SATELLITE HYPERSPECTRAL IMAGING IN SUPPORT OF NUCLEAR SAFEGUARDS MONITORING

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ABSTRACT

Nuclear safeguards regulators now have access to a growing body of remote sensing imagery that provides a range of types of information. High-resolution panchromatic imaging that provides detailed information from photo-interpretation is still the most commonly used, but multispectral, thermal and hyperspectral imaging are now being applied. Using well-calibrated hyperspectral imagery, surface materials can be characterized, identified and potentially tracked from source to destination.

An obstacle to the routine usage of hyperspectral imagery for various applications is the considerable pre-processing required to remove sensor artifacts and atmospheric effects. We have developed semi-automated routines for pre-processing hyperspectral imagery from the Hyperion sensor on the American EO-1 satellite, and are also working to build up a body of experience in safeguards applications. This paper presents examples of our analysis of Hyperion imagery over the Akashat phosphate mine and Al Qaim fertilizer plant in western Iraq, chosen as a safeguards-related case study to determine if it would be possible to monitor the transfer of ore from a mine to a processing facility using satellite hyperspectral imagery.

INTRODUCTION - THE PROMISE OF HYPERSPECTRAL IMAGING

In general, panchromatic high-resolution imaging sensors allow an analyst to use photo-interpretative techniques to recognise *structures and objects* by their shape, texture, shadows, orientation and context. By contrast, multispectral and hyperspectral systems permit identification of *material, composition or surface chemistry* of targets by their spectral signature or colour, not by their shape since they usually have lower spatial resolution.

High-resolution black and white imagery has been the basis of much military reconnaissance; first with aerial photography and then with ever-increasing resolution satellite imagery. Commercial high-resolution satellite imagery with spatial resolution of about 1m (Ikonos and Quickbird) has recently become available and is used as a substitute for aerial photography in many applications, especially in remote areas and in trans-border analysis. Such imagery now sees important safeguards-related use by IAEA. For most current applications, the satellite must be tasked. Because these satellites produce very small images, and do not view the earth continuously there is a very small archive. Pricing varies: US$3000 for tasking and from $7 to $30/km^2 depending on whether the data are to be newly acquired or from the archive, and the area of interest.

The more common multispectral sensors generally have lower spatial resolution (5 to 30m), having traded spatial detail for spectral resolving power and wider, and more frequent coverage. The earliest multispectral Landsat satellites were launched in the early 1970s, and have continuously acquired data over the entire globe, providing repeat coverage every 16 days. There is now a 30-year archive of Landsat data that allows for long-term change detection studies. Since the American government provides this imagery, it is inexpensive (US$500/scene or $0.02/km^2) and carries no copyright restrictions.

Geologists have known since the early 1970s that one can differentiate many kinds of rocks and minerals by their diagnostic spectral signatures [1]. Aerial hyperspectral remote sensing began shortly thereafter [2] and can now be considered a mature technology. However hyperspectral satellite sensors have only recently been launched. Data from the experimental American sensor Hyperion, the first hyperspectral imager to become operational in space, only became available in 2001. Tasking the satellite costs US$2,500 if a scene is not in the archive. All imagery costs US$250/scene or about $0.75/km^2. In 2005 the system is operating well beyond its originally planned 1-year lifetime.

IDENTIFICATION, MAPPING AND TRACKING OF FEED STOCKS
Especially in studies of the first part of the nuclear fuel cycle, image analysts are often tasked to identify, map the distribution of, and track feed stocks, ore and other material. This is not always possible using panchromatic alone, but is an area where hyperspectral can be expected to contribute. The power and promise of hyperspectral analysis is that spectral signatures observed at spacecraft altitude can be matched to reference library spectra of known materials [3]. In a paper presented at the 2004 INMM [4], we showed that if the spectral properties of materials of interest are known, they could be found in a well-calibrated hyperspectral image. We used laboratory spectral measurements of samples of raw phosphate ore to empirically correct the image to ground-level Reflectance, then locate, identify and differentiate ore, fertiliser and other materials within a single Hyperion image of the fertiliser plant at Al Qaim in western Iraq. In this paper, we describe attempts to map and track ore between two different sites, imaged at different times, and discuss some of the current impediments.

