FINAL REPORT

OASRTRS-14-H-CAL "Improved Satellite and Geospatial Tools for Pipeline Operator Decision Support Systems"

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GLOSSARY OF TERMS

AOI	Area of Interest
BP	British Petroleum
Cal Poly	California Polytechnic State University San Luis Obispo
CR	Corner Reflector
CTM	Coherent Target Monitoring
DCRFD	Dual Corner Reflector Field Design
DNR	Department of Natural Resources
DOT	Department of Transportation
DSS	Decision Support System
EMS	Encroachment Management Service
FEMA	Federal Emergency Management Agency
FGDC	Federal Geographic Data Committee
GBSAR	Ground Based Synthetic Aperture Radar
GIS	Geographic Information System
GUI	Graphical User Interface
IMP	Integrity Management Plan
InSAR	Interferometric Synthetic Aperture Radar
ISAT	Integrated Spatial Analysis Technology
ISPDM	Industry Standard Pipeline Data Management
PODS	Pipeline Open Data Standard
PDM	Pipeline Data Model
LOS	Line of Sight
MDA	MacDonald, Dettwiler and Associates Ltd.
NASA	National Aeronautics and Space Administration
NOAA	National Oceanic and Atmospheric Administration
NRT	Near Real Time
NSF	National Science Foundation
OASRT	Office of the Assistant Secretary for Research and Technology
OGC	Open Geospatial Consortium
PHMSA	Pipeline and Hazardous Materials Safety Administration
PRCI	Pipeline Research Council International
RADAR	Radio Detection and Ranging
RAPID	REST Access for Pipeline Integrity Data
REST	Representational State Transfer
ROW	Right-of-Way
SAR	Synthetic Aperture Radar
SME	Subject Matter Expert
USGS	United States Geological Survey
WCS	Web Coverage Service
WFS	Web Feature Service
WSDOT	Washington State Department of Transportation
WV-2	WorldView-2

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CHAPTER 1: EXECUTIVE SUMMARY

Under Cooperative Agreement No. OASRTRS-14-H-CAL, California Polytechnic State University San Luis Obispo (Cal Poly), partnered with C-CORE, MDA, PRCI, and Electricore to design and develop improved satellite and geospatial tools for pipeline operator decision support systems. The goal of this project was to extend the available Commercial Remote Sensing & Spatial Information tools to enhance the use of satellites to provide an efficient and effective means of monitoring pipeline right-of-ways (ROW) and detecting potential threats before they impact pipeline operations. The team used satellite remote sensing, geospatial data information, and readily available web-based datasets to enhance existing pipeline operator Decision Support Systems (DSS) for pipeline integrity management. The overall technical approach was broken down into the following three areas:

- "Big Data" in support of Commercial Remote Sensing and Spatial Information (CRS&SI) technologies for pipeline and critical transportation infrastructure;
- Encroachment Monitoring & DSS; and
- Ground Movement & DSS development.

Traditionally, monitoring large, geographically distributed pipeline networks has been accomplished using ground or aerial surveys, both of which are time and cost intensive. The use of satellite radar imagery can reduce time and costs, shorten the repeat interval, and allow for monitoring independently of weather or remoteness. Satellite monitoring can provide an effective means of long-term monitoring, and also has the potential to detect possible issues along pipeline routes before they impact operations.

Encroachment Monitoring - The team examined the capabilities of a new generation satellite-based synthetic aperture radar (SAR) systems that have higher resolution modes to provide all-weather, day or night monitoring of a specific geographic location. This monitoring, dubbed Encroachment Management Service (EMS), is achieved using computerized change detection to identify potentially hazardous activities, combined with analyst quality control of the computerized results to create an output product of activity. This report includes the evaluation of optimizing detection algorithms and reducing false detections to make the service 'more practical and cost effective. In particular, the project has helped illustrate the potential of reducing false positives and detecting early or leading indicators in satellite imagery.

Ground Movement - The objectives of ground movement monitoring are to examine the utility of the techniques for land classification, deformation, and change analysis utilizing SAR data from the RADARSAT-2 satellite program, and then effectively upload the derived information into a DSS for easy access, analysis, and response action (as needed) by pipeline operators. The goals included: Identify the reliability of slope stability risk mapping using the combined; Approaches of polarimetric change detection and ground deformation mapping; Create a product that would easily portray the information needed for pipeline operators to identify areas of risk; Generate the basis of an operational service that the pipeline industry could rely on to monitor ground surface and vegetative changes.

Data Model - Under this project, a data model system for managers of critical infrastructure to select the appropriate remote sensing data and tools for monitoring and ensuring integrity of the system was created. The model consists of multiple layers which provides benefits for scalability, high availability, easy access, and easy integration into other applications. The model uses existing literature on data integration, analytics, satellite imagery, visualization, geophysical data, geospatial data, infrastructure hazard monitoring and mitigation, DSSs and others.

CHAPTER 2: INTRODUCTION

The two main objectives of this project were to (1) enhance and validate commercial remote sensing and spatial information technology for new applications in pipeline infrastructure planning, construction and operational management and (2) allow pipeline operators to obtain easy access to basic geospatial and attribute data, documents and derived geospatial ground movement-related information products from near-real time monitoring to support pipeline integrity management.

The goal was to develop a data model using "Big Data" concepts to provide rapid access to multiple discrete users (multi-tenant system) to a wide range of data and information relevant to developing integrity management approaches for infrastructure systems. By providing an open-source, web-based data model, small and large service providers of geospatial management and intelligence services can integrate data into existing Decision Support System (DSS) tools. This new data model can provide relevant data delivered to multiple DSSs that can be applied by pipeline operators in identifying and prioritizing pipeline segment(s) for inspection and maintenance, selecting a specific inspection method and technology, and providing guidance on interpreting results.

At the onset of this work Cal Poly conducted a series of literature searches focusing on data integration, analytics, satellite imagery, visualization, geophysical data, geospatial data, infrastructure hazard monitoring and mitigation, and decision support systems. Many works found were completed by government agencies such as the National Aeronautics and Space Administration (NASA), National Oceanic and Atmospheric Administration (NOAA), National Science Foundation (NSF), and US DOT Pipeline and Hazardous Materials Safety Administration (PHMSA), developing proprietary systems or relying on the industry geographic information system (GIS) standard ESRI® ArcGIS® and associated established pipeline data models such as: Integrated Spatial Analysis Technology (ISAT), Pipeline Open Data Standard (PODS), Pipeline Data Model (PDM), and Industry Standard Pipeline Data Management (ISPDM). Based on these findings computer science graduate students completed two draft papers summarizing the literature review associated with designing and developing the Cal Poly data model as outlined in Chapter 4 below. These papers are presented in Attachment A – Surveying GIS Data Storage and Analysis & Attachment B – Pipeline Operator Decision Support Systems Data Model Preliminary Literature Review.

The Cal Poly team also reviewed existing web-based GIS products to study capability and limitations to inform the development cycle. These products included GeoPro, Voyager, ArcGIS, and GeoServer. Based on end user feedback, Cal Poly also investigated GIS standards, particularly the Open Geospatial Consortium's (OGC) Web Feature Service. Chapter 4 will outline the data model design and how OGC compliance was addressed.

CHAPTER 3: DATA COLLECTION

The Cal Poly team working with Pipeline Research Council International (PRCI), MDA, C-CORE, and outside domain experts, determined the specific data sources for each of the types of data to be stored in the Cal Poly data model. While all pipeline operating companies rely on available sources of data to support the development of their Integrity Management Plan (IMP), there is no unified and readily available data base that can be accessed by pipeline operators that identifies atmospheric, environmental, geologic, and other conditions within the vicinity of their pipeline assets. This information could be relevant to identifying and mitigating/preventing risks to pipeline integrity. Building upon recent work that involved creating the State of California Hazard Mitigation Plan and advanced data models/analytics, Cal Poly identified readily and publicly available robust data sets using sources that are easily accessed and that will integrate with existing pipeline integrity management data sources.

The means of accessing the data and format in which the data is available from the source was established and confirmed. The part of the data set that needed to be stored in the data base was extracted, cleaned and prepared for integration. Once the data sources were identified, Cal Poly built proof-of-concept automatic retrieval scripts for the data model.

PRCI supported Cal Poly and organized a telephone conference on April 28, 2014 with pipeline industry subject matter experts (SME) to discuss two key questions: what information needs to be stored in the database and which queries the system needs to be able to process. The Cal Poly team started to gather preliminary data working with PRCI, MDA, C-CORE, and outside domain experts to determine the specific data sources for each of the types of data to be stored in the database.

Both the subset of the records that pertains directly to the pilot regions Washington State and Minnesota for this project, and the subset of the attributes that was deemed necessary by the data requirements were identified.

Sources for Minnesota include:

- Minnesota Geospatial Information Office – mostly statewide or countywide datasets, including: admin/political boundaries, geology, wells, transportation, radio/cell towers, and some restricted access to transmission lines, and similar topics (http://www.mngeo.state.mn.us).
- Minnesota Department of Natural Resources (DNR) Data Deli – includes extensive lists of data including hunting access, historical temperature averages, environmental datasets, hiking/snowmobile trails, geology, hydrography, land cover, railroads and right-of-ways, public/tribal land ownership, and much more (http://deli.dnr.state.mn.us/).
- We were also able to work directly with Blue Earth County, MN to access their parcel dataset free-of-charge.

Sources for Washington State include:

- Department of Ecology – links to various sources for WA datasets (http://www.ecy.wa.gov/services/gis/data/data.htm).
- WA Department of Natural Resources – faults and landslide hazards
- WA State Parcel Database 2012 – available from the University of Washington as an ArcGIS Map Service online (http://50.18.49.187/arcgis/rest/services).
- Department of Ecology – links to mostly statewide datasets, and also some for counties such as: county flood data (http://www.ecy.wa.gov/services/gis/data/data.htm).
- Washington Department of Fish and Wildlife - Elk Areas of Washington State for the 2014-2015 Hunting Season
- Washington State Department of Natural Resources, Division of Geology and Earth Resources - mapped landslides
- Washington State Department of Transportation, GIS and Roadway Data Office - Railroads in Washington State
- Cowlitz County Assessor's Office - Cowlitz Streets and Parcel
- Private Forest Land Grading system (PFLG) - Cowlitz Soils
- MGS Engineering Consultants and Oregon Climate Service - Precipitation Intensity Cells for Washington State, Oregon Climate Service
- Washington State Department of Transportation (WSDOT): Maintenance, Northwest Region - Sensitive Areas - Aquatic, Washington State Department of Transportation
- Division of Geology and Earth Resources, Washington State Department of Natural Resources – Earthquakes
- State of Washington - Wetlands Inventory 2011
- Washington State Department of Natural Resources, Division of Geology and Earth Resources - 1:24,000-scale polygons defining the extend of mapped landslides in the state of Washington

Other pertinent sources for both states include:

- Federal Emergency Management Agency (FEMA) – used for flood data
- U.S. Geological Survey (USGS) – used for earthquake data
- Federal Geographic Data Committee - Content Standard for Digital Geospatial Metadata - Flood Hazard
- Federal Geographic Data Committee (FGDC) and the associated www.geo.data.gov
- Department of Commerce’s *Commerce Data Service* which collaborates with the 12 Bureaus of the U.S. Department of Commerce and private sector partners to improve data product delivery. The data tool is available at https://www.commerce.gov/dataservice/.
- https://coast.noaa.gov/dataviewer/?redirect=301ocm#/
- Wunderground Weather Data API Access
- Washington DOT Traffic Conditions API Access
- Minnesota DOT Traffic Conditions API Access
- Demographic Data by Coordinate

- NOAA Climate Data API Access
- AccuWeather API Access
- Seismic Data Portal API Access
- Google Earth Engine API
- USA Land Cover API Access
- Seismi API Access
- Minnesota Public Land Survey API Access
- Open Street Map API

Attachment C, “RAPID Data Index Methodology” presents a report for accessing all data sources that are cataloged on an internal excel file for the project team.

CHAPTER 4: DATA MODEL DESIGN

The goal of the integrated data model is to store in one place the wide range of data about the conditions in the immediate vicinity of operating pipelines, and use the data to conduct a hazard screening and risk analysis of threats that may be present and that could affect the integrity of the pipeline. Cal Poly's approach to this project was to develop a prototype model for an integrated data base and system architecture to allow for scaling the system without significant changes to the core data model and the core system architecture. This approach ensures that the prototype solution is scalable from day one and in theory be applied to the entire natural gas and petroleum liquids energy pipeline network in North America. While the ultimate goal of the project was to develop an advanced analytical system capable of detecting such causes and predicting changes and threats to the entire natural gas and petroleum liquids pipeline infrastructure, the project concentrated on the development of an effective data base and data management tool to provide added intelligence for existing pipeline DSS (i.e., pipeline IMP) with other forms of data used in implementing the IMP, such as satellite and other ground based ground disturbance and encroachment tools. Cal Poly built an integrated view of multiple data sources and made the data manageable and available on-demand from multiple perspectives. See Figure 1 below for graphical representation of the interconnections for this project.

