Landsat and Earth Systems Science: Development of Terrestrial Monitoring

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Abstract

One of the major catalysts leading to the development of the global-scale Earth Systems Science concept, the International Geosphere-Biosphere Program, and the U.S. Global Change Research Program were the unique views of Earth provided by Landsat sensors over the past 25 years. This paper addresses Landsat's contributions in the Earth Systems Science arena.

Early successes in observing the Earth's cloud patterns from space led to the use of this new spaceborne perspective to observe surface terrestrial features. Deployment of Landsat demonstrated that significant information about the Earth's land areas could be acquired from such an observatory. Numerous studies indicated that assessments of agricultural production, forest resources, human population surveys, and environmental conditions could be derived from Landsat data. Thus, an unanticipated outcome of the Landsat program was the evolution of unique new insights concerning terrestrial biospheric patterns and dynamics. The electronic, high precision spectral radiometry, combined with Landsat's repetitive coverage, revealed that a critical new environmental measurement, the spectral vegetation index, could be acquired with these sensors. These measurements are also of critical importance in understanding the hydrology, land surface climatology, and biodiversity characteristics of the Earth.

Recognition of the value of this vegetation index in regional and global-scale studies of the Earth's environment served as a strong stimulus to the development of the Earth Systems Science research agenda, one of the major foci of NASA's Mission to Planet Earth, Earth Observing System. Since the innovation of the Landsat Thematic Mapper instrument in the early 1980s, significant progress has been achieved in assessing human impacts within the Earth systems. Significant further inputs to Earth Systems Science from Landsat are expected when Landsat 7 is launched in 1998. Refinements in radiometric response and calibration, inclusion of a 15-m panchromatic band, improvement of the spatial resolution of the thermal band to 60 m, and an aggressive acquisition strategy will all contribute to Landsat's new role as a major component of NASA's Mission to Planet Earth, Earth Observing System. Development of technologies for more refined, as well as lower cost, sensors and platforms is now underway to continue the Landsat science mission. These technology advances are expected to further enhance the capability to monitor the Earth's land areas.

Introduction

Over the last 10 to 15 years, national and international scientists have begun to focus on improving our understanding of the Earth's environmental systems. Measurements of atmospheric chemistry and models of the global climate system suggest that changes which have occurred in the Earth system over the last century, and which are continuing today, may alter environmental conditions over the next century (Houghton *et al.*, 1990). Initial efforts to estimate how the Earth might change over the next century revealed that our current understanding of Earth systems is incomplete. For example, the annual atmospheric CO_2 budget cannot be balanced, with about 30 percent of the budget not understood (Tans *et al.*, 1990). Linkages between land conditions and atmospheric dynamics are poorly defined and rarely specified in planetary climate models (Sellers *et al.*, 1997). The role and dynamics of human activities within the Earth system are only beginning to be investigated but appear to be a major source of Earth systems change (Turner *et al.*, 1990). An integrated understanding of how the various elements of the Earth system, including climate, hydrology, biospheric processes, and human activities, interact to produce current and possible future Earth system conditions is clearly needed (National Aeronautics and Space Administration, 1988).

One of the major forces leading to the development of the global-scale Earth Systems Science concept, the International Geosphere-Biosphere Program (IGBP), and the U.S. Global Change Research Program (USGCRP), was Landsat (National Research Council, 1995). In the mid-1980s, after a decade of Landsat research, it was evident that satellite remote sensing could provide the type of globally consistent, spatially disaggregated, and temporally repetitive measurements of land conditions needed to describe the Earth's terrestrial systems (National Research Council, 1986a). Early studies of Landsat images, particularly in numerical form, led to an appreciation that such measurements recorded a generalized measurement of land vegetation conditions, the spectral vegetation index (SVI) (Goward, 1989). This index of vegetation green foliage is a fundamental attribute of the landscape, describing, at least in part, absorption of sunlight, photosynthetic capacity, and evaporation rates (Kumar and Monteith, 1982). These physical and biological processes are primary descriptors of how land conditions modulate the Earth system. Once it was understood that space-based, Earth imaging could and did provide such information about land patterns and dynamics, the possibility

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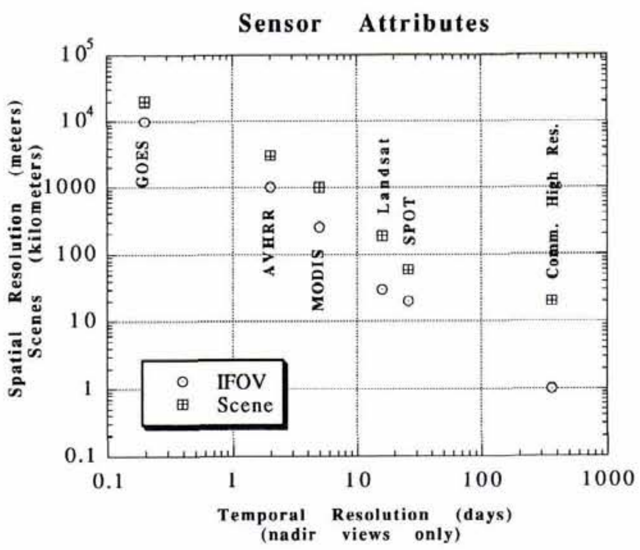

Figure 1. Interaction between spatial and temporal resolution for typical satellite remote sensing systems.

of developing fully integrated land-ocean-atmosphere monitoring and modeling capabilities was realized (National Aeronautics and Space Administration, 1986). Thus, Landsat provided the critical element of Earth observation needed to develop the concept of Earth Systems Science.

The Landsat Science Mission and its Origins

The Landsat mission has been variously described as a land mapper, mineral explorer, and resource monitor (Short *et al.*, 1976). Each of these descriptions is valid because the images derived from this technology have multiple applications. In fact, each of these applications is a specialized example of the more general contribution Landsat brings to Earth Systems Science.

The Observation Problem

Earth Attributes

The Earth physically can be characterized as consisting of matter in gaseous, liquid, and solid forms or, as more often described, atmosphere, ocean, and land. The time and space scales of variations in conditions of these Earth components differs significantly. Under the influence of gravity, planetary motion, solar heating, and human activity, the atmosphere mixes rapidly; the oceans at a slower rate; and the land's surface at a much, much slower rate. Atmospheric systems typically display spatial patterns on the order of thousands of kilometres; oceans, hundreds of kilometres; and, on land, kilometres to metres. In the time domain, land conditions, on average, vary seasonally and inter-annually; oceans over weekly to monthly time intervals; and the atmosphere, minutes to hours. The Landsat mission design is directed specifically to capture the detailed spatial heterogeneity and seasonal dynamics of land areas of the Earth.

Land Patterns

One of the most poorly understood attributes of the Earth system are terrestrial patterns and processes (DeFries and Townshend, 1994). This is particularly evident in patterns of land-cover/land-use change. Unlike the atmospheric and oceanic systems, horizontal and vertical mixing of land attributes is exceptionally slow, occurring primarily at geological time scales, with the exception of changes brought about by human activities. As a result of both slow natural processes and localized human activities, considerable spatio-temporal heterogeneity is characteristic of the Earth's land areas. This fine scale heterogeneity presents a daunting prospect to Earth systems analyses because, in many cases, detailed specification of these patterns is fundamental to understanding Earth systems processes (Sellers and Schimel, 1993). For example, a decade ago carbon budget researchers concluded that the "missing" planetary carbon sink must exist in the land biosphere (National Research Council, 1993). Until, of course, it was pointed out that rapid deforestation of tropical rainforests was taking place (Woodwell *et al.*, 1983). The search for this missing carbon sink continues today, still unresolved because of uncertainties with respect to human influences in land cover dynamics. Current work suggests that the sink may reside in the northern hemisphere mid-latitude forests (Tans *et al.*, 1990). This leads to the speculation that changes in land-use patterns over the last century have resulted in significant regrowth of northern mid-latitude forests compared to the late 1800s to early 1900s. This conclusion appears to be supported by terrestrial remote sensing measurements from Landsat and other land observing systems (Sellers *et al.*, 1995).

