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APPLICATION OF GROUND MOVEMENT AND AUTOMATED ROUTE PLANNING TECHNOLOGIES FOR PIPELINE PLANNING AND MANAGEMENT – THE PIPEMON PROJECT

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ABSTRACT

Innovative technologies provide the key to making pipeline operations more efficient. Thanks to recent progress in satellite-based remote sensing and image processing, it is now possible to design pipeline monitoring systems with remote sensors and context-oriented image processing software, as has been demonstrated in particular by the three-year ESA funded market development activity "PIPEMON – Geo-information services for pipeline operators: ground motion monitoring and route planning".

Business partners involved in the Project are currently undertaking pre-commercial trials with market players and potential customers, to better introduce and demonstrate Earth Observation (EO) data and services to the pipeline industry.

1 INTRODUCTION

PIPEMON (www.pipemon.com, hereafter referred to as "the Project") is a three-year integrated remote sensing and pipeline industry activity that is funded by the European Space Agency (ESA) as part of its Earth Observation Market Development (EOMD) Programme (www.eomd.esa.int). The Project is primed by Nigel Press Associates Ltd. (NPA) in collaboration with six business partners.

The long-term objective of the Project is to develop, implement and validate integrated services for pipeline operators using Earth Observation data to achieve efficiency and cost saving for pipeline companies. The services include:

1. Pipeline-related ground and structure motion monitoring, for example:

    - Develop new methodologies aimed at integration of InSAR (that is, radar interferometry as measured with satellite-based Synthetic Aperture Radar (SAR)) reflectors or transponders into newly built pipelines.
    - Measure motion along pipelines in relation to landslip, river crossing or tectonic hazard zones using the Persistent Scatterer Interferometry (PSI) technique.

2. Pipeline route planning, for example:

    - Determine where there may be clear benefits for the pipeline industry in terms of integrated use of EO data and services (i.e., both optical and radar data, used in combination with spatial data such as digital elevation models (DEMs) and terrain, land cover or other mapping).
    - Demonstrate the utility of interferometry methods such as PSI for detection and characterization of ground hazards, as a part of pipeline route planning.

The multi-skilled team of seven partners has built a strong working relationship over a number of years within previous projects (e.g., PRESENSE (www.presense.net) and other ESA EOMD projects). It has particular experience in the EO industry (NPA, Definiens and Tele-Rilevamento Europa (TRE)) and the pipeline consultancy industry (EBA Engineering Consultants, Advantica, Intergraph). In addition, the British Geological Survey has the role of science and technical reviewer for the Project.

The Project is part of ESA's EOMD Programme and aims to promote and develop the use of EO techniques by pipeline operators for, in particular, pipeline monitoring and route planning. The three-year work program began in November 2003 and is currently in Phase 2. Phase 1 was focused on the definition and implementation of these two EO service areas for pipeline operators, while Phase 2 is concentrating on applying these services at real test site locations, as well as marketing and expanding the customer base.

In Phase 2, in particular, the project team is working in close co-operation with pipeline companies in order to provide the most appropriate integrated and easily accessible system for supplying geo-information that encompasses their requirements.

A key component of Phase 2 is to execute pre-commercial trials to test and validate the service. These trials are currently being undertaken in various locations as requested by pipeline companies, and each is using a selection of established EO techniques, in particular, radar interferometry and very high resolution optical data. As part of Phase 2, commercial and economic implications from the trials are also being studied to determine that the meet the technical requirements but also are cost-effective, and fall within price-sensitive limits for the pipeline industry. Ground motion monitoring and route planning services components of the Project are further addressed in the following sections of this paper.

2 USER REQUIREMENTS

2.1 Ground Motion Monitoring

The following subsections summarize some typical requirements for applications of pipeline-related ground motion monitoring as investigated within the Project. The ideal ground motion monitoring tool provides a reliable basis for pipeline integrity risk prediction, such that subsidence events can be managed and pipeline structural incidents/failures avoided.

Underground Storage Areas

Natural gas underground storage areas are frequently composed of leached salt domes or depleted natural gas reservoirs where storage monitoring is governed by mining law, which typically requires ongoing documentation of any soil subsidence and upheaval. Typically, ground movements of more than 1 cm above a closed, usually circular area with a diameter of 500 m to 5 km need to be detected and closely monitored over time.