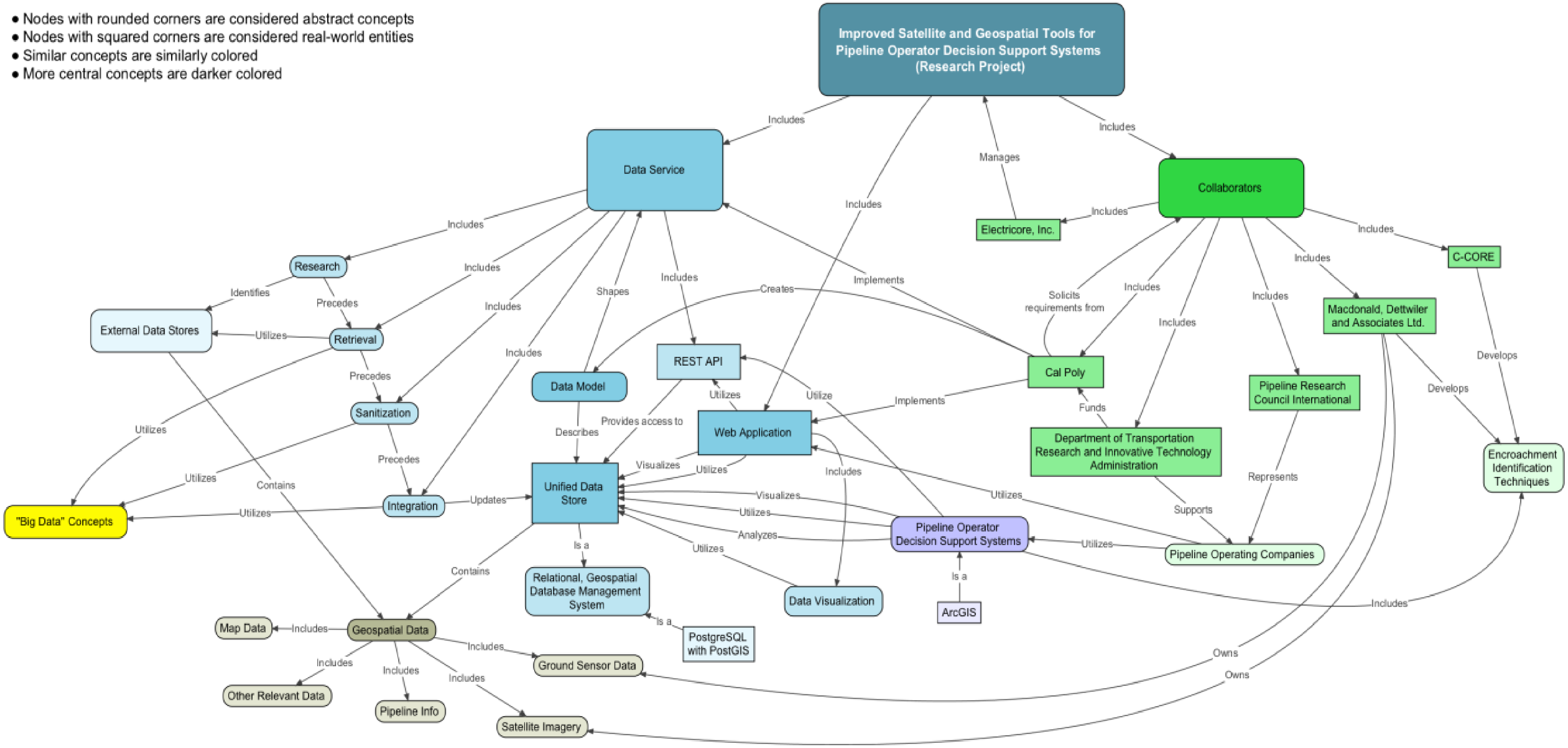

Figure 1: Conceptual Working Relationships / Solutions Diagram

The Cal Poly team solicited feedback on the preliminary design from project team partners. In late 2014 the Cal Poly team designed and proposed a Representational State Transfer (REST) API for Pipeline Integrity Data "RAPID" and the corresponding data model for storage and retrieval of pipeline-related geospatial data, taking into account the initial project proposal and several popular GIS file formats and data specifications. With the goal of keeping stored data comprehensive and up-to-date, the team set up a basic acquisition service that retrieves and parses publicly-available geospatial datasets. The initial versions of the service concentrated on a few publically available data sources; while more sources can be added with time.

In early 2015 Cal Poly set up an application server to host RAPID, getting in place the project's technical dependencies. A prototype was built that imports sample GIS data and, additionally, exports that data for specified geographic regions. After learning more about required geospatial file formats and standards for the prototype, the data model was reworked resulting in an improved data model and code base architecture. This improved design more clearly meets our requirements and eases maintainability for future developers.

The software/code, RAPID, was migrated to Cal Poly's project server. The code can be accessed on the following GITHUB project site: https://github.com/chrislupo/dot-rapid

Cal Poly built a prototype data base and querying service (RAPID) that meets the core data and system requirements elicited on the prototype data model as outlined above. RAPID is built on the Python-based Django web framework with a PostgreSQL database, with PostGIS extension. In summer 2015, a prototype data model was completed. A video was created for internal knowledge capture. A link to the prototype data model and instructional video (https://vimeo.com/132036977) demonstrates the current prototype data model's basic functionality for adding and retrieving data.

The Django web framework allows third-party software to manage and query an arbitrary number of geographic data sources through one centralized REST API. RAPID was built with permission management capabilities for DataLayers and GeoViews, thus a multi-tenant system allowing scalability for multiple proprietary data users. The querying service was built to provide access to the data for the crucial information requests elicited as part of the system requirements. The prototype was built, and tested in-house and delivered for testing and integration with partner MDA and C-CORE.

Preliminary tests on the performance of the RAPID system were completed on three dataset sizes, each separated by a multiplication factor of 100 Features: small (10), medium (1,000), and large (10,000). Test queries were run on a development server—a virtual machine with 1 GB RAM and a 2.5 GHz CPU.

PostGIS indexes and WITHIN queries are constructed such that, even with hundreds of thousands of table rows (and, for polygon geometries, encoded data for tens of millions of data points), GeoView results can be evaluated in under half a second on commodity hardware. In addition, increasing the number of features in a DataLayer by two orders of magnitude only shows, at most, a thirty-three times slowdown. In general, each leap in size only adds fractions of a second to the whole query—less than a ten times slowdown.

Throughout 2015 and 2016 the Cal Poly team worked to develop a “Manager Portal” and Graphical User Interface (GUI) for customer feedback. The current GUI to the data model can be found at: www.geocontex.com:8000/rapid/. Screenshots of the system are shown below.

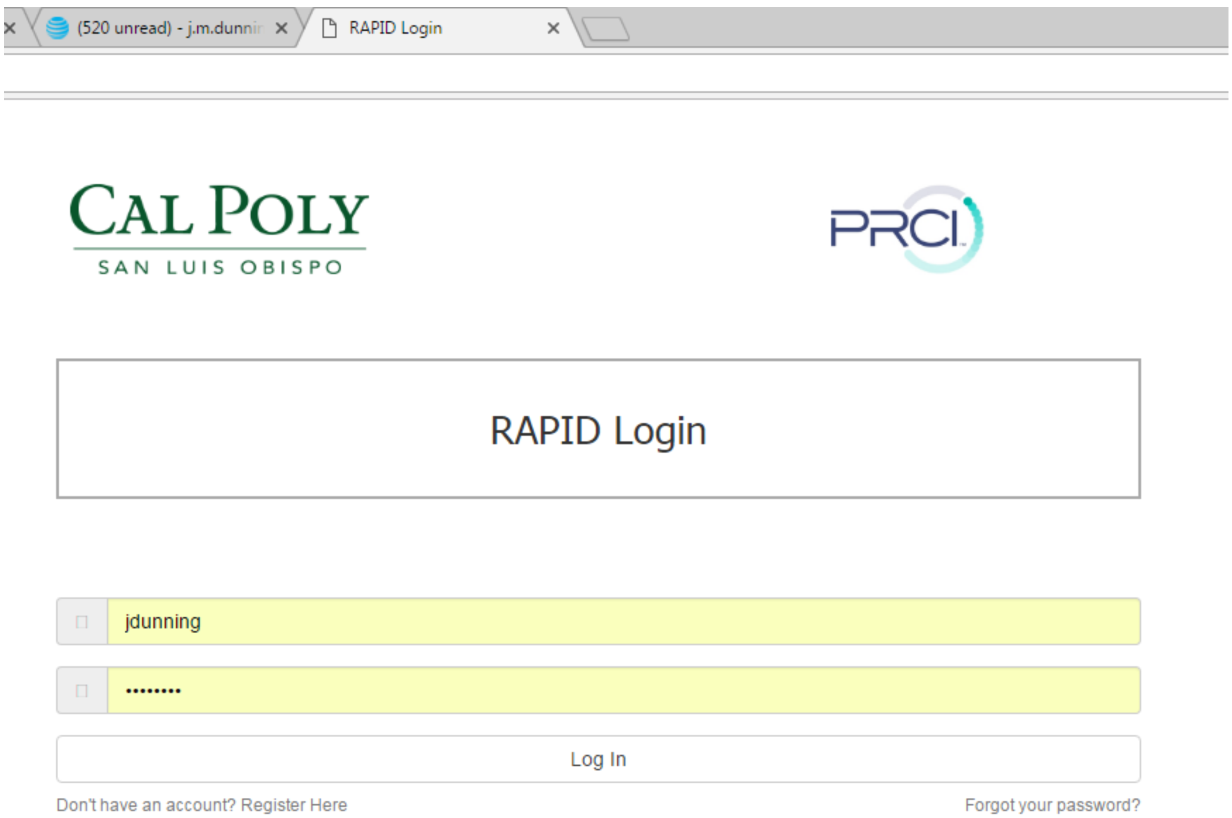

Figure 2: RAPID Login Screenshot

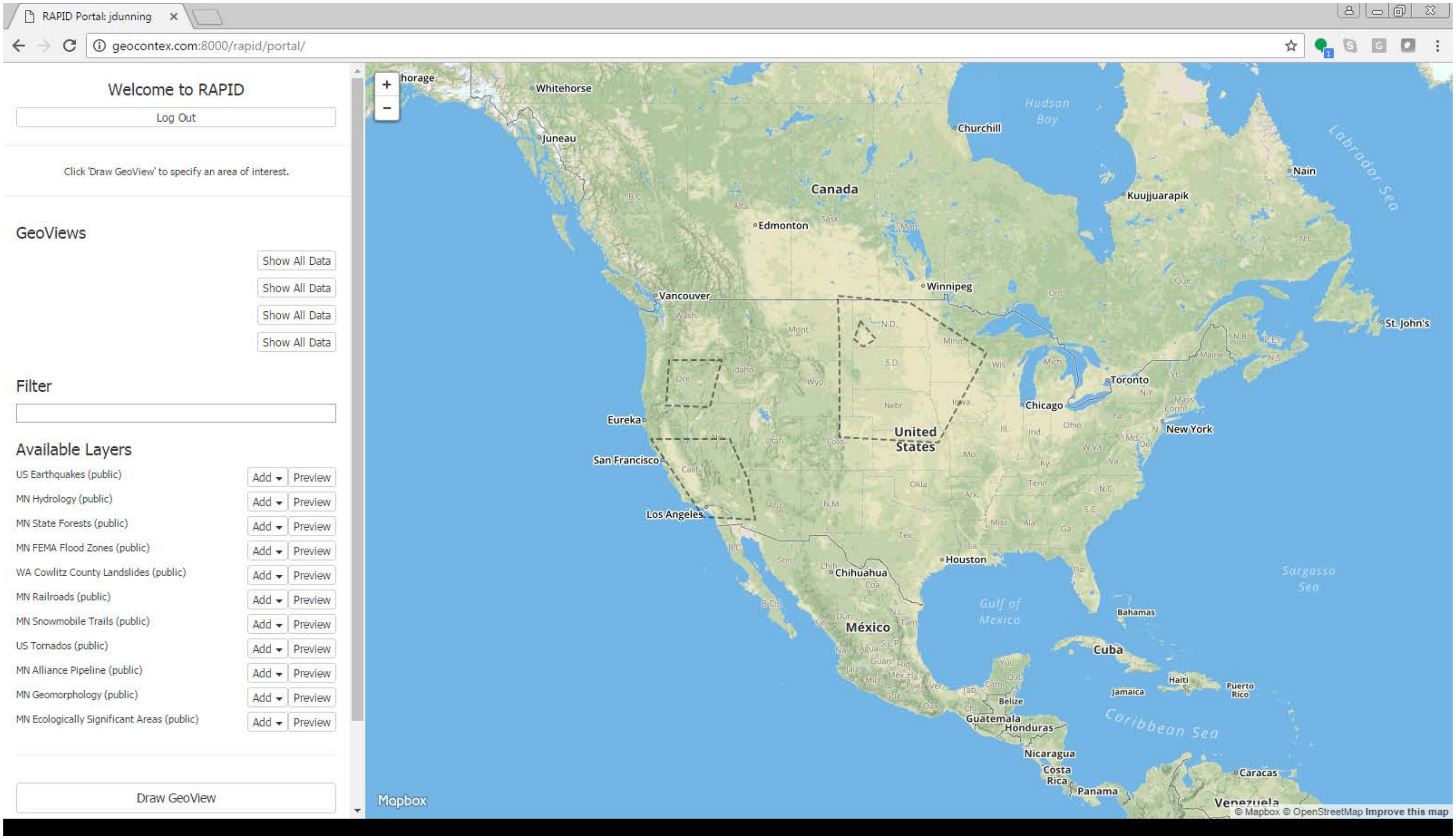

Figure 3: GeoView Screenshot #1

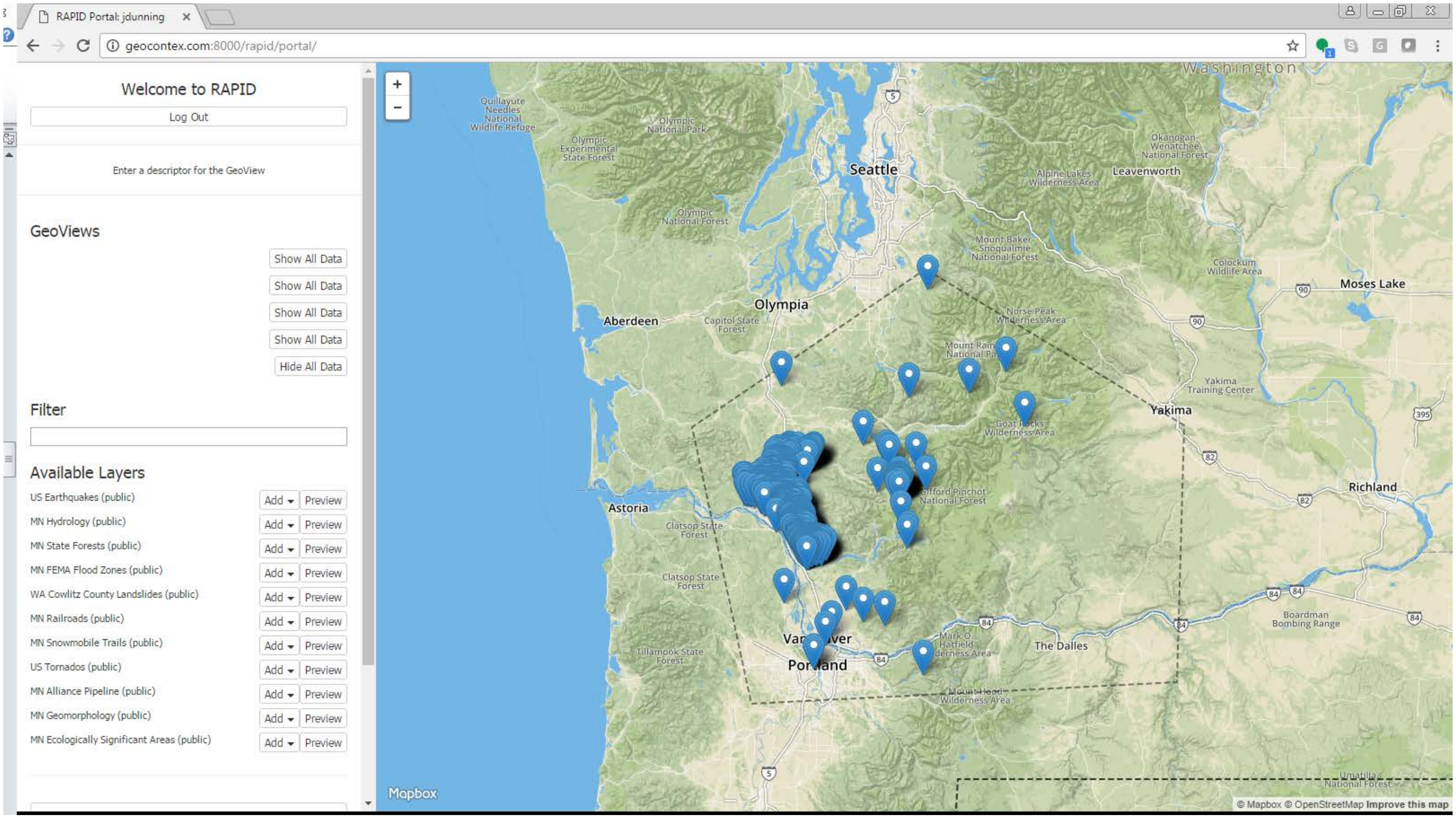

Figure 4: GeoView Screenshot #2

Cal Poly successfully integrated the RAPID data model with the OGC compliant GeoServer web-platform. GeoServer automatically serves out web coverage service (WCS), web map service (WMS), and web feature service (WFS), all OGC-compliant, data formats and is easy to set up utilizing a PostGIS database. Below is a summary of tasks completed:

