Exploring the use of High Resolution Multi-Spectral Satellite Imagery to identify Subsurface Structures

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Summary: Two known tunnel sites located within the Mendip Hills in Somerset, UK, are inspected by examining fluctuations in the spectral response of the near infrared bandwidth. One of the anomalies is then verified with microgravity modelling before attempting to detect tunnel generated signatures in the near infrared using different image processing techniques. Four new subsurface linear anomalies were detected and a three tier image processing workflow was devised to generically identify linear subsurface anomalies, including that of tunnel systems. The workflow was tested on underground irrigation channels in Helmand Province, Afghanistan where mixed results were observed.

Keywords: Multi-Spectral Imagery, Near Infrared, Microgravity, Karez Tunnel Systems, Archaeological Exploration.

1. INTRODUCTION

Man-made irrigation tunnels are extensively used in Afghanistan and Iraq. More commonly termed in these countries as Karez, this type of subsurface structure is traditionally a horizontal oriented tunnel that is excavated into alluvium to extract shallow groundwater (Shirazi, 2006). Dried karez systems and other man made variants seen across hostile regions of countries like Afghanistan can provide insurgents with covered manoeuvre during fire fights. Additionally, they can be used to hide weapon caches (ISAF Joint Command, 2010), escape from Prison of War camps (Agence France-Presse, 2011), and transport explosive materials (North Shore Journal, 2009). As a result, man-made tunnel systems and underground irrigation systems have, and clearly still are, posing a threat to coalition forces on military operations.

1.1 INDICATORS OF AN IRREGULAR SUBSURFACE

Underground structures like tunnel networks and archaeological remains can affect their surrounding landscapes in different ways including changes in thermal inertia (Gunn et al., 2008), changes in localised soil moisture content and drainage rates (Parcak, 2009), soil composition, and vegetation vigour (Rowlands and Sarris, 2007). This latter indicator is often observed on the ground as a crop mark (figure 1), a phenomena which can be used to denote the presence of underground structures (Masini and Lasaponara, 2006). This paper critically assesses the capability of using high resolution, multi-spectral satellite imagery from passive remote sensing to identify subsurface tunnel structures in support of military operations.

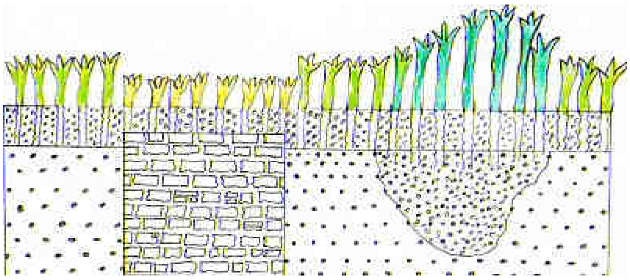

Figure 1. Crop marks can be formed both as negative marks above wall foundations and as positive marks above the damper and more nutritious soil of buried pits and ditches. Tunnels are likely to produce positive crop marks.

2. TRAINING SITES

Two trainings sites (TS) were identified in the Priddy Mineries area in the Mendip Hills, Somerset (figure 2). The first training site (TS1) constituted three 25 m long and 2 m deep parallel flues, striking NE-SW towards the building foundations of St Cuthberts Lead Works, a 19th Century Lead Mine. Additionally, two partially collapsed flues bearing a similar structure to those at TS1 and located near the Victorian site of Chewton Lead Mine became the second training site (TS2). QuickBird (QB) Multi-Spectral Imagery (MSI) dated 17 Aug 2005 with an MSI pixel size of 2.4 m was acquired for both training sites.

