NASA's Earth Science Use of Commercially Available Remote Sensing Datasets

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Introduction

The NASA Scientific Data Purchase (SDP) was undertaken to test the value and utility of commercial land remote sensing data in the NASA Earth science community. The SDP resulted from a 1997 Congressional mandate directing NASA to allocate $50 million for the purchase of remotely sensed data from commercial sources to meet NASA's science requirements (U.S. Senate, 1996). This mandate stated specifically that NASA should purchase commercial data "where feasible and cost-effective" if these data sources "fully satisfy the scientific requirements of NASA."

In anticipation of the Congressional mandate, NASA researched the available and planned commercial industry data products through the release of a Request for Information (RFI) in May 1996. The RFI's purpose was to determine if the commercial sector could supply Earth observation data suitable for NASA's basic and applied research in Earth system science; it also explored the willingness of industry to accept a major portion of the up-front financial responsibility.

To minimize the project's risk to the government, NASA implemented the SDP using a two-phased approach. In Phase I, NASA science assessment teams evaluated the critical characteristics and value of proposed data before actually committing to specific, longer term data purchases. In Phase II, NASA procured volumes of potentially valuable data products, generally not available to NASA Earth science researchers, from the companies selected in Phase I.

Five companies were awarded Phase II data purchase contracts; however, difficulties in the development and launch of AstroVision International, Inc.'s satellite system prevented the company's participation in the SDP. Therefore, the data procured through the SDP consisted of:

(1) the first-ever global database of orthorectified Landsat imagery from Earth Satellite Corporation (EarthSat, 2007);
(2) STAR-3*i* Interferometric Synthetic Aperture Radar high-accuracy digital elevation model and orthorectified image data provided through EarthWatch, Inc., in association with Intermap Technologies, Inc. (DigitalGlobe, 2007);
(3) very high spatial resolution airborne multispectral imagery from Positive Systems, Inc. (Bossler *et al.*, 2002); and
(4) high spatial resolution IKONOS satellite panchromatic and multispectral imagery acquired from Space Imaging, LLC (GeoEye, 2007).

Earth Satellite Corporation

The Earth Satellite Corporation (EarthSat; now MDA Federal Inc.) of Rockville, Maryland, was awarded a $16.4 million contract to deliver orthorectified Landsat imagery covering global land areas for two historical time frames. The first time frame contains Multispectral Scanner (MSS) imagery collected during the mid-1970s. The second contains Thematic Mapper (TM) imagery collected during the late 1980s and early 1990s. Both datasets were intended to serve as a baseline for studies of global change. EarthSat achieved global coverage by acquiring historical imagery from U.S. archives and foreign ground stations. The best available scenes for each Landsat path/row were selected through collaborative evaluation with scientists at NASA's Goddard Space Flight Center. The TM and MSS imagery were orthorectified to an accuracy of ±50 meters root mean square error (RMSE) and ±100 meters RMSE, respectively, using control points from government sources. The company also provided mosaic scenes of the TM coverage.

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EarthWatch, Inc.

EarthWatch, Inc. (now DigitalGlobe, Inc.) of Longmont, Colorado, in partnership with Intermap Technologies, Inc., was awarded a $6.2 million SDP Phase II contract to provide radar and elevation data from an airborne Interferometric Synthetic Aperture Radar (IFSAR) system. The STAR-3*i* X band radar imagery was collected at 2.5-meter resolution and processed into 7.5' quadrangle mosaics. Orthorectified radar image maps have a horizontal accuracy of ±2.5 meters RMSE. Digital elevation model (DEM) products have a horizontal accuracy of ±2.5 meters RMSE and a vertical accuracy ranging from ±1 meter to ±3 meters RMSE. The data is useful for a wide range of applications involving land use, land cover, and terrain modeling.

Positive Systems, Inc.

A $2.9 million contract was awarded to Positive Systems, Inc., of Whitefish, Montana, to provide 1 meter multispectral imagery, image mosaics, and collateral ground truth data. The imagery was captured with the Airborne Data Acquisition and Registration (ADAR) 5500, an 8-bit sensor with bands similar to the first four Landsat bands. The sensor is capable of producing imagery and mosaics referenced to 1:24,000-scale national map accuracy standards. In addition to providing high-resolution detail on land use and land cover, Positive Systems datasets and products are useful for ground calibration and cross-sensor comparisons.

