



Landsat continuity: Issues and opportunities for land cover monitoring

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Abstract

Initiated in 1972, the Landsat program has provided a continuous record of earth observation for 35 years. The assemblage of Landsat spatial, spectral, and temporal resolutions, over a reasonably sized image extent, results in imagery that can be processed to represent land cover over large areas with an amount of spatial detail that is absolutely unique and indispensable for monitoring, management, and scientific activities. Recent technical problems with the two existing Landsat satellites, and delays in the development and launch of a successor, increase the likelihood that a gap in Landsat continuity may occur. In this communication, we identify the key features of the Landsat program that have resulted in the extensive use of Landsat data for large area land cover mapping and monitoring. We then augment this list of key features by examining the data needs of existing large area land cover monitoring programs. Subsequently, we use this list as a basis for reviewing the current constellation of earth observation satellites to identify potential alternative data sources for large area land cover applications. Notions of a virtual constellation of satellites to meet large area land cover mapping and monitoring needs are also presented. Finally, research priorities that would facilitate the integration of these alternative data sources into existing large area land cover monitoring programs are identified. Continuity of the Landsat program and the measurements provided are critical for scientific, environmental, economic, and social purposes. It is difficult to overstate the importance of Landsat; there are no other systems in orbit, or planned for launch in the short-term, that can duplicate or approach replication, of the measurements and information conferred by Landsat. While technical and political options are being pursued, there is no satellite image data stream poised to enter the National Satellite Land Remote Sensing Data Archive should system failures occur to Landsat-5 and -7.

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1. Introduction

International requirements for reporting on the environment dictate the need to monitor land cover and land cover change through time. Earth observation (EO) data are an integral component of large area land cover (LALC) monitoring. The longevity and continuity of EO programs are essential to the success and viability of LALC monitoring programs over long time horizons. The value of the information produced from

Landsat measures is well known and supported; both Cohen and Goward (2004) and Leimgruber et al. (2005) have chronicled the vital role Landsat data have played in a wide variety of ecological applications. Supported by a range of government and non-government agencies, a Millennium Ecosystem Assessment (MEA) was recently completed; the program was designed to provide policy and decision makers with information regarding the links between ecosystem change and human well being. In summarizing the findings of the MEA report, Carpenter et al. (2006) point to the lack of a lengthy and uninterrupted time series of Earth observation data as a key information shortcoming for current and long-term understanding of the linkages between

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anthropogenic activities and ecological outcomes. Without this information, we have no means of informing, nor of gauging the effectiveness, of our management strategies.

The Landsat program has provided EO data to meet a wide range of information needs since 1972 (Williams et al., 2006). Unfortunately, temporal and spatial discontinuities in the extensive 35-year archive of Landsat data appear unavoidable. For example, failures such as the 2003 loss of the Scan Line Corrector (SLC) onboard Landsat-7 (Markham et al., 2004) and problems with the solar array drive mechanism onboard Landsat-5 in 2005 (Frederick, 2005) have occurred throughout the history of Landsat missions. To date, the implementation of successor missions has proceeded more slowly than desirable (e.g., Goward & Skole, 2005). Today, Landsat-5, launched in 1984, has far exceeded its 3-year design life (Engel, 1987) and continues to provide quality data products, although it is expected to run out of fuel by September 2010 (Covington, 2006). Despite the SLC failure, the United States Geological Survey (USGS) maintains delivery of data from Landsat-7, in a form that meets the observation requirements of many applications (Cohen & Goward, 2004).

The US Administration, bound by the Land Remote Sensing Policy Act of 1992 (U.S. Code, Title 15, Chapter 82) and under increasing pressure from the science community, has acknowledged the potential implications of a gap in Landsat data collection and has reinvigorated the Landsat Data Continuity Mission (LDCM) (Marburger, 2005); however, bureaucratic machinations have impeded rapid progress on a Landsat procurement (Berger, 2006). The institutional history of the Landsat program and the ongoing need to justify and secure funding is well documented (Mack, 1990). Further, over time the Landsat program has become embroiled in changes in funding and operating philosophies (e.g., public vs. private), with difficulties in securing a successor to Landsat-7 having been foreseen early on (Malakoff, 2000). The potential crisis in Earth observation has arrived; exemplified by the dire need for a successor to Landsat-7, as well as the need for institutional arrangements (nationally and internationally) to be established to prevent similar situations from developing in the future (Goetz, 2007).

Our objective in writing this paper was to identify and synthesize the key features of the Landsat program that have made Landsat data indispensable for LALC applications. We augment this list of key features by examining the data requirements of current LALC monitoring programs. In doing so, we hope to provide insights into what features should be maintained by the Landsat program (under the auspices of the current Landsat Data Continuity Mission), or be emulated by future non-Landsat missions. In addition, we use these identified features as a benchmark against which the existing constellation of EO satellites are examined, to identify potential alternative data sources for LALC monitoring. We conclude by identifying research priorities that would facilitate the integration of these data sources into existing monitoring programs.

2. Key characteristics of the Landsat program

Declared a “national asset” by the President’s Science Advisor in 2004 (Marburger, 2004), the Landsat program is more than just

a data source (Freeborn et al., 2006). In reality, the success of the Landsat program can be attributed to a number of factors, not the least of which is the US Land Remote Sensing Policy Act of 1992 (U.S. Code, Title 15, Chapter 82), that has legislated many of the functions contributing to the longevity of the Landsat program. The significance of this legislated mandate cannot be ignored, especially in comparison to the EO satellite programs of other nations; the US government policy has essentially enabled both the technology and the market for this data (Williamson, 1997).

There are many features of the Landsat program that are desirable for large area land cover monitoring. The observation data alone represent a distinctive combination of spatial, spectral, and temporal resolutions, over a large image extent, resulting in information that can support management, monitoring, and scientific activities (Franklin & Wulder, 2002). The Image Assessment System developed for Landsat-7 facilitates the most rigorous calibration and quality assurance of all the sensors in the Landsat series (Markham et al., 2004). In turn, this system facilitates both the radiometric and geometric accuracy of Landsat-7 ETM+ data products (Irons & Masek, 2006). Current policies that ensure the collection of a systematic data archive, distribution of data on a non-discriminatory basis, and low data costs, have set the standard for EO data accessibility and affordability. The Landsat-7 data policy facilitates the widespread use of these data. The official data policies cover data acquisition, processing, archiving, distribution, and pricing, with priorities for acquisition indicated in the data policy.

2.1. U.S. National Land Remote Sensing Long-Term Data Archive

The systematic collection and archiving of data supports both current Landsat applications as well as retrospective or change analyses. The infrastructure required to efficiently and safely preserve the archived data, must also enable data queries and data access. Landsat data were originally downloaded and sorted at the NASA Goddard Space Flight Centre, with the USGS Center for Earth Resources Observation and Science (EROS) assuming primary reception and archiving responsibilities in the late 1970s. In 1992, the US Land Remote Sensing Policy Act mandated the archive of land remote sensing data in Section 5601:

“It is in the best interest of the United States to maintain a permanent, comprehensive Government archive of global Landsat and other land remote sensing data for long-term monitoring and study of the changing global environment.”

The National Satellite Land Remote Sensing Data Archive (NSLRSDA) is the responsibility of the United States Department of Interior (DOI) and is operated out of the DOI/USGS EROS data center (Goward et al., 2006a). The NSLRSDA stores data from a wide variety of satellite programs, including Landsat, some of the NOAA Polar Orbiting Environmental Satellites (POES) for land areas, and Satellite Pour l’Observation de la Terre (SPOT) collections for the US. In 1996, the archive was made part of the National Space Policy (Presidential Decision Directive/NSC-49/NSTC-8, National Space Policy, dated September 14, 1996) and its mission has subsequently been refined through various

executive orders and presidential decision directives (Gabrynowicz, 2001). While the NSLRSDA also contains non-Landsat imagery, current database queries indicate a collection of over 2 million Landsat scenes occupying over 1000 TB of data (Table 1).