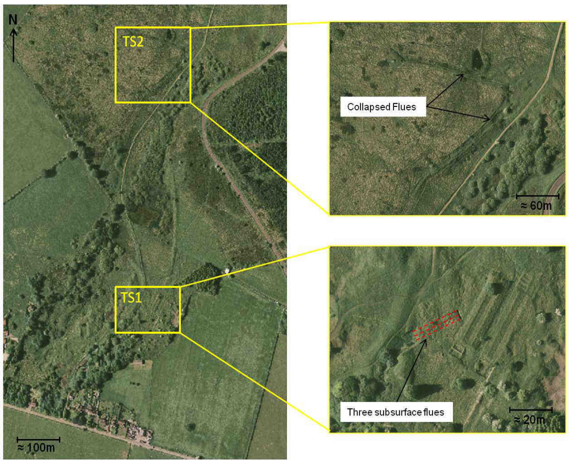

Figure 2. An aerial photograph of Priddy Mineries (Next Perspectives Imagery supplied by Infoterra Ltd). Insets show the ground in detail and flue orientation at each TS respectively. Red dashed lines denote the orientation and length of flues that bear no obvious surface outcrop.

Figure 3. TS1 (left) features three flues, each with round-arch ceilings that are approximately 1.2 m high and 1 m wide. TS2 (right) consists of two 100 m long flues which have partially collapsed and are largely covered by dense vegetation.