Space Imaging, LLC

Space Imaging, LLC, of Thornton, Colorado (now GeoEye of Dulles, Virginia), provided space-based 1-meter panchromatic and 4 meter multispectral images, image mosaics, and DEMs through an $11.3 million Phase II SDP contract. The IKONOS satellite collects data in visible and near-infrared bands with an 11-bit radiometric resolution. Images can be provided at two levels of horizontal geometric accuracy. High spatial resolution, broad coverage (11 x 11 km scene), and the relative stability of a spaceborne platform provide significant potential for efficient land-use/land-cover mapping, as well as for validation of coarser resolution systems.

MANAGEMENT AND CHARACTERIZATION

The management and responsibility for implementing the SDP was assigned to NASA's former Commercial Remote Sensing Program Office at the Stennis Space Center (SSC). The SDP functioned much like a typical NASA mission with centralized tasking, verification and validation, data distribution, and data archiving components to facilitate the project's effectiveness. Consequently, the complexities of commercial Indefinite Delivery/Indefinite Quantity contracting, continual product deliveries, and vendor invoicing/payment also had to be managed.

Furthermore, as a way to monitor the vendor's compliance with contract data specifications and to ensure data quality for scientific use, samples of each of the Phase II datasets underwent an independent characterization at SSC. Characterization provided the science community with a detailed understanding of the data products' characteristics through dissemination of the following results: laboratory characterizations of system performance, in-flight measurement of geopositional accuracy and spatial response, and radiometric accuracy estimation, using independent ground-based reference data.

Hence, the centralized functions, science and industry interactions, and independent characterization efforts enabled SSC to gain significant insight, rather than oversight, into the commercial sector and then in turn to share this information with the science community. This process has increased confidence in the commercial sector's ability to meet science needs.

SCIENCE DATA USER OUTCOME

The SDP was funded under the NASA Earth Science Enterprise (ESE) (now the NASA Science Mission Directorate) to provide scientific data to the Earth science community for almost three years. The project was designed as an opportunity to advance global-systems research, to strengthen the U.S. economy through development of remote sensing technologies, and to test a new way of doing business (Davis, 1999). Based on the quality of data, lessons learned (Goward et al, 2003), and number of publications, the SDP project was very successful.

NASA Earth Science and Applications Areas Served

Commercial data acquired through the SDP benefited many NASA research and applications studies. To represent this benefit, scientists were asked to categorize their research into one of the NASA Earth science research or applications theme categories in place at that time. Science research themes included Land Cover Land Use Change, Terrestrial Ecosystems, Solid Earth, Land Surface Hydrology, and Polar Environment. Applications Research categories included Resource Management, Community Growth, Disaster Management, and Environmental Quality. The impact of commercial imagery's availability on research is represented by the number of scientific publications produced. To date, NASA-affiliated research scientists using SDP-provided commercial data have produced over 350 publications, including peer-reviewed journal articles, conference presentations, and Web articles. Although all of these studies cannot be described in detail, a subset of publications is summarized in Tables 1 and 2.

Scientific Applications and Uses of SDP Data

To exemplify the diverse range of applications, a few specific examples of noteworthy research follow.

EarthSat Orthorectified Landsat Data

In 2002, the National Academy of Sciences conducted a study titled *Down to Earth: Geographic Information for Sustainable Development in Africa* to determine the most important spatial information available for global sustainable development activities (NRC, 2002a). The report concluded that to conduct sustainable development projects in developing and developed countries, it is essential to have "framework foundation data" that can be placed into a national or global spatial data infrastructure. The framework foundation data consist of (1) geodetic control, (2) orthorectified imagery, and (3) digital elevation and bathymetry data.

The National Academy report found that the only global orthorectified dataset available for sustainable development projects is NASA's Global Orthorectified Landsat Dataset prepared by Earth

Table 1. Example publications of science use of NASA SDP commercial imagery datasets.