The value of a data archive is not measured solely by the data it contains, but also by the ease with which the archive may be searched and data retrieved. The USGS is a global leader in the management of EO data and has developed sophisticated infrastructure to meet the growing demand for data access (Holm, 1999). The NSLRSDA has an advisory committee made up of sixteen individuals from government, academia, and industry. The mandate of the advisory committee is to (United States Department of the Interior, 2004):

“...advise the United States Government in maintaining an archive of land remote sensing data for historical, scientific, and technical purposes; including long-term global environmental monitoring; controlling the content and scope of the archive; and assuring the quality, integrity, and continuity of the archive.”

Demand for NSLRSDA data has greatly exceeded projections and given limited resources and storage capacity, the NSLRSDA Advisory Committee has made recommendations regarding priorities for data inclusion within the archive. These recommendations give priority to long-term observations that provide consistent, repetitive coverage over extended periods of time, with a moderate spatial resolution (*i.e.* between 10 m and 1 km), that represent the best available quality for any given location (*i.e.*, minimal cloud cover) (NSLRSDA Advisory Committee, 2003). Given the increasing availability of EO data and the limited resources available for archiving, questions regarding what should be archived, duration of storage, and funding sources are emerging. For commercial sensors (*e.g.*, QuickBird, IKONOS), there may not be sufficient incentive for the commercial operator to maintain a costly image archive. Harris and Olby (2001) provide the example of SPOT data, where 88% of data requests are for data that is less than five years old. It is important to acknowledge that other jurisdictions do not have the legislative mandate that the United States has to establish the infrastructure and funding for a long-term data archive for public good (Harris & Olby, 2001).

2.2. Landsat-7 mission operations

A long-term acquisition plan for Landsat-7 has been developed (Arvidson et al., 2001). Although upwards of 850

Table 2

A listing of international ground stations that currently collect Landsat data, as of March 2006

International Cooperator	Ground Station Location	Landsat-5	Landsat-7
Argentina	Córdoba, Argentina	x	x
Australia	Alice Springs, Australia	x	x
Australia	Hobart, Australia	x	x
Brazil	Cuiaba, Brazil	x	
Canada	Gatineau, Canada	x	
Canada	Prince Albert, Canada	x	
China	Beijing, China	x	
European Space Agency	Matera, Italy	x	
Indonesia	Parepare, Indonesia		x
Japan	Hatoyama, Japan	x	
Japan	Hiroshima, Japan		x
South Africa	Hartebeesthoek, South Africa	x	
Sweden	Kiruna, Sweden	x	
Thailand	Bangkok, Thailand	x	

After Goward et al. (2006a) and http://landsat7.usgs.gov/project_facts/ground_assets/igs_network/index.php.

scenes are in view of the ETM+ sensor in a 24 hour period, logistical and satellite resource issues limit the actual number of scenes that can be collected to about 400 per day, of which about 250 per day are archived within the USGS EROS, with the remainder being directly downlinked to ground stations operated by International Co-operators (ICs) (Arvidson et al., 2001). The Landsat long-term acquisition plan or LTAP is used to select the best possible scenes, using criteria such as cloud-cover forecasts, seasonality, and priorities for acquisition laid out in the Landsat-7 data policy (Arvidson et al., 2006).

The archived ETM+ data are captured from two ground receiving stations; one operated by the USGS EROS in Sioux Falls, South Dakota and the other an IC station in Alice Springs, Australia. Ground sites in Poker Flat Alaska (DataLynx) and Svalbard Norway (SGS) are used as backup sites when extra ground resources are necessary to fulfill mission objectives.¹ While the quality of the ETM+ images are now compromised as a result of the SLC failure, Landsat-7 continues to provide seasonal coverage of the global land mass to the archive at USGS EROS (aided by delayed transmissions of data stored on an on-board data recorder). In fact, the Landsat-7 long-term acquisition plan was modified in 2004, to acquire pairs of low cloud cover imagery within the same growing season, generally no more than 32 days apart, so that imagery could be merged to reduce the impact of the SLC failure (Maxwell et al., *in press*).

As of March 2006, there were 14 international ground receiving stations distributed across the globe that directly receive data from the Landsat-5 and -7 satellites (Table 2). Prior to the Landsat-7 ETM+ scan line corrector failure in 2003, most of the IC ground stations received data exclusively from Landsat-7. Since the failure, many ground stations have switched back to receiving data from Landsat-5 with only five IC stations currently receiving data directly from Landsat-7 (Table 2). Goward et al. (2006a) have reported that even following the Landsat-7 LTAP (SLC-off era), one nearly cloud-free image of the global land mass

Table 1

A summary of NSLRSDA Landsat data

Sensor	Records	Dates	Volume
Landsat MSS	649,412	1972–1992	19 TB
Landsat TM	692,566	1982–present ^a	347 TB ^b
Landsat ETM+	704,770	1999–present	654 TB ^c

^a The USGS EROS data store queried on March 27, 2007.

^b The volume of TM data is estimated to be increasing by 40 GB daily.

^c The volume of ETM+ data is estimated to be increasing by 260 GB daily.

¹ http://landsat.usgs.gov/project_facts/ground_assets/usgs/.

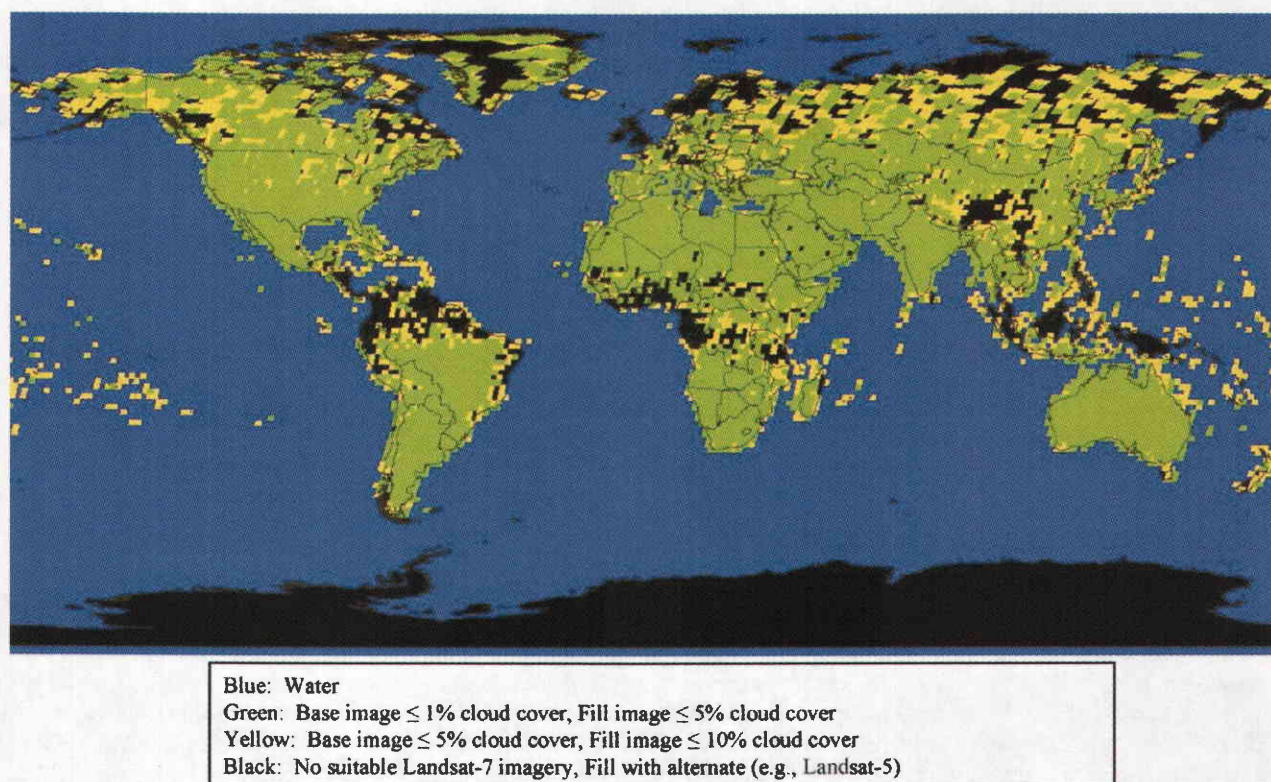


Fig. 1. Availability of Landsat-7 SLC-off pairs for production of a mid-decadal (2005) global GeoCover image data set.

