diverse scientific community, or to an even larger group of public and private users. Consequently, NASA reached agreement with USGS and several resource management agencies to transfer responsibility for the program's ground segment to the USGS, while NASA retained responsibility for the space segment.

After the launch of Landsat 1, NASA's Goddard Space Flight Center (GSFC) hosted a series of symposia in quick succession starting in March 1973 (Nat'l Aero. and Space Admin., 1973). These were designed especially for the Landsat-sponsored investigators to report "user identified significant results." The application categories were agriculture/forestry, environment, geology, land use/land cover, water, and marine. Each of the *Proceedings* approached 2,000 pages of text and graphics, mostly detailing early application concepts and models. The Landsat program had such a powerful impact in so many application arenas that management of the program became the subject of a prolonged debate between participating government agencies (U.S. Dept. of Commerce, 1980).

In the decades following Landsat 1, the program experienced severe political uncertainty and was casually labeled a "technology in search of an application." Thomas S. Kuhn's prescription for scientific revolutions forewarned these developmental stages by predicting a period of scientific uncertainty, if not outright denial, by whole sectors of the science and technology community (Kuhn, 1962). Once the critical mass of support was reached, the individual actions of sensor developers, data suppliers, data analysts, and end users

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[1] Later the "S" in EROS was changed from "Satellite" to "Systems."

Table 1. Background Information and Status of Landsat Satellites.

Satellite	Launched	Decommissioned	Sensors
Landsat 1	23 Jul 1972	06 Jan 1978	MSS and RBV
Landsat 2	22 Jan 1975	25 Feb 1982	MSS and RBV
Landsat 3	05 Mar 1978	31 Mar 1983	MSS and RBV
Landsat 4	16 Jul 1982	*	TM and MSS
Landsat 5	01 Mar 1984	**	TM and MSS
Landsat 6	05 Oct 1993	***	ETM
Landsat 7	May 1998****		ETM+

* in standby mode
** operational
*** never achieved orbit
**** anticipated launch

ensured continuation of the technology, even if it seemed chaotic, and even if the directions of development were obscure. After a quarter century of successful data gathering, the fate of the Landsat program beyond Landsat 7 remains uncertain, but the technology derived from it continues to permeate user communities and becomes more complex as the applications it spawned mature.

The Landsat System

ERTS-1 was launched from Vandenberg Air Force Base in California on 23 July 1972. A Nimbus-type platform was modified to carry the sensor package and data-relay equipment. ERTS-2 was launched 22 January 1975. It was renamed Landsat 2 by NASA, which also renamed ERTS-1 to Landsat 1. Three additional Landsats were launched in 1978, 1982, and 1984 (Landsats 3, 4, and 5, respectively). As documented by the USGS (1979) and by the USGS and NOAA (1984), each successive satellite system had improved sensor and communications capabilities (Table 1).

Landsats 1, 2, and 3

The first three Landsats operated in near-polar orbits at an altitude of 920 km. They circled the Earth every 103 minutes, completing 14 orbits a day and produced a continuous swath of imagery 185 km wide. Eighteen days and 251 overlapping orbits were required to provide nearly complete coverage of the Earth's surface. The amount of swath sidelap varied from 14 percent at the Equator to nearly 85 percent at 81° north or south latitude. These satellites carried two sensors: a return beam vidicon (RBV) and a multispectral scanner (MSS). The RBV sensor was a television camera designed for cartographic applications, while the MSS was designed for spectral analysis of terrestrial features. The MSS sensor scanned the Earth's surface from west to east as the satellite moved in its descending (north-to-south) orbit over the sunlit side of the Earth. Six detectors for each spectral band provided six scan lines on each active scan. The combination of scanning geometry, satellite orbit, and Earth rotation made possible the global coverage originally suggested by Arthur Clarke for viewing Earth's entire land surface. Spatial resolution of the MSS was approximately 80 m with spectral coverage in four bands from visible green to near-infrared (IR) wavelengths (Table 2). Only the MSS sensor on Landsat 3 had a fifth band in the thermal-IR.

Table 2. Radiometric Range of Spectral Bands and Spatial Resolution for the MSS Sensor (from *Landsat Data Users Handbook*, USGS, 1979 and USGS and NOAA, 1984).

