International Collaboration in Satellite Observations for Disaster Management

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***Abstract*— When lives are threatened or lost due to catastrophic disasters, and when massive financial impacts are experienced, international emergency response teams rapidly mobilize to provide urgently required support. Satellite observations of affected areas often provide essential insight into the magnitude and details of the impacts. The large cost and high complexity of developing and operating satellite flight and ground systems encourages international collaboration in acquiring imagery for such significant global events in order to speed delivery of critical information to help those affected, optimize spectral, spatial and temporal coverage of the areas of interest, and distribute associated expenses. The International Charter – Space and Major Disasters was established to enable such collaboration in sensor tasking during times of crisis and is often activated in response to calls for assistance from authorized users. Insight is provided from a U.S. perspective into sensor support for Charter activations and other disaster events through a description of the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER), which has been used to support emergency situations for over a decade through its expedited tasking and near real-time data delivery capabilities. Examples of successes achieved and challenges encountered in international collaboration to develop related systems and fulfill tasking requests suggest operational considerations for new missions as well as areas for future enhancements.**

***Index Terms* - International Charter, ASTER, disaster, natural hazards, emergency response, satellite remote sensing.**

I. Introduction

THIS work describes an expedited satellite data delivery mechanism for global emergency response efforts and the associated international collaboration involved to develop and use this capability. Comprehensive summaries of the availability and relevant contributions of currently orbiting and planned international spacecraft for these applications have been recently compiled by others [1]-[3].

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Disasters result in widespread human suffering, adverse infrastructure and environmental impacts, and significant financial burdens, often over extended periods of time. During 2010, nearly 300,000 people lost their lives globally as a result of disasters, while over 217 million other people were affected and economic impacts totaled $123.9 billion [4]. These events involved geophysical, climatological, hydrological, and meteorological processes. Though over half of the 120 events listed in a summary for 2010 were hydrological in nature, 74.8% of total deaths during this year were the result of an earthquake in Haiti [4]. In the year 2010, 77% of human displacement caused by sudden-onset disasters occurred in Asia, with 19% in the Americas and 4% in Africa [5]. While countries have made gains in their capacity to reduce some risks, such as weather-related mortality, there has been substantial increase in asset exposure, especially in nations undergoing strong economic growth [6].

Disaster situations involving loss of life or significant economic impact receive rapid attention from the emergency response community. These groups and senior policymakers often rely upon post-event remote sensing observations and ancillary data to characterize and map existing conditions and identify necessary supportive actions [2], [3], [7], [8]. Comparison of current imagery with historical archived data can reveal the extent of any change that has occurred. In addition to initial response activities immediately following an event, satellite data also contribute applicable information for disaster pre-event preparation and risk reduction as well as for later recovery efforts [9], [10].

Events commonly supported include storms, floods, earthquakes, wildfires, and volcanoes as well as other situations, so optimum sensor characteristics vary depending on the type and scale of the event. The International Charter - Space and Major Disasters (hereafter referred to as the Charter) provides a mechanism for international collaboration in emergency satellite imaging by utilizing the varied orbiting assets of participating members when activation occurs [11]. Such coordination enables the sharing of costly and limited resources, greatly expands the type of data available, and can reduce time lags between overpass opportunities by using multiple observation platforms with different orbits. [1], [2], [12].

In these disaster situations the delivery of data must occur rapidly to provide maximum value. To illustrate highly successful international collaboration in satellite observations covering the full range of disaster management activities, Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) systems, data characteristics, and application examples are described in the context of the supportive role for Charter activations and other emergency events. Related data production at the National Aeronautics and Space Administration's (NASA) Land Processes Distributed Active Archive Center (LP DAAC) is also discussed.

The multispectral ASTER instrument on the Terra spacecraft is often tasked in response to Charter activations and many other urgent situations. The ASTER global mapping mission provides an excellent example of close international collaboration for initial system development as well as ongoing operations. ASTER is a joint effort between NASA and Japan's Ministry of Economy, Trade and Industry (METI). The three ASTER sensor subsystems offer spectral coverage at spatial resolutions useful in a wide variety of investigations. Of particular interest, ASTER has a specially designed capability to acquire and deliver emergency, or expedited, observations. The instrument has been employed for over a decade to support global crisis situations and science ground campaigns. In addition, by employing an off-nadir pointing capability, ASTER has been used in tandem with Landsat capabilities, for example, to image when Thematic Mapper (TM) and Enhanced Thematic Mapper Plus (ETM+) nadir-only viewing sensors cannot, thus decreasing the effective multi-sensor revisit time and maximizing information available to responders.

Many aspects of the ASTER example could serve as a useful reference for planning future disaster imaging capabilities. This international collaboration to build and operate satellite systems and then to closely coordinate imaging and make data available to assist nations in times of crisis has proven highly effective as measured by the very successful global mapping initiative and strong continuing demand for these data by international investigators for science endeavors and by emergency responders for crisis applications.

II. REMOTE SENSING FOR DISASTER RESPONSE

Several U.S. organizations fulfill key responsibilities for disaster response and related satellite imaging. In addition, an international organization coordinates global satellite observations during disasters. The varied nature of such situations results in differing sensor requirements, though some commonalities in desired imaging exist for most events.

A. Key U.S. Coordinating Organizations

When a significant event occurs, the U.S. Department of Homeland Security (DHS) follows the National Response Framework [13]. The Federal Emergency Management Agency (FEMA) receives assessments from local, State, and Tribal groups following their initial responses. For a major event, after receipt of requests from the Governors of the affected States, the President of the United States declares a Major Disaster.

The DHS Interagency Remote Sensing Coordination Cell (IRSCC) assesses imaging requirements and provides recommendations to the FEMA Remote Sensing Coordinator. The USGS hosts multi-agency teleconferences with participation by NASA, remote sensing specialists, emergency response groups, and representatives from the affected areas. Target locations and specifications for imagery applicable to the situation are defined and appropriate sensors are tasked. The USGS and other groups activate the Charter to obtain imagery from a broader suite of sensors. [14].

