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IBP347_030

EVALUATION OF SATELLITE TECHNOLOGY FOR PIPELINE ROUTE SURVEILLANCE AND THE PREVENTION OF THIRD PARTY INTERFERENCE DAMAGE

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Abstract

The damage caused by Third Party Interference (TPI) is one of the major causes of pipeline failures. Consequently, new technologies for identifying activities that may cause damage to our pipelines are constantly being developed. A recently completed project sponsored by a number of pipeline operators has investigated the use of high-resolution satellites for the integrity management of onshore transmission pipelines. The sponsors were BG Technology (on behalf of Transco), Dansk Olie NatureGas, Gasunie, BP, Gaz de France, Distrigas, and the Health and Safety Executive.

The project started with a general review of the satellite technologies available and their potential. The study was then focussed on the identification of activities that might result in damage to the pipeline and the potential of high-resolution optical satellites in identifying hazardous activities. A key element of the study was a comparison with existing surveillance systems, which generally involve regular aerial patrols of the pipeline route. To achieve this a survey was carried out to try and evaluate the costs and benefits of existing systems. In addition a simple model for analysing the cost benefit of pipeline surveillance was constructed, and a functional specification for a surveillance system drafted. Finally the performance of the IKONOS 2 high-resolution satellite system was tested in a controlled experiment using targets placed along a pipeline route. The results of this test were compared with a similar test of helicopter-based surveillance carried out by one of the sponsors.

1 Introduction

Preventing damage to pipelines from Third Party Interference (TPI) is one of the major challenges facing pipeline operators around the world. A variety of techniques incorporated in both design (e.g. burial) and operation (e.g. surveillance) are used to try to prevent damage. New technologies that can help prevent damage may offer significant benefits to pipeline operators.

Advances in satellite technology have resulted in greatly improved data resolution and much greater availability of data. In 1996 it was felt that the technology was sufficiently advanced

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that a feasibility study was justified. A joint industry project "The Use of Satellites for Pipeline Surveillance" was sponsored by a number of pipeline operators to:

1. Review remote sensing capabilities.
2. Review pipeline surveillance requirements
3. Assess the suitability of satellite data for pipeline surveillance.

Following the initial review of satellite capabilities the progress of the JIP was held up by delays in the launch of the high resolution imaging satellites, one was destroyed during launch, one was found to be faulty once launched and the launch of the third was delayed by bad weather. Finally a high resolution optical imaging satellite became active and it was possible to test it and compare the results with more traditional surveillance methods.

Other researchers have also been looking at the potential of Satellites for pipeline integrity management, a team in North America have completed a test using radar satellite data [1].

2 Remote Sensing Capabilities

A selection of remote sensing technologies were reviewed the findings of this review are presented below.

2.1 Satellite based high resolution optical imaging

In 1996 satellite imaging technology was expecting a revolution. There were proposed significant improvements in:

1. Resolution (1m)
2. Data delivery (less than 1 week)
3. Image update frequencies (every 1 to 4 days)
4. Mapping accuracy (12m)
5. Cost

These improvements made the timely identification of third party activities a realistic proposition.

The proposed very high resolution optical satellites would use two cameras to collect black and white images at a high resolution of 1m, and colour images at a lower resolution of 4m. The colour camera will record light in the visible spectrum and the very near infrared (VNIR). The use of this near infrared data can aid image analysis, and the identification of particular features such as damaged vegetation and artificial objects adjacent to vegetation. An artificial sample published by Space Imaging before the launch or their satellite is shown in Figure 1.

The main perceived advantages of this data were the high resolution, the wide availability, and the relative ease of interpretation. The main perceived technical disadvantage was that cloud cover would prevent surveillance for significant periods in the areas of most interest to the project (i.e. northern Europe). Issues relating to cost and data handling were also identified.

It was expected that 3 high resolution satellites would be launched before the end of 1999, one by Earthwatch (now Digital Globe) and two by Space Imaging. After some delays the Space Imaging IKONOS satellite was the first to become operational in October 1999. It has since been joined by a number of other satellites (e.g. Digital Globe's Quickbird, and Orbimage's Orbview-3).

2.2 Satellite Based Radar

The radar systems used for remote sensing are called Synthetic Aperture Radar (SAR). The principle advantage of SAR is that cloud cover or darkness does not affect it; consequently, they can collect data at any time. In addition they can provide very accurate elevation information (this could provide valuable information in areas of possible subsidence etc.). The main disadvantages are that the resolution is lower (approximately 8m is the best available at present), and the images require more experience to interpret. A sample image from the Radarsat website is given in Figure 2 [2].

2.3 Laser Altimetry

Laser altimetry or LIDAR is not a satellite based technology, but it offers high resolution, and excellent elevation accuracy.

2.4 Infrared

Infrared is also not a satellite based system, but one which offers the potential to identify subtle changes in ground temperature. Changes in temperature may be due to the presence of a buried pipeline, or be evidence of leakage of water or hydrocarbons.

2.5 Summary of Review of Remote Sensing Capabilities

The review of the different remote sensing technologies indicated that there were two technologies that offered the potential to improve pipeline surveillance and identify activities that might result in damage to the pipeline. These were:

1. High resolution optical satellite imaging.
2. Satellite SAR.

It was decided to concentrate on optical imaging since it was felt that the resolution available from SAR would not allow the identification of small excavations and small machinery.

3 Pipeline Surveillance Requirements

The project sponsors were asked to provide information on the methods they used for pipeline surveillance, what they were looking for and how effective these systems were. The primary form of surveillance is by helicopter flight, with a dedicated observer, every 2 or 4 weeks.

The data provided was used to prepare the following list of requirements:

1. Must be able to detect the following features:

       a. Soil disturbance
       b. Manmade objects
       c. Areas of vegetation stress
2. Feature detection rate to be 75%
3. Feature location accuracy to be 40m
4. Data required for 500m to each side of the pipeline route.
5. Must be able to collect data 26 times per year.
6. Data delivery time must be less than 24 hours

These requirements were based on the activities that were considered to present a hazard to buried pipelines, the performance of existing surveillance methods, the need to follow up any significant features identified (i.e. get to the right place on the ground), and the need to at least match the frequency and delivery times of current surveillance systems.

4 Test

A test of data from the IKONOS satellite launched in 1999 was carried out in 2000.

4.1 Test Aims and Objectives

The aims and objectives of the test carried out were:

- QUALITY - Assess the intrinsic quality of IKONOS data, with respect to the recognition of ground features such as houses, hedges, fields, roads, etc..
- ACCURACY - Quantify target detection performance of IKONOS data. This will be done by:
  - o Evaluating the probability of detection of features.
  - o Evaluating the positional accuracy of feature location.
- PRACTICALITY - Assess the operational practicality of IKONOS data for pipeline surveillance.
  - o Determine the feasibility of detecting disturbed soil/previous excavations.
  - o Evaluate the practical data supply and handling aspects of using satellite imaging.
- COST - Assess the current and possible future cost of image collection, processing and feature reporting.
- OPTIMUM DATA - Identify which combination of visible and very near infra-red (VNIR) bands are best for pipeline surveillance.