Land Spatio-Temporal Dynamics

The particular challenge in monitoring land areas is to capture patterns of spatially-detailed land-cover change within the context of seasonal land-cover dynamics (Hall *et al.*, 1991). Images taken at any particular time of year record both the spatial patterns of land cover, as well as seasonally variable conditions of land cover. As a result, it is not possible, in general, to define accurately regional land-cover patterns in a single observation. Only after the full seasonal variation of land-cover conditions is recorded is it possible to describe definitively regional land-cover patterns and land-cover changes between years (Townshend *et al.*, 1991). Because of this basic attribute of land cover, satellite-based sensors operating at spatial resolutions from kilometres to metres, and time resolutions from yearly to daily, have been found to be of considerable value for terrestrial monitoring (Rasool, 1987). However, fundamental technical, monetary, and data handling limits act collectively to constrain satellite remote sensing such that direct trade-offs between spatial and temporal resolutions must be made (Figure 1). Historically, Landsat has operated at the balance point between high spatial resolution and seasonal temporal resolution.

Landsat Mission Origins

The evolution of terrestrial remote sensing as a major contributor to Earth Systems Science is built upon more than a century of research and development in the use of electromagnetic sensors, flown on balloons, aircraft, and spacecraft, to study the Earth's land areas. From the first aerial photographs collected from balloons, the value of remote sensing for terrestrial analysis was evident. Advances in light measurement and spectral differentiation led to significant analytical improvements. The shift to electronic detection fundamentally altered basic analytical methods. The combination of spectroradiometry, electronic detection, and spacecraft platforms created a new type of remote sensing method, one based on numerical analysis of digital image data (Schott, 1997). Whereas images, when visually analyzed, in general provide spatially defined nominal information, an image, when analyzed numerically, generally provides per-pixel, spatially disaggregated interval or ratio information.

Areal Perspective

It was clear from the first photographs taken from aerial platforms (~1860) that the landscape perspective captured from

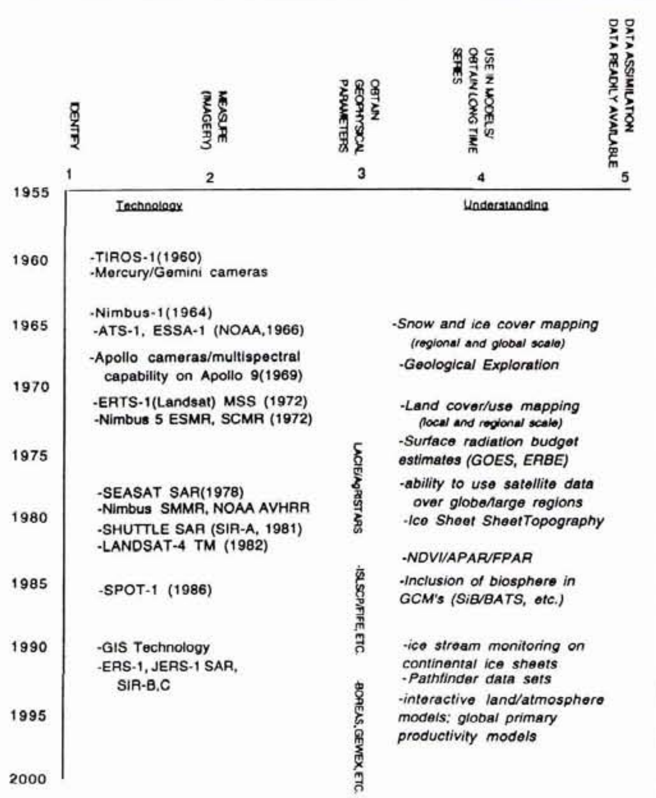

Figure 2. Remote sensing of land surface processes (geological, biospheric, hydrological) from space (Salomonson, 1995).

platforms above the Earth's surface provided information on the spatial arrangement of land features (Colwell, 1960). These "aerial" photographs quickly became a basic tool for military strategists, explorers, and resource managers. Indeed, a quality historical record of aerial photographs, extending back to the 1930s, is still maintained by the U.S. Major advances in aerial photographic technology were achieved during major international conflicts, particularly during World Wars I and II. Primary civilian applications of this technology developed in agricultural and forest monitoring, as well as land-cover/land-use mapping. Nearly all scientists or administrators concerned with the analysis and management of land resources saw the need to become expert in, or dependent on, aerial photointerpretation. In fact, with the development of photogrammetry, detailed topographic and land-cover mapping became a standard component of local, regional, and national land resources management. By the 1950s, aerial photography had become a standard tool for land research and management. At the onset of the space age, there was already substantial understanding of the value of aerial and "spaceborne" views of the Earth's land areas.

Spectral Differentiation

As the theory and technology of light measurement evolved in the late 19th and early 20th centuries, methods were developed to measure light in limited spectral wavelength regions. Photography systems to record visual spectra (red, green, blue) and non-visual spectra (near infrared) were being subject to a variety of experiments as early as the 1930s (Ives, 1939). More sophisticated laboratory spectrometers became readily available in the 1940s and 1950s. This led to a variety of laboratory and field studies which repeatedly demonstrated the unique spectral reflectance characteristics of living, green vegetation (Krinov, 1947; Billings and Morris, 1951; Colwell, 1956; Gates *et al.*, 1965; Richardson and Wiegand, 1977). This research suggested that detailed spectral imaging might provide considerable improvements in distinguishing vegetation types, monitoring plant phenology and stresses, and characterizing land cover. Most "spectral" color photography was visually interpreted and converted into maps of nominal land-cover categories (Anderson *et al.*, 1976). There were a few attempts to convert these photographic records into physical measurements of albedo (Pease and Pease, 1972), vegetation stress (Colwell, 1956), and indices of green vegetation foliage for estimating evapotranspiration (Jones 1977). However, calibration and cross-comparison of photographs taken with various films and cameras was a time-consuming and inexact task. The chemical process of recording light does not lend itself to derivation of land surface measurements.

Electronic Sensing

By the 1950s, electronic imaging technologies were beginning to migrate out of laboratories and defense-related intelligence gathering to civilian applications; home television is an early example. With respect to land remote sensing, the aircraft-based multispectral scanner (the M-7 instrument) operated by Willow Run Laboratories at the University of Michigan provided the first source of high quality, calibrated electronic measurements (Lowe, 1975). This device, which periodically was reconfigured for particular purposes, was, in general, able to record simultaneously 12 separate portions of the electromagnetic spectrum, extending from ultraviolet (0.3 μm) through thermal infrared (12 μm) wavelengths. Given that these measurements were recorded electronically, coupled with the fact that electronic computers were becoming common and visual interpretation of 12-dimensional images was exceptionally difficult, serious efforts were given to develop computer-based numerical image interpretation approaches. Interestingly, at first there was considerable competition between use of analog and digital computers in these early efforts (Reeves, 1975). It quickly became evident that such technologies would provide an excellent source of measurements relevant to land surface climate studies (Kung *et al.*, 1965; Malila and Wagner, 1972; Pease *et al.*, 1976; Goward and Oliver, 1977).