- Migrated project to Amazon AWS server
- User authentication and registration for the RAPID portal
- Authentication as a requisite for using the REST API (in order to hide secret keys and manage users solely on the server side) is implemented.
- Customizable Area of Interests (AOI)s also known as GeoViews, have been implemented enabling the user to draw on a Leaflet web map and ingest the AOI into the data model.
- Implemented ability to upload shapefiles and create public or private data layers from user machine via web browser.
- User can view data available for his or her account via the web portal.
- GeoServer Integration
- Main user portal page with map
- Create GeoViews on map
- Create GeoViews by specifying bounding box

Cal Poly began to catalogue the open source third party software and data packages/platforms that are incorporated and made part of the Cal Poly data model. This information dictates how the data model can be commercialized and to ensure that proper citation / license information is preserved in the data model code going forward. A list of preliminary sources is shown below in Table 1.

Table 1: Third Party Open Source Software for Data

Third Party Packages/Platforms	Version	Open Source Licenses
Bitnami Djangostack (there are many technologies embedded in this stack)	1.9.4-0	
- Django	1.9.4	BSD license
- Python	2.7.11	Python License
- SQLite	3.7.15.1	Public Domain license
- MySQL	5.5.48	GNU General Public License v2
- Apache	2.4.18	Apache License v2.0
- PostgreSQL	9.4.6	BSD License
- OpenSSL	N/A	Apache License
- zlib	N/A	zlib License
- Boto AWS API	2.6.0	MIT License
- Libiconv	N/A	LGPL license
Geofence	N/A	GNU GPL v2
GeoServer	2.7.2	GNU GPL v2 or any future versions
gsconfig	N/A	MIT License

Third Party Packages/Platforms	Version	Open Source Licenses
Java	V8, update 77	GNU GPL v2
Nginx	N/A	2-Clause BSD License
Bootstrap JS	3.3.6	MIT License
Leaflet	0.7.7	2-Clause BSD License
Leaflet Draw	N/A	MIT License

Cal Poly also investigated a series of web-based 3D visualization modelers for terrain and GIS data utilizing WebGL and Javascript to show proof of concept of utilizing the RAPID system. The tool uses Digital Elevation Models (UTM NAD 1927 coordinates and DBF format) to model the terrain, and GIS data (in decimal degrees and GeoJSON format) to model scientific data. Sample model data for San Luis Obispo was used to prove the concept of the tool. The current terrain data represents San Luis Obispo County, and the current GIS data contains a GeoJSON 'LineString' feature representing a stretch of US Highway 101, and a GeoJSON 'Point' feature representing an earthquake recorded on July 13, 2014 at 17:52:47. The prototype tool is currently hosted at the following URL, http://users.csc.calpoly.edu/~abcross/SLO.html. A single screen shot of the prototype model is below.

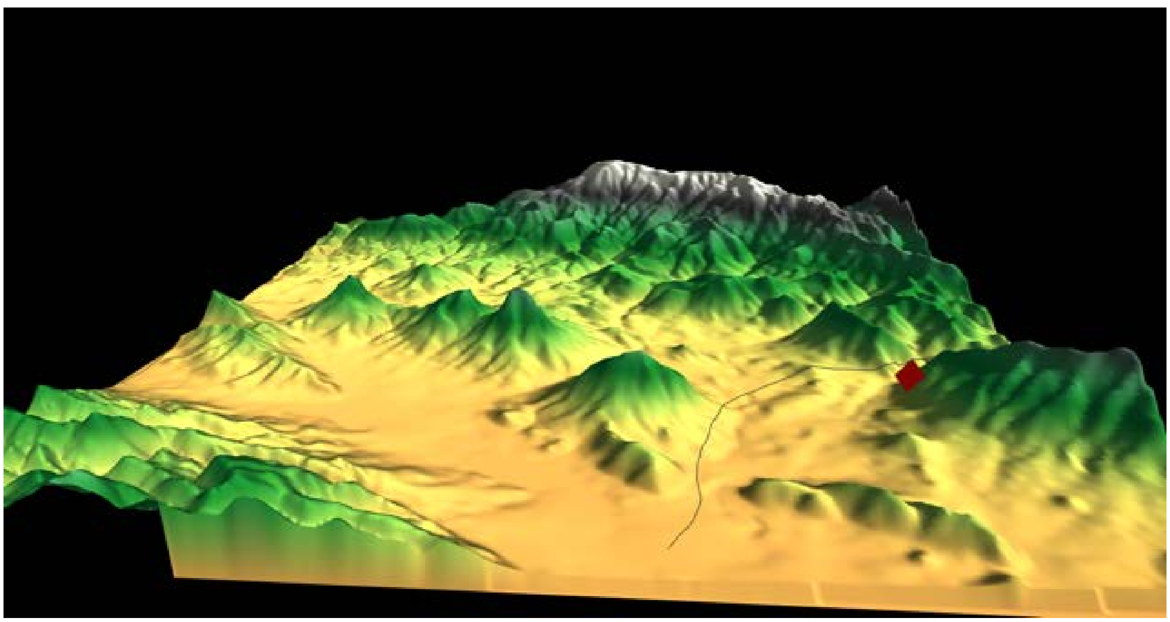

Figure 5: Data Model Prototype Screen Shot

The prototype visualization model utilizes two shaders: one shader to provide multi-textured coloring for terrain geometry based on relative elevation, and one shader to provide standard coloring for GIS data representations. The project takes in a DBF file representing the terrain, and creates a 2D rectilinear array of averaged elevation values. This 2D array is then triangulated to create renderable WebGL geometry. GeoJSON 'Point' features are represented by diamond shaped glyphs on the terrain, which are translated to line up each 'Point' feature. GeoJSON 'LineString' features are represented by creating new WebGL 'LINE_STRIP' geometry, with a vertex created for each GeoJSON coordinate.

Future work to be completed on the Cal Poly data model, with separate and additional funding and not under the current scope of work is listed below.

- Data import from URL
- Links to various data formats (e.g. WFS, WMS, KML) available via GeoServer in portal page
- Ability to apply SQL queries to individual layers
- Import of aspatial data (e.g. PDFs)
- Data management page in portal
- Ability to share GeoViews
- Add ability to use raster layers
- Scheduled background data updates from URLs
- Refactor import/export code to employ GDAL/OGR
- View all available data in given GeoView
- Integration with 3rd party APIs (e.g. WeatherUnderground)
- Integration of RAPID data model and permissions with Geoserver for serving data in multiple OGC-compliant formats to multiple tenants.
- Automated update of data from web-based sources.
- Web portal layout and functionality improvements.
- Fetching and ingesting data from a URL supplied by user.

Also, currently the team is exploring the following static and dynamic features that will supplement ground movement and encroachment DSSs being developed by MDA and C-CORE. The goal is build a series of custom analytics based on user needs. The list below is not a comprehensive list of features, and some data may not be available in a format that is usable for the system without extensive user pre-processing to make use feasible.

Static Features / Layers or Query Capability

1. Along a section of pipeline show me:
    a. Areas of topographic anomalies (slopes < XX%)
    b. Fault crossings or faults within XX feet
    c. River or gorge crossings on or within XX feet of pipeline
    d. Soils with elasticity of XX or susceptible to caving – sandy / silt soils
    e. High population density
    f. Jurisdictional boundaries (city/municipal unit/county/tribe/federal/international)
    g. Wildlife corridors
    h. Designated sensitive flora / fauna areas
    i. Regulatory authority for safety/maintenance/reporting
    j. 811 contact information
    k. Established public access points and/or route intersection for hiking, trails, recreation

Dynamic Features / Layers or Query Capability

1. Along a section of pipeline show me:

a. Precipitation events (establish triggering thresholds)
    i. Type (snow, rain, mix, etc.)
    ii. Intensity
    iii. Duration
    iv. Maximum
b. Temperature (soil and/or rapid freeze/thaw event tracking (establish triggering thresholds)
    i. Intensity
    ii. Duration
    iii. Maximum
c. Tornado events (establish triggering thresholds)
    i. Intensity
    ii. Duration
    iii. Maximum
d. Seismic events (establish triggering thresholds)
    i. Intensity
    ii. Duration
    iii. Maximum
e. Anemometer (wind speed direction – abnormal (establish triggering thresholds))
    i. Intensity
    ii. Duration
    iii. Maximum
f. Fire events
g. Landslides
h. Land APN parcel ownership changes
i. Consolidation of APNs from multiple to single land owner
j. Proposed sensitive flora / fauna areas under review
k. Proposed changes to jurisdictional boundaries (proposed annexation)
l. Proposed public access points and/or route intersection for hiking, trails, recreation
m. Development activity – permitting, news of development proposed
n. Published reports (geologic, environmental impact statements, surveys, etc)
o. 811 ticket volume (historical)

CHAPTER 5: SATELLITE-BASED PIPELINE ENCROACHMENT MONITORING ACTIVITIES – APPROACH & OBJECTIVES

Satellite-based monitoring of third party encroachment involves persistent acquisition satellite imagery over a pipeline right-of-way (ROW). Satellite monitoring offers unique advantages to the industry in meeting the objectives of managing third party encroachment and potential for mechanical damage. These advantages have been recognized by the industry, and efforts to improve the service have been underway under the auspices of PRCI since 1999. Some of these advantages include:

- The ability to identify damage threats;
- The ability to monitor area footprints allowing the surveillance of the ROWs of multiple operators and the cost-sharing of these services;
- The weather-independence monitoring, facilitated by radar imagery and analysis; and
- The ability to monitor without installing equipment or infrastructure on the ROWs.

This monitoring, dubbed Encroachment Management Service (EMS), is achieved using computerized change detection to identify potentially hazardous activities, combined with analyst quality control of the computerized results to create an output product of activity. Third party encroachment monitoring using satellite synthetic aperture radar (SAR) is a valuable service that provides all-weather, day or night monitoring of a specific geographic location.

To date, service development efforts have primarily focused on the detection of heavy construction equipment, which manifest as point-like targets in the satellite imagery. In addition to the detection of heavy equipment, PRCI members indicated the desire to extend the monitoring beyond simple vehicle detection and include the detection of early or leading indicators of encroachment. These indicators can generally be described as environmental indicators and include excavations or other ground disturbances, the appearance of infrastructure (transmission poles), erosion, vegetation growth and other associated encroachment effects.

On the basis of the above, a research program was formulated to address the following two objectives:

1. Reducing false detections, thereby improving the automation aspect of the service and placing fewer demands on operating personnel; and
2. Testing the capability of detection of early or leading indicators of encroachment.

Concerning Objective 1, EMS primarily utilizes change detection between two recent scenes to detect the emergence of new targets within a specified zone surrounding key infrastructure. Both subtraction and ratio methods are implemented. This approach reliably detects larger vehicles and construction machinery and can indicate the presence of on-going human activity such as construction within the AOI. Due to differences in imaging geometry among scenes being compared, significant numbers of false positives may also be generated. Further complications arise in the process of aligning the imagery prior to performing change detection. The alignment process is never perfect across the entire scene, and is particularly challenged when the scenes to be aligned were acquired with differing viewing geometry. As a result, change detection performed between any two scenes generally produces many false positives. False positives create significant additional work for analysts performing the monitoring service as each detection must be examined and verified as a legitimate target or ruled out. This limits the extent of area that can be monitored with a given number of resources. Further, false positives lead to unnecessary costs resulting from field visits by EMS clients attempting to verify the encroachment, and reduces confidence in the technology. Thus, developing a means to reduce false positives in EMS will provide significant value to the service. The research described herein examines these issues and makes recommendations for improvement of the EMS process.

Concerning Objective 2, the present EMS is for vehicular encroachment only (heavy construction equipment) and does not examine any area environmental disturbances. Point targets of interest are classed as a Notice, Alert, or Alarm based on their proximity to the pipeline ROW. There has been a desire by operators to consider enhancing the point target detection service by including early or leading indicators that include excavations or other ground disturbances, the appearance of infrastructure, stock-piling of material, erosion and vegetation removal. Changes in ground disturbances from digging can be detected using satellite SAR, in addition to standing pools of water depending on the size of the area, terrain type and surroundings. Thus, the research described herein investigated detection methods of leading or environmental indicators for pipeline encroachment monitoring.

To facilitate the objectives described above, a large series of CSK satellite images were considered for analysis. Due to scheduling and logistics, no field work was conducted during this project. Therefore, attempts were made to determine the minimum size (length and width) of area changes from the CSK imagery and obtain ground verification, where possible, from Alliance personnel.

