THE PRESENSE AND PIPEMON PROJECTS –
DEFINING THE WAYS OF USING SPACE-BORNE EARTH
OBSERVATION SERVICES FOR PIPELINE MONITORING

Werner Zirnig
E.ON Ruhrgas Aktiengesellschaft, Germany

Russ Pride
Advantica Ltd, United Kingdom

Iris Lingenfelder
Definiens Imaging GmbH, Germany

Richard Chiles
Nigel Press Associates, United Kingdom

Dieter Hausamann
German Aerospace Centre DLR, Germany

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 natural gas pipeline monitoring systems with remote sensors and context-oriented image processing software, as has been demonstrated in particular by the co-funded European “PRESENSE - Pipeline REMote SENsing for Safety and the Environment” project. In addition the three-year ESA funded market development activity “PIPEMON – Geo-information services for pipeline operators: ground motion monitoring and route planning” aims at undertaking pre-commercial trials with market players and potential customers, hence to introduce Earth Observation services to the pipeline industry.
INTRODUCTION

In western Europe the total length of natural gas transmission pipelines adds up to some 200,000 km. Regardless of the requirements imposed by authorities, which differ substantially from country to country, gas companies themselves take a host of measures to ensure that their pipeline systems are operated in a safe, economic and environmentally friendly way and that they are protected effectively against damage caused by third parties. The monitoring methods most widely used include foot and vehicle patrols along the pipeline route as well as aerial surveillance using small helicopters or fixed-wing aircraft. While these methods ensure a high level of safety for pipeline operation, they also involve high costs.

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 natural gas pipeline monitoring systems with remote sensors and context-oriented image processing software, as has been demonstrated in particular by the co-funded European “PRESENSE - Pipeline REMote SENsing for Safety and the Environment” project. PRESENSE is a collaborative project of 17 partners that aims to assess the potential benefits of remote monitoring techniques compared with conventional techniques. PRESENSE, which started in January 2002 and will be completed by September 2004, has identified a number of satellite-derived services which are expected to be viable and cost-effective for pipeline operators (www.presense.net). In addition the three-year ESA funded market development activity “PIPEMON – Geo-information services for pipeline operators: ground motion monitoring and route planning” with nine partners started in November 2003 to define, implement and validate an integrated service chain for supplying ground motion information along the routes of existing pipelines and ground information for pipeline route planning (www.pipemon.com). The aim of PIPEMON is to undertake pre-commercial trials with market players and potential customers, hence to introduce Earth Observation (EO) services to the pipeline industry.

The format of this paper is to provide results of these two major projects. The development of an intelligent processing and analysis chain is described that will ultimately provide an automated management information tool for pipeline operators for both routine pipeline monitoring and for pipeline route planning. The paper then reviews in greater detail some of the available remote sensing systems and how these may be utilised to provide information for pipeline monitoring tasks.

PIPELINE OPERATOR REQUIREMENTS

Most pipelines in the European high pressure gas transmission network are under a soil cover of about 1 m and depending on pipeline diameter, a 4 m to 10 m wide ROW (Right-of-Way) is specified above the pipeline route. Buildings and large trees with deep roots are not admissible in these pipeline corridors. Work in the ROW is not admissible unless prior approval has been obtained from the relevant pipeline operator. The monitoring tasks break down into object and situation detection to prevent third party interference, monitoring of soil movement and early detection of gas emissions. These monitoring tasks have to be carried out throughout the year at regular intervals, largely
regardless of weather conditions. Although the areas monitored differ quite significantly in terms of soil characteristics, vegetation and building density, it is important for the monitoring methods employed to be usable in almost all types of terrain.

Although the standards’ situation for natural gas pipeline monitoring differs greatly in the various European countries, it is covered by one general European Standard EN 1594 [1]. In principle, there are no legal obstacles for introducing a pipeline monitoring system based on EO remote sensing data. However, the technological challenge is that, on the basis of a rapid automatic data fusion and evaluation process, such a future remote monitoring system must be capable of identifying objects and situations representing real threats to the pipeline. It must also be able to meet the requirements of regular and secure information. In terms of its price/performance ratio it must at least correspond to the monitoring methods presently in use, or be better. False alarms would not be accepted by pipeline operators as these alarms would increase monitoring costs.