is collected at least once per year. However, there are cases when such images were collected in the wrong season or where images were collected repeatedly in locations that experience little seasonal change (Arvidson et al., 2006). The nature of this problem was recently revealed when a project team, dedicated to developing a 2005 mid-decadal extension (acquisition period 2004 to 2007, with 2005 and 2006 as prime selection years) to the previous global GeoCover data sets (Tucker et al., 2004), began to examine the availability of Landsat 7 SLC-off pairs with low cloud cover (Fig. 1). In this case, a paucity of images with low cloud coverage exists for areas in Russia, Central Asia and equatorial portions of Africa and South America, indicative of possible limitations with current Landsat-7 acquisitions. To enable development of a global coverage, rules were developed to select the most appropriate base image and adjacent image(s) for filling the SLC related gaps. In Fig. 1, green indicates path/row locations where EROS has two SLC-off images, acquired within ± 32 days of each other that are suitable for gap-filling. The primary (base) scene must be $<1\%$ cloud cover and the “fill” scene must be $<5\%$ cloud cover. The yellow path/row locations are indicative of a more relaxed criterion and are flagged for possible inclusion in the global dataset. As indicated in Fig. 1, suitable SLC-off pairs are available for about 63% of the global land area (based upon queries of Landsat-7 cloud cover metadata), with images with a relaxed criterion available for most of the remaining land base. Over a 3-month acquisition window, approximately 95% of the global land mass is covered with base and fill imagery. As indicated in Table 2, Landsat-5 is available to provide imagery to fill remaining coverage gaps. In

the event no Landsat data (5 or 7) are available, data from other sensors could be acquired (e.g., ASTER, ALI, AWIFS or CBERS, in roughly decreasing priority); however, the availability and utility of these data is confounded by many outstanding political, scientific, and technical issues. Therefore, gaps in Landsat coverage and continuity will be inevitable upon instrument failure. Furthermore, at this time, no thermal bands are planned for the LDCM. While the focus of this communication is on LALC applications, it is acknowledged that a critical information gap is forthcoming due to the lack of thermal imagery; this information gap will severely and negatively impact focused applications, such as characterization of evapotranspiration (Allen et al., 2005), and cloud screening. For the latter, thermal imagery plays an important role in differentiating cloud from other bright targets (Irish, 2000).

It is mandated by law that Landsat data be available and widely accessible to all, having no associated restrictive copyright or licensing requirements. Under the “Land Remote Sensing Policy Act of 1992” (U.S. Code, Title 15, Chapter 82), un-enhanced Landsat data must be provided to all users at the cost of fulfilling user requests. This cost is limited to the incremental cost associated with product generation, reproduction, and distribution and does not include acquisition, amortization, or depreciation costs (Williamson & Baker, 2004). While the trend is towards low or no cost access to Landsat data, depending on the sensor, product, and level of processing requested, costs can vary from free to approximately \$800 USD (United States Geological Survey, 2005a). Data agreements for Landsat data purchased from USGS EROS, allow for the unencumbered use and redistribution

Table 3

Linking the GEO areas of societal benefits with global land cover observation user requirements

GEO area of societal benefits	Key land cover observations and desired products
Disasters: reducing loss of life and property from natural and human-induced disasters	• Fire monitoring (active+burn) • Surface cover type changes and land degradations due to disasters • Location of population and infrastructure
Health: understanding environmental factors affecting human health and well-being	• Land characteristics/change for disease vectors • Land cover/change affecting environmental boundary conditions • Demographic/socio-economic conditions and location and extent of settlement patterns
Energy: improving management of energy resources.	• Bio-fuel production sustainability • Biomass yield estimates (forestry and agriculture) • Assessments for wind and hydro power generation and explorations
Climate: understanding, assessing, predicting, mitigating, and adapting to climate variability and change.	• Greenhouse gas emissions caused by land cover change • Land cover dynamics forcing water and energy exchanges • Location and extent of energy consumption
Water: improving water resource management through better understanding of the water cycle.	• Land cover change affecting dynamics the hydrological system • Available water resources and quality Distribution of water bodies and wetlands • Water use pattern (<i>i.e.</i> irrigation, vegetation stress) and infrastructure
Weather: improving weather information, forecasting, and warning	• Land cover/change affecting radiation balance and sensible heat exchange • Land surface roughness • Biophysical vegetation characteristics and phenology
Ecosystems: improving the management and protection of terrestrial, coastal, and marine ecosystems.	• Changes in environmental conditions, conservation and provision of ecosystem services • Land cover and vegetation characteristics and changes • Land use dynamics and driving processes
Agriculture: supporting sustainable agriculture and combating desertification.	• Distribution and monitoring of cultivation practices and crop production (type, rotations, conditions) • Forest types and changes (<i>i.e.</i> logging) • Land degradations and threats terrestrial resources and productivity
Biodiversity: understanding, monitoring, and conserving biodiversity.	• Ecosystem characterization and vegetation monitoring (types, species) • Habitat characteristics and fragmentation of invasive and protected species • Changes in land cover and use effecting biodiversity

of the data, provided the data are properly acknowledged (United States Geological Survey, 2005a,b).

The Landsat program has shown that there are many facets to the provision of information that is useful for long-term, large area terrestrial mapping and monitoring (Goward and Masek, 2001). Many of the considerations that have made Landsat a success are not sensor related, but are elements of data downlink, storage, archiving, access, and cost. These non-sensor elements are known and should be addressed in any EO system to ensure the utility of future satellite programs. Further, the Landsat program has also highlighted the utility of sensor redundancy, and given the importance of these data to monitoring programs, cross-system capability is a feature that should be an option for a long-term large area monitoring program. Among the positives identified for the Landsat program, a systematic weakness has been identified related to governance (Mack, 1990), as Landsat has experienced “precarious institutional support” (Goward et al., 2006b). To aid in addressing this systematic shortcoming, the Future of Land Imaging Interagency Working Group (FLI-IWG) has been

formed by the White House Office of Science Technology and Policy. The mandate of the FLI-IWG is to “develop a long-term plan to achieve technical, financial, and managerial stability for operational land imaging” (Marburger, 2005). The plan needs to ensure due consideration of data continuity, redundant systems, rigorous calibration, global data acquisition strategy, open data policy, and long-term data archiving.

3. Data needs for large area land cover monitoring

The need for operational and global land cover observations has recently been emphasized by the Group on Earth Observation (GEO) and the related activities to build a Global Earth Observation System of Systems (GEOSS). GEO, as a high-level political process (66 member states and 46 participating organizations), has defined nine areas where society directly benefits from earth observations; land cover observations are important for all of these areas (GEO, 2005). In Table 3 the societal benefits are related to the key land cover

observation requirements. Although being global in scope, GEO seeks to stimulate national and regional implementation activities.