Landsats 1, 3	Landsats 4, 5	Wavelength (μm)	Resolution (metres)
Band 4	Band 1	0.5–0.6	79/82*
Band 5	Band 2	0.6–0.7	79/82
Band 6	Band 3	0.7–0.8	79/82
Band 7	Band 4	0.8–1.1	79/82
Band 8**		10.4–12.6	237

* The nominal altitude was changed from 920 km for Landsats 1 to 3 to 705 km for Landsats 4 and 5 which resulted in a resolution of approximately 79 and 82 metres, respectively.
** Landsat 3 only.

Landsat 1 delivered high-quality data for almost five years beyond its designed life expectancy of one year and was finally shut down on 6 January 1978. Landsats 2 and 3 were decommissioned in February 1982 and March 1983, respectively, both well beyond their design lifetimes.

Landsats 4 and 5

Landsats 4 and 5, still partially operational at this writing, and carry both the MSS[2] and a more advanced sensor called the thematic mapper (TM). At 705 km, their orbit is lower than their predecessors', and provides a 16-day, 233-orbit repeat cycle with image sidelap that varies from 7 percent at the Equator to nearly 84 percent at 81° North or South latitude. The MSS sensors aboard Landsats 4 and 5 are identical to earlier ones. Both sensors detect reflected radiation in the visible and near infrared (VNIR), but the TM sensor provides seven spectral channels of data compared to only four channels collected by the MSS. The wavelength range for the TM sensor spans the blue through the mid-IR spectra (Table 3). Sixteen detectors for the visible and mid-IR wavelength bands in the TM sensor provide 16 scan lines on each active scan. The TM sensor has a spatial resolution of 30 m for the visible, near-IR, and mid-IR wavelengths and 120 m for the thermal-IR band. Like all earlier Landsats, sensors on these satellites image a 185-km swath. Landsat 4 has lost nearly all capability to transmit data and is in standby mode. Landsat 5 has lost its Tracking and Data Relay Satellite System (TDRSS) capability, but continues to provide data via direct downlink to the United States and the international ground stations.

Landsat 6

Landsat 6 was launched 5 October 1993, but failed to achieve orbit. It was similar to Landsats 4 and 5 in terms of spacecraft design and planned orbital configuration. The MSS and TM sensors were replaced by an improved TM sensor called the enhanced thematic mapper (ETM) from which, of course, no data were received.

Assessing the Impact

Landsat 1 not only inaugurated a global research agenda, but also spawned a new category of careers in engineering and the natural sciences. Arguably, Landsat 1 provided academic geographers and other researchers with real-world data to apply and test their theoretical models, thus giving access to a first new set of spatial analytical tools since the electronic calculator. At first, Landsat 1 augmented, and then gradually changed, the 1960's approach to remote sensing as a multispectral tool, to one capable of adding time to the analytical toolkit for studying and monitoring Earth resources.

As expected, Landsat 1 promoted business applications for Earth resources data and stimulated a proliferation of complementary international platforms. Both the *American* and *International Societ[ies] of Photogrammetry* quickly added *Remote Sensing* to their organizational titles, as adoption of the technology produced a flood of new members and research foci. In short, Landsat 1 broadened participation and coalesced a diverse community of devoted practitioners into an international body whose collective efforts gave birth to a new remote sensing science. Like all such phenomena in

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[2] Routine collection of MSS data over North America was terminated in late 1992.

Table 3. Radiometric Range of Spectral Bands and Spatial Resolution for the TM Sensor (from *Landsat Data Users Handbook*, USGS and NOAA, 1984).

Landsats 4, 5	Wavelength (μm)	Resolution (metres)
Band 1	0.45–0.52	30
Band 2	0.52–0.60	30
Band 3	0.63–0.69	30
Band 4	0.76–0.90	30
Band 5	1.55–1.75	30
Band 6	10.40–12.50	120
Band 7	2.08–2.35	30

the throes of birth, growth of remote sensing technology was partly ordered and partly chaotic; after 23 July 1972, it evolved into a complex system of technology developers, data suppliers, and data analysts and users. Landsat 1 data became the keystone around which the technology would adjust and grow.