A starting premise of the PRESENSE project was that simply replacing, highly human intensive conventional monitoring real time processes, with similarly time-consuming analysis of EO imagery, would not in itself provide the required improvements to costs, or any enhancements to safety, to justify a change in operations. It was therefore an integral part of the project to assess the potential of EO data to provide a range of additional benefits to the pipeline operator, beyond the normal monitoring requirements, and to demonstrate the potential to integrate these strategies into an automated monitoring system. For example, an increased frequency of monitoring, without incurring additional costs over today’s helicopter survey, should improve the probability of detection of events. In addition the provision of an integrated geo-referenced pipeline database would provide support information to aid analysis and classification of identified hazards. These can then be converted into prioritised status alarms, hence improving efficiency of pipeline operation.

OPTICAL AND RADAR SENSOR TECHNOLOGY FOR THE MONITORING OF NATURAL GAS PIPELINE SYSTEMS

Today, both optical and radar systems are operated on airborne as well as space-borne platforms [2]. Space-borne systems presently provide a geometric resolution on the ground of up to 0.6 m x 0.6 m for optical and 10 m x 10 m for radar systems, allowing imaging of strips with a width of 11 km and 50 km, respectively. Optical sensors are hindered by cloud cover, which, from an operational point of view, constitutes a substantial limitation of their use in pipeline monitoring. Conversely, radar sensors can be operated regardless of weather and light conditions and therefore have a much higher rate of availability, particularly in Northern Europe, which is frequently covered with clouds.

Optical and Infrared Remote Sensing Systems

Developments in high resolution optical systems have moved relatively fast during recent years. For space-borne systems several commercial satellites have become available with panchromatic resolutions of 0.6 m and 1 m and multispectral resolutions of better than 3 m. For airborne platforms a wide variety of optical digital scanners and
cameras is available commercially. The principle of optical sensors is that via an optical lens system and a detector the amount of radiation incident from a target is sensed. A sensor gathers light in one or more specific spectral windows, e.g. red, green or blue light.

**Panchromatic Sensors.** They have only one, relatively broad, spectral band, generally covering the region of 500 nm to 700 nm, resulting in a 'black and white' image. Therefore, the image contains little spectral (colour) information. Differences between objects with different colours but the same intensities cannot be observed. On the other hand very high spatial resolutions can be reached because of the wide spectral band, collecting relatively high energy levels. Sometimes the spectral band is extended up to 800 nm. This gives the advantage that a significant amount of energy reflected by vegetation is included and also that the vegetation can clearly be recognised in the images.

**Multispectral Sensors.** These sensors contain a limited number of spectral bands (3 to 10). The spectral bands are defined by spectral filters which only pass light within a certain spectral region, generally with a bandwidth of 10 nm to 100 nm. Because of the narrow spectral bands, energy is limited and thus the spatial resolution of multispectral images is usually less than for panchromatic images. The most wide spread kind of multispectral sensors show three bands: green (550 nm), red (650 nm) and near infrared (850 nm). These three bands are represented as false colour image, in blue, green and red respectively. Some multispectral sensors do have more spectral bands.

**Blue Band (400 nm).** Combined with the green and red band this gives natural colour images. Also this band contains information on the atmosphere so that it can be used for the atmospheric correction of the other spectral bands.

**Bands in Infrared (1,000 nm – 15,000 nm).** While spectral bands in the near and middle infrared (900 nm to 2,500 nm) mainly contain information on vegetation, minerals and soil moisture, the spectral bands around 10,000 nm are governed by the emitted thermal radiation of the surface and contain information about temperature and emissivity.

**Synthetic Aperture Radar (SAR) Remote Sensing Systems**

SAR systems emit their own microwave radiation and provide a two-dimensional image of the area scanned by the radar. A three-dimensional image can be obtained in the interferometric mode, which involves acquisition and combination of two or more images of the same area from slightly different antenna positions. During the flight, the SAR sensor periodically transmits microwave pulses orthogonal to its flight direction which are scattered back by the illuminated targets and finally received and stored by the system. The geometry, the surface roughness, and the electromagnetic properties of the object illuminated as well as the frequency and polarisation of the radar will influence the magnitude and phase of the backscattered signal. The geometric resolution in flight direction is determined by the length of the synthetic aperture and is therefore independent of the distance between object and sensor. In cross-track direction the
resolution is defined by the bandwidth of the transmitted signal and again is independent of the distance between object and sensor.