Coal Mining Activity Areas

In particular in parts of Europe, natural gas pipelines may run through regions of current or former coal mining activity that are affected by considerable differential subsidence. The conventional requirement of pipeline operators and regulators in these areas is that subsidence of more than 5 cm in usually single, but not necessarily regularly shaped areas, sized 0.25 km² to 100 km² must be detected and closely monitored over time.

Landslides

For landslide areas, including local landslip zones, instable locations associated with river crossings or other features, or pipelines constructed through regions characterized by inherently unstable terrain, requirements for ground motion detection and ongoing monitoring are typically similar to those as for coal mining activity. Landslide areas have to be regularly checked to measure possible drift or movement of buried or surface pipelines, and to understand – over time – characteristics and rates of movement, for example, predictable seasonal patterns and extents of ground motion.

2.2 Route Planning

A general objective of the planning phase of a proposed pipeline is to iteratively test and refine the routing options for the pipeline, carefully evaluating a wide range of constraints associated with a proposed corridor, including environmental, engineering, physical, socioeconomic, land ownership, legal and other spatially-based considerations. The exercise is complex and involves considerable ongoing scenario testing and evaluation of options/alternatives.

While pipeline route planning is unique to each proposed project because of the range of considerations that must be examined and evaluated, the general process of spatial data management and iterative constraint assessment is similar from project to project. The Project has focused upon the development of tools that expedite the use of EO data in combination with other corridor-related data and information used to perform the iterative assessments.

In densely populated areas, where there is a greater amount of general infrastructure (roads, plants, buildings, agriculture, protected areas, existing pipelines, etc...), large amounts of spatial and spatially-related information describe the physical environment to a great extent. In such cases, planning a pipeline route means: 1) collation / assembly of required information; and 2) spatial analyses that focus upon constraint mapping with a particular emphasis upon existing infrastructure. Limitations are often in the form of physical barriers/buildings, existing land ownership (e.g., financial limitations related to property transfer / property access) or land dedications, as well as "no go" environmental constraints. Routing options are often highly limited.

In sparsely populated areas, where there is often less infrastructure or existing development, there are other challenges – for example, limited spatial data upon which to initially base constraint investigations, regional land use / ownership / management and regulatory issues, significant environmental issues (for example, difficult issues to address, such as remoteness, complexity of wildlife habitat use, identification of location and extents of sensitive ecosystems) and physical barriers associated with rugged or challenging landscapes. While routing options may not be limited by existing land use conditions, there are a range of other issues to address and weigh in the route selection process.

For sparsely populated areas, it is also typical that available information is incomplete, and coverage of available spatial information is scattered or piecewise. In these cases, remotely available spatial and spatial related information can become an important component of the information base for initial routing planning. New satellite platforms and more robust analytical tools are further assisting pipeline planners in filling the "spatial data gap", so that they can undertake iterative studies of corridor alternatives.

3 PROJECT SERVICES

The following subsections address how some of the services defined and tested in the Project can address needs of pipeline operators and route planners/designers.

3.1 Ground Motion Monitoring

In 1993 Synthetic Aperture Radar interferometry (InSAR) was introduced to the wider remote sensing community with a publication in *Nature* of the interferogram depicting the ground deformation caused by the Landers earthquake [1]. Although the power of interferometry was demonstrated, the conventional technique has not always been applicable in all operational scenarios. Over the last few years, however, a number of technical developments have emerged that provide a higher precision of motion rates, the extraction of specific motion histories, and precise targeting [2].

The following subsections show how the requirements of various applications outlined in Section 2.1 are met with the most applicable InSAR techniques.

Underground Storage Areas

A new satellite radar technique called Persistent Scatterer Interferometry (PSI) [3, 4] can be applied to measure ground movement over underground storage areas. The technique measures the motion of individual structures and ground features to millimetric precision over entire regions in a single process. The power of PSI resides in the archive of radar data that stretches back to 1992, allowing for an up-to-date motion history for every measurement point. The technique assumes the existence of buildings or other man-made infrastructure overground, as these will provide the measurement point locations. In Europe, storage areas are usually below cultivated land so that farmhouses, farm outbuildings and pipeline surface infrastructure may all act as suitable measurement points.