For Objective 1, owing to the nature of EMS, significant false detections will always be a factor. However, it was shown that these detections can be mitigated. False detections can arise from several sources including misalignment of the images being compared, natural variations in image brightness, foreshortening and shadowing resulting from the viewing geometry, and real changes between scenes. To reduce these false positives, three techniques were researched, including adaptive alignment, beam mode subtraction and automatic masking. Imagery demonstrations have provided evidence to suggest that each of these methods holds promise for significantly reducing human oversight needed for EMS. While the performance of each technique was not fully characterized, a representative set of examples provide some valuable insight into the problem of false detections in EMS.

The adaptive alignment method appears to perform well for reducing false positives when the imaging geometry of the scenes to be compared varies significantly. Further, when combined with the normal subtractive EMS outputs, the number of detections is further reduced, owing to the differing spatial distribution of the detections. The beam mode subtraction method actually increased the number of false detections, however, when combined with the normal EMS process, a significant reduction in detections was found. The automated masking approach also shows significant promise for reducing false detections that arise repeatedly. This approach can lead to a highly detailed exclusion map that replaces the manually generated one currently in use. Automated masking is easily integrated into EMS as it can be implemented as a separate process that feeds into EMS in the form of an updated exclusion mask.

The key recommendations for improving EMS in the future include:

- Modifying EMS to allow for multiple simultaneous change detection methods to be implemented, and create a tool for managing the combination (fusion) of the results.
- Combining bright-pixel detection in the most recent image with change detection results.
- Implementing the grayscale automatic masking algorithm in EMS to augment the manually generated exclusion mask currently in use.

For Objective 2, it was shown that using detected targets during EMS operations was the most successful and effective method to locate area changes caused by construction vehicles located in the general vicinity. There were 44 area changes found among five sites during EMS's operations. These changes included new commercial building construction, suspected quarry expansion, and pipeline repair work. Many other seasonal and agricultural changes, such as crop harvesting were noted, but not included as events since these changes required a very low threshold resulting in many false detections.

Area change detection using satellite SAR images is possible and can be added to near real time (NRT) services for encroachment monitoring by using target detection to locate areas of change. Automated area change detection requires more research due to the current challenges, such as image alignment. Segmentation and texture measures methods of area change detection have shown promising results as a tool for leading indicators. More work is required in the future to refine the methods and determine which method would provide more consistent results.

Area based changes would help weigh the importance of investigations by field personnel. If an area change is detected near the pipeline ROW, then there might be ground disturbance activities occurring that pose a threat to the pipeline. Area change information would help investigate potential encroachment events and provide a tool to inform managers when construction starts and stops at a known site.

CHAPTER 6: SATELLITE-BASED DETECTION OF GROUND DISTURBANCE NEAR PIPELINES

RADARSAT-2 Ultra-Fine (3-m ground resolution) data was collected starting in March 2014 – one ascending and one descending image collected on a 24-day basis. This data collection continued at this interval for the duration of the project. An additional nine months of data were collected over and above the in-kind data contribution for this project during the extension period from March to December 2016. A total of more than 85 images were acquired and analyzed for this project. Figure 6 shows the descending coverage over the AOI.

Figure 6: RADARSAT-2 UltraFine image coverage over Kalama, Washington

In addition to the above data, WorldView-2 (WV-2) high-resolution 8-band multispectral (1.85 m) and panchromatic (46 cm) data was collected coincident to the ground-truthing campaign. The WV-2 data was used primarily for terrain and ground cover assessment and interpretation.

The Dual Corner Reflector Field Design (DCRFD) over a segment of the Olympic Pipeline operated by British Petroleum (BP) near Kalama in Washington State was finalized in May 2014 after negotiations and approval from the landowners in the area. A total of 13 locations were selected for the installation.

26 Corner Reflector (CR) units (aluminum trihedral, lexan weather cover, galvanized steel end caps) and 13 cross-arms with 2’x2’ steel base plates were manufactured through MDA’s supplier. These were shipped to BP in Washington State in the summer of 2014. The thirteen dual CRs were installed in October 2014. The final locations of the dual CRs are shown in Figure 7.

Figure 7: Dual Corner Reflector locations, Kalama, Washington

These were aligned to the RADARSAT-2 ascending and descending satellite passes between the end of November and beginning of December 2014. A picture of CR #15 is included below.

Figure 8: Dual Corner Reflector #15, Kalama, Washington. ©MDA, 2014

The purpose of the installed CRs was to provide a field of monuments for exact slope monitoring by Interferometric Synthetic Aperture Radar (InSAR) methods in the AOI.

Two MDA staff visited the site in Kalama, WA along with the pipeline operator on March 12, 2015. MDA verified the orientation of 19 CRs, including 14 dual-look reflectors, and took photographs and field notes about any local conditions, including visible signs of surface deformation.

Figure 9: Dual Corner Reflector #9, Kalama, Washington. © MDA Geospatial Services Inc., 2015

Field notes were collated and compared to both the high resolution optical data and the RADARSAT-2 data to aid in the interpretation of preliminary results.

In order to verify that the CRs were properly oriented to the satellite path, a "visibility check" was performed soon after the CR installation. An example of the radar backscatter signal pre- and post-installation is included below.

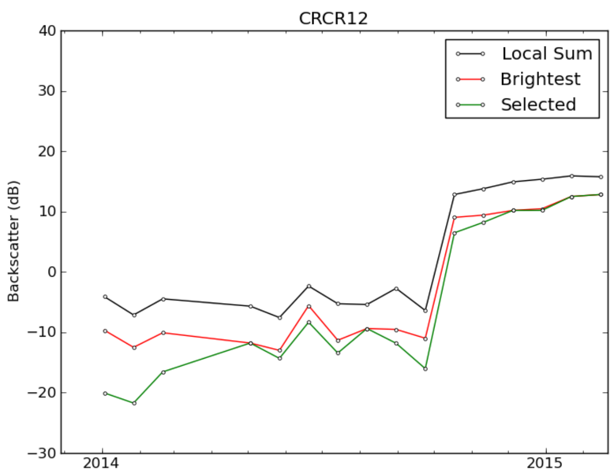

Figure 10: Example of the change in backscatter prior to and after CR installation. © MDA Geospatial Services Inc. (2015)

Monthly discussions with the pipeline operator were on-going for the duration of the project. The InSAR results were delivered and reviewed as required. An in-person meeting was also made possible in March 2015. Knowledge of the area, problems encountered by the operator due to heavy precipitation and slope movement in the area were discussed.

Pipeline ROW monitoring aims to detect risk factors that might influence safety and reliability of a pipeline system. Traditionally, monitoring large, geographically distributed pipeline networks has been accomplished using ground or aerial surveys, both of which are time and cost intensive. The use of satellite radar imagery can reduce time and costs, shorten the repeat interval, and allow for monitoring independently of weather or remoteness. Satellite monitoring can provide an effective means of long-term monitoring, and also has the potential to detect possible issues along pipeline routes before they impact operations.

The purpose of this work was to measure changes in the terrain surface utilizing InSAR approaches in order to identify areas of surface stability risk, changes in the vegetation and ground cover and to highlight areas of slope instability and erosion hazards.

CRs are passive instruments (they have no on-board electronics) designed to reflect all incident microwave energy back to the satellite sensor. They consist of a simple aluminum trihedral, which is precisely oriented toward the satellite Line of Sight (LOS) (the exact alignment depends on location, beam mode and pass direction). The reflector base-plate is bolted to an anchored piling. Hence, the reflectors experience precisely the same motion as the underlying ground and serve as measurement points to capture the overall deformation of the reservoir. More specifically, any deformation having occurred between two dates (satellite image acquisitions) creates a relative phase difference in the returned signal, which can be measured with very high accuracy to provide an estimate of the vertical deformation having occurred in that time period. Deformation measurements are expressed relative to a temporal and spatial reference. The *temporal reference* is the date at which we assume zero deformation.

This date can be moved forward to accommodate the installation of a new batch of reflectors, and ensures that all cumulative measurements are directly comparable. The measurements are also calibrated relative to the *reference reflectors*, which are located outside the area of anticipated deformation. The reference CRs are used to eliminate any residual atmospheric or unwanted seasonal trends from the deformation profiles.

Starting in July 2015, monthly InSAR measurements from CRs were provided to the end client on a monthly basis. These included a summary of the InSAR results at the CRs, horizontal and vertical measurements of the ground movement at the Kalama, WA site. The following figures shows a summary of these measurements over the project area.

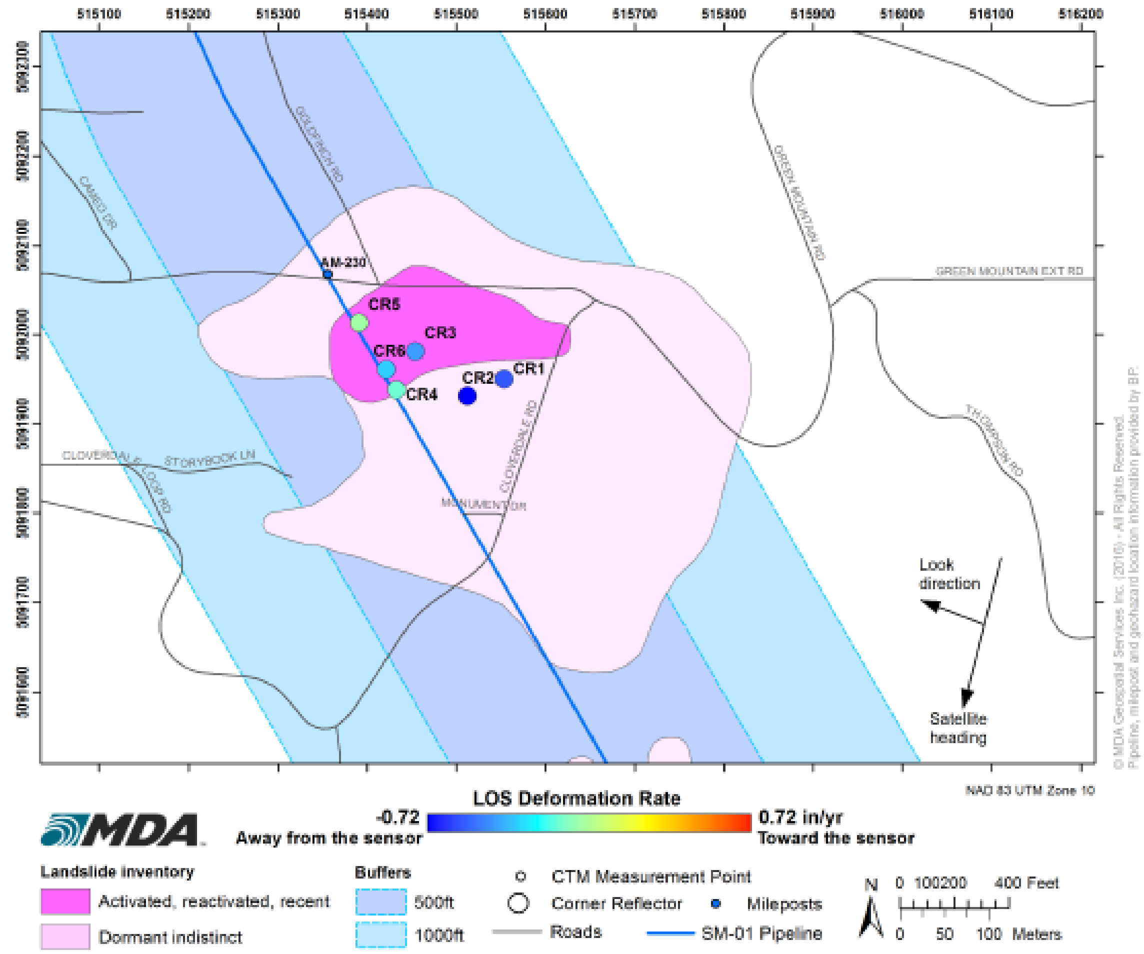

Figure 11: Line-of-sight InSAR measurements at original single-look CR locations. CRs 1, 2, 3, and 6 show an overall trend of subsidence. © MDA Geospatial Services Inc. (2015) – All Rights Reserved.

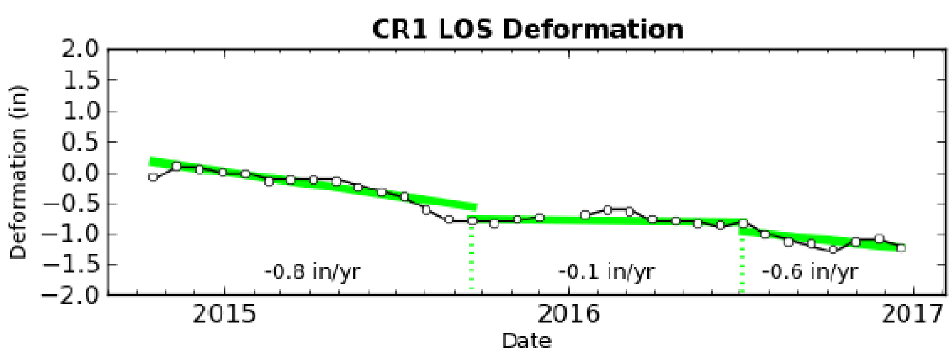

Figure 12: Westward CR1 ground movement profile. © MDA Geospatial Services Inc. (2015) – All Rights Reserved.