A new theme of the Integrated Global Observations Strategy (IGOS) on “Integrated Global Observations on Land” (IGOL) is currently under development. Following the requirements laid out by GEO, IGOL defines detailed observation requirements for different areas such as agriculture, forestry, land degradation, ecosystem goods and services, biodiversity and conservation, human health, water resource management, disasters, energy, urbanization, and climate change. One of the principle IGOL recommendations is Landsat-type data continuity.

There are a number of ongoing large area land cover monitoring programs. Table 4 summarizes a selection of programs, largely aimed to meet national reporting and planning needs, to satisfy the reporting requirements of international treaties, or in support of scientific research. Many of the programs rely on historical Landsat data. Other programs, such as the Monitoring and Assessment of Resources in Europe-Forest (MARIE-F) (Environmental Analysis & Remote Sensing (EARS), 2000) and the Satellite Based Environmental Monitor-

ing of European Forests (SEMEFOR) (IVL Swedish Environmental Research Institute, 2000) are less dependent on Landsat data and employ a variety of remotely sensed data in addition to Landsat, including SPOT and Indian Remote Sensing (IRS) data. Other LALC monitoring programs have been designed to be data self-sufficient. For a further summary of large area land cover mapping programs see Franklin and Wulder (2002). However, the national and regional experiences have stimulated the development of further and politically mandated global and operational regional implementation activities. One particular driver is the needs advocated in the context of implementing the United Nations Framework Convention on Climate Change. Global land cover data are essential to provide consistent observations of the climate system (GCOS, 2004), and for policy options to reduce emissions from deforestation in developing countries (DeFries et al., 2006). Recognizing such importance, the Global Monitoring for Environment and Security (GMES) program is an initiative of the European Commission to provide data for a number of broad application areas and services, including LALC through a so-called fast track service for land monitoring. Thus, land monitoring is a priority of GMES and will be enabled by the

Table 4

Examples of national and regional land cover/use mapping and monitoring programs building upon Landsat and Landsat-type observations

Region covered	Mapping/monitoring program	Objective	Data products
Australia	National Carbon Accounting System — Land Cover Change Project (LCCP, Furby, 2002; Waterworth et al., 2007)	Monitoring land cover change for the past 30 years for an integrated and comprehensive greenhouse gas emissions reporting for land based emissions and to underpin policies for greenhouse and natural resource management	Land cover change 1972–2000 based on Landsat: maps of forest cover at each time slice; maps of land cover change between each pair of consecutive time slices.
Canada	Earth Observation for Sustainable Development of Forests (EOSD, Wulder et al., 2003)	To produce a land cover map of the forested area of Canada for monitoring of Canada’s forests (internal monitoring and reporting, participation in international programs)	Land cover map of forested areas from Landsat data for 2000.
Different countries worldwide	United Nations Global Land Cover Network (GLCN)	Improve the availability of reliable and standardized information on land cover and its changes at the global level and for a large user community.	More than 15 countries fully mapped using Landsat data (<i>i.e.</i> Africover, Asiaver). Translation and harmonization of existing databases. Continuing effort.
European Union	Coordination of Information on the Environment (CORINE, Bossard et al., 2000)	To provide an inventory of the Earth surface features for managing the environment; to compile consistent data of the land cover for Europe in order to determine EU’s environment policy, assess the effects of this policy and incorporate the environment dimension into other policies	Land cover/use dataset and land change based on 1990 and 2000 Landsat data. Continuation planned for 2006 and beyond under Global Environment and Security (GMES).
Great Britain	Land Cover Map of Great Britain (LCMGB, Fuller et al., 2002)	To provide a census of the countryside of the UK, in the form of digital maps and databases, plus a range of derived products, for use in a geographical information system (GIS) and statistical packages.	Land cover and land use and change for 1990 and 2000 using Landsat data.
New Zealand	New Zealand Land Cover Database (LCDB, 2000)	To investigate the feasibility of using satellite imagery for forest resource mapping and monitoring within New Zealand	Land cover and land use and change for 1996/97 (based on SPOT) and 2001/02 (based on Landsat).
South Africa	South African National Land Cover Database (NLC, Thompson et al., 2001)	To provide strategic, national-coverage, land cover information, on an operationally achievable, repeatable basis for general modeling, natural resource assessment, statistical and data integration purposes.	Land cover database 1994/95 and 2000 based on Landsat data including change assessment.
United States	National Land Cover Dataset (NLCD, Homer et al., 2004)	To generate a consistent, seamless, and accurate land cover data set for the conterminous United States	Land cover/use maps from 1992 and 2001 Landsat data interpretations and independent per-pixel estimates of imperviousness and tree canopy. Continuation planned.

Table 5

A comparison of the number of images required for given spatial resolutions and image extents, assuming no image overlap exists

Spatial resolution (m)	Example extent (km)	Number of scenes required to cover 1,000,000 km ²
1000	2400 × 6400	0.065
250	1200 × 1200	0.69
30	185 × 185	29
20	60 × 60	278
10	30 × 30	1111
5	15 × 15	4444

construction and launch of its own series of space assets through the European Space Agency beginning with the Sentinel series (ESA, 2005). Certainly, any ongoing and new efforts for global land cover observations must consider user requirements (Table 3), and existing and evolving international standards for data product specifications to ensure consistency and continuity of observations (Herold et al., 2006; Townshend & Brady, 2006).

3.1. Spatial, spectral, and temporal resolutions

LALC monitoring programs have several common information needs. Perhaps the most significant requirement is that of spatial resolution. Initially, large area land cover monitoring programs relied on low spatial resolution data (e.g., IGBP-DISCover: Loveland et al. (2000)); however, a shift towards medium resolution sensors, in an effort to generate more detailed estimates of land cover (Cihlar, 2000), has resulted in a need for tradeoffs between spatial resolution and image footprint (Franklin & Wulder, 2002). Table 5 compares the relative number of scenes required to cover one million square kilometers, and assumes that there is no overlap between adjacent scenes. In reality, some scene overlap does exist and would increase the total number of scenes reported in Table 5. A total of 29 Landsat-like images (e.g., with a 30 m spatial resolution and 185 km wide swath), or 4444 high spatial resolution images (e.g. 5 m spatial resolution, 15 km wide swath) would be required to map this area. Although the trend in commercial satellites has been towards the development of sensors with increasingly higher spatial resolution, the small scene footprints and higher costs of the imagery from these sensors limits practicality for LALC monitoring projects. The size of the image footprint is important, since a smaller footprint results in a greater amount of image processing (e.g., increases the number of scenes requiring processing such as radiometric normalization, geometric registration, and classification) (Cihlar, 2000). In addition, conventional definitions of land cover classes pertain to scales of about one hectare. Very high resolution imagery tends to separate land cover into individual landscape elements (tree crowns, shrubs, gaps, etcetera) which must be re-aggregated to form consistent land cover types (Wulder et al., 2004). The aforementioned issues related to the footprint size are exacerbated by the use of pointable sensor heads, non-nadir view angles, and difficulty in replicating geometric and illumination conditions over time (and for adjacent images).

It is important to ensure clarity in the terminology used here regarding the distinction between low, medium, and high

resolution imagery. Here we refer to high resolution imagery as that which has a spatial resolution of less than 10 m. Conversely, low resolution would be any imagery with a spatial resolution greater than 100 m. Medium spatial resolution therefore refers to imagery with a spatial resolution between 10 and 100 m. Examples of low, medium and high spatial resolution imagery and their spectral and spatial properties are provided in Table 6. Ideally, the spatial resolution of the data will enable characterization of land cover and land cover change that is commensurate with the information requirement. A minimum suitable swath width would be 60 km; however, something closer to, or greater than, 200 km is desirable.

