PIPELINE LEAKAGE REVEALED BY VEGETATION ANOMALIES MEASURED WITH REFLECTANCE SPECTROSCOPY

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ABSTRACT:

This study presents the results of 2 years of field campaigns in May 2004 and 2005 in Holland, investigating a test trajectory of a 21 km long pipeline, and a HyMap scene covering the whole pipeline. The pipeline is 'sweating' benzene condensates at approximately 50% of the connection points between the 9 meter segments of the pipeline. Hydrocarbons can establish locally anomalous zones that favor the development of a diverse array of chemical and mineralogical changes. Vegetation present in these zones is likely to be influenced by the hostile and polluted environment. Geobotanical anomalies occur as a result of the effect of hydrocarbons on the growth of vegetation. The most likely changes in the vegetation are expected to occur in the chlorophyll concentrations which are an indicator of the health state.

Therefore, spectral field measurements were conducted at 8 different locations in the test trajectory. The test locations were covered by various types of vegetation. We can confirm the presence of geobotanical anomalies in most of the locations using various spectral interpretation techniques like linear red edge shifts, Carter stress indices, normalized difference vegetation index en yellowness index. After the interpretation of the geobotanical anomalies, derived from hyperspectral measurements, we compared the findings with information on pollution levels obtained by drilling at some of the locations. We can confirm a strong coherence between high pollution levels derived from the drilling and the geobotanical anomalies interpreted from the spectral measurements. We will show results of automatic detection algorithms, like Hough transforms, to find weak and non-unique spectral signals with a pre-defined spatial pattern.

INTRODUCTION

In 1996, a Dutch oil company constructed a 20 km long pipeline for transportation of benzene condensates. In the following years, the pipeline started 'sweating' on the connection points between the 9 meter segments of the pipeline. Extensive investigation of a 1 km trace revealed that approximately 50% of the connection points are sweating and benzene condensate is leaking into the ground (Figure 1).

Leakage of hydrocarbons can establish locally anomalous zones that favor the development of a diverse array of chemical and mineralogical changes. Any vegetation present in these zones is likely to be influenced by the hostile and polluted environment. Geobotanical anomalies occur as a result of the effect of hydrocarbons on the growth of vegetation. The most likely changes are expected to occur in the chlorophyll concentrations in the vegetation which are an indicator of the health state.

Traditional methods for investigating leakage and pollution, like drilling, are time consuming, destructive and expensive. A non-destructive and more economic exploration method would be a valuable complement to sub-surface investigative methods. Imaging spectroscopy (or hyperspectral remote sensing) is such a non-destructive investigative tool. Spectroscopy can identify anomalous vegetation and assist in linking the vegetation status to abnormal concentrations of toxic elements resulting from pipeline leakage.

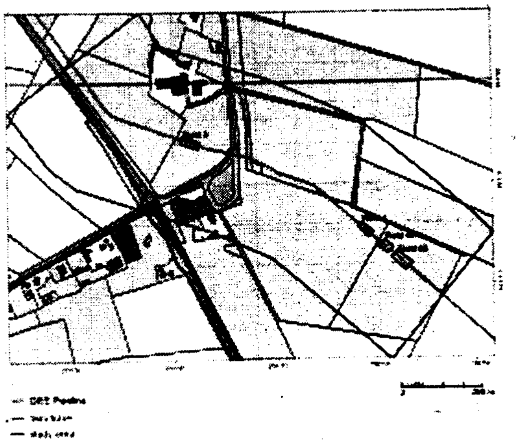

Figure 1: Overview of the study area. Indicated in purple is the GRE pipeline, in blue the 1 km trajectory and in red the 4 different fields that were investigated

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during this field campaign.

Different names have been coined to this field of remote sensing including "reflectance spectrometry", "reflectance spectroscopy" and "hyperspectral remote sensing". Although they have a different meaning in the sense of a direct translation of the term (i.e., spectrometry = "measuring", spectroscopy = "seeing", hyperspectral = "too many bands"), the significance and perception to the remote sensing community is the same: "the acquisition of images in hundreds of registered, contiguous spectral bands such that for each picture element of an image it is possible to derive a complete reflectance spectrum. The objective of reflectance spectroscopy is to measure quantitatively the components of the Earth System from calibrated spectra acquired as images for scientific research and applications. Thus we are interested in measuring physical quantities at the Earth surface, such as reflectance.