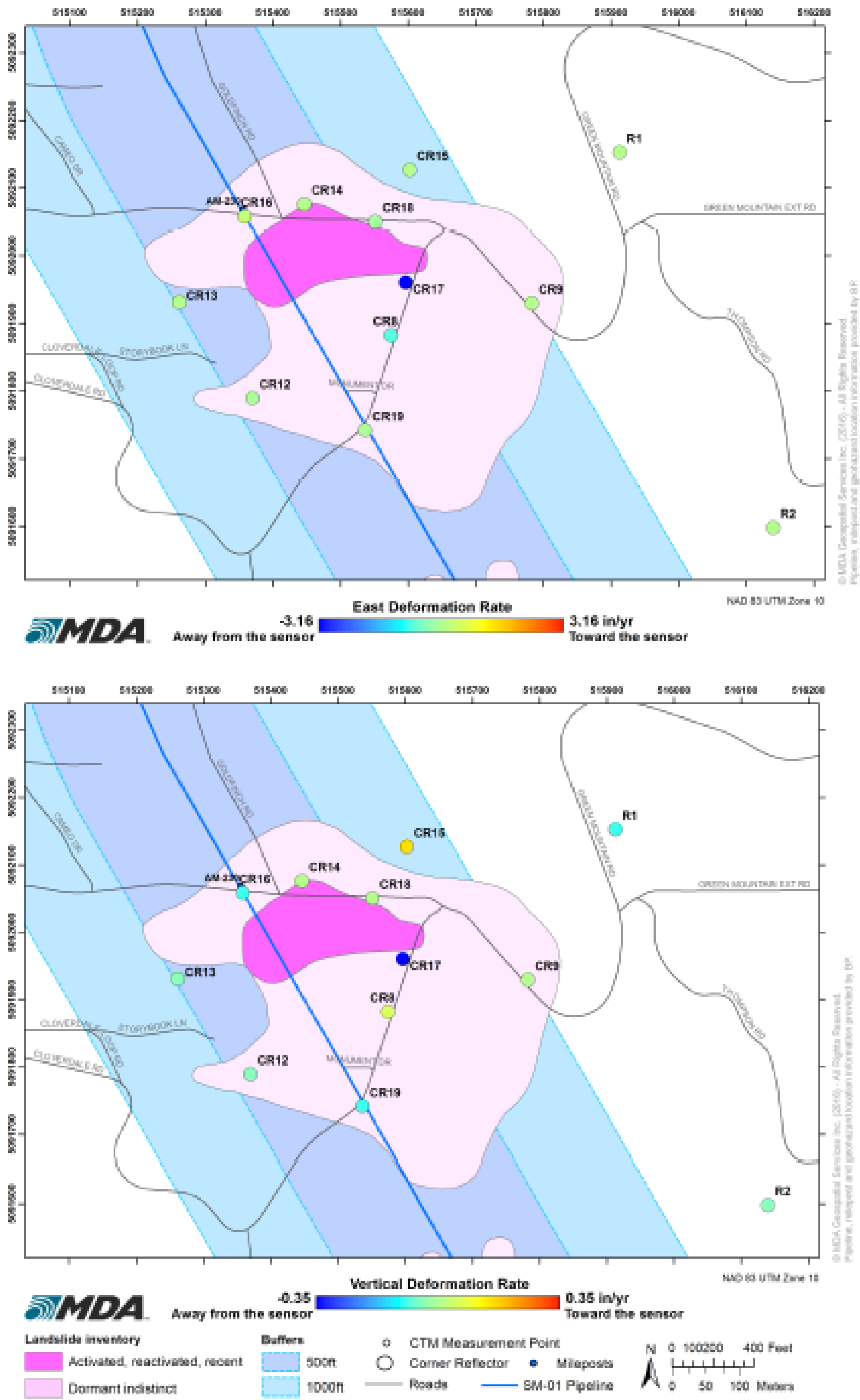

Figure 13: Horizontal and vertical deformation rates at the 13 dual-look corner reflectors. CRs 8 and 17 have shown a continued trend of subsidence during the course of the project. © MDA Geospatial Services Inc. (2015) – All Rights Reserved.

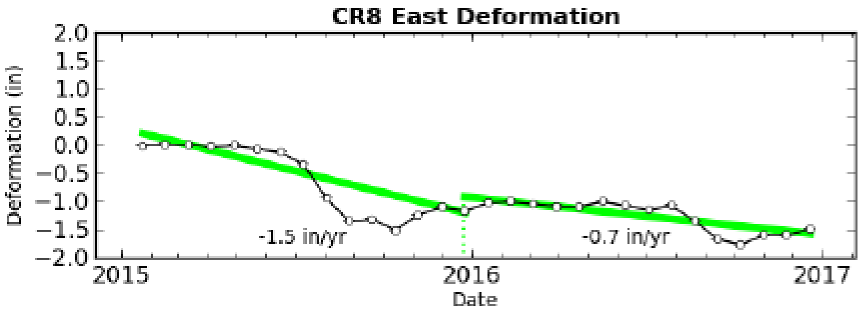

Figure 14: Westward ground movement profile at CR8. © MDA Geospatial Services Inc. (2015) – All Rights Reserved.

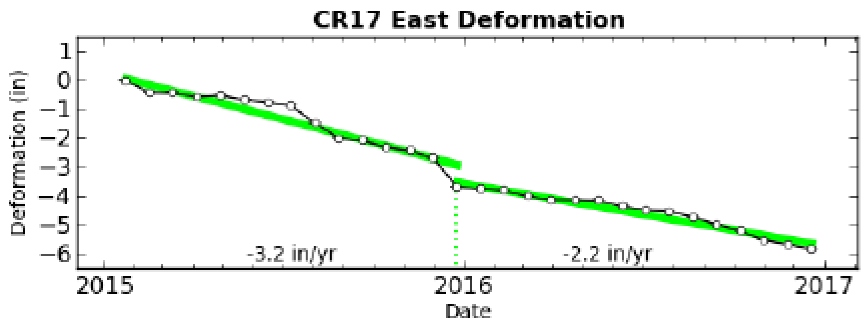

Figure 15: Westward ground movement profile at CR17. © MDA Geospatial Services Inc. (2015) – All Rights Reserved.

MDA's ground movement mapping from InSAR provides information necessary to both measure surface deformation and identify potential geohazards occurring at the operator's selected AOI.

Slope movement in the westward direction was the main geohazard identified in the selected AOI during the project period. In the fall of 2015 the line was excavated due to increased strain from persistent slope movement. Figure 16 shows the excavating equipment and open trench ROW seen from the resulting RADAR Amplitude change detection analysis. There is an increase in backscatter around the pipeline, between CRs 16 and 4, from disturbed ground surface. There is also a large increase in backscatter uphill of the pipeline which was confirmed to be the excavating equipment.

Amplitude change detection relies on large-scale changes (on the multiple pixel level) to provide a qualitative indication of change. Where InSAR measures change in surface deformation on the order of millimeters but fails when the change is too large (order of 10s of centimeters in a small area), the use of an amplitude change algorithms can provide highlights of large changes, such as natural changes in the river course or infrastructure change such as this example.

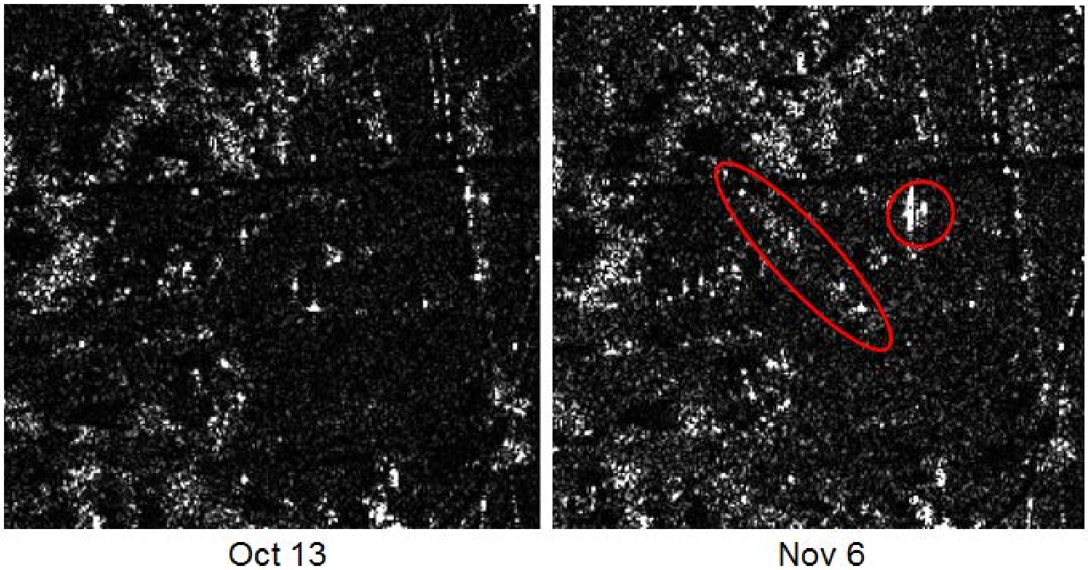

Figure 16: Excavation equipment (small red circle) and excavated line (larger red oval) from Amplitude Change Detection analysis between October 13, 2015 and November 6, 2015.

Ground movement measurements were also measured using the Coherent Target Monitoring (CTM) technique in the Kalama area. CTM is used to supplement and complement the information provided by the CR analysis. A *coherent target* (also referred to as a *persistent scatterer*) is a location on the ground for which the ground cover is temporally stable (does not undergo rapid changes). Human-made features such as processing plants, tanks, roads, pipelines and buildings, and natural features such as consistent snow pack or gravel cover make good targets. Because these targets are coherent, the phase difference can be calculated as with CRs in order to derive an accurate deformation estimate. CTM points are selected based on the *temporal coherence* of targets, some points having higher coherence than others. High temporal coherence is normally associated with higher accuracy of the deformation estimate. Major physical changes on the target can lead to miss-estimation of the deformation for that point. Running a CTM analysis for the first time requires a minimum number of RADARSAT-2 acquisitions in order to evaluate temporal coherence and select suitable targets. As is the case for CRs, CTM deformation estimates are expressed relative to a given temporal and spatial reference. In most cases one of the reference CRs is used as a spatial reference. CTM monitoring provides information about infrastructure health, and warns of potential problems with subsidence or uplift of pads, plants, well heads, pipelines, etc. It also expands the spatial coverage of the CRs to increase the sampling density of the deformation patterns.

In the AOI few CTM targets were identified and used due to the region being primarily dominated by pasture and grazing areas with a few farms and homes. The small number of identified homes and buildings were used as CTM targets, as shown in the next figure. These targets were monitored during the project period.

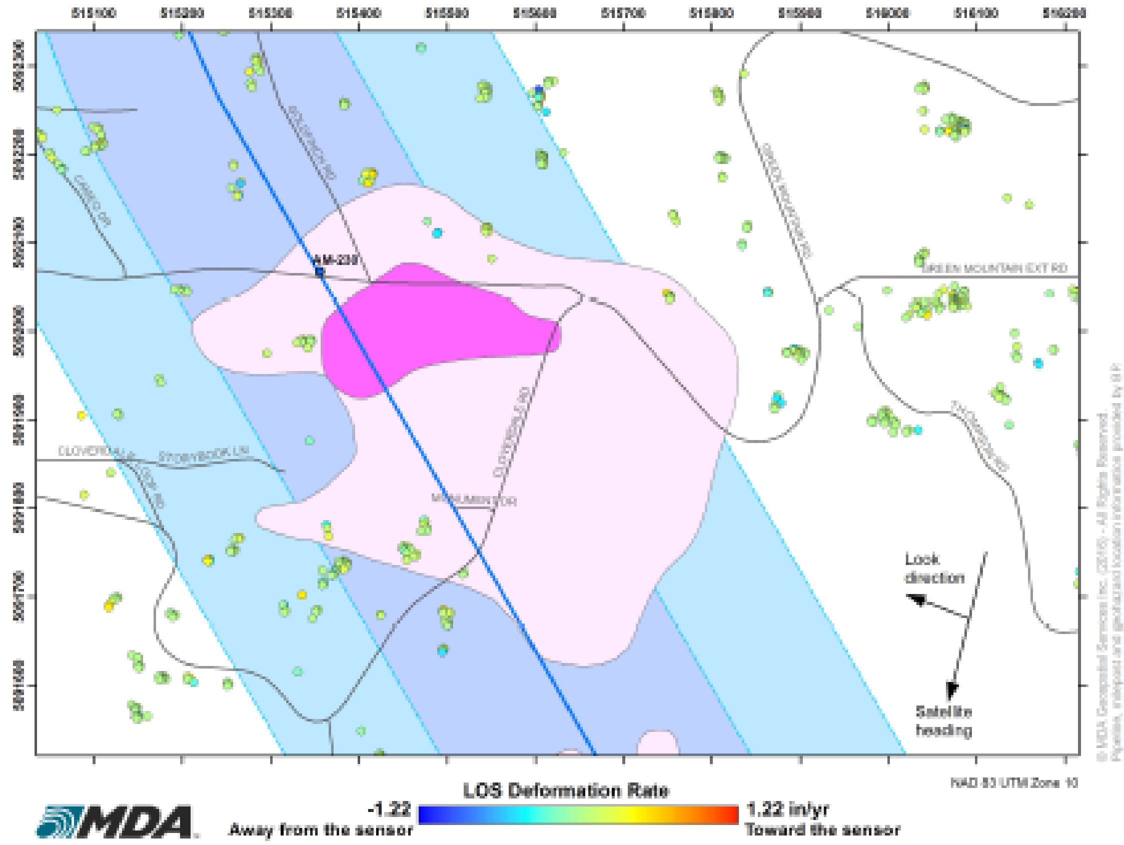

Figure 17: Deformation rates for the identified CTM targets in the area, where blue indicates movement toward the west, while yellow and red indicates movement toward the east.

The CTM analysis was also expanded to include a wider region of interest. Deformation rates for this area are shown in Figure 18 below. There were no large scale deformation patterns in the area.

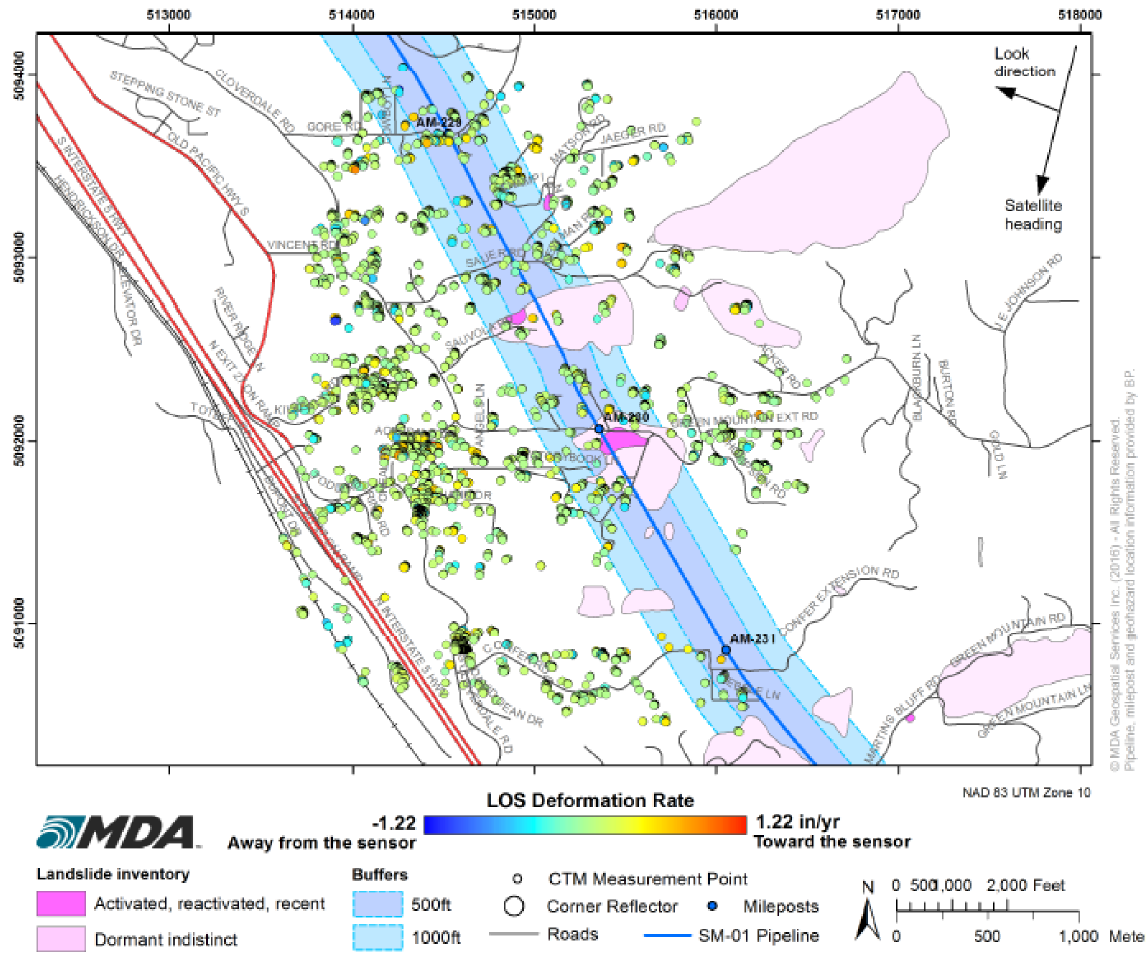

Figure 18: Deformation rate for the identified CTM targets in the area where blue indicates movement toward the west, while yellow and red indicates movement toward the east.

