# The Earth Observing One (EO-1) Satellite Mission: Over a Decade in Space

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***Abstract*—The Earth Observing One (EO-1) satellite was launched in November 2000 as a technology demonstration mission with an estimated 1-year lifespan. It has now successfully completed 12 years of high spatial resolution imaging operations from low Earth orbit. EO-1's two main instruments, Hyperion and the Advanced Land Imager (ALI), have both served as prototypes for new generation satellite missions. ALI, an innovative multispectral instrument, is the forerunner of the Operational Land Imager (OLI) onboard the Landsat Data Continuity Mission's (LDCM) Landsat-8 satellite, recently launched in Feb. 2013. Hyperion, a hyperspectral instrument, serves as the heritage orbital spectrometer for future global platforms, including the proposed NASA Hyperspectral Infrared Imager (HyspIRI) and the forthcoming (in 2017) German satellite, EnMAP.**

**This JSTARS Special Issue is dedicated to EO-1. This paper serves as an introduction to the Hyperion and ALI instruments, their capabilities, and the important contributions this mission has made to the science and technology communities. This paper also provides an overview of the EO-1 mission, including the several operational phases which have characterized its lifetime. It also briefly describes calibration and validation activities, and gives an overview of the spin-off technologies, including disaster monitoring and new Web-based tools which can be adapted for use in future missions.**

***Index Terms*—Advanced Land Imager, ALI, Earth, EO-1, Hyperion, imaging spectrometer, remote sensing.**

## I. Introduction

THE Earth Observing One (EO-1) program is a one-of-a kind high-resolution sampling mission that has now completed its twelfth year in orbit at the end of 2012. EO-1 [Fig. 1] was launched in late 2000 as the first Earth observing platform in NASA's New Millennium Program (NMP). It was launched into the first ever formation flying configuration with Landsat-7, another well-calibrated and respected Earth observing satellite, following one minute behind and observing the same suborbital track, with equatorial local overpass times for both satellites at $\sim$10:00 am [Fig. 2] [1]. From its humble beginnings, this mission has developed into a mature global sampling project within the NASA Earth Science Program. It provides advanced technology capabilities that include extraordinary spacecraft agility, onboard intelligent data processing, a variety of specially developed and highly reliable space technologies, and innovative spectral imagery.

EO-1 simultaneously acquires high spatial resolution (30 m) data for terrestrial monitoring with both of its unique passive optical instruments, the Advanced Land Imager (ALI) and the Hyperion imaging spectrometer [Fig. 1]. The Hyperion and ALI spectral bands, which cover the visible (VIS), near-infrared (NIR), and shortwave infrared (SWIR) regions, are given in Table I. EO-1 is a sampling mission, which means that continuous global imagery is not collected. Instead, ground targets are individually selected by the science team and public users and scheduled in advance for image collections. During more than a decade in orbit, each instrument has collected over 66,000 scenes (as of January 2013), providing globally distributed spectral data over sites on all continents [Fig. 3].

Numerous scientific and technical papers about EO-1 have appeared in peer-reviewed journals and proceedings. The first collection was in a 2003 Special Issue on EO-1 published by IEEE *Transactions in Geoscience and Remote Sensing (TGARS)* [3] and additional papers appeared in a 2008 Special Issue of the *Canadian Journal of Remote Sensing* on "Hyperspectral Remote Sensing" [65]. These and subsequent journal publications have covered many science and application mapping topics, including forests [4]–[17], land cover and agriculture [18]–[26], invasive species [27], [28], canopy chemistry [29], [30], general vegetation [31]–[35], disturbances [36]–[38], volcanoes and geology [39]–[42], water resources [43]–[48], satellite sensor comparisons [49]–[53], and algorithm evaluations [54]–[61]. Over half of these papers have been published in the past 3 to 5 years, after EO-1 data became available at no cost, and they represent investigations conducted by researchers all around the world. A complete list of EO-1 publications can be viewed at the EO-1 Web site (http://eo1.gsfc.nasa.gov/new/SeniorReviewMaterial_References.doc).

## II. The Satellite Platform

Originally, the footprints of both ALI and Hyperion were located on the eastern edge of the Landsat-7 ground track, as shown in Fig. 2. Hyperion's 7.7 km swath falls on the western edge of the 37 km wide ALI swath. The along-track length of ALI and Hyperion scenes are somewhat variable. For the first two years of the mission, scenes were generally 185 kilometers

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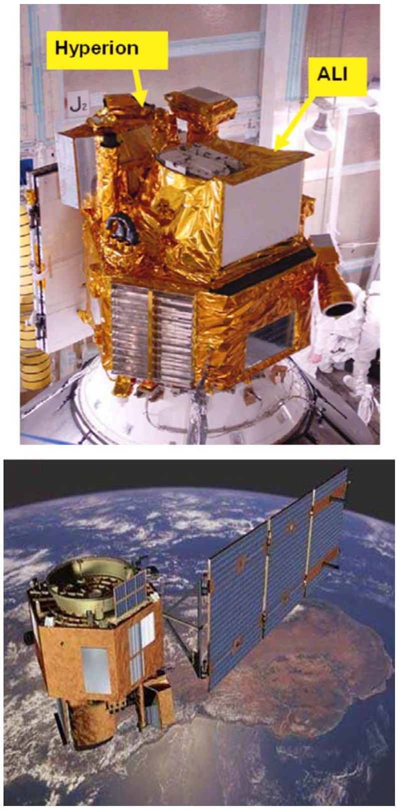



Fig. 1. The EO-1 instrument package before launch (top panel) and the satellite in orbit with solar panels extended. (Lower panel, artist's rendering.)

in length, matching the length of a standard Landsat scene. Currently, the default length of acquired scenes is 42 kilometers, but may be increased depending on the requestor's requirements.

The satellite is capable of pointing off-nadir and routinely does so to acquire special targets for science and disaster support. To image these targets, EO-1 alters its platform pointing by using internal gyroscopes to roll and yaw the spacecraft. This allows the satellite to point its nadir axis up to 23 degrees to the east or west of the satellite ground track. EO-1 can image any particular spot on the Earth up to 5 times every 16 days during daylight. Five night-time images can also be taken during a 16 day period, but this has rarely been done. Although the nominal look angle maximum for pointing scenes is $<23$ degrees, EO-1 is capable of slewing to image any object, including stars and planets. For both the ALI and Hyperion instruments, the normal rate of image acquisition is about 140 scenes per week. Before 2009, only one or two images per orbit were routinely taken, but in June of 2009 an upgrade of the autonomy software enabled acquisition of three (sometimes four) images per orbit. With 14 daily overpass orbits, many over the oceans, typically $\sim$20 scenes are taken over land each day, at locations distributed all over the globe [Fig. 3]. Of the $\sim$450 images taken every month 100–150 have relatively clear views of the Earth (cloud cover 20% or less).