VEGETATION CHARACTERISTICS

Geobotanical anomalies occur as a result of the effect of pollution on the growth of vegetation. Environmental changes affect the root structure of vegetation and ultimately influence these plants' vigor and hence, spectral reflectance. To identify vegetation anomalies by remote sensing, the "normal" plant variability can be assessed by judging the plant distribution, presence of indicator plants, or morphological changes in plants induced by excesses or deficiencies in available soil nutrients. This research focuses on the spectral characteristics of the anomalous or stress vegetation species caused by environmental pollution.

Reflectance properties of vegetation in the visible part of the spectrum are dominated by the absorption properties of photosynthetic pigments of which chlorophyll, having absorption at 0.66 and 0.68 m for chlorophyll a and b, respectively, is the most important. Changes in the chlorophyll concentration produce (1) a decrease in the height of the infrared shoulder due to structural damage; (2) an decrease in the absorption at the chlorophyll absorption maximum due to decreased leaf chlorophyll; and (3) a shift in the position of the red edge (slope around 0.7 m) towards shorter wavelengths (figure 2).

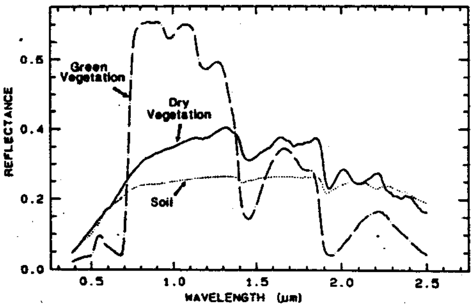

Figure 2: Reflectance spectra of photosynthetic (green) vegetation, non-photosynthetic (dry) vegetation and a soil. The green vegetation has absorptions around 0.7 m due to chlorophyll. Healthy vegetation has a steep transition around this point where dry vegetation shows a flat ramp.

The following methods, which are explained below, have been used to assess the vegetation status:

- ormalized Difference Vegetation Index (NDVI)
- arter stress indices
- ellowness Index (YI)
- inear Red Edge shift

NDVI

The Normalized Difference Vegetation Index (NDVI, Wessman et al. 1993) is the most popular and widespread vegetation index used in remote sensing purposes. NDVI is calculated by using a band in the red (667nm) and a band in the near infrared (774nm) part of the spectrum:

$$NDVI = (R_{774} - R_{667})/(R_{774} + R_{667}),$$

where R_{667} and R_{774} are the reflectance values at 667 and 774nm respectively.

The common drawbacks of the NDVI (influenced by state of the atmosphere, illumination, observation geometry and background reflectance) are assumed to be neutralized by the experimental setup in fields 3 & 4. The setup in field 1, however, does not correct for illumination effects and background reflectance from soil. Together with the highly variable illumination by clouds, the results of field 1 do not only indicate vegetation health, but also vegetation coverage. Consequently, the results should be interpreted with more care than the results of field 3 & 4.

Carter stress indices

The so-called Carter ratios (Carter, 1994) are band ratios that are sensitive to vegetation stress as shown by laboratory analysis done by Carter and his group. We computed these two ratios as

$$R = R_{695}/R_{420}$$
and
$$R = R_{695}/R_{760}$$

R_{420}, R_{695} and R_{760} are the reflectance values at 420, 695 and 760nm respectively.

Yellowness Index

The yellowness index (YI) (Adams et al 1999) is a simple, three-point approximation of the second derivative of spectra, and should be less sensitive to atmospheric influences than many other vegetation indices such as NDVI. YI gives an estimate of chlorosis of leaves in stressed plants, and is calculated as:

$$YI=(R_{-1}-2R_{0}+R_{+1})/\quad^{2}$$

where R_{-1}, R_0 and R_{+1} are the reflectance values at 580, 624 and 668nm respectively, and thus is 44nm.

