

Remote Sensing and GIS Applications for Pipeline Security Assessment

William E. Roper and Subijoy Dutta

Abstract

A variety of advanced technologies are available to enhance planning, design, management, operation, and maintenance of pipeline system. Aerial and satellite remote sensing integrated with GIS represents one area of rapid development that can be leveraged to assist pipeline risk assessment to assure the safety of pipeline facilities. Industrial and scientific advances in airborne and satellite remote sensing systems and data processing techniques are opening new technological opportunities to develop an increased capability to accomplish the pipeline mapping and safety needs of the industry. These technologies when combined with GIS have significant and unique potential for application to a number of cross cutting system security issues. This paper addresses some of the applications of these technologies to pipeline security assessment.

Key Words: Remote sensing, satellite imagery, pipeline monitoring, LIDAR, radar, spectral imagery, thermal infrared, environmental risk assessment, waste management, digital elevation models, GIS and GPS

1. Introduction

Advances in geospatial sensors, data analysis methods and communication technology present new opportunities for users to increase productivity, reduce costs, facilitate innovation and create virtual collaborative environments for addressing the challenges of security improvement and risk reduction. Sensor developments include a new generation of high-resolution commercial satellites that will provide unique levels of accuracy in spatial, spectral and temporal attributes. An example is Digital Globe's commercial Quick Bird satellite with a spatial resolution of sixty-one centimeters. An example of an image from this system is the open pit mining and pipeline facility in Thailand (Digital Globe 2003) shown in figure 1. This image was taken by Quick Bird from 450 miles in space and provides a degree of detail not available previously to the civil community from space based monitoring of infrastructure on the ground.

In addition to the high resolution panchromatic imagery illustrated in figure 1, there are a number of other commercial imagery products that are potentially applicable to pipeline transportation and power industry infrastructure. They include air borne and satellite radar, LIDAR, multi-spectral, and hyper-spectral sensors. Part of the challenge is matching the best sensor to the specific transportation related application. Visualization and advanced data analysis methods are also important capabilities. Automated change detection within a defined sector is one example of analysis capability that will assist in detection of unauthorized intrusion events. A specific application of these techniques to power distribution security is the detection of unauthorized intrusion onto pipeline right of ways. Pipelines often cover thousands of miles and are located in remote areas that are

difficult and expensive to monitor. In one case study satellite imagery and target identification analysis is used to detect unauthorized intrusion onto a pipeline right-of-way in a remote area of Canada.

There are also challenges that may slow or impede the application of geospatial technologies to the electric utility sector. These include the need for improved methods and authorities for better data sharing across institutional boundaries. The developers and user communities need to communicate better and overcome some significant disciplinary differences. There are also challenging technical issues in the multi-sensor data fusion area to be overcome. Finally, there is a need for a focused interdisciplinary effort to match geospatial capabilities with specific user requirements.

2. Pipeline Industry and Safety Issues

The pipeline network in the United States consists of approximately 1.9 million miles. Part of this network is made up of 302,000 miles of natural gas transmission pipelines operated by 1,220 operators and 155,000 miles of hazardous liquid transmission pipelines operated by 220 operators. In addition to transmission pipelines, there are 94 liquefied natural gas facilities operating in the United States. This vast network's was initially developed in the early 1900's and has continued to expand each year to meet the growing energy needs and product requirements of the United States (US DOT, 2003). Growing worldwide demand for gas-fired electric power generation and to a lesser extent by growing industrial, commercial and residential demand is driving demand for gas. Natural gas projects continue to dominate construction and engineering work.

Estimated miles of natural gas, crude oil and refined products pipelines underway or planned for construction outside the U.S. and Canada total 122,276 km., new construction linear distance is 17,564 km, which is above last year's figure of 15,214 km due to ongoing projects all over the world (A Staff Report, 2001). In addition, natural gas distribution pipeline systems are being built, expanded, replaced, and planned worldwide. Much of the new construction is in the Middle East and South East Asia. In a number of cases there have been environmental pollution problems associated with leaks and damage to pipelines in this area of the world.

Safe pipeline transportation of energy resources is a major concern for the public and the pipeline industry. The pipeline Safety Act of 1992 requires that Research and Special Programs Administration (RSPA) adopt rules requiring pipeline operators to identify facilities located in unusually sensitive areas and high-density population areas, to maintain maps and records detailing that information, and to provide those maps to federal and state officials upon request. The Department of Transportation's Office of Pipeline Safety (OPS) currently does not have access to a reasonably accurate and national depiction of natural gas and hazardous liquid transmission pipelines and liquefied natural gas facilities operating in the United States. To ensure the safe, reliable, and environmentally sound operation of the pipeline transportation systems, OPS is working with state agencies and the pipeline industry to create a National pipeline Mapping System (NPMS, 2003). This system is a full-featured geographic information

system database that will contain the locations and selected attributes of natural gas transmission lines, hazardous liquid lines, and liquefied natural gas facilities operating in onshore and offshore territories of the United States (NPMS, 2003).

The most widely used methods for pipelines monitoring include foot patrols along the pipeline routes and aerial surveillance using small planes or helicopters. These patrols perform facility inspections, check for construction activity in the vicinity of the pipeline, and maintain the pipelines' right-of-way. Heavily congested areas are inspected and patrolled more frequently. In addition, the pipelines undergo periodic maintenance inspections, including leak surveys, and safety device inspections. So the developments and events that could place high-pressure pipelines, the surroundings of pipelines or security of supplies at risk could be prevented. In a continuing effort to remove the guesswork from pipeline operations and reduce costs, many new techniques have been employed to develop software and hardware systems that analyze pipeline risks and maintenance needs in a scientific fashion.

