

SUBSIDENCE DETECTION USING INTEGRATED MULTI TEMPORAL AIRBORNE IMAGERY

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ABSTRACT:

Multi temporal aerial photography and airborne hyper spectral imagery have been integrated for the detection and monitoring of coal mining subsidence hazards. Digital elevation models derived from successive epochs of aerial photography provide estimates of topographic change which may be indicative of the collapse of abandoned underground mine workings in the study area. Ground disturbed by subsidence can also be identified in hyper spectral imagery from soil moisture anomalies or vegetation stress.

Archive photography originally acquired for topographic mapping over the last forty years was scanned and processed in a digital photogrammetric workstation. Since uncertainties in surface stability preclude the use of conventional ground control points for controlling historic photogrammetric models, each model was processed only to relative orientation stage. A control surface, created from a photogrammetric model comprising present-day imagery with contemporary ground control, was used in conjunction with a surface matching algorithm to provide the absolute orientation for each archive model. Subsidence features were then identified by subtracting the control DEM from each of the archive DEMs.

Three epochs of airborne hyper spectral CASI and ATM imagery were acquired for the study area during a twelve month period. In the vegetated areas the Red Edge Position (REP) and parameters of the chlorophyll absorption feature were mapped. In the areas identified as exposed soil the thermal band of the ATM imagery is enhanced to show soil moisture variations. The results of the photogrammetric and hyper spectral processing were integrated to produce a subsidence hazard map of the study area.

1. INTRODUCTION

The collapse of workings in abandoned coal mines in the North East of England results in subsidence of the ground surface, disrupting agriculture and causing damage to buildings and infrastructure. Airborne remote sensing offers the potential to monitor the ground above abandoned mine workings and identify potential subsidence hazards. Subsidence may have a direct topographic expression due to underground collapse and an indirect spectral expression, due to the affect of the subsidence on surface hydrology and indirect affect on vegetation. Techniques from photogrammetry and hyper spectral image processing have been utilised to process airborne imagery acquired for an area of active subsidence in the Durham coalfield at Houghton-le-Spring. This area has been extensively undermined using both longwall and pillar and stall mining techniques, both of which can result in subsidence (Bell et al., 2000). The last coal mine in the area closed in 1981. This paper discusses the application of airborne remote sensing in subsidence research and reviews progress that has been made in this area.

1.1 Subsidence above abandoned coal mines

The use of pillar and stall mining technique in the seams of the Durham coalfield has left a legacy of instability and subsidence. The potential for unstable ground conditions above abandoned

pillar and stall workings is well documented, though the area has not received much attention (Taylor, 2002). This is distinct from the planned subsidence that occurs during longwall mining, with residual subsidence occurring within a year of the cessation of mining activities (Goult, 1998).

The deterioration of pillar and stall workings is difficult to quantify and a direct consequence of this is that subsidence may occur at any time. Gray and Bruhn (1982) stated that future subsidence above old workings cannot be ruled out even if subsidence has not been recognised within 50 to 100 years of the cessation of mining.

1.2 Surface expression of subsidence

Depressions form on the ground surface as a direct consequence of subsidence. Surface depressions or troughs can occur due to pillar crushing or failure (Taylor, 2002), the dimensions of which depend on a variety of factors including the depth of the workings and the overlying geology. In the Durham coalfield two distinct mechanisms of failure may be observed (Figure 1). In areas of exposed Carboniferous coal measures subsidence results in bowl-shaped depressions, the extent of which depends on the depth of the worked seam and the degree of collapse. A second mechanism of failure is observed in a significant part of the coalfields that is overlain by Permian magnesian limestone. In these areas subsidence is expressed as linear fissuring and the

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development of crown holes (Young and Lawrence, 2002). This mechanism of failure is associated with geological discontinuities and faults (Wigham, 2002).