Technology Convergence in Landsat

Early experiments in Earth imaging from space, from Explorer-6 in 1959 and the TIROS series of satellites beginning in 1960, combined with astronaut-acquired Earth photography during the Gemini and Apollo missions, convinced Earth scientists that detailed imaging of the Earth's land areas was possible from spacecraft (Salomonson, 1995) (Figure 2). The first Landsat system (initially called Earth Resources Technology Satellite-1 or ERTS-1) included a three-spectral-band (green, red, near infrared) return beam vidicon (RBV) camera, which was essentially a high-quality, calibrated television camera. ERTS-1 also carried a new experimental instrument called the multispectral scanner (MSS), a four-spectral-band instrument (i.e., green, red, and two near infrared bands) (Short *et al.*, 1976; Freden and Gorden, 1983). As originally planned, the RBV sensor was meant to be the primary ERTS-1 imager, producing replicates of the high-altitude aircraft-acquired color infrared photography then widely used in Earth resources management (Colwell, 1956; Anderson *et al.*, 1976). The MSS imager was considered experimental, testing the concept of calibrated line scanner multispectral imaging, essentially duplicating the basic concept represented by the M-7 aircraft multispectral scanner. The simplified four-band visible-near infrared MSS configuration was initially flown to test the MSS concept while the development of advanced, space-qualified sensors in other spectral regions proceeded (Park, 1983). The possibilities of handling and analyzing either the RBV or MSS data numerically was envisioned, but the RBV was viewed primarily as a source of visual pictures, whereas the MSS was directed more toward numerical, spectral imaging. An early failure of the RBV sensor on ERTS/Landsat 1 caused a significant paradigm shift toward numerical imaging analysis during the early years of the Landsat mission.

The Spectral Vegetation Index Concept

In terms of Earth Systems Science, the most important discovery in Landsat research was the universal generality of the spectral vegetation index (SVI). There are a multitude of defined spectral vegetation indices now in existence (Jackson, 1983; Perry and Lautenschlager, 1984; Huete *et al.*, 1994; Myneni *et al.*, 1995; Huete *et al.*, 1997). They are all derived, at least in part, by considering the contrast between visible and near infrared spectral reflectance from land surfaces. For typical broad-band visible/near infrared measurements, green vegetation foliage produces a stepped reflectance, with low visible and high near infrared reflectance, a result of pigment absorption in the visible region and strong light scatter from cell walls in the near infrared (Wooley, 1971; Tucker, 1979). Other land surface material such as bare soil and litter generally record slowly increasing reflectance between the visible and near infrared. Thus, any SVI will record high values for land surfaces covered with green foliage and low values for non-foliar land surfaces. Considerable research had been completed on this phenomenon well before the design and launch of Landsat (Gates *et al.*, 1965; Gausman *et al.*, 1973). In fact, the first recorded use of this metric for vegetation research was in under-canopy field research (Jordan, 1969). However, it was not until Landsat observations had been analyzed for several years that it became clear that SVIs were a general measure of landscape green foliage status, diagnostic of vegetation state, phenology, and inter-annual variability (Dethier, 1974; Kauth and Thomas, 1976; Blair and Baumgardner, 1977; Richardson and Wiegand, 1977; Jayroe, 1978; McDonald and Hall, 1980; Price and Bausch, 1995).

Spectral Dimensions of Land Observations

Early numerical studies of the multi-dimensional M-7 scanner conducted at University of Michigan-Willow Run Laboratory and Purdue University-LARS (Laboratory for Agricultural Remote Sensing and later Applications of Remote Sensing) showed that the typical 12-spectral-band M-7 data could be grouped into four dominate, independent spectral regions of land information: visible (0.4 to 0.7 μm), near infrared (0.7 to 1.3 μm), short-wave infrared (1.3 to 2.5 μm), and thermal infrared (8 to 14 μm) (Swain and Davis, 1978). This conclusion was reinforced by the results from the 13-channel sensor flown on the NASA Skylab mission in 1973. In fact, the Landsat Thematic Mapper (TM) design was strongly influenced by these early experiments which provided many bands of spectral observations (Park, 1983). The multispectral scanners flown on Landsats 1 through 3 were all broad-band instruments covering only two visible and two near-infrared regions, with 6-bit radiometric precision and 80-metre spatial resolution.[1] Intensive numerical studies of the spectral information content in this four-band MSS data revealed basically two dimensions, one in the visible domain and one in the near infrared, from which one can derive the spectral vegetation index (Deering *et al.*, 1975; Kauth and Thomas, 1976; Richardson and Wiegand, 1977; Jayroe, 1978; Tucker, 1979).

Spectral Discrimination versus Continuum

Initially, the discovery of the pervasive character of SVIs in Landsat observations was considered problematic. The early numerical, multispectral image analysis techniques were directed toward spectral discrimination of land cover, where each cover type could be distinguished by its "spectral signature" (Swain and Davis, 1978). However, because the Landsat MSS was essentially a two-spectral-band sensor, many landcover features produced quite similar spectral signatures at any given time of year. For example, in the NASA Large Area Crop Inventory Experiment (LACIE), it was found that, in any given 35,000 km² Landsat scene, climate variations across the scene and equivalent phenologies between wheat and grasslands caused substantial confusion in automated identification of wheat fields in many regions of the globe (National Aeronautics and Space Administration, 1982). In general, this problem could only be solved when three or more images, from different times within the growing season, were combined in a single, multi-date image database (McDonald and Hall, 1980). Further, substantial progress in using multi-temporal spectral vegetation index measurements for several different crops occurred during the LACIE follow-on experiment known as the AgRISTARS program (Badhwar, 1984; Hogg, 1986; Hall and Gadhwar, 1987).

Thematic Mapper, Commercialization, and the AVHRR

In 1982, there was considerable confidence that more sophisticated crop identification and land-cover analysis was imminent. The new Thematic Mapper instrument had just been put into orbit on Landsat 4 (Townshend *et al.*, 1983; Salomonson, 1984; Williams *et al.*, 1984). This advanced sensor incorporated significant improvements with seven spectral wavelengths extending across the visible, near infrared, short-wave infrared, and thermal infrared; 8-bit radiometric precision; and, 30-m spatial resolution. The early results were indeed highly promising and it looked like a whole new generation of information possibilities was looming (Salomonson, 1984; Williams *et al.*, 1984; Markham and Barker, 1985). However, the affairs of U.S. Government and industry intervened, and, in 1984, Landsat was shifted to a commercialization effort under the guidance of the National Oceanic and Atmospheric Administration (NOAA) in response to the Landsat Commercialization Act of 1984.

Landsat privatization also coincided with a sharp increase in scientific attention to the global Earth system and the role of land conditions in this system (Duvigneaud *et al.*, 1979; Matthews, 1983; National Aeronautics and Space Administration, 1983; Eddy, 1986; National Aeronautics and Space Administration, 1986; National Research Council, 1986b; Willmott and Klink, 1986). It quickly became evident that satellite remotely sensed observations could provide a critical improvement in assessing land conditions and dynamics (Scientific Committee on Problems of the Environment, 1984) and Landsat was the primary candidate observatory. Unfortunately, the impact of the Landsat commercialization effort was immediate and negative on Landsat-based scientific activity. The high costs and limited availability of Landsat TM observations caused a sharp scientific shift away from Landsat observations with regard to addressing these global-scale land issues. Research scientist's interests shifted toward the newly refined NOAA Advanced Very High Resolution Radiometer (AVHRR) instrument, flown on the polar-orbiting meteorological satellites.