Citation	Data Type	Location	Topical Description
Science Use: Land Cover/Land Use			
Asner and Warner, 2003	IKONOS	Brazilian Amazon	Tropical rain forests and savannahs
Beck, 2003	Landsat	Afghanistan	Geological rock formations
Donato and Klemas, 2001	IKONOS & Landsat	Mid Atlantic coastal region	Coastal zone environment
Enclona *et al.*, 2004	IKONOS	Syria	Agricultural cropland
Garvin *et al.*, 2000	IKONOS	Iceland	Volcanic island
Hurtt *et al.*, 2003	IKONOS	Brazilian Amazon	Tropical rain forest
Morisette *et al.*, 2003	IKONOS	Africa	Land production validation, core sites (wooded grassland, savanna tropical forest)
Read, 2003	IKONOS & Landsat	Brazilian Amazon	Tropical rain forest, logging canopy disturbances and features
Small, 2003	IKONOS	14 cities around the world	Urban reflectance
Tucker *et al.*, 2004	Landsat	Earth	Global land data
Yang *et al.*, 2003	IKONOS & Landsat	United States	Urban impervious surfaces
Zhang *et al.*, 2000	Landsat	Africa	Evergreen forest, shrub land and agricultural cropland
Science Use: Terrestrial Ecosystems			
Cohen *et al.*, 2003	Landsat	North America	Agricultural cropland, prairie grassland, boreal forest and temperate forest
Turner *et al.*, 2003	Landsat	Northeastern USA & Canada	Hardwood forest (NE USA) & Boreal forest (Canada)
Science Use: Solid Earth			
Rankey, 2002	Landsat	Bahamas	Tidal flat sedimentation
Rankey and Morgan, 2002	IKONOS	Bahamas	Coastal tidal flat system
Science Use: Land Surface Hydrology			
Li and Sturm, 2001	IKONOS	Alaska, USA	Spatial distribution of snow precipitation
Nolan *et al.*, 2003b	Landsat	Siberia, Russia	Lake ice dynamics
Prokein *et al.*, 2001	STAR-3*i*	Alaska, USA	Putuligayuk (Put) River -- a small, low-relief watershed
Science Use: Polar Environments			
Hall *et al.*, 2003	IKONOS & Landsat	Austria	Glacier position
Musket *et al.*, 2003	STAR-3*i*	Alaska, USA	Glacial surface area
Rozell *et al.*, 2002	STAR-3*i*	Alaska, USA	Ice elevation data

Satellite Corporation for the NASA SDP. The orthorectified Landsat dataset includes Landsat MSS data for the mid-1970s, and Landsat TM 4 and 5 data collected circa 1990.

Orthorectified individual scenes and 5 x 6 degree mosaics are in the public domain and are accessible from the U.S. Geological Survey (USGS) Center for Earth Resources Observation and Science for a nominal fee. Large blocks of data are available free from the University of Maryland's Global Land Cover Facility (GLCF, 2007) (Figure 1).

For the first time, a geodetically accurate global dataset of orthorectified multi-epoch digital satellite data at the 30- to 80-meter spatial resolution spanning 30 years was produced (Tucker *et al.*, 2004). It represents a significant baseline dataset for assessing global and local change. The data are also useful as cartographic basemaps for registering other types of remotely sensed data and thematic map products (NRC, 2002a).

EarthWatch/Intermap STAR 3*i* Data

In the past, hydrological and permafrost research studies have been severely limited because of the low resolution of DEMs available for these study areas. Therefore, assessments of the role that terrestrial hydrologic processes play in climate change and, in particular, the processes unique to Arctic hydrology have also been lacking. However, with the availability of EarthWatch/Intermap STAR-3*i* high quality DEMs through NASA's SDP, previously impossible computer modeling is now possible. Studies that involve assessing regional impacts of climate change using a combination of image analysis and field validation within Alaska can now be conducted.

