Test Cases and Prospects of Pipeline Management Using Space Borne Earth Observation

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Thanks to recent progress in satellite-based remote sensing technologies and object oriented image analysis, as well as to the availability of new very high-resolution sensors, it is now possible to design gas pipeline monitoring systems, as has been demonstrated by the co-funded European “PRESENSE - Pipeline REmote SENsing for Safety and the Environment” project. In parallel, the European Space Agency ESA has launched initiatives in Earth Observation Market Development (EOMD), such as business case studies for the pipeline operations segment and the project “PIPEMON – Geo-information services for pipeline operators”, which aim to introduce Earth Observation services to the pipeline industry in Europe and the Russian Commonwealth of Independent States. Key requirements of gas pipeline operators in remote observation are third party interference, ground subsidence detection, pipeline route planning and gas detection. Further, pipeline security is a major issue in several European studies such as GMOSS (Global Monitoring of Safety and Security).

Keywords: Pipeline monitoring, object-oriented image analysis, satellite-based earth observation, UAV

1. PIPELINE OBSERVATION REQUIREMENTS

Today, the share of natural gas in Europe’s primary energy consumption is about 24 %. This figure is expected to increase to about 30 % by 2030. The gas is transported via high pressure (up to 85 bar), large diameter (up to 1,2 m) steel pipelines from sources within and outside western Europe. 450,000 km of high pressure pipelines (Figure 1) form the backbones of the international gas transport, starting at the site of production and ending at certain national and regional distribution points, from where the gas is transferred to distributors serving the individual customer. Two thirds of European gas supplies are from West European production, whereas Russia is the main supplier in interregional gas trade. Natural gas and its production and transportation infrastructure form an economic and security aspect for the European society as well as for the involved gas providers. In comparison, the oil transport pipeline network is of rather reduced size in length, with the NATO fuel pipeline network of some 10,000 km forming the larger part (ESA, 2003).

Safeguarding the integrity of the pipelines was an issue of concern for the pipeline operators long before the advent of the theme “homeland security” on the political agenda. However, the primary concern in Europe was and still is not criminal acts to the pipeline infrastructure, but mostly accidental interference with the pipes. Nearly all high pressure gas pipelines in Europe are buried in the ground and may only be recognized by sign-poles indicating the underground presence of a gas pipeline about every 500 m. Though, underground pipelines have a lot of technical and environmental advantages, they can also be target of certain man-made and natural risks.

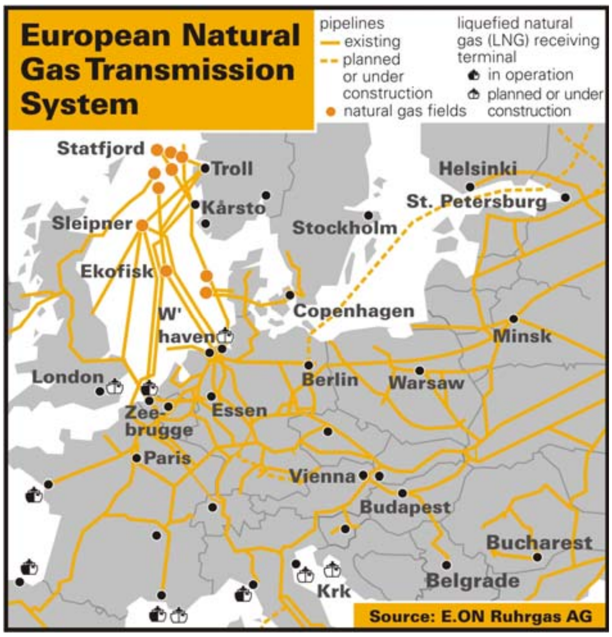

Figure 1 European natural gas pipeline

Construction activities such as laying of cables, building of houses and deep-plough farming could scratch the steel of the pipeline and therewith damage its anti-corrosion protection shell. In worst cases, such construction activity could cause a significant gas escape. Such “third party interference” events contribute the biggest threat to the pipeline network integrity on the European scale. The current measure against these threats is to observe the pipeline either by walking along the lines (mainly in urban areas) or by regularly flying the line with helicopters or fixed-wing aircraft (for most of the pipeline network). Whilst the pilot is often guided by electronic maps (GIS) and satellite navigation (GPS) to fly the route, the observation is left to the naked eye of the human observer. Only in few cases, digital pictures or videos are taken. The frequency of such flight surveys varies from country-to-country, but can be assumed to be performed about every two months up to every two weeks. Giving the extend of the gas pipeline infrastructure and the potential economic losses and even threats to lives, the regular observation of the pipeline is a costly but necessary task. The concern of the studies being discussed in this paper was therefore to demonstrate the capabilities of new high resolution earth observation sensors, linked with automated image analysis/feature recognition and Geographic Information Systems (GIS), for substituting the helicopter and fixed-wing aircraft based survey with space borne assets.