Research and application efforts are developing cost-effective ways to enhance pipeline integrity, inspection, and monitoring, as well as new tools and techniques for managing the risks involved in pipeline operations (Willke, 1996). Some of these efforts have investigated the use of satellite-based technology for pipeline protection. This work has identified the potential for satellite imagery to detect significant slope motion and ground movements that could threaten nearby pipelines with a less expensive means (Hartdraft, 1998). Some specialized software systems such as PIMOS can model five types of pipeline defects: external corrosion, internal corrosion, stress corrosion cracking, material/ manufacturing defects, and mechanical damage (Leewis, 1998). Other work by Zirinig et al. (2001) has studied natural gas transmission pipeline monitoring using high-resolution satellite imagery

Pipelines and their associated facilities pose potential environmental pollution risks that can also be monitored by a variety of remote sensing systems. Pipelines are required to meet all EPA hazardous waste management standards. Some pipeline wastes are excluded from the hazardous waste standards but others are not. Some large volume, or "special wastes", are believed to be lower in toxicity than other wastes regulated as hazardous wastes under the Resource Conservation and Recovery Act (RCRA). Subsequently, Congress exempted these wastes from the RCRA Subtitle C hazardous waste regulations pending a study and regulatory determination by EPA. In 1988, EPA issued a regulatory determination which stated that control of exploration and production (E & P) wastes under RCRA Subtitle C regulations are not warranted. Hence E & P wastes have remained exempt from Subtitle C regulations (IOCC, 1990). However, the RCRA Subtitle C exemptions did not preclude these wastes from control under State regulations, RCRA subtitle D regulations, or other federal regulations. Although, these wastes are exempt from the requirements of hazardous wastes, this exemption does not mean that these wastes could not present a hazard to human health and the environment if they are ill managed. Management of these wastes continues to be a requirement of the pipeline industry (U.S. EPA, 1993, U.S. EPA 1988).

Hazardous wastes related to the transport process of oil and gas in pipelines is fully covered by EPA regulations for the control of hazardous material. Examples of these wastes include: 1) waste in transportation pipeline related pits, 2) waste compressor oil, filters, and blowdowns, 3) waste solvents, 4) Vacuum truck and drum rinsate from trucks transporting or containing non-exempt waste, 5) used hydraulic fluids, and 6) used equipment lubrication oils (Dutta and Alam, 1995).

The remote sensing methodologies described in this paper could support international environmental improvements in many countries. This includes specifically the use of remote sensing technologies to assist in the ongoing efforts of the Association of South East Asian Nations (ASEAN) to provide an effective means of waste and environmental hazards management during an emergency response in various cities in Southeast Asia. Figure 2 is an illustration of the transportation system and land use in the area just south of Jakarta, Indonesia. The ten member countries, Brunei Darussalam, Cambodia, Indonesia, Lao PDR, Malaysia, Myanmar, Philippines, Singapore, Thailand, and Viet Nam of ASEAN have a combined population of over 500 million and include some of the fastest growing metropolitan areas in the world. The recent devastation in many of these countries caused by the Tsunami on December 26 2004 and at the end of January, 2005 has totally demolished many facilities supporting clean land initiative and rendered a major blow to the growing infrastructure for the clean land initiative in these countries.

The major partners involved in this effort are still providing assistance to some of the Tsunami impacted areas by exploring development of a robust and sustainable water supply system in the highly vulnerable coastal areas. The study authors plan to make some effort to use the remote sensing methodologies for waste and environmental hazards management in a project involving a Thematic Workshop on Clean Land for the ASEAN cities. The primary goals and objectives of the proposed project include a move towards sustainable production and consumption patterns and to manage an effective disposal of solid waste, industrial waste and toxic wastes to safeguard public health. A better understanding of pipeline environmental and health risk conditions following disasters and/or spill situations are an important component of response planning. The remote sensing systems described in this paper provide guidance for selection of the best approach for different impact scenarios.

3. LIDAR Systems

Airborne LIDAR is an aircraft-mounted laser system designed to measure the 3-D coordinates of Earth's surface. It has been proven to be an effective technology for acquiring terrain surface data with high accuracy. The LIDAR may provide a supplemental technology to pipeline risk management to assure safety in design, construction, testing, operation, maintenance, and emergency response of pipeline facilities. It provides rapid 3-D data collection of long, linear objects such as pipeline corridors, roads, railway tracks, waterways, coastal zone or power lines (Fowler, 2000). It is easier to obtain many terrain parameters (e.g., slope) and to generate a 3D fly-through using these data. Since LIDAR systems have a narrower swath width in comparison to many optical sensors, they are well suited for capturing high resolution long linear

ground features in 3D, such as pipelines.

3.1 Terrain Analysis

When the LIDAR is combined with a digital photograph, the client has the added value of an image geo-referenced to the laser data set. By combining traditional photogrammetric mapping services with advanced data collection and processing techniques, the new technology provides pipeline monitors with better information for solving problems and making decisions. LIDAR data also could facilitate the planning of new lines and deciding safe routes for placement of a pipeline by considering the terrain parameters such as slope.

LIDAR-topographic-mapping systems have considerable promise for producing high-resolution digital elevation models (DEMs). Satellite communications and GPS navigation systems are critical parts of LIDAR mapping systems. In one study the Topographic Engineering Center (TEC) acquired multiple LIDAR-topographic-mapping data for the purpose of producing high-resolution DEMs. These were evaluated and the results used to help develop criteria for future applications for floodplain mapping (Roper, June 1999).

However, processing of raw LIDAR data into useful and reliable DEMs is not yet mature. Unless exceptional effort is made to produce accurate LIDAR calibration, significant merging artifacts, and their associated errors, can occur. Another example is with merging artifacts that can presently be found in Houston Advanced Research Center (HARC) data.

Merging artifacts in LIDAR data are generally due to miss-calibration of the LIDAR sensor or residual GPS errors. Both kinds of errors can be described by mathematical models and corrected. Because data within overlap regions should match, the parameters of the mathematical models can be calculated. Subsequently, the data can be adjusted so that the errors are minimized. Least-squares estimation techniques have proven to be efficient, accurate, and reliable for this purpose. The overall process is a least squares model-based merging.