The AVHRR sensor, designed primarily for weather observations, had been refined in 1981 to include visible and near infrared observations along with three thermal infrared sen-

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[1] There, in fact, was a thermal infrared sensor flown on Landsat 3 but problems with outgassing and calibration limited its use as a spectral measurement source. There was also an attempt to use the RBV system on Landsat 3 as a "high" spatial resolution (30-m) panchromatic imager. Electronic noise in the analog transmission system limited the utility of this sensor.

sors, collecting daily global images at 1-km and 4-km spatial resolutions (Allison and Schnapf, 1983). The resultant observations were available, at cost of reproduction, to any interested user. It quickly became evident that these "low" spatial resolution observations could be used to study regional vegetation patterns, as well as to provide valuable measurements of the seasonal dynamics of land vegetation (Townshend and Tucker, 1981; Schneider and McGinnis, 1982; Goward *et al.*, 1985). This shift to AVHRR research was made possible initially by the understanding of SVIs, as a general descriptor of vegetation foliage conditions, derived from Landsat MSS observations between 1972 and 1984. This shift to the AVHRR sensor also reinforced the emphasis placed on the simple, two-band, visible-near infrared spectral vegetation index as the primary terrestrial satellite remote sensing contribution to Earth Systems Science (Tucker and Sellers, 1986; Fung *et al.*, 1987; Box *et al.*, 1989; Heimann and Keeling, 1989; Sellers *et al.*, 1994; Townshend *et al.*, 1995).

Evolving Landsat Applications

During the commercialization hiatus of Landsat science development, there continued to evolve a wide range of efforts to exploit Landsat observations for resource monitoring, particularly agriculture, as well as to further develop practical applications of these images (Nelson *et al.*, 1987; De Keersmaecker, 1989; Jewell, 1989; Belward *et al.*, 1990; Wu and Maitre, 1990; Woodcock *et al.*, 1994). These efforts have often been constrained to examination of a single Landsat observation because of data costs during the Landsat "commercial" era (1985-1998).

Agricultural Monitoring

One exception to single image use was found under the U.S. Department of Agriculture (USDA), Foreign Agricultural Service (FAS), Commodities Forecasting Group. The technologies developed under the NASA/NOAA/USDA AgRISTARS program were, in 1982, transitioned to operational use by researchers in the USDA FAS program. Over the last 15 years, the USDA purchased regional, growing-season, Landsat coverage for many of the primary commercial agricultural regions of the Earth. This monitoring included intensive growing-season coverage in the former Soviet Union, South America, Asia, and Australia, as well as selected regions in the U.S. The intensive demands placed on these analysts have limited communication of their experiences gained from this intensive application of Landsat observations; therefore, there are no references which can be cited here. However, as a general rule, Landsat observations have provided critical information on inter-annual variations in specific cropping patterns (location and crop type) from year to year (T. Taylor, USDA FAS, personal communication, 1996). The spectral, spatial, and radiometric attributes of the Landsat TM instruments are fundamental to successful analysis of this time-critical information.

Tropical Deforestation

One of the more difficult science issues which continued to challenge Earth scientists in the 1980s was the rate at which human occupants of the Earth's land areas were converting tropical forest lands from natural vegetation cover to agricultural and other uses (Vitousek *et al.*, 1986; Houghton *et al.*, 1990). The issue of the missing global carbon sink, raised in the early 1980s, continues today as a global-scale mystery (Tans *et al.*, 1990), with conflicting evidence over whether the terrestrial biosphere is a source or a sink of carbon. In fact, the whole question of how terrestrial land-cover change perturbates the Earth system still remains unresolved (Turner *et al.*, 1990; Turner *et al.*, 1993). A specific example of this uncertainty concerns the recent rapid increases in tropical forest clearing (Whitten 1987; Feeny, 1988). Efforts were begun to examine these tropical land-cover dynamics (Woodwell *et al.*, 1983) with the first assessments completed with AVHRR observations (Tucker *et al.*, 1984). This was paralleled by efforts to employ Landsat observations (Nelson and Holben, 1986; Nelson *et al.*, 1987; Woodwell *et al.*, 1987). It quickly became evident that the 1-km AVHRR observations were seriously over-estimating deforestation rates as a result of the relatively coarse spatial resolution of this sensor (Cross *et al.*, 1991).

The spatial fragmentation of land cover introduced by human modifications clearly needed the detailed imagery collected by Landsat to resolve these land-cover dynamics (Skole and Tucker, 1993). In 1990, an EOS Pathfinder project was initiated under a consortium of NASA Goddard Space Flight Center, University of New Hampshire, and University of Maryland at College Park, to inventory systematically tropical deforestation rates throughout the globe (Townshend *et al.*, 1995). To date, over 3000 Landsat MSS and TM scenes, from the three decades of Landsat operations, the 1970s, 1980s, and 1990s, have been acquired and analyzed for the continents of South America and Africa, and for tropical Southeast Asia. This effort constitutes the largest use of Landsat data for scientific research to date. One of the many outcomes of this work is that the full visible, near infrared, and short-wave infrared complement of TM spectral measurements, rather than a simple VIS/NIR spectral vegetation index, provides critical information on the identification of forest clearing and recent regrowth (Steininger, 1996). The lessons learned from the Landsat Pathfinder effort are still emerging, but results to date suggest that the Landsat TM observations contain information about the Earth's land areas beyond that already documented by VIS/NIR spectral vegetation indices.

Land-Cover Change

Land-cover information derived from Landsat TM data is critical for many different major on-going federal programs. For instance, the USGS Biological Resources Division's Gap Analysis Program (Scott *et al.*, 1996) uses Landsat TM data to generate detailed data sets mapping natural/semi-natural plant assemblages. This information is linked with modeled vertebrate habitat preference distribution data to map (and ultimately manage) biodiversity on a national scale. Most states or groups of states currently have Gap Analysis Program activities, and are actively using Landsat TM data to derive the pertinent land-cover information. Similarly, NOAA's Coastal Change Analysis Program (Dobson *et al.*, 1995) relies heavily on TM data for assessing land-over changes in coastal areas (with "coastal areas" defined broadly, because these areas are heavily influenced by land-use activities taking place upstream and far from the coast). Land-cover classification data from Landsat are an important foundation for these activities. In this case, effects of land-cover changes are being investigated with special emphasis on determining long-term effects on estuarine systems. Additionally, the USGS's Water Resources Division National Water-Quality Assessment Program (Leahy *et al.*, 1993; NRC, 1990) is actively using Landsat TM data to derive land-cover information to be used as input for nutrient and pesticide run-off models. This is a concerted effort involving the major watershed drainage units within the United States. In all of these cases, Landsat TM data are being used to develop detailed land-cover classification data layers. The spatial and spectral properties of TM are very appropriate for these purposes.

Land-cover classification information derived from Landsat is also being used to further the field of landscape ecology (Formon and Godron, 1986). A series of landscape metrics (Riiters *et al.*, 1995) has been developed for the assessment of landscape patterns and processes, including investigations of forest contiguity and fragmentation, wildlife corridors, and patch size variables. Within temperate regions, landscape metrics have been shown to be very useful for assessing the impact of human activities, such as logging practices and urbanization, on forest fragmentation (Vogelmann, 1995; Ripple *et al.*, 1991). In addition, Landsat TM coverage of the short-wave and thermal infrared regions has proven especially valuable in monitoring vegetation condition (Moran *et al.*, 1989; Moran *et al.*, 1996), snow cover, and hot spots associated with active moving lava flows (Flynn *et al.*, 1994) and forest fires (Flynn and Mouginis-Mark, 1995).

