Capabilities and Potential Safeguards Applications of High Resolution Imagery

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1. Introduction

The CSSP has been investigating potential safeguards applications of optical and radar satellite imagery at various resolutions..This paper provides an overview of the progress during the past several years and recent advancements in the quality of the imagery and processing and analysis techniques that assist in the extraction of information from the imagery.

The Satellite Imagery Analysis Unit (SIAU) at the IAEA maintains a strong capability in the analysis and exploitation of optical satellite imagery for safeguards applications. This capability is currently based largely on visual interpretation of high-resolution panchromatic imagery, since this imagery is the most appropriate for describing buildings and manmade structures at most nuclear facilities. Experienced image interpreters can extract considerable information about a site based on their knowledge of the activities taking place at similar facilities. Since the examination is often focused on well-known or well-located target facilities, a wide area search is not usually carried out. However, when a task involves a search over large areas for changes over time, or identification of materials in stockpiles found at nuclear facilities, then lower resolution multi- and hyperspectral and radar imagery can provide important additional information. Several examples are presented in this paper to illustrate the benefits arising from the integration of additional information from lower resolution optical and radar sensors to high-resolution imagery analysis.

2. Optical

Case studies using imagery obtained for nuclear facilities located at different parts of the globe were carried out to demonstrate the strategy of using a combination of imagery and analysis techniques to better extract information from satellite imagery analysis. Three case studies are presented.

Case study #1 illustrates the use of high-resolution panchromatic imagery to show the structural details of an underground mining operation. Information on material composition derived from from hyperspectral sensors can then be overlaid over the high resolution image.

Case study #2 demonstrates the use of hyperspectral imagery to help define the spatial extents of surface disturbances at an *in situ* leaching mine that may not be readily spotted in high-resolution imagery.

Case study #3 illustrates the combined use of hyperspectral, high-resolution panchromatic and change detection methodology for a remote site where small scale, undeclared uranium mining activities were suspected

2.1. Case study #1: Olympic Dam Mine (Underground)

Olympic Dam in south Australia is a large underground mine that is a source of uranium, copper, gold and silver ores. From a safeguards standpoint it is useful as a test site, as ample ground information is available to provide validation of the remote sensing observations. The deposit being mined is a granite- and hematite-rich, underground breccia complex. The ore is excavated and crushed below ground before being brought to the surface where it is further ground and the copper, uranium, gold and silver extracted by leaching. Mined out tunnels are filled using a mixture of tailings and cement produced on site.

A high resolution Ikonos panchromatic image shows the central processing facility, tailings ponds to the west, quarry, and various support facilities, all of which can be recognized from their physical properties (Figure 1). In Figure 2 the composition of the materials in the some of the excavations and tailings dumps is shown, as derived from hyperspectral analysis. In this rather simple example, the findings support the physical interpretation: the feature identified as a quarry shows the spectral properties of limestone, consistent with its role in the manufacture of cement. The tailings dumps contain hematite, consistent with the hematite-bearing host rocks associated with the main ore deposits, and jarosite, another iron containing mineral. Clay minerals are found in a surface excavation near the tailings ponds. Overlaying the spectrally derived information on the high-resolution imagery as shown in the Figure allows the analyst to supplement and confirm the visual observations.