Coal Mining Activity Areas

Conventional differential interferometry (DifSAR) can be used to measure ground subsidence over coal mining areas. Ground movements are typically very fast during the removal of a mining panel (for example, 50 cm within two months). In contrast to PSI, which cannot measure velocities of more than 10 cm per year, DifSAR can measure faster movements after or during the mining activity event.

Landslides

For landslide areas with slowly creeping soil, PSI and DifSAR may be used under some circumstances, or alternatively, artificial corner reflectors can be employed in an array to precisely measure the sliding ground at specific locations. Corner reflector interferometry (CRInSAR) allows ground displacement measurements at centimetric precision, carried out remotely. As CRInSAR can acquire new measurements every month, they cannot be used for real-time measurements or to measure fast-moving landslides.

3.2 Route Planning

Route planning requires constraint mapping along the corridor(s) being considered for a proposed pipeline, such that various scenarios or alternatives can be compared objectively and – as new information may become available, for example – rapidly updated and re-analyzed with new information, new weighting scenarios or additional logic / constraints. Geographic Information System (GIS) based constraint (or "suitability") mapping, in particular, is well suited to support route planning, as it can provide an automatic system for spatial data interpretation and weighting. Moreover, it can readily incorporate and integrate spatially based EO data and information.

A clear advantage of using an automated GIS-based method for route selection constraint mapping is that it is inherently reproducible, even when there are needs to integrate vague models, weighting matrices or linguistic information. The automatic reasoning process associated with a GIS-based constraint mapping process, if properly incorporated into the GIS environment, will be transparent and available for iterative testing of options / alternatives. The system readily incorporates weighting and ranking protocols, so that individual constraint features can be emphasized / de-emphasized in the constraint mapping process. Use of a GIS-based analysis can also help the route planner to avoid the need for time-consuming reinvestigations and recalculations, as the iterative process proceeds.

The procedure, as developed and tested within the Project, directly incorporates EO data as part of the overall information base for constraint mapping, and consists of 4 main steps:

1) Undertake a coarse land cover analyses, update as required any available land use GIS, and incorporate overall constraint features. Undertake an initial ranking of routing options, in overview, to exclude difficult terrain and pre-select general route corridors. This process can usually be conducted using more generalized land cover / land use information, including lower cost / lower resolution EO data.

2) Identify viable route alternatives within those corridors identified in step 1. Pre-select routing options and spatially delineate critical corridor / route segments using constraint mapping of input data and information, including higher resolution EO data or digital airborne imagery. Constraint evaluations at this stage may also incorporate a combination of ground-based features/measures. The result of step 2 is a set of routing alternatives, such that each corridor / route segment alternative is associated with different numbers and different weightings of constraint features.

3) Select those route alternatives that are associated with fewer and/or lower weighted constraint features, and undertake further analyses. Step 3 involves further combination of EO and other spatial / constraint data / information using GIS modeling and expert knowledge tools. At this point, it is important that the analyses are driven by experts familiar with the routing selection criteria so that, as the investigation proceeds, there can be iterative refinements applied as constraint features are evaluated/re-weighted and any remaining information content requirements determined. Step 3 is then iteratively repeated, based upon feedback from experts / consultations, or the addition of new or updated information, for example, reassessed/updated engineering costing constraints.

4) Conduct one final round of analyses, incorporating all final GIS modeling rule-sets, appropriate spatial information and expert knowledge (as applied at the completion of step 3), to create final constraint maps. The final outputs which identify one or a few preferred routing option(s) then need to be checked and further considered by pipeline planning experts.

4 PRE-COMMERCIAL TRIAL RESULTS

The Project is undertaking several pre-commercial trials at a number of test sites, in conjunction with pipeline operators. Following are preliminary results from some of these trials.

4.1 Ground Motion Monitoring

In the Project, all applications described in Section 3.1 have been investigated over real test sites from pipeline operators. The following subsections summarize some preliminary results.