Instrument out-gassings are performed every 14–15 days over a 20 hour period, using instrument heaters to purge any contaminants and to cycle Hyperion's cryo-cooler. Generally, the instruments do not continue to collect data during these out-gassings, since the SWIR focal plane detectors experience degraded performance when operating outside their designed

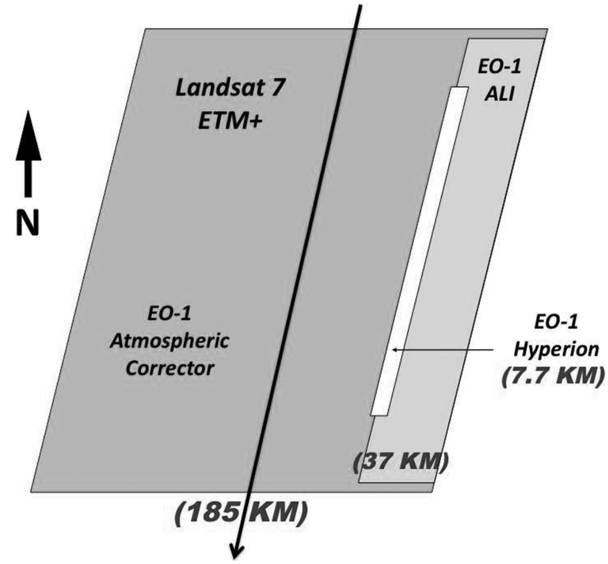



Fig. 2. A schematic is shown for the imagery collections made with three unique passive optical instruments (Landsat-7, ALI, and Hyperion), all having 30 m spatial resolution and collected within 2 minutes of each other (2001–2006) in the first low Earth orbit formation flying effort. In this original joint sampling plan, EO-1 data overlaid the east side of a standard Landsat image. The 7.7 km wide Hyperion data were originally, and are still currently, acquired on the western edge of the ALI imagery.

temperature range. Once a month, near the full moon, EO-1 flips itself over and images the moon for the ongoing lunar calibration program, during which Earth imaging is precluded for 2–3 orbits. Additional housekeeping maneuvers performed every 3 months require that no images be taken for the duration of one orbit.

At launch and for more than half of its mission life, EO-1 operated in a nominal 705 km circular orbit and flew one minute behind Landsat-7. The initial end-of-mission plan required de-orbiting maneuvers between September 2006 and October 2007, in order to arrive at the orbital debris compliant altitude (605 km perigee) specified for re-entry (originally set for 2012). These maneuvers caused EO-1 to drop out of formation flying with NASA's AM Earth Observing System (EOS) Constellation, moving it to a lower orbit at approximately 690 km. At the end of 2007, a waiver was granted that allowed EO-1 to dedicate all remaining fuel to maintaining a mean local time (MLT) equatorial crossing time of $\sim$10:00 am instead of altitude adjustments, thus extending EO-1's useful lifetime by several years. This flight mode was maintained until late 2011 when the fuel was exhausted. At that point the precessing mission stage began as the satellite started to drift lower and lower, while still collecting usable image data. EO-1 should be able to collect data into 2015, when the equatorial crossing time will drift to before 9:00 am and increased ground shadows are expected to render the images unusable. Current orbit determination models predict that the spacecraft will re-enter the atmosphere around the year 2040.

### A. The ALI Instrument

Since EO-1 was originally intended as a technology demonstration mission, the focal plane of ALI was not fully populated, providing a 37 km cross-track ground swath width that is approximately one-fifth that of a Landsat scene (185 km) [Fig. 2].

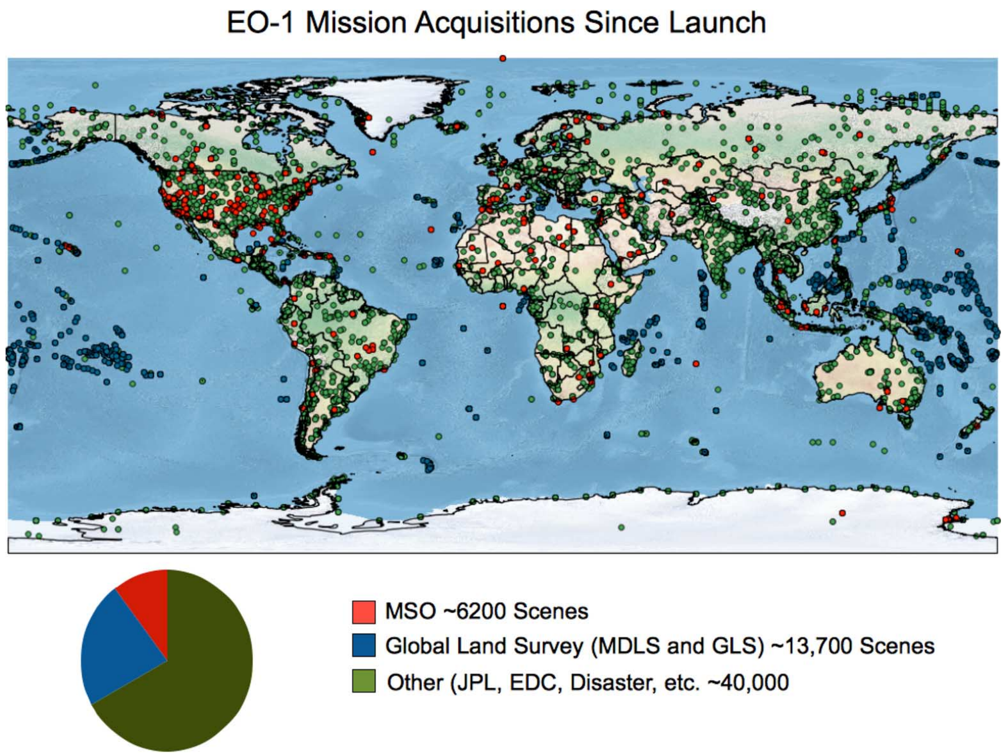



Fig. 3. Global Map showing locations of EO-1 scene collections from launch on 11/23/2000 through February 14, 2012. Acquisitions are divided into three types: those requested by the EO-1 Mission Science Office (MSO) for science activities, red circles; those acquired in support of the two Global Land Surveys, blue circles; and other scenes acquired for disaster monitoring and requests from the general public, green circles.