A grid network was created over the full AOI using 50 meter grid squares and each square calculated the average deformation within, as shown in the figure below. While the grid more clearly illustrates the deformation pattern, it but does not reveal a distinct large scale motion in this particular area.

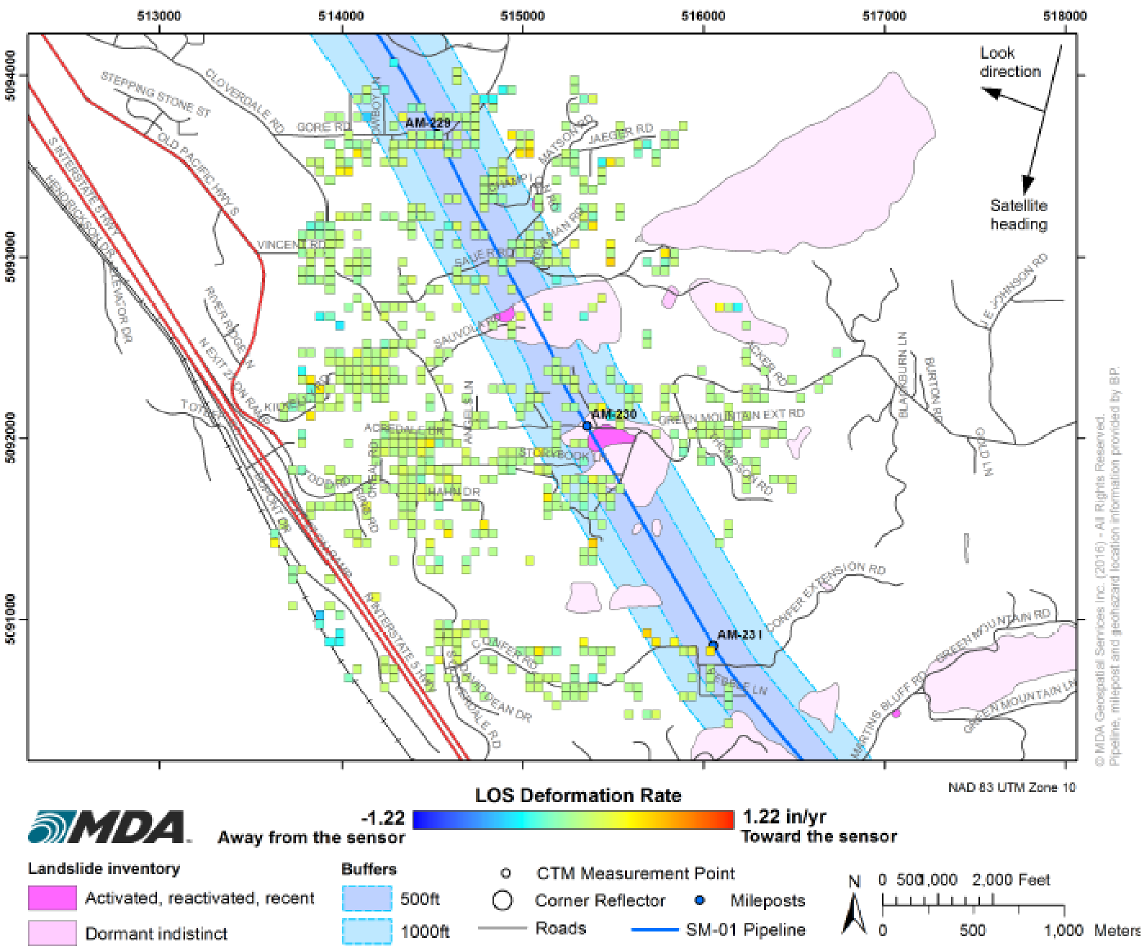

Figure 19: Grid network (50m) illustrating the deformation rates for the CTM targets in the area where blue indicates movement toward the west, while yellow and red indicates movement toward the east.

Additionally, an in-depth analysis of the uncertainty of 3D (north/east/vertical) and 2D (east/vertical) decompositions of line-of-sight deformation was newly created. In particular, we focused on projecting LOS deformation to the local terrain, providing slope-following deformation estimates (amount of deformation in the direction of the steepest slope gradient). The resulting map is illustrated in the figure below.

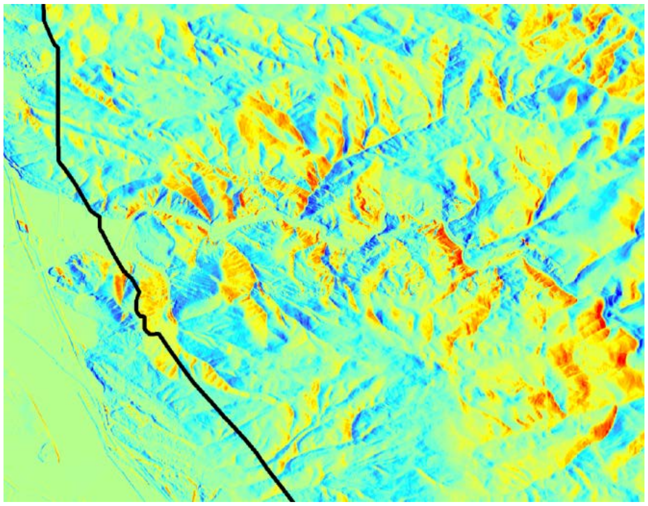

Figure 20: Depiction of expected magnitude of east-west deformation given local terrain, under the assumption of slope-following deformation. Actual deformation measurements from InSAR can be projected to a similar frame of reference.

This tool proved very useful for a number of other pipeline projects we were involved with in the last year. Understanding the local terrain provided a more concrete look at the optimal look-direction for radar data collection, the direction of the potential ground movement, and in certain cases where the slope/topography was extreme, areas where no signal could be measured.

The objectives of the Research Project were to examine the utility of the techniques established by MDA for land classification, deformation and change analysis utilizing SAR data from the RADARSAT-2 satellite program, and then effectively upload the derived information into a Decision Support System (DSS) for easy access and action by pipeline operators. Specifically, quantifying the utility of progressive change information from interferometric terrain mapping enabling wide-area strategic risk assessment for geohazard alerts and risk identification in areas where terrain (both ground cover and topographic) change may enhance the potential for adverse effects of erosion and the risk of landslides near pipeline infrastructure. An illustration of the information collection and dissemination is included below.

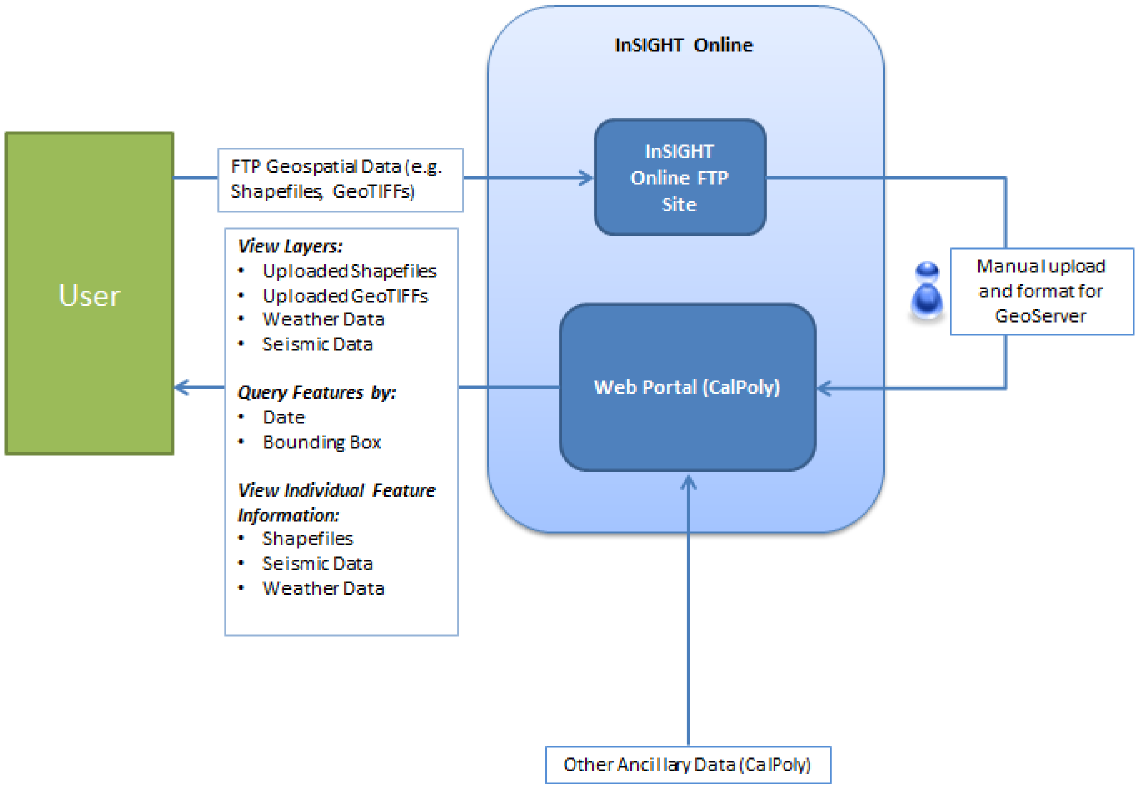

Figure 21: Example of DSS for Geohazard Assessment data collection and dissemination

A number of various DSS service providers were evaluated by MDA for ease of use and applicability, as well as integration into client workflow work package. These included an available in-house program, Google Earth, GeoPro and finally ArcGIS Online. An example of GeoPro (Intermap) with available data layers in the AOI is included below.

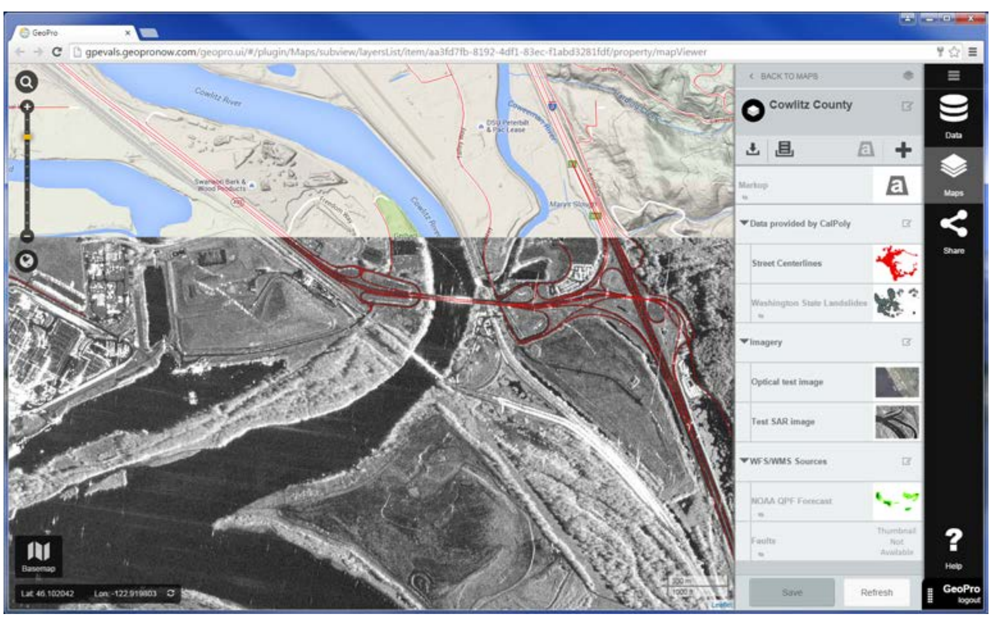

Figure 22: Example of a radar image, roadway and landslide polygons (off –screen) loaded into the GeoPro interface

After a thorough evaluation, GeoPro proved to be the most suitable; however, due to MDA's IT restrictions and customization requirements the cost for the service became prohibitive. MDA is currently looking into the possibility of using ArcGIS Online. This tool is being investigated for other types of operational projects at MDA and may prove useful as well for pipeline projects. In the meantime however, during the latter part of this project, InSAR measurements were converted to kml files and were displayed using Google Earth, as show in Figure 23 below.