Driven by scientific interest in high-latitude climate change impact on global climate change, a series of intense hydrologic studies have been ongoing in the Kuparuk River watershed on the North Slope of Alaska. The acquisition of the STAR-3*i* DEM of this basin has facilitated the studies of many detailed hydrologic processes that previously were not achievable. Since these are relatively young surfaces underlain by permafrost and the drainage networks are poorly developed both in the foothills and in the coastal plain, a high-resolution DEM is required for even the most basic hydrologic analysis. Because of the higher resolution of the STAR-3*i* DEM data (compared to the USGS DEM data), the most

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Table 2. Example publications of practical applications of NASA SDP commercial imagery

Citation	Data Type	Location	Topical Description
Resource Management: Precision Agriculture			
Doberman and Ping, 2004	IKONOS	Nebraska, USA	Agricultural cropland
Johnson *et al.*, 2003	IKONOS	California North Coast, USA	Commercial wine grape vineyards
Johnson and Pierce, 2004	IKONOS	California North Coast, USA	Commercial wine grape vineyard
Seelan *et al.*, 2003		Upper Midwest, USA	Agricultural cropland
Resource Management: Forest Inventories			
Goetz *et al.*, 2003a	IKONOS	Maryland, USA	Tree cover and riparian buffer zones
Sader *et al.*, 2001	Landsat	Central America (Mesoamerican Biological Coridor)	Monitoring tropical forest
Resource Management: Other			
Claborn *et al.*, 2002	Landsat	Korea	Mosquito larval habitats
Masuoka *et al.*, 2003	Landsat	Korea	Mosquito larval habitats
Environmental Quality Research: Water Quality Assessment			
Bauer *et al.*, 2001	Landsat	Minnesota and Wisconsin, USA	Water clarity/quality monitoring
Sawaya *et al.*, 2003	IKONOS	Minnesota, USA	Land and water resource monitoring
Environmental Quality Research: Coral Reef Environment Studies			
Andréfouët and Guzman, 2005	Landsat	Caribbean Panama	Coral reef geomorphology
Capolsini *et al.*, 2003	Landsat & IKONOS	Tahiti & Moorea, French Polynesia Islands, South Pacific Ocean	Barrier and fringing coral reefs
Mumby and Edwards, 2002	Landsat & IKONOS	Islands of South Caicos, Turks, and Caicos (British West Indies)	Marine habitats (Coral reefs, seagrass beds, macroalgae and sand)
Palandro *et al.*, 2003	Landsat	Florida Keys, USA	Coral reef environments
Purkis and Riegl, 2005	IKONOS	Arabian Gulf	Coral reef environments
Environmental Quality Research: Community Growth			
Bauer *et al.*, 2004	Landsat	Minnesota and Wisconsin, USA	Impervious surface areas
Goetz *et al.*, 2003b	Landsat & IKONOS	Chesapeake Bay Watershed, USA	Impervious surface areas
Yuan *et al.*, 2005	Landsat	Minnesota and Wisconsin, USA	Impervious surface areas

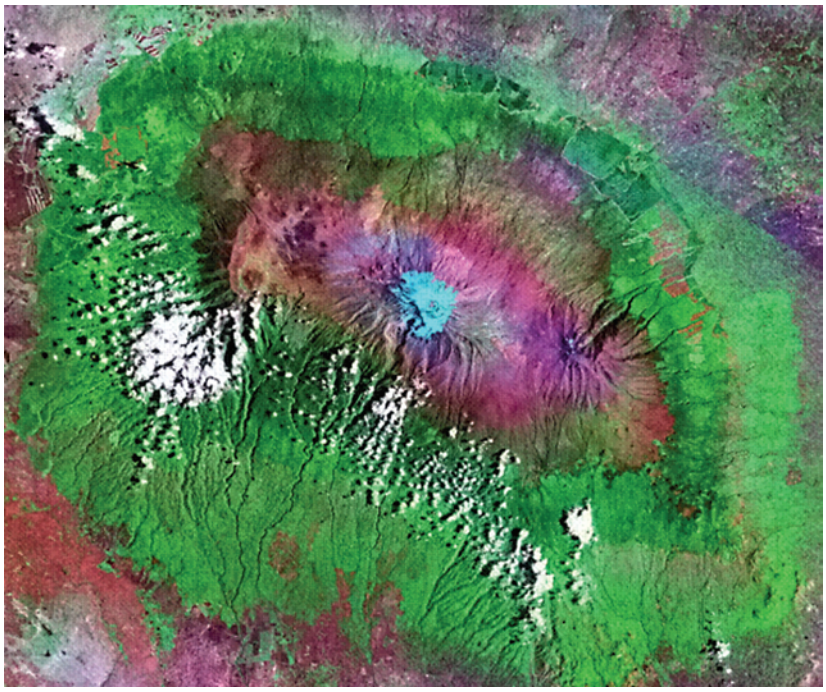

Figure 1. An orthorectified Landsat TM image of Mount Kilimanjaro in East Africa. The bottom third center of the image along Mount Kilimanjaro's lower slopes contains areas of clear cuts (in pinks) surrounded by uncut verdant forest (bright greens). The top of the mountain is snow-covered and the white areas are clouds. The width of the depicted area is 110 km (courtesy of NASA and Earth Satellite Corporation).