In addition to man-made threats, also geologic risks could harm the integrity of the pipeline. Motion of the surface – and therewith the motion of the buried pipeline – could eventually lead to a damage of a pipeline. These motions can be induced by underground mining activities, land slides and seismic events, just to name a few. In many cases, the exposition of land areas to surface motion is already known at the time of pipeline construction. Either avoiding the problematic areas or measuring the soil motion with ground based devices, is an appropriate measure in these cases. However, the observation of large areas is costly. Space based radar interferometry delivers a tool for a frequent and large area surface motion observation. Hence, the European projects, being discussed in this paper, studied radar interferometry as an important warning measure for protecting pipeline against geo-tectonic risks.

Finally, the study efforts also tried to detect eventual small leakages of pipelines, by measuring the methane either directly, or by the environmental effect, methane is imposing to the vegetation. Whilst the direct detection studies have been performed with Laser based measurements (LIDAR), the effect on the vegetation is primarily being measured with high resolution multispectral imagers.

2. THE PRESENSE PROJECT

2.1. Overview

The largest scale demonstration project, funded under the European Commission 5th Framework Programme on Research and Development was named PRESENSE (Pipeline REmote SENsing for Safety and the Environment). The 17-partner PRESENSE consortium, lead by UK based Advantica, comprised three strands of capability, namely pipeline operator, remote technology provider and system integrator from five European countries (Zirnig, 2001; 2004; Dekker, 2004). The ultimate target of the PRESENSE project was to provide pipeline operators with a new form of pipeline management system based upon remote satellite surveillance, and a computer based information system that is capable of alerting them to potential pipeline damage, in all weather and lighting conditions. Replacing helicopters with combined optical, Synthetic Aperture Radar (SAR) space borne remote surveillance techniques, and employing advanced image processing, scene understanding, data fusion and dissemination methods enables accurate feature identification and leads to reliable hazard extraction and improvements in system response time.

PRESENSE investigated air- and spaceborne observations, to respond to the three main threats to gas pipelines:

Third Party Interference (TPI)

Targets typically associated with third party interferences (e.g. diggers) were set up at three test sites, in the Netherlands, in Germany and in France. Airborne sensors collected imagery utilising SAR, 12 band optical (including thermal) and LIDAR. The target objects were then moved and further imagery collected to provide data for analysis and change detection.

In order to automate the detection of targets an approach was taken to include as much as possible existing geographic information (e.g. the pipeline track itself and the surrounding buildings, roads, etc.) and to identify such existing features in the updated satellite image. Objects, already known and identified as “harmless”, also identified in the new image, remain classified as “harmless”. New objects, which in addition have a certain thematic or geographic relation (e.g. a car not on the road and on the pipeline) are classified as “dangerous”. The capability of identifying and labelling objects and setting them in relation to existing geographic information not only in the traditional “pixel-by-pixel” image merging process, but by thematic and geo-relational links is implemented in the object-oriented image analysis software eCognition (Benz, 2001; 2004).

Figure 2 Identification of objects near a pipeline track based on 1 m resolution IKONOS images. The right image contains the eCognition object classes separated into areas inside and outside the surveillance corridor

Within eCognition digital raster images are “segmented” to generate a hierarchy of objects, i.e. homogenous areas (such as houses, streets, but also cars on streets) are treated as “objects” and no longer as set of individual pixels. All identified objects are annotated with their colour, colour statistics, size, shape and neighbourhood relations to other objects. In order to tell eCognition, what kind of objects would be of interest, user defined “rule bases” specify the visual appearance of objects, and are able to incorporate other information (such as the position of the pipeline corridor supplied in a GIS structure). Rule bases also apply certain reliability weights to the defined information (e.g. a “car” has a minimum and a maximum size). This reliability is introduced by means of fuzzy logic reasoning. The therewith defined rules can now be applied to an automatically generated network of image objects. The result is the identification of the image objects defined in the rule base. Due to the fuzzy logic implied, all identified image objects are labelled with their reliability of detection. Based on the quality of the input image data and the unambiguous definition of rule bases, objects can carry certain degrees of “danger” to be imposed on the pipeline system (Figure 2). At a certain “danger” level, these objects are subject to further – possibly human – intervention and inspection. Because eCognition identifies objects with a clear outline, such objects can directly be vectorized and exported to Geographic Information Systems (GIS) for further management and analysis.