4.2 Test Site Specification

The test site specification prepared is given below:

1. The test site should include the following terrain types:
   - Images for suburban, rural - intensively farmed and rural - moor / upland areas are essential.
   - Images for rainforest, mountains, desert, tundra and wetland areas are desirable.
2. The areas defined above must contain the following features for identification:
   - Major roads, minor roads and drainage ditches are essential
   - Rail routes, tracks, rivers, field boundaries and areas of ground instability are desirable.
3. The areas must also contain the following infringements for identification:

- Permanent buildings, a small construction site, drainage works and disturbed soil are essential.
- Temporary buildings, a large construction site and road works are desirable.
- It would be desirable to include a selection of coloured plastic squares, to mimic tests carried out of helicopter surveillance effectiveness.

4. The test site containing the terrain, features and infringements identified in 1-3 must meet the following criteria:
- It is essential that accurate pipeline route maps (1:10,000 scale or better) are available.
- It would be desirable for the test route to be approximately 20 - 40 km long
- It would be desirable for these maps to be available in a geographic information system format.
- It would be desirable to have video records of helicopter surveillance carried out at approximately the same time as the satellite data collection.

4.3   Test Site

The test used a pipeline in Europe. Two 11km long sections of a buried pipeline were surveyed, the northern one using the visible colour bands and the southern one using the combined visible and near infrared bands. A schematic of the test site is shown in Figure 3.

4.4   Test Site Terrain

Both the northern and southern sections cover areas of 'suburban', rural - intensively farmed, and rural - moorland terrain. The terrain can be subdivided as follows:

- Farmland makes up the majority of the route. This is typical of the location of high-pressure hydrocarbon pipelines in Europe.
- Forestry; the pipeline runs in a narrow cleared easement through a few forest areas.
- Hills; there is an area of small hills, with steep slopes.
- Highly populated; there are some densely populated areas near to the pipeline route, within the test area.

4.5   Data Collected

1. Satellite images were collected on two occasions for both sections.
2. Helicopter surveillance was conducted over both sections in April 2000.

4.6   Features

Features of interest that are close to the pipeline within the test areas include:

- 1 Railway crossing.
- 2 River crossings.
- 1 major (trunk) road, 12 main roads, and a number of minor roads.
- There are 6 drainage ditches crossing the pipeline.
- There are some areas where there are scattered houses and numerous minor road crossings.

1.1   Infringements

- There are 3 locations where there are houses very close to (or on) the pipeline route.

- There were temporary buildings located near to the houses identified above.
- There were no large construction sites within the test area.
- Five excavations of the pipeline were expected[1] for the period when data collection was planned. These were expected to be either open excavations (e.g. Figure 4) or areas of disturbed soil.
- 30 artificial targets were used. The artificial targets comprised 24 white boards (1m by 1m square), and 6 larger targets (1m wide by 3m long, see Figure 5). These targets were considered to be representative of the size and reflectance of small excavation machinery. It was also thought that they would be at the limit of detectability given the 1m resolution of the IKONOS data. Each target was identified by a letter or number painted on in red.
  - ➢ Data collection 1 - all 30 targets were in place.
  - ➢ Data collection 2 - only 11 targets were in place.
    - ◆ 7 were unchanged from the first collection.
    - ◆ 4 were in new places
  Note that the locations of 2 Targets were not supplied in time to include them in the test.

5 Data acquisition

This section contains details of the IKONOS data acquired across the test areas described in Section 4. Space Imaging Europe (SIE) markets IKONOS data for Europe. A number of features of this acquisition are examined as part of this analysis. These are as follows:

- The exact acquisition specification of the data acquired.
- An appraisal of Space Imaging Europe's acquisition process.
- The ability to acquire data over complex spatial configurations.

5.1 Data Acquisition Parameters

Satellite data was obtained on two separate occasions for both sites, as defined in Figure 3. These two images for each site allowed 'change' to be detected.

Therefore, four sets of data were acquired for the two test sites. A key element of the study has been to appraise whether a purely visible image, or a visible and VNIR[2] collection is optimum for pipeline surveillance. For this reason, purely visible imagery was collected for the Northern site and a visible/VNIR composite was acquired across the southern site.

In both cases, the IKONOS product chosen for acquisition is a combination of data from the Panchromatic (black and white) and Multispectral (colour and VNIR) sensors on the IKONOS satellite. The product acquired, was the "Geo" product. SIE produce this combined product in a way transparent to the client, using standard image combination techniques. A full technical description of the Panchromatic and Multispectral sensor characteristics is given in full on the Space Imaging Inc. website [3].

- All data was acquired with the satellite pointing vertically downwards.
- The extents of the southern site differ between acquisition 1 and 2. This change was made to ensure that activity on the ground near the pipeline in the north of the area was included.

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[1] The pipeline operator later reported six excavations.
[2] Very Near Infra Red

- The time of day was the same for each collection.

5.2 Space Imaging Acquisition Process

An important parameter in this study was the appraisal of the way in which data is acquired from the IKONOS satellite, through the receiving station infrastructure operated by SIE. Although this particular acquisition was experimental, and covered only two small areas, a number of observations can be made regarding:

- SIE's credibility in terms of acquisition ability,
- SIE's quality control procedures, and
- SIE's potential ability to deliver larger areas in a repeated fashion.

5.2.1 SIE Data Acquisition Process

All data acquisition transactions are handled through the use of a standard order form. This is used, regardless of the size of the order. This form is comprehensive, but simple to fill in and submit. At the time of the test, in order to generate repeat acquisitions for the same area, additional forms were required. This is an obvious area for improvement and change should regular repeat data be required for a given area.

5.2.2 Quality Control (QC)

SIE's quality control was considered to be good and comprised the following steps:

- SIE confirm the acquisition parameters submitted by the customer. This provides a useful check as to the exact data acquisition specification.
- As part of the acquisition specification, the customer specifies minimum allowable cloud cover. (For the product used in this analysis, the user cannot specify less than 10%). Two levels of QC are imposed to ensure that this criteria is met:
  i) Onboard satellite sensors review the acquisition area to assess cloud cover prior to data capture. Should the level of cloud exceed specification then the acquisition is postponed.
  ii) Images are reviewed by SIE prior to delivery.

5.2.3 Communication

SIE's communication was thorough throughout the acquisition stage. Failed acquisition attempts were communicated and notification of successful acquisition was also made.

5.2.4 Complex Operational Acquisition Configurations

The spatial configuration (location definition) of the test sites used for this study are relatively straightforward, as they are short sections and easily geographically described. Under real operational conditions this would be very different, as pipelines are long and have constantly changing routes. It is understood that complex configurations can be handled by Space Imaging. This requires the supply to Space Imaging of a digital representation of the pipeline corridor over which data is required.

This is significant, as it will allow the use of corridors as narrow as 1km, thereby significantly reducing the cost of images of the pipeline.

6 Appraisal of Data Quality

This section deals with the quality of the IKONOS data acquired as part of this project, particularly with reference to its suitability for pipeline surveillance. This analysis covers:

- Data processing requirements. The level of processing required to convert the data from its raw to a useable form will be discussed.
- An appraisal of the overall data quality. This will involve an analysis of the clarity of typical features within the data.