SAR acquisitions can be carried out in different modes according to the user’s requirements. The most popular Strip map mode allows to map contiguous strips with reasonable resolution. In Spotlight mode, higher azimuth resolution can be achieved, whereas in ScanSAR mode wider swaths are obtained, yet at the expense of a significantly lower resolution. SAR systems are operated on airborne as well as on space-borne platforms. Space-borne systems presently provide a geometric resolution of up to 10 m x 10 m, allowing strips with a width of 50 km. Due to this extended coverage and the typically realised repeat cycles of a few days only, space-borne systems are ideally suited for operational global monitoring. With today's standard airborne systems, geometric resolutions up to 0.5 m can be achieved, depending on several parameters such as the carrier frequency. Those systems usually illuminate strips of a few km width. In terms of performance, today's airborne systems can be seen as the predecessors of future satellite systems. Due to the side looking characteristics of the imaging geometry shadowing (similar to optical observations) as well as layover may occur in the final images, which is a fundamental limitation especially for areas with steep terrain slopes or man-made structures.

Experimental Optical and SAR Data

The suitability of optical and SAR sensors for the inspection of gas pipelines has been shown in demonstration flight campaigns in the PRESENSE project. Different objects (e.g. excavators) were placed on sites typical for gas pipeline surroundings. After the observation of these scenarios with the airborne optical and SAR sensors, the objects were moved to different places, and data were taken for these changed scenarios. The excavators and their different appearance in the respective data sets can well be seen by eye inspection (Figure 1). Three test sites were selected, in France, Germany and the Netherlands. Three aircraft carrying respectively, Multi-spectral, SAR and Lidar sensors, each flew the test sites before and after objects had been repositioned on the ground. All the data sets were subsequently geo-referenced and made available to the PRESENSE partners involved in developing the data processing chain. Promising results demonstrated that using an automatically operating feature extraction system, such as described below, this type of data can be processed to produce the correct alarms for cases of real threats to pipelines.

AUTOMATIC FEATURE RECOGNITION USING OBJECT-ORIENTED IMAGE ANALYSIS TECHNOLOGY

The combination of object identification and a semantic knowledge network appeared to be an image processing procedure which is especially well suited for pipeline monitoring. The commercial analysis system eCognition allows data from different sensors (optical and radar) to be merged and combined with geographic information system data for object identification [3]. The eCognition method includes the
Figure 1. Pipeline scenario with excavator in operation on pipeline test site. 
Top: photo image (E.ON RuhrGas)
Upper left: airborne optical image (German Aerospace Centre DLR)
Upper right: airborne infrared image (German Aerospace Centre DLR)
Lower left: airborne SAR image (Intermap Technologies)
Lower right: airborne Lidar image (Nigel Press Associates)
The position of the excavator is indicated by a white circle.

Identification and generation of objects from the original pixel-based files and the establishment of semantic links between these objects and known features, for example in the form of a feature database (Figure 2). Image features such as vehicles or pits are classified on the basis of radiometric, geometric and other links between the image
objects and placed in relation to neighbouring objects and known information from geographic information systems. Any vehicles detected not on defined roads but in open country near to the coordinates of a pipeline route could therefore be identified as potential hazards. By assessing the area concerned, assumptions can be made concerning a possible distinction between agricultural vehicles and construction equipment.

**Figure 2.** Workflow of object oriented image analysis in software eCognition.

One of the characteristics of object recognition is that small objects are often “swallowed” by the large ones. To overcome this problem a CFAR (Constant False Alarm Rate) detector, that is designed to detect small objects, is applied [4, 5]. Such a CFAR detector compares the backscatter of one pixel with the backscatter of the background clutter. That filter is applied to the difference of two images because it is more accurate than filtering the separate images and comparing them afterwards.

In the PRESENSE project two possible applications were followed, one focussing on airborne sensors using the higher resolution data and one on space-borne sensors, for which the airborne SAR data were degraded to three metre resolution. An important issue in the detection of hazards is false alarm reduction because false alarms would raise the survey costs. Figure 3 shows a result of detected changes from a pair of SAR images of the Netherlands test site showing a relocated shovel near a farm. The other detections are due to incidental activities on the farm.
Figure 3. Detected changes from a pair of SAR images of the Netherlands test site.

Pixel-based image processing techniques are often unable to recognise characteristics that are obvious to human visual inspection. This is because pixel-based image classification uses the spectral information represented by the digital numbers in one or more spectral bands, and attempts to classify each pixel based mainly on this spectral information. eCognition's unique approach is based on a simple concept: important semantic information necessary to interpret an image is not represented in single pixels but in meaningful image objects and their mutual relations. The eCognition software allows the analysis of image objects instead of single pixels. A hierarchical image object network is used to select and combine appropriate scales for image classification. Based on this image object network neighbourhood and context can be integrated. Furthermore fuzzy classification is part of the system so that expert knowledge can be implemented and inherent uncertainties of remote sensing data can be taken into account.