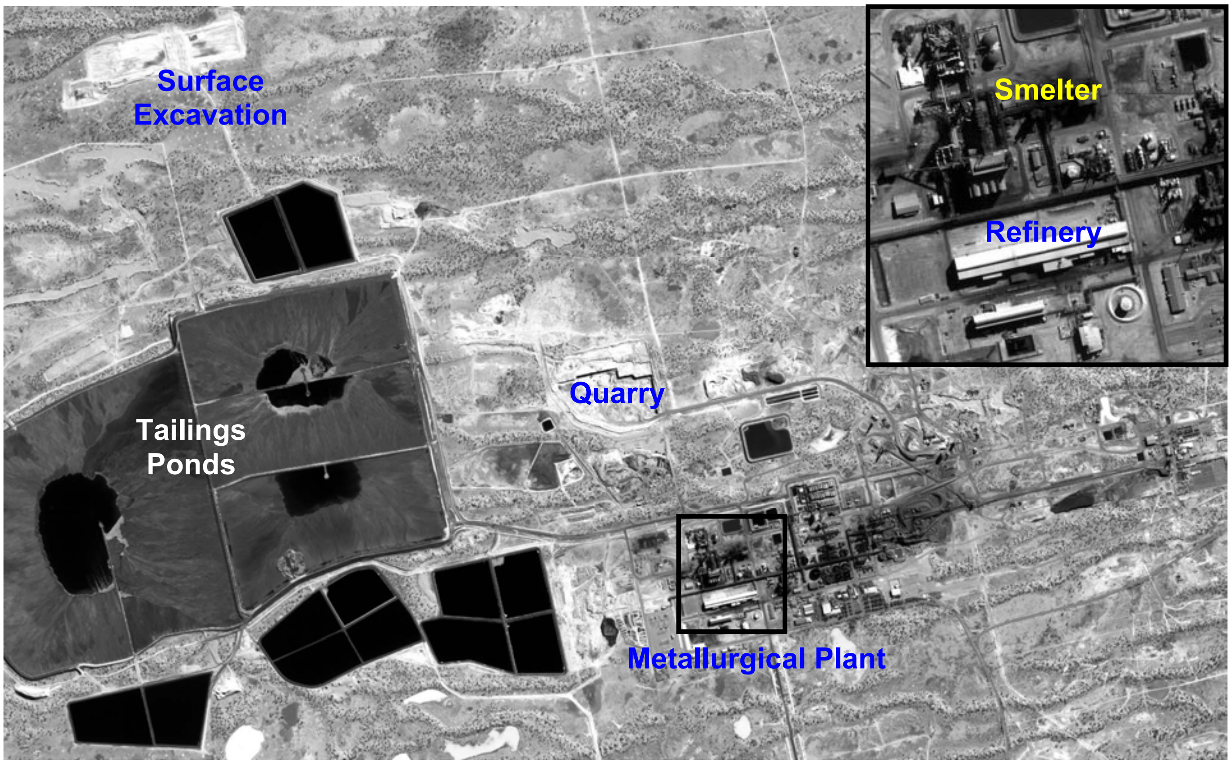

Figure 1. 2001 Ikonos image of Olympic Dam uranium, copper, gold and silver mine, showing details of the processing facility.