Land Biogeochemical Cycles

Spatial variability in ecosystem properties, such as that represented in the tropical deforestation patterns, and non-linearity in biogeochemical fluxes as a function of land-cover characteristics, complicate regional and global-scale Earth systems analyses. For example, in studies of trace gas fluxes in the central Amazon Basin, where ecosystems are normally classed under the generic term "tropical rainforest," there are a number of ecosystem types including relatively fertile upland forests, highly infertile forests growing on sandy soils, flooded forests, and a variety of altered sites, most notably cattle pastures, each of which has unique biogeochemical cycling rates (Matson *et al.*, 1990). The necessary land-cover classification and areal estimation tasks require the precision provided by Landsat TM observations. This combination of remote sensing data, plus a ground-based understanding of trace gas controls, is required for regional and global extrapolation of fluxes by ecosystem type. For example, pastures converted from forest accounted for only 11 percent of the area but were responsible for more than 40 percent of the nitrous oxide flux in a region near Manaus, Brazil (Matson *et al.*, 1990).

The detailed local knowledge of land-cover patterns and dynamics, as provided by Landsat observations, sets the stage for developing models that estimate regional responses to continued land disturbances. Remote sensing measurements of vegetation properties, disturbance types and extent, inundation characteristics, and climate system parameters are essential for translating local site measurements to regional and global-scale analyses. High spatial resolution, combined with precision radiometry and broad spectral coverage, such as that provided by Landsat data, are required to satisfy most scale-dependent Earth Systems Science issues. The patterns of land-use and/or land-cover change around the world, and the non-linear processes associated with them, can only be accurately quantified using data that can resolve landscape scale features on the order of a few tens of metres. Use of coarse resolution data alone (e.g., AVHRR) in the same mode without scaling corrections (which, in turn, must be developed by direct comparisons of coarse and fine resolution data) often leads to large biases in derived estimates of surface cover type and associated processes.

Landsat and Mission to Planet Earth

After two and a half decades of Landsat monitoring of the Earth, the significance of these observations for scientific and strategic purposes was finally given full recognition when the U.S. Congress replaced the Landsat Commercialization Act of 1984 with the Land Remote Sensing Policy Act of 1992. Under this law, basic Landsat operations returned to the U.S. government, under the guidance of NASA, NOAA, and the U.S. Geological Survey. A critical part of the new Landsat initiative, beginning with the launch of Landsat 7 in 1998, is the role Landsat will play in NASA's Mission to Planet Earth (MTPE) Earth Observing System (EOS) and the U.S. Global Change Research Program (USGCRP).

The Landsat terrestrial measurement contribution to Earth Systems Science is clearly delineated within its new role in MTPE/EOS and the USGCRP (Sellers *et al*, 1995). The primary goal of the USGCRP is to improve understanding of the integrated Earth System (Committee on Earth Studies, 1990). USGCRP has prioritized the scientific research that needs to be done using the following criteria:

- the importance of a science area to Earth System functions (e.g., land conditions and dynamics strongly influence conversion of sunlight into plant matter, heat, and evaporation of water, all of which are the significant components of the Earth System); and
- the uncertainty associated with a science area (e.g., knowledge of global and regional land-cover patterns and dynamics is poor).

USGCRP science priorities, directed toward resolving the largest uncertainties in Earth System Science, are reflected in the recently defined major MTPE Science Research Plan (National Aeronautics and Space Administration, 1996). These include

- Land-Cover and Land-Use Research,
- Seasonal to Interannual Climate Variability and Prediction,
- Natural Hazards Research and Applications,
- Long-Term Climate: Natural Variability and Change Research, and
- Atmospheric Ozone Research.

The top three priority areas all contain critical requirements for better understanding of land patterns and dynamics. The EOS multi-sensor complement of MISR (Multi-angle Imaging SpectroRadiometer), MODIS (Moderate-Resolution Imaging Spectroradiometer), ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer), and Landsat ETM+ (Enhanced Thematic Mapper Plus) is directed toward collection of the requisite land measurements, with Landsat playing the critical role of resolving both the spatial detail and the temporal dynamics of land-cover change.[2] The specifics of how Landsat and the other EOS "land" sensors accomplish these objectives can be understood in the context of Earth System process rates and the land characteristics which influence, or are determined by, these rates (Table 1) including

- Biophysics: energy-water-carbon exchange (fast processes — on a time scale of seconds to seasons),
- Biogeochemistry: carbon and other trace gas cycles (intermediate processes — on a time scale of seasons to years), and
- Ecology: ecosystem dynamics and land-cover change (slow processes — on a time scale of years to decades).

These three areas are not distinct; the overlaps are large and important (Sellers and Schimel, 1993) and are summarized below.

Biophysics

These are the processes which determine exchanges of carbon-energy-water between the atmosphere and the terrestrial biosphere. The geographic and seasonal patterns of these processes in large part determine immediate and medium-term climate dynamics over the continents. The land aspect of these biophysics is determined by the state (vigor, density, type) of the vegetation, the water-holding properties of the soil column, and the emissivity and temperature of the vegetation and soil components in the scene. Combined, these land conditions regulate the flux of moisture from the soil to the atmosphere and also the uptake and release of CO_2.

Biophysical land-cover attributes are described by remotely sensed variables including land-cover type, percent-

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[2] Although ASTER offers spatial resolution data similar to that of the Landsat 7 ETM+ for the purpose of high-resolution cross-correlation of data sets such as MODIS, ASTER has only an 8 percent duty cycle and ASTER data acquisition requests will be at least partially controlled by non-U.S. personnel. Thus, given the apparent limited availability of ASTER data, Landsat 7 ETM+ data will more easily fulfill the role necessary to interpret coarser resolution data.

TABLE 1. EARTH SYSTEM SCIENCE NEEDS AND EOS TERRESTRIAL REMOTE SENSING

USGCRP Priorities	Climate and Hydrology	Biogeochemical Dynamics	Ecological Systems and Dynamics
Land Attributes	BIOPHYSICS	BIOGEOCHEMISTRY	ECOLOGY
Processes	Land-Atmosphere fluxes of radiation, water, heat	Photosynthesis, Respiration, Nutrient cycling.	Land cover state, Land cover change, Net primary production
Time-scale	seconds → seasons	seasons → years	years → decades
Spatial Domain	Global and Regional	Regional → Global	Local → Regional
Science Goals/Integrating Tools	Global Climate models Data Assimilation	Biochemistry Tracer models Carbon Flux models	Land Cover/Use Change, Ecosystem dynamics
Earth Observing System Land Objectives	BIOPHYSICS	BIOGEOCHEMISTRY	ECOLOGY
Remotely Sensed Variables	FPAR, LAI, Vegetation type, Surface Temp. (T_s), Surface albedo, Snow cover, etc.	FPAR, LAI, T_s Vegetation type, Disturbance patterns, Canopy BGC.	Vegetation type, Disturbance regime, Change dynamics, Sediment loads in aquatic systems
Image Frequency	Few days	Days → weeks	Seasons → annual
Frequency Factors	seasonal foliage state Cloud Screening Surface Temperature	seasonal foliage state Cloud Screening Surface Temperature	Changes in land cover Cloud Screening
Spatial Resolution	250m → 1km	30m → 1km	1m → 30m
Spatial Factors	Cloud screening Surface Heterogeneity.	Cloud screening Vegetation type	Vegetation type Surface Heterogeneity
Appropriate Instruments (Primary)	MODIS MISR CERES GOES	MODIS Landsat TM / ETM+ MOPITT	Landsat TM / ETM+ ASTER
Appropriate Instrument (Secondary)	Landsat TM / ETM+ Landsat Ocean Color Instrument ASTER AIRS, MIMR	CERES GOES	MODIS MISR

age of vegetated cover, albedo, roughness length, moisture availability, and photosynthetic capacity. High temporal resolution satellite observations (e.g., AVHRR, MODIS, and MISR) are needed to define variables such as moisture availability and photosynthetic capacity. However, because of detailed spatial heterogeneity, land attributes such as cover type and roughness length require the spatial attributes of Landsat TM/ETM+ observations. Combined, multi-scale analysis of both MODIS and Landsat TM/ETM+ observations are needed to describe properly land biophysics.