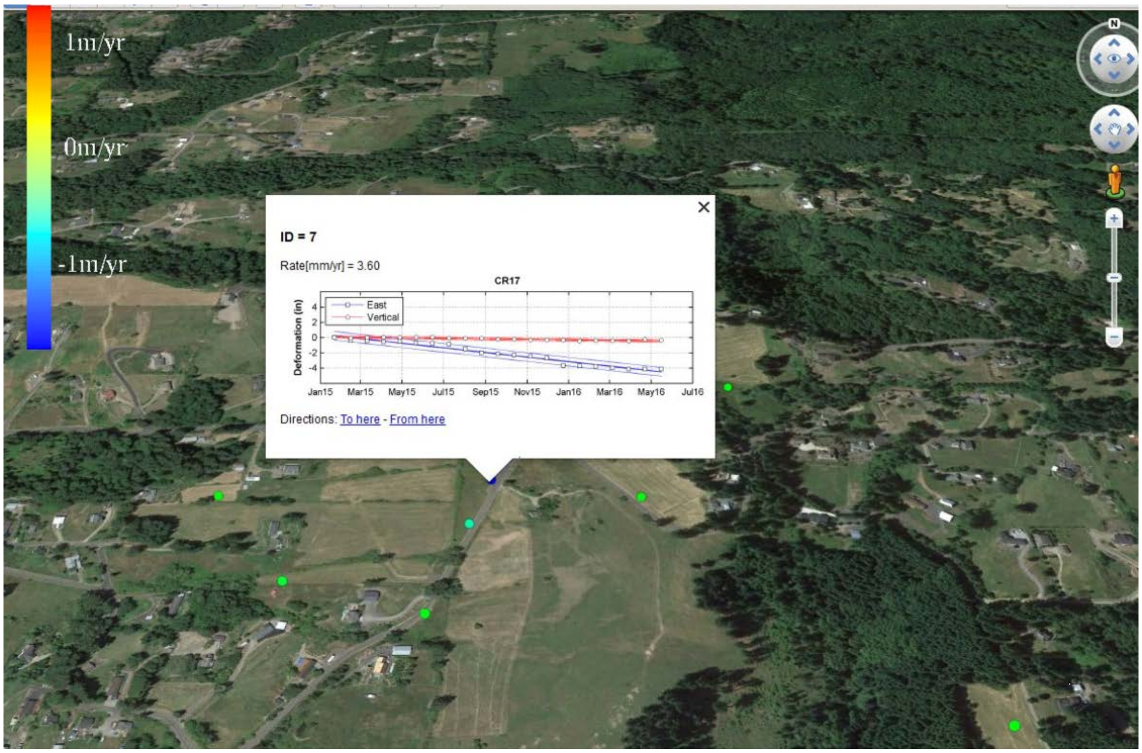

Figure 23: Horizontal and vertical deformation rate profile for CR 17 displayed in Google Earth. The color legend for the rate of deformation is also included and indicates for this CR a westward trend (blue).

MDA received from BP the landslide map for the area as well as train gauge measurements.

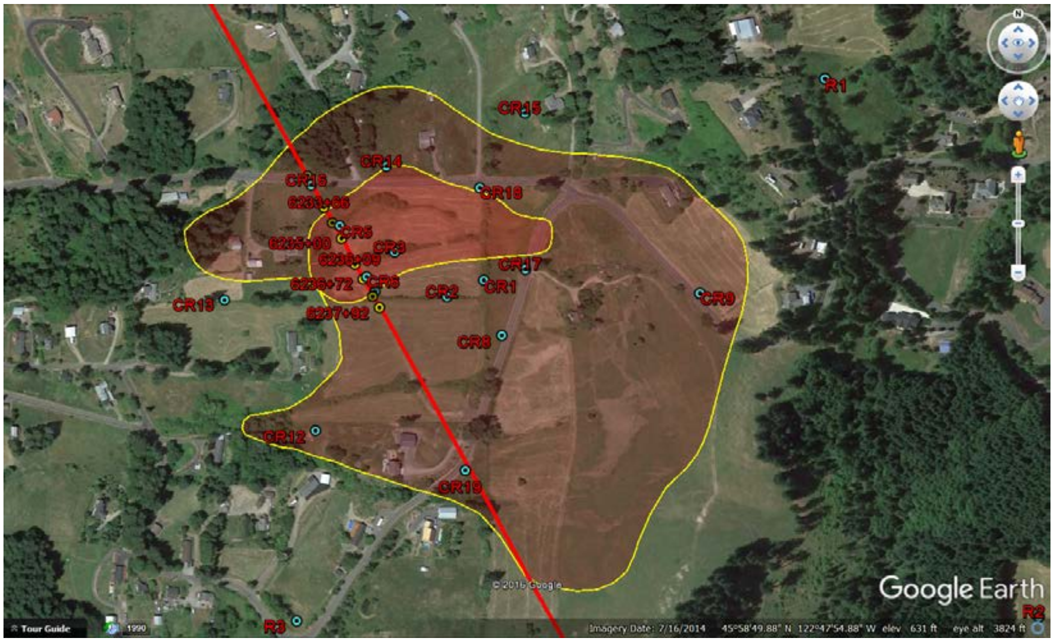

Figure 24: Landslide polygons and strain gauge locations

A first set of geospatial data from Cal Poly was received for the Kalama, WA area, including: rail, sensitive aquatic areas, land parcels, soils, streets, elk areas, landslides, precipitation, earthquake magnitude, wetland inventory, and flood hazard.

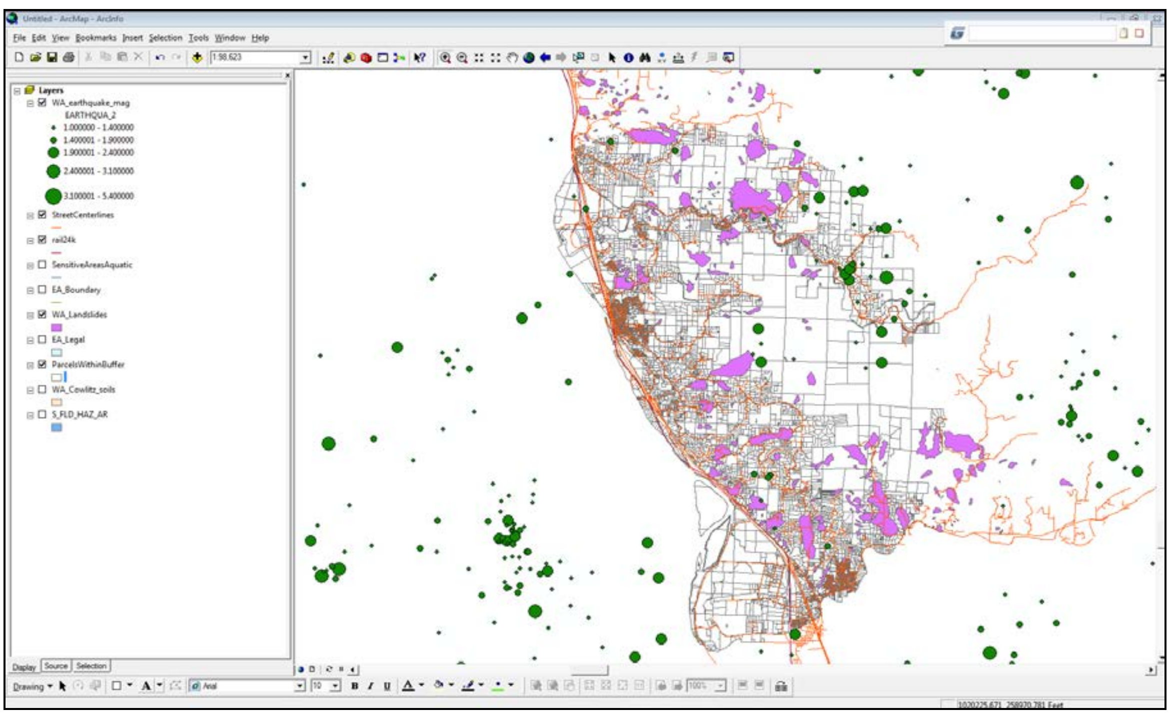
Figure 25: Geospatial data displayed in ArcGIS. Image © MDA Geospatial Services Inc. (2015), data from various sources.

Geospatial modeling using ArcGIS system was used to look at the resulting geohazard risks in the AOI. An example of the InSIGHT product which combines the information derived from satellite and other sources as a decision tree is shown below. The goal of the InSIGHT product was to provide quick actionable results for the pipeline operator staff and their managers using the DSS.

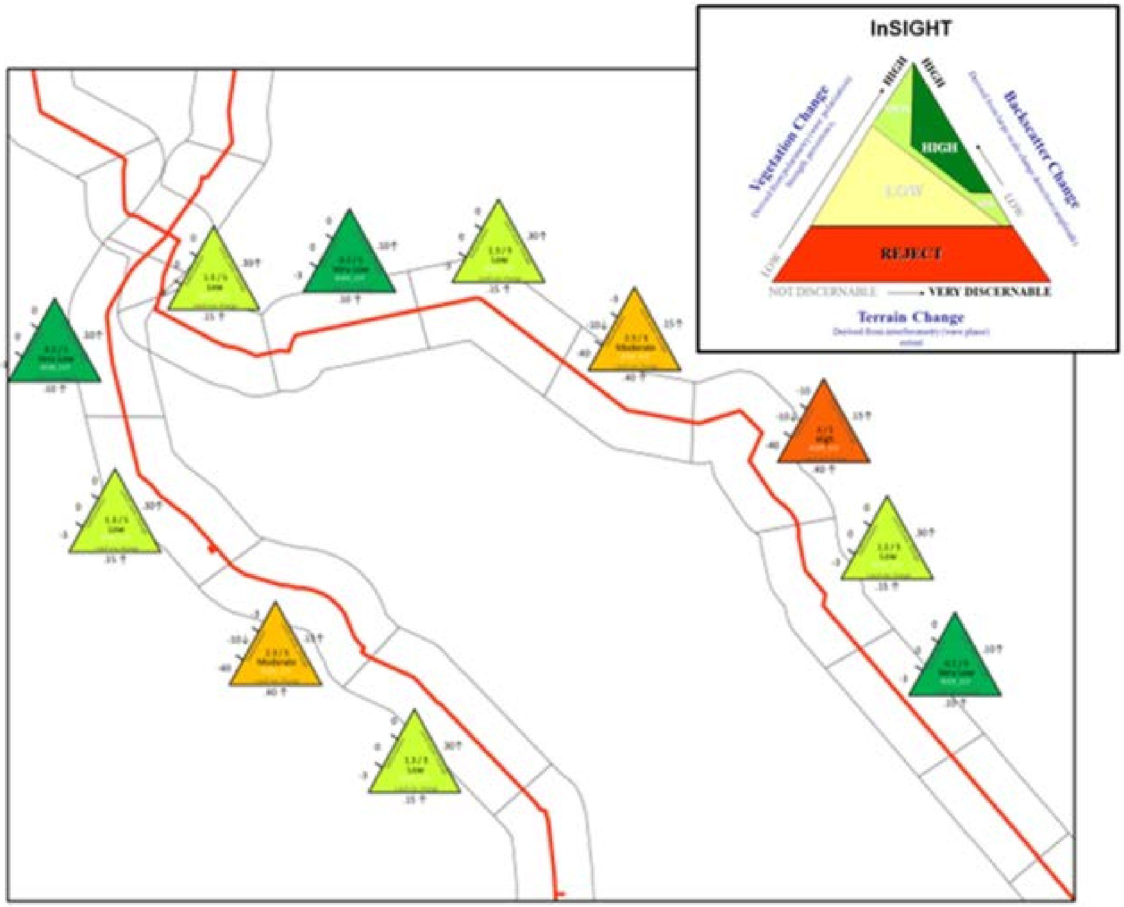

Figure 26: Example of the custom InSIGHT mapping index of observation results. The InSIGHT mapping index product provides a means to combine results on the ground change from different data sources. It combines the information in a methodology that provides operators the information required.

The InSIGHT product provides a means to communicate information about the pipeline ROW that does not require in-depth training and interpretation of RADAR imagery. It was designed to provide a simple interface to pipeline operators and present information in a GIS or map format. While the AOI selected was a good candidate for the slope monitoring aspect of the InSIGHT mapping index, vegetative change and land use change related to geohazards were minimal and therefore not measured for this area. In the last year, however, a version of the InSIGHT index was applied to other commercial projects thereby enhancing our operational services for the pipeline industry in supporting regular geohazard monitoring and pipeline risk assessment.

Finally, in addition to the continued development and refinement of the InSIGHT index, we looked at how precipitation and seismic information could be utilized in our system as rain rates and other weather information which can potentially be a direct predictor of landslide risk. Similarly, seismic reporting from the USGS may also be critical in the prediction of pipeline integrity and necessary to the isolation of areas requiring remediation. These data sources can be mined to provide complementary information that may not be available from the satellite but are important information sources for decision makers. To that end, we looked into developing automated precipitation alerts. A system has now been put in place to gather historical and forecast data from NOAA sources and produce precipitation updates (Figure 27) for any number of weather stations within the pipeline AOI.

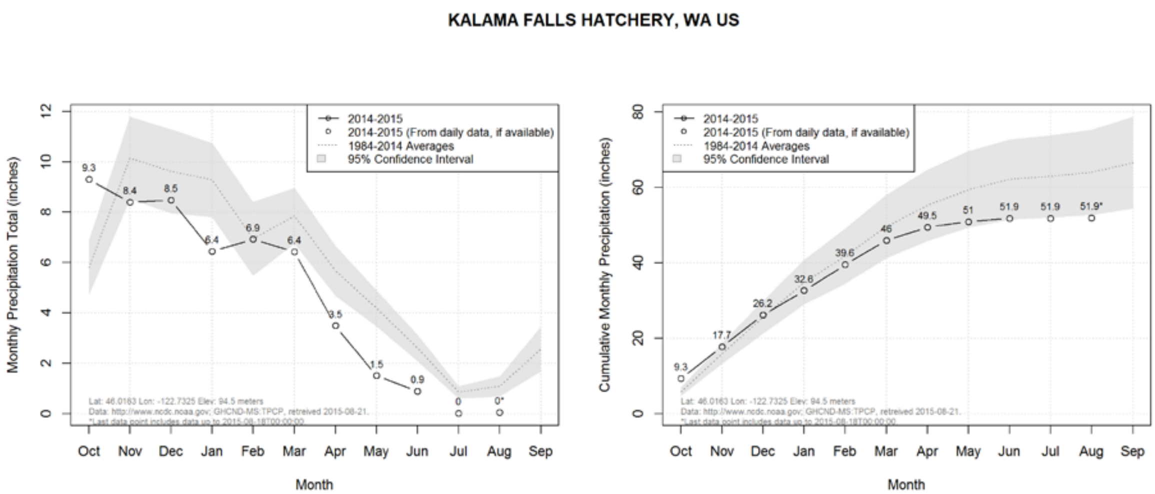

Figure 27: Example of a monthly, automated precipitation update. Showing monthly precipitation totals for the current year, and historical average plus confidence interval. The left plot shows monthly totals, and the right plot, cumulative totals.

The system can also produce heavy precipitation alerts, where an email message is automatically sent out if precipitation greater than a selected threshold occurs at any point of the pipeline AOI, in the last 24-hours (Figure 28). The plotting and email system is fully automated and documented.