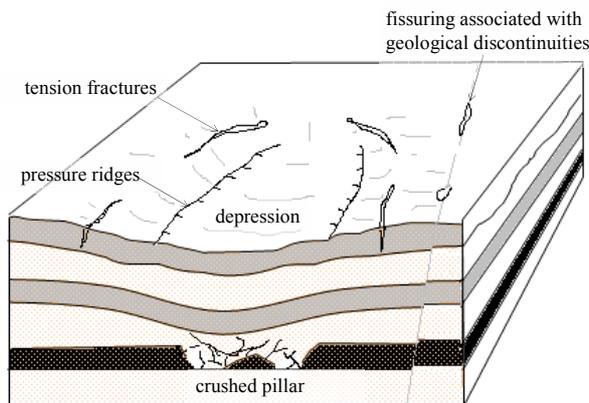


Figure 1. Surface expression of subsidence due to collapse of support pillar in underground coal workings (after Bell and de Bruyn, 1999)

Using examples of subsidence observed during field surveys of the Houghton-le-Spring area it has been possible to characterise the different subsidence features in terms of their topographic expression and appearance. The disruption of groundwater flow and surface hydrology, and the break up of the surface caused by subsidence affect the condition and species of vegetation growing in the proximity of subsidence features. Water can pool in surface depressions, saturating the soil. Biomass may be increased due to the water until vegetation becomes water logged beyond critical tolerance levels resulting in stress and reduced productivity (Steven et al. 1992). Conversely, fissuring may lead to preferential drainage of an area, resulting in vegetation stress or creating a niche environment for a different species.

1.3 Airborne remote sensing

It has been observed that some examples of subsidence observed in the field have a distinct topographic expression but no anomalous spectral response. Conversely, examples have also been noted that are too small to be observed at the scale of the aerial photography but do have associated spectral anomalies in hyper spectral imagery. Many examples were found to have both a topographic and a spectral expression.

This research integrates the two disciplines of photogrammetry and hyper spectral image processing in order to maximise the value of airborne imagery for subsidence mapping and monitoring.

Subsidence research is active in both areas but tends to proceed in isolation. This work has involved developments in both areas and seeks to demonstrate that an integrated approach, processing aerial photography and hyper spectral imagery in parallel and combining the results, maximises the value of the individual data sets.

Conventional land surveying techniques such as levelling have been routinely employed to investigate subsidence but are not suitable for the repetitive surveying at a regional scale necessary to monitor the Durham coalfield. Coal Authority abandonment plans indicate areas of pillar and stall workings across the extent of the coalfield and subsidence may occur in any of these areas. Photogrammetry offers a viable alternative to land surveying for the production of surface models and the extraction of profiles and is a proven tool in subsidence investigations. In the absence of old survey records, photogrammetric processing of archive photography is the only viable method for generating historic surface profiles for comparison with contemporary data.

The application of remote sensing for mapping surface spectral properties is well established. Thermal imagery can be employed to investigate soil moisture anomalies and the application of hyper spectral imagery in vegetation studies is a proven tool, although with limited application to subsidence studies.

2. DATA ACQUISITION

Three survey flights were made over the Houghton-le-Spring test site in the Durham coalfield, in September 2002, March 2003, September 2003 by the Natural Environment Research Council's (NERC) Airborne Remote Sensing Facility (ARSF) aircraft. The September surveys involved the simultaneous capture of aerial photography with a Wild RC10 survey camera and acquisition of imagery with a Daedalus 1268 Airborne Thematic Mapper (ATM) and Compact Airborne Spectrographic Imager (CASI-2). No photography was acquired during the March flight due to financial restrictions. The two September flights were flown at different altitudes (1800 m and 1200 m), providing photography and hyper spectral imagery at different scales under comparable ground conditions. The photographs were subsequently scanned using a Vexcel, Ultrascan 5000 photogrammetric scanner for processing in a digital photogrammetric workstation.

The flights were timed to capture data after the winter, a prolonged wet period, and after the relatively dry summer, in order to assess what conditions are most suitable for the identification of subsidence features, and to characterise the temporal variation of the natural vegetation cover.

An Analytical Spectral Devices (ASD) field spectroradiometer from the NERC Equipment Pool for Field Spectroscopy (EPFS) was used to acquire ground spectra from calibration targets during the survey flights. Field spectra were acquired over tarmac, grass and an artificial white tarpaulin target. Spectral profiles were also captured across an area of fissured ground to enable simulation of CASI-2 spectra for processing algorithm development and subsequent comparison of results.

3. TOPOGRAPHIC EXPRESSION OF SUBSIDENCE

Photogrammetry is an established technique in subsidence investigations (Faig 1984, LaScola 1988) which has benefited from recent advances in photogrammetry and the development of new digital sensors (Spreckels, 1999). It offers a viable method for monitoring mining subsidence of working mines though the accuracy and limitations of the technique are not well documented and work is still needed to quantify the accuracy and precision of photogrammetry in subsidence research.