3. METHODOLOGY

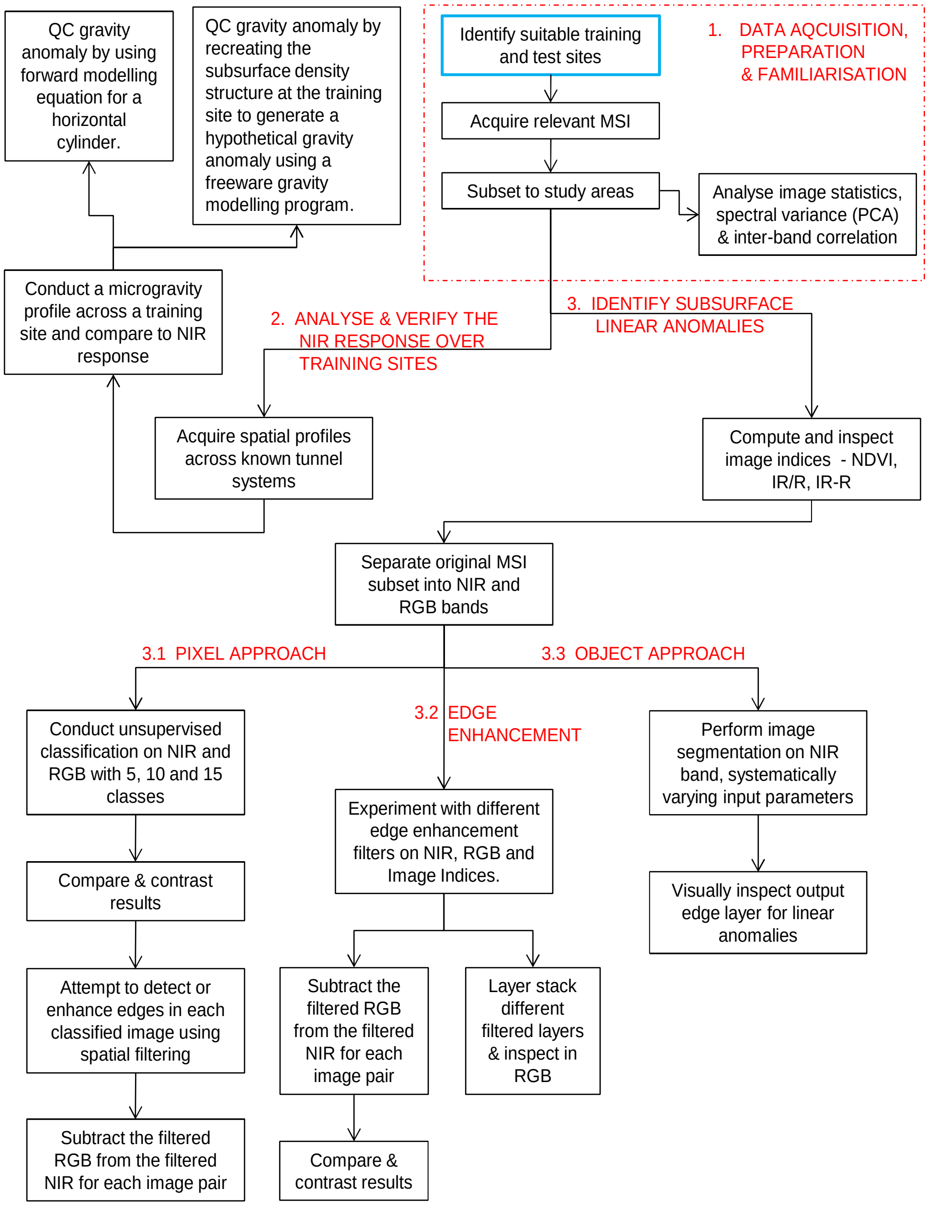

Figure 4. A flowchart of the methodology employed in this paper. The blue box denotes the starting point, with each subsequent stage seen in red.

4. ANALYSING AND VERIFYING THE NEAR INFRARED RESPONSE USING MICROGRAVITY

A series of transects were laid perpendicular to the azimuth of each tunnel system at each TS and the spectral signatures for each band were plotted and compared as a function of distance along the profile[1]. As seen in figures 6 – 8, an increase in Near Infrared (NIR) pixel intensity of varying magnitude is seen across each of the spatial profiles with the optimal value seemingly coinciding with the body of the tunnel underground.

[1] Accomplished by employing the 'Spatial Profile' (SP) tool in ERDAS Imagine v10.1.

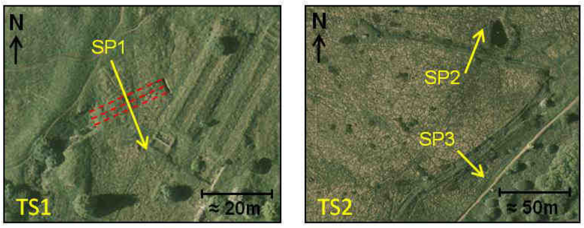

Figure 5. Arrows denote length, position and direction of each spatial profile (SP) conducted across the TSs, with red dashed lines denoting the position of underground flues which bear no surface outcrop.

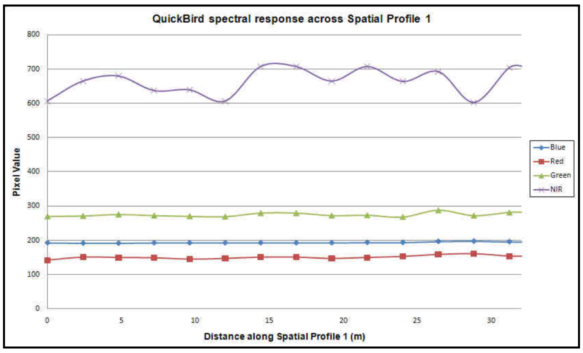

Figure 6. Spatial Profile 1 (SP1) – a line graph comparing the spectral response from the four QB bands as a function of distance along the profile traversing TS1.

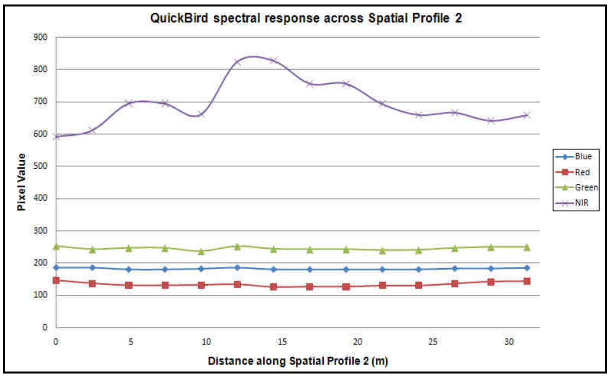

Figure 7. Spatial Profile 2 (SP2) – the spectral response from the four QB bands as a function of distance along the profile traversing the E-W flue at TS2.