Underground Storage Areas

The PSI technique was applied over a salt cavern field in Germany, which is used for storage of crude oil and natural gas. Subsidence of the cavern field has been monitored since 1975 with a yearly ground-leveling survey over the entire field area.

PSI processing was carried out using a dataset of 70 descending ERS-SAR images, covering a time span of 12 years, from 9 May 1992 to 25 January 2005. An extract of the final estimated velocity field in the direction of the satellite line-of-sight is shown in Figure 1.

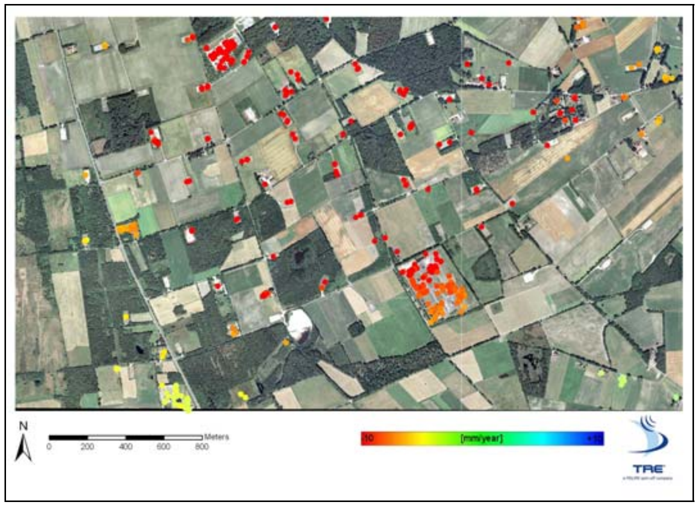

Figure 1. Extract of the estimated ground movement velocity (mm/yr) over an underground storage cavern, Germany (PSI data copyright TRE 2005. ERS data copyright ESA 1992-2005. Background image copyright Landesvermessungsamt Nordrhein-Westfalen).

Measurement points were obtained from pipelines and related infrastructure as well as farmhouses and outbuildings on the site, which individually provided a strong reflection of the radar signal back to the satellite. A close-up of the point coverage is shown in Figure 2, and an example of the surface pipeline infrastructure for the gas storage cavern is shown in Figure 3.

The sampling involves a non-invasive monitoring technique that can measure ground movement over a wide area with sub-millimetre precision. For each positioned point that is mapped in Figure 1, a motion history dating back to 1992 can be derived from archival satellite radar data (see Figure 4).

Figure 2. Close-up of point coverage for an underground storage cavern, Germany (PSI data copyright TRE 2005. ERS data copyright ESA 1992-2005. Background image copyright Landesvermessungsamt Nordrhein-Westfalen).

Figure 3. Surface infrastructure associated with an underground gas storage cavern, Germany.

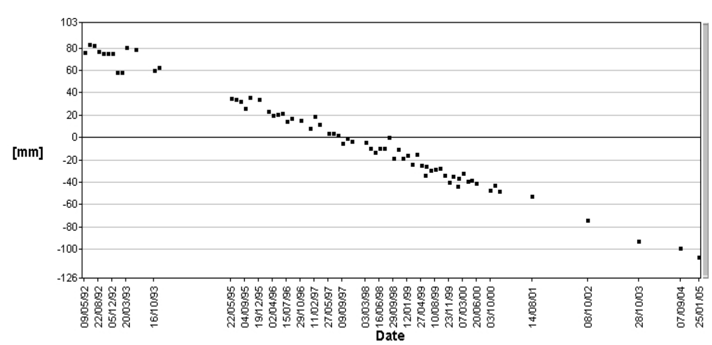

Figure 4. Example of time series of ground displacement of a single measurement point. The displacement values are relative to a chosen reference point.

The network of ground leveling measurements was compared to the PSI processing result. For this, the leveling measurements had to be interpolated to the PSI results, both spatially and temporally. Figures 5 and 6 present the average annual velocities over the entire cavern field, as derived from leveling and PSI measurements, respectively.