B. International Charter – Space and Major Disasters

In order to provide emergency satellite data in response to global crisis situations, in 1999 the European Space Agency (ESA) and the Centre National d'Etudes Spatiales (CNES) initiated the International Charter – Space and Major Disasters. The Canadian Space Agency (CSA) signed the Charter in 2000. Membership in the Charter is limited to space agencies and national or international space system operators. In the United States, the USGS and NOAA participate. Over a dozen other international groups are represented as current members [11], [15], [16].

Activating the Charter to acquire satellite imagery is performed by authorized users. This was first done in 2000, and through June 2011 there have been over 300 activations, with some of these referencing multiple types of events [17]. Fig. 1 shows the annual activation trend since inception. There has been a steadily increasing trend in the number of activations per year. The 53 activations in 2010 were nearly four times the 14 occurrences in 2001. Activations occur throughout the year as the need arises, with overall peaks recorded during the months of August and September since the Charter was initiated, as shown in Fig. 2 [17]. The frequency of support during the Charter's existence for various types of events is shown in Fig. 3. Approximately half of the events during this period involved flooding, and other types of situations included storms, earthquakes, landslides, wildfires, volcanoes, oil spills, tsunami/waves, ice/snow, and accidents [17]. No funds are exchanged for delivered Charter data, but varied licensing requirements may affect access [11], [14]. Data enhancements are performed by recipients [8].

C. Sensor Considerations

The scale and nature of the event determine the optimum imaging characteristics [2], [3], [7], [8]. Repeated imaging is often required, for example, during volcanic eruptions [18]. The temporal persistence and rate of change of phenomena to be observed determine the appropriate frequency and duration of taskings. Imaging of large-scale east-west oriented areas of interest can require multiple overpasses to acquire full coverage by a single finer resolution sensor. Coarse resolution sensors with large swaths such as GOES, AVHRR, and MODIS typically offer more frequent updates and cover larger areas with a single scene but may not offer the detail needed to discern targets of interest. Some finer resolution sensors with narrower swaths such as Landsat, Système Pour l'Observation de la Terre (SPOT), and ASTER provide less frequent target overpasses but offer smaller pixel sizes.

Desired wavelength ranges vary depending on the characteristics of the targets. Multiple data sources are typically accessed, ideally with very high resolution optical data, thermal imagery, and synthetic aperture radar (SAR) data for analysis as appropriate [8]. A visible and near-infrared view is commonly used in addition to longer shortwave infrared and thermal infrared wavelengths, for example when monitoring volcanic activity. Often, a combination of sensors are used to provide a more thorough understanding of a situation, such as coarser resolution views of a large hurricane along with finer resolution images for post-event land surface change detection and damage assessment. For volcano monitoring, coarse resolution imagery is used to provide initial hot spot detection, which then initiates the tasking of a finer resolution sensor for a more detailed view [18], [19].

Optical sensors are subject to various forms of atmospheric interference. Radar data in the microwave portion of the electromagnetic spectrum can provide useful surface information in such conditions but have other limitations. Satellite observations are also often complemented by aerial reconnaissance using a variety of sensors and platforms, plus ground teams, ground sensor networks, and in-situ field instrumentation.

III. The ASTER Mission

The ASTER mission is a major component of NASA's Earth-imaging capabilities and has a long service life. The instrument characteristics have proven highly useful in responding to emergencies throughout the world during the last decade. Flexibility in tasking, coupled with effective data handling processes and procedures, enables timely information to be provided when situational uncertainty exists in the initial stage of a crisis.

A. Overview

Launched aboard the Terra spacecraft on December 18, 1999, ASTER is a part of the NASA Earth Observing System (EOS) [20]. The EOS series of satellites obtains long-term records of the Earth to develop an improved understanding of the integrated atmospheric, surface, and subsurface systems. Terra is considered the EOS "flagship" and carries five instruments used to assess key characteristics of Earth in order to identify changes in the Earth system and offer insight into the significance of any detected change (http://terra.nasa.gov/). The wide variety of challenges encountered in developing EOS required continual collaboration within the U.S. and international communities as technical requirements and funding evolved [21], [22].

ASTER is a global mapping endeavor involving NASA and METI. Close long-term international collaboration resulted in sensor development, launch, and continuing operation. The Joint U.S./Japan ASTER Science Team establishes acquisition policy and directs the mapping strategy to optimize global coverage during the life of the mission. From launch through May 31, 2011, ASTER has acquired over 1.8 million 60x60 km multispectral scenes of the Earth's surface at 15 to 90 m ground resolution. Approximately 500 new scenes are added to the archives daily. Throughout the mission, ASTER has contributed in many ways to all nine societal benefit areas outlined for the Global Earth Observing System of Systems (GEOSS) [23].

Key participants in ASTER operations are located at the Earth Remote Sensing Data Analysis Center (ERSDAC) in Tokyo, Japan (http://www.gds.aster.ersdac.or.jp/gds_www2002/index_e.html); the Jet Propulsion Laboratory (JPL)/California Institute of Technology in Pasadena, California (http://asterweb.jpl.nasa.gov/); Goddard Space Flight Center (GSFC) in Greenbelt, Maryland (http://www.nasa.gov/goddard/); and NASA LP DAAC near Sioux Falls, South Dakota (https://lpdaac.usgs.gov/). Bi-annual science team meetings are held to review data policies and consider large tasking requests, discuss operations and mission planning topics, study calibration test results and identify necessary radiometric and geometric corrections, review the status of product algorithm development, and discuss data applications [24].