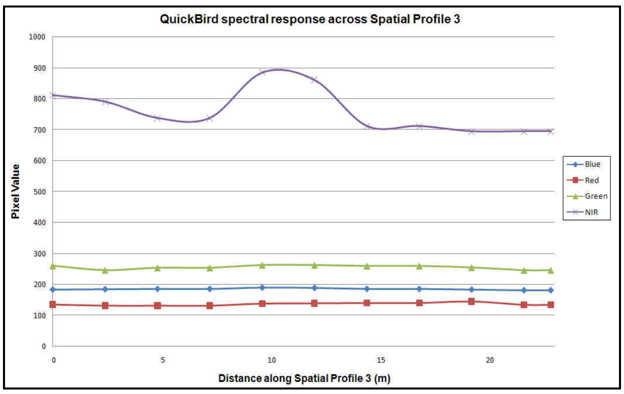

Figure 8. Spatial Profile 3 (SP3) – the spectral response from the four QB bands as a function of distance along the profile traversing the N-S flue at TS2.

A microgravity survey was conducted across TS1 to ensure that a reduction in gravity is seen to correlate with an increase in NIR along the profile. The microgravity profile was undertaken using a Scintrex CG-5 autograv gravimeter (accurate to 1 µGal) and height measurements at each station were acquired using a Trimble 4500 Theodolite (accurate to 5 mm). Figure 9 highlights the observed correlation between the 30 - 50 pixel value increase in NIR response over the three flues (located between 19-26 m) with the 0.014 mGal reduction in gravity seen over the same area.

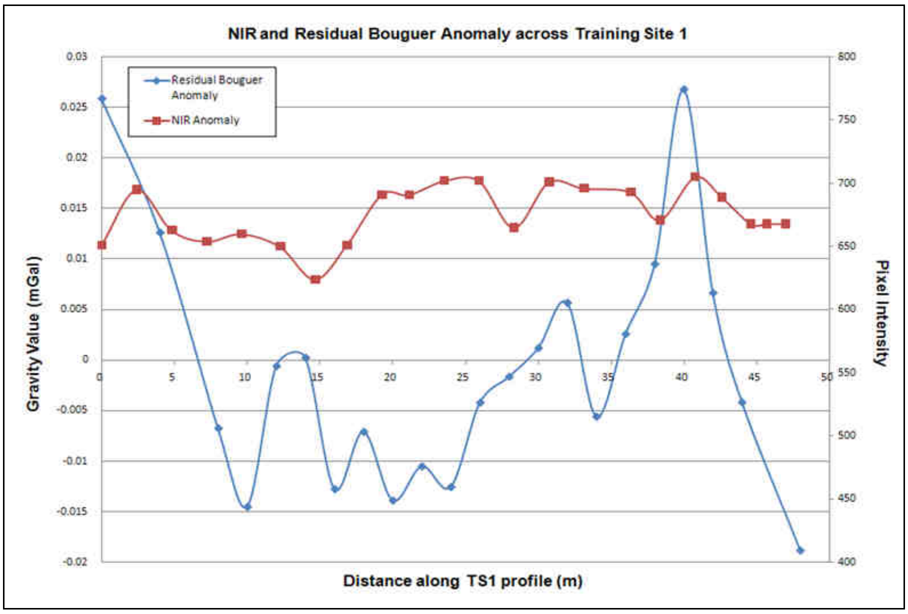

Figure 9. The residual bouguer anomaly (in blue) and NIR pixel response (in red) seen across TS1.

5. IDENTIFYING SUBSURFACE LINEAR ANOMALIES

Three differing image processing techniques were applied to the NIR and Red, Green, Blue (RGB) bands separately. Each approach was designed to detect, enhance or extract linear anomalies that exist only within the NIR response. Efforts were focussed on the known tunnel systems within the TSs although each approach was performed on a comparably wider area with the intent of detecting new linear anomalies which were currently unknown to the authors.