Airborne LIDAR systems are capable of precise platform-to-ground ranging that produce decimeter-level height accuracy and meter-level post spacing topographic information of the surface. Some systems are capable of return pulse waveform digitization, which provide precise ground surface and vegetation height and volume measurements. Laser altimeter measurements are acquired along profiles or swaths up to a few hundred meters wide using small aircraft (Schnick, 2001). These swaths could replace channel and pipeline right of way cross-sections (currently obtained via costly ground-based surveys) required by flood backwater models, which are used to predict floodplain extent.

A portion of the Jet Propulsion Laboratory (JPL) LIDAR data collection effort was over the levee and pipeline systems of the Sacramento River valley near Sacramento, California. A segment of this DEM data set in the Meling Orange Grove area of

California (Jorgensen, 1998) is shown in Figure 3. The three dimensional data bases that can be created from LIDAR sensor data can be viewed from different orientations and in a virtual fly-thru mode. The fly-thru capability allows the viewer to experience the terrain in a way that provides unique information about the terrain and a better understanding of the conditions on the ground.

3.2 Submerged Infrastructure Assessment

Some parts of the pipeline systems are constructed underwater at critical crossings and low-lying areas. This presents a new challenge for LIDAR systems that has led to the development of an advanced LIDAR system for this application. The Scanning Hydrographic Operational Airborne LIDAR System (SHOALS) system provides the capability for high spatial density utilizing state-of-the-art LIDAR technology consisting of a scanning laser transmitter/receiver that produces 200 soundings per second. The SHOALS System operates from a helicopter (or fixed wing aircraft) and includes a separate ground based data processing system. It is a highly mobile system capable of rapidly covering large areas. This unique capability produces a more comprehensive measurement of inlets, pipeline rights of way and the adjacent near shore bathymetry. Output from SHOALS is an accurate X, Y and Z (position/depth) from each laser (Lillycrop, Parson, etal, 1994) sounding that is easily formatted for most data analysis software tools such as Geographic Information Systems (GIS), volumetric computations, or other contouring and mapping systems.

The SHOALS hydrographic survey system was developed for the U.S. Army Corps of Engineers (USACE) through a cost-shared project with the Canadian Department of Science, Industry, and Technology. Built by Optech, Inc., of Toronto, SHOALS consists of an airborne laser transmitter/receiver capable of measuring 200 soundings per second. The system operates from a Bell 212 helicopter, flying at an altitude of 200 – 1,000 m with a ground speed of 0 to 100 knots. The Bell 212 was provided by the National Oceanic and Atmospheric Administration (NOAA), Aircraft Operations Center, through a Memorandum of Agreement. The SHOALS system also includes a ground-based data processing system for calculating accurate horizontal position and water depth. Data processing utilizes a state-of-the-art depth extraction algorithm developed by the NOAA National Ocean Service. The SHOALS system completed field tests in February 1994. John E. Chance and Associates operate and maintain the SHOALS system, providing survey services nationwide (Roper, 1996).

The SHOALS System uses LIDAR technology with the reflective and transmissive properties of water and the seafloor to gather high-density survey data. When a light beam hits a column of water, part of the energy is reflected off the surface and the rest, unless absorbed by particles in the water, is transmitted through the column. Using this principal, SHOALS fires a laser into the water, where a significant amount of energy from the infrared beam is reflected off the surface and detected by receivers in the helicopter. The blue-green laser penetrates the surface and reflects off the sea floor. A computer calculates the depth from the time interval between the two reflected energy readings (Lillycrop, Parson, etal, 1994).

As the beam travels through the water column and reflects off the ocean floor, scattering, absorption, and refraction all combine to limit the strength of the bottom, return and, therefore, the system's maximum detectable depth. This depth is a function of water clarity; generally about three times the Secchi depth. A typical plot of these energy readings, or waveform as illustrated in Figure 4. This graph shows the reflection off the water surface—the left most peak—to be a very strong return, while the bottom return, or right most peak appears much weaker.

4. Thermal Infrared Remote Sensing

Temperature differences between the pipeline and the environment, whether the lines are buried or above ground is another detection opportunity. The principle of thermal infrared imagery is that the detected objects produce maximum temperature difference against the background. In addition the weather condition at that time and the possible interference factors on the ground must be taken into consideration.

The thermal conduction caused by underground pipes usually forms temperature anomalies on the ground that often appeared as a difference in temperature. Imaging time: Imaging at night is the presupposition for the thermal target detection with the surface as background, because the ground temperature-increasing phenomenon caused by sun radiation is removed. Test data have shown that for high latitude area, the ground surface temperature tends to be stable at 2000 hours at night to 0600 hours the next morning at this season. The maximum difference in temperature usually appears just before dawn (Jensen, 2000).

The mathematical expression for object resolution is:

$$d = \beta.H \quad (2)$$

Where:

d = Object resolution (m)

β = The transient view angle for scanning (2.5m rad.)

H = imaging flight relative altitude (m)

It is shown in the expression (2) that the object resolution is inversely proportional to the flight altitude, i.e. the lower flight altitude, the higher. Object resolution. Field test data have shown that the temperature anomaly width appeared on the ground for the petroleum pipe was usually 1-1.5m at night. Considering the safety of aircraft flying at night, pilots will often use 600m as their imaging flight altitude. The ground resolution (d) is in the range of 1.5m. So, the pipe anomalies easily detected.

Typical instrumentation is a DS-1230 quantitative double-channel infrared scanner with two blackbodies as reference source to control the upper and lower limitation of the received temperature signal. According to the ground test data and the signal in the flight, usual set limits would be BB2=-2°C (the upper limit temperature), BB1=-1.5°C (the lower limit temperature) for imaging. In this way, the radiant temperature from different

objects on the ground was in the range. The upper limit of the normal temperature range is a little higher, in order to identify the pipe anomalies against the relatively dark background of the images.