6.1   Data Processing Requirements

IKONOS data is delivered in a form readily integrated into standard GIS systems. For this project data was acquired as '.img' format, which can be used with, for example, ERMAPPER, ArcView and ArcInfo. It can also be delivered in 'GeoTiff' format, conformant with the above and other software packages (for example MapInfo and Intergraph).

In addition, the data is delivered re-sampled to a mapping projection system specified by the customer. This delivered data does require additional processing in order to make it suitable for pipeline surveillance operations. These processes are shown in Figure 6, and are described in Section 6.2. It might be possible for the data vendor to do this processing.

6.2   Image/Map Registration

There is a distinct difference between the processing required for the first IKONOS data set and subsequent sets. This difference lies in the spatial processing of the data.

6.2.1   First Data Set

The first data set must be tied to the pipeline route map. This is necessary to achieve accurate and reliable integration of map/pipeline-based features such as valve stations, the pipeline, and recognised encroachment zones, as well as to allow integration of field survey data. In this study, the initial IKONOS data for the Northern and Southern sites was 'tied' to standard 1:25,000 Maps. Accuracy of the geo-coded IKONOS data used in this test therefore never exceeds 1:25,000. All geographical calibration was carried out using the geographical imaging GIS software Erdas Imagine.

6.2.2   Repeat Data Set

The repeat acquisition data is not subjected to this process. It is only necessary for this data to be co-registered with the initial data set, or, in an operational scenario to the previously collected data. This difference is significant in any future operational scenario, as 'image-to-image' matching, based on spatial correlation techniques is an efficient, robust and automatic procedure. Therefore, large volumes of new data can be handled simply and efficiently without the intervention of operational staff.

6.2.3   Spatial Enhancement

On completion of image/map registration, both the original and repeat IKONOS data are subject to identical processing. This process starts with 'Spatial Enhancement'. The data is initially re-sampled to a finer image pixel size of 0.5m. This process allows for the extraction of very fine features, and hence improved 'interpretability' of the data. Re-sampled data is subsequently processed to enhance edges and lines, again improving interpretability. An example of this process is shown in Figure 7.

6.2.4 Contrast Enhancement

On completion of spatial enhancement, the contrast of the data is enhanced. This is achieved using standard histogram manipulation procedures that can be applied automatically to the data. An example of this process is shown in Figure 7.

6.3 Data Quality

This section discusses aspects of the IKONOS data quality relevant to pipeline management activities.

6.3.1 General Feature Recognition

It is important for pipeline management operations to be able to locate and recognise key features such as:

- Roads.
- Rail routes.
- Rivers.
- Tracks.
- Houses.
- Field boundaries and hedgerows.
- Industrial units.

Examination of the data received from SIE confirms that recognition of these features is possible.

Figure 8 shows an example from the first collection for the northern area. A number of features are immediately obvious. Houses and roads are shown with clarity. Note also the identification of individual gardens, shrubs and paths within these. Finally, note the clear identification of the water treatment plant shown in the top left hand corner the image.

6.3.2 Excavation Detection

Figure 9 shows two examples of areas of recent excavation. Figure 15 (top two images) shows the change in one of the excavation features with time. The left hand image shows the excavation in April, the right hand image in July. Note the change in vegetation in some of the surrounding fields, and also the way in which the visible nature of the excavation reduces over the period between April and July as the excavated area becomes more settled.

6.3.3 Vegetation Assessment

Figure 10 shows how differences in vegetation health within two fields. Healthy crops are shown as bright red, areas of reduced crop growth are less bright. These differences may be caused by variations in natural or manmade drainage, crop health, or perhaps by methane emission. They can be detected using the VNIR properties of IKONOS data.

6.3.4 Small Target Detection

Figure 11 shows how small features are detected in the test data. This is discussed in detail in Section 7.

However, the two examples in Figure 11, show the differences in detection with purely visible, and visible/VNIR data. The two sites shown were identified as potential artificial targets deployed by the operator. Although the targets appear bright in both images, it was considered qualitatively that the target detection in the visible/VNIR is better due to the clear colour contrast between the target and background vegetation, which is strongly red in colour,

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due to its high reflectance at this wavelength. The quantitative data presented in this report does not support this assessment (see Table 3), but is a small sample. This issue will be discussed in greater detail in Section 7.

6.3.5 Summary of Data Quality Assessment

In summary, the results show that the overall quality of data is high, allowing features pertinent to many aspects of pipeline operations to be detected. In addition, this qualitative review indicates that the combined visible and VNIR data will be the best for pipeline surveillance, due to the easier identification of man-made material and vegetation health. However, the quantitative data presented in this paper does not support this view (see Table 3), but is a small sample.

7 Target Detection by satellite

The central exercise of this study was to determine if IKONOS data could be used to detect features close to a pipeline that may be potentially damaging. In order to quantify this ability, a controlled experiment was carried out in which a number of excavations were made, and artificial targets distributed along the route of the pipeline.

This controlled experiment is described in more detail below.

7.1 Distribution of 'Third Party Features' Along the Pipe

The test site (Figure 3) was chosen because the operator was planning to carry out some excavations of the pipeline. In addition, they were prepared to place target boards to give a larger data set.

7.1.1 Excavations

Each section included areas recently excavated:

(i)   Two in the Northern section.
(ii)   Two in the Southern section (data only collected by the second survey).

The two excavations in the southern section had been filled in before the data was collected due to the difficulty of co-ordinating a one-off collection of satellite data for experimental purposes with the operational requirement to excavate and re-instate the pipeline.

7.1.2 Targets

To provide a larger sample of features than the recent excavations, a number of artificial targets were used. The artificial targets comprised 26 white boards (1m by 1m square), and 4 larger targets (1m wide by 3m long). Each target was identified by a letter or number painted on in red. All 30 targets were placed for the first collection and 11 for the second (6 of which were unchanged from the first collection and 4 were in new positions).

7.2 Data Analysis Procedures

A simple procedure has been carried out for the detection of targets and excavations. Throughout this exercise, target detection was carried out by the technician viewing the satellite images independent of any knowledge of target position. Consequently, target detection has been carried out 'blind', so as to represent a 'real' operational situation.

The steps of the detection process were as follows:

Step 1: The initial set of data on the northern and southern sites was analysed. This involved detailed visual analysis of a 200m corridor around the pipeline, whose position is defined by the survey points supplied by the operator. This visual analysis comprised the detection of all 'bright' anomalous features in the corridor, as well as the detection of areas of disturbed soil.

Step 2: The above process was repeated for the data collected on the second pass. It should be noted that this is not representative of an operational scenario. The rationale for this was to demonstrate the differences between single image target ID, and the use of change detection.

Step 3: The two images were reviewed simultaneously for each site. Features that are present on either the first, or second image, but not both, are identified. This allows changes that have occurred, (i.e. potentially transient third party features simulated by the synthetic targets) to be detected.

7.3   Discussion of Identified Features

A number of examples of features identified are shown in Figure 12 and Figure 13.

7.3.1   First data Collection

Figure 12 shows a number of the features that were detected as potential ground targets. All of the examples are taken from visible band data on the Northern site. A striking feature concerning the examples is the high level of contrast between the potential target features and the background. This level of clarity makes interpretation very simple. An encouraging point concerning all of the features is their proximity to boundaries. In other words, none of the examples shown are in 'ideal' open field areas.