TABLE I
THE HYPERION (242 CONTINUOUS ~0.01 $\mu$M BANDS, 0.4–2.5 $\mu$M) AND ALI'S NINE SPECTRAL BANDS (0.433–2.35 $\mu$M) ARE DESCRIBED HERE. MS=MULTISPECTRAL BANDS FOR BOTH LANDSAT-7 AND ALI; MS-1P, 4P, 5P=ADDITIONAL MS BANDS FOR ALI

| ALI | | Hyperion |
|---|---|---|
| **Band Designations** | **Band Names (wavelength, µm)** | |
| Pan | Pan (0.480 – 0.690) | Continuous Spectra 0.4 -2.4 µm<br>242 Bands<br>Bandwidth: 10nm |
| Blue | MS-1p (0.433 – 0.453) | |
| | MS-1 (0.450 – 0.515) | |
| Green | MS-2 (0.525 – 0.605) | |
| Red | MS-3 (0.633 – 0.690) | |
| NIR | MS-4 (0.775 – 0.805) | |
| | MS-4p (0.845 – 0.890) | |
| SWIR | MS-5p (1.20 – 1.30) | |
| | MS-5 (1.55 – 1.75) | |
| | MS-7 (2.08 – 2.35) | |
| Spatial Resolution | Pan: 10m, MS: 30m | 30m |
| Swath Width | 37km | 7.7km |

The multispectral (MS) ALI imager has nine Landsat-type 30 m resolution MS bands: six VIS/NIR (0.400–1.200 $\mu$m) and three SWIR (1.200–2.500 $\mu$m) bands, and a 10 m panchromatic (Pan) VIS band [Table I]. The ALI Pan band can be used to spatially sharpen the resolution of the MS bands, allowing the creation of 3-band images at 10 meter resolution. ALI's push broom MS sensor array radiometrically out-performs Landsat-7's ETM+. Compared to ETM+, ALI is 1/7 the volume, 1/5 the mass, and uses 1/4 the power. It has a fivefold increase in SNR (signal to noise ratio) with better 12-bit radiometric sensitivity. Because of its improved design, ALI was the prototype for the Operational Land Imager (OLI), the MS instrument on the Landsat Data Continuity Mission's (LDCM) Landsat-8 satellite, launched in February 2013.

ALI's spectral bands were designed to mimic the Landsat-7 bands, but with three alterations—a shorter wavelength blue band (MS 1p), an extra SWIR band (5p), and a splitting of the ETM+ VNIR band into two VNIR bands (4, 4p). Combined with judicious selection of the bandwidths and edges, particularly the splitting of the VNIR band to exclude atmospheric features (as recommended by J. Irons, NASA's Deputy Landsat-7 Project Scientist), these augmentations have proven valuable enough to influence band selection for OLI, such that the wavelength characteristics of several ALI bands (1p, 4p, Pan) have been adopted with slight adjustments, instead of those corresponding to Landsat-7.

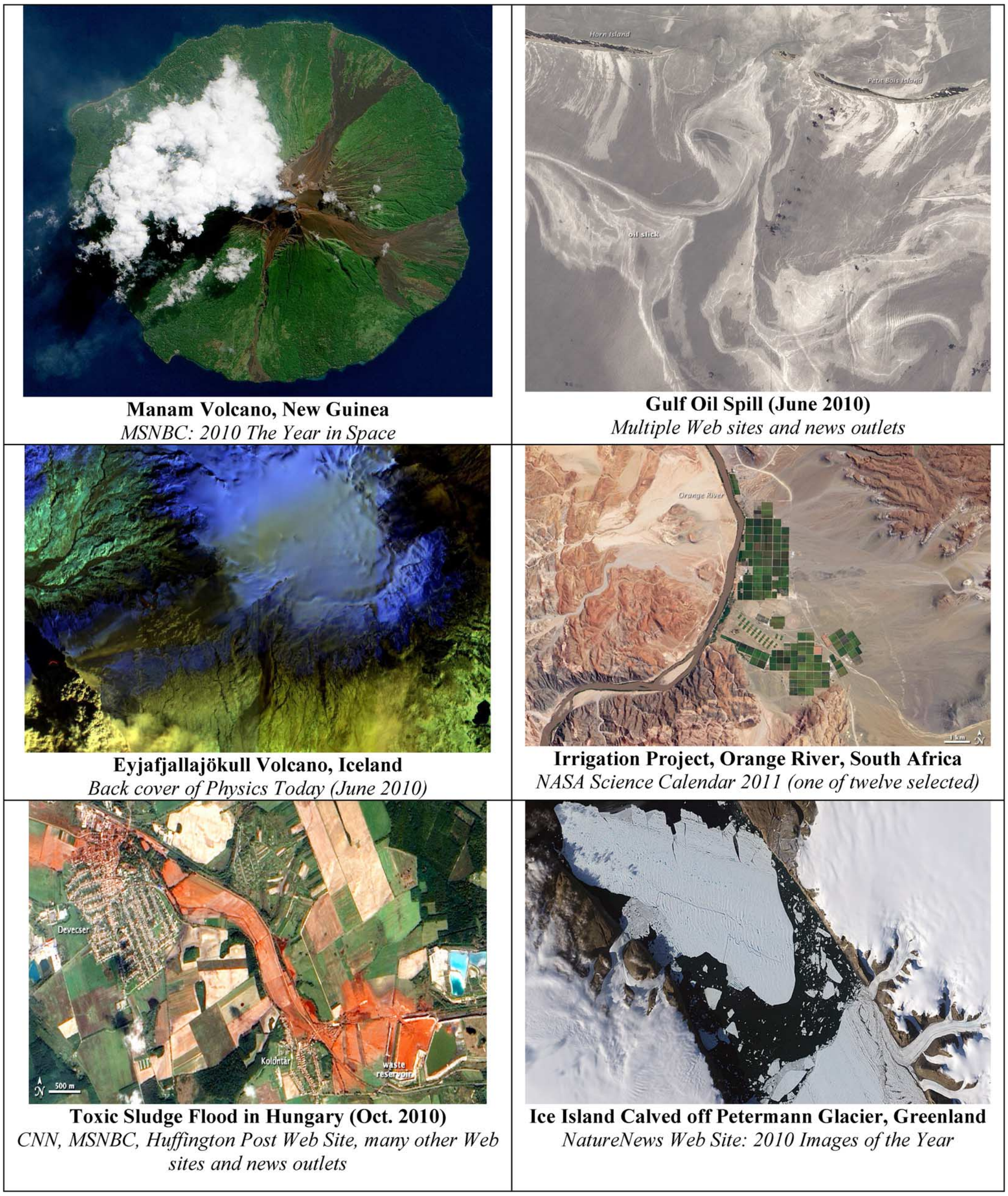
With its increased SNR and the extra SWIR channel (5p), ALI produces data that are highly useful for remote sensing