Recent tests have successfully proven that the airborne thermal infrared remote is a new and efficient technology for petroleum pipe detection, and can be used in production. The selection of imaging season, imaging time, flight altitude and the normal temperature range for the thermal infrared remote sensing investigation are reasonable and the effectiveness of test were good. The advantage of airborne thermal infrared remote sensing for petroleum pipe detection is: good visualization, easily positioned and convenience for comparison and because it is not limited by access its cost is lower than the other ground geophysical methods.

5. Interferometric Synthetic Aperture Radar (IFSAR)

The state of the art in exploiting interferometry synthetic aperture radar (IFSAR) for terrain information is advancing, and provides significant potential for use in floodplain mapping, pipeline right of way evaluation and emergency support operations, as well as other situations. Unlike conventional SAR imagery, IFSAR data permits the generation of rectified synthetic aperture (SAR) images co-registered with an accurate terrain elevation file (Jorgensen, 1998). This imagery can have an absolute geographic accuracy of 3 meters RMS or less. The rapidity with which IFSAR data can be collected and processed over wide areas, and the all-weather, day-night capability offers significant potential for providing direct support to crisis and security situations as well as enhancing the performance of spectrally based assistance (Roper, 1998). In addition, IFSAR terrain elevations can be employed to rectify Hyperspectral and other imagery, allowing for the registration of radar and Hyperspectral imagery in the ground plane thus providing an improved, rapid digital elevation model (DEM) product.

The Interferometric Synthetic Aperture Radar for Elevations (IFSARE) was a joint industry-government program between TEC, the National Aeronautics and Space Administration, JPL and the Environmental Research Institute of Michigan (ERIM). This research effort resulted in the fabrication of an interferometric radar system integrated with a GPS inertial navigation system which was mounted on a Learjet 36A. The National Aeronautics and Space Administration joined with the Jet Propulsion Laboratory in California to develop the processing software and the ground-processing environment. This software and ground processing capability has now been transitioned to Intermap Technologies Company and is available for commercial applications (Roper, 1998).

A number of universities and government laboratories have been actively involved with the development of a capability to create maps from IFSAR with a minimum of human intervention. Automated algorithms operate on the IFSAR data files to extract land use classification, DEM generation, and bald earth estimations. Hydrology, elevated structures, power lines, and road network data layers can also be automatically extracted. The effort continues to enhance these automated algorithms to assess floodplain soil

roughness and extend infrastructure identification capabilities (Remote Sensing Users' Guide, 1997).

Three files are generated from the IFSAR instrument; a magnitude file, correlation file, and an elevation file. The magnitude file is a backscatter image that provides information on the shape of features, as well as terrain texture. The correlation image provides information on surface or volume backscatter. The elevation data, or DEM, provide information on terrain elevation and height of features (Jorgensen, 1998). A sample DEM of the San Joaquin Valley is shown in Figure 5.

6. Unmanned Airborne Vehicles

Unmanned airborne vehicles (UAVs) are an emerging category of airborne sensors that provide good resolution imagery at a lower cost than large scale manned airborne systems. Some of the UAVs, particularly military systems, have long range in-flight capabilities. Most of the small UAV systems, however, have limited range and flight time capability. For applications to pipeline monitoring larger UAV systems would probably best meet system wide coverage requirements. For critical segments of a pipeline system that is of more limited geographic area the small UAVs could be very effective. A number of Unmanned Aerial Vehicles (UAVs) presently exist, both domestically and internationally. Their payload weight carrying capability, their accommodations (volume, environment), their mission profile (altitude, range, duration) and their command, control and data acquisition capabilities vary significantly. Routine civil access to these various UAV assets is in an embryonic state and is only just now emerging.

A buildup of domestic UAV configurations, promoted by the Department of Defense (DOD) occurred in the late 1980s and well into the 90s. This occurred as the DOD sought UAVs to satisfy their mission unique surveillance requirements in either a Close Range, Short Range or Endurance category of vehicle. Close Range was defined to be within 50 kilometers, Short Range was defined as within 200 kilometers and Endurance as anything beyond. With the advent of newer technology and with the demonstrated performance of the UAVs provided to the DOD by industry, the Close and Short Range categories have since been combined, and a later separate Shipboard category has also been incorporated with them. The current classes or combination of these type vehicles are called the Tactical UAV, followed by the Endurance category.

For the potential civilian user of Unmanned Aerial Vehicles, the following categories are often used: LOCAL, REGIONAL, and ENDURANCE. Within these three categories of vehicles (LOCAL, REGIONAL, and ENDURANCE), approximately twenty-two companies domestically within the U.S. are or have been involved, and represent approximately forty-five different UAV configurations. The appearance of these UAVs and their known performance capabilities and payload accommodations vary considerably. They range in size from hand-held to runway-operated behemoths, whose payload weight capabilities range from a few pounds to 2000 pounds

New capabilities projected for UAVs over the next 25 years include:

- Silent flight using fuel cells to supplant internal combustion engines in some systems.
- 60 percent gains in endurance due to increasingly efficient turbine engines.
- Rotorcraft capable of high speeds (400+ kts) or long endurance (24+ hrs) while retaining the ability to hover.
- Endurance UAVs serving as GPS pseudo-satellites and airborne communications nodes to provide theater and tactical users with better connectivity, clearer reception, and reduced vulnerability to jamming.
- Faster cruise missile targeting due to more precise terrain mapping by high altitude UAVs.
- Self-repairing, damage compensating, more survivable UAVs.
- Significantly speedier information availability through onboard real-time processing, higher data rates, and covert transmission.

UAVs will likely play a major role in the increasingly complex world of security and homeland defense that will evolve in the 21st century. There will be micro air vehicles as well as behemoths. UAVs will stay airborne for weeks or months and longer, fly at hypersonic speeds, sense data in revolutionary ways, and communicate their data at unprecedented rates. Challenges, such as providing an adequate command, control and communication infrastructure to capitalize on unmanned as well as manned operations, remain to be overcome. However, the decisions made now will lay the foundation for how far and how fast these advances are implemented. Only our imagination will limit the potential of UAVs in the 21st century.