A New Paradigm

A premise of remote sensing is that the Earth's features and landscapes can be discriminated, identified, categorized, and mapped on the basis of their spectral reflectances and emissions. Pre-Landsat literature in the ERIM symposia reveals this focus. Sensor designs spanned the electromagnetic spectrum from ultraviolet wavelengths to passive and active microwave frequencies. The multispectral concept combined sensors across these electromagnetic regions, and partitioned within them, to study the spectral domains of the hydrosphere, lithosphere, biosphere, and atmosphere. NASA, among other government agencies, contracted with industry to develop 12-, 24-, and 48-channel scanners for aircraft research in geology, agriculture, forestry, and land use and land cover. Major emphasis was on building libraries of spectral reflectances under controlled laboratory conditions and through data gathered by aircraft. Interpretation keys and crude machine-processing algorithms were commonly employed to identify features, but with a persistent apprehension that such results were, in each case, riveted to a study area's specific time and space.

The Landsat 1 MSS sensor fit into this framework as a *four-channel*, wide-bandwidth scanning system designed for first-order observations of surface covers from space altitudes — for essentially all of the Earth's land surface. These basic phenomena included the global land/water interface, vegetated/unvegetated areas, forested/unforested lands, urban/nonurban areas, and agricultural/nonagricultural lands. Each category of these observations is the foundation for increasingly sophisticated interpretations of economic uses of the land, for assessing environmental health, and for addressing what would later be called *Earth System Science* (Nat'l Aero. and Space Admin., 1988).

By virtue of its 18-day orbital repeat cycle, it was also recognized that Landsat 1 would offer scientists their first significant opportunity to observe synoptic changes in surface covers that had been difficult to record using aerial platforms. The temporal dimension of remote sensing had always been appreciated, but seldom usefully employed outside the Department of Defense because high-quality time-series data were essentially nonexistent. With Landsat 1, the time dimension not only was a key design parameter, but also was immediately recognized by the scientific community as an essential ingredient in spectral analyses. By holding solar azimuth relatively constant with an equatorial crossing of approximately 9:30 AM local time, the orbital design offered an opportunity to radiometrically calibrate spectral readings across latitudes and longitudes and throughout the annual greening and yellowing cycles of vegetation. Attention moved sharply away from building spectral libraries to monitoring temporal changes and patterns.

Time was also the enabling parameter for promoting a deeper understanding of physical models in several land analysis applications (Reeves, 1975; Colwell, 1983). In surface hydrology, for example, measurements from data collection platforms (DCP's) were merged experimentally with Landsat 1 data to monitor spatial and temporal changes in water levels of Lake Okeechobee (Florida) to better understand the swamp ecology and Miami's urban water needs. Run-off prediction models were augmented by monitoring the geographic extent and depth of river basin snow levels; and temporal dynamics of major floods like those occurring along the Mississippi River and Cooper's Creek (Australia) in 1973 were examined for purposes of disaster assessment.

Other time-sensitive applications were also advanced. In agriculture, MSS imagery was used to improve an existing production estimation model for wheat in western Kansas, proving that satellite-acquired data could facilitate accurate and timely crop predictions (Morain and Williams, 1975). Forest clearcuts in Oregon and Washington were monitored, and in Washington were actually used to assess lessee compliance with timber harvest licenses. Rangeland studies included spectral responses through time to assess biomass production and general range condition.

These early modeling efforts evolved into satellite applications that address today's social and environmental issues (e.g., food security, deforestation impacts, desertification trends, resource sustainability, and news gathering). None of them, however, led directly to these more profound applications. They all needed iterations that included many false starts. Early applications, therefore, were important as pioneering efforts and for what they taught scientists about future satellite requirements and the need for collateral input for problem solving. All of the Landsat 1 results relied on collateral, ground-based data [today's relational database, or geographic information system (GIS), technology] and suffered from gaps in temporal data that would have made them more robust. Furthermore, the spectral data often were too coarse. If satellite-based Earth observations were to deliver on their early promise, then more spectral channels having narrower bandwidths would have to be acquired from a larger number of platforms providing more frequent observation. If this could be achieved, it was believed with certainty that the data and imagery would have commercial, as well as public, value.