Red Edge

Guyot & Baret (1988) assumes that the reflectance curve at the red edge can be simplified to a straight line centred near a midpoint between the NIR reflectance (near 780nm) and a reflectance minimum of the chlorophyll absorption feature (near 670nm).

First, they estimated the reflectance value at the inflection point:

$$R_{re}=(R_{670}+R_{780})/2$$

Secondly, they applied a linear interpolation procedure between the measurements at 700 and 740nm for estimating the red edge wavelength ($_{re}$) corresponding to the estimated reflectance value at the inflection point:

$$_{re}=700+40*((R_{re}-R_{700})/((R_{740}-R_{700}))$$

where R_{670}, R_{700}, R_{740} and R_{780} are the reflectance values at 670, 700, 740 and 780nm wavelength, respectively.

DATA COLLECTION AND PROCESSING

Instrument setup

Absolute reflectance spectra were collected using a FieldSpec Pro Fr instrument from Analytical Spectral Devices in combination with a High Intensity Contact Probe (with internal light source and spot size of 10mm) and a calibrated spectralon reference panel (Labsphere Inc.). The ASD FieldSpec Pro Fr has the following specifications:

Spectral Range	350-2500 nm
Spectral Resolution	3 nm @ 700 nm 10 nm @ 1400/2100 nm
Sampling Interval	1.4 nm @ 350-1050 nm 2 nm @ 1000-2500 nm

Field 4A

Field 4A was the first field to be measured. This field was covered with 30-40cm long grass, with a few bad and bare spots of approx. 50cm Ø. The sampling scheme was to measure every 1m along 20m long, 2m spaced, transects perpendicular to the pipe (figure 3).

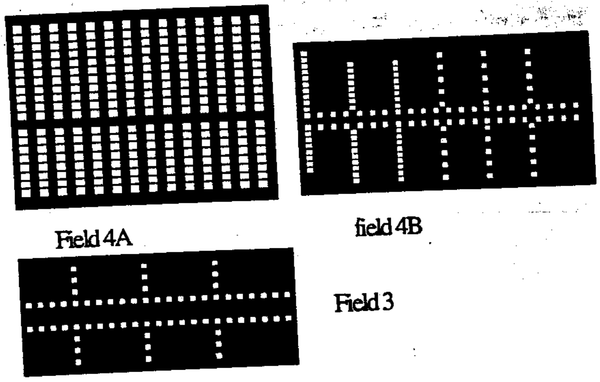

Figure 3: Sampling scheme of field 4A and 4B. The left-top corner of the image is the north-west corner of the field. Sampling started at 1m intervals in transects with 2m spacing. Every pixel resembles a 1x1m area; the red pixels indicate measurement points on top of the pipeline.

Grass samples were collected from an approx. 30x30cm area in the grass by removing the upper 10cm and cutting the next 10cm into a little jar. The contact probe was pushed in the jar for the actual measurement (figure 5a & 5b). Per sample point, five measurements have been averaged after visual inspection for instrument or measurement errors.

Field 4B

Field 4B was covered with 30-40cm long grass, with the difference that no obvious bad spots were found by visual inspection. The sampling scheme consisted of three, 50m long, transects parallel to the pipe, with transects perpendicular to the pipe every 7m (see figure 3). One parallel transect with a 1m sampling interval was located on top of the pipe. The other two parallel transects had a 2m sampling interval, and were located 1m to the left and 1m to the right of the centre transect.

In this setup, ten points were measured twice for quality control. The measuring itself was done by pushing the grass down on the soil in order to cover any visible soil. The grass was measured directly with the contact probe (figure 7) instead of inside the little jar. Per sample point, five measurement have been averaged after visual inspection for instrument or measurement errors.

Field 3

Field 3 was covered with 30-40cm long grass, with no obvious bad spots. This field has been measured with the same approach as field 4B, though the sampling scheme was slightly changed (Figure 3). The parallel transects had a 2m spacing, with measurements every 2m. The perpendicular transects had a 12m spacing (figure 8), also with measurements every 2m. In this setup, nine points were measured twice for quality control.