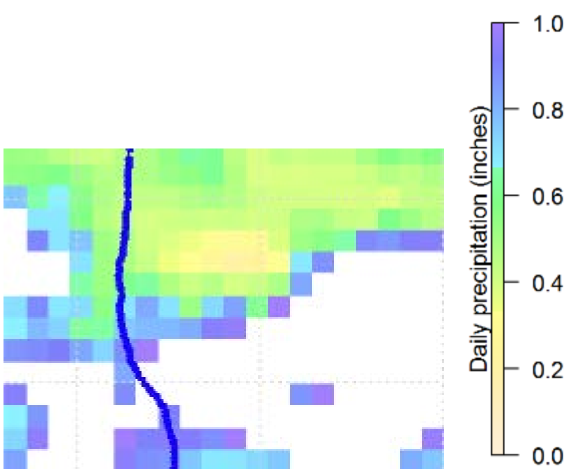

Figure 28: Example of a portion of a heavy precipitation alert plot, showing an area of the pipeline having experienced more than 1-inch of precipitation in the 24-hour period (in white)

A new type of monitoring technology – GBSAR - has been proven in mining applications and shows promise for monitoring deformation of infrastructure or slope movement with accuracy of better than one millimeter (0.040 in.). This type of monitoring was devised to test the utility of this technology for monitoring above-ground gas pipeline infrastructure that is being impacted by ground subsidence. The infrastructure monitored included: a compressor building, a segment of pipeline, pipe supports and foundations. The first objective was to demonstrate the logistics involved to operate the system both on site and remotely, the measurements and output products of the GBSAR for monitoring pipeline-related infrastructure. The second objective was to compare the GBSAR results to satellite InSAR ground movement estimates. A four month monitoring program was successfully executed in Blythe, California, at a compressor station.

A segment of pipeline along with its supports and foundations, and the compressor building were monitored. The results generated from the GBSAR data for the pipeline showed that for the portion of pipe nearest the radar the pipeline moved away from the radar slightly, while for the portion of pipeline further from the radar the direction of motion was towards the radar. The north facing wall of the compressor building showed movement in a general southerly direction. The magnitudes of the movements measured near the eastern corner of the wall were less than the movements measured near the center and western corner. These measured displacements indicated that the top of the wall is tilting towards the south, with more tilting occurring towards the western corner. While the GBSAR data detected lateral movement, the satellite data showed that the building was not moving in the vertical direction.

Laser scanning was proposed as a source of data for validation of the GBSAR results. The idea was to take before and after laser-scan of the building and compare the differential to the GBSAR results. Unfortunately, the laser scan of the building was not conducted because it required the shutdown of the compressors at the station building. However, there might be interest in considering what the GBSAR has to offer compared to laser scanning, and vice versa. Laser scanning is primarily designed for precise 3D models of infrastructure. It could be used to derive infrastructure movement, but it was not designed for this purpose. Conversely, the GBSAR has been designed to do exactly this. Nonetheless, in simple cases (small structures, simple movement), laser scanning and the GBSAR could be used interchangeably. However, the GBSAR has several advantages over laser scanning, including the ability to ‘average out’ vibrations and diurnal movement. Also the GBSAR will be superior for monitoring slopes, and for monitoring wide-scale movement over large distances up to 4 km (2.5 miles).

CHAPTER 7: DECISION SUPPORT SYSTEM

The objective of EMS is to quickly identify third party intrusions so that pipeline operators can act to protect the public and prevent pipeline damage. The current service is based on a simple change detection algorithm applied to satellite-based radar data. The algorithm generates too many false positives which have to be manually removed. Data fusion is a process of combining information from multiple sources to create a more informative result than either source could produce individually. By considering other data sources in addition to SAR, it is expected that the estimate of potential encroachment events can be refined to reduce the number of false positives requiring manual assessment. The desired result is a cheaper, faster, more consistent process.

To determine what other data could be brought to bear, C-CORE EMS analysts and pipeline integrity management experts were consulted, and pipeline incident reports and pipeline incident summary data from government and industry pipeline organizations was gathered. Overall, the result was a roughly quantified list of important, mostly common sense, facts. For example, the 3 leading causes of accidental third party intrusion are: construction, agriculture, and infrastructure. And, the most important pipeline design factors in risk mitigation are pipeline diameter and depth of cover.

Bayesian reasoning defines a method of integrating new evidence into existing beliefs based on conditional probability. Because Bayesian belief networks are based on conditional probability they are a robust way of dealing with uncertain cause-effect relationships, and uncertain knowledge generally. One way they are robust is that missing evidence (data) can be simply ignored with the result that the existing beliefs will not incorporate it. Therefore they were chosen as the method for achieving the data fusion.

Based on the collected data and expert opinion, a Bayesian belief network was designed. The network incorporates both change detection output from the satellite-based SAR, and geographic information system (GIS) based vector data as inputs. The output is an assessment of the relative threat level of the potential intrusion. It is planned that the lowest priority threats will be filtered as false positives. The model addresses the 3 top causes of accidental third party intrusion, and assesses threat level based on distance and pipeline design parameters.

The Bayesian belief network was implemented within C-CORE's Coresight framework, a web platform that has been designed for operational services derived from satellite imagery. The web implementation has been tested to show that EMS satellite detections can be easily prioritized to allow satellite analysts to quickly generate EMS report for industry follow-up. The Coresight framework has been tested internally and is now ready for industry wide implementation. Coresight accesses Cal Poly's data model to allow a continuous update of GIS layers for the Coresight platform.

CHAPTER 8: CONCLUSIONS

8.1 - Findings

Based on an extensive open source GIS software and data base literature review, Cal Poly designed and implemented a geospatial data service, REST API for Pipeline Integrity Data (RAPID) to improve the amount and quality of data available to project partners DSS. Rather than leaving the DSS and their users to identify, model, convert between, and store dozens of data formats and repositories, our system manages and exposes simple REST calls for more consistency and centralization. The Cal Poly RAPID system was built with PostgreSQL's PostGIS extension spatial database and the Python-based Django web framework and allows third-party software to manage and query an arbitrary number of geographic data sources through one centralized REST API. The API provides means of looking up geospatial data for particular regions (in space and time), as well as necessary metadata and documentation for its use and interpretation. RAPID was built with permission management capabilities for DataLayers and GeoViews, thus a multi-tenant system allowing scalability for multiple proprietary data users. Cal Poly successfully integrated the RAPID data model with the OGC compliant GeoServer web-platform. GeoServer automatically serves out web coverage service, web map service, and web feature service, all OGC-compliant data formats and was set up with our PostGIS database. Cal Poly will continue to develop the RAPID system and add functionality based on user/customer demands. This open source GIS software product developed as part of this DOT sponsored project complements and adds to the growing body of research and demonstration of open source GIS software systems, such as those catalogued by The Open Source Geospatial Foundation (OSGeo - http://www.osgeo.org/).

Owing to the nature of EMS, significant false detections will always be a factor. However, it was shown that these detections can be mitigated. False detections can arise from several sources including misalignment of the images being compared, natural variations in image brightness, foreshortening and shadowing resulting from the viewing geometry, and real changes between scenes. To reduce these false positives, three techniques were researched, including adaptive alignment, beam mode subtraction and automatic masking. Imagery demonstrations have provided evidence to suggest that each of these methods holds promise for significantly reducing human oversight needed for EMS. While the performance of each technique was not fully characterized, a representative set of examples provide some valuable insight into the problem of false detections in EMS.

It was shown that using detected targets during EMS operations was the most successful and effective method to locate area changes caused by construction vehicles located in the general vicinity. Many other seasonal and agricultural changes, such as crop harvesting were noted, but not included as events since these changes required a very low threshold resulting in many false detections.

Area change detection using satellite SAR images is possible and can be added to near real time (NRT) services for encroachment monitoring by using target detection to locate areas of change. Automated area change detection requires more research due to the current challenges, such as image alignment.

Area based changes would help weigh the importance of investigations by field personnel. If an area change is detected near the pipeline ROW, then there might be ground disturbance activities occurring that pose a threat to the pipeline. Area change information would help investigate potential encroachment events and provide a tool to inform managers when construction starts and stops at a known site.

The above improvements to EMS were implemented into a new DSS built into C-CORE's Coresight platform, a web platform that has been designed for operational services derived from satellite imagery. The results is a system that can quickly identify third party intrusions in satellite imagery so that pipeline operators can act to protect the public and prevent pipeline damage. By considering other data sources in addition to satellite imagery, it was shown that potential encroachment events can be refined to reduce the number of false positives requiring manual assessment. The desired result is a cheaper, faster, more consistent process.

In addition to the algorithmic changes, a Bayesian belief network was implemented within the Coresight framework. The web implementation has been tested to show that EMS satellite detections can be easily prioritized to allow satellite analysts to quickly generate EMS report for industry follow-up. The Coresight framework has been tested internally and is now ready for industry wide implementation. Coresight accesses Cal Poly's data model to allow a continuous update of GIS layers for the Coresight platform.

The results of the GBSAR monitoring program show the GBSAR can provide measurements of the lateral displacement of the building and pipeline, and achieve better than 1 mm (0.040 in.) accuracy. The GBSAR is most sensitive to movement that occurs along its LOS, therefore, radar LOS must be aligned to the primary direction of the expected movement to achieve the highest accuracy. Once installed, the GBSAR can be operated remotely for an indefinite period of time providing continuous measurements (up to once every 5 minutes) of the infrastructure.

When compared with satellite InSAR technique, there are some differences between the two techniques. The GBSAR may be installed in such a manner as to optimize the viewing geometry of the infrastructure being monitored. For satellite monitoring, the viewing geometry is fixed within limits defined by the satellite orbit. This makes the satellite technique sensitive to vertical or east-west lateral movements, but not north-south movements. The satellite technique also does not work well in very steep terrain. The GBSAR may be used to provide complementary movement information when combined with the satellite-derived movement history, allowing the complete (vertical and horizontal) movement history of the infrastructure being monitored.

8.2 - Commercialization Plan

The products and services developed as part of this project are currently being commercialized by C-CORE and MDA respectively as part of existing services to customers worldwide.

The Cal Poly data model is available to C-Core and MDA to incorporate, as needed, into their existing service offerings. Cal Poly will continue to maintain the data model and seek commercialization through strategic partners in the public and private sector.

C-CORE has expertise and world-leading technical capability in Remote Sensing, Ice Engineering and Geotechnical Engineering, provides research-based advisory services and technology solutions to help clients mitigate operational risk in harsh environments and to address security, sustainability and safety issues related to their regulatory and operating needs worldwide. The Bayesian belief network developed as part of this project was implemented within C-CORE's Coresight framework, a web platform that has been designed for operational services derived from satellite imagery. The Coresight framework has been tested internally and is now ready for industry wide implementation. Coresight accesses Cal Poly's data model to allow a continuous update of GIS layers for the Coresight platform.

MDA's Geospatial Services (MDA) is a market leader in the operational delivery of time-sensitive, business process-specific, geospatial information for essential decision making. MDA is the leading provider of advanced geospatial information solutions derived from the high-resolution RADARSAT satellites, commercial optical satellites, and aerial systems. The worked performed under this DOT contract builds upon existing tools that will continue to deliver near real-time information solutions for complex and demanding operational support has made us a primary source of geospatial solutions for the Oil and Gas, Defense and Security, Disaster Management, Aviation, Natural Resources, Agriculture, and Mining markets.

WEBSITE

The project website was led by Cal Poly Professors with assistance from project team members. The website served as the main portal for disseminating project progress and reports. The website went live on June 2014 and was updated and maintained throughout the length of the project. In addition, the site was made publically available for outside stakeholders. Please see the following web address: http://quorra.ored.calpoly.edu/pipeline/.

The project team also developed a commercial facing website for the Cal Poly data model development activities and it is currently hosted here: geocontex.com:8000/rapid/.

In addition, please find a list of publications, conference papers, and presentations prepared under this project.

Conferences

- Electricore and PRCI attended the Government/Industry Pipeline R&D Forum being presented by the Department of Transportation, Pipeline and Hazardous Materials Safety Administration, and the National Association of Pipeline Safety Representatives in August 2014 in Rosemont, IL.
- PRCI and MDA attended the 10th International Pipeline Conference (IPC) 2014 in Calgary.
- The team attended the PRCI Pipeline Program Technical Committee Meetings in San Ramon, CA in October 2015.
- Cal Poly participated in a DOT-lead workshop in Oklahoma City in December 2015; the workshop was focused on Technology Transfer and highlighting pathways to commercialize new products and tools that are being developed as part of university research.

Papers

- Two (2) master's thesis reports were completed by Cal Poly graduate students:
    - "Geospatial Data Modeling to Support Energy Pipeline Integrity Management," Austin Wylie (June 2015) – Attachment D
    - "REST API to Access and Manage Geospatial Pipeline Integrity Data," Alexandra Francis (June 2015) – Attachment E

Presentations

- MDA presented a paper, "Multi-Satellite InSAR Deformation Analysis for Pipeline Monitoring: Operational Application, Results and Validation in the Belridge Oil Field, 2001-2012" at the 10th International Pipeline Conference (IPC) 2014 in Calgary.
- C-CORE's Adam Burry presented a paper titled, "A Decision Support System for Pipeline Encroachment Monitoring," at Geomatics Atlantic in November, 2014 in St. John's, Newfoundland, Canada.
- A summary project poster was presented at the February 2015 PRCI Research Exchange Meeting in Houston, Texas.
- Cal Poly computer science graduate students, Austin Wylie and Alexa Francis, presented a poster "Database & Tools for Improved Satellite and Geospatial Tools for Pipeline

Operator Decision Support Systems” as part of a Cal Poly “Technology Show-and-Tell” event on the Cal Poly campus.

- MDA presented a paper titled, “Monitoring Aboveground Pipeline Infrastructure in Permafrost Environment with InSAR from Multiple Satellites,” at the EPRG, APIA and PRCI Joint Technical Meeting in Paris, France in May 2015.

APPENDIX

Attachment A: Surveying GIS Data Storage and Analysis

Attachment B: CSC 419 Final Project: Pipeline Operator Decision Support Systems Data Model Preliminary Literature Review

Attachment C: RAPID Data Index Methodology

Attachment D: Thesis - GEOSPATIAL DATA MODELING TO SUPPORT ENERGY PIPELINE INTEGRITY MANAGEMENT

Attachment E: Thesis - REST API TO ACCESS AND MANAGE GEOSPATIAL PIPELINE INTEGRITY DATA

Attachment F: RAPID Technical Knowledge Base