advanced spatially distributed hydrologic models are now able to generate both drainage networks and areas for the four catchments being studied (Imnavait Creek, Upper Kuparuk River, Kuparuk River, and Putuligayuk River; Figure 2). For example, topography is very important to many hydrologic processes, such as soil moisture distribution and snow distribution. Using accurate slopes and aspects provided by precise DEM data, soil moisture can be routed in the active layer above the permafrost and the heterogeneous snowpack can be redistributed, therefore making it possible to model the windy environment. Hence, the STAR-3*i* data enabled essential hydrologic research, analysis, and modeling at a previously impossible level of detail on a large scale Arctic watershed (Nolan, 2003a).

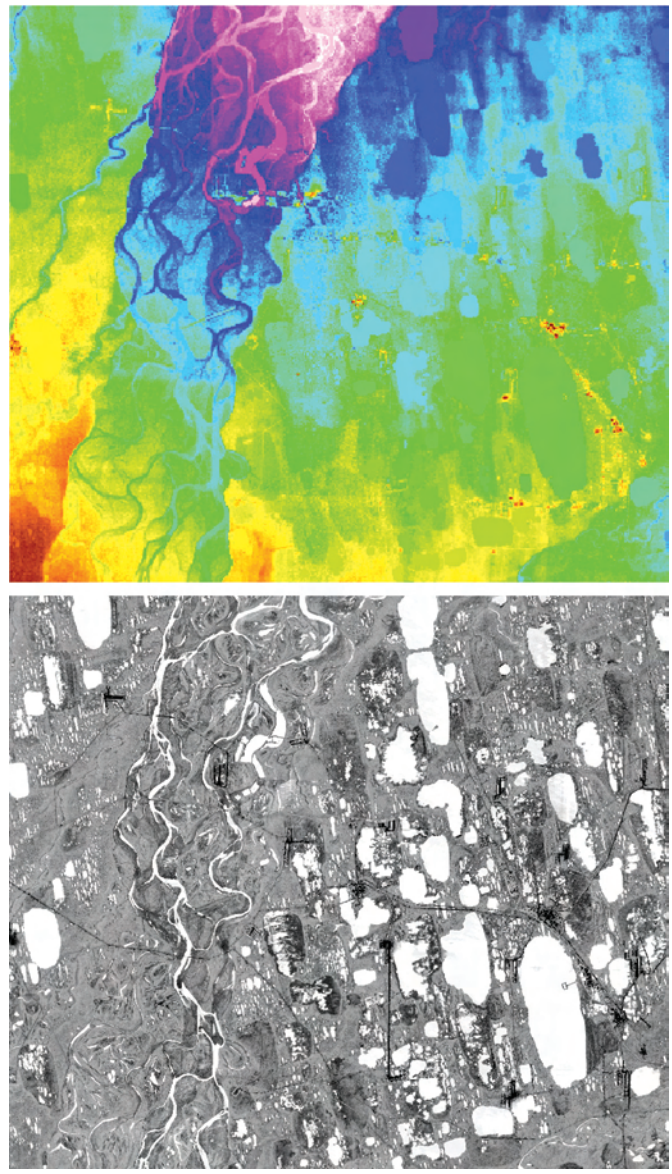

Figure 2. EarthWatch/Intermap STAR-3*i* DEM data (above) significant elevation detail is shown and with subsequent processing (below) vertical variation (gray scales) and flat areas, such as lakes (white) are also shown. Includes material © EarthWatch and/or its suppliers, Longmont, CO, USA. All rights reserved.