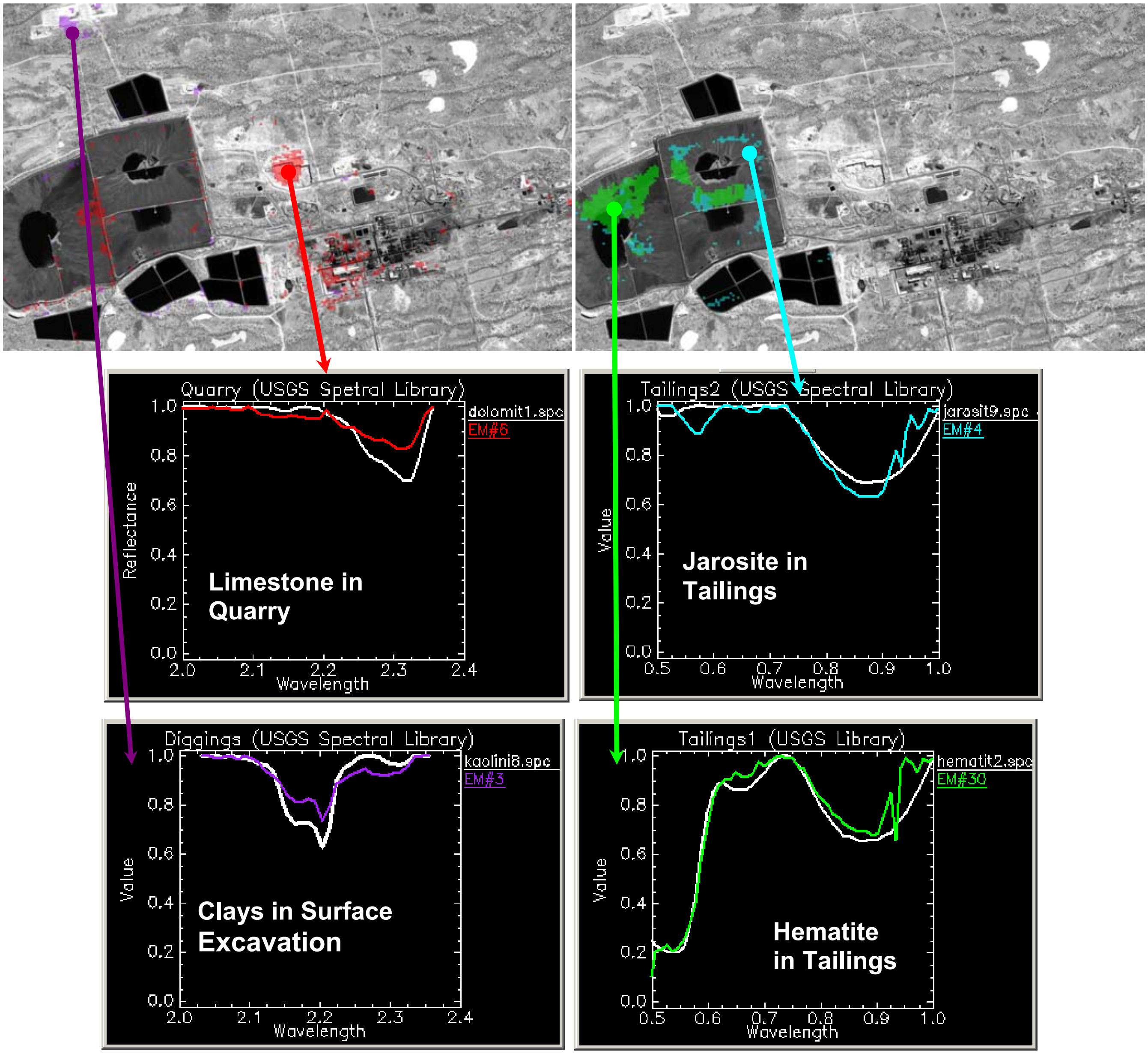

Figure 2. Remote analysis of materials present in surface excavations and tailings ponds at Olympic Dam mine, determined from hyperspectral imagery. In these images the hyperspectral results are overlaid in colour on the Ikonos scene depicted in monochrome.

2.2. Case study #2: Beverley Mine (In Situ Leaching)

Beverley Mine in Australia is an example of an *in situ* leaching (ISL) uranium mine. In contrast with open pit or even underground excavation mines, *in situ* leaching operations have minimal surface infrastructure and therefore the opportunities for remote surveillance are less. In the Ikonos image in Figure 3, the evidence of mine operations at Beverley is small, consisting of an airstrip and road, a processing plant, camp, and scattered well heads and pipelines.