7. Integrated Satellite Based Detection System for Pipeline Monitoring

One of the largest and fastest growing markets for high-resolution satellite imagery in digital mapping is the utility industry. Utility companies and semi government bodies are turning to high-resolution satellite imagery to identify optimum facility and infrastructure locations. Using highly accurate, digital, ortho-rectified images, utility companies have a valuable information resource for planning, implementing and maintaining facilities and infrastructure, supporting disaster management efforts (Lindsay, 2001). High-resolution satellite imagery can aid utilities in monitoring electric and gas transmission corridors and rights-of-way; accurate and economical corridor analysis for power and gas pipelines; monitoring vegetation intrusion on transmission and distribution lines; and mapping for cable placement.

The integration of high-resolution imagery with geographic information systems to allow accurate geo-positioning of pipeline and power line vector information on to the local land use and topography representation becomes a very useful planning and decision support tool. The pipeline location can be placed as a vector file over a one-meter spatial resolution satellite image and colored red. Sensitive environmental areas are then identified as green through a land classification analysis on the GIS product. . The location of roads, agricultural areas and structures are also clearly distinguishable due to the high spatial resolution of the image.

Unauthorized intrusion by individuals onto power line or pipeline rights of way and the conduct of damaging activities to the pipeline infrastructure is a concern that has grown particularly in recent times. In North America there are thousands of miles of pipelines that are located in remote rural and wilderness areas. Monitoring of these vast networks on even an intermittent basis is difficult and costly. The most common monitoring method is to use small aircraft to fly over the rights of way on a monthly or less frequent basis and conduct a quick visual inspection. These methods provide a very limited monitoring effectiveness and even less security protection.

With the recent availability of high-resolution commercial satellite imagery, advanced radar system, and target detection algorithms significantly improved monitoring of power distribution networks are now possible. These imagery collects were sequenced in time and change detection analysis was conducted to identify potential security and encroachment events. In this example additional one-meter spatial resolution imagery was collected over the target area. In figure 6 the three different imagery products are shown as overlays in the area of highest interest.

An example of this kind of imagery coverage and data analysis system for a pipeline network is shown in figure 7. In this application multi-spectral four-meter spatial resolution imagery was collected over larger areas of the pipeline system. In addition synthetic aperture radar (SAR) imagery was collected over the same area, which provides all weather, day and night coverage that is not possible with optical sensors. Multiple satellite systems can be tasked to image entire pipeline distribution networks on a daily basis. Time sequenced image analysis is then conducted using computerized change detection analysis to identify potential unauthorized encroachment, environmental risks and security problems. As shown in step four of figure 7, before and after changes in imagery are identified and analyzed. Detected target information is reviewed and geo-referenced to map locations. Additional higher resolution imagery maybe collected over the geo-referenced locations if needed to determine if the situation calls for a notice, alert or alarm category of response. If determined necessary field personnel would be notified and dispatched to the predetermined location.

8. Effectiveness of Satellite Based Pipeline Monitoring System

Conventional monitoring of the massive pipeline systems in Canada is most commonly done on a sporadic schedule by used on visual observation from aircraft flying the lines. Typical flight observation coverage is in the order of once every one to two months for most of the pipeline miles. Detection of unauthorized intrusion and security risk events with current practice is low due to a number of limitations that are inherent with this approach to monitoring. These limitations include; infrequent coverage, human error in detection, limited data analysis capability, high mobilization costs and limited trend analysis.

In an effort to evaluate alternatives to airborne remote sensing of the pipelines a study was conducted to compare this mode of data collection with satellite based remote

sensing. A summary comparison of the results is given in table 1. Based on satellite coverage schedules three imagery collection frequencies were used. These included collection frequencies of once per week, twice per week and once per day. For each category the use of satellite based remote sensing was able to detect pipeline security problems 30 % to 100% better than aircraft based remote sensing. The most significant improvement was with once per week imagery collection where airborne systems had a 20% detection rate compared to a 32% to 55% detection rate for satellite systems. The highest rate of detection (93%) was also achieved with satellite systems with once per day imagery collection. For airborne systems the best detection rate of 88% was achieved using a twice per day imagery collection rate.

9. Summary

Advances in Information systems, satellites imaging systems and improved software technologies have led to opportunities for a new level of information products from remote sensed data. The integration of these new products into existing response systems can provide a wide range of analysis tools and information products that were not possible before. For example, with the higher resolution imagery and change detection analysis pipeline situational awareness and damage assessment can be conducted rapidly and accurately. Power utility infrastructure and system wide evaluations over a broad area could also be addressed using remote sensing data sources. All of these information products can be useful in the response, recovery, and rehabilitation phases of infrastructure management preparedness.

The strength of any paradigm shift is realized if new questions can be answered along with traditional ones. Using remote sensing technologies combined with information sharing will address many, if not most, traditional safety, hazards, and disaster issues facing pipeline and infrastructure managers, as well as provide for those raised by deliberate acts of aggression. Despite technological advance, disaster risk continues to grow. Infrastructure emergency managers and others continue to be called on to make decisions during emergency events, as well as in the pre-and-post disaster phases, with incomplete information. In order to make optimal decisions to reduce the loss of life and property, stakeholders uniformly must be able to obtain the needed information in a format that is appropriate for their capabilities. There is also the need for parties at great distances from each other to be able to share information in a seamless fashion. The shared information needs to be interactive with local data allowing it to be used in creating new integrated products tailored to the situation.

The remote sensing systems presented have unique capabilities for the applications they were initially designed for; As a result, each system may fill a different need for the pipeline system manager. For underwater detection, and characterization of changes the SHOALS system is a good choice. For small area, high-resolution terrain features and changes, the LIDAR system works well. For rapid, wide area, elevation terrain characterization, IFSAR is a good choice. In each case, the capabilities represented provide new tools to the managers and security personnel for better response, recovery, and preventative planning.