5.1 PIXEL APPROACH

A series of unsupervised classifications were performed on the NIR and RGB bands respectively. The Iterative Self-Organising Data Analysis Technique (ISODATA) was used with a maximum number of 30 iterations and a convergence threshold of one. During the process, 5, 10 and 15 classes were compared using the classified NIR band, the classified RGB bands and the classified Normalised Difference Vegetation Index (NDVI) band ratio.

Figure 10 compares the results of the pixel based classification between the NIR band and the RGB bands at TS1 and TS2, both divided into 10 classes with the same colour scheme. One New Linear Anomaly (NLA) in the NIR image was seen to extend across a field to the east of TS1 (labelled NLA1).

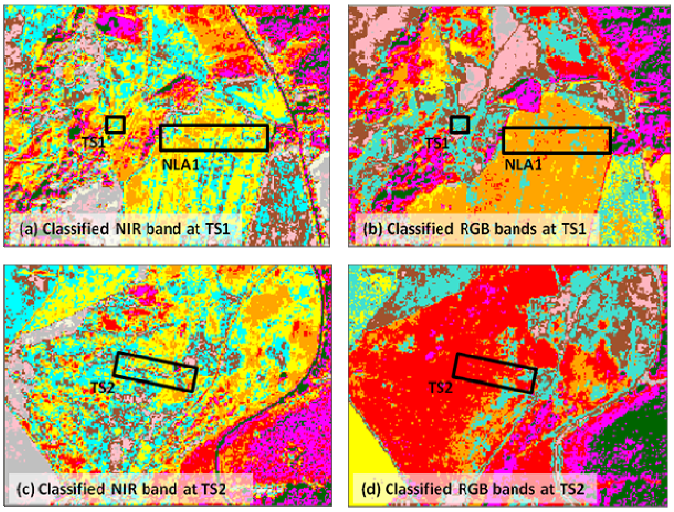

Figure 10. Ten class pixel based classification results of TS1 and TS2 using the unsupervised ISODATA algorithm. Insets (a) and (b) compare results between the classified NIR band and RGB at TS1 and (c) and (d) compare the same at TS2.

5.2 EDGE ENHANCEMENT

Edge enhancement, edge detection and non-directional edge detection filters with kernel sizes ranging from 3x3 to 7x7 pixels were applied to the raw NIR, RGB bands and image indices respectively. These filtered images were then image differenced but in addition, various image combinations were layer stacked and inspected through RGB. Three New Linear Anomalies (NLA2 – NLA4) were identified approximately 1 km to the west of Priddy Mineries.

5.3 OBJECT APPROACH

An object based classification was performed on the original NIR band using an experimental image segmentation procedure. An output edge layer was generated which contained the edge detection results produced prior to the image being segmented (figure 11). This output edge layer was routinely inspected for any edge extraction at the TSs and for any NLAs before the input parameters were re-adjusted and the process re-run.