A suite of ASTER Level-1, Level-2, Level-3, and Level-4 data products is made available by ERSDAC and LP DAAC [20], [25]-[27]. The ASTER Global Digital Elevation Model (GDEM) was released in June 2009 [28]. ERSDAC staff perform acquisition scheduling, and process, archive, and distribute data products. The Japan team also develops executable code used for Level-1 product generation and provides Observation Schedule Files (OSF) to LP DAAC for Level-1 processing. The ASTER JPL team oversees science aspects from the U.S. perspective, develops executable code for Level-2 product generation, performs pre-release product validation, and participates in sensor tasking. Flight operations and ground systems interface considerations are coordinated by teams at GSFC, and a team at EOSDIS Data and Operations System (EDOS) performs initial processing on raw input data. Data are archived, produced, and distributed by LP DAAC, where science software received from affiliates is integrated and tested prior to use, and coordination services are provided for emergency tasking. LP DAAC receives new Level-1A products from ERSDAC daily and uses executable code received from ERSDAC and JPL to produce Level-1 and Level-2 data for distribution. LP DAAC uses commercial off-the-shelf software for the generation of Level-3 digital elevation models (DEM) and orthorectified products.

Orbit and Instrument Characteristics

Terra orbits Earth at an elevation of 705 km in a sun-synchronous orbit with 98.2 degree inclination and a period of 98.88 minutes. Terra has a nominal 10:30 AM equatorial crossing time for the descending orbit, with a 16-day nadir revisit time. The revisit time is shortened at high latitudes, through off-nadir pointing, and when night observations are combined with day scenes. For example, it was possible to schedule night imaging of the Puyehue Volcano in Chile on June 11, 2011, at 03:41 UTC, and a day scene on the same day at 14:46 UTC (scheduled center point latitude 40°35'5"S, longitude 72°8'9"W). ASTER does not image continuously; it acquires data through scheduled observations and operates under the constraint of an 8% duty cycle. A complex scheduling equation is used to determine each scene collected, with higher priority assigned to urgent emergency observations to ensure they are successful. The dimensions of each scene are approximately 60x60 km, for an area of 3,600 km^2.

ASTER has three instrument subsystems, Visible and Near-Infrared (VNIR), Shortwave Infrared (SWIR), and Thermal Infrared (TIR). Each subsystem has a different ground resolution, with several bands spanning each range of wavelengths, as depicted in Fig. 4 and detailed in Table 1. ASTER acquires VNIR, SWIR, and TIR in "full mode" operation. VNIR-only is collected when wide off-nadir pointing is employed. A wide-angle off-nadir VNIR point allows collection to occur sooner and is often used in emergency situations where time is of the essence when these wavelengths can provide useful information. Only SWIR and TIR bands are typically observed for night scenes.

VNIR Subsystem

The VNIR subsystem has three wavelength bands in the range from 0.52 to 0.86 µm, with a ground resolution of 15 m. In addition to three nadir-view bands in the pointable VNIR subsystem, another backlooking band is present to acquire data enabling the generation of DEMs. The VNIR subsystem can be pointed up to 24 degrees off nadir, which is greater than that possible by the SWIR and TIR subsystems. Consequently, some data products may contain only VNIR bands.

SWIR Subsystem

The SWIR subsystem has six wavelength bands in the range from 1.600 to 2.430 µm, with a ground resolution of 30 m. The SWIR subsystem performed well beyond its design life but experienced an increase in the detector temperature with a corresponding saturation of values. While some data acquired in 2007 and early 2008 may exhibit this problem, no SWIR data acquired after April 2008 are useful for analyses. Archived SWIR data before this time are not affected. VNIR and TIR data continue to be acquired normally and remain fully useful for research purposes. The SWIR subsystem can be pointed up to 8.55 degrees off nadir.

TIR Subsystem

The TIR subsystem has five wavelength bands in the range from 8.125 to 11.65 µm, with a ground resolution of 90 m. The TIR subsystem can be pointed up to 8.55 degrees off nadir.

B. Sensor Tasking Policies and Procedures

U.S. and Japan ASTER Science Team members collaborate to establish policies for sensor tasking in support of mission objectives. All interested users may apply to the ASTER Science Team to request collection of data for specific research objectives by following data acquisition request procedures outlined on the ASTER JPL web site (http://asterweb.jpl.nasa.gov/NewReq.asp). In addition, requests are received by ASTER emergency response points of contact from remote sensing representatives of the global support communities. These requests for emergency, or "expedited," data are typically restricted to single collections of a point of interest, though in extenuating circumstances multiple observations over a larger area have been acquired. For example, extensive imaging occurred in response to the 2011 Japan earthquake and tsunami, the 2010 U.S. Gulf oil spill, the 2005 landfall of Hurricane Katrina in the U.S., and the 2004 earthquake in the Indian Ocean near Indonesia and the related tsunami. ASTER also supports a multi-year NASA-funded north Pacific volcano monitoring program through expedited taskings [18], [29].

A formal ASTER team agreement is in place regarding the allocation of expedited taskings between the U.S. and Japan. However, these allocations might be reassigned from one side to the other if necessary. For example, the U.S. team offered additional tasking allocations to the Japan side during the 2011 Japan earthquake and tsunami crisis. The Japan team has assisted U.S. members with additional scheduling support at other times. Following the 2011 Japan earthquake and tsunami, the total allocation for expedited observations was increased to 20 per day with a portion for each team.