Ground Movement

The detection of two types of ground movement was evaluated with the objective of identifying an approach that would ultimately provide an automated monitoring system. Interferometric SAR from satellite imagery was used to quantify, with cm resolution, subsidence resulting from coal mining on two test sites, whilst airborne LIDAR was used to quantify a landslide with mm resolution at a further test site. A strategy was developed that enabled these monitoring activities to be incorporated into the final demonstration of the automated monitoring system.

Gas Detection

Detection of natural gas was addressed within the PRESENSE project by assessing stress effects in vegetation that might be detected remotely. A special test site was developed where several varieties of crop could be stressed with controlled underground gas leaks throughout their growing season and compared with non-stressed crops. Comparison was also made with stress induced from other sources such as shading. Monitoring of the spectral response of the foliage over a wide band of wavelengths enabled the selection of specific wavelengths to be used in algorithms to highlight gas stress. Using IKONOS satellite imagery it was able to identify gas leak sites as indicated by the red superimposed on the known position of a pipeline (Steven, 2003; Smith, 2004). The involved project partners (University of Nottingham/UK and TNO/Netherlands) developed a strategy based on the image analysis software eCognition by Definiens Imaging. First step of the analysis is the extraction of image objects using a hierarchical segmentation approach. The objects are only created within a defined pipeline corridor that is based on existing pipeline GIS information. Each image object has its average NDVI attached as an attribute that can be used in a second step to classify the objects as possible gas leakages.

2.2. The Pipeline Information Management System (PIMS)

Demonstration of a change detection and alarm handling system was one of the key targets of the PRESENSE project. The objective was to show how an integrated and fully automated pipeline monitoring system could provide the level of detail required by the pipeline operators in response to real alarm scenarios, whilst minimizing the number of false alarms. The prototype information system comprises four linked components:

- Pipeline Operator System (POS)
- Pipeline Information Management System (PIMS)
- Hazard Extraction System (HES)
- Image Collection System (ICS)

The area of interest surrounding a pipeline is defined within the knowledge base of the Pipeline Information Management System (PIMS). PRESENSE will detect changes in features within this area using Earth Observation imagery and categorise these changes into priorities. Data layers from many sensor technologies as well as basic map data and GIS information are geo-referenced and stacked, increasing the reliability of the change detection process. Detected changes are then classified within the HES into potential hazards, with priority levels, by reference to land classification and the PIMS. These hazards are presented to the pipeline operator through a web browser front end of the Pipeline Operator System (POS). The operator can interrogate the system through the web browser or in more depth through a further Graphical User Interface (GUI). The operator can analyse the alarm in further detail and review its history and finally provide the system with information on how the alarm has been handled e.g. by sending a pipeline inspector to the site in question. The pipeline database is then updated to reflect the current situation.

2.3. Results of PRESENSE

The PRESENSE system was successfully demonstrated in September 2004 using the previously acquired test site data. The consortium partners concluded that further developments are required on several fronts before a commercially viable system can be achieved:

- A need for better satellite resolution for both optical and SAR
- A need for more satellites carrying either optical, SAR or both sensor technologies
- Ideally satellite borne Lidar
- Lower cost imagery available on-call
- Reduction in false alarm rates through improved algorithms

3. EARTH OBSERVATION MARKET DEVELOPMENT STUDY ON PIPELINE MONITORING WITH EARTH OBSERVATION

Addressing the broader business perspectives on using Earth Observation information for pipeline management, ESA's Earth Observation Market Development (EOMD) program awarded a study on these topics to an international team (C-Core, Canada, Definiens Imaging, DLR, EON-Ruhrgas and MICUS, all Germany), lead by Terra Map Server of Germany. Starting in December 2002, aim of the study was to review the demand on satellite based GIS information, the market driving factors, technical prospects and the commercial sustainability for an operational business (ESA, 2003).

On the technical side, the study reviewed the Earth Observation capabilities, thus taking advantage of the on-going PRESENSE study, and the availability of both public and commercial Earth Observation systems in the future. The results have been presented to a wider audience of experts at an ESA workshop in late 2003.