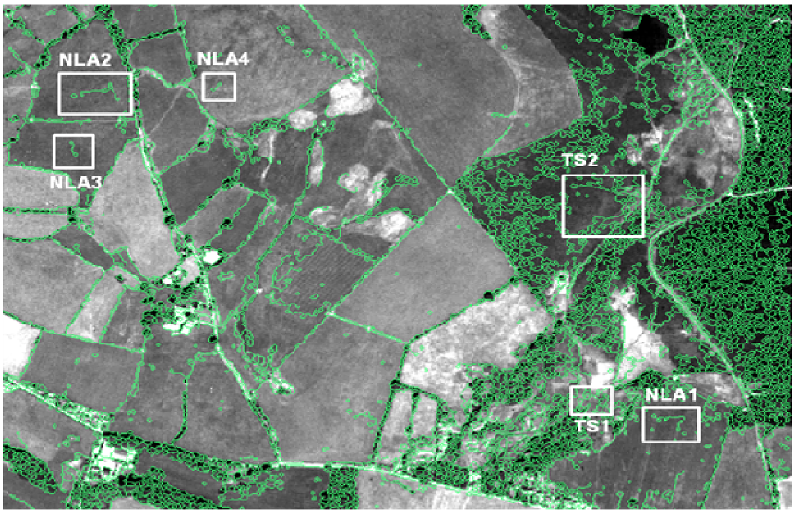

Figure 11. Output edge layer (green) derived from performing an image segmentation on the NIR band using an edge detection threshold of 50 pixels, an edge length of at least 30 pixels, a minimum value difference of 40 and a variance factor of 50. Both TSs are highlighted and the edges from each of the previously identified NLAs were also detected.

6. STUDYING THE RESIDUAL BOUGUER ANOMALY ACROSS NLA1

The residual bouguer anomaly and the NIR pixel intensities were plotted perpendicular to NLA1 and then compared with the intent of using the observed variations in gravity to reinforce the changes observed in the NIR (figure 12).

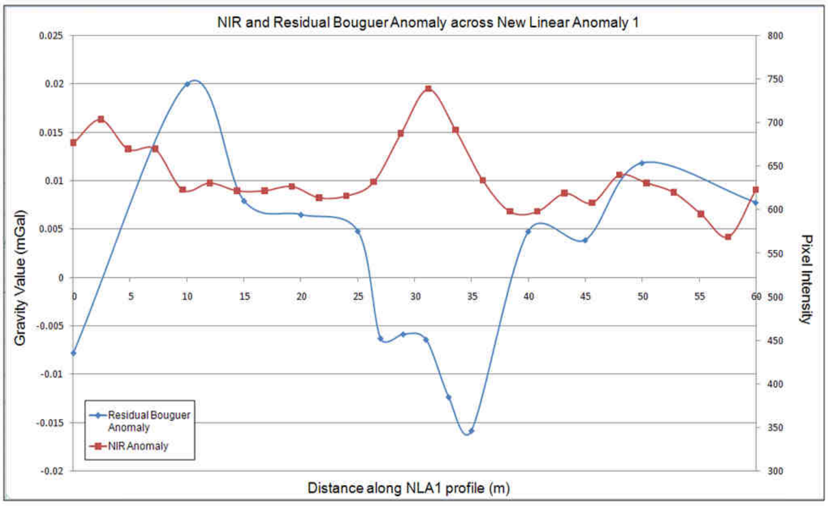

Figure 12. The residual bouguer anomaly (in blue) and NIR pixel response (in red) seen across NLA1.

The NIR pixel response increases by approximately 120 pixel values over the anomaly, correlating with a reduction in gravity of approximately 0.015 mGal. This mass deficiency could denote the existence of a bedrock depression (McDonald and Davies, 2003), a fracture line filled with a lower density material or an air-filled void, which could signify the presence of an old mine shaft or a shallow caving passage (Mikekk.org.uk, 2008).

7. ANALYSING AND INTERPRETING THE REMAINING ANOMALIES

According to Williams (1998), a number of Roman Mining Settlements were present in the Priddy and Chewton Mendip area. NLA2 and NLA3 may delineate the remnants of an old field boundary or an old road whilst the irregular shape and earthwork formation seen at NLA4 could possibly delineate the buried remains of a pre-roman hill fort or farmstead.