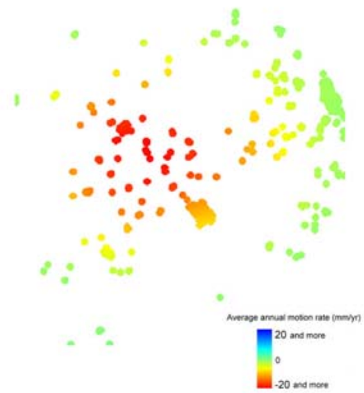

Figure 5. Average annual velocities derived from leveling measurements.

Figure 6. Average annual velocities derived from the PSI result (PSI data copyright TRE 2005. ERS data copyright ESA 1992-2005).

Coal Mining Activity Areas

A coal mining subsidence test site associated with a gas pipeline in the UK was processed for the PRESENSE project and its utility further studied in the PIPEMON project. Figure 7 shows a prominent displacement contour amounting to at least 12 cm within a 2-month period, centered on an elongated subsidence pattern of 1.5 km × 1 km.

Subsidence in Figure 7 is directly attributable to mining activity along the block highlighted in red. The area of subsidence extends in width over a previously mined block (in yellow) and onto a section of the pipeline (blue).

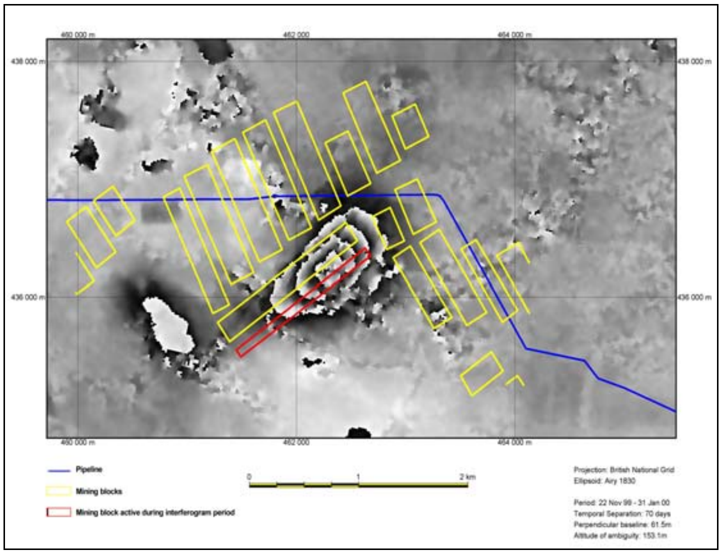

Figure 7. Displacement of pipeline related to subsidence associated with old subsurface coal mining activities (InSAR data copyright NPA 2003. ERS data copyright ESA 1999-2000).

Landslides

A cluster array of 6 metallic corner reflectors (CRs, see Figure 8) was placed within the pipeline right-of-way to measure ground movement rates over a known landslip area associated with a pipeline river crossing in north-central Canada. CRs guarantee a clear, strong and time persistent target response to the satellite radar sensor, which is necessary especially in vegetated areas where few or no natural reflectors are present in the target area. CRs were deployed in March 2006 at the Canadian test site, and data collection has been continuing since this time.

Figure 8. Corner Reflectors: a) ground view of a deployed CR (copyright NPA), b) CR and protective wooden fencing installed at the Canadian site (copyright EBA).

The underground pipeline is subjected to deep seated and slow land creep on a slope just before the river crossing. The slope drops 100m in height over a distance of 600m (see Figure 9).

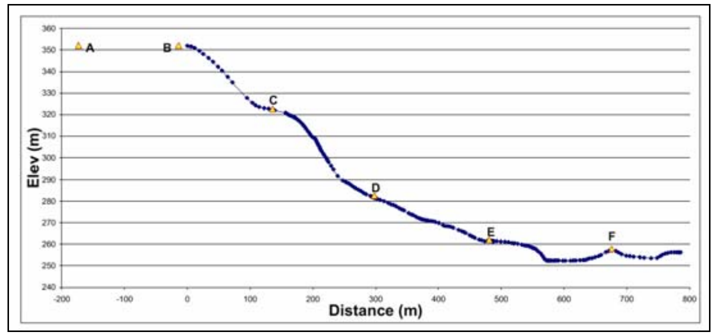

Figure 9: Profile of the slope before a pipeline river crossing in Canada, showing the locations of the six Corner Reflectors (A to F) that were installed. Corner Reflectors A and F act as references on stable locations.