Monitoring of land cover requires spectral coverage and resolution that is well suited to characterizing vegetation. Broad spectral coverage in the visible and near infrared is required, along with coverage in the shortwave infrared (around 1.5 μm) with longer wavelengths also desired for geological studies and mapping of post-fire conditions (around 2.2 μm). Based on changes to the location and width of spectral bands demonstrated with the Advanced Land Imager (ALI) sensor onboard the EO-1 satellite, two improvements to Landsat's spectral bands, which will impact land cover applications, have been incorporated into the LDCM specification (Irons & Masek, 2006). These include a change to the NIR band, which will shift from 775–900 nm to 845–885 nm, thereby eliminating the water vapor absorption feature located approximately at 825 nm. Changes will also be made to the panchromatic band, resulting in increased contrast between vegetation and soil features: the proposed panchromatic band will extend over a more narrow width from 500–680 nm, compared to the current broader Landsat-7 ETM+ panchromatic band which

Table 6
Examples and attributes of low, medium, and high resolution sensors

Sensor	Footprint (km ²)	Spatial resolution (m) (^a)	Spectral resolution (nm)
<i>Low resolution sensors (>100 m)</i>			
NOAA 17 (AVHRR)	2940	1100	500–1250
SPOT 4 (VGT)	2250	1000	430–1750
Terra (MODIS)	2330	500	366–14385
<i>Medium resolution sensors (10–100 m)</i>			
Landsat-5 (TM)	185	30	450–2350
Landsat-7 (ETM+)	185	30 (MS/SWIR); 15 (pan)	450–2350
SPOT 2 (HRV)	60	20 (MS); 10 (pan)	500–890
SPOT 4 (HRVIR)	60	20	500–1750
SPOT 5 (HRG)	60	10 (MS); 20 (SWIR)	500–1730
IRS (ResourceSat-1)	141	23.5	520–1700
Terra (ASTER)	60	15	530–1165
CBERS-1 and -2	120	20	485–830
EO-1 (Hyperion)	37	30	433–2350
<i>High resolution sensors (<10 m)</i>			
Orbview-3	8	4 (MS); 1 (pan)	450–900
QuickBird-2	16.5	2.44 (MS); 0.6 (pan)	450–900
IKONOS	13.8	4 (MS); 1 (pan)	450–850

^a MS = multispectral, SWIR = shortwave infrared, pan = panchromatic.

extends from 515–896 nm. Two new bands will also be provided, centered at 443 and 1375 nm. The latter band will provide information on cirrus cloud contamination, currently a significant source of error for land cover mapping efforts. Besides monitoring vegetation cover, monitoring other land surface types such as urban areas may require different spectral information (Herold et al., 2003).

Defining an optimal temporal resolution is difficult as the requirement is often application specific (to enable acquisition of cloud free imagery or during a desired time period or interval). Based upon current experiences, a temporal resolution for LALC mapping and monitoring a repeat cycle of 14–16 days has proven useful, but could be improved upon. The definition of an optimal temporal resolution needs to be placed in the context of the desired measurement goals. For instance, what revisit rate is required to meet: 1–5 year mapping of land cover type, annual assessment of land cover conversion and major disturbance, seasonal evaluation of transient ecosystem disturbance, monitoring crop phenology, or water quality monitoring? The majority of these aforementioned measurement goals can be accommodated with a single appropriate cloud free image per year; however, some applications such as water quality monitoring, may require several cloud free images per season to satisfy their information requirements (Baban, 1999; Glasgow et al., 2004). Kloiber et al. (2002) identified the need for bi-weekly or monthly measurements for water quality monitoring; however, cloud free satellite imagery is often unavailable for these regular time intervals, resulting in the design of a monitoring system based upon annual imagery. This water quality application is indicative of the types of compromises made when considering both temporal and spatial characteristics. While current revisit rates have been largely adequate for LALC applications, shorter revisit cycles of 7–8 days may be preferred. A shorter cycle increases the opportunities to acquire cloud-free imagery, although in some areas, cloud/pressure systems are persistent and a shorter repeat time will not necessarily guarantee acquisition success. To achieve a shorter cycle, two sensors would likely be required, as a shorter cycle could be achieved by lowering the satellite's orbit, but would have an undesirable impact on the sensor's swath width. A sun synchronous polar orbit facilitates repetitive coverage of all Earth's landmass at the same local time for every acquisition (Bailey et al., 2001). It has been suggested that a constellation of satellites with both polar and equatorial orbits would ensure that sufficient data are collected in tropical areas along the equator, which have not experienced the same data collection intensity as higher latitudes (Hansen et al., 2006).

There are tradeoffs between the different types of resolution (*i.e.*, in terms of spatial, temporal, and thematic detail). An operational large area or global land cover monitoring system has to integrate different observations types of moderate-resolution, fine-scale and *in situ* data to make best use of available information. Coarse spatial resolution satellite systems provide near-daily global coverage (Table 6), with information suitable to: identify major surface types, vegetation life forms and phenological cycles; detect hot spots of change; and, assist in the defining acquisition strategies for higher spatial resolution

datasets. Thus, moderate resolution monitoring products support the production of high resolution change information required to address societal benefits important to many nations and as defined by GEO (Table 3). Very-fine scale or *in situ* observations are essential to refine mapping products and for robust thematic accuracy assessment (Strahler et al., 2006; Wulder et al., 2007b). Consistency and observation continuity on all these scales is essential for such a system to be implemented.

3.2. Geometric and radiometric properties

There are three essential geometric requirements that must be achievable within some recognized limit of error: band-to-band registration; image-to-image registration for multi-temporal studies; and registration to a user-selected cartographic projection (image-to-map registration) (Goward et al., 2001). Landsat-7 had rigorous requirements for geometric accuracy (Storey & Choate, 2000), and the requirements for LDCM specify 4.5 m or less for band-to-band registration, less than or equal to 12 m for image-to-image registration, and less than or equal to 25 m for image-to-map registration excluding terrain effects. Information on satellite ephemeris should be captured, stored, and made accessible to facilitate geometric correction or orthorectification.

The radiometric properties of the sensor should also be robust and well documented. Landsat-7 incorporated three separate devices for onboard radiometric calibration, an improvement over the single internal calibration lamp used by Landsat-4 and -5 (Goward et al., 2001). A major objective of the Landsat-7 program was to improve the radiometric quality of the images by achieving radiometric calibrations of the data to $\pm 5\%$ uncertainty over the estimated 5-year life of the mission. A similar standard has been proposed under the LDCM, along with requirements for greater signal-to-noise ratios for all bands, and an increase in quantization from 8-bit to 12-bit.

3.3. Data acquisition plan

Building on the knowledge gained from the LTAP developed for Landsat-7, an acquisition plan can significantly improve the efficiency and effectiveness with which EO data is acquired. Similar to LTAP, a broader scale tool could be used to prioritize areas based on changes in NDVI (*e.g.*, MODIS or AVHRR) or from MODIS change products — as is currently being suggested by the SDSU EROS Decadal Study (Hansen et al., 2006).

3.4. Data archive

One of the most important requirements for any land cover monitoring program is a continuous archive of imagery with associated metadata:

“Data preservation is required both for the immediate needs of the user community as a record of the Earth system, yet it also has undefined value for future generations since the applications by future generations are unknown” (Harris & Olby, 2001).

Experience has shown that after a period of time the value of the archived remotely sensed data increases, as it becomes an indelible historical record of the condition and configuration of the landscape (Holm, 1999), and the long-term archiving of EO data is essential for LALC monitoring. A continuous archive facilitates retrospective analyses, change detection, model calibration, and predictions of future states (Harris & Olby, 2001). To be effective, such archives must be enshrined in policy, and provided with adequate funding to sustain them over time. Compiling the archive is however, only part of the equation. Users must be able to access and query the archive, and obtain data in a rapid and efficient manner. As discussed in a previous section, the NSLRSDA has set the standard for data archive and management. Much can be learned from the experience and efforts of the NSLRSDA and as more and more data becomes available, the question becomes does the NSLRSDA expand to take on a larger, more globally significant role or do other entities attempt to build a similar archive system?