Figure 13 shows a number of features detected in the visible and near infra-red data collected across the Southern site. Similar observations can be made concerning this data as can be made concerning the visible data. Features are probably brighter in this data than in the visible data of the Northern site. This is illustrated in indication 8, where a feature is visible in the woods.

The results of the analysis carried out, are that 32 potential targets and 3 excavation sites were reported for the first pass. However, one of these (Excavation 3, in the Northern area.) appeared to be a target situated on some disturbed ground.

7.3.2   Second data collection

There were 16 potential targets and 4 excavation sites reported for the second pass. The additional 2 excavation sites observed on the second pass relate to an area at the extreme northern end of the Southern site. This data was only collected on the second pass.

There appear to be 4 significant excavation sites along the pipeline. These are shown in Figure 14.

It is interesting to note how the contrast of the excavation site reduces over the time between data acquisition, but that it is still visible. This is shown in Figure 15. This shows the

advantages of this approach for accurate quantification of potential third party threat outside of those detected directly at the time of acquisition.

8   Results of Satellite test

Two quantifiable parameters are considered: percentage of targets detected, and accuracy of target location.

8.1   Detection of Excavations

The Northern excavations were open at the time of the first collection. All of the excavations had been closed by the time of the second data collections. The disturbed soil left by the two excavations in the northern section was clearly identified (see Figure 14, and Figure 15). Close examination shows a dark line/mark at the centre of each excavation, it is possible that this is the pipeline. The excavations in the southern areas were in an area of woodland. Data for this area was only collected during the second pass. The excavations can be seen but were not both identified during this exercise as areas of potential excavation. The ground within the clearing is not fully visible due to the surrounding trees. It is likely that in an operational situation, comparing subsequent images, the creation of the excavations would be clearly identified.

In summary, three of the four excavations where images were taken were detected. One excavation was not detected.

8.2   Detection of Targets

The detection of features of interest on the ground is a key measure of the effectiveness of a surveillance system. The higher the probability of detecting features the better the system and the more likely it is that damage to the pipeline can be reduced.

8.2.1   First Collection Targets

A summary of the results of detection of targets placed for collection 1 is given in Table 1.

Parameter	
Total targets placed for pass 1 by the operator (see note 1).	30
Number of targets in identifiable locations (see note 1).	28
Targets correctly detected.	22
Percentage of targets detected - %	78.6
Probability of detecting a target at 95% confidence based on this test - %	78.6 ± 3.7
Standard deviation of probability of detecting target - %	9.9

Note 1. 2 of the 30 targets placed have not been included. Target F was in an area not covered by the collected data at the first pass, and target L was reported lost. Therefore, the number of targets confirmed as identifiable is 28 and this is the sample number that has been used.

Table 1 Statistics of Detection of Targets Placed for the First Collection

8.2.2   Second Collection Targets

For the second collection most targets were removed. Six targets were left in place and four targets were moved to new locations. Of the 4 targets that were moved, the new locations of 3 could not be confirmed, hence it was not possible to measure detection. Of the 6 that were not moved, the location of 1 showed a significant change in field conditions, indicating that the

target had probably been moved. Therefore, at pass 2 there were 7 targets that could be seen, of these 4 were detected. The probability of detection is 57% ± 25%, at a confidence level of 95%, but this sample is too small to assign any statistical significance to the result.

8.2.3 <u>False Positives</u>

There were 10 'indications' made during the 'blind' analysis of the IKONOS data which were not confirmed as targets. Of these 5 were seen at the second collection. It is likely that in repeat surveys these would not be identified as infringements.

8.3 Location Accuracy

If a feature can be accurately located on a map then the investigator can be certain that the correct location has been visited and that the feature has not been missed because buildings or trees hide it. However, the location reporting accuracy for the satellite system has less significance than it might when reporting locations by helicopter survey. If an investigation were required, the satellite image could easily be printed, providing an easy method for the investigating person to identify the exact ground location of the feature.

There are a number of sources of inaccuracy in the location of the targets:

- The GPS target location readings have an average accuracy of 20m.
- The satellite images have been referenced to maps at a scale of 1:25,000 which gives an accuracy of 25m.
- The pipeline route is taken from maps at a scale of 1:2000 which gives an accuracy of 2m.

The average difference that might be expected is 20m to 40m. The average difference3 between the target position from the GPS readings and the target position from the satellite images is 32m. The standard deviation is 20m

8.4 Effect of Terrain

The majority of the terrain covered by the test is farmland. This is typical of the location of high pressure hydrocarbon pipelines. The operator classified the locations of the targets as: suburban, rural – intensively farmed, and rural moorland. The results for the different terrain types are summarised in Table 2. It should be noted that the 2 targets not detected in the rural moorland locations were placed in forested areas, where the detection of features is likely to be very difficult using any method.

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[3] The difference for each target is calculated as $diff = \sqrt{(x_{GPS} - x_{sat})^2 + (y_{GPS} - y_{sat})^2}$

Parameter	Suburban	Rural Intensive Farming	Rural Moorland
Total targets placed (see note 1).	9	12	9
Number of targets in identifiable locations (see note 1).	9	11	8
Targets correctly detected.	6	9	7
Percentage of targets detected - %	66.7	81.8	87.5
Probability of detecting a target at 95% confidence based on this test - %	66.7 ± 15.4	81.8 ± 8.4	87.5 ± 9.3
Standard deviation of probability of detecting target - %	23.6	14.2	13.4

Note 1. 2 of the 30 targets placed have not been included. Target F (rural moorland) was in an area not covered by the collected data at the first pass, and target L (rural intensively farmed) was reported lost. was reported lost. Therefore, the number of targets confirmed as identifiable is 28 (9 Suburban, 11 rural intensively farmed and 8 rural moorland), and these are the sample numbers that have been used.

Table 2 Statistics of Detection of Targets Placed in Suburban, Rural – Intensively Farmed and Rural Moorland Locations

8.5 Effect of Data Type

Data over the Northern area was collected for 3 bands in the visible spectrum only. Data over the Southern area was collected for 2 bands in the visible spectrum and 1 band in the VNIR. Results for the different data types are summarised in Table 3. This data indicates that at a confidence level of 95% the data from the 3 visible bands is more effective than data for 2 visible bands and 1 VNIR for the detection of small features. However, a qualitative assessment of the difference between the two types of data concludes that the visible and VNIR data is superior.

Data Type	3 bands Visible	2 Bands Visible + 1 band VNIR
Number of Targets Detectable	14	13
Number Seen	13	9
Percentage of targets detected - %	93	69
Probability of detecting a target at 95% confidence based on this test - %	93 ± 4	69 ± 10
Standard Deviation of probability of detecting target - %	7.4	18.5

Table 3 Effect of Data Type on Target Detection Probability

9 Effectiveness of Helicopter Surveillance

For comparison the operator carried out a test of the effectiveness of helicopter surveillance using the targets placed for the satellite test. Another sponsor of the project had also carried out tests of the effectiveness of helicopter surveillance.

9.1 Operator Tests

The pipeline operator carried out a test of the effectiveness of helicopter surveillance over the same route and targets as the satellite test. The locations of targets were not recorded; there were a relatively large number of targets within a short distance and it was not practical to record the positions. The results of this helicopter test are given in Table 4.