TABLE II
TECHNOLOGIES INNOVATIONS ON EO-1

| Technology Innovations for EO-1 | Type | Description | Time Frame | Company or Agency | Success/ Spinoffs |
|---|---|---|---|---|---|
| **X-band Phase Array Antenna (XPAA)** | hardware | No moving parts satellite antenna which is Avoids lightweight, compact, supports high downlink (100's Mbps) rates. Allows simultaneous instrument collection and data downlink. | 2000 - present | Boeing | Used operationally on EO-1 for over 11 years |
| **Enhanced Formation Flying (EFF)** | software | Flight software that is capable of autonomously planning, executing, and calibrating routine spacecraft maneuvers to maintain satellites in their respective constellations and formations | 2000 | JPL, GSFC, Hammers | Validated during first year of EO-1 operations |
| **Light Weight Solar Array (LFSA)** | hardware | Lightweight photovoltaic(PV) solar array which uses thin film CuInSe2 solar cells and shaped memory hinges for deployment. Chief advantages of this technology are greater than 100Watt/kg specific energies compared to conventional Si/GaAs array which average 20-40 Watts/kg. Simple shockless deployment mechanism eliminates the need for more complex mechanical solar array deployment systems. Avoids harsh shock to delicate instruments. | 2000 | Phillips Lab, Lockheed Martin | Validated during first year of EO-1 operations |
| **Pulse Plasma Thruster (PPT)** | hardware | Small, self contained electromagnetic propulsion system which uses solid Teflon propellant to deliver high specific impulses (900-1200sec), very low impulse bits (10-1000uN-s) at low power. Advantages of this approach include that is an ideal low mass precision attitude control device, is a replacement of reaction control wheels and other momentum unloading devices. and Increases science payload mass fraction. Also avoids safety and sloshing concerns for conventional liquid propellants. | 2000 | LeRC, Primex, GSFC | Will be utilized during the decommissioning phase to show that no contamination affects Hyperion image quality. Follow-on development of micro-PPT for 3D axis control by the US Air Force, with upcoming launch of a student (Cornell Univ.) nanoSAT on Falcon 9 from Vandenberg AFB. |
| **Wideband Advanced Recorder Processor (WARP)** | hardware | High Rate (up to 840Mbps capability), high density (48Gbit storage), low weight (less than 25.0 Kg) Solid State Recorder/Processor with X-band modulation capability. Utilizes advanced integrated circuit packaging (3D stacked memory devices) and "chip on board" bonding techniques to obtain extremely high density memory storage per board (24Gbits/memory card). Includes high capacity Mongoose 5 processor which can perform on-orbit data collection, compression and processing of land image scenes. Runs ASE. | 2000 | Litton Amecon | Since 2005, has enabled autonomous control of ASE without disturbing the command and data handling by spacecraft control computer. |
| **Autonomous Sciencecraft Experiment (ASE)** | software | Autonomy flight software that allows satellite to make autonomous decisions based on data observations or other events and can schedule imaging choices base on near term criteria uploaded by users. | 2005 to present | JPL | Used operationally on EO-1 since 2006. Spinoff to other missions such as TBS |
| **SensorWeb** | software | Provides a "do-it-yourself" interface for users to task EO-1, specify the type of processing required on data, and automate delivery of data products over the Internet. NASA Software of the Year 2011 award, honorable mention. | 2008 to present | GSFC, JPL, Ames | Used since 2008 for EO-1 operations |
| **Elastic Compute Clouds for Operations** | software hardware | Multicore elastic cloud delivering Software As A Service to store and distribute satellite data products | 2010 to present | GSFC, Univ. of Chicago, Open Cloud Consortium | Operational in EO-1 since 2010 |

analysis of active fires and lava flows. Most active fires are within the expanded dynamic range of ALI's band 5 (as compared with Landsat-7) [85]. By utilizing EO-1's pointing capability, ALI data have been used in numerous real-time fire assessments to show the locations of active fires or burn scars so that ground crews can allocate resources and manpower [85]. In addition, ALI has continued its role as a technology heritage instrument for LDCM by providing critical on-orbit detector data and a means to test operational hypotheses about the new OLI instrument.

In addition to user requests, ALI images were collected to support the 2005 and 2010 NASA/HQ Global Land Surveys (GLS2005, GLS2010) with collections centered over islands, coral reefs, and atolls globally [Fig. 3], which are routinely under-imaged by other satellites. ALI is also the choice for disaster relief organizations (e.g., the International Red Cross) to acquire images over areas suffering impacts of major cataclysmic events such as the 2010 Gulf Oil Spill, earthquakes (e.g., Haiti and Chile, 2010), hurricanes (e.g., Katrina, 2005), wildfires, floods, mudslides, and volcanic eruptions. ALI images have frequently been posted as the favorite satellite "Scene of the Day" on the Earth Observatory (http://earthobservatory.nasa.gov), and a small selection are presented in Fig. 4.



**Manam Volcano, New Guinea**
*MSNBC: 2010 The Year in Space*

**Gulf Oil Spill (June 2010)**
*Multiple Web sites and news outlets*

**Eyjafjallajökull Volcano, Iceland**
*Back cover of Physics Today (June 2010)*

**Irrigation Project, Orange River, South Africa**
*NASA Science Calendar 2011 (one of twelve selected)*

**Toxic Sludge Flood in Hungary (Oct. 2010)**
*CNN, MSNBC, Huffington Post Web Site, many other Web sites and news outlets*

**Ice Island Calved off Petermann Glacier, Greenland**
*NatureNews Web Site: 2010 Images of the Year*

Fig. 4. **EO-1 in the news**. ALI images have frequently been posted by the Earth Observatory (http://earthobservatory.nasa.gov) as the favorite satellite "Scene of the Day" (e.g., 130 times in 2010). Examples include: (top row) the active Manam Volcano (2010), and the 2010 Gulf Oil Spill; (middle row) the 2010 Eyjafjallajökull volcanic activity in Iceland (*Physics Today*), and an irrigation project in South Africa (chosen for the 2011 NASA Science Calendar); (bottom row) the 2010 Toxic Sludge Flood in Hungary, and the Petermann Glacier, Greenland.

## *B. The Hyperion Instrument*

Hyperion is a visionary "full-spectral" (0.400–2.500 $\mu$m) imager that has no comparable civilian satellite sensor, being the first grating-based, Earth-looking imaging spectrometer to orbit our planet. Hyperion has the distinction of being the first high spectral *and* high spatial resolution satellite for Earth observations, and has been an essential contributor to NASA's Earth Science goals [2]. Hyperion is unique, in that it collects high spectral resolution ($\sim$ 0.010 $\mu$m $=$ 10 nm) data spanning the VIS/NIR and SWIR wavelengths, with 220 contiguous spectral bands. Of these, 196 are well calibrated, but 24 bands are considered uncalibrated because they did not meet desired performance requirements or were noisy [Table I]. This wide spectral range greatly assists in the discrimination among ecosystems and their components within the Hyperion scenes, covering land areas up to 7.7 km $\times$ 185 km. Thus, Hyperion has become the critical and primary space-based data source for numerous investigators conducting cutting edge research for ecological and geophysical studies around the world. The only serious drawback is Hyperion's narrow 7.7 km swath width, which limits its utility to relatively small local areas. Hyperion data have also proved essential for monitoring volcanoes worldwide, and these sites are routinely imaged [84].