Whilst it was important to develop a methodology for the continuous monitoring of subsidence, it is also valuable to examine old photography for evidence of past subsidence. Two sources of aerial photography were available for this research; historical survey photography and photography flown for the study by NERC. Historical photography for 1971 and 1996, flown at an approximate scale of 1:10,000 was purchased from commercial archives and photogrammetrically scanned. Camera calibration certificates were also obtained but no ground control points (GCPs) were available from the time of the surveys.

The photography acquired during the September 2002 and September 2003 surveys was controlled using phase processed GPS. The surveys were controlled using two sources of GCPs. Prior to the survey flights identifiable photo features were surveyed on the ground and these were complemented by circular white targets of 1m diameter which were set out for the duration of the overflights.

Whereas traditional photogrammetric processing relies on GCPs to scale and orientate blocks of photography, this process is not feasible using modern GCPs to control historical photography in areas of potential surface instability. The historical blocks were processed in a photogrammetric workstation to the relative orientation stage and digital elevation models (DEMs) were extracted using stereo autocorrelation. The absolute orientation of these photogrammetric DEMs was achieved using a surface matching algorithm (Mills et al., 2003). The rigorously controlled contemporary DEM from 2002 photography provided a control surface to orientate the historical DEMs.

The fully orientated DEMs have two applications in this research; surface profiling and differencing. Surface profiling involves the extraction of sections through a DEM to identify the characteristic depressions that form when subsidence occurs. This approach has proven particularly useful at identifying the position of lines of fissuring. Surface differencing involves subtracting each of the historical DEMs from the contemporary control surface. Areas of change, including drops in the land surface due to subsidence, are identified and can be quantified. The potential of this approach for identifying potential pillar collapse requires further investigation.

Spurious changes results from areas of poor autocorrelation in the DEM extraction process. It is most important to compare 'bare-earth' surfaces to ensure that surface changes are real and not artefacts of different land use, for example a field covered with a mature cereal crop in one epoch may be ploughed on a subsequent date giving an erroneous difference. These affects can be minimised by user interaction in the DEM extraction process and by careful photo-interpretation of the source photography.

Acquisition of future aerial photography will enable the monitoring of Houghton-le-Spring to continue and the accuracy of the method to be quantified. It is anticipated that the effectiveness of the surface matching process will reduce the need for photo-control for future surveys (Mills et al., 2003).

4. SPECTRAL ANOMALIES

CASI-2 and ATM imagery from each of the three surveys was geometrically corrected using simultaneously acquired navigation data and a 10 m post spacing DEM acquired by the

Ordnance Survey (OS) using NERC proprietary software. The accuracy of this geometric correction was sufficient to locate the footprint of individual pixels on the ground. As one aim of this research is multi temporal analysis of the spectral response of subsidence features it was necessary to correct the data for atmospheric effects. At-sensor radiance values were converted to apparent ground reflectance using the Empirical Line Method (Smith and Milton, 1999). This process involves normalising the spectral response of the calibration targets observed in airborne imagery to surface reflectance measurements made with the ASD spectroradiometer. The thermal band of the ATM imagery was not corrected as no suitable calibration data was available.

The mapping of soil moisture anomalies utilises the thermal band of the ATM scanner. Exploiting the relationship between soil moisture and temperature noted by Pickerill and Malthus (1998), it is possible to identify areas of anomalous soil moisture in otherwise homogeneous areas. A qualitative approach was applied, by extracting the pixels on a parcel by parcel basis using field boundaries. A simple standard deviation contrast enhancement was then applied to each parcel, maximising the contrast and highlighting any anomalous area. Thermal anomalies were recorded that are associated with subsidence features observed in the field. However, observation of the same areas on different dates demonstrated that the thermal anomalies are affected by prevailing soil moisture conditions and easily obscured by vegetation.