The fertiliser plant at Al Qaim, and the Akashat mine about 135 km south, played important roles in Iraq's nuclear activities during the 1980s (Figure 1). There are significant phosphate reserves in the area around Akashat. Phosphate rock mined at Akashat was shipped by rail to Al Qaim as feedstock for phosphoric acid production and subsequently for phosphate fertilizer production. However, as with most Middle East phosphate deposits, uranium is present in low concentrations in the Akashat phosphate rock. Before being used for fertiliser production, the acid was piped to a special unit that produced yellowcake after extracting uranium from the acid. The uranium extraction facility operated from late 1984 to late 1990 and produced about 168 tonnes of yellowcake [5]. The Al Qaim fertiliser facility and the uranium extraction unit were heavily damaged by American air attacks during the 1991 Gulf war. Post war, the fertiliser facilities were repaired and returned to production. The uranium extraction unit was not repaired and, by 1996, had been dismantled. Critical items such as mixer-settlers were subject to monitoring by the IAEA's Iraq Nuclear Verification Office (INVO).

An obvious question that could be asked of an analyst is "Can we monitor whether ore from Akashat is being transferred to Al Qaim or another undeclared facility? The ability to chemically inspect these sites via satellite imagery would have been of some utility to the IAEA. There is a rail link between the Akashat and Al Qaim, so this particular question is perhaps moot. However, we use imagery collected over Akashat and Al Qaim here solely to develop and demonstrate this capability.

Figure 1. Map of the study area. Al Qaim and Akashat are circled in red.

PREPROCESSING HYPERSPECTRAL IMAGERY
A good deal of work goes into preparing hyperspectral imagery for analysis. Hyperspectral sensors are very complex, with thousands of individual detectors. Each detector must be calibrated and characterised very precisely, and this calibration maintained through launch and over time in space. The Hyperion data presently available arrives at the lab with only an approximate calibration. We have produced automatic routines to quickly perform several adjustments to the instrument calibration that would otherwise take many hours labour. Figure 2 illustrates one of several such adjustments required - compensation for spatial non-uniformities caused by small non-linearities in the calibration.

Figure 2. A single Hyperion band (band 172 at 2015nm) of the Akashat mine site before and after automatic destriping.

In our previous work with Hyperion [4] we used Reflectance spectra measured in the laboratory from ground samples acquired at Al Qaim to empirically calibrate the imagery. This approach is very successful for 'within image' classifications where one or more ground samples are available. However, it does not allow comparison of two images taken at different times unless ground samples are available for both sites. In the work reported here, we were working with imagery corrected to ground Reflectance using the ATREM atmospheric correction package within the commercial image processing software ENVI^{TM} rather than ground samples. In this procedure, the Radiance spectra acquired at the sensor altitude are converted to ground level Reflectance using an optical model of the illumination and interactions within the atmosphere. The ATREM model must take into account the spectral properties of the solar illumination, the absorption and scattering properties of gases and aerosols in the atmosphere, as well as the complete viewing and illumination geometry. The aim of the modelling method is the same as the empirical method, namely to convert the satellite image into Reflectance similar to that which would be measured on the ground, thus making possible comparisons between different scenes and dates.

We found that ATREM as we are currently using it, did not reproduce the ground-level Reflectance measured on *in situ* samples. Further, we were unable to classify the Akashat scene from the Qaim end-members of vice versa, because ATREM did not fully correct the images. As an interim measure, we worked out a technique to normalise the two Hyperion scenes, using the 'pseudo-invariant target' technique [6]. A Landsat scene was used to locate areas in both the Qaim and Akashat areas in the desert away from both facilities that had similar spectral signatures and which were assumed to be constant over time. These areas were then used to normalise the Al Qaim Hyperion scene to the Akashat scene.

ATTEMPTS TO MATCH AKASHAT AND QAIM ORES USING THEMATIC MAPPER AND HYPERION

We used a number of image classification methods to compare a single Landsat Thematic Mapper (TM) image (6 spectral channels) with two Hyperion scenes (220 spectral bands) for Akashat and Al Qaim. In the 'supervised' Mixture Tuned Matched Filtering (MTMF) classification method shown here, the analyst chooses a training area and asks the program to map the distribution of other pixels in the image with the same spectral signature as a training area from within the scene. We used the technique in an attempt to locate pixels at Qaim that had a spectral signature similar to that of the ore at Akashat, and vice versa.