3.5. Data copyright and distribution

In many countries, access to remotely sensed data is restricted, despite widespread recognition that access to this data is critical for sustainable development (Harris, 2003). Harris and Krawec (1993) identified three restrictive policies commonly associated with remotely sensed data: retention of property rights by data suppliers; a requirement for a license to use the data; and pricing above marginal costs of fulfilling user requests. These policies reflect a trade-off between the need for cost-recovery and a need to accurately assess the value of the data to justify future investment in the EO program. Conversely, it has been suggested that free or low cost data can create an artificial demand for the data that is not commensurate with the benefits provided by the data (Thomas et al., 1995). The data policies of commercial data suppliers are generally very restrictive; however, the niche for commercial remote sensing satellites appears to be in high spatial resolution data and therefore, these restrictive policies do not have a significant impact on LALC monitoring programs. The United Nations Remote Sensing Principles is an international agreement that supports the idea that EO systems are public goods — both in economic and ideological terms (Harris & Browning, 2003). The notion that moderate resolution EO data should be considered as, and developed as, public utilities has as been posited (Williamson, 2001).

4. Sensor options for large area land cover and monitoring

At the beginning of 2006, there were approximately 30 optical EO sensors in orbit with a spatial resolution finer than 40 m. These systems are operated by at least 18 different countries. In addition, there are 25 new satellites proposed for launch prior to 2010 (Stoney, 2006). Unfortunately, only a fraction of these current and planned satellites have the required attributes to support an LALC monitoring program and these can be broadly grouped by satellite program: IRS, CBERS, SPOT,

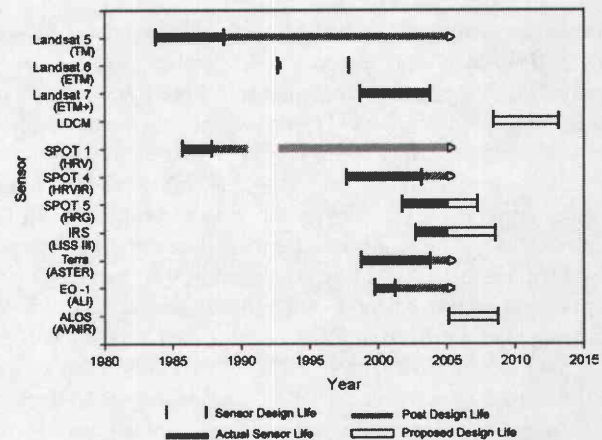


Fig. 2. Projected design life of current and proposed medium resolution sensors.

TERRA (ASTER) and EO-1 (ALI). The projected design life of these satellite systems is shown in Fig. 2.

4.1. Current sensors

The Landsat Data Gap Study Team (LDGST), formed in 2005 and jointly chaired by NASA and the USGS, was charged with identifying alternate data sources for the NSLRDA in the event of a gap in Landsat data continuity before the launch of LDCM. As part of its mandate, this team has examined a variety of EO sensors to determine data characteristics and quality, data availability and coverage, comparability to Landsat, and data processing and archiving requirements. The team also examined issues associated with data procurement, such as data policies, copyright, licensing, and funding. Of the systems considered by the LDGST, the most relevant for LALC monitoring programs are the IRS ResourceSat and the CBERS sensors, as they have the necessary spectral, spatial, and temporal attributes, and have the potential capability to acquire large-area coverage needed for land cover studies (Chander, 2007). SPOT, ASTER, and ALI are also possible data sources, although logistically, they are better suited to regional LALC characterization. One conclusion from the data gap study was that meeting data needs will require data collection from all compatible systems. The possibility that other sensors may acquire data in an emergency, should not be equated to mean that the data acquired will replicate the information that would have been possible with Landsat.

4.1.1. IRS ResourceSat

The Indian Remote Sensing (IRS) Satellite ResourceSat-1, launched in 2003, has a sun-synchronous polar orbit of 817 km and carries three sensors. The High-Resolution Linear Imaging Self-Scanner (LISS-IV) features three VIS-NIR bands and 5.8 m resolution. The Medium Resolution Linear Imaging Self-Scanner (LISS-III) features four bands in the VNIR-SWIR with a resolution of 23.5 m and swath width of 141 km. The Advanced Wide Field Sensor (AWIFS) features four VNIR-SWIR bands with a resolution of 56 m and swath width of 740 km.

From the standpoint of Landsat continuity, both the LISS-III and AWIFS sensors possess desirable qualities. Both sensors effectively duplicate the green, red, near infrared, and shortwave (1.6 μm) capabilities of ETM+, although neither sensor offers coverage in the blue or 2.2 μm region. While the resolution of LISS-III is somewhat finer than ETM+, the narrower swath width limits the return cycle to 24 days, restricting the utility of LISS-III for applications requiring intra-seasonal coverage (e.g., agriculture). Alternately, the AWIFS sensor offers 5-day repeat coverage, a significant improvement over current Landsat capabilities. Following the failure of the ETM+ Scan Line Corrector in May 2003, the Foreign Agricultural Service of the USDA adopted the AWIFS as their primary sensor for monitoring crop conditions in the United States and elsewhere. Initial investigations by the LDGST have found the radiometric and geometric quality of the AWIFS data to be sufficient for many land cover applications. However, for land change studies, the 57 m resolution of AWIFS limits the detection of fine-scale local changes.

Global data acquisition presents a significant challenge with the ResourceSat system. ResourceSat-1 lacks a comprehensive global ground station network and has only 15 GB of onboard memory, compared with nearly 50 GB for Landsat-7, limiting its ability to routinely acquire imagery over a global extent. Implementing ResourceSat as a solution for Landsat continuity would presumably require installation and coordination of international ground stations dedicated to acquiring IRS data for the US archive.

4.1.2. CBERS

The China–Brazil Earth Resources Satellite (CBERS) program currently consists of two satellites launched in 1999 (CBERS-1) and 2003 (CBERS-2) which both have a sun-synchronous orbit at an altitude of 778 km. The CBERS-2 satellite carries three sensors: a high resolution (20 m) CCD sensor (HRCCD) with a 113 km wide swath and a revisit interval of 26 days; a moderate-resolution (80/160 m) scanner (IRMSS) with 120 km wide swath and revisit time of 26 days; and a coarse-resolution (260 m) pushbroom array (WFI) with 885 km swath width and 3–5 day revisit. Of the Landsat-like sensors (HRCCD, IRMSS) the HRCCD has coverage in the visible and near infrared, while the IRMSS has coverage in the shortwave and thermal infrared.

CBERS-2B is scheduled for launch in 2007, but is not currently forecast to include a replacement for the IRMSS sensor. As a result of the success of the CBERS-1 and -2 sensors, China and Brazil signed an agreement in 2002 to ensure continuity to the program with the launch of CBERS-3 scheduled for 2008 and CBERS-4 in 2010. While the orbits of these two satellites will be the same as CBERS-1 and -2, the satellites will carry four cameras having improved radiometric and geometric properties. CBERS has a data policy aiming for no distribution fees. Any government could therefore pay the annual fee, download CBERS data, and freely distribute data products. In March of 2006, it was demonstrated that CBERS imagery could be successfully downloaded and processed at the USGS EROS.

Like ResourceSat, CBERS presents several challenges when considered as a tool for mitigating a gap in Landsat continuity.