The first step for optical change detection can be described as a post-classification change detection algorithm in which changes are detected based on the results of land cover classification. Changes occur if the land cover between two images is different. For that Basic Land Cover Classification optical data and a thematic GIS layer are imported in the software eCognition (Figure 4). Then image objects are created by a patented algorithm called Multiresolution Segmentation. These objects have certain attributes, that are used in the next step for classification based on a hierarchical knowledge base. The knowledge base uses attributes and their combinations to describe different classes. In the optical imagery some of the small objects that had to be detected could only be identified because of the shadow they cause. Thus in the optical change detection approach elevation information is used together with optical data to distinguish between expected shadows and unexpected shadows. Only if a shadow is located in a certain position to an elevated object dependent on the sun angle it is classified as an expected shadow. In case the object is not elevated according to the elevation information and therefore a new object that causes an unexpected shadow, this object is labelled in the preliminary change
detection as a possible hazard (Figure 5). Additionally, as a final step object size can be taken into account. Thus large and small machines can be distinguished [6, 7].

![Figure 4. Basic land cover classification of the German test site for optical change detection (first step). The white circle indicates the position of the excavator shown in Figure 1.](image)

![Figure 5. Distinction of changes in radar and change in optical/infrared only with added GIS information for location of change (e.g. on-road or off-road). Again the circle indicates the position of the excavator shown in Figure 1.](image)
MONITORING GROUND MOVEMENT ALONG PIPELINE CORRIDORS WITH INTERFEROMETRIC RADAR

Interferometric processing of satellite Synthetic Aperture Radar data (InSAR) is the analysis of phase differences between two or more images recorded from slightly different orbital positions. With the effects due to terrain elevation and atmosphere removed, these phase differences take the form of interference fringes. These correspond to the component of relative displacement of the ground surface along the satellite’s line-of-sight and allow measurement of displacements to sub-centimetre or millimetre accuracy, according to the technique employed. The great benefit of these techniques is they can reveal slowly developing problem areas such as landslides or subsidence, which can only be detected with very great difficulty and expense by existing means.

InSAR analysis currently can take three major forms:
1) Standard InSAR: processing of the phase differences, between individual image pairs, for all image backscattered signal data.
2) Corner Reflector InSAR (CRInSAR): processing displacements between 2 or more images only at specially constructed signal reflectors.
3) Persistent Scatterer Interferometry (PSI): stacking of multiple images (15 or more) to identify and only use returns from naturally persistent, strong signal reflectors.

In addition to continuous ground movement monitoring, Standard InSAR and PSI both can utilise an archive of imagery going back to 1992, which provides an insight into the history of areas with either known or unknown ground movement. Both these techniques can be undertaken without the requirement of field visits, thus making them particularly appropriate for analysis and monitoring of large or remote regions where mobilization and access costs are high.

Standard InSAR. Particularly in areas lacking a high density of strong signal reflectors, Standard InSAR is the optimum technique for locating large (centimetric to sub-centimetric) displacements occurring over large areas (> 500 m extents). The time interval that can be encompassed by an image pair depends on the surface cover, but typically is from weeks to months. Intervals of several years are possible in some areas, such as dense urban environments, or if vegetation is sparse. Generally, however, the coherence of the phase difference fringes reduces with longer periods of time. Limitations with this technique, result from the sensitivity to small physical changes (vegetation growth, agricultural soil disturbance, etc) of the relatively weak backscatter from most natural surfaces within an image cell. Significant changes result in almost random phase differences between image pairs. The fringe pattern relating to ground movement is only apparent (coherent) when a majority of adjacent cells have not had a significant phase change due to surface cover changes. Consequently, standard InSAR can be used to provide relatively low-cost snapshots for scanning large areas for rapidly occurring, wide area ground subsidence, for example such as movements resulting from large area mining subsidence and earthquakes (Figures 6 and 7).
Figure 6. Cawood (United Kingdom) test site, interferogram showing three ‘fringe’ areas of displacements of 5 cm to 10 cm over 35 days with one formed from active mining (red). Two areas of subsidence have the gas pipeline (blue line) running through their centres.