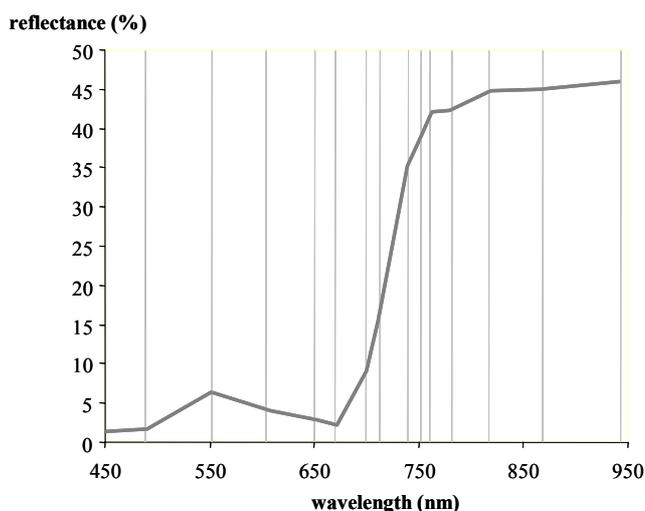


Figure 2. Typical CASI-2 vegetation reflectance spectrum showing position of individual bands.

The identification of vegetation anomalies associated with subsidence exploits two features of vegetation spectra that are found within the CASI-2 bandwidth of 405-945nm (Figure 2); the red edge and the chlorophyll absorption feature.

Zarco-Tejada & Miller (1999) noted that spectral parameters have the inherent advantage that they are relatively insensitive to variations in illumination or inaccuracies in atmospheric correction. This indicates that they are also an appropriate tool for multi temporal studies. In order to investigate the most appropriate techniques for defining red edge and chlorophyll absorption parameters two test data sets were used; continuous field spectra acquired using the ASD, and simulated CASI-2 band spectra derived from the ASD using published full width at half maximum (FWHM) for CASI-2. The processing

techniques were then applied to the airborne CASI-2 imagery acquired for the Houghton-le-Spring test site during 2002 and 2003.

4.1 Red edge position

The red edge is defined as the ramp in green vegetation reflectance between the red and near infrared wavelengths, between 670 nm and 780 nm (Figure 3). It is related to the concentration of chlorophyll in the vegetation canopy (Miller et al., 1990) and may be characterised by the position of maximum slope or Red Edge Position (REP). The slope and position of the red edge change under stress conditions, with the REP moving towards shorter wavelengths in response to senescence (Rock et al., 1988). The REP is therefore an appropriate tool for investigating the effect of subsidence on vegetation.

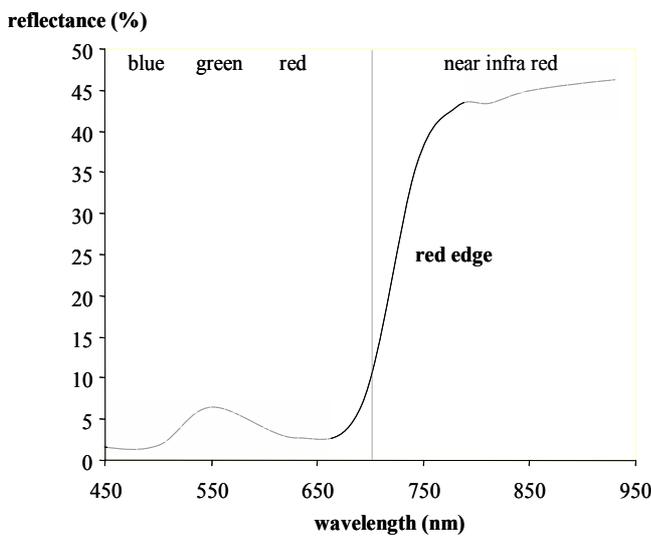


Figure 3. Typical vegetation reflectance spectrum in the CASI-2 spectral range. The red edge is highlighted.

A method was required to estimate the REP from the discrete bands that bracket the red edge in the CASI-2 vegetation bandset. Several methods are available for estimating the REP from discontinuous data, each of which has its advocates and detractors. Two methods were assessed; Guyot and Baret (1988) method and Lagrangian interpolation (Dawson and Curran, 1998). The former method, as implemented by Clevers et al. (2001) is computationally simple but approximated the red edge to a straight line and is therefore less sensitive to shifts in the REP. The Lagrangian method involves calculation of the first derivative and the fitting of a polynomial function in order to estimate the REP. Although it is computationally more intensive it theoretically provides a more accurate estimate of the REP.

Accurate measurement of the REP can be made from the ASD spectra by derivative analysis and the position compared to that calculated using the Guyot and Baret, and Lagrangian methods applied to the simulated CASI-2 data set. Clevers et al. (2001) noted the possibility of artefacts in the calculated REP where more than one maximum is present in the first derivative. This phenomena has been noted in ASD spectra from the test site and requires further investigation.