Privatization/Commercialization

NASA, as the Nation's civilian research and development space agency, successfully executed its role by launching Landsat 1. The hand-off of responsibility for data dissemination from NASA to the USGS's EROS Data Center was already completed by the time Landsat 1 was launched. The plan was for the USGS to serve as the supplier of Landsat products, while NASA continued to develop future sensors and platforms. Differing responsibilities and management agendas at NASA, NOAA, DoD, USDA, and USGS, however, plagued the Landsat program from its inception. To resolve these varying agency responsibilities, the Carter Administration undertook an extensive review of both military and civilian space policies, and by 1979 new policies were formulated in which the civilian program was to be made operational, administered by NOAA, and eventually turned over to the private sector (U.S. Dept. of Commerce, 1980; White House, 1979). At about this same time Congress merged land-, ocean-, and weather-sensing systems under the administration of NOAA in the Department of Commerce (DOC).

A crisis ensued (National Research Council, 1985). The major players in this crisis included a burgeoning community of Landsat data users, among them the news media, who wanted inexpensive, publicly accessible data; an increasingly vociferous industrial sector concerned about pending international competition and who believed privatization would preserve America's niche in commercial Earth observations; and a federal establishment disinclined to commercialize all land, ocean, and weather satellite data systems.

In its effort to reduce the size of government, the first Reagan Administration acted quickly to move the Landsat program to the private sector. The result was Public Law 98–365, the *Land Remote-Sensing Commercialization Act of 1984* (U.S. Congress, 1984). NOAA solicited bids to manage the existing Landsats and civilian meteorological satellites and, aided by large government subsidies, to build and operate future systems. Proposals were received from such diverse bidders as aerospace companies, an insurance company in New York, a small geoscience firm in Michigan, and a farmer in North Dakota (U.S. Dept. of Commerce, 1984). In 1985, a contract was signed with EOSAT Company and the transfer of the Landsat system but not the weather satellites was complete (U.S. Dept. of Commerce, 1985).

A history of the national debate leading up to and going beyond privatization is given by Morain and Thome (1990). It is interesting that the most compelling arguments given to Congress for Landsat commercialization focused on data and program continuity — not spectral analyses and fine-resolution, time-sequential data. In spite of the fact that data continuity was never defined, and that program continuity remains a political question, Congress continues to legislate most aspects of America's space remote sensing activities.

Following extensive study by NOAA (U.S. Dept. of Commerce, 1988) and another series of program reviews, the National Space Council released its National Space Policy Directive #5, establishing new goals and implementation guidelines for the Landsat program (White House, 1992). The Directive called for a joint DoD/NASA effort to build, launch, and operate Landsat 7. In October 1992, the Land Remote Sensing Policy Act (P.L. 102–555) was signed into law. This law reversed the 1984 decision to commercialize the Landsat system and recognized the scientific, national security, economic, and social utility of "land remote sensing from space" (Sheffner, 1994). The law mandated DoD and NASA to (1) establish a management plan, (2) develop and implement an advisory process, (3) procure Landsat 7, (4) negotiate with EOSAT for a new data policy regarding existing systems, (5) assume program responsibility from DOC, (6) conduct a technology demonstration program, and (7) assess options for a successor system (U.S. Congress, 1992).

Hardly a year had passed before the Landsat program was evaluated for a third time, principally because of severe budget constraints surrounding the high resolution multispectral stereo imager instrument proposed by DoD for Landsat 7. The National Science and Technology Council (NSTC) recommended that Landsat 7 be developed only with an improved TM instrument and that a new management structure be established so that DoD could withdraw from the program. This resulted in Presidential Decision Directive/NSTC-3, dated 5 May 1994, reconfirming the Administration's support for the program but giving NASA, NOAA, and the USGS joint management responsibility (White House, 1994). These three agencies negotiated with EOSAT for new Landsat 4 and 5 product prices for the U.S. Government and its affiliated users, and are proceeding to develop Landsat 7. Meanwhile, a worn but operable Landsat 5 (into its 14th year!) remains aloft, transmitting consistent and reliable TM images of the Earth to the United States ground station and its foreign counterparts.