The stability of the Hyperion measurements are within $\pm$1.5%, which is considered to be "moderate fidelity" [Fig. 5]. Hyperion data have a variable SNR ($\sim$150:1, 0.4–1.0 $\mu$m; $\sim$60:1, 1.0–2.5 $\mu$m) that is comparable to its heritage aircraft instrument, the 1995 Airborne Visible/Infrared Imaging Spectrometer (AVIRIS, http://aviris.jpl.nasa.gov/aviris/index.html)

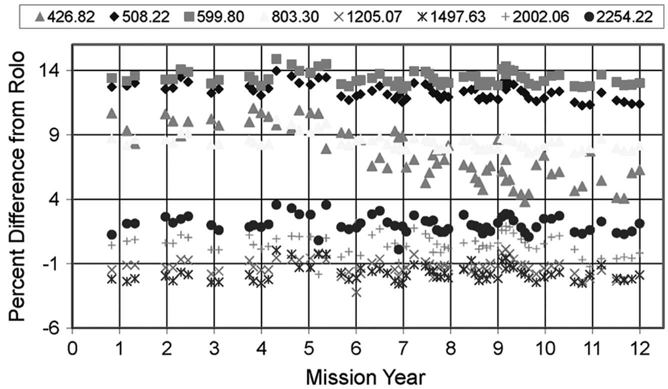



Fig. 5. Stability of Hyperion measurements is within ±1.5%, with a "moderate fidelity". This comparison of integrated radiance values of a few selected bands from the Hyperion images, along with those provided by the Robotic Lunar Observatory (ROLO) lunar model, shows that the Hyperion instrument has remained stable over twelve years.

[62]. The success of Hyperion has spawned the development of several state-of-the-art orbital imaging spectrometers now planned for launch in 2015–2017 by international partners (e.g., EnMAP by Germany; Prisma by Italy). NASA is also planning a new satellite, the Hyperspectral Infrared Imager (HyspIRI), a Tier 2 mission described by the 2007 National Research Council's first Earth Science Decadal Survey [63]. Hyperion's success has invigorated the international community, as evidenced by the IEEE sponsorship of the International Satellite Imaging Spectrometry (ISIS) Working Group, which has representatives from many nations and coalitions (Australia, Canada, Japan, India, Brazil, Israel, South Africa, European Union, NASA, etc.).

## III. Mission Overview

### A. The EO-1 Mission's Programmatic Elements

The EO-1 project is comprised of two interconnected NASA/Goddard Space Flight Center (GSFC) teams—the Mission Science Office (MSO, within the Biospheric Sciences Laboratory, Code 618) and the Missions Operations (MO, within the Engineering Directorate, Code 581). Together, these teams conduct science support activities and operations that augment, test, and improve sensor and satellite technologies. Science support activities include: i) developing new EO-1 Level 2 science demonstration products [e.g., Fig. 6], and prototype products for HyspIRI; ii) conducting lunar and terrestrial calibration studies, and participating in international calibration/validation (cal/val) activities and organizations; iii) providing a technical interface for the scientific user community, including the NASA HyspIRI mission concept team; and iv) providing support for the Landsat-7 and LDCM satellite programs. Operations support includes: i) developing enhanced software to automate scene tasking and prioritization; ii) providing an interface with national and international disaster relief organizations; iii) developing/upgrading autonomous SensorWeb technologies that link ground-based and satellite observations; and iv) developing a state-of-the-art Intelligent Payload Module (IPM) for on-board autonomous capabilities for HyspIRI and other missions.

The EO-1 project has an established partnership with the USGS Earth Resources Observation and Science (EROS) Data Center (USGS/EROS) where Level 0 data are received and processed to Level 1 (radiometrically corrected, L1R; geometrically corrected, L1G) products, stored in an on-line archive, and provided to users at no cost. Raw data are also processed at NASA/GSFC by the EO-1 MO Team. The NASA MSO maintains an internal EO-1 Level 0 data archive and advocates for science-quality products at EROS. An additional archive is maintained at NASA/Jet Propulsion Lab (JPL) for volcano and other scenes collected for disaster monitoring. The MO has also established an experimental remote "cloud computing" platform to archive and automatically process Hyperion and ALI data, starting with recently acquired data (2008–2012) and supplemented with older data as resources allow. "Cloud computing" enables a more efficient data processing chain for various data products, processing EO-1 data to L1R and L1G products, and generating higher level products for specific user community needs (e.g., flood extent maps). This system allows users to design their own products and automatically have them generated as new images of interest are acquired by EO-1.

The MSO handles numerous special requests from the science/application community, especially from scientists conducting field studies. Others can use the Web to submit image requests to EO-1's task management system (the Campaign Manager), resulting in image collects specified by the user community (e.g., U.S. Forest Service, Caribbean Institute for Meteorology and Hydrology, the Pacific Disaster Center, and collections facilitated by the NASA Earth Observatory) without relying on EO-1 or USGS personnel. This could serve as a model for future sampling missions with global acquisition programs.

SensorWebs are groups of sensors linked together with an information fabric that virtualizes access and control of the sensors, allowing the sensors to behave in a coordinated manner. EO-1 has been used as a pathfinder to develop a SensorWeb capability that enables users to discover sensors (especially space based sensors) and make them searchable on the Internet. Users may then create customized data products using sensor data from multiple sources, automate the production of those products, and request data collections (also called "tasking") from available sensors. Specifically, EO-1 was a core component in many pilot efforts to develop SensorWeb standards, leveraging the Open Geospatial Consortium (OGC) Sensor Web Enablement (SWE) suite of Web service standards.

Another concept that was prototyped on EO-1 was the GeoBliki which is a secure software environment for a SensorWeb which provides users a portal with authentication, data distribution, and tasking capability. Contained within the GeoBliki environment are the various SensorWeb services to provide a powerful data product distribution capability using georeferenced data, paired with a tasking capability called Campaign Manager or alternatively, GeoBPMS. Users can use Campaign Manager to click on a map to task EO-1 and then subscribe to areas of interest. They will be notified when the sensor data and the resultant products are available for download. This system is used by over 100 users internationally now.

The EO-1 project provides an adaptive technology platform to deliver new capabilities for the Committee on Earth Observation Satellites (CEOS) and GEO that build the Global Earth