Figure 7. East looking view of the Dorsten (Germany) test site: Interferogram overlain on satellite imagery shows three areas of rapid subsidence, up to 10 cm over 35 days (based on interferogrammetric processing by Tele-Rilevamento Europa TRE).
Corner Reflector InSAR (CRInSAR). Radar reflectors (corner reflectors, or active transponders) can be used to provide a very strong return of the satellite’s signal from a single point. This strong reflection means that natural changes in the environment within the same image cell as the reflector have an insignificant impact on the phase measurement. As a result, the use of reflectors enables the phase changes caused by motion of the ground beneath them to be quantified. The strong reflection from a single point also means that displacements down to a few millimetres or less can be detected over both short or very long time intervals (days to years). The sighting of reflectors (corner reflectors or transponders), either during or post pipeline construction, provides an efficient means to monitor pipeline sections in areas with a high probability of ground movement over almost any time period and with an extremely high resolution of movement detection. However, a limitation of this technique is that reflectors need to be spaced within a few hundred metres of each other to differentiate ground movement from atmospheric effects, and need to have at least one reference reflector at a stable location.

Persistent Scatterer Interferometry (PSI). Particularly in urban, developed and rocky environments, man-made and some natural features form strong reflectors of the satellite radar signal. By stacking many SAR images (e.g. 15 or more), it is possible to identify and remove from analysis all features reflecting temporarily (vehicles etc) and retain naturally occurring reflector points which can be up to between 50 and 400 points per square km. Additionally, areas with a continuous spread of such reflectors allow the effects of the atmosphere, terrain elevation and satellite orbit errors to be accurately modelled and removed. As with CRInSAR, the dominance of the backscatter of the reflector within an image cell enables monitoring of displacement histories to millimetric precision. Therefore, this technique is particularly suited to the identification of extremely gradual (creeping) movements of only millimetres per year for sites within areas ranging from kilometres to hundreds of kilometres in size, which would be impractical using GPS and levelling techniques. A limitation of PSI is that very rapid movements (more than about 1 cm every 35 days for ERS system) cannot be reliably measured. Furthermore, the unplanned location and orientation of naturally reflecting features means the ability to monitor movement may be reduced for the pipeline Right-Of-Way, especially as pipelines usually bypass urban areas where most persistent scatterers are found. However, for ongoing monitoring, radar reflectors can be installed at critical sites which lack natural reflectors.

REFERENCE 3D LIDAR SURVEY FOR AIDING AUTOMATED PIPELINE CORRIDOR MONITORING

Automated analysis of remotely sensed data depends upon the ability to register data sets and interpret land cover and image response accurately. Laser technology potentially provides numerous beneficial enhancements to an overall system for monitoring developments and activity in the vicinity of a ROW of a gas pipeline.

Whilst Light detecting and ranging (Lidar) measurement with lasers has been in operation from airborne and some space-borne platforms for many years now, the technique is adapting increasingly to respond to new applications and has particular features that suit the nature of repetitive, long route monitoring, rather than large area
imaging. Whilst Lidar data is currently best acquired from airborne platforms, the next generation of satellite systems will provide data capable of similar application. In theory, from the vantage point of space, a laser could extremely rapidly map long linear features such as pipelines within very narrow windows of opportunity, with low redundant data, and without the requirement of airspace restrictions. High density Lidar elevation data, with typically 10-20cm vertical accuracy, provides a very detailed reference for pipeline networks which complements and maximises the effectiveness of other remotely sensed data.

CONCLUSIONS

Within the PRESENSE project initial tests to classify objects within the pipeline corridor have been performed. With the use of shape and neighbourhood relations in object-oriented image classification, the dependence on spectral reflection from the objects is reduced. It has also been shown that it is possible to use radar instead of optical images. The rule sets defined enable a classification of scenery that is as independent as possible from the sensor technology used. One of the operational advantages of pipeline monitoring is the general knowledge of the scenery as a result of the frequent pipeline observation. An operational image analysis system therefore has to concentrate less on identifying the entire scenery as such, but can address the various changes in the scenery which have occurred since the last observation.

Radar interferometry techniques such as PSInSAR (Permanent Scatterer Interferometric SAR) and CRInSAR (Corner Reflector Interferometric SAR) can either use the existing archive of radar satellite imagery (often going back to 1992) to detect very small amounts of ground movement or ‘creep’ with the accuracy of a few mm of movement per year, or monitor current ground movement using the satellite overpass frequency twice per month. These techniques can therefore reveal slowly developing problem areas such as landslides or subsidence which can only be detected with very great difficulty and expense by existing means. The great benefits of radar interferometry are that subtle ground movement trends can be identified and the density of sample points, especially in urban and semi-urban areas, can be anywhere between 50 and 400 points per square km. Such a monitoring service as to be presented to the marketplace by the PIPEMON project would offer great advantages for remote areas where mobilization and access costs are high.

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