Matched filtering performs a partial unmixing - finding the abundances of user-defined endmembers (the spectral signatures of 'pure' surfaces). Not all of the endmembers in the image need to be known. This technique maximizes the response of the known endmember and suppresses the response of the composite unknown background, thus "matching" the known signature. It provides a rapid means of detecting specific materials based on matches to library or image endmember spectra and does not require knowledge of all the endmembers within an image scene [7].
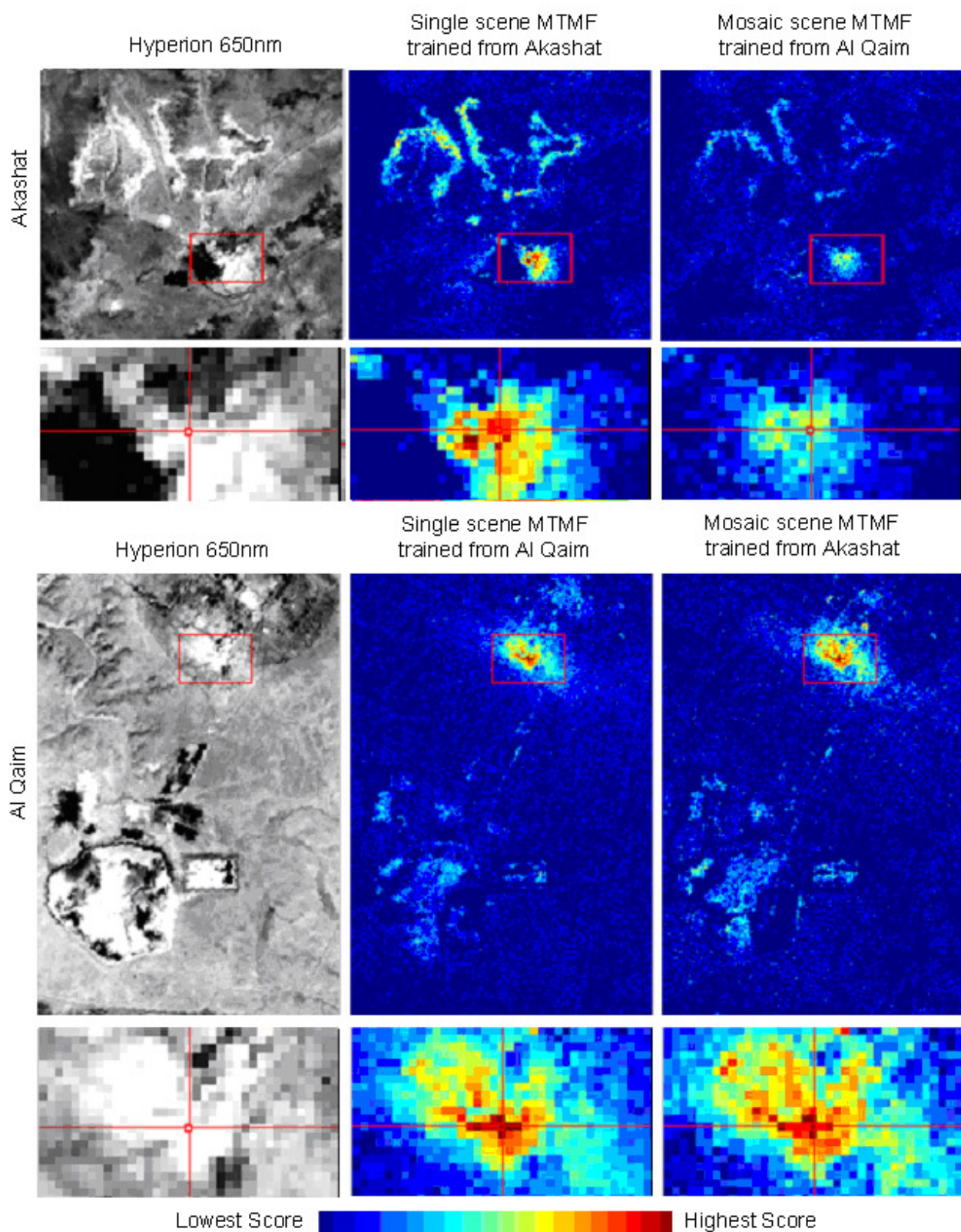
Figure 3. Left: Hyperion 670nm image for localisation. Centre: Within-scene classification of the ore in the single Hyperion scenes. Right: Classification of the normalised mosaicked Hyperion scenes. The enlargements shown are centred over the ore piles in each image.