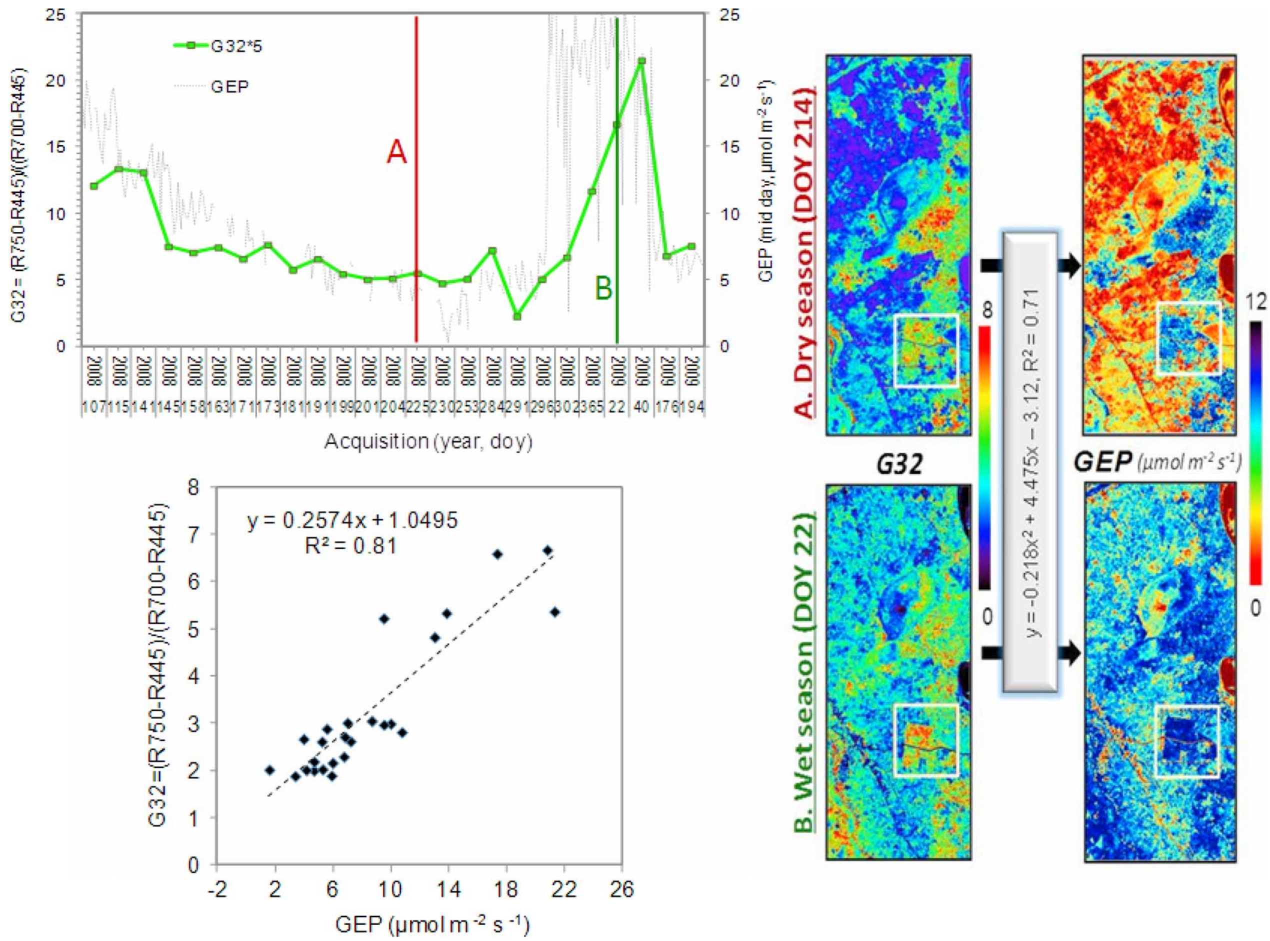



Fig. 6. An MSO study (Campbell *et al.*, in progress) is depicted here for an EO-1/Hyperion time series over a flux tower in Mongu, Zambia in Southern Africa. Top Left: The correspondence of Gross Ecosystem Production (GEP) measured at the flux tower is presented along with a spectral index obtained from Hyperion—the G32 index $(\times 5)$ developed for estimation of chlorophyll by Gitelson *et al.* (2003) using reflectances at 0.750, 0.700, and 0.445 $\mu$m [(G32=R750-R445)/(R700-R445)]. Two dates were chosen from the time series (A (red): DOY, 214 in wet season, B (green): DOY, 22, dry season) were chosen for the GEP maps (on right). G32 is strongly related $(r^2 = 0.81)$ to GEP, as shown in lower left panel. From this G32:GEP relationship, the estimation of GEP $(\mu\text{mol m}^{-2}\ \text{s}^{-1})$ per Hyperion pixel can be obtained in the vicinity of the tower. The seasonal GEP differences at $\sim$10:00 am local time are shown in the dry season (A: DOY, 214) versus wet season (B: DOY, 22).

Observation System of Systems (GEOSS). The EO-1 project provides a technical interface for NASA to CEOS (S. Frye) by leading two regional end-to-end disaster pilot activities that demonstrate SensorWeb technical capabilities to improve utilization of remote sensing data by disaster managers and emergency responders. Also, the EO-1 project leads an effort to create a disaster response architecture (D. Mandl) that would be applicable for all CEOS agencies in providing disaster-relevant data as quickly as possible. The EO-1 project provides technical leadership for GEOSS in a number of international cal/val activities which support the ability to compare and retroactively process satellite data from various instruments [64]. Project personnel chair working groups in international standard organizations, such as the Open Geospatial Consortium and the Open Cloud Computing Consortium (P. Cappelaere) which specify standards for remote sensing data interoperability. EO-1 personnel (S. Frye) are leading the GEOSS Architecture Implementation Pilot disaster working group. The EO-1 project also provides NASA leadership/partners (S. Ungar, P. Campbell) to a Group on Earth Observations (GEO) task to establish uniform guidelines and standards for inter-comparison of satellite data, so that Earth observing data from disparate sources (including EO-1) can be used in the construction of long term climate records. MSO staff members (led by EO-1 Project Scientist E. Middleton) serve on the HyspIRI mission development project.

The EO-1 project also supports several ground-based domestic and international data networks, including SERVIR for disasters such as landslides and flooding, the International Federation of the Red Cross/Red Crescent Societies (IFRCS), the International Charter on Space and Major Disasters, and the US Forest Service for forest fires. The team is involved in community capacity building by training/assisting the operational staff at regional and national level disaster management and civil protection offices, and international organizations such as USAID (U.S. Agency for International Development), the World Bank, the United Nations, the IFRCS, and other international development agencies. EO-1 contributes to the US Operational Programs, meeting societal needs at especially critical times (e.g., after hurricanes, fires, volcanoes, floods) by employing its pointing capability to acquire imagery to assist with impact evaluations for relief providers.

EO-1 Team members are dedicated to high performance at minimum cost, contributing extra hours and effort (nights and weekends) to ensure mission continuity and improvement. This large collaborative team is coordinated by the MSO through a small on-site team. While the MSO and MO are led from GSFC, personnel at NASA/JPL are also key participants for sustaining engineering for autonomous scene planning and acquisitions, as well as volcano and related science tasks and technologies. The extended EO-1 team consists of flight operations and spacecraft subsystem engineers, research and applied scientists, and advanced technologists across NASA centers at GSFC, JPL, Ames Research Center (ARC), and Marshall Space Flight Center (MSFC), as well as numerous universities and research institutes around the globe. These experts, all of whom work only part time on EO-1, are the reason EO-1 is still flying.

The EO-1 Project maintains a Website that provides mission information, a reference list, user support tools, and links to data (http://eo1.gsfc.nasa.gov/).

## B. Phases of the EO-1 Lifetime

The EO-1 mission has evolved through several stages in its more than twelve years of service (Jan. 2001 to Feb. 2013+), transitioning from a technology demonstration mission to a technology test-bed, science pathfinder, and critical link to disaster monitoring and calibration applications.