The REP has indicated species changes in areas affected by subsidence and shifts in REP have also been noted within species in affected areas.

4.2 Chlorophyll absorption feature

The chlorophyll absorption feature is found between the red peak and the red edge of the vegetation reflectance spectrum. Increases in canopy chlorophyll result in a minor deepening and major broadening of this feature (Banninger, 1991). Continuum removal, which is widely used in geological spectral studies, is a normalisation technique that emphasises the wavelength and depth of individual absorption features (Clark and Roush, 1984). The chlorophyll absorption feature is described by the reflectance values of ten CASI-2 bands between 450 nm and 750 nm.

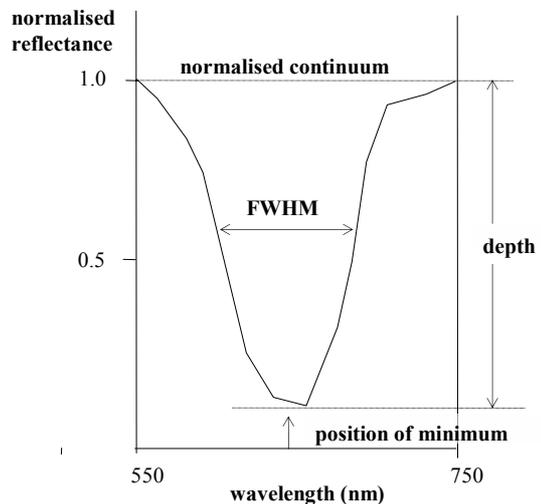
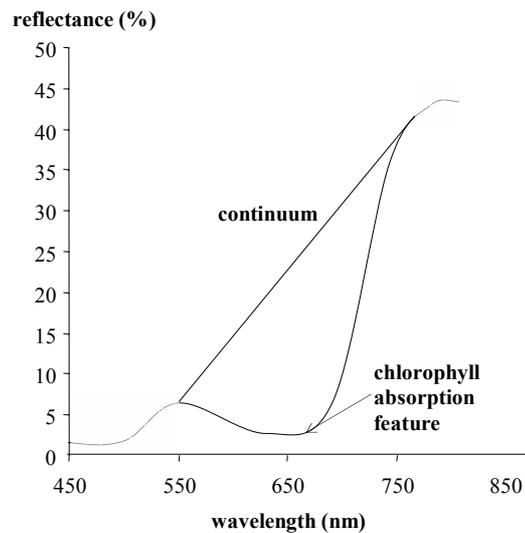


Figure 4. Continuum removal of the chlorophyll absorption feature and parameters.

The continuum is a convex hull connecting the maxima at 550 nm and 750 nm, defined by CASI-2 band positions (Figure 4). Continuum removed values for each band are obtained by dividing the reflectance value for each band by the convex hull value, resulting in values between zero and one. The discrete band positions of the CASI-2 dictate that the position of the

absorption minimum can only be estimated. Lagrangian interpolation (Dawson and Curran, 1998) was used to estimate the position of the minimum, using the band closest to the true minimum and two adjacent bands.

Absorption feature parameters are then extracted from the continuum removed chlorophyll absorption feature. The maximum depth, wavelength of maximum depth and the FWHM were found to be useful indicators of subsidence features. A relationship has been demonstrated by a shallowing in depth of the absorption feature of vegetation in areas affected by fissuring. Fischer et al. (2003) also noted a decrease in the band depth when vegetation showed any changes caused by different hydrological conditions. Further work is required to further the understanding of the relationship between these parameters and known subsidence features.

5. RESULTS AND DATA INTEGRATION

The British National Grid is the reference projection used for all data processing. This common reference frame is compatible with existing GIS data, including topographic and geological mapping, and mine plans. This approach allows the results from photogrammetric and hyper spectral processing to be compared in a GIS environment. A common reference frame is also required for subsequent integration of results.

5.1 Aerial photography

Photogrammetric processing and surface matching has facilitated the creation of a DEM for each epoch of aerial photography. The rigorously controlled contemporary surfaces, processed from photography acquired in 2002 and 2003, serve as a baseline for future change and as a reference surface to assess changes in the historical data sets. Using known subsidence occurrences within the test areas it has also been possible to develop a priori models of the topographic expression of subsidence. Consequently, areas affected by subsidence may be identified using aerial photography either as a difference in surface elevation between survey dates or directly, where the area has a topographic expression which is characteristic of subsidence.