When expedited data collection requests are received by ASTER representatives and approved by the Joint U.S./Japan ASTER Science Team, the next observation opportunities are identified as determined by the Terra orbit, the limits of the 60 km swath width, and the off-nadir pointing capabilities. Cloud forecasts are disregarded to ensure data collection occurs. The ASTER Overpass Predictor is useful in identifying possible observation dates and times (https://igskmncnwb001.cr.usgs.gov/aster/estimator/reference_info.asp). A choice is then made considering possible conflicting requests, spacecraft maneuvers, and any planned service outages. Finally, scheduling is confirmed a minimum of two to four days prior to collection and added to a master priority coordination calendar (http://asterweb.jpl.nasa.gov/gettingdata/calendar.asp), acquisition commands are uplinked to the Terra spacecraft, and imaging occurs as specified if all systems perform normally. High prioritization is specified to ensure critical expedited collections take precedence over general global mapping and other observations. A scheduling lead time of two days is possible when a "late change" system capability is in effect, and approximately four days are required when this is not the case. While such a lag time does impact responsiveness, this delay in collection after an event may not be a factor in some cases and could even be desirable. For example, it provides time for skies to clear after a major storm system leaves a target area.

The ASTER Emergency Scheduling Interface and Control System (AESICS) was created to receive semi-automated expedited tasking requests for north Pacific volcano monitoring that are initiated by hot spot detection using coarse resolution imagery [18], [29]. An expansion in the use of AESICS to include other locations is underway.

C. Data Product Generation and Distribution

Product Generation

ASTER data products are generated in Japan at ERSDAC and in the U.S. at LP DAAC. Standard Level-1 data are produced by ERSDAC and transferred to LP DAAC for archiving, higher level product generation, and distribution.

Early in the ASTER mission, transfers of Level-1 data from ERSDAC to LP DAAC took several weeks via tape shipments. This was reduced substantially when a transition to network data transfers was implemented to speed data availability. Standard ASTER Level-1 data products presently become available via network transfers from search and order clients in the U.S. and Japan within several days after collection.

Recognizing the need for rapid data availability in certain circumstances, an expedited data delivery and processing capability was developed and is used to support science field campaigns and disaster response activities [30]. Expedited data are commonly made available within six hours or less after collection.

Raw ASTER expedited data are downlinked from Terra via the Tracking and Data Relay Satellite System (TDRSS) to a receiving facility at White Sands, New Mexico, and then transferred via network to EDOS at GSFC. EDOS processes the raw data to Level-0 and transfers Level-0 data to LP DAAC. Using Level-1 executable code and OSFs received from ERSDAC, LP DAAC processes the Level-0 data to Level-1AE and Level-1BE expedited products [31], [32]. Level-1A Routine Reconstructed Unprocessed Instrument Data consists of depacketized, demultiplexed, and realigned instrument data. Geometric correction coefficients and radiometric calibration coefficients are appended but not applied to Level-1A data. Level-1B On Demand Registered Radiance at the Sensor data are geometrically co-registered and radiometrically calibrated. Expedited Level-1AE and Level-1BE products are generated for each emergency collection. Higher level products may be created on-demand from standard Level-1A data after these are produced.

Expedited Level-1 data have been used extensively for over a decade and the faster availability greatly enhances value in crisis situations. There are some differences in expedited data compared to standard ASTER products. There is no backlooking band 3 included so DEMs cannot be created, but they can be produced when standard products are available days later. However, the GDEM provides topographic information for all land areas ASTER can image, and these data are readily available at any time. Short-term calibration for TIR is not available so long-term calibration is used. The inter-telescope registration quality may be lower since adjacent scenes are not available for use. Expedited processing uses raw spacecraft ephemeris data, thus the geometry is slightly different than standard products that are created using refined (post-processed) ephemeris data. Nonetheless, the expedited image data are of excellent quality.

Operational anomalies sometimes delay data availability or prevent data collection. There could be tasking conflicts on the same orbit and a decision must be made as to which target to acquire. Occasionally, tasking uplinks to Terra do not occur as anticipated, bit flips might occur in the data and require special handling, and arrival of the ancillary OSF might occur after the arrival of data and cause a need for manual intervention in Level-1 processing. The downlink of two temporally adjacent but separate taskings at the same time resulted in a Level-1 processing anomaly requiring special intervention to produce the second group of scenes. Delays in data availability might occur if manual intervention is required since operation centers are not staffed constantly at LP DAAC in the U.S. or at ERSDAC in Japan. Unscheduled ground system downtime also hinders data flow.

Nonetheless, the vast majority of ASTER expedited data collections occur successfully as planned, though clouds and smoke may sometimes obscure areas of interest since passive optical sensors are used. For example, during the six-month period from June 1 through November 30, 2010, there were 248 science team and field campaign acquisition tasking requests uplinked to the Terra spacecraft. Of these, 98% were successfully acquired, with the few anomalies resulting from a variety of causes [33]. Processing throughput is normally prompt. During the period from January 4 through March 10, 2011, LP DAAC received 85.1% of Level-0 data from EDOS within 90 minutes or less from the time of acquisition. LP DAAC in turn processed, archived, and made 81.1% of the Level-1BE products available for download within three hours after acquisition [34].

Data Distribution

Data distribution mechanisms used in major crisis situations must be highly robust and capable of handling large volumes of data. For example, several terabytes were distributed daily by the USGS following the Haiti earthquake in 2010, supported by Optical Carrier (OC)-12 circuits and a 10-gigabit Ethernet connection. The USGS distributed over 600,000 files totaling 54 terabytes within six weeks after this event [14]. Rapid high-bandwidth access via FTP must be provided, with longer-term archives holding products for future reference. Examples of systems offering prompt access to images for emergency response include the ASTER Expedited distribution sites, the MODIS Rapid Response System (http://lance.nasa.gov/imagery/rapid-response/), and the USGS Hazards Data Distribution System (HDDS; http://hdds.usgs.gov/hdds/) where some event-specific ASTER products are archived. HDDS contains a variety of image products as well as ancillary data [14].