The study also reviewed possible business models, incorporating the entire supply chain from the Earth Observation data supplier/satellite operator, via the value adding companies down to the pipeline operator. Four basic business models have been analysed:

- Every pipeline operators does its own analysis based on purchased EO information
- Pipeline operators form consortia to join their efforts
- An external service provider acts as interface between data provider and pipeline operator
- The pipeline monitoring service is offered by the satellite operator itself

Within these assessments, it became evident that the current pricing scheme of very high resolution satellite data would not allow monitoring all European pipelines with the needed frequency within the available financial framework. Even optimistic calculation (i.e. only the data covering the 200m pipeline corridor is charged) showed that current satellite imaging data prices would be at least two times higher than current helicopter based surveys. These figures do not include the necessary information technology and GIS structure (e.g. PIMS) required to take advantage of the digital information. Also technically, it would be a challenge to program all current available optical satellites covering the about 270,000 km European pipeline tracks, set aside the problem of cloud cover and the design of the sensors to target "area mapping" and not necessarily "corridor mapping".

Nevertheless, using satellite imaging data for pipeline monitoring has the potential to address an international growing market in case the initial business focuses on key areas and new business/value schemes would be implemented based on innovative automation technology. Such technologies are the automated extraction of third party interference (TPI) by means of object oriented image analysis (Benz 2004) interfacing to large scale, satellite operator supplied on-line image libraries and the service supply via on-line web interfaces.

The application of such technologies would allow a “pay-for-value” approach in geoinformation supply, instead of the traditional “pay-for-data” (in fact: “pay-for-satellite-time”) approach and therewith a more scalable risk for the user demanding customized information. However, on the large scale, such approach would only be viable if – amongst other factors – satellite data providers would be able to serve multiple users with acquired data sets. At the end, the costs of the commercial satellites need to be covered by the market – either by data or by service sales.

4. PIPELINE ROUTE PLANNING: PIPEMON

Satellite images are traditionally used for assessment of the land cover characterisation. Merged with available GIS information on the ownership and other legal/financial information, such satellite image derived land cover helps to optimize the route planning for new pipelines. Within the ESA project PIPEMON lead by NPA of UK (Zirnig, 2004; http://www.pipemon.com), such satellite based route planning was demonstrated using automated analysis and expert knowledge parameterized into Definiens’ eCognition.

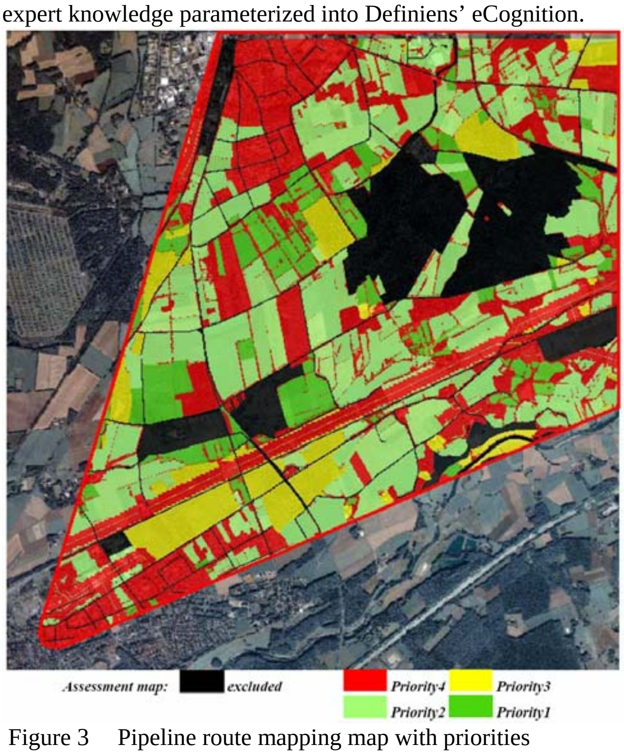

Figure 3 Pipeline route mapping map with priorities

The project work showed the suitability of the technology for this task, but also the need for a user interface for dynamic adaptation of rules in the course of the planning process is mandatory. The planning based on the object oriented technology inside eCognition is a modular process. First, an actual land use map is generated from earth-observation data and – if available – GIS data. Secondly, the user can provide soft knowledge concerning the polygon, e.g. knowledge on owners or neighbours of specific areas.

An actual test site in Germany was used to demonstrate the capabilities based on satellite very high resolution IKONOS data, cadastral information, a GIS of existing pipeline routes and additional ground movement information to avoid dangerous areas.