*1) The Mission's Beginning:* The EO-1 mission was originally scheduled to last one year. This initial "Operational" Phase went from launch at Vandenberg Air Force Base (USA) on Nov. 21, 2000 until Feb. 2002. This 14-month period included an instrument calibration phase and a science validation phase, which involved several intensive Southern Hemisphere field campaigns in Australia and South America to gather ground truth data. A competitively selected Science Validation Team compared the performance of EO-1 imagery with that of the simultaneously-acquired and well-characterized Landsat-7 data. This team addressed a variety of terrestrial and ecological interests, including forestry, agriculture, invasive species, desertification, land-use, vulcanization and natural disasters. Papers addressing those topics appeared in a Special Issue on EO-1 [2], published in 2003. The original objective of gathering two hundred paired Landsat/EO-1 scenes during the first year was far exceeded, and led to publication of many technical/scientific papers and a 2008 Special Issue [65].

*2) The Early "Extended Mission" Phase (2002–2005):* With its initial year-long mission completed, and the satellite still performing well, EO-1 entered a new phase. This was enabled by interagency support and subsidies, during which the usefulness of EO-1 led NASA/HQ to direct scene acquisitions for Homeland Security and natural disaster monitoring. This provided a "bulk customer" constituency in the intelligence community that contributed toward EO-1's operating expense. It also helped subsidize processing costs incurred by the USGS/EROS Data Center for functions transferred from NASA to EROS, such as science data acquisition, data processing, and ground reception. During this time, an on-board autonomous planning system was developed by the MO, greatly reducing EO-1's operational costs.

*3) The "Ad Hoc Mission" Phase (2005–2007):* During this two year period, the EO-1 mission continued to address important agency priorities, even though it had neither a NASA programmatic commitment nor an explicit budget. These priorities included the LDCM, which drew heavily on ALI to refine design and performance specifications, operating strategies, and processing algorithms for the new OLI instrument. In addition, Hyperion provided critical imagery for terrestrial ecology programs, such as the Large Scale Biosphere-Atmosphere Experiment in Amazonia (LBA) and the North American Carbon Program (NACP).

In 2006, the EO-1 mission began lowering the satellite's orbit, following a NASA dictate to perform a de-orbit maneuver, for a planned reentry in 2012. This broke the formation-flying with Landsat-7, but allowed the use of EO-1's strong calibration/characterization potential with a variety of instruments on various EOS platforms. NASA funding for EO-1 was restored after the 2007 Senior Review.

*4) The Extended Mission (2007–2010):* In 2007, the EO-1 Project received both a new Mission Scientist, Dr. Elizabeth Middleton, and increased funding from NASA. Its mission was greatly expanded, to take additional images to help "fill in gaps" in the Landsat coverage of the Earth, due to growing problems with Landsat-7, and to support additional NASA/HQ Science and Applications programs. The EO-1 staff continued to support Landsat-7 (e.g., GLS2005 and GLS2010), LDCM, and scientists' requests, while developing autonomous technologies and strategies that significantly reduced the costs for acquisition and distribution of EO-1 data. Prototype products were developed for science and technology, to better utilize EO-1 and future satellite data. The new SensorWeb concept was also tested, where ground stations, aircraft, and even other satellites could trigger the automatic scheduling of EO-1 acquisitions to capture unfolding disaster scenes, such as fires or downstream flooding based on excessive upstream rainfall.

In 2009, USGS decided to make EO-1 archive data available to all requestors at no cost. This led to a huge increase in the use of EO-1 data. In addition, USGS also decided to cease scene tasking requests, transferring that function back to NASA. To deal with this, the EO-1 project developed procedures to automate scene acquisition requests from the general public, investigators, and disaster monitors. With only four possible scenes on each orbit, a method had to be found to decide which requests had priority. The EO-1 project developed streamlined methods to predict the best candidate scenes by integrating ground truth data and satellite observations into predictive models. Disaster targets identified by these predictive models—plus target inputs provided by national partners, regional centers, and other satellite observations—are integrated into the Campaign Manager tasking queue. There they are sorted, prioritized, scored for cloudiness prediction, from the global cloud data base provided by the National Oceanic and Atmospheric Administration's (NOAA) National Center for Environmental Prediction (NCEP), and the "in-view" times are calculated for upcoming imaging opportunities. A recent improvement has allowed for targeted scenes to be replaced up to 5 hours before the target image time. This allows insertion of priority requests for disaster monitoring and science support, and for substitution of alternate scenes when the primary targets are too cloudy. These steps allow the team to automate the tasking selection process and to send autonomous requests to the CEOS satellite operators to optimize event coverage. In December 2010, NASA sponsored a 10 Year EO-1 Celebration at the Goddard Space

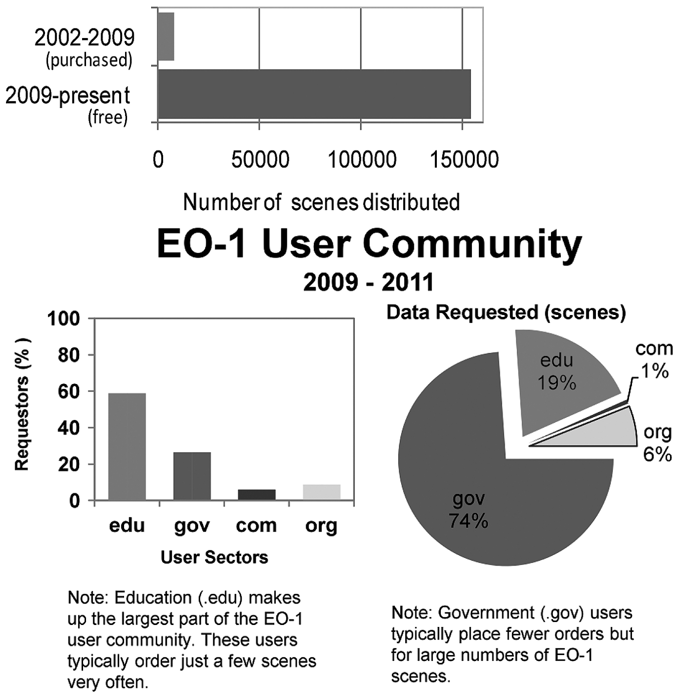



Fig. 7. Top: USGS reports that 20 times more EO-1 data have been distributed (2009–2011) since it became cost free in 2009, compared with all previous years (2000–2008). Bottom: Most of these requests have come from educational and governmental institutions. Although a larger number of requests are made for educational purposes, a greater variety of scene locations are requested for government studies.

Flight Center Visitor Center, in conjunction with a 2-day science symposium.