Parameter	
Total targets placed.	30
Number of targets in identifiable locations (see note 1).	28
Targets detected.	25
Percentage of targets detected - %	89.3
Probability of detecting a target at 95% confidence based on this test - %	89.3 ± 2.4
Standard deviation of probability of detecting target - %	6.5

Note 1. The route of the helicopter did not include 2 of the targets.

Table 4 Results of Operator Helicopter Surveillance Test

The Operator test results can be broken down by terrain type, see Table 5.

	Detection performance	%
Rural – intensive farming	9/11	81
Suburban	7/8	87
Rural-moorland	9/9	100

Table 5 Results of Operator Helicopter Surveillance Test by Terrain Type

9.2   Other Sponsor Tests

Another sponsor of the project has carried out studies of the effectiveness of helicopter surveillance with the aim of assessing the benefits of introducing new technology such as digital mapping to the surveillance process. These studies are relevant to our present work, particularly for comparative purposes. Therefore, some of the results of this work are included in this report.

The effectiveness of surveillance can be measured against 3 parameters:

- Probability of Detection (POD).
- Accuracy of feature detection and location.
- User-friendliness.

It was also considered desirable to measure possible performance differences due to the influence of different observers, routes and inspection systems. Therefore, during the first series of test flights, the variant "known/unknown" route was also added to the selection.

9.2.1   Probability of Detection
Research was performed into the effect on the effectiveness of helicopter surveillance of:
1. **The type of inspection system used**. Two systems were used:
   a. System A, paper maps with stickers to mark incidents.
   b. System B, a digital map system where incidents are marked using an on-screen cursor.

2. **Pipeline route**. Two different pipeline routes were used.
    a. A – H – approx 40km
    b. H – E – approx 75km
3. **Observer**. Four observers were used.
4. **Route knowledge**. Two of the observers were familiar with the routes surveyed, and two were not.

The effectiveness indicators chosen were the (average) detection probability of simulated incidents and the accuracy of incident location (reported in section 9.2.2). Incidents were simulated by installing red/white coloured signs at varying locations in varying numbers along 2 routes. Table 6 contains an overview of the findings of the test flights in detection probabilities, depending on the route, observer and the system variant.

Case A - Survey system A - Paper maps, plus observers on known route.			
observer	route	score (*)	POD (%)
W1	1. A – H	3/10	30
W2	2. H – E	11/17	65
Case B, - Survey system B Digital map and GPS, plus observers on known route.			
Observer	route	score	POD (%)
W2	1. A – H	6/10	60
W1	2. H – E	10/12	83
Case C, - Survey system B - Digital map and GPS, plus observers on unknown route.			
Observer	route	score	POD (%)
W3	1. A – H	6/12	50
W4	2. H – E	15/16	94
POD = probability of detection. * = number detected test signs/number test signs installed.			

Table 6 Effects of variations in surveillance system and environment on the effectiveness of helicopter surveillance.

Effect of different inspection systems on performance (POD).

- System A (Paper) - 52 % average POD with standard deviation Sa = 9.6 %.
- System B (Digital) - 74 % average POD with standard deviation Sb = 6.2 %.

Therefore System B is more reliable than system A (95% certainty)

Effect of different routes on performance (POD).

- Route 1 - 47 % average POD with standard deviation S1 = 9%.
- Route 2 - 80% average POD with standard deviation S2 = 6%.

Route 1 shows a lower POD than route 2 (98% certainty)

Effect of different observers and known/unknown terrain on performance (POD).

Using the digital mapping system for aerial surveillance it does not matter that observers fly over (un)known terrain. (98% certainty)

Under similar conditions, observers have similar performance with a reasonably small variation (standard deviation S=8%).

9.2.2   Accuracy of incident location.

One of the objectives of the implementation of the digital mapping system was the desire to improve the accuracy of locating incidents requiring ground investigation. In practice, it appeared that poor positional data could lead to considerable delays in tracing an incident on site (in some cases they could not be found at all). Therefore, the indication performance, alongside the detection probability, is an important indicator for the effectiveness of aerial surveillance, and the test plan was designed to measure the performance of the different incident locating techniques. However, due to the early termination of the project, only 2 variants were tested, and the results of these have been summarised in Table 7.

Aerial surveillance variant /indication method.	n	R (m)	Δx (m)	Δy (m)	Δr (m)	Sx (m)	Sy (m)	Sr (m)
1. "old" flight routine; attach arrow sticker on to paper flight map.	7	-1 to 68	-1	-3	43	32	41	22
2. Digital map and dGPS system with cursor manipulation on screen.	2 0	-154 to 94	-34	-43	104	87	52	25
legend: n = number of useful measurement values. R = maximum variation in measurement results over x and/or y. Δ.. = average measurement deviation relative to the actual position in triangular co-ordinates. Δr = average radial measurement deviation relative to the actual position. Sx and y = estimate of the standard deviation of the measurement deviations Δx and Δy. Sr = estimate of the standard deviation of the radius within which the deviations x and y are located.								

Table 7 Incident position measurement accuracy

When the location accuracy data is plotted with an incident as a "goal" on the zero point, then several things occur with respect to the zero point ("incident") within which indication will most probably take place. It becomes obvious that with the "old" flight system, incidents were indicated more precisely (values of Δr), but that the accuracy (values of Sr) of both systems are similar.

In addition the locations recorded using the digital mapping system were clearly skewed in one direction pointing to a system error. It was discovered that a program error as well as the slowness in the processing of dGPS signals (receiving frequency 2 Hz) were the causes of this. These system errors were repaired by adjusting the software and by using a dGPS receiver with a higher receiving frequency (20 Hz). However, due to the termination of the project, the effects of these improvements were not measured.

10 Comparison of Satellite System and Helicopter Surveillance

Two direct comparisons between satellite surveillance and helicopter surveillance are possible: detection efficiency, and location accuracy.

10.1   Detection

A comparison of detection rates for helicopter surveillance and satellite surveillance is given in Table 8.

	Satellite Test	**Helicopter Surveillance (all tests all systems)**
Number of targets confirmed as in identifiable locations.	28	105
Targets detected.	22	76
Percentage of targets detected - %	78.6	72.4
Probability of detecting a target at 95% confidence - %	78.6 ± 3.7	72.4 ± 1.2
Standard Deviation of probability of detecting target - %	9.9	6
Location Accuracy	$32m \pm 20$	$43m \pm 22$

Note. Helicopter surveillance was not tested solely on the same route and targets as the satellite; therefore, this comparison should be treated with caution.

Table 8 Target Detection by Satellite and Helicopter

10.2   Accuracy

Tests of helicopter surveillance carried out show the average location accuracy for the targets spotted from a helicopter to be 43m (with a standard deviation of 22m) when using a paper map, and 104m (with a standard deviation of 25m) when using a computer based map system.

The average location accuracy of 29m (with a standard deviation of 16m) estimated for the satellite method is superior to that achieved with helicopter surveillance.

11 Operational Implementation

The aim of the analysis carried out here has been to quantify the intrinsic ability of IKONOS data to detect potential third party features. However, an important factor in this analysis is how data can be both acquired, and processed on an operational scale.