Positive Systems, Inc., ADAR Data

Remotely sensed data has enhanced the ability of The Montana State University TechLink Center in Bozeman, Montana, to understand long-term land changes by enabling regional-scale monitoring of ecosystem integrity. One of the most daunting challenges facing land cover/land use change research is developing scientifically valid indicators for monitoring ecosystem integrity at a regional scale. Remote sensing researchers have traditionally had limited information on streams and riparian areas because the relatively low spatial and spectral resolution systems that had been available were not conducive to successful analysis of these types of ecological areas. However, finer-scale data, such as the ADAR 5500 imagery acquired by Positive Systems, enabled a breakthrough in the utility of remote sensing technology for both scientific and commercial applications for stream and riparian study.

Through the SDP, TechLink helped the Yellowstone Ecological Research Center (YERC) to acquire ADAR 5500 datasets of the Yellowstone ecosystem. The ADAR 5500 datasets were valuable to this project (1) as a coordinate base for coregistering other remote sensing data because the data are georeferenced, have many visual tie points, and have high resolution (0.7 meter), (2) for validation of classification of Landsat data of Yellowstone Park and the surrounding region, and (3) in enabling the long-term evaluation of changes in floodplains and riparian vegetation in the Yellowstone Park region. The data allowed YERC researchers to explore a wide range of applications involving land use, land cover, and terrain modeling, and subsequently enabled improved estimates of plant biomass. It was also used to map current work and future change detection, as well as for the basis of a spatial model to predict future change (Figure 3).

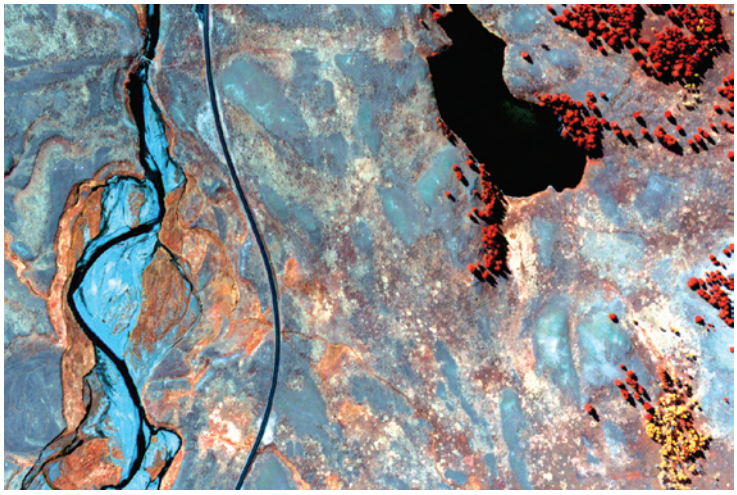

Figure 3. Positive Systems ADAR 5500 imagery used for watershed analysis in Yellowstone National Park. Includes material © Positive Systems, Inc.

Space Imaging, LLC, IKONOS Data

Space Imaging data was used at the Complex Systems Research Center at the University of New Hampshire, where investigators coordinated the acquisition and distribution of IKONOS imagery for use in the NASA-supported Large-Scale Biosphere-Atmosphere (LBA) Experiment in Amazonia. The LBA was designed to improve the understanding of the climatological, ecological, biogeochemical, and hydrological functioning of Amazonia; the impact of land use change on these functions; and the interactions between Amazonia and the Earth system. IKONOS data has been used to examine end-member selection; to validate large-scale remote sensing of land cover; to detect selective logging in forests (Figure 4); to detect secondary forests' stage, age, and pathway; to detect fine-scale land use change; to detect forest canopy gap and natural disturbance; to determine

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forest basal area and biomass; and to describe landscapes for aircraft campaign information. In this activity, many investigators from various LBA teams requested specific IKONOS imagery. A much larger set of registered users (approved using formal data sharing guidelines) requested and downloaded data using the NASA Earth Science Information Partner EOS-WEBSTER (University of New Hampshire, 2006), a completely free distribution system of Earth science remotely sensed data. In addition to the core LBA holdings, EOS-WEBSTER also distributes some non-LBA NASA IKONOS imagery using the technology developed for serving LBA. This data is a very popular featured item on the EOS-WEBSTER and is actively used by many investigators. IKONOS data shows features not visible from NASA government systems, such as Landsat (Read, 2003). Additionally, the detail provided by IKONOS data improves accuracy of carbon sequestration prediction (Hurtt *et al.*, 2003).