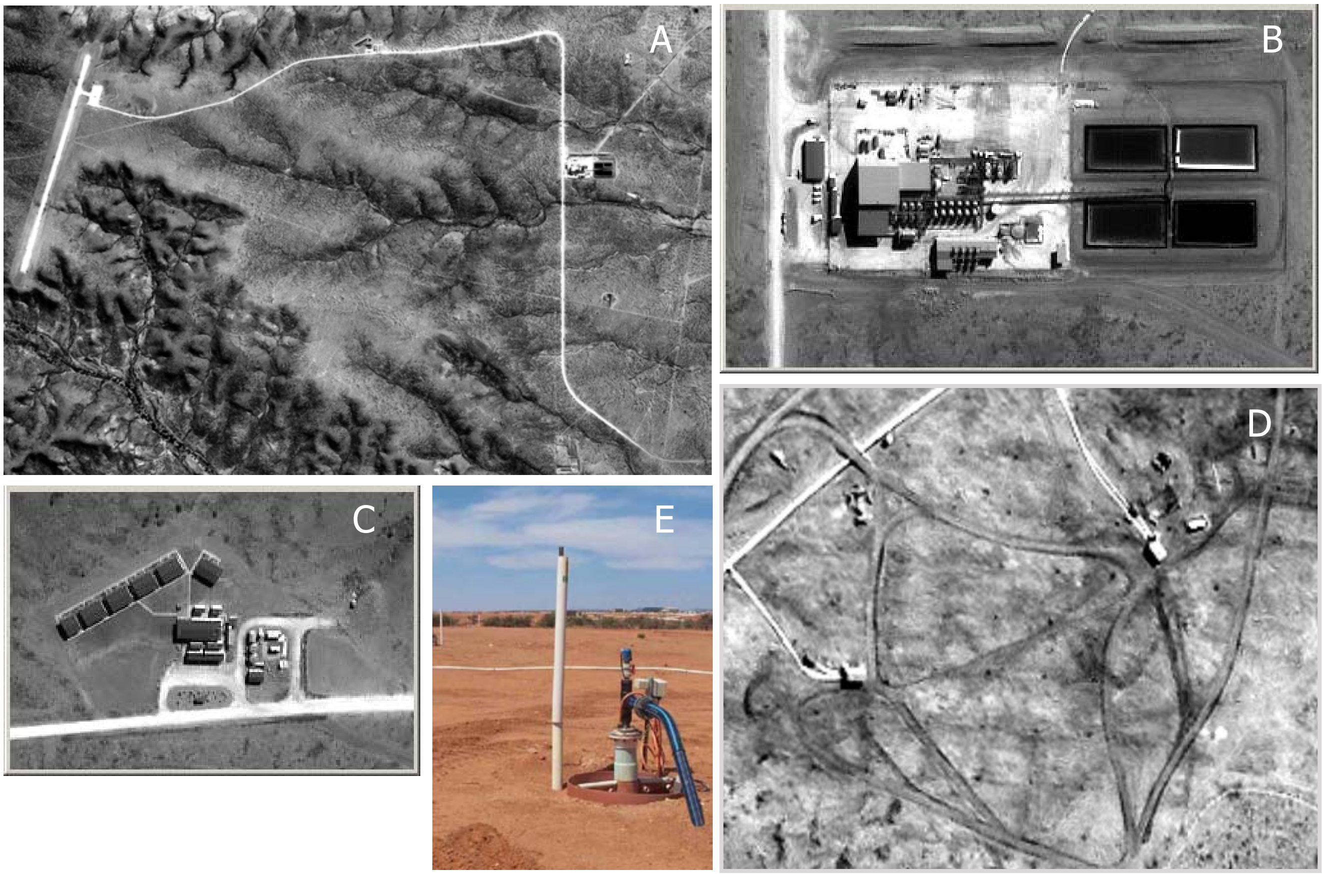

Figure 3. 2001 Ikonos image over Beverley Mine. (A) Overview showing airstrip and road. (B-D) Closeups of the main processing plant (B), camp (C), and well heads (D). (E) Photo showing the small footprint of each well head.

Spectral analysis of a Hyperion scene over Beverley yielded the disturbance map shown in Figure 4. In this case the map was generated without prior knowledge of the area or input of ground truth spectra, and represents the detection of spectral anomalies rather than a search for particular materials. In fact, it shows very good correspondence with a surface map of drill hole positions and the underground projection of ore body location. Overlaying the Hyperion result on the Ikonos imagery quickly focuses attention on areas of mine operations and as such can be used as a guide to the locations of small scale infrastructure.

This example demonstrates the use of hyperspectral to help define the spatial extents of surface disturbances that may be less readily spotted in high resolution imagery.