LP DAAC distributes ASTER expedited data and other products via NASA's Warehouse Inventory Search Tool (WIST; https://wist.echo.nasa.gov/api/) and Reverb (http://reverb.echo.nasa.gov/reverb/), as well as through the LP DAAC Data Pool, a fast-access direct-download interface (https://lpdaac.usgs.gov/lpdaac/get_data/data_pool). Members of emergency response teams requesting an ASTER tasking are notified of data availability and download procedures via email after processing is completed. ASTER expedited data are provided at no cost to the user and have no redistribution restrictions.

In addition to new post-event expedited imagery, archived standard pre-event scenes are commonly used to illustrate changes that have occurred and for pre-event planning. The spatial breadth and temporal depth of the ASTER archive accumulated at LP DAAC and ERSDAC during the last decade provide great value for such purposes. This collection now enables the creation of global and regional data products such as GDEM and the North American ASTER Land Surface Emissivity Database (NAALSED;

http://emissivity.jpl.nasa.gov) [35], as well as thematic archive subsets such as the ASTER Volcano Archive (http://ava.jpl.nasa.gov/).

IV. ASTER Expedited Data Examples

In addition to routine global mapping and frequently acquiring expedited data for science field campaigns, the ASTER team has collected imagery on an emergency basis for a wide range of disasters and other significant events during its period of operation. These phenomena included floods, wildfires, volcanoes, landslides, hurricanes, earthquakes, tsunamis, tornadoes, iceberg calving, hazardous material releases, and many other situations. A detailed listing of scheduled expedited observations from 2001 to the present is provided in the ASTER Priority Coordination Calendar (http://asterweb.jpl.nasa.gov/gettingdata/calendar.asp). A small sampling of representative expedited imagery is presented here to illustrate some of the capabilities of the instrument in disaster situations.

A. Japan Earthquake and Tsunami

On March 11, 2011, a magnitude 9.0 earthquake occurred off the east coast of Honshu, Japan, initiating a large tsunami that caused massive destruction along the coast and resulted in the later meltdown of reactors at the Fukushima nuclear power plant. The Charter was activated on March 11, and ASTER observations were scheduled through April when overpasses occurred. GDS offices in Tokyo were closed for a period of time due to this event, but staff ensured that expedited taskings and related data processing could continue normally. ASTER team members in the U.S. and Japan worked together to ensure rapid availability of new imagery during this crisis. ASTER's March 14 observation of Ishinomaki revealed extensive flooding caused by the tsunami, as shown in Fig. 5.

B. U.S. Gulf Oil Spill

An explosion on Transocean's *Deepwater Horizon* oil rig occurred in BP's Macondo prospect (Mississippi Canyon Block 252) in the Gulf of Mexico on April 20, 2010, resulting in fatalities and an extensive oil spill. The rig located at 28° 44' 12" North latitude, 88° 23' 14" West longitude sank on April 22, 2010.

The Charter was activated by the USGS on April 22, 2010, and the ASTER instrument was tasked to obtain multispectral remote sensing imagery of the affected areas. For this event, ASTER acquired 149 expedited scenes on 39 observation days during the period May 1 through September 24, 2010, for a total of over half a million square kilometers of coverage. This was a departure from the more typical limited number of collections for single point locations, as was the response to Hurricane Katrina in 2005 [36]. Sunglint revealed the location of oil on the water surfaces, as shown in Fig. 6.

C. Australia Wildfire

Extensive wildfires raged in southern Australia north of Melbourne during early 2009. These caused loss of lives and destruction of many structures, as well as resultant ecological impacts. The Charter was activated on February 12, 2009, and the ASTER instrument was tasked to acquire multiple observations of affected areas during February and March of that year. Fig. 7 is an ASTER image which shows active fires and the burn scar surrounding the community of Marysville, which suffered devastation.

D. Iceland Volcano

A major eruption of Eyjafjallajökull Volcano in Iceland occurred in 2010. The extensive plume of emissions caused local evacuations and interrupted air travel in many countries in Europe for an extended period. The Charter was activated for this event on April 20, 2010. ASTER imaged the volcano on numerous occasions from March 25 through May 28, 2010, with one example included as Fig. 8.

E. U.S. Alabama Tornadoes

Numerous tornadoes occurred throughout much of the eastern U.S. in April 2011, causing widespread destruction with hundreds of fatalities. Impacts in Alabama were especially severe. ASTER was tasked to acquire several observations, and team members assisted staff at NASA's Marshall Space Flight Center to obtain images used for delineating track locations. Multiple tracks were clearly evident in ASTER scenes. One of these tracks which passes through Tuscaloosa is shown in Fig. 9.

F. Hungary Toxic Spill

On October 4, 2010, there was a breach in a reservoir at an alumina plant in Ajka, Hungary, that allowed a large quantity of toxic sludge to enter the Marcal River and eventually reach the Danube River. Some fatalities occurred, and nearby villages experienced damage. The ASTER image in Fig. 10 shows the presence of this contaminant in the river system on October 11.

V. Future Directions

Major accomplishments have been achieved in recent years through the formalization of international space asset-sharing agreements and the deployment and successful operation of numerous Earth-orbiting sensors. Expanded participation in collaborative data-sharing agreements has supported applications by an increasing number of global response organizations. As is typical in such complex political, financial, and technical endeavors, obstacles have been encountered and opportunities for enhancements remain.

A. Organizations

The International Charter – Space and Major Disasters has proven to be an effective mechanism for swiftly providing a wide variety of observations on short notice when emergency situations occur. Membership and use have increased substantially since the initial agreement. Increased demand for products and services has been noted following examples of successful data delivery and application [37].

The Group on Earth Observations (GEO) is a partnership of governments and international organizations formed to promote international collaboration in Earth observations. GEO is constructing the Global Earth Observation System of Systems (GEOSS). The 10-year implementation plan covering

2005 to 2015 specifies nine societal benefit areas, including natural and human-induced disaster situations. The GEOSS goal is to speed information dissemination through enhanced coordination of related activities at local through global scales [38]. The GEO Work Plan for 2009 to 2011 includes task DI-06-09 Use of Satellites for Risk Management as a step in implementing actions for GEOSS societal benefit areas. The goal is to guide the implementation of satellite constellations to manage risk in multi-hazard scenarios [39].