Some of these aspects can be addressed at this stage. Others, such as how to deal with large data volumes cannot be addressed fully and would require a rigorous appraisal of IT infrastructure and satellite capacity to achieve a full understanding. Issues such as these would require the full participation of Space Imaging, which at this stage is not possible.

The aspects addressed in this section are:

- Data ordering and processing speed.
- Future for automatic interpretation.
- Data cost.
- Discussion of cloud cover impact.

11.1   Data Ordering and Processing

It is clear from the experiences discussed in Section 5 that the planning of large and complex acquisition corridors is practical and relatively simple. All that is required from an operator is the generation of the coverage coordinates, and a number of parameters such as described in Section 5. Furthermore, appropriate liaison with Space Imaging should allow regular collection of data, to a given specification, without repeat submission, resulting in minimum project management costs on behalf of the operator.

However, there should be a note of caution surrounding:

- Whether the IKONOS satellite would have the capacity to acquire large areas representative of a realistic HP Gas Transmission network on a regular basis.
- How such large areas of data could be reliably transmitted to a client, and the level of IT infrastructure necessary to support this.

These issues require further cooperative work with Space Imaging and other potential suppliers in order to achieve a resolution. There are a number of potential solutions including:

1. The ability of Space Imaging to carry out image matching, colour balance and enhancement of data automatically. This should be feasible, given the image processing software employed at Space Imaging's receiving stations.
2. Image compression techniques to be applied to data prior to transmission.
3. The provision of internet based services to allow users web access to data, without the requirement to download or transmit large volumes of data onto a local system. This would have the advantage of data safety, as well as removing the necessity for the operation to have a large IT infrastructure.

11.2   Automatic Interpretation

Given the complex nature of the terrain through which most pipelines run, automatic, image-based detection of features will prove extremely difficult. The reasons for this are as follows:

- There are likely to be changes of vegetation coverage between repeated acquisitions.
- Small changes in sun angle and hence shadow, will result in difficulties in carrying out change detection in the vicinity of trees, hedges and buildings.
- Changes in atmospheric conditions will lead to overall changes in reflectance.

However, the above factors do not preclude the potential development of a number of steps that may make operational screening a practical option.

The overriding issue regarding operational use should be the speed of interpretation. A key factor in addressing this is the adoption of the approaches outlined in Section 11.1, allowing automatic registration, enhancement, and colour balancing of the data, at source through a dedicated Image Processing facility. Purely human interpretation of data converted into this form is rapid, and reliable, and may in itself provide a practical solution.

A second, and complimentary step is to employ change detection processing that will allow areas of 'change' along the route to be identified. This 'screening' as opposed to 'detection' approach would present the user with significantly smaller areas on which to carry out visual inspection, thereby increasing surveillance speed.

An example of this is shown in Figure 16. In this example data has been registered, balanced and subtracted. Areas of change show as bright areas in the change detection image. This is not foolproof, but it does offer significantly less data to be scrutinised by the human interpreter. As with some of the colour balance, enhancement and registration processes, this step is relatively straightforward, and could be applied to the data at source, again reducing the time and IT burden on a pipeline operator.

11.3   Cost

The price of satellite data is still high; in Europe the price at the time of the study was $24 per square km for suitable data, with minimum dimension limitations (11km smallest dimension) that make ordering long narrow corridors of data costly. In the US prices were lower - approximately $15 per square km, and as described in Section 5.2.4 the possibility of ordering complex areas was being investigated by Space Imaging. The current price in Europe for the data used by this study is approximately USD $30 per square km [5]. However, due to the minimum dimension of 11km, the pricing per line kilometre is $300. This is much higher than the cost of digital aerial photography, which typically costs less than $50 per km, or helicopter surveillance, which typically costs $5 to $10 per km.

11.4   Cloud Cover

Satellite image data of the ground can only be collected when the ground is not obscured by cloud. Most northerly areas of Western Europe have frequent cloud cover. The proportion of the time that the ground is obscured by cloud will affect the average frequency with which it is possible to collect data. In addition if the ground is obscured for long periods the gaps between some collections may be considered excessive.

Some data on cloud coverage is readily available, and can be used to make a very simplistic estimate of achievable average data collection frequencies. Data collected by the International Satellite Cloud Climatology Project indicates that average annual cloud cover in the Netherlands is approximately 70% [4]. If this is taken to mean that the ground is obscured 70% of the time, it means that the ground is not obscured 30% of the time. Consequently, every time the satellite passes there is a 30% chance that it will be able to collect data. If the satellite passes once every 3 days then over the period of a year the satellite will make 120 passes and should be able to collect data an average of 36 times. For an average of 14 days between collections 25 collections per year are needed. Therefore, an average satellite data collection frequency of 14 days is achievable.

There are a number of complicating factors that must be considered such as minimum and maximum periods between collections, seasonal variations in cloud cover, etc.. A further study of cloud data would give more information on achievable data collection schedules.

12 Conclusions and Recommendations

12.1   Conclusions

The images produced by the current generation of satellites can be used by pipeline operators to detect third party activities along a pipeline route. They are either comparable or superior to the detection of these features using helicopters.

1. DETECTION
   The current generation of satellite can be used to detect features around pipelines, such as 3rd party activity, that could lead to damage.
2. ACCURACY
   The accuracy of location of features is 32m +/- 20m, using satellite data, and 43m +/- 22m for helicopters.
3. RELIABILITY
   The feature detection rates using satellite data (78% probability of detection) are similar to helicopter systems (72% probability of detection).
4. REPEATABILITY
   An average data collection frequency of 14 days is achievable, even in areas with frequent cloud cover.

12.2   Recommendations

The field trials have shown satellite data to have similar detection capability to helicopter data. However there are a number of practical issues that need to be addressed before satellites can be considered as a replacement for helicopters:

- Time for delivery of images.
- Effect of cloud cover over collection areas.
- Data handling.
- Cost of images.

13 ACKNOWLEGEMENTS

14 references

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2. Radarsat International, http://www.rsi.ca/
3. Space Imaging Inc., www.spaceimaging.com
4. http://isccp.giss.nasa.gov/isccp.html
5. www.euspaceimaging.com