Two satellite images have been acquired so far and successfully processed with DifSAR. An example of the radar amplitude response of the six Corner Reflectors is shown in Figure 10 for the first image acquired. All reflectors were orientated correctly towards the satellite and returned a sufficiently strong signal back to the satellite.

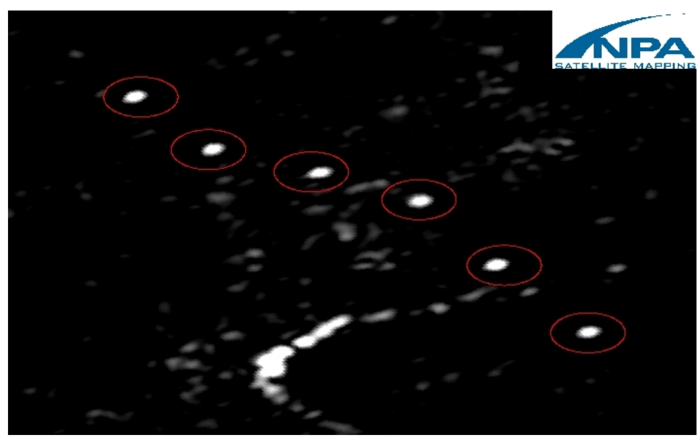

Figure 10: Interferometry response from the six deployed Corner Reflectors (encircled in red) (Envisat ASAR data, copyright ESA 2006).

Preliminary results suggest a centimetric downhill movement of the slope within 35 days, but further acquisitions need to be made to confirm this trend. A comparison will be made between the DifSAR measurements and the readings of the slope inclinometers installed at the site.

4.2 Route Planning

Route planning Test Sites 1 and 2, as outlined below, illustrate the application of steps 3 + 4, and steps 1 + 2, respectively, as described earlier in Section 3.2. Results from the two test sites demonstrate that hard data, such as land cover and GIS-based positions of existing pipelines, can be appropriately assessed and weighted along with manually input “soft information” – for example, information about interests expressed by adjacent land owners and local planners to undertake specific activities if certain conditions are met.

Test Site 1

For a test site in Northern Germany, Ikonos© imagery and other spatial data incorporated within a land-use GIS were used to help construct constraint mapping for a section of a proposed pipeline route (Figure 11). Also contained within the project GIS for the northern German test site was spatial information about existing pipeline networks, as well as interpreted patterns of ground movement over time (derived from PSI analyses) within the vicinity of the proposed pipeline corridor.

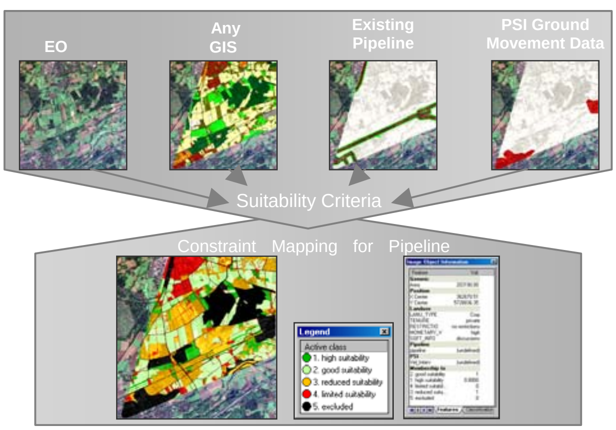

Figure 11. Incorporation of EO and other data within an analytical GIS system, as a basis for constraint mapping of proposed pipeline routes.

The constraint mapping was undertaken using eCognition© software (see www.definiens.com); eCognition is an object oriented image analysis software which intuitively fuses EO data with thematic data like ESRI© shapefiles, so that derivative analyses can be performed. In a first step of the route planning constraint mapping, image objects are created containing all information of the EO data and the GIS plus their mutual relations. This enables the planning expert to later access all information for every area in the test site.

Selection preferences/priorities as identified by pipeline planning experts were translated into sets of rules, which the eCognition software could then use, in a fuzzy logic way, to classify spatial extents into 5 constraint classes.