Based on this information, the system calculates a suitability map, where five classes of suitability are identified, ranging from “excluded” to “best suited". The rules to set the priorities are currently build on preliminary assumptions. The goal is to get a concept for a support system for pipeline planning with convenient parameterisation and adaptation by the user.

5. PIPELINE MONITORING IN THE CONTEXT OF EARTH OBSERVATION AND SECURITY

The European Commission White Paper on Space,(European Commission 2003) describes the European strategy on developing independent access to space technology and operational capabilities. Besides defining the framework for GMES, the Commission included a chapter entitled “Space as a contribution to the CFSP (Common Foreign and Security Policy), the ESDP (European Security and Defence Policy) and to the anticipation and monitoring of humanitarian crises”. Therein the Commission urges the reinforcement of space technologies in support of security and defence policy requirements. While deliberately addressing military and dual use requirements, the paper and several other documents (European Commission, 2004; Gubert 2004; Dillon, 2005) also emphasise the need to protect “critical infrastructure”. The transportation lines for energy and other critical goods are especially mentioned.

In order to start initial R&D projects, managed by the European Commission in the domain of Space and Security, a “Network of Excellence” on “Global Monitoring Of Security and Stability” (GMOSS) was launched in 2004, which aims to integrate Europe’s civil security research so as to acquire and nourish the autonomous knowledge and expertise in Europe for research and applications for security based on satellite image information. GMOSS addresses generic methods and algorithms for automated image interpretation as well as application scenarios such as border control, infrastructure mapping and nuclear treaty monitoring. Managed by the German Space Agency (DLR), GMOSS integrates about 25 organisations and companies in Europe and run for four years (intelligence.jrc.cec.eu/gmoss). In GMOSS, specific work packages are concerned with the state-of-the-art in pipeline security as well as in technological approaches in automated feature detection available in Europe.

A more broader approach in security research is addressed with the Preparatory Actions on Security Research (PASR). Implemented with a relatively small budget, these actions shall be a precursor to a large scale European Defence Research Program, which would support research in major critical areas of defence and security with about 1 Bio € per year from 2007 onwards. This new program was recommended by a “Group of Personalities”(European Communities, 2004) to the European Commission and specifically also includes the security and thus the monitoring of critical infrastructure.

6. SATELLITE SCENARIOS

The future pipeline monitoring scenarios can only be turned into reality if sufficient supply from spaceborne data will be available for reasonable economic conditions and with certain technical performance. Observation of TPI requires very high resolution optical and in most cases radar sensors. Very high resolution is here defined as a resolution of 1 meter and better. As it has been shown, this scale is required to allow the detection of pipeline interfering targets in the TPI case. Very high resolution satellite observation, formerly limited to national and strictly classified reconnaissance tasks, has become a commercial business in the recent years. However, national security users are still the basis for the commercial viability of that business. Affected by satellites losses and pioneered with Space Imaging’s IKONOS satellite, better than 1 meter resolution optical data is now available for science and commercial use. With insecure defence budgets in the future, commercial satellite data providers are also looking ahead to explore new markets. Currently much smaller than the market for national defence customers, pipeline monitoring could well be such a market in the future (Schreier, 2004). Behind the general need for image intelligence from space, three major drivers push the supply of very high resolution space image data:

In the United States, a Presidential order tasked the national security and defence agencies to purchase the better part of their space based imaging needs from the private sector, thus also stimulating the dominance of US suppliers on the international market place. The National Geospatial Intelligence Agency (NGA) initiated two programmes, ClearView and NextView, under which the governmental demand in very high resolution satellite data have been implemented. The NextView programme allows two US companies (DigitalGlobe and Orbimage) to built their next generation very high resolution systems, named WorldView and Orbimage-5.

The 25 member states of the European Union have declared space and security issues a major political and technological strategic task of the future. Under the driving program of the “Global Monitoring for Environment and Security” (GMES), especially the security issues are now being addressed by a growing fleet of European imaging satellites, which shall guarantee an independent access to critical and global geo-information. Besides the continuation of optical satellites in a higher resolution domain (e.g. the French Pleiades system), radar satellites with day and night and all weather imaging capabilities are on the European schedule (e.g. TerraSAR-X from Germany and Cosmo-Skymed from Italy). The ESA Sentinel fleet of satellites will complete the European capabilities, though their capabilities (i.e. especially the geometric resolution) is more aimed towards environmental and repetitive land and sea mapping. The high resolution national systems serve a dual-use market either by definition or by market demands. That means that all systems are also targeted to receive considerable revenue from non-military, commercial markets. Pipeline monitoring/planning is one such valuable emerging commercial market.