APPENDIX 1

List of tables and figures

- Table 1: Comparison of Aerial and Satellite monitoring systems for pipeline security applications
- Figure 1: Digital Globe satellite image of Mining and pipeline system operation in Thailand
- Figure 2: Satellite image of major transportation arteries and land use in the area south of Karachi, Indonesia in May 2005
- Figure 3: DEM generated from LIDAR data of irrigation and pipeline in Southern California
- Figure 4: Signal response characteristics of the SHOALS system
- Figure 5: IFSAR generated DEM of the San Joaquin Valley showing drainage topography and crop height information
- Figure 6: Multi-Sensor data fusion example for pipeline monitoring
- Figure 7: Satellite Imagery based decision support system for pipeline monitoring

Frequency of Imagery Collection	Probability of Detection (%) With Aerial Sensor Systems	Probability of Detection (%) With Satellite Sensor Systems
Once per year	0.4%	
Once per 6 months	1.0%	
Once per 3 months	2.0%	
Once per month	5.0%	
Once per week	20.0%	32% to 55%
Twice per week	40.0%	50% to 70%
Once per day	70.0%	78% to 93%
Twice per day	88.0%	

Table 1: Comparison of Aerial and Satellite monitoring systems for pipeline security applications



Figure 1: Digital Globe satellite image of Mining and pipeline system operation in Thailand



Figure 2: Space Imaging Inc. satellite image of major transportation arteries and land use in the area south of Jakarta, Indonesia in May 2005



Figure 3: DEM generated from LIDAR data of orange grove, irrigation channel and pipeline in Southern California

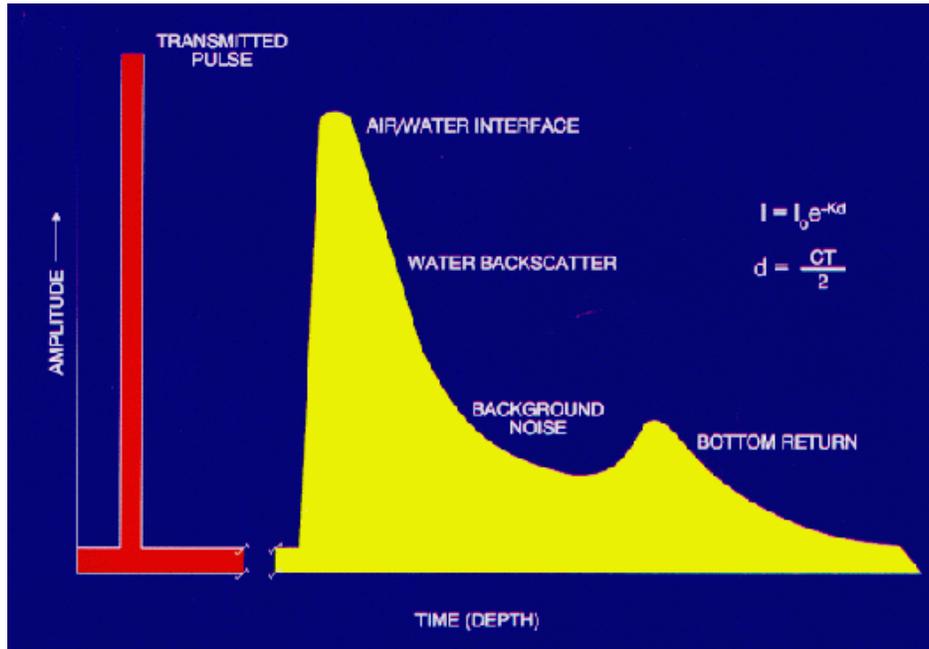


Figure 4: Signal response characteristics of the SHOALS system

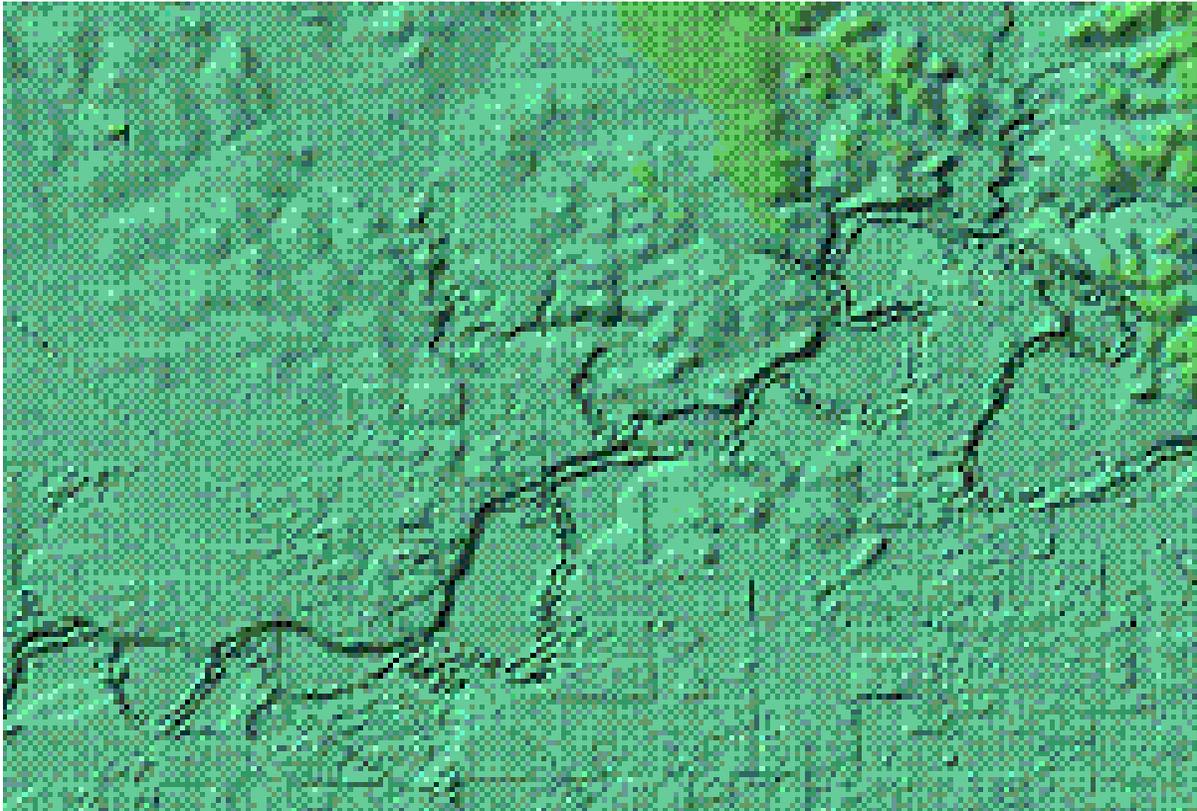


Figure 5: IFSAR generated DEM of the San Joaquin Valley showing drainage topography and crop height information