Test Site 2

For a second test site in Germany, two different levels of detail were analyzed (Figure 12).

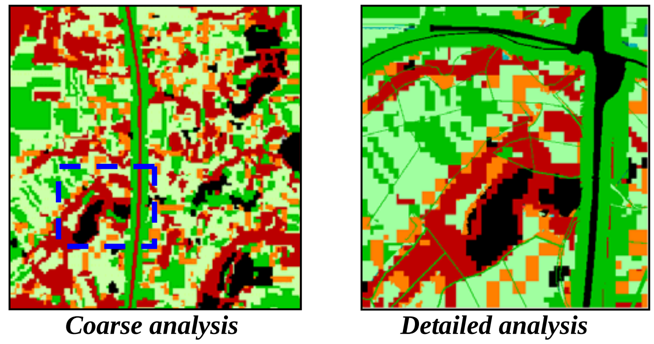

Figure 12. Spatial representation of GIS output from coarse and detailed analysis of constraint features associated with a proposed pipeline route.

The coarse level 1 analysis, as shown in Figure 12, uses publicly available data such as Landsat imagery and broad DEM data to generate a generalized overview over the test site. In the second step (see Figure 13), areas of interest were analyzed using more detailed input data, such as aerial photo-imagery and spatially based land use and ownership data.

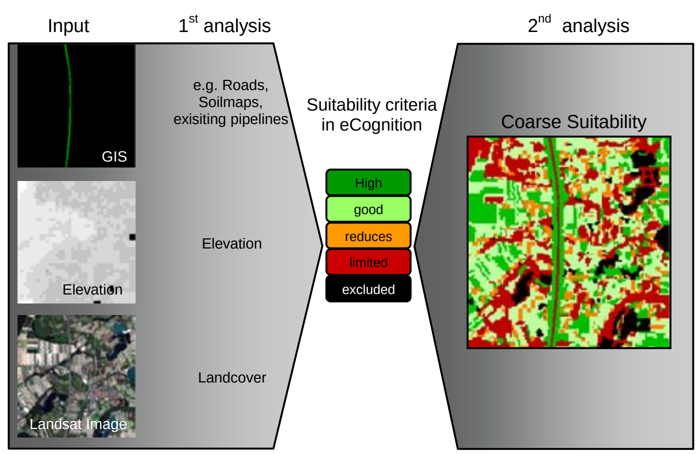

Figure 13. Application of route planning steps 1 and 2 (as described in Section 3.2) to create constraint maps.

5 ANALYSIS AND EVALUATION

As part of Project’s evaluation of the suitability of EO data and services for the pipeline industry, pipeline operators participating in the Project were asked to evaluate the service results. The following subsections summarize preliminary comments received regarding the utility of what are preliminary results only, at this point.

5.1 Ground Movement Monitoring

The operator of the German gas storage facility indicated that the PSI measurements corresponded to the leveling survey results, despite some differences in the centre of the bowl. The subsidence bowl was however clearly defined by the PSI data (Figure 6). A strict direct comparison between ground survey data and PSI data was not possible, as measurements were interpolated spatially and temporally. The operator indicated that more measurement points might have further improved results; in such instances, where natural scatterers for PSI are insufficient or lacking, CRs can be installed. The operator sees InSAR as being particularly useful for providing important information on areas, such as wetlands, that are typically inaccessible for ground survey teams.

The PSI technology has the advantage of exploiting a satellite data archive from potentially 1992 onwards, providing historical ground movement data that is not possible to replicate with conventional ground movement methods. Especially slow ground movements can be detected and spatially defined, in particular movements that might be overlooked using conventional ground-based methodologies. PSI's high point density over urban areas allows the identification of unstable areas at a glance.

DifSAR has proven to be useful to measure fast ground movement over short intervals, for example over coal mining activity areas. While both DifSAR and PSI cover wide areas, CRs can be installed in arrays within relatively localized areas, to monitor the movement of specific sites or structures.