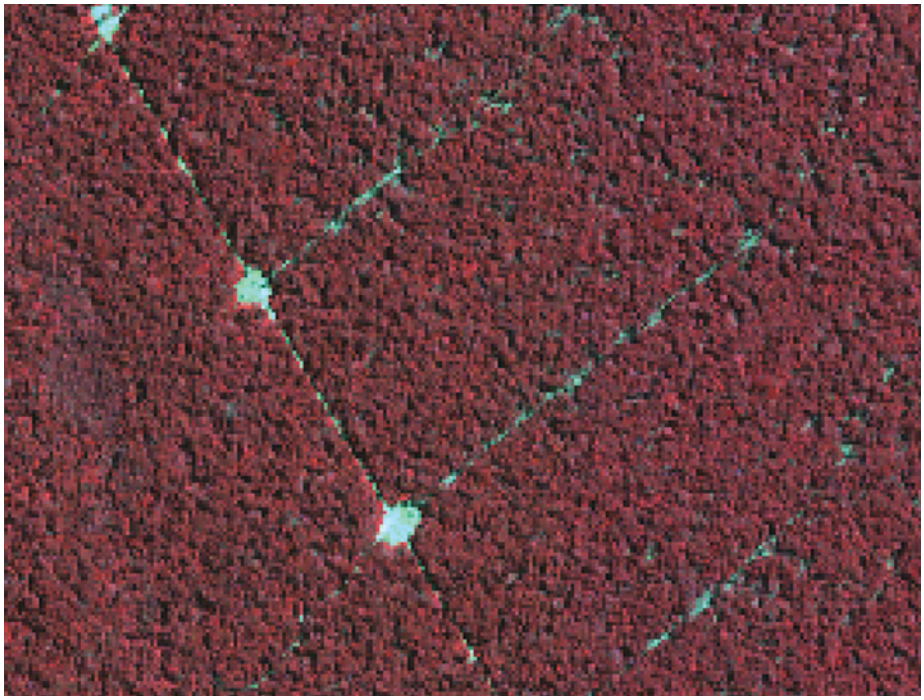

Figure 4. Space Imaging IKONOS imagery used to detect heterogeneity in the Amazonian forest (red areas) from selective logging (blue areas). Includes material © Space Imaging, LLC.

IKONOS imagery has also been effective in developing new directions in studies about the Earth and other planets. NASA's Earth systems scientists have been using IKONOS imagery to observe highly sensitive and previously inaccessible oceanic island landscapes (Figure 5, left). Unpopulated, relatively pristine islands are ideal control experiments for quantifying the sensitivity of landscape systems to differing forcings and climate change. Valuable information correlating a variety of landscape responses to change can serve as models for global/planetary observations and offers a mechanism for the development of response models. Through the SDP, over one dozen IKONOS island datasets have been acquired. The value of these images lies not only in direct scientific observations of these remote and sometimes inaccessible locations and the ability to measure changing features, but also in providing cost-effective approaches for directing field observations and for suggesting additional remote sensing-based experiments.

In this same vein, NASA's SDP IKONOS imagery has been used to study landscapes of extremely remote locations on Earth to develop prospective Mars studies. IKONOS imagery acquired over Iceland's Vatnajokull ice cap details the sub-meter scale morphology of a volcanic collapse cauldron in temperate ice. This imagery has been combined with previously acquired 3 D perspective 3-meter scale lidar topography. This combination has offered the first opportunity to reconstruct the physics of the collapse process associated with sub-glacial volcanism. This information is not only valuable for understanding how potentially explosive sub-glacial volcanism operates on Earth but is directly relevant to the physics of similar processes on Mars, where volcanoes associated with the permanent water-ice polar caps have been identified. These field analogue studies influenced NASA's selection of a sub-meter imaging system for the Mars Reconnaissance Orbiter (MRO), launched in August 2005. NASA's MRO carries an IKONOS-like imaging system to Mars to investigate whether geologically recent ice cauldrons (and many other features) exist there today. The NASA SDP IKONOS image of the Vatnajokull ice cap (Figure 5, right) is an excellent example of how sub-meter imaging of a potentially unobservable Earth phenomena was enabled and investigated from a spaceborne perspective. Because IKONOS offers global targeting access with relatively rapid turnaround time, NASA investigators were able to request imaging of the potential sub-glacial activity in Iceland and to capture unique images of the consequences.