Our comparison of Landsat TM and Hyperion is not completely equivalent, since the TM data for both Al Qaim and Akashat came from two adjacent scenes from the same orbit (12 February, 2001). They therefore were acquired under the same conditions and can, as a first approximation, be considered as coming from the same image. It was therefore unnecessary to atmospherically correct the TM data since these effects can be assumed to be constant between the two images. On the other hand, the two smaller Hyperion scenes were acquired two years apart and in different seasons (29 October, 2002 and 18 May, 2004) and so were definitely not directly comparable. In order to correct for differences in illumination and atmospheric effects, we performed both ATREM atmospheric correction and a further normalisation using pseudo-invariant targets.

Within the single Landsat Thematic Mapper image trained on the Akashat ore pile, MTMF performed poorly. It did not find the Al Qaim ore pile and mistakenly identified the exposed area at the active part of the Akashat quarries, as well as many areas within the Qaim processing plant (the fertiliser sheds and the slime ponds).

By contrast, MTMF mapped the distribution of the ore in the Hyperion image very well (Figure 3). Four separate analyses were carried out: the Akashat and Al Qaim scenes were each classified separately using their own ore piles as training areas, then the scenes were mosaicked and classified once with the Akashat ore as a training area, and once with the Al Qaim ore pile as the training area.

In the MTMF results shown here, the degree of similarity to the training areas is expressed as a 'rule' image. The pixels with the highest score (most similar to the training areas) are red and orange. Pixels with the lowest score (least similar) are blue. The results of all four analyses were very similar. Training at Akashat and searching at Qaim (lower right in figure 3) produced almost identical results as the within-scene Qaim analysis (bottom centre in figure 3). However while training at Qaim and searching at Akashat (upper right figure 3) produced similar spatial distributions, it reported slightly lower scores than the within-scene Akashat analysis (upper centre panel in figure 3). In both cases, the pixels with the highest scores were tightly located around the ore piles, with only a few very similar pixels in the active area of the quarry. Other areas around the quarry were much less similar. At Qaim, the Hyperion classification showed the main ore pile, and a large halo of what is probably wind blown ore dust around it. The bright white non-ore areas show much less similarity.

Overall, classification of the hyperspectral imagery was more satisfactory than the multispectral imagery – more spectral bands improved the ability to classify the phosphate ore. The fact that all four Hyperion analyses were alike increases our confidence in the results, and confirms that we have in fact been able to compare spectral signatures between different scenes. We recognise that we will not always have a common scene to use in the normalisation procedure, but this analyses reinforces our contention that the Hyperion data is capable of being used to track material from one scene to another. It focuses our future effort on improving the atmospheric correction procedures. Other researchers have reported similar problems with atmospheric correction of hyperspectral imagery, particularly Hyperion [8].

DEVELOPMENT OF HYPERSPECTRAL REMOTE SENSING FOR SAFEGUARDS
Our long-term goal is to be able to use laboratory reference spectra to search for and identify materials in the hyperspectral imagery. The Reflectance spectra generated from the ATREM model

were very unlike the laboratory spectra from ore samples from either location, explaining why using the ground sample Reflectance spectra to search for ore in the images was not successful. However, when we used a ground sample to empirically correct the modelled Reflectance [4], we could then use the laboratory Reflectance measurements of ground samples of other materials to successfully locate and differentiate those targets in the imagery. This once again suggests that the present problem is calibration and atmospheric correction. Once we are able to produce ground-level Reflectance, we should be able to extend similar analyses to other scenes without the normalisation step used here. At the present time, the reference spectral libraries available in the open literature have been developed for other geological environments, and include few, if any safeguards-related materials. Assuming that we will eventually solve the atmospheric correction problem, we will be working to build up such a library collection to allow recognition of materials relevant to this application.