Government policies designed to transfer the Landsat program from the public to the private sector were seriously flawed. These policies did not result in market growth, were more costly to the Federal Government than if the system had been federally operated, did not significantly reduce operating costs, and significantly inhibited applications of the data (Lauer, 1990). Nevertheless, the program continued to provide a flow of high-quality, well-calibrated, synoptic imagery of the Earth.

Whether or not Landsat privatization was premature given existing and anticipated markets, it can be argued that an expanding global community of government, academic, and private sector users, particularly among developing nations in Africa, Latin America, and Asia, stimulated proliferation of international Landsat look-alike satellites. After 1986, these systems augmented Landsat data around the world, further verifying proof-of-concept applications, and boosting overall space-based capabilities to a new level.

The Legacy

Landsat 7

Landsat 7 is scheduled for launch in mid-1998. Its payload will be an enhanced thematic mapper (plus) instrument, designated the ETM+. It has the same basic design as the TM sensors on Landsats 4 and 5 but includes some conservative advancements (Obenschain *et al.*, 1996). It will provide 60 m (as opposed to 120 m) spatial resolution for the thermal-IR band and a full-aperture calibration panel leading to improved absolute radiometric calibration (5 percent or better). The geodetic accuracy of systematically corrected ETM+ data should be comparable to that characterizing Landsat 4 and 5 TM data with a specific uncertainty of 250 m (one sigma), or better. Other features have been added to the Landsat 7 program to facilitate use of the data. For example, Landsat 7 will directly downlink ETM+ data to domestic and international ground receiving stations at 150 Mb per second using three steerable, X-band antennae. Although transmissions to international ground stations will continue, the system is being designed so that the United States can capture and refresh a global archive that will be located at the USGS's EROS Data Center. To enable ETM+ to capture data over regions beyond the range of EROS Data Center's receiving antenna in South Dakota, Landsat 7 will use a 378-Gb solid-state recorder capable of storing approximately 40 minutes, or 100 scenes, of ETM+ data. A second North American receiving station is being added near Fairbanks, Alaska, to allow 250 scenes of data per day to be collected. Thus, the recorder will downlink recorded data when the satellite is within range of either the South Dakota or Alaska station, and the EROS Data Center will receive and archive 250 ETM+ scenes per day. These features provide the capacity for global coverage of continental surfaces on a seasonal basis.

Beyond Landsat 7

The 1992 Land Remote Sensing Policy Act calls for developing cost-effective, advanced technology alternatives for maintaining data continuity beyond Landsat 7 (Sheffner, 1994). To satisfy this requirement, NASA plans to launch Earth Orbiter-1 (EO-1) as part of its New Millennium Program. This mission (see Ungar (1997), pages 901–905, in this issue) will be devoted to testing new technologies for use beyond Landsat 7. Some concepts for an advanced sensor are described by Salomonson *et al.* (1995) and Williams *et al.* (1996). In essence, advanced Landsat concepts employ solid-state, pushbroom, multispectral linear arrays, and hyperspectral area arrays that employ grating and wedge filter technologies.

Exactly how an advanced Landsat observing capability will be achieved is still under study. One option is to fly the advanced technology Landsat sensor on one of the NASA

TABLE 4. CHRONOLOGY OF LANDSAT AND LANDSAT-LIKE LAUNCHES 1972–2007. ITALICIZED ENTRIES FAILED TO ACHIEVE ORBIT, OR DID NOT FUNCTION ON ORBIT (EXCERPT FROM MORAIN AND BUDGE (1996) AND STONEY *ET AL.* (1996)).