*5) The Ongoing Mission (2011–2013+):* EO-1 continued to receive funding support as an Extended Mission due to the successful 2011 Senior Review. Current MSO and MO activities include: i) expanding existing time series acquisitions for Hyperion, to develop a baseline for HyspIRI; ii) investigating Hyperion data products as HyspIRI prototypes; iii) quantifying the changes to SNR and data quality due to earlier local overpass time ($<$10:00 am) with precession; and iv) providing long term exo-atmospheric spectral lunar irradiance records for radiometric calibration of spaceborne imaging sensors, and continuing a baseline for lunar irradiance models (e.g., RObotic Lunar Observatory). Applied science and technology advancements addressed by the MO include: i) advancing SensorWeb developments and disaster support efforts; and ii) continuing to automate and simplify technologies for EO-1 and transfer them to other NASA missions. The EO-1 Project also plans to provide cal/val for Landsat-8 in the first year after launch (2013–2014) using ALI data to validate OLI data.

In preparation for upcoming global missions, the EO-1 program has continued to provide and test new technologies and strategies for satellite acquisitions and data handling. In this Special Issue devoted to EO-1, the mission staff has contributed several papers. These detail advancements for data volume throughput, autonomous operations, and on-board processing [66], algorithms for terrestrial environmental monitoring [67], efforts that support calibration and validation (cal/val) in international studies and collaborations [68], and development of ALI products to support quick-look disaster response [69], [70]. Through its disaster response capability, the EO-1 mission has become an international leader in SensorWeb demonstration projects and is supplying timely imagery to first responders during and after disaster events.

The USGS reports that 20 times more EO-1 data have been distributed since it became cost free (in 2009), compared with all previous years (2000–2008) [Fig. 7]. These developments have led to the EO-1 mission serving an expanded global user community and constituency, as evidenced by the papers contributed to this Special Issue (2013) from the at-large community for science and science/application studies that cover a variety of topics: land cover [71], forests [72]–[75], water resources [76], volcanoes [77], cal/val [78], automated processing [80], satellite sensor comparisons [81], [82], and unique spectral observations [83].

*6) Final Stage (2013–2016):* In 2013, EO-1 is in the final stage of its useful lifetime. The spacecraft fuel was expended in late 2011, but its instruments continue to collect quality data as the satellite precesses, crossing over the equator at earlier and earlier times with each orbit. There is a possibility that a small amount of fuel may still be available for a collision avoidance maneuver; however, there is not enough left to perform an inclination burn that could slow the drift toward earlier local overpass times, a process which is underway. It is anticipated that a 9:00 am equatorial crossing time will be attained about February 2015, and the mission will continue to track the impact on data quality during this process. The platform components have exceeded all life expectancy bench tests and are therefore now providing critical data for future missions that will be using these components. So long as the solar array charge degradation remains nominal and is sufficient to maintain attitude, EO-1 will continue to acquire images throughout 2015 and possibly longer. We anticipate that satellite de-commissioning activities will be initiated sometime during 2016. Also, during this time, the EO-1 data archive will be organized and finalized to facilitate easy access and use by the science community when financial support for the EO-1 project has finally ceased.

## IV. Summary

The EO-1 mission has far exceeded its original, primary goals to enable more effective (and less costly) hardware and data strategies for Earth science orbital missions in the 21st century. From the onset, EO-1 has provided advanced technology capabilities including extraordinary spacecraft agility, onboard intelligent processing, a variety of highly reliable support technologies, and unique passive optical imagery. Both Hyperion and ALI have paved the way for future, essential Earth observing satellite missions, including the Landsat-8/OLI, and the NASA HyspIRI mission concept under development. The EO-1 project has substantially expanded its utility for science investigators, including science-quality products, and critically augmented applications/spin-offs to the disaster monitoring community. A prominent example is the SensorWeb network initiated and championed by EO-1. The project has continued innovative technology tests and development that improved operations and reduced costs. In summary, the EO-1 mission has been a vibrant, responsive, and innovative space-based program. The lessons learned will benefit other missions for years to come.

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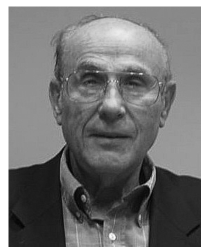

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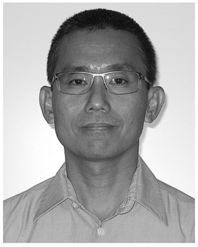

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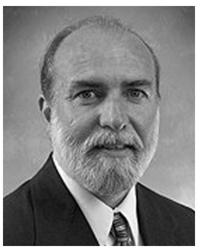

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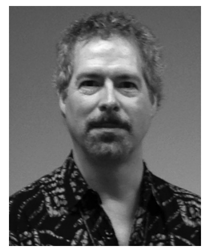
Currently she is a Research Assistant Professor at the Joint Center for Earth Systems Technology, University of Maryland Baltimore County (UMBC). She is affiliated with the Department of Geography and Environmental Systems at UMBC, where she has taught GES481/681 undergraduate/graduate classes in "Remote sensing for environmental applications." She is a research associate at the Biospheric Sciences Laboratory at NASA Goddard Space Flight Center (GSFC), Greenbelt, MD. Her research focuses on remote sensing of vegetation bio-physical parameters and function for assessing ecosystem processes and dynamics, conducting spectral reflectance and fluorescence analyses and using satellite, airborne, field and laboratory measurements. At GSFC she contributes to the research of spectral bio-indicators of vegetation function, and participates in the Mission Science team for the Earth Observing One (EO-1).

Dr. Campbell is a member of American Society for the Advancement of Science (AAAS), Geoscience and Remote Sensing Society (IEEE GRSS), International Association for Landscape Ecology (IALE), and Society of American Foresters (SAF), and has previously served as the Technical Secretariat for the WGCV/CEOS.



**David R. Landis** received the B.S. degree in Computer Programming from Elizabethtown College, Elizabethtown, PA, USA.

He is a Senior Programmer with the Biospheric Sciences Laboratory (Code 618) at NASA/GSFC, Greenbelt, MD. He is currently working on the Earth Observing One (EO-1) satellite. Mr. Landis has over 25 years of experience as a contract staff programmer-analyst at GSFC. He has experience working for MODIS, Landsat, and EO-1. His information technology experience is extensive, having worked on data systems and data publication tasks for five large climatology projects (FIFE, BOREAS, BOREAS Follow-on, SAFARI 2000, ISLSCP-2). He has considerable programming skill and Web designer experience. He also has significant science background, and has worked with scientists in many disciplines.

**Joseph P. Young** was the Earth Observing One (EO-1) Technology Transfer Manager from 2001 until his death in September 28, 2012. He was responsible for managing the documentation and assisting in the infusion process for the new technologies being tested on EO-1 during its primary mission in the first year and the extended mission which thus far has lasted 11 years. The documentation includes 11 instrument and spacecraft technologies tested during the first year of the mission and also three flight/ground software technologies over the next 11 years.

**Nathan Pollack** is a senior software developer specializing in development of tools for use in the acquisition, processing, distribution, and analysis of NASA remotely sensed satellite data. In addition, he has focused on making NASA satellite data more readily available to users of Geographic Information Systems (GIS) and on the creation of Web-based applications to interface with legacy scientific analysis software. Mr. Pollack has worked with the EO-1 project since 2008.