B. *Sensors*

International coordinating organizations rely on orbiting sensors when responding to disasters. The available assets can evolve over time as older missions expire and new spacecraft and sensors are launched [2], [3], [7]. In the absence of any critical operational anomalies, ASTER will continue to remain available on Terra for tasking during times of crisis. NASA headquarters completed a formal review of the Terra mission in early 2011 and granted approval for continuation of the mission for an additional two years, until the next formal assessment in 2013. Though data have proven to be of tremendous value in a wide range of applications, no ASTER follow-on mission is scheduled. The U.S. Landsat Data Continuity Mission (LDCM) offers some similar, but not identical, sensor characteristics [40]. The launch of the LDCM Operational Land Imager (OLI) and Thermal Infrared Sensor (TIRS) is anticipated to occur in late 2012. In contrast to Landsat predecessors, but similar to the current ASTER capability, this instrument will include off-nadir pointing [41].

International organizations continue development of significant observing capabilities applicable to disaster management. The NASA Decadal Survey provided guidance on desirable future U.S. Earth-imaging sensor capabilities and several new missions are planned; however, implementation plans have been modified somewhat due to budgetary concerns [42]. Continuing collaborative efforts are dependent on the political, financial, and technical support of nations, with the benefit of acquiring access to data at a lesser cost than if individually supporting missions. Data pricing and redistribution policies can complicate and limit the ability to exchange information.

C. *Obstacles and Opportunities*

It has been proposed that nearly all satellite data information requirements for interdisciplinary science and applications can be provided by just a few basic sensor types, thus supporting the rationale of employing collaborative endeavors to avoid undesirable redundancy in orbiting platforms [1]. Regarding international collaboration in satellite observations of Earth, the need for consistent and coordinated data access and pricing for remote sensing products has been noted, along with the need to fully address related national security concerns, to minimize policy divisions between the developed and developing world and to ensure that nations honor long-term commitments [12].

While the Charter has expanded access to space assets, reduced costs, and unified disaster management efforts, some areas for improvement in its coordinating work have been suggested [8], [43]. Non-uniform data policies among participants and legal liability issues were cited as important considerations [43]. To enhance effectiveness in Charter operations, some have proposed the provision of ready-to-use map products, an increase in data delivery speed, and further coordination and cooperation among satellite operators [8]. The benefit of an expanded use of interoperable spatial data infrastructures has also been noted [8].

The implementation of the multi-mission EOS concept, development of the ASTER instrument and product algorithms, the launch of Terra, and establishment of the supporting infrastructure were significant large-scale international collaborative endeavors with numerous complicating factors [21], [22], [44]-[47]. Prior to the launch of Terra, ERSDAC leadership commented on many challenging aspects of developing the ground system, noting the complex mission operations, large data volumes, data processing considerations, data transfers to U.S. affiliates, and other aspects [46]. Also in the pre-launch era, others offered system architecture considerations and raised policy questions for enabling data access to best serve the anticipated broad user community via the NASA EOS Data and Information System (EOSDIS) Core System (ECS) and other proposed approaches [48]. Soon after data began being acquired during the operational phase of the ASTER mission, LP DAAC leadership noted the complexity of managing highly varied stakeholder expectations, defining requirements, and ensuring overall performance in a rapidly evolving multi-mission environment [47]. Maintaining clear communications with all participants and focusing on core objectives are two of the several obvious but critical management techniques cited to enable a successful outcome.

A variety of difficulties have been reported in the use of remote sensing data for disaster situations, and improvement where possible in these areas can enhance future responsiveness [14], [49]. Handling large volumes of markedly different and often redundant satellite data with urgency can pose challenges to analysts. In addition to large-volume data throughput considerations, selecting the best scenes from the many available scenes and ensuring their correct registration delays the output of final products and the resultant response actions. Extraction of thematic information via image processing substantially lags the rate of image acquisition by multiple sources. In general, decreased staff familiarity with microwave products, which are used to overcome cloud effects in optical images, can also be a factor. Inadequate hardware sometimes used for large processing operations also increases response time.

VI. Conclusion

Satellite observations have proven highly useful in emergency situations, with consistently strong demand experienced for newly acquired data characterizing crisis events. Data-sharing through formal international agreements enables a coordinated response with substantial cost savings while also providing a broad suite of products from which to select in order to characterize and understand significant events on the Earth.

Pre-established communication channels enable swift action when required. Close coordination of satellite utilization through formal meetings of data requestors, sensor tasking representatives, and data distribution outlets optimizes the value obtained from all participating assets and minimizes inefficiencies.

The ASTER mission provides a noteworthy example of strong international collaboration persistently spanning pre-launch development through over a decade of post-launch operations, with consistent timely performance by the expedited data system and supporting staff. Multi-mission data contributions to the USGS HDDS archive and distribution portal enable a centralized source for data downloads in addition to other data retrieval mechanisms. On-call customer service staff at data distribution facilities such as LP DAAC provide insight on data specifications, handling procedures, and suitable applications when necessary. ASTER team members also inform the remote sensing and hazard response communities of data applicability and availability through a variety of outlets.

As new missions join the available suite of sensors, and nations continue jointly pursuing large-scale technological solutions to address urgent humanitarian endeavors, opportunities exist to realize further progress in emergency response coordination, satellite infrastructure and operations, and data production and applications. Given the support of firm political resolve, international collaboration in satellite observations for disaster management will continue to serve a key role in meeting these future global time-sensitive imaging requirements.