5.2 Hyper spectral imagery

A relationship has been established between thermal anomalies and some subsidence features. However, these anomalies may be masked by vegetation cover and are very dependent on the weather conditions prior to image acquisition.

Spectral parameters, describing the red edge and the chlorophyll absorption feature (Figure 5) have proven to be useful indicators of the presence of subsidence features. Further work is required to increase understanding of the affects of seasonal changes in vegetation on these parameters. This will facilitate change detection and future monitoring of subsidence using hyper spectral imagery.

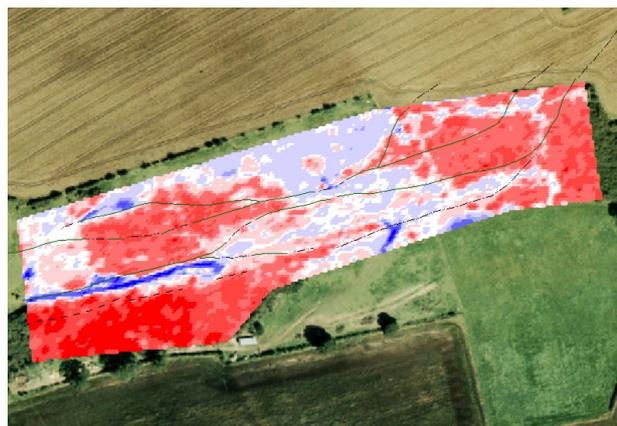


Figure 5. CASI-2 image of chlorophyll absorption continuum removed depth for part of the Houghton-le-Spring site. The overlay shows the position of fissuring mapped during field work.

5.3 Integrated analysis

Research is now exploring the use of multi criteria analysis and other integration approaches, to combine the results from the aerial photography and hyper spectral imagery with other relevant data sets. Coal Authority mine abandonment plans show the location of pillar and stall workings and can be used to identify areas of possible risk which can then be investigated using the airborne imagery and techniques outlined above. Simple decision rules can be applied to remove spurious anomalies and apply a degree of confidence to anomalies. For example, red edge and continuum parameters are meaningless if no vegetation is present, and photogrammetric measurements are unreliable in areas of crops awaiting harvest. Further work is required to develop a fully integrated system for subsidence monitoring and mapping.

6. CONCLUSION

The legacy of mining subsidence in the North East of England is difficult to quantify and has economic implications for the development of the area. This ongoing research has two aims. The first aim was to develop methodologies for the extraction of relevant information from aerial photography and hyper spectral imagery for subsidence hazard mapping. This has been achieved by characterising the topographic and spectral response of subsidence features in the study area, and developing existing processing techniques to enhance these characteristics to enable areas of subsidence to be identified above abandoned coal mines. The second aim was to develop a methodology for integrating results from the two disciplines with ancillary data for subsidence hazard mapping. Multi temporal airborne imagery has considerable potential for subsidence hazard mapping and there is considerable potential in integrating photogrammetric and hyper spectral data sets. This research is ongoing and further results will be reported at the ISPRS Congress presentation of this work.

REFERENCES

Banninger., C., 1991, Phenological changes in the red edge shift of Norway spruce needles and their relationship to needle chlorophyll content. In: *Proceedings of the 5th International Colloquium – Physical Measurements and Signatures in*