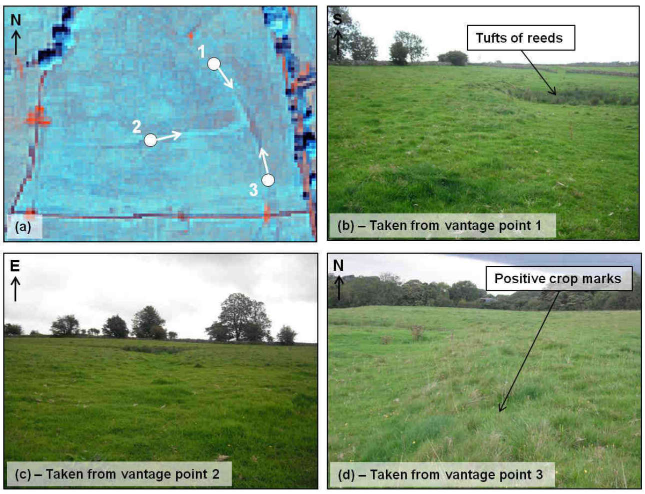

Figure 13. Ground reconnaissance at NLA2. Vantage points are mapped at differing ends of the linear anomaly (a), with their associated photos seen in (b) to (d).

8. DEVELOPING THE OPTIMAL WORKFLOW

Ground truthing has increased the reliability and significance of these NLAs and has endorsed the effective techniques applied in Section 5. Within each approach, the successful techniques were used to shape a three tier workflow (figure 14).

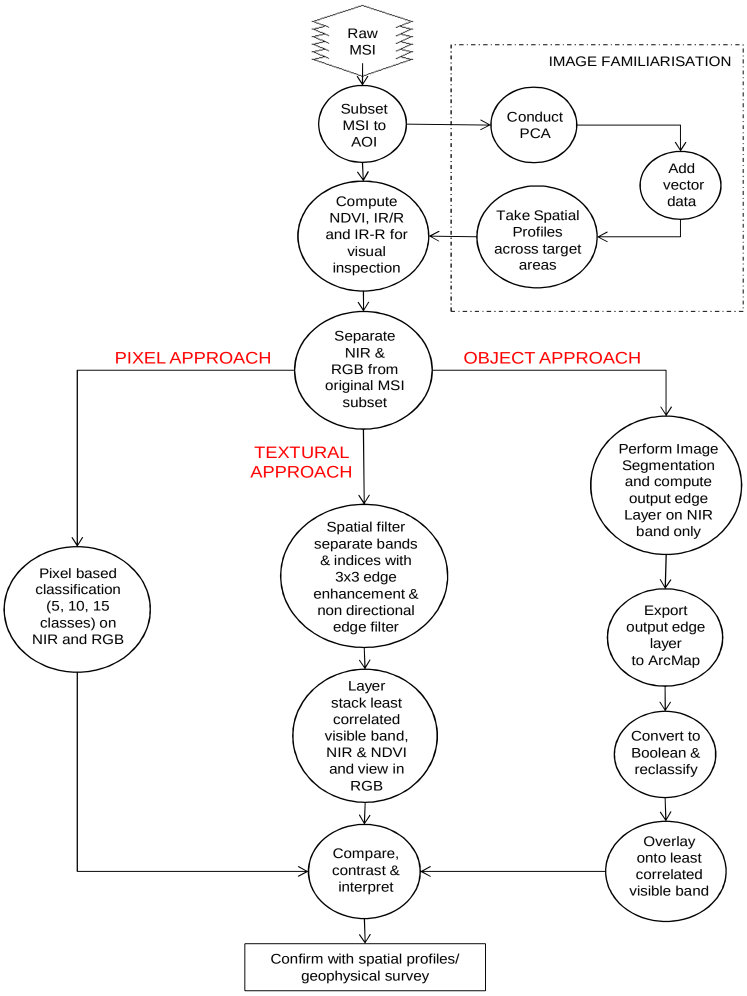

Figure 14. An image processing workflow designed to identify linear subsurface anomalies, including that of tunnel systems.

9. TEST SITES

Two test sites were identified 35 km north of Gereshk in Helmand Province, Afghanistan. Test Site A featured two separate karez networks, both of which can be identified by the delineation of numerous qanat shafts across desert terrain. Test Site B featured three karez networks, with two separate irrigation tunnels seen passing across both desert and agricultural land cover (Figure 6). WorldView 2 (WV2) MSI dated 8 Jan 2011 with an MSI pixel size of 2.0 m was acquired for both test sites.