In general, satellite-based ground motion monitoring can be very attractive when compared to conventional approaches to monitoring ground movement along pipelines. The process can be conducted remotely (following CR installation, if required), and may be particularly cost-effective when applied to remote geographical areas, such as the Canadian far north. It can be used in a non-invasive manner to accurately and effectively survey large remote areas. It can also be used to further confirm provisional findings regarding ground movement as measured by ground-based measurement tools, or to help establish spatial limits around areas that are suspected to be moving over time.

5.2 Route Planning

The following general statements were derived from pipeline operators who provided feedback, in relation to evaluation of route planning services:

- The Project's route planning tool is a good support for the early phases of coarse planning.
- The consideration of existing pipeline tracks as planning parameter is essential.
- The consideration of planners' knowledge in the automated decision process is essential.
- The approach itself shows a promising development for automated planning support.

Service Strengths

The following general statements were derived from pipeline operators who provided feedback:

- The service is especially suitable for sparsely populated remote areas where only spatial information is available.
- The service may use EO data and include non-EO data so that a full coverage of the terrain under investigation can be achieved.
- The service may produce results in a little time. Once basic data for an area is given different planning projects can be realized with less effort.
- Automated processing with low costs for repeated planning runs with changed parameters are possible. The service may be carried out during non-working hours.
- The service can be used to update and enhance existing non-EO data using the object recognition feature.
- In densely populated areas, a preliminary coarse planning phase may be obsolete because available corridors are obvious to the planner. In order to achieve the desired result in these cases, the service requires a lot of ancillary data to properly reflect the planning process.

Service Opportunities

The following general statements were derived from pipeline operators who provided feedback:

- The Project's planning service gives a good opportunity for placing further EO based services within a service portfolio for the pipeline industry.
- The planning service is scalable and allows the user to initially use a simple version in a smaller project, and thereafter introduce enhancements for more complex data requirements or larger pipeline planning tasks.
- The Project's methodology appears to be very useful in terms of addressing main technical threats for a route planning activity, but there are at least two issues that need further consideration:

    1. *Protection of customer sensitive data:* Proposed future pipeline network configurations are sensitive strategic data for a pipeline operator, but also needs to be addressed / considered in the route selection process for an individual route / corridor. Perhaps there are ways to protect this larger corporate information while making portions protected but available for constraint mapping and route selection activities; certain services are already in use for third party interference information [5].

2. *Reduce production costs (especially in relation to EO data and services costs):* The general uptake of a planning service product requires adequate pricing. This requires low data costs, clearly defined costs associated with population of the GIS analytical tools, and iterative development of the constraints mapping components. There are perhaps several ways of reducing costs, such as service/data pooling, and these should be considered further.

6 CONCLUSION

The Project has been undertaken to better define the potential for geo-information services for pipeline operators, in particular in relation to ground motion monitoring and route planning. The Project's pre-commercial trials, when completed in late 2006, are expected to further introduce and demonstrate the potential for EO data and services to the pipeline industry.

Based on the Project's preliminary findings, it is already clear that there is considerable interest by pipeline operators in the technology and potential for EO data and services to assist them in their operational requirements. Some examples of advantages include the following:

- Satellite-based ground motion monitoring can be very attractive when compared to conventional approaches to monitoring ground movement along pipelines. The process can be conducted remotely (following CR installation, if required), and it may be particularly cost-effective when applied to very remote geographical areas, such as the Canadian far north. It can be used in a non-invasive manner to accurately and effectively survey large remote areas. It can also be used to further confirm provisional findings regarding ground movement as measured by ground-based measurement tools, or to help establish spatial limits around areas that are suspected to be moving over time.
- With respect to route selection, the Project has identified that EO data and services can be combined with analytical tools to assist route selection. EO data and services can be used, in particular, as a key component of spatially based constraint mapping, which is conducted in an iterative manner to refine routing and to help select final corridor options for a proposed pipeline route.
- More specifically, regarding the use of PSI over gas storage facilities, there are several preliminary findings that show the approach to be very useful. These include: 1) the high point density over urban areas allows the identification of unstable areas at a glance; 2) the methodology can make use of archival satellite data (e.g., from 1992 to 2000 at the current test site) and such over-time data cannot be accessed / generated using other ground measurement methodologies; and, 3) the approach can detect ground movements that can be overlooked using conventional ground-based methodologies.

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