Biogeochemistry

A critical process of Earth systems is the cycling of specific chemical elements, especially carbon, nitrogen, sulfur, and phosphorus. These chemicals strongly influence life processes on Earth and, specifically with carbon, also affect the basic energy balance of the atmosphere (Schlesinger, 1991). It is particularly important to understand how and where the terrestrial biosphere may be absorbing and storing atmospheric carbon and how these processes might change with a change in climate (Hansen *et al.*, 1981). The terrestrial biosphere appears to have acted as a net sink for carbon over the past few decades. The exact mechanisms involved and the spatial contributions to this sink are as yet unknown, but the evidence points to carbon being stored in either the living tissue of vegetation or within the soil profile (Tans *et al.*, 1990; Enting and Mansbridge, 1991). The cycling of carbon and other trace elements, many of which are important to atmospheric greenhouse gas chemistry, is not well understood at these intermediate (months to years) timescales. To assess this geochemistry accurately, it is necessary to know about the different contributions of plant growth and decomposition respiration to the total fluxes at detailed spatial scales (Running and Coughland, 1988; Sellers and Schimel, 1993).

Satellite remotely sensed observations provide the land information, such as cover type, absorbed photosynthetically active radiation (APAR), and annual foliage phenology needed to identify the major sinks and sources of carbon and other trace elements. Again, MODIS, MISR, ASTER, and Landsat TM/ETM+ data may be used to define the magnitude of photosynthetic sinks and sources around the world. In the near term, classification information provided by Landsat data and inverse modeling are the only means available to describe regional patterns of planetary geochemistry.

Ecology

The patterns and dynamics of terrestrial and aquatic ecosystems are defined both by climate and human activity and produce feedback's which alter the hydrology/climate system. Changes in the ecological function and structure of terrestrial ecosystems occur as a result of changes in the physical climate system, in addition to direct changes as a result of anthropogenic activities. Classically, progressive successional changes have been proposed as the most likely response; however, recent thinking has been focused on changes in disturbance regime [e.g., fire frequency and extent, disease, etc., associated with ecosystems undergoing changes (Shugart, 1984)]. Alterations in the surface properties of ecosystems, specifically albedo, surface roughness, and biophysical control of evapotranspiration, could in turn

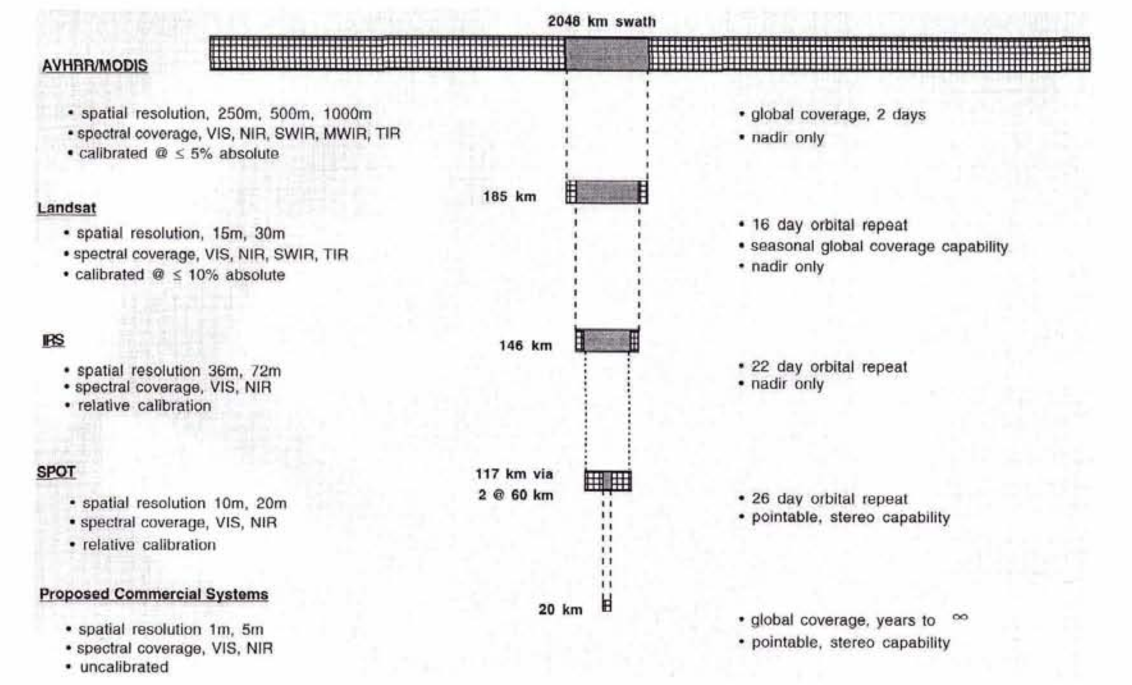

Figure 3. Chart depicting Landsat's unique land observing characteristics relative to other satellite systems.

have feedback effects on the near-surface climatology (Sato *et al.*, 1989). Key research questions include: How will ecosystems change in response to climate change and anthropogenic pressure? How will the changes feedback into the climate system, particularly with respect to the cycling and storage of carbon and trace constituents? Critical attributes of ecosystems which must be understood to describe the ecology component of the Earth system include heterogeneity, disturbance patterns and frequency, land-cover change and succession, ecosystem fragmentation, and biodiversity.

Assessment of these ecosystem patterns and dynamics requires the spatial resolution and temporal frequency of Landsat observations. For example, early estimates of tropical deforestation rates were seriously in error when evaluated with 1-km AVHRR (Cross *et al.*, 1991). Refined analysis with Landsat data revealed much lower rates than first reported (Skole and Tucker, 1993). High spatial resolution data such as that provided by the Landsat TM/ETM+ sensors are required to satisfy most of the objectives of the Ecology science area. The patterns of land-use and/or land-cover change around the world, and the non-linear processes associated with them, can only be quantified accurately using data that can resolve landscape-scale features, on the order of a few tens of metres. Use of coarse resolution data alone (AVHRR, MODIS) in the same mode without scaling corrections (which, in turn, must be developed by direct comparisons of coarse and fine resolution data) leads to large biases in the derived estimates of surface cover type (Moody and Woodcock, 1994) and associated processes.

The central role that EOS, Landsat, and other land sensors play in addressing primary USGCRP priorities clearly demonstrates the mature evolution of the Landsat science mission. There is now widespread scientific appreciation of the unique terrestrial information Landsat-type sensors provide Earth systems scientists. Without this measurement source, a comprehensive strategy to study the integrated Earth system would not be possible.

Landsat 7 within NASA's Earth Observing System

The digital image data provided by the Landsat series of satellites over the past 25 years are among the most valuable scientific assets available to the Earth Sciences community. Indeed, Landsat data have done as much to solidify the concept of Earth Systems Science over the past two decades as any other single source of terrestrial information. These data provide the most consistent, reliable documentation of global land-cover type and land-cover change over the past quarter century. The high spatial resolution data provided by the MSS/TM/ETM+ instruments is used to scale detailed local knowledge to interpret coarser resolution observations, such as that provided by the AVHRR, MODIS, and MISR class of instruments, so that the relations between local conditions and global dynamics can be understood. In addition, the spatial and spectral resolution of TM/ETM+ data make it the primary source of information for ecological studies, and for a plethora of other applications developed to support a wide community of users: from farmers to foresters, from water managers to land managers, from surveyors to explorers, and from local governments to federal agencies.