10. TESTING THE WORKFLOW

When applying the pixel approach to the test sites in Afghanistan, the results lacked spectral continuity between the qanat shafts. This may be due to the engulfment of the tunnel related spectral signatures by the signatures related to the overlying and adjacent landscape features. An alternative pixel based technique could have been the employment of a supervised classification although if the given study area lacks known tunnel sites, the results of the classification may run the risk of becoming biased.

The results generated from performing the textural approach also lacked success. The non-directional edge detection filtered layer stack produced the more interesting result, where some indication of underground tunnelling seemed apparent between select qanat shafts in test site B.

The most consistently effective approach appeared to be the object based approach. The image segmentation procedure produced the clearest signs of subsurface detection, where an output edge layer was generated during the image segmentation process and then superimposed on a band less correlated with the NIR (figure 15). It soon became apparent that this process could be employed as an interactive edge detection algorithm, which unlike spatial filtering, enabled the user to specify the edge detection threshold and a minimal length of edge detection.

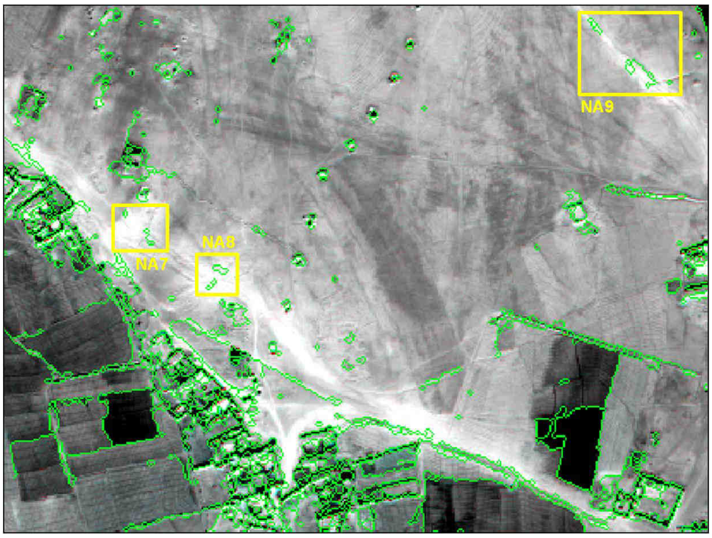

Figure 15. The output edge layer in green is superimposed on the coastal band for enhanced interpretation at test site B. Three areas containing new anomalies (NAs) are highlighted as yellow boxes. The anomalies are disassociated with any visible outcrops and may signify the presence of shallow culverts passing under tracks.

11. DISCUSSION AND CONCLUDING REMARKS

By using a range of different image processing techniques, this research has fully exploited the information contained within the near infrared to detect known tunnel systems in both the UK and Afghanistan. The results generated were of mixed success, where only one known tunnel system at training site 2 was successfully detected. However, auspiciously, additional subsurface anomalies were identified in each study area. The four UK anomalies, ranging from probable shallow caving passages to prospective Roman and Bronze Age ruins, were confirmed as subsurface structures by performing microgravity surveys and on-the-ground reconnaissance. Conversely, the five anomalies identified in Afghanistan could not be verified although they may signify the presence of culverts passing under tracks.

By comparing the successful identification of these anomalies with the difficulty of detecting known tunnel sites suggests that the tunnel structures may be too deep, limiting their influence on the soil and vegetation at the surface. Therefore, the workflow developed in this paper lays the foundation for further testing and refinement, both of which are required before the purpose of this research is fully satisfied. Nevertheless, the results generated in this paper are promising, indicating that high resolution multi-spectral satellites have the capacity to identify subsurface structures providing they are shallow, with depths ideally less than one metre.

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14. BIOGRAPHY

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