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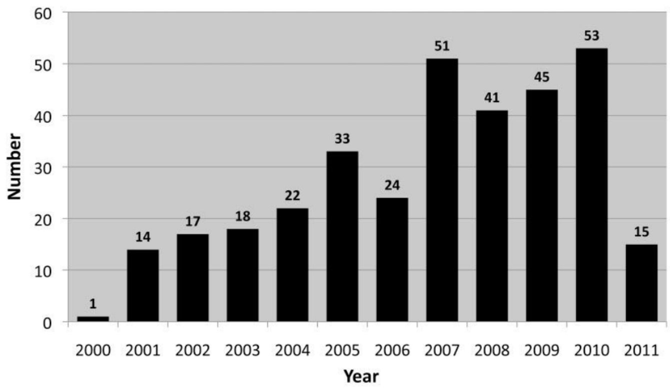

Fig. 1. Activations of International Charter - Space and Major Disasters from inception through June 2011.

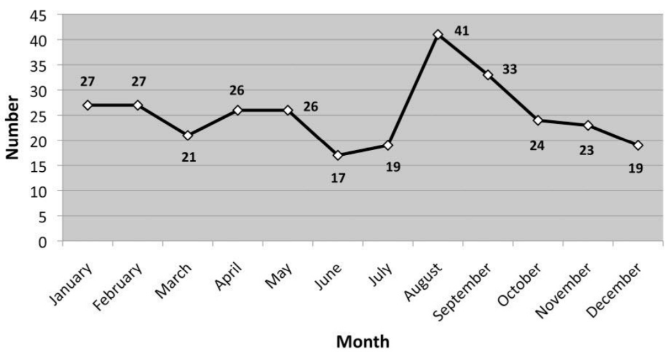

Fig. 2. Monthly distribution of activations for International Charter - Space and Major Disasters during the period 2000 through June 2011.

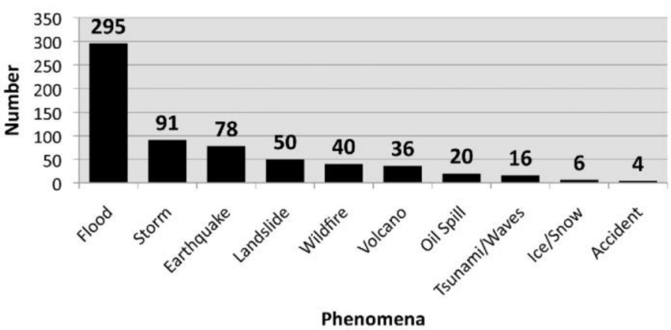

Fig. 3. Activation count by phenomenon for International Charter -Space and Major Disasters for the period 2000 through June, 2011.

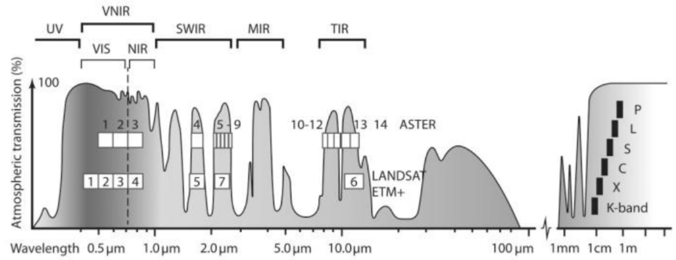

Fig. 4 ASTER bands superimposed on a model atmosphere. The position of the 14 ASTER spectral bands are shown in the electromagnetic spectrum, with Landsat ETM+ bands included for comparison [50].

Table 1
ASTER key sensor characteristics. Band 3N is nadir (or pointed off-nadir) and is aligned with bands 1 and 2, whereas Band 3B is backlooking.

Spectral Bands			Ground Resolution (m)	Cross-track Pointing	Swath Width (m)
Sub-system	Number	Wavelength Range (µm)			
VNIR	1	0.52-0.60	15	+/-218 km (+/-24 degrees)	60
	2	0.63-0.69			
	3N	0.76-0.86			
	3B	0.76-0.86			
SWIR	4	1.600-1.700	30	+/-116 km (+/- 8.55 degrees)	
	5	2.145-2.185			
	6	2.185-2.225			
	7	2.235-2.285			
	8	2.295-2.365			
	9	2.360-2.430			
TIR	10	8.125-8.475	90	+/-116 km (+/- 8.55 degrees)	
	11	8.475-8.825			
	12	8.925-9.275			
	13	10.25-10.95			
	14	10.95-11.65			

Fig. 5. ASTER March 14, 2011, simulated natural color expedited image of Ishinomaki, Japan, following landfall of a tsunami caused by a major March 11, 2011, earthquake. The epicenter was located offshore. Extensive damage and fatalities resulted. Inundated land areas appear dark grey, with standing water colored shades of blue.

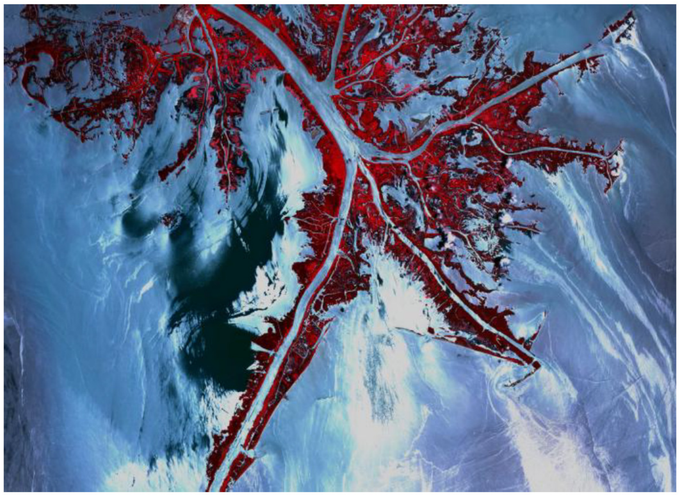

Fig. 6. The Gulf oil spill in the Mississippi River Delta was imaged by ASTER on May 24, 2010. Sunglint on oil is revealed by light-colored areas in the lower central portion of this false-color expedited scene below projecting strips of land. Vegetation appears red, and water appears as shades of blue.