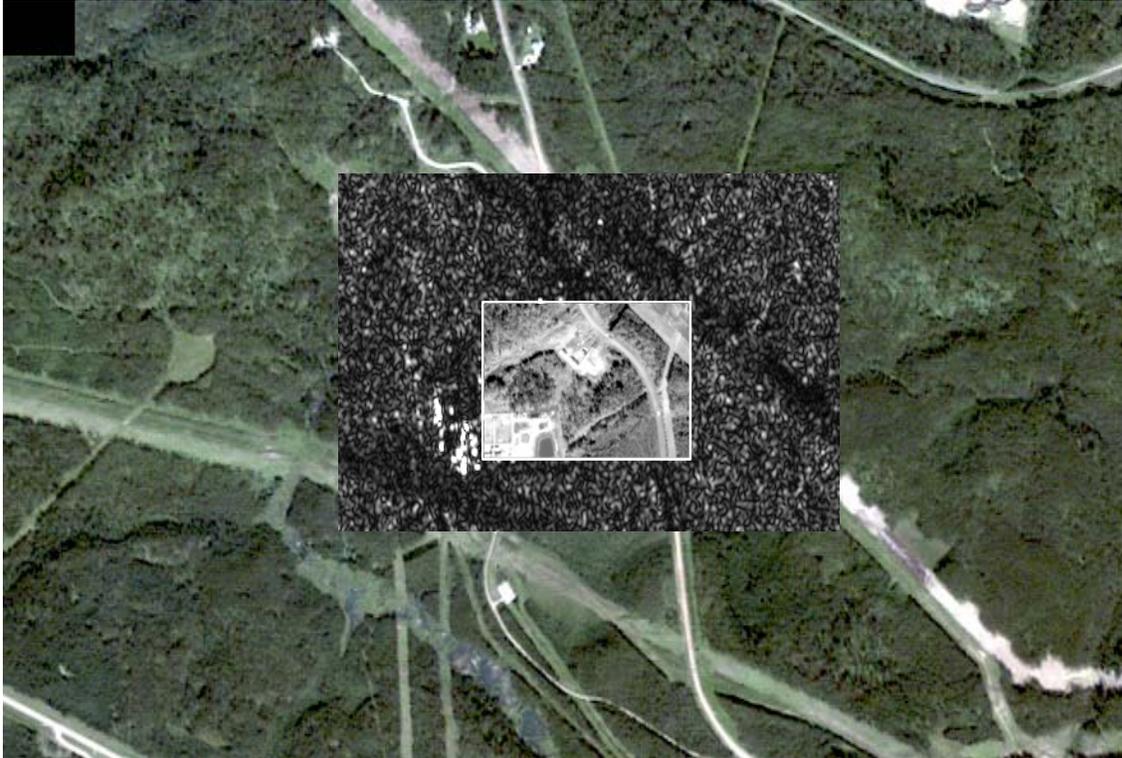


Figure 6: Multi-Sensor data fusion example for pipeline monitoring

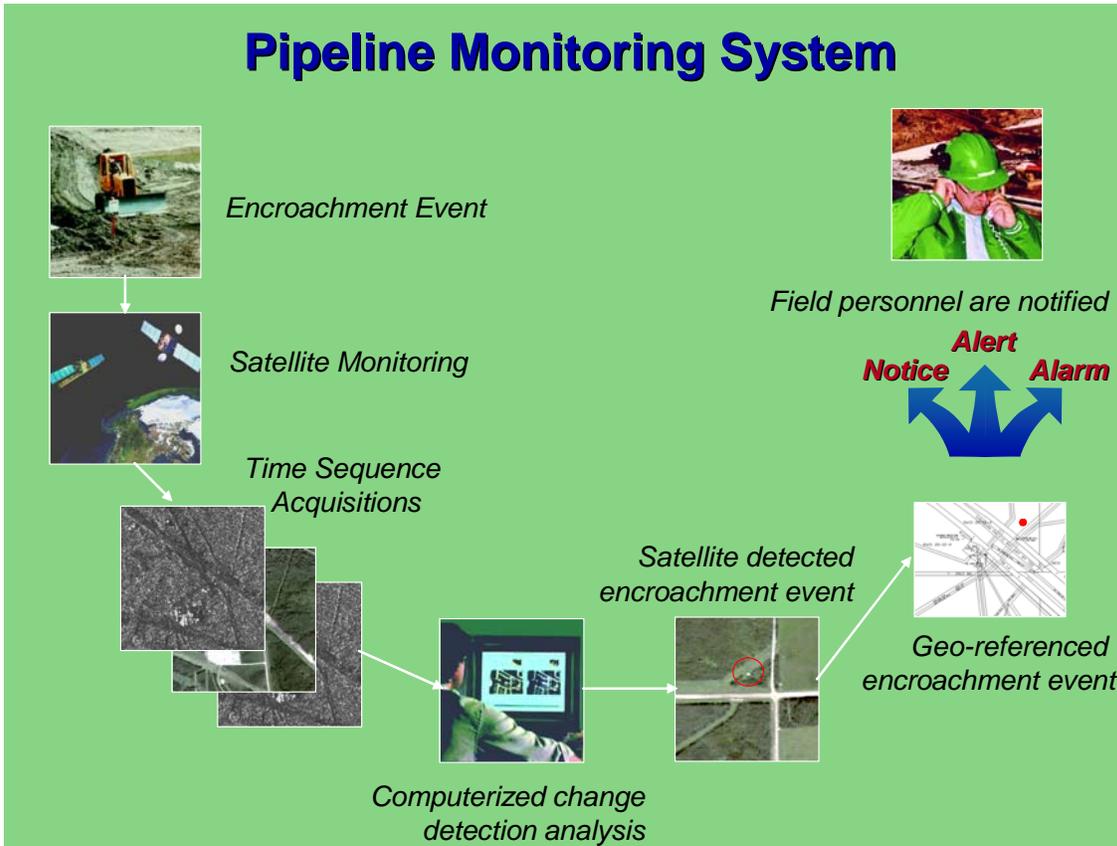


Figure 7: Satellite Imagery based decision support system for pipeline monitoring

References

A Staff Report. (2001). Natural gas development continues to drive worldwide pipeline construction activities. *Pipeline & Gas Industry*, 84(11).

Digital Globe, (2003), Image Library, URL: www.digitalglobe.com

Droessler, M (1998). Using pipe Hawk TM radar to hunt for underground pipe. *GRID Magazine*, URL: <http://www.gri.org/pub/content/sep/19980923/185450/p,JJawkhilite.html>

Dutta, S., and Alam, (1995), W., *Oil & Gas Exploration and Production Waste – RCRA Exemptions and Non-exempts*, National Conference, Society of Petroleum Engineers, Houston, Texas,

Fowler, R. (2000), The lowdown on LIDAR. *EOM*, 9(3).

Hartdraft, R. (1998). *Satellite Radar Interferometry to Detect and Characterize Slope Motion Hazardous to Gas Pipelines: A Demonstration Study of Three Sites*. Topical Report, 49 p. URL: <http://www.gri.org/pub/abstracts/gri99-~.html>

Jensen, John, R., (2000), Remote Sensing of the Environment, An Earth Resource Perspective, Pages 260 – 267

Jorgensen, Thomas, Airborne Platform Remote Sensing and Related Technology, Research Report, U.S. Army Topographic Engineering Center, December 1998

Interstate Oil Compact Commission (IOCC), "EPA/IOCC Study of State Regulation of Oil & Gas Exploration and Production Waste", December 1990.

Leewis. K. (1998). PIMOSTM software optimizes maintenance activities. *GRID Magazine*, URL: <http://www.gri.org/pub/content/sep/19980918/163748/pimos.html>

Lillycrop, W. J., Parson, L. E., Estep, L. L., Laroque, P. E., Guenther, G. C., Reed, M. D., and Truitt, C. L., "Field Test Results of the U.S. Army Corps of Engineers Airborne LIDAR Hydrographic Survey System," in proceedings U.S. Army Corps of Engineers 1994 Training Symposium, Surveying and Mapping Remote Sensing/GIS, New Orleans, LA, pp SM: 2A 1-5, 1994.

Lindsay-Smith N. (2001). In the pipeline - satellite will check gas transmission infrastructure from space. URL: <http://www.advanticatech.com/Information-Room/Press%20Releases/case-12-1O.html>