The on-board storage capacity of the current vintage of CBERS sensors and the lack of a network of global ground stations precludes global acquisition. As noted above, the CBERS-2B system will not include the IRMSS sensor, apparently eliminating data acquisition in the vital shortwave-infrared spectral region, although CBERS-3 may carry the shortwave-infrared bands. Finally, although the radiometric qualities of CBERS-1 and -2 are not well understood, they are currently being investigated by the LDGST with communication of the initial radiometric comparisons forthcoming.

4.1.3. SPOT

Two Satellite Pour l'Observation de la Terre (SPOT) satellites acquire EO data with a 20 m spatial resolution, in a 26-day revisit cycle from 832 km above the earth's surface. The SPOT-4 and -5 satellites both carry sensors that acquire data in the visible, near infrared, and shortwave infrared. The cost of purchasing SPOT data varies depending on resolution, scene size, and whether the data are archived or collected on demand. While SPOT has the potential to image very large areas, an ongoing global acquisition and archiving strategy is not a feature of the current SPOT programs. A full SPOT-5 color or black and white scene (60 km by 60 km) can range from \$3142 to \$16,676 CAD (SPOT Image, 2004). Unlike the Landsat sensor, data are typically purchased with a standard license for one user, or a multi-license agreement for multiple users, and the data cannot be redistributed. The Land Cover Database in New Zealand used SPOT multispectral data, for an 18 class 1:50,000 digital thematic coverage circa 1996/1997 using visual delineation (Ministry for the Environment, 2005). Canada has purchased a complete national coverage of SPOT-4 data to be collected over the period 2005 to 2010.

4.1.4. ALI

The Advanced Land Imager (ALI) sensor onboard Earth Observation-1 (EO-1) was built as a prototype for the next generation Landsat satellites. The sensor maintains similar characteristics to Landsat-7 with a spatial resolution of 30 m; however, the swath width is 37 km as opposed to 185 km (National Aeronautics and Space Administration, 2002). Although the EO-1 satellite was designed with a one-year mission life, at the time of writing the sensor is still acquiring data. While the sensor has been used in scientific and research projects (National Aeronautics and Space Administration, 2004), the sensor may not be suitable for large area land cover mapping due to the narrow swath width and limited global acquisition potential (Irons & Masek, 2006). The cost of purchasing ALI data ranges from \$250–500 USD depending on desired radiometric or geometric corrections (United States Geological Survey, 2005c). The generation of ALI mosaics may provide an additional data source for large area land cover mapping.

4.1.5. ASTER

Launched in 1999, the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) sensor onboard the Terra satellite is part of NASA's Earth Observing System

and is a collaboration between NASA, Japan's Ministry of Economy, Trade and Industry, and Japan's Earth Remote Sensing Data Analysis Center. The Terra satellite has a polar, sun synchronous orbit with an altitude of approximately 704 km and a revisit cycle of 16 days (Gillespie et al., 2005). ASTER collects multispectral data with a swath width of 60 km and a spatial resolution of 15 m in the visible near infrared (VNIR) and 30 m in the short wave infrared (SWIR). The sensor also has the capacity to generate stereo imagery. Data acquisition, limited by the allocation of Terra duty cycles to higher priority instruments, and limited by onboard storage capacity, is approximately 770 scenes per day. The spectral resolution of ASTER is similar to that of Landsat TM and ETM+ data. The ASTER acquisition time is very similar to Landsat, which results in consistent illumination and spectral comparability between ASTER and Landsat. The first three spectral bands (with 15 m spatial resolution) correspond to the blue, green, red, and NIR portions of the electromagnetic spectrum. Bands 4 through 9 (with 30 m spatial resolution) correspond to different portions of the SWIR, while the remaining bands are thermal (Abrams et al., 2004).

Radiometrically, ASTER experiences crosstalk in the SWIR, particularly in association with high contrast targets (e.g., islands surrounded by water) (Hewson et al., 2005; Qiu et al., 2006). Crosstalk is a term used to describe the encroachment of unwanted signal from an optical or electrical source on an image band. Geometrically, an error in the value of the Earth's rotation rate causes geolocation errors in ASTER data, and in addition, the use of the WGS-84 ellipsoid introduces altitude errors in the data. All of these aforementioned issues have been addressed, and software and algorithms for corrections have been made widely available to end-users (National Aeronautics and Space Administration, 2007). The current data processing capacity for ASTER ground stations supports both routine and "on-demand" processing. Routine processing includes standard Level-1A (unprocessed instrument data at full resolution) and Level-1B (radiance registered at the sensor and all bands geometrically co-registered) products. On demand processing includes products such as surface reflectance and surface radiance; these products are not routinely archived. As of March 2006, over 1.1 million ASTER images had been collected over the Earth's land surface since 2000 (National Aeronautics and Space Administration, 2007). The cost of purchasing an ASTER scene is \$55 USD plus the cost of shipping (United States Geological Survey, 2005d).

ASTER is an on-demand sensor, meaning users must specify where and when data are to be collected. Acquisition is scheduled based on priority and NOAA's cloud-cover forecast. ASTER's acquisition strategy was initially to satisfy tasking requirements in three broad categories: local observations, regional monitoring data, and global map data. Regional monitoring is distinguished from local observations by spatial extent required for acquisition. Currently, the ASTER science team has identified three regional monitoring tasks: mountain glaciers, active and dormant volcanoes, and Long-Term Ecological Research (LTER) field sites. Finally, the global

data set is intended as a one-time effort, encompassing the entire Earth's land surface, including all ASTER bands and stereo capability, collected with a high sun angle, and optimal timing for local phenology. The ASTER science team has identified high priority areas for this global data acquisition. Approximately 25% of ASTER's resources are allocated to local observations, 50% to regional monitoring, and 25% to global observation product (National Aeronautics and Space Administration, 2007). Given these priorities for data acquisition, it is not surprising that geological and geomorphological applications of ASTER data dominate the literature (e.g., Hirano et al., 2003; Hubbard & Crowley, 2005; Hubbard et al., 2007; Stevens et al., 2004). The small footprint and sparse archive of ASTER imagery confound its use for vegetation applications, although these types of applications are emerging (Falkowski et al., 2005; Muukkonen & Heiskanen, 2007).

4.1.6. Operational limitations

The inability of an *ad hoc* collection of sensors to replace the measures available from Landsat is evident from this survey. A given sensor(s) may lack required spectral information (i.e. no SWIR), have unknown radiometric or geometric characteristics, have insufficient coverage (e.g., non-global collection), lack of ground receiving stations, collect narrow swaths and have related expanded revisit rates, have more coarse spatial resolution (precluding sensitivity of cover mapping and change capture), limited on-board data storage capacity, and so on. In summary, with Landsat-5 operating on a reduced duty cycle and Landsat-7 operating, although with a partially addressed technical malfunction, both beyond sensor design life, a systematic malfunction prior to fuel loss of either sensor (expected during 2010) could happen at anytime. The assemblage of sensors identified may enable data collection, but the potential of these data to actually replicate the information commonly generated from Landsat is questionable.

4.2. Future sensors

It is desirable that data continuity for large area land cover monitoring projects will be met with a combination of improvements upon existing sensor technology, the development of new generation sensors, and advancements in global acquisition strategies (e.g., multi-sensor LTAP) and capabilities.

4.2.1. Landsat Data Continuity Mission

After 35 years of continuous Landsat data acquisition, the Landsat Data Continuity Mission (LDCM) is responsible for the prolongation of this series of satellites. The Landsat-5 system carries enough fuel onboard to remain in orbit until 2009 or 2010 depending on need for fuel using orbital adjustments. Although data acquisition problems have occurred with the ETM+ sensor onboard Landsat-7, the system has sufficient fuel to possibly operate until 2011. It is anticipated that the next satellite from the Landsat series will be launched in 2011. After considerable delay, a Request for Proposal for the LDCM Operational Land Imager (OLI) instrument was issued by NASA in January 2007, with Ball

Aerospace and Technologies Corp. selected as the successful proponent in July 2007. As previously mentioned, the ALI sensor onboard the EO-1 satellite was created to examine the future directions for continuation of the Landsat series beyond Landsat-7 and some of the knowledge gained from this mission have been incorporated into the LDCM specifications (Irons & Masek, 2006).