Figure 1Golden Colorado, Space Imaging Artificial Sample Image.
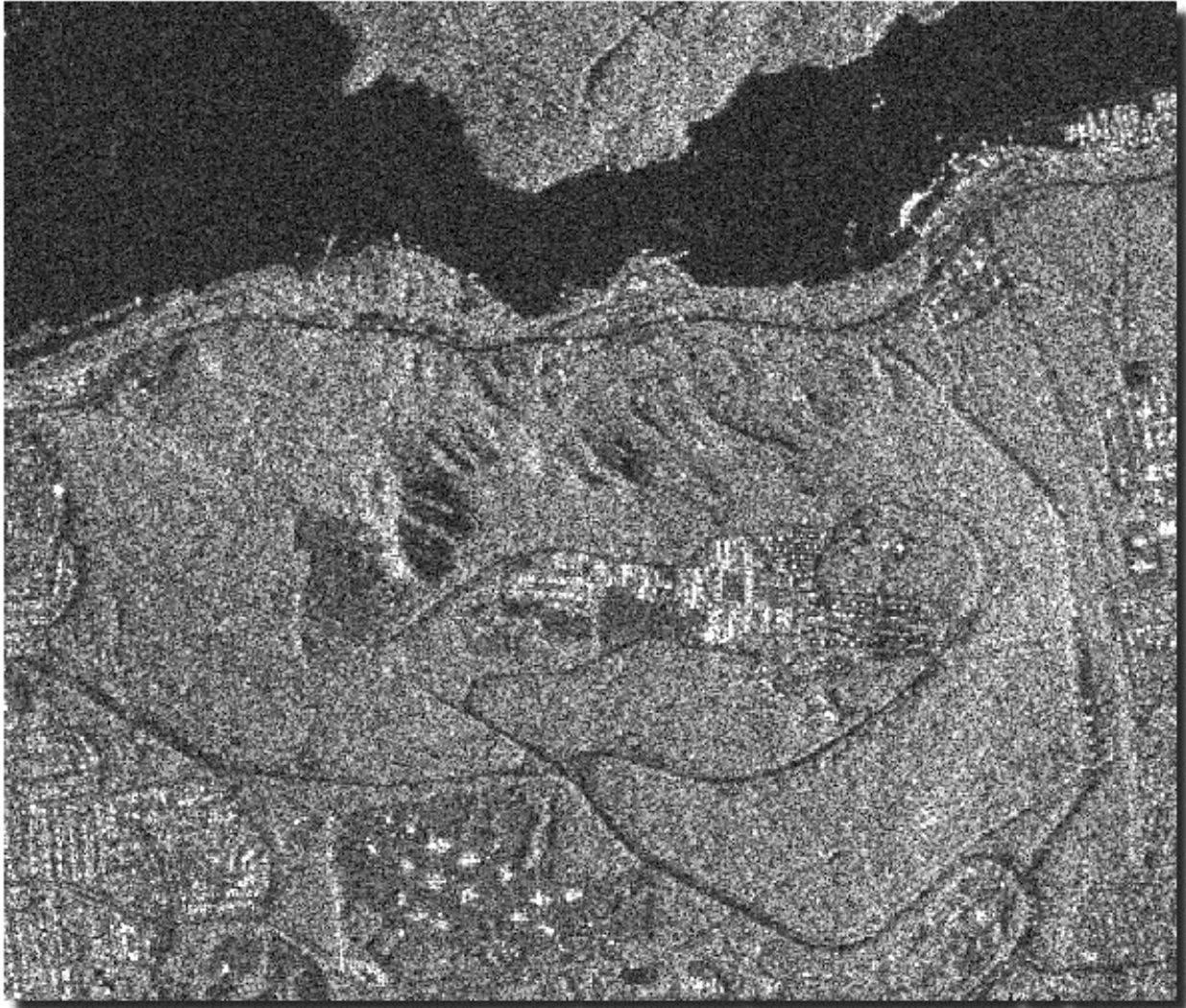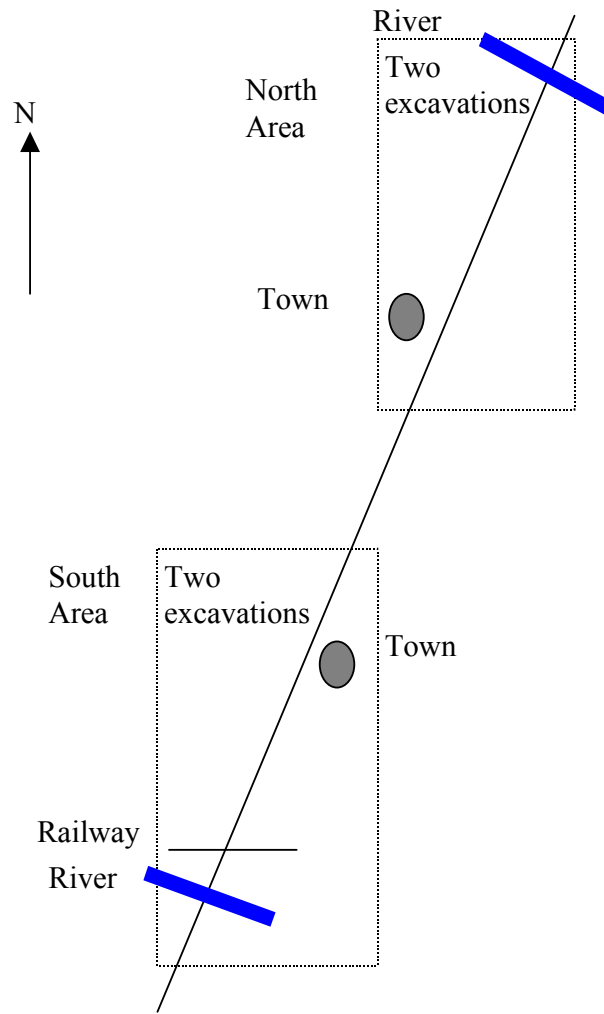
Figure 2 Radarsat-1 Sample Image (www.rsi.ca)

Figure 3 Schematic of Test Site

Figure 4 Excavation

Figure 5 3m by 1m "Target"
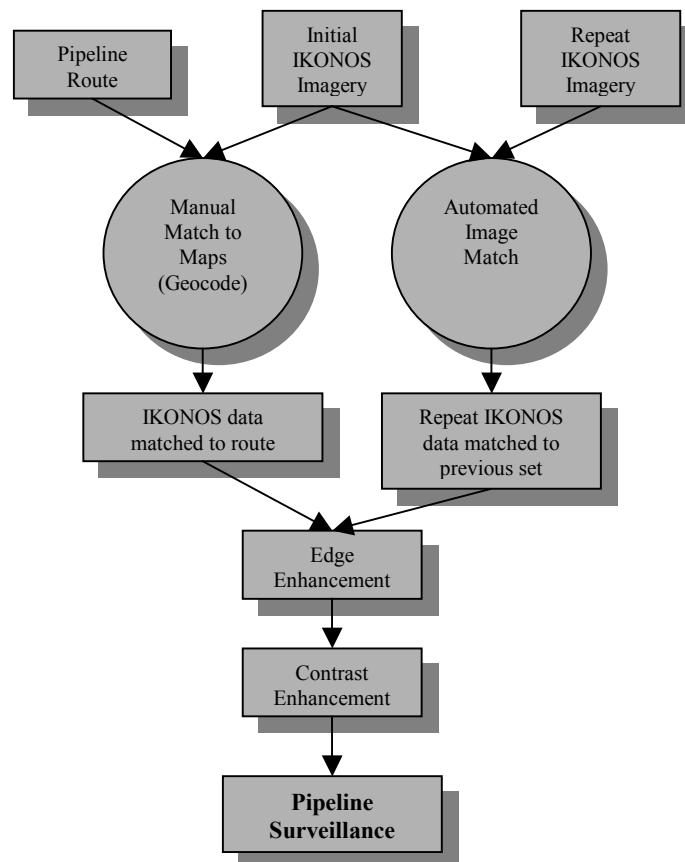
Figure 6 Data Processing