NPMS, (2003) National Pipeline Mapping System, web site URL: (<http://ops.dot.gov/>; <http://www.bts.gov/gis/reference/npms-content.html>)

Remote Sensing Users' Guide, U.S. Army Topographic Engineering Center, 1997

Roper, William E., High Resolution Terrain Characterization with LIDAR and RADAR Sensors, proceedings of the Fourth International Airborne Remote Sensing Conference and Exhibition, Ottawa, Canada, June 1999

Roper, William E., Geospatial Analysis Support to Natural Disasters, United States/Japan Wind and Seismic Conference, May 1998

Roper, William E., Assessment of Hurricane Opal Impact on East Pass, Florida, with Airborne LIDAR, U.S./Japan Workshop on Two Great Tsunamis, Hilo, Hawaii, April 14, 1996

Schnick. S., and Tao, V. (2001). Applications of LIDAR technology for pipeline mapping and safety. *Proceedings of ISPRS WG III2 Workshop on Three-dimensional Mapping from InSAR and LIDAR* (CD ROM}, 11-11 July, Banff, 11p.

U.S. EPA, "Clarification of the Regulatory Determination for Wastes from the Exploration, Development, and Production of Crude Oil, Natural Gas and Geothermal Energy." March 22, 1993, Federal Register (FR) Volume 58, Pgs. 15284-15287.

U.S. EPA, "Regulatory Determination for Oil and Gas and Geothermal Exploration, Development, and Production Wastes." July 6, 1988, FR Vol. 53, Pgs. 25446-25459.

US DOT, Research and Special Programs Administration Web Site URL: (<http://www.bts.gov/gis/reference/npms-chall.html>; <http://www.npms.rspa.dot.gov>)

Willke T.L. (1996) ~ Addressing pipeline safety: GIU's and the industry's commitment to developing cost effective technologies. URL: <http://www.gri.org/pub/oldcontent/pubs3/trans/w96t-d-featr.html>

Zirrig, W., Hausmann; D., and Schreier; G. (2001); A concept for- natural gas- oil pipeline monitoring based on new high-resolution remote sensing technologies. *IGRC* 2001,5-8 November, Amsterdam.

Author Information

William E. Roper, PhD., P.E.
Professor, School of Computational Sciences
4400 University Drive, mail stop 5C3
George Mason University
Fairfax, Virginia 22030
Phone: 703 993 1648
Fax: 703 993 1521
Email: wroper@gmu.edu

Subijoy Dutta, P.E.
Technical Director,
S&M Engineering Services
1496 Harwell Ave.
Crofton, MD USA 21114-2108
Ph: 410-721-7706
Fax: 410-721-6265
Email: snengineering@yahoo.com