Because of Landsat's significant contributions to Earth Systems Science, as well as its broader applications potential, it should be no surprise that the primary purpose of the Landsat 7 mission, as spelled out in the Land Remote Sensing Policy Act of 1992, was to maintain continuity of this valuable data set. Indeed, it was always assumed by EOS scientists that Landsat TM-class data would be routinely available to support EOS science goals.

Landsat 7 Mission Profile

The unique aspects of the high-resolution Earth observations afforded by the Landsat series of satellites since 1972, compared to other Earth observing sensors (e.g., AVHRR, SPOT, IRS, and proposed commercial sensors) is clear (Figure 3). Landsat's capacity to provide fine spatial resolution (15 to 30

m) and seasonal repeat coverage places it in a unique observation category among existing and near-term future sensor systems. Technically, it would be possible to provide even higher spatial (and spectral) resolution with more frequent temporal coverage, with a multi-satellite constellation of sensors systems in orbit at the same time. However, both the operational complexities and the enormous data volumes would be a challenge to operations, data archiving, and research personnel alike. In short, no other satellite or sensor configuration can match the unique combination of providing repetitive, broad-area, global coverage at high spatial resolution in all four passive optical regions of the electromagnetic spectrum (e.g., visible, near IR, short-wave IR, and thermal IR regions), while offering very good to excellent radiometric calibration[3], and a long term data archive stretching back over the past 25 years.

The horizontal bars in Figure 3 represent the swath width of the various types of sensors being compared, and these bars are scaled relative to one another to permit easy comparison of the coverage provided by each. In conjunction with each instrument, there are words that summarize the swath width, the spectral regions covered, the quality of radiometric calibration (relative versus absolute, etc.), orbit repeat cycle, "point and shoot" stereo capability, and the estimated time needed to complete full coverage of the global land masses. The top and bottom entries in Figure 3 represent an AVHRR/MODIS class of instrument (top), and a generic proposed commercial "point and shoot" sensor (bottom). The MODIS class instrument will provide two-day global coverage employing wide field-of-view optics, coupled with coarse spatial resolution (250 to 1000 m) in all four passive optical regions (VNIR, SWIR, TIR), and excellent absolute radiometric calibration.

In contrast, the generic proposed "commercial" sensor at the bottom of the chart offers high flexibility to "point and shoot" to acquire a narrow swath of coverage (7 to 20 km) at high spatial resolution (1 to 5 m) using a silicon detector array covering only the VNIR regions. Radiometric calibration plans for such instruments are usually relative at best, and it would be extremely difficult to attain a complete archive of the global land mass with such an instrument. These sensors at the bottom of the chart are truly intended to be on-orbit replacements for the niche that is currently filled by aerial photographic missions; they do not come close to being an adequate replacement for the Landsat MSS/TM/ETM+ series of sensors.

Careful study of all of the information contained in this chart reveals that the Landsat series of satellites provide truly unique, high-quality global coverage. To support this capability and capture the requisite Earth System Science goals, the data acquisition and processing system for Landsat 7 has been sized to acquire and archive at the USGS EROS Data Center (EDC), *seasonal*, global coverage (i.e., 250 scenes of data are to be acquired globally and archived daily at EDC — this represents roughly an order of magnitude increase in scene acquisition and storage in a US archive over any past Landsat mission). The ability to assess *seasonal* variations in global vegetation green-up and senescence at relatively high spatial resolution is a unique niche that is filled by Landsat. Such coverage is an ingredient for assessing linkages between land use and regional land-cover change and global environmental trends (Goward *et al.*, 1996).

Landsat Adopted as an EOS instrument

The Land Remote Sensing Policy Act of 1992 (P.L. 102-555) provided the U.S. Government with guidelines for developing Landsat 7 and follow-on land remote sensing missions. A joint Department of Defense (DoD) and NASA Landsat 7 program was outlined and initiated early in 1992 whereby DoD was to build and launch the satellite and sensor, and NASA was to operate it once in orbit. However, a variety of factors came together in late 1993, particularly lead by DoD budget cuts associated with the "peace dividend." The DoD decided to step away from their Landsat obligation, and a bulk of the Landsat 7 development money went with them. This, in turn, necessitated a 1994 Presidential Decision Directive from the National Science and Technology Council (Landsat Remote Sensing Strategy; PDD/NSTC-3) which established the current government management strategy for the Landsat program. The Directive gave NASA responsibility for Landsat program development, while assigning NOAA the task of post-launch Landsat 7 operations, and USGS the Landsat 7 data archive and distribution function [see Sheffner (1994) for a more complete description of historical events].

Although NASA was given responsibility for building and launching Landsat 7, there were serious funding shortfalls associated with DoD's departure from the Program. Given Landsat's historical role in the evolution of Earth Systems Science concepts, and the desire of EOS investigators to fuse Landsat data with EOS data, the MTPE Program Office decided in 1995 to adopt the Landsat program as a component of EOS. It also agreed to follow the P.L. 102-555 guidelines for developing of Landsat 7 *and* follow-on systems.

Landsat's Role in Global-Scale Land-Cover Monitoring

The EOS suite of sensors consists mainly of coarse spatial resolution instruments directed at observing important aspects of the Physical Climate System, the Carbon Cycle, and Atmospheric Chemistry. EOS-AM, the first EOS mission, is especially focused on the first two — the Physical Climate System and the Carbon Cycle. For example, it will carry MODIS, a moderate resolution instrument designed specifically to monitor vegetation properties at high temporal resolution; MISR and CERES, which will quantify atmospheric and surface radiative properties and incoming radiation fluxes, respectively; MOPITT, an atmospheric chemistry instrument; and ASTER, a relatively high spatial resolution (i.e., 15 m, 30 m, and 90 m), pointable sensor of limited swath (60 km), built by the Japanese primarily for geological applications. The land-surface imaging role of EOS-AM is to quantify the swiftly varying surface parameters that govern the exchanges of energy, water, and carbon between the land and the atmosphere.

By contrast, the Landsat TM/ETM+ sensors are high spatial resolution sensors that can provide detailed information for interpreting EOS-AM data and serve as the lead EOS instrument for ecological, land-cover, and human dimensions (e.g., natural hazards) studies. Thus, the primary contributions of Landsat to EOS scientists are expected to be in the areas of land surface parameter-scale integration and validation, monitoring land cover changes, vegetation classification, and radiometric rectification of coarser resolution MODIS data. It was felt that the benefits associated with comparing these two types of data sets would increase in value if the EOS-AM and Landsat 7 ETM+ observations were brought closer together in time on orbit. For example, the EOS-AM data could be used to atmospherically correct Landsat images for the effects of aerosols and atmospheric water vapor, while the higher spatial resolution image data provided by the ETM+ could serve to greatly simplify data processing and validation tasks for EOS-AM coarse resolution data sets. Another example is that the EOS-AM and Landsat data sets could be used to study rapidly changing thermal anomalies, such as those associated with ac-

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[3] The benefits and necessity of absolute radiometric calibration may be difficult for the layman to appreciate. However, in order to more accurately monitor changes on Earth over time, precise radiometric calibration is needed to perform the necessary intra-system and inter-system data comparisons (Moran *et al.*, 1995; Teillet, 1995).

tive lava flows or wind-driven forest fires (Flynn *et al.*, 1994; Flynn and Mouginis-Mark, 1995).