CONCLUDING REMARKS

The SDP represented an unprecedented partnership between NASA and commercial data providers. Many of the processes were developed as the SDP grew and evolved, resulting in lessons learned both by NASA and by the commercial data providers regarding government/vendor/researcher communication and expectations (Goward *et al.*, 2003).

The SDP successfully demonstrated that Government agencies can obtain high-quality remote sensing Earth science data from the private sector to enhance and advance Government Earth science studies, and that industry is willing to accept the majority of up-front financial responsibility when providing data to the Government. The data was valuable to many of the recipients and has had significant impact on many projects as evidenced through numerous publications produced (Tables 1 and 2).

Noteworthy, however, and as is pointed out in the National Research Council's report (2002b), data purchase programs are still maturing. By evaluating this program, assessing the strengths and weaknesses, applying the lessons learned, and addressing remaining challenges, NASA and its commercial partners can expand the resources available to the Earth science community in its quest for knowledge about the Earth and its changing environment (NRC, 2007).

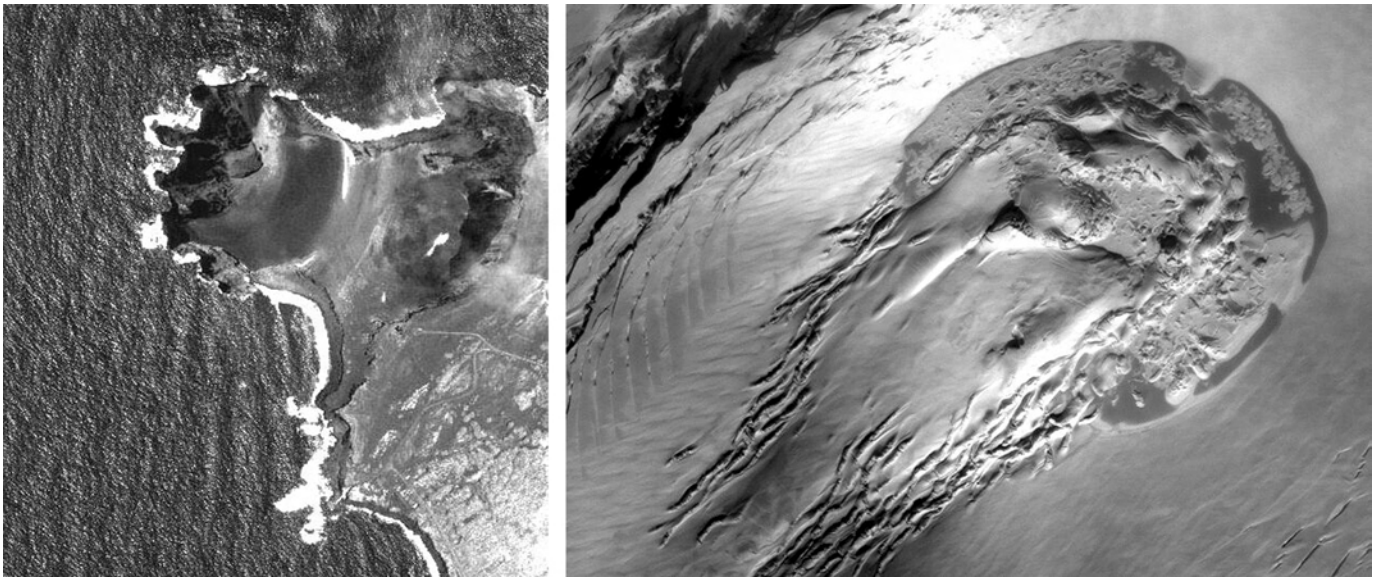

Figure 5. Space Imaging IKONOS imagery of (left) Faial Island, monitoring coastal erosion, and (right) a "ketil" (ice cauldron) atop Iceland's Vatnajokull icecap in the aftermath of what is presumed to have been subglacial volcanism. Includes material © Space Imaging, LLC.

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