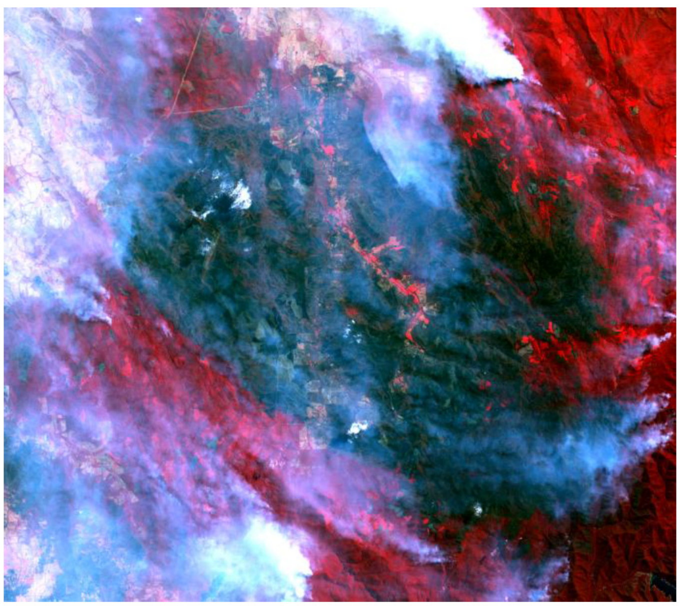

Fig. 7. ASTER expedited image of active wildfires and burn scar in Victoria, Australia. The town of Marysville is located at the lower tip of the red peninsula of vegetation surrounded by the dark gray burned area. Image acquired on February 16, 2009, and bands 3, 2, 1 are displayed as red, green, blue, respectively. Numerous fatalities occurred.

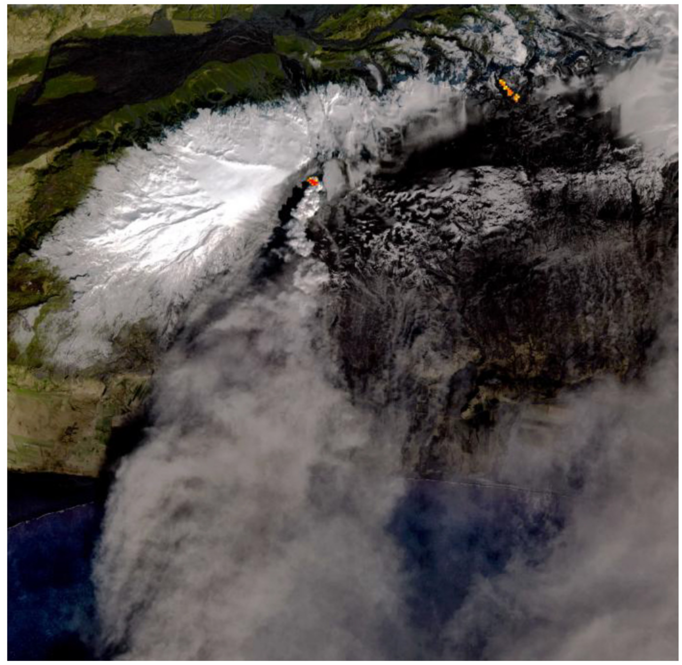

Fig. 8. ASTER simulated natural color VNIR image of Eyjafjallajökull Volcano, Iceland, acquired on April 19, 2010. Eyjafjallajökull is visible emitting a large plume at lower right. Residual heat from an earlier event at Fimmvörduháls is also apparent at the upper right. Hot TIR pixels are shown overlayed in red (high), orange (moderate), and yellow (low). The plume had a significant effect on regional air travel, with numerous flight cancellations.

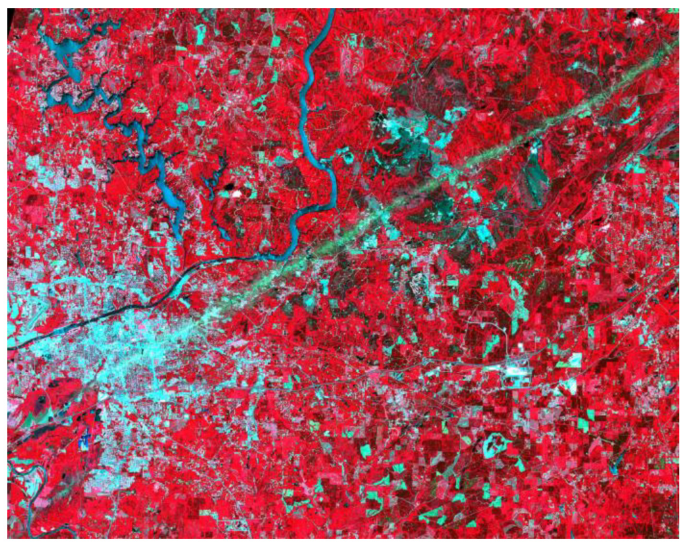

Fig. 9. Tornado track through Tuscaloosa, Alabama. ASTER expedited data acquired on May 4, 2011, displayed in red, green, and blue as band 3, band 2, band 1. The track is evident in Tuscaloosa at lower left, and the light brown linear feature extends diagonally to the upper right. Many tornadoes swept through the region during this event.

Fig. 10. ASTER expedited image acquired October 11. 2010, showing toxic red sludge released from a breach in a reservoir at an alumina plant in Ajka, Hungary. The flow initially affected nearby downstream villages and later reached the Danube River. Natural color was simulated using VNIR bands.