4.2.2. AVNIR-2

The payload onboard Japan's Advanced Land Observing Satellite (ALOS), launched January 24, 2006, includes the Advanced Visible and Near Infrared Radiometer-2 (AVNIR-2). The AVNIR-2 sensor is designed to be the successor of the AVNIR sensor onboard Advanced Earth Observation Satellite (ADEOS) launched in 1996. With a design life of 3 years, AVNIR-2 will acquire data at an improved spatial resolution of 10 m, with a swath width of 70 km (Japan Aerospace Exploration Agency, 2004). One of the purposes for this sensor is to provide land cover and land-use classification maps for monitoring at regional levels. The instrument, however, does not have SWIR capabilities.

4.2.3. Sentinels

With the approval of the 7th European framework program, the European activities of GMES have evolved its operational precursor services. GMES includes a number of Earth observation satellite assets, called the Sentinels, scheduled for launch commencing in 2011. There are currently five different Sentinel satellite observation categories with Sentinels one, two, and three being of particular interest for land cover observations. Sentinel 1 is a continuation of the ERS-1/2 and ENVISAT/ASAR heritage on C-band SAR observations. Different observation modes (spatial resolution *versus* swath) will be available for a 12 day repeat cycle. Sentinel-2 expands the SPOT HRV experiences with more than 10 spectral bands in the VIS, NIR, and SWIR, 10–60 m spatial resolution, a 10 day repeat cycle and 285 km swath planned. Sentinel-3 will contain several sensors including a MERIS and AATSR type instrument for moderate resolution land imaging. Although all Sentinel configurations are still preliminary, current plans involve the launch of two parallel satellites of each type between 2011 and 2013 to increase the temporal frequency of observations.

4.3. Towards a constellation of data sources

In designing LALC monitoring programs, more effort must be invested in defining the information requirements prior to identifying a potential data source. By remaining flexible with regards to data, and by clearly defining the information requirements necessary to meet a specified mandate, the opportunity for flexibility in the selection of data sources is created. The long time span of an LALC program may necessitate the reliance on multiple data sources, which can be facilitated by a constellation of satellites, all of which are able to provide data that is in keeping with a set of standards, and more importantly, can provide the necessary information to the end user.

There are multiple reasons to have satellites working in concert, both from the operations and applications point of view. In general, the goal is to use synergy among different assets and

provide improved temporal, spatial, and spectral imaging coverage that ultimately leads to improved land characterization. One successful example is the International Charter on Space and Major Disasters,² whereby several national space agencies have committed to rapidly providing ready-to-use EO data for aiding in damage assessment and required planning activities when the terms of the Charter are triggered. The purpose of the International Charter is to have member agencies collectively provide a unified system of space data acquisition and delivery to those affected by natural or man-made disasters.

In terms of coordination, satellite data acquired following defined acquisition plans should be made more available globally allowing data users to choose from the most suitable images available for a given application. The next level of coordination could focus on joint observation targets (e.g., an annual global coverage). Different national Earth observing programmes may take responsibility to ensure sufficient regional coverage to meet the global imaging target. For instance, nations with space programs, such as Brazil, China, and India, could have a regional or continental focus, complementary to other regional efforts, toward synergistic global coverage. A more comprehensive constellation implementation involves joint or coordinated acquisition and operation plans to increase temporal, spatial and spectral coverage considering regional differences, observation gaps, and known challenges (e.g., data collection in tropical regions due to cloud cover). The Committee on Earth Observation Satellites (CEOS) advocates virtual constellations of satellites whereby disparate Earth observation data can contribute to the information requirements of specific applications (acknowledging that different applications have different information needs).

The keys to success of such an approach is in the explicit definition of information requirements from the user community (e.g., through the GEO SBA and national/international reporting commitments) and the commitment to meeting those requirements by the participating agencies. The standards, much like those presented in this paper for LALC, and a process for reviewing data products is essential for meeting those defined requirements. However, this approach also implicitly requires a research component that includes developing the ability to merge multiple sources of remotely sensed data to form consistent land cover and biophysical products. Such approaches must bridge differences including spatial resolution, spectral band locations and widths, acquisition times, and view angles.

5. Research priorities

A number of critical research priorities emerge based upon a need for continued monitoring of large areas over long time periods. As indicated above, some considerations are technological, yet many are institutional. Topic areas that may be addressed on a technical basis can be undertaken immediately through applications trials or through sensor cross-comparison (similar to the geometric and radiometric investigations reported in Chander (2007)). Issues, such as public access and sharing of data that is currently privately delivered and copyright

² <http://www.disasterscharter.org/>.

restricted, are also of a high priority, requiring government and industry engagement internationally at high levels.

In terms research priorities, the following thematic areas are suggested:

- Synthesis of information requirements for LALC monitoring. Determination and description of what data and program characteristics are needed to meet commonly held global LALC monitoring needs,
- Verification of radiometric and geometric standards required for LALC monitoring,
- Investigations to understand the applications outcomes (with regards to land cover, change) that emerge when using systems with comparable or differing specifications. For instance, what is the impact on a change monitoring program if lower spatial resolution data AWIFS is used in place of, or resampled to resemble, Landsat?
- Development of cross-sensor applications (including land cover, change detection, and mosaicking approaches) (e.g. Wulder et al., 2008),
- Further investigation of cross-sensor radiometric and geometric calibration (for compatible sensors, and for applications requiring consistent reflectance information, such as biophysical attribute estimation),
- Notions of global LALC generic acquisition planning (identification of issues, considerations, and recommendations) including a multi-sensor global LTAP,
- Consideration of appropriate data formats, archive and delivery, and metadata,
- Determination, documentation, and mitigation recommendations for institutional and policy barriers to increasingly open data access, and
- Develop appropriate validation strategies for land characteristics and dynamics.

Organizations such as Global Observation of Forest Cover/Global Observation of Land Dynamics (GOFC/GOLD) may provide an appropriate forum for international dialog that leads to the refinement of an LALC research agenda.

6. Conclusions

The Landsat example demonstrates that there is more to a successful EO system than a physical sensor. The Landsat experience has confirmed the critical importance of non-sensor specific program characteristics including a global data acquisition strategy, long-term data archiving, easy data access, low cost availability, and web based ordering and delivery. Sensor specific attributes contributing to the success of the Landsat program include rigorous geometric and radiometric standards, large on-board storage capacity, minimization of receiving stations, and the spatial, spectral, temporal, and radiometric image characteristics that are well known and established in large area land cover mapping and dynamics studies. To avoid possible information gaps, the potential of multi-sensor constellations is also illustrated with acquisition opportunities for improved spatial and temporal coverage and redundancy in data collection. The summary of

Landsat characteristics contrasted with other existing and envisioned satellite programs illustrated that there is more to being “Landsat-like” than spatial and spectral resolution. It is the intention of this communication to promote the continuity of the Landsat series of sensors and to encourage and enable the development of future non-Landsat satellite systems with characteristics that will increase the utility of the data through programmatic improvements, thereby adding more sensors to the suite of those available for the characterization of our changing planet.

Investigators in the United States should not take the Landsat program for granted; international investigators should not only support and encourage the continuation and longevity of the Landsat program, but should also work domestically towards increased global synergy and cooperation in the development of truly integrated systems, collecting not only compatible imagery but ensuring that the non-sensor elements so important to the Landsat program are also included.

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