Figure 7 Image Enhancement

Figure 8 Feature Identification

Figure 9 Excavations

Change in Crop Growth Rates

Figure 10 Vegetation Growth

Figure 11 Small Targets in Visible and Visible/VNIR

Indication 1

Indication 3

Indication 4

Indication 6

Indication 9
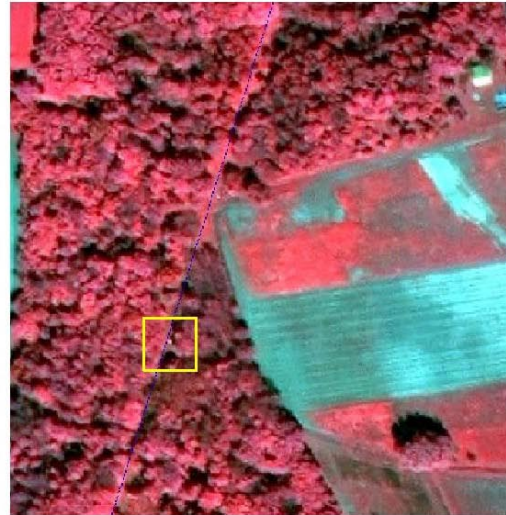
Indication 11

Figure 12 Suspected Targets - Northern Area

Figure 13 Suspected Targets - Southern Area

Northern Site: Excavation 1

Northern Site: Excavation 2
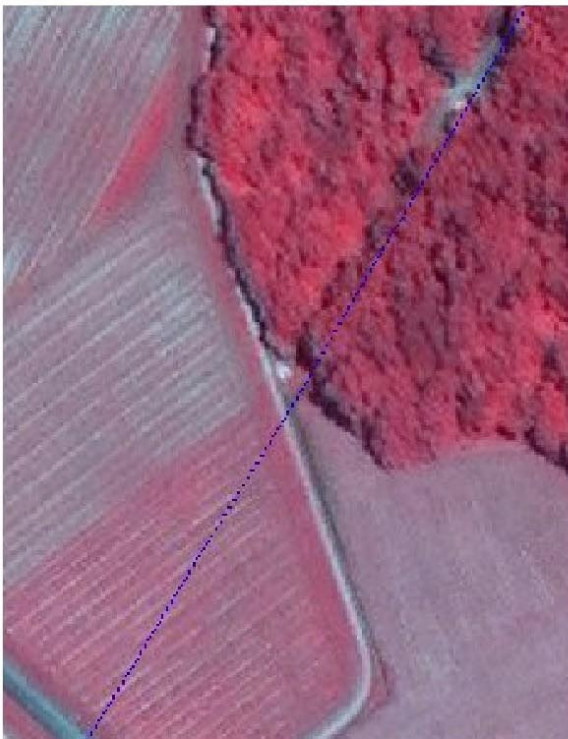
Southern Site: Excavation 1

Southern Site: Excavation 2

Figure 14 Excavations

Pass 1: Northern site excavation 1

Pass 2: Northern site excavation 1

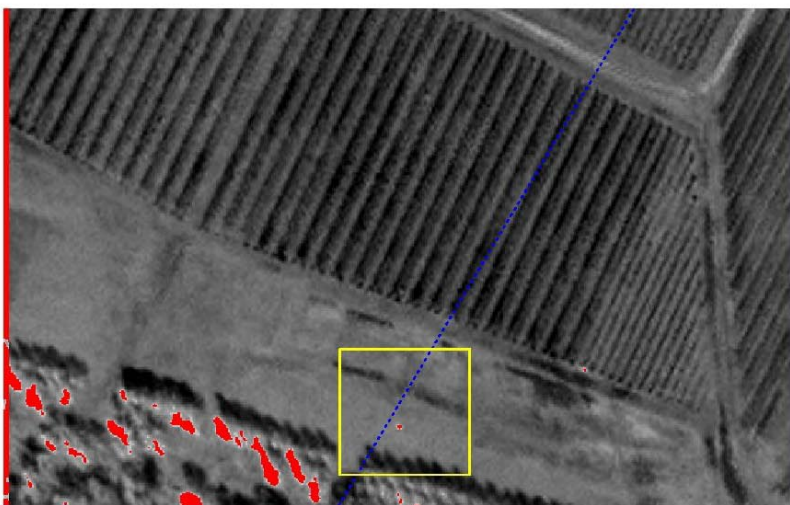Pass 1: Northern site excavation 2

Pass 2: Northern site excavation 2

Figure 15 Change in Excavation Appearance
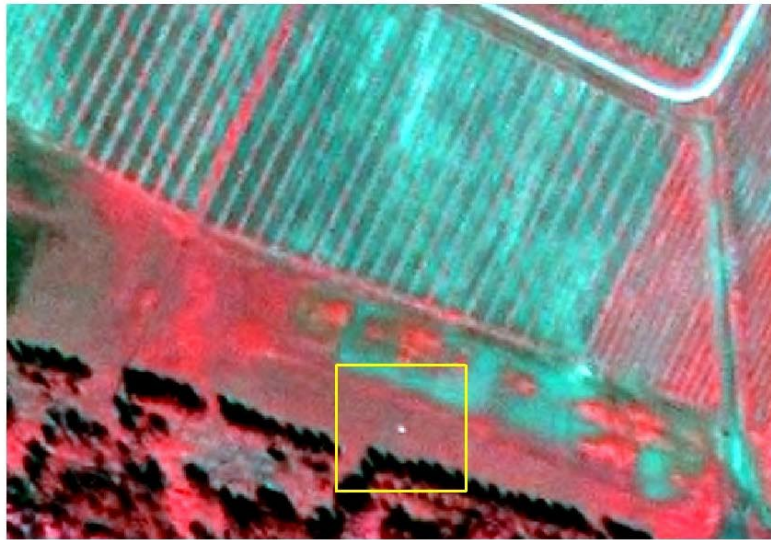
Southern area pass 1
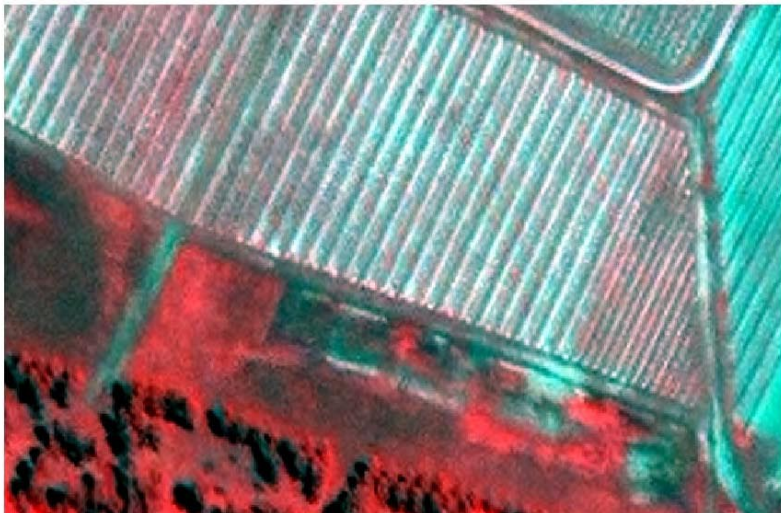
Southern area pass 1
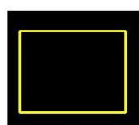
Changes detected between passes

Greatest change

Target feature

Figure 16 Automatic Detection of Changes