USE OF HYPERSPECTRAL IN AN INTEGRATED APPROACH

For many tasks, the best approach will be to integrate panchromatic, multispectral and hyperspectral imagery. The low spatial resolution of the multispectral and hyperspectral sensors can make the imagery difficult to interpret, but it can be combined with the higher spatial detail of panchromatic imagery to provide both structural and compositional information. In other applications, the use of Digital Elevation Models can also assist in interpretation. In Figure 4, we have merged the Ore class derived from Hyperion (large red squares) with the higher resolution imagery from Quickbird, and draped both over an *exaggerated* Digital Elevation Model for Akashat. The Hyperion classification provides differentiation of the otherwise bright areas, while the oblique view and exaggerated terrain assists in interpretation.
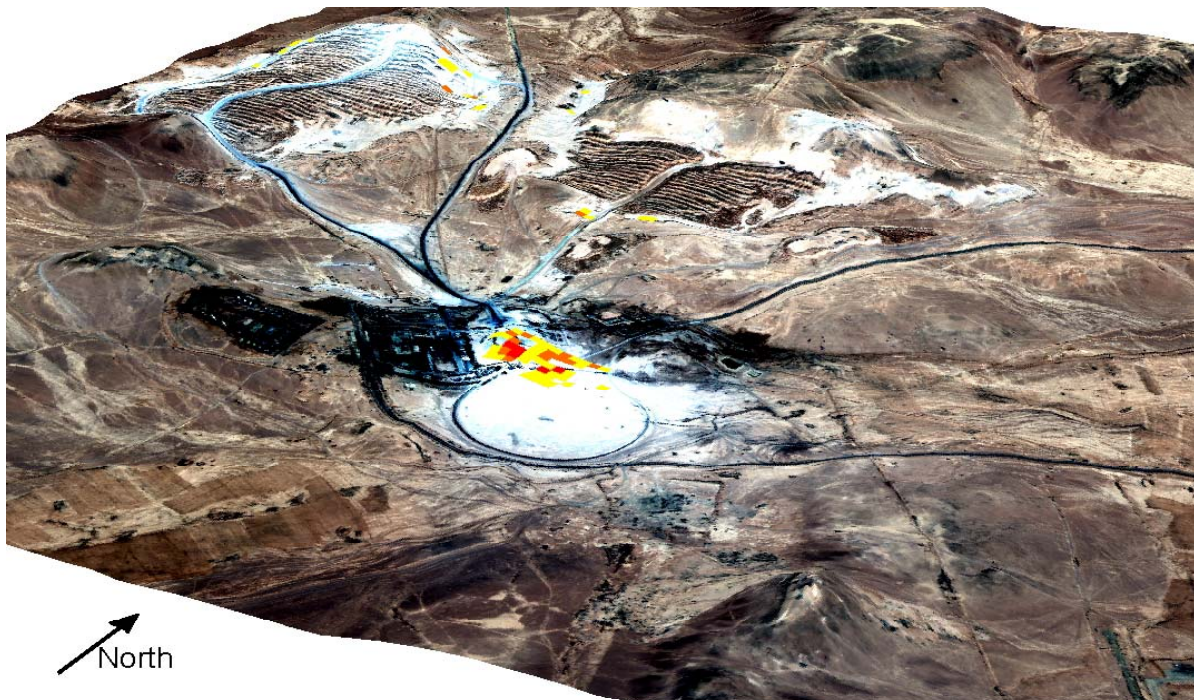

Figure 4. The Hyperion pixels with the highest similarity to the ore pile at Akashat (from figure 3), overlaid on a high resolution Quickbird image, and draped over a Digital Terrain Model with *exaggerated* vertical relief. Arrow indicates the direction of North.

SUMMARY

We are investigating the new dimension to satellite imaging offered by hyperspectral imaging, and developing tools and libraries for use by the IAEA. With full development, hyperspectral will add the ability to detect the *composition, material and surface chemistry* of a target to the *identification of structures and objects* in panchromatic images, now being used at the IAEA. Our current effort shows that if the aim of the image analyst is to identify minerals, or track material from one scene to another, it is necessary to use well-calibrated imagery, in which all effects associated with the remote measurement (atmospheric absorption, scattering and viewing geometry) have been removed or compensated for. Only then will it be possible to derive spectra identical to those acquired by ground measurements.

Future effort should be focussed on atmospheric correction of hyperspectral imagery, and on building up a spectral reference library of safeguards-relevant materials. Hyperion is the only hyperspectral satellite sensor currently available and is nearing the end of its life. However many countries including the US, Canada, Germany, India and Italy are considering launching hyperspectral sensors that will provide continuity after this sensor is decommissioned.

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