Year	Platform (Country)	Sensor
1972	Landsat 1 (USA)	MSS; RBV
1975	Landsat 2 (USA)	MSS; RBV
1978	Landsat 3 (USA)	MSS; RBV
1982	Landsat 4 (USA)	MSS; TM
1984	Landsat 5 (USA)	MSS; TM
1986	SPOT-1 (France)	HRV
1988	RESURS-01 (Russia)	MSU-SK
1988	IRS-1A (India)	LISS-1
1990	SPOT-2 (France)	HRV
1991	IRS-1B (India)	LISS-2
1992	JERS-1 (Japan)	OPS
1993	*Landsat 6 (USA)*	*ETM*
1993	SPOT-3 (France)	HRV
1993	*IRS-P1 (India)*	*LISS-2; MEOSS*
1994	IRS-P2 (India)	LISS-2; MOS
1994	RESURS-02 (Russia)	MSU-E
1995	IRS-1C (India)	LISS-3
1996	ADEOS (Japan)	AVNIR
1996	PRIRODA (Germany/Russia)	MOMS
1997	CBERS (China/Brazil)	LCCD
1997	IRS-1D (India)	LISS-3
1998	SPOT-4 (France)	HRVIR
1998	Landsat 7 (USA)	ETM+
1998	EOS AM-1 (USA/Japan)	ASTER
1998	IRS-P5 (India)	LISS-4
1999	Resource 21 (USA)	Resource 21
2000	IRS-2A (India)	LISS-4
2002	ALOS (Japan)	AVNIR-2
2002	SPOT-5A (France)	HRG
2004	IRS-2B (India)	LISS-4
2004	SPOT-5B (France)	HRG
2004	ALOS-A1 (Japan)	AVNIR-3
2007	ALOS-A2 (Japan)	AVNIR-4

Earth Observing System (EOS) satellites, such as the AM-2 mission. Doing this would reduce launch costs. Other options include flying the sensor on a separate, smaller and less expensive, advanced technology spacecraft. A third possibility would be to see the advanced technology capabilities and Landsat continuity requirements incorporated in a commercial venture. Other papers in this issue describe the growth in capability provided by private industry that makes this option one to be considered. In any case, it is clear that the Earth science and applications communities require that the Landsat TM quality and type of data be provided and continuity ensured to preserve the integrity of the data bases inaugurated by Landsat 1. It appears clear, too, that advanced technology can be used to meet these requirements and possibly provide highly desirable enhancements.

Table 4 is a chronology of Landsat and similar international satellite systems. It lists only so-called *Earth Resources* satellites having sensors with channels roughly equivalent to those of the Landsat MSS and TM sensors. In the past 25 years there have been nearly 20 launches and four distinct international systems (a fifth, CBERS, is expected in 1997). Data from these systems are used daily by international donor agencies, government agencies at all levels, oil and mineral exploration companies, environmental consultants, value-added commercial firms, academia, and the general public. The first-order land-cover categories predictable in 1972 have grown to include rather sophisticated higher order applications. Continuity has been achieved in more than one sense (Morain and Budge, 1995). Use of time as a discriminant has been enthusiastically embraced by the user community in ways that were not foreseen, and it surely will be used in future applications in ways that are not yet perceived. Spectral analytical procedures have evolved around the time dimension and also will be stimulated by future hyperspectral data collectors. Even as the Landsat program teeters toward possible extinction, its progeny continue to nurture the vibrant technology it created.

Conclusions

The earliest visionaries, like Jules Verne, Arthur Clarke, Robert Alexander, William Fisher, Archibald Park, William Pecora, and many others, predicted great things to come as humans and their satellites ventured into space. Of all the efforts to date, the United States Landsat program ranks among the most successful. Interestingly, most of the problems that have plagued this national program have been not technical, but more administrative and political. Despite the difficulties related to national security issues, agency roles, delays in data delivery, funding uncertainties, and a shaky attempt to commercialize a federal program, its accomplishments have been extraordinary. For 25 years between 1972 and 1997, synoptic, high-quality data have been routinely acquired, processed into an ever-improving array of digital and photographic products, and used to better measure and monitor Earth resources. The Landsat series has opened new insights into geologic, agricultural, and land-use surveys, and new paths in resource exploration. An understanding of the Earth and its terrestrial ecosystems, as well as its land processes, has been advanced remarkably by the Landsat program. Of equal importance, this program stimulated new approaches to data analysis and academic research and provided opportunities for the private sector to develop spacecraft, sensors, and data analysis systems and to provide value-added services. It also has fostered strong international participation and a whole new generation of foreign-operated Landsat-like systems. The political, scientific, and commercial currents over the next 25 years of Earth-observing systems will be no easier to chart than were the first, but the systems they spawn positively advance human understanding and use of the planet's resources.

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