RESULTS

We calculated all the aforementioned spectral products to assess the vegetation health. The results for the different spectral products were very much alike, therefore only the Red Edge product will be discussed and shown in this chapter.

For field 3 we found a repetitive pattern of botanical anomalies, separated by approx. 9 meter (Figure 4). Since this is equal to the distance between the pipeline connectors, this gave us a very strong indication that we were indeed mapping botanical anomalies related to the pipeline leakage.

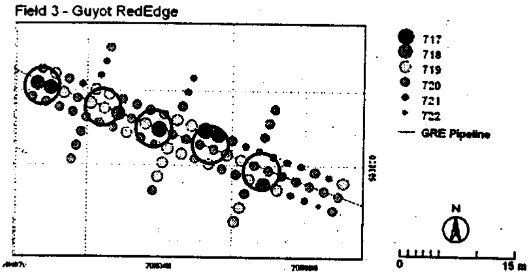

Figure 4. Red Edge analysis for field 3.

Field 4B was found to be strongly polluted. Most of the field suffered to some extent from pollution but two major anomaly clusters were identified in the analysis (Figure 5). Due to the extent of the pollution there is no clear relationship anymore with the 9m distance of the leaking connection points.

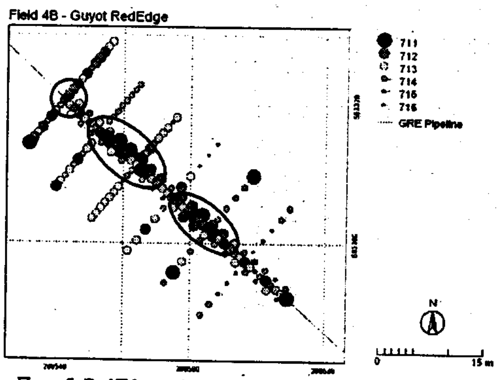

Figure 5. Red Edge analysis for field 4B

Comparison with drilling results

For field 4B drilling measurements were performed in an earlier stage of the research. The drilling samples were analyzed for the presence of benzene and samples that were exceeding environmental threshold values were identified. Comparison of these locations with our botanical anomalies shows a strong correlation between the two independent data sets (Figure 6). The polluted drilling samples coincide with the largest botanical anomalies.

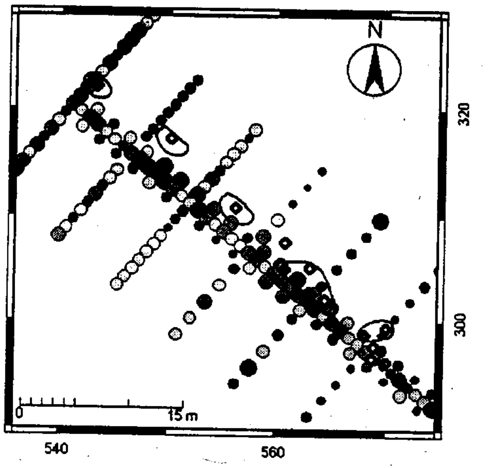

Figure 6. Comparion of drilling measurements with the botanical anomalies. Drilling locations are indicated in squares, samples exceeding environmental threshold values are circled and grouped in a best-case pollution scenario.

AIRBORNE ANALYSIS OF VEGETATION ANOMALIES

In June 2005 airborne hyperspectral imagery was acquired over the full 21 km length of the pipeline. Analyzing such an extensive data set with traditional techniques would require significant manpower and will lead to possible subjective interpretation of the data. For this reason we developed objective analysis techniques. These techniques (HoughTR) combine spectral information from the desired object of study with spatial information (van der Werff et al., 2005). For the pipeline this means in practice that we will use the aforementioned spectral products and combine this in the analysis with information on the location of the pipeline (Figure 7).