The demand for very high resolution space data will not only be satisfied by North American and European suppliers. Some emerging economies and even former developing countries have embarked on national Earth Observation capabilities, which are comparable and even better than the US and European systems. Apart from servicing national security needs, nearly all systems are and will be available to international customers under commercial terms. This means that Indian high resolution satellites (e.g. the CartoSat series), Taiwanese (RocSat) and Thai (Theos) data can be incorporated in future operational infrastructure survey services. Interestingly, global data suppliers have positioned themselves to offer customers a range of different high resolution satellites: Space Imaging is the global distributor for the Indian Satellites, whereas SPOT Image – besides being appointed to distribute Pleiades data – has got the global distribution rights for the Taiwanese and Thai satellites.

7. ALTERNATIVES TO SPACEBORNE MISSIONS

The observation of elongated corridors, may it be land borders, highways or pipeline tracks, are ideally suited for carriers, which are dedicated to fly along just this corridor. Satellites cross these corridors (which are mostly in east-west direction if European major pipelines are concerned) regularly in north – south direction, which means that only a fraction of their operational time could be used to monitor pipelines. On the other hand, the operational costs of dedicated and manned aerial vehicles (helicopters and small planes) have forced the pipeline operators to consider possible alternatives.

In this case, civil unmanned aerial vehicles (UAVs) seem to have a great potential to contribute to many surveillance applications such as pipeline monitoring (Hausamann, 2002). The civil UAVs can perform where manned flight is too dangerous, dirty and dull (so called D^3 tasks). In addition nowadays smaller UAVs are affordable and can carry optimized and miniaturized sensor payloads. However, the use of the Civil UAV is presently highly limited by the lack of regulations, standards and procedures necessary to operate the Civil UAV in a civil Air Traffic Control/ Management (ATC/ATM) environment. The establishment of airworthiness and operational certification standards is necessary to open the airspace for Civil UAVs.

These airworthiness standards for UAV must ensure that the appropriate safety level (with respect to potential risks on the persons and the property on the ground) is met and that UAV gain public trust as well as social and political acceptance. For the case of monitoring and surveillance applications, a real cost saving factor would only be gained if the UAV is really operating fully automatically. Nowadays navigation technologies would indeed allow such operations, but at the cost of sophisticated automation and special concern in automatic Traffic Alert and Collision Avoidance System (TCAS) into UAVs.

Once these safety and guidance issues have been solved and operational certification procedures exist, Civil Unmanned Aerial Vehicles will be ready to operate in civil airspace and serve numerous civil applications including the potential of regular inspections of gas pipelines. The requirements with respect to sensor type and size for operational monitoring of gas pipelines, however, depend on the type of UAV. These can range from small and lightweight, low altitude UAVs with limited sensor weight and capacity, up to medium-size, mid-altitude systems with enough capacity to carry multisensor applications.

8. OUTLOOK

The safe supply with primary energy is a major factor in the stability of the economy and an important driver in international policy. Besides carrying for good relations with those regions of the world, where the prime energy is exploited, the transport of this energy to the recipients is attracting more and more attention.

The cost of the transport is one major factor and contributes – in the case of natural gas – significantly to the end user price. The security of pipelines is a matter of concern long before issues of "homeland security" appeared on the political agenda. In most OECD countries, Third Party Interference is mainly caused accidentally by construction activities. Nevertheless, the new concern in security against terrorist acts promoted the use of new technologies to reconsider the traditional observation and surveillance tasks.

In addition the new concerns and new military demands have enlarged the availability of space borne capabilities, which are suitable for a regular observation. New image analysis approaches would allow to automate this surveillance to a large degree.

However, the current way of operating satellites and trying to make commercial business with selling the data are hardly meeting the technical and financial demands of the pipeline operators in the regular survey of long pipeline tracks. New ideas and business approaches are demanded.

Observation platforms, such as UAVs will be an interesting alternative, though today Air Traffic Control regulations prevent UAVs to fly in civil airspace. One way to these problems is to have platforms which fly above this airspace. Projects such as the Belgian PEGASUS proposal (www.pegasus4europe.com) are pointing to a solution in the middle between low flying UAVs and polar orbiting satellites.

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