- Remote Sensing*, ESA SP-319, European Space Agency, Noordwijk, pp. 155-158.
- Bell, F. G. and de Bruyn, I. A., 1999, Subsidence problems due to abandoned pillar workings in coal seams, *Bulletin of Engineering Geology and the Environment* 57, pp. 225-237.
- Bell, F. G., Stacey, T. R. and Genske, D. D., 2000, Mining subsidence and its effect on the environment: some differing examples, *Environmental Geology*, 40 (1-2), pp.135-152.
- Clark, R.N. and Roush, T.L., 1984, Reflectance Spectroscopy: Quantitative Analysis Techniques for Remote Sensing Applications, *Journal of Geophysical Research*, 89 (B7), pp. 6329-6340.
- Clevers, J. G. P. W., De Jong, S.M., Epema, G. F., van der Meer, F., Bakker, W. H. and Skidmore, A. K., 2001, MERIS and the red-edge position, *Journal of Applied Geophysics* 3 (4) pp. 313-320.
- Dawson, T. P. and Curran, P.J., 1998, A new technique for interpolating the reflectance red edge position, *International Journal of Remote Sensing* 19 (11), pp. 2133-2139.
- Faig, W., 1984, Subsidence monitoring in mountainous terrain - an example of four dimensional photogrammetry. *ISPRS XVth Congress*, Rio de Janeiro, pp. 276-285.
- Fischer, C., Brunn, A., Dittmann, C. and Vosen, P., 2003, Detection of plant reflectance anomalies in mining areas using imaging spectroscopy. In: *3rd EARSeL Workshop on Imaging Spectroscopy*, Herrsching, Germany, pp. 305-312.
- Goulty, N. R., 1998, Mining subsidence in the concealed coalfields of north-east England. *Mechanics of Jointed and Faulted Rock*. Rossmanith. Rotterdam, Balkema, pp. 431-436.
- Gray, R. E. and Bruhn, R. W., 1982, Subsidence above abandoned coal mines, State of the art of ground control in longwall mining and mining subsidence. In: *Proc. ASME*, Littleton, Colorado, pp. 253-271.
- Guyot, G. and Baret, F., 1988, Utilisation de la haute resolution spectral pour suivre l'état des couverts vegetaux. In: *Proceedings of the Fourth International Colloquium on Physical Measurements and Signatures in Remote Sensing*, ESA-SP 287, European Space Agency, Noordwijk, pp. 279-286
- LaScola, J. C., 1988, *Comparison of Aerial and Ground Surveying of Subsidence Over an Active Longwall*. Washington, US Bureau of Mines, pp. 1-12.
- Miller, J. R., Hare, E. W. and Wu, J., 1990, Quantitative characterisation of the vegetation red edge reflectance. An inverted-Gaussian reflectance model. *International Journal of Remote Sensing*, 11 (10), pp. 1175-1773
- Mills, J. P., Buckley, S. J. and Mitchell, H.L., 2003, Synergistic Fusion of GPS and Photogrammetrically Generated Elevation Models. *Photogrammetric Engineering and Remote Sensing*, 69 (4), pp. 341-349.
- Pickerill, J.M. and Malthus, T.J., 1998, Leak detection from rural aqueducts using airborne remote sensing techniques, *International Journal of Remote Sensing*, 19 (12), pp. 2427-2433.
- Rock, B. N., Hoshizaki, T. and Miller, J. R., 1988, Comparison of in situ and airborne measurements of the blue shift associated with forest decline. *Remote Sensing of Environment*, 24, pp. 109-127
- Smith, G. A. and Milton, E. J., 1999, Technical note: The use of the empirical line method to calibrate remotely sensed data to reflectance. *International Journal of Remote Sensing* 20 (13), pp. 2653-2662.
- Spreckels, V., 1999, Monitoring of Hard Coal Mining Subsidence by Airborne High Resolution Stereo Scanner Data. *ISPRS Joint Workshop on Sensors and Mapping from Space*, Hannover.
- Steven, M. D., Malthus, T. J. and Clark, J. A., 1992, Achievements and unresolved problems in vegetation monitoring. In: *Terra 1: Understanding the terrestrial environment; The role of earth observations from space*, edited by P. M. Mather, Taylor and Francis, London, pp. 133-145.
- Taylor, J. A., 2002, *Potential stability and subsidence issues arising from abandoned bord-and-pillar coal workings*. PhD thesis (unpublished), The University of Leeds, Department of Mining and Mineral Engineering, Leeds, UK.
- Wigham, D., 2000, Occurrence of mining-induced open fissures and shear walls in the Permian limestones of County Durham. *Transactions of the Institution of Mining and Metallurgy (Section A: Mining Technology)* 109, pp. A172-A178.
- Young, B. and Lawrence, D. J. D., 2002, *Recent fissuring in the Magnesian Limestone at Houghton-le-Spring, City of Sunderland*. Nottingham, UK, British Geological Survey, NERC, pp. 1-22.
- Zarco-Tejada, P. J. and Miller, J. R., 1999, Land cover mapping at BOREAS using red edge spectral parameters from CASI imagery. *Journal of Geophysical Research* 104 (D22), pp. 27921-27933.

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