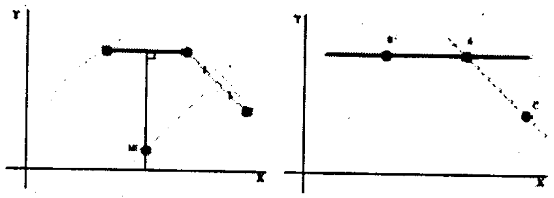

Figure 7. The fitting of circles and lines through a point data set by the HoughTR algorithm: (a) a circle is fitted through three pixels. From these pixels, the circle center M and the circle radius are calculated. When the radius is in between user-defined extremes, the circle is added to the accumulator array; (b) lines are calculated by defining a line (bold) through reference points A and B. Candidate point C is evaluated by calculating a new line through reference point A and the candidate point. When the slopes of both lines are equal, independent of direction, the candidate point is added to the line.

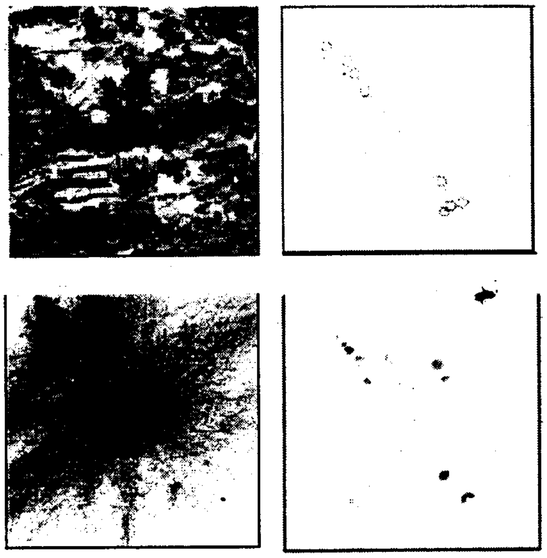

Figure 8. Results for a case-study on natural hydrocarbon leakage in Hungary. Left top shows the study area and right top shows the present natural leakage locations. Bottom left shows all possible solutions based on traditional criteria. Bottom left is the final outcome of the algorithm based on the spatial and spectral criteria (van der Werff et al, 2005). Good fit is in black colors, bad fit in white colors.

A simple case study in a natural hydrocarbon seepage area in Hungary shows the effectiveness of the improved algorithm (Figure 8). This approach will be extended towards the full 21 km of the benzene pipeline for leakage detection based on spectral and spatial criteria.

CONCLUSIONS

Reflectance spectroscopy (or hyperspectral remote sensing) proved to be a tool that offers a non-destructive investigative method to identify anomalous spectral features in vegetation. This is the main conclusion after an extensive field campaign in May 2004 near Anjum in Friesland. At four different test locations several survey designs were tested to reach the objective of locating variations in health of vegetation. All survey designs proved useful and several anomalies were found in three of the four different locations. At this stage, it cannot be concluded if these anomalies are related to possible leakage of the NAM GRE-pipeline. To determine if reflectance spectroscopy can assist in linking the vegetation status to abnormal concentrations of toxic elements resulting from pipeline leakage a ground validation (drilling at selected locations) is necessary. Without ground validation it can only be determined if vegetation stress is present but not what the exact cause is of any anomaly that is found.

The HoughTR algorithm has been applied for the detection of alterations resulting from natural seepage of carbondioxide and light hydrocarbons. These alterations, which can be seen as circles (halos) that are located on a line (faults), do not have an unique spectral signature. As a result, the outcome of a pixel-based spectral classifier showed many false anomalies. When using the specific spatial pattern of these alterations in the HoughTR algorithm, the spectral signal of the seepages could be distinguished from image pixels that have a similar spectral signature but do not belong to the object. Combining the results of the three optimization methods in a mean fit results in an accurate measure for seepage probability. Furthermore, the outcome of the HoughTR algorithm is stable for a different amount of input pixels. An important benefit of a contextual algorithm like the HoughTR algorithm is that the required parameters, such as the spectral endmember and the spatial contraints, can be determined by expert-knowledge from the field or from literature. This makes the algorithm case-specific which allows its application to other areas and datasets.

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