In simple terms, Landsat 7 ETM+ data might help EOS scientists monitor the slowly changing, spatially detailed land surface properties (land-cover type, spatial heterogeneity and complexity, relations between vegetation and topography, etc.) and processes (principally land-cover change). This amounts to defining important land surface **states**. These data are needed by the EOS-AM sensors, in association with most Earth Systems Science models, to calculate the critical transfer **rates** (e.g., energy, water, and carbon transfer rates) between the land and the atmosphere that are the focus of the USGCRP. Landsat ETM+ data will help with the solution of problems which are related to spatial scale and/or are sample frequency dependent, thereby complementing the AM-1 measurements of MODIS, MISR, and ASTER.

In summary, the main reasons for integrating Landsat and EOS Science are as follows:

- Landsat data are an essential integral component of EOS to achieve the highest scientific use of other sensor data, particularly the EOS-AM land surface imaging cluster (MODIS, MISR, and, to a lesser extent, ASTER). The combined data sets address high priority USGCRP issues over the land; namely, biophysics, biogeochemistry, and ecology.
- There are direct benefits associated with bringing the Landsat and EOS-AM data streams closer together in the areas of:
- MODIS/MISR land surface product generation (FPAR, LAI, etc.),
- cross-scale product integration and validation,
- radiometric rectification of MODIS data with Landsat data,
- atmospheric correction of Landsat data with MODIS and MISR data,
- temporal interpolation of Landsat data with MODIS data, and
- linking the EOS data to the Landsat 25-year archive.

Obviously, these benefits would all be enhanced if the instruments were mounted on the same platform; this is currently being planned for the EOS-AM2 mission scheduled for flight in 2004.

- EOS scientists have always assumed that Landsat data would be available to them to provide information vital for all aspects of the "land science" to be conducted as part of USGCRP.
- There are several practical benefits to be realized for both programs from closer scientific, institutional, and data integration.

Formation Flying of Landsat 7 and EOS-AM1

Given the above arguments, coupled with the fact that both Landsat 7 and EOS-AM1 were scheduled for mid-1998 launches into identical 705-km, sun-synchronous orbits, a decision was made in 1996 to place the two spacecraft in a same-day orbit, spaced ideally 15 minutes apart, i.e., equatorial crossing times of 10:00 to 10:15 AM for Landsat 7 and 10:30 AM for EOS-AM1. Thus, multispectral data having both high (30-m) and medium-to-coarse (250- to 1000-m) spatial resolution will be acquired repetitively on a global basis under nearly identical atmospheric and plant physiological conditions. This near simultaneous acquisition of data will also serve as a beneficial pathfinder for both technique and algorithm development for the EOS-AM2 mission in 2004, when plans call for the Landsat 7 follow-on sensor to be flown as part of the AM2 mission.

Earth Systems Science and Landsat in the 21st Century

Landsat 7 has been designed for at least a five-year mission life. Based on the longevity of Landsats 4 and 5, Landsat 7 is expected to operate well into the next century. Since 1994, NASA has been making plans to fly a Landsat 7 follow-on sensor on the EOS-AM2 satellite slated for launch in 2004 (Williams *et al.*, 1995). This follow-on sensor design will utilize advanced technologies which should maintain or improve most ETM+ performance specifications in an instrument package that will be much smaller, lighter, more energy efficient, and simpler to operate (i.e., no or few moving parts) than the TM/ETM+ instruments. Such an instrument should be less expensive to build, accommodate on a satellite, and launch than Landsat 7. A separate article in this special issue by Ungar (1997) will provide a more in-depth discussion of the type of advanced technologies that are being investigated to build this new class of instrument. By mid-1999, NASA plans to build and launch the first Earth Orbiter (EO-1) mission as a land remote sensing system utilizing New Millennium Program (NMP) technologies. Development and flight of such a sensor on this timetable dovetails with an on-orbit proof-of-concept checkout flight before finalizing the design of the Landsat 7 follow-on sensor scheduled for flight as part of EOS-AM2.

Summary

The Landsat series of satellites constitute an explicit and integral component of the U.S. Global Change Research Program and, as described within this paper, helped to lead the scientific research community to develop and expand the concept of Earth Systems Science over the past two decades. The Landsat satellites have also provided data to a broad and diverse constituency of users who apply the data to a wide spectrum of tasks. This constituency encompasses the commercial, academic, government (federal, state, local), national security, and international communities. As of mid-1997, the Landsat satellites will have provided a continuous and consistent 25-year record of the Earth's continental surfaces that is unique and invaluable, and continuation of this database is critical to our global change research strategy.

Within NASA's MTPE/EOS program, the basic Landsat mission is to provide a detailed source of information on inter-annual land-cover change. To accomplish this goal requires not just once-per-year, cloud-free observations of all land areas but, for most locations, multiple observations are required to capture seasonal variations in land cover. As noted earlier, an individual Landsat scene includes land-cover patterns which originate from both long-term land-cover change and seasonal variations in land-cover conditions. To separate seasonal variability from inter-annual land-cover change, it is necessary to record seasonal land-cover dynamics for each location where cover conditions change with the seasons. This places significant demands on Landsat operations, far beyond that attempted since early experiments with ERTS-1.

Unlike previous Landsat satellites, Landsat 7 and its follow-on systems will co-exist with a plethora of real and proposed on-orbit remote sensing systems. These systems will include EOS, U.S. national security systems, commercial ventures, and systems launched by other nations. Thus, future Landsat satellites can only be justified if they serve a unique and valuable role within this constellation of remote sensing systems. Landsat 7 and follow-on missions will serve such a role if the scientifically essential capabilities of the Landsat TM/ETM+ sensors are continued. These include repetitive, synoptic coverage of continental surfaces; spectral bands in the visible, near-infrared, short-wave infrared, and thermal infrared regions; spatial resolution on the order of 30 m; absolute radiometric calibration to 5 percent or better; and robust data acquisition and archive scenarios that will facilitate the goal of global, seasonal coverage. No other current or planned remote sensing system, public or private, fills the role of Landsat in global change research or in national security, civil, commercial, and educational applications.

Continuation of these capabilities are required for clear reasons. Repetitive, broad-area coverage is needed for observation of seasonal changes on regional, continental, and global scales. Other systems (e.g., MODIS on the EOS-AM1 platform) will afford more frequent global coverage, but not at the 30-m spatial resolution of the Landsat TM/ETM+. Unlike the oceans and atmosphere, the land surface is distinguished by high spatial frequency processes that require high spatial resolution to characterize. In particular, human-caused changes are often initiated at scales requiring high resolution for early detection. The Landsat sensors potentially offer unique capabilities for monitoring important local processes both seasonally and globally. Key elements of land dynamics, including the inter- and intra-annual cycles of vegetation growth; deforestation and forest fires; agricultural land use; volcanic eruptions, lava flows, soil erosion, and other forms of land degradation; snow accumulation and melt, and associated fresh-water reservoir replenishment; and urban expansion, all are subjects for the Landsat observatory. Other system configurations which afford global coverage do not provide the spatial and spectral resolution to observe these processes in detail, **and** only the Landsat system provides a 25-year retrospective record of these processes.

Significant additions to Earth Systems Science from Landsat are expected with the launch of Landsat 7. Refinements in radiometric response and calibration, inclusion of a 15-m panchromatic band, improvement in the spatial resolution of the thermal band to 60 m, and an aggressive acquisition strategy will all contribute to Landsat's new role as a major component of NASA's Mission to Planet Earth, Earth Observing System. Development of technologies for more refined, as well as lower cost, sensors and platforms is now being pursued. Implementation of these technology advances is expected to further enhance our capability to monitor the Earth's land areas in the decades to come.

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