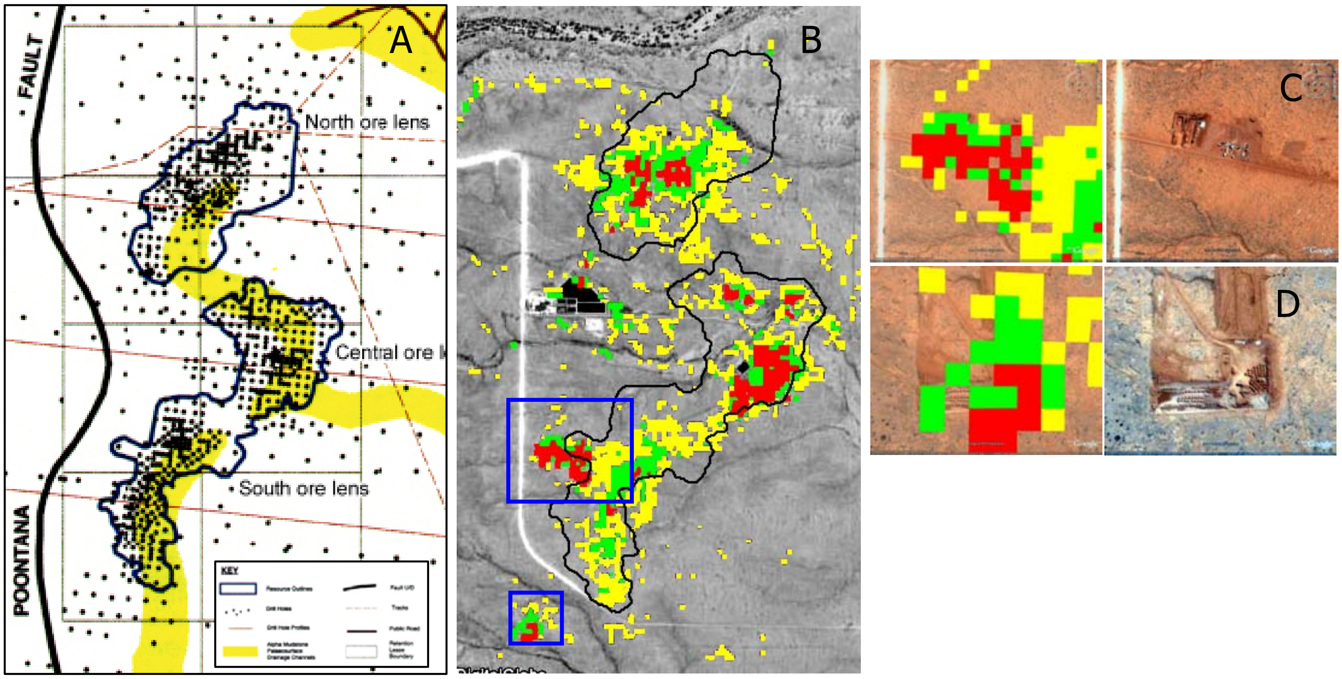

Figure 4. (A) Projected underground location map of the Beverley ore body (black outline) and drilling sites (black dots). (B) Spectral anomalies detected from analysis of a 2007 Hyperion scene, overlaid on a 2005 Quickbird image, here shown as greyscale. (C) and (D) High resolution close-ups of mine infrastructure detected as spectral anomalies in (B) (blue boxes)

2.3. Case Study #3: Combining High Resolution, Spectral and Change Analyses

Figure 5 illustrates a remote site where small-scale, undeclared uranium mining activities were suspected. Geologically the area was recognized as a salt dome, with the likely host rock for uranium identified as rhyolite. Examination of a Quickbird scene revealed several areas showing evidence of possible mining activity.

Spectral analysis of a Hyperion image was used to map the distribution of a mineral group tentatively identified as rhyolite, sandstone and/or hemimorphite, based on comparisons with standard Spectral Libraries. This identification has not been confirmed with *in situ* observations. (Figure 6). A comparison of this with the high-resolution image pointed to a subset of the disturbed areas where uranium ores were potentially present. These are indicated by the red boxes in Figure 5 and Figure 6.

Following spectral analysis, the Hyperion image and a second image acquired four years later were input to a MAD (Multivariate Alteration Detection) automated change analysis. This revealed several locations that had undergone spectral change over the four years (Figure 7). MAD analysis alone does not differentiate between natural change and human influence, but when compared with the high-resolution imagery and the hyperspectral mineral map, five areas could be identified that (a) had undergone change, (b) were areas of potential uranium ores, and (c) displayed physical evidence of human activity. These five areas could therefore be identified as being of potential interest and targeted for closer scrutiny.

From a safeguards standpoint, this three-step analysis used spectral information to both focus the analytical effort and provide information about the distribution of materials of interest. The operational benefits are increased analyst efficiency and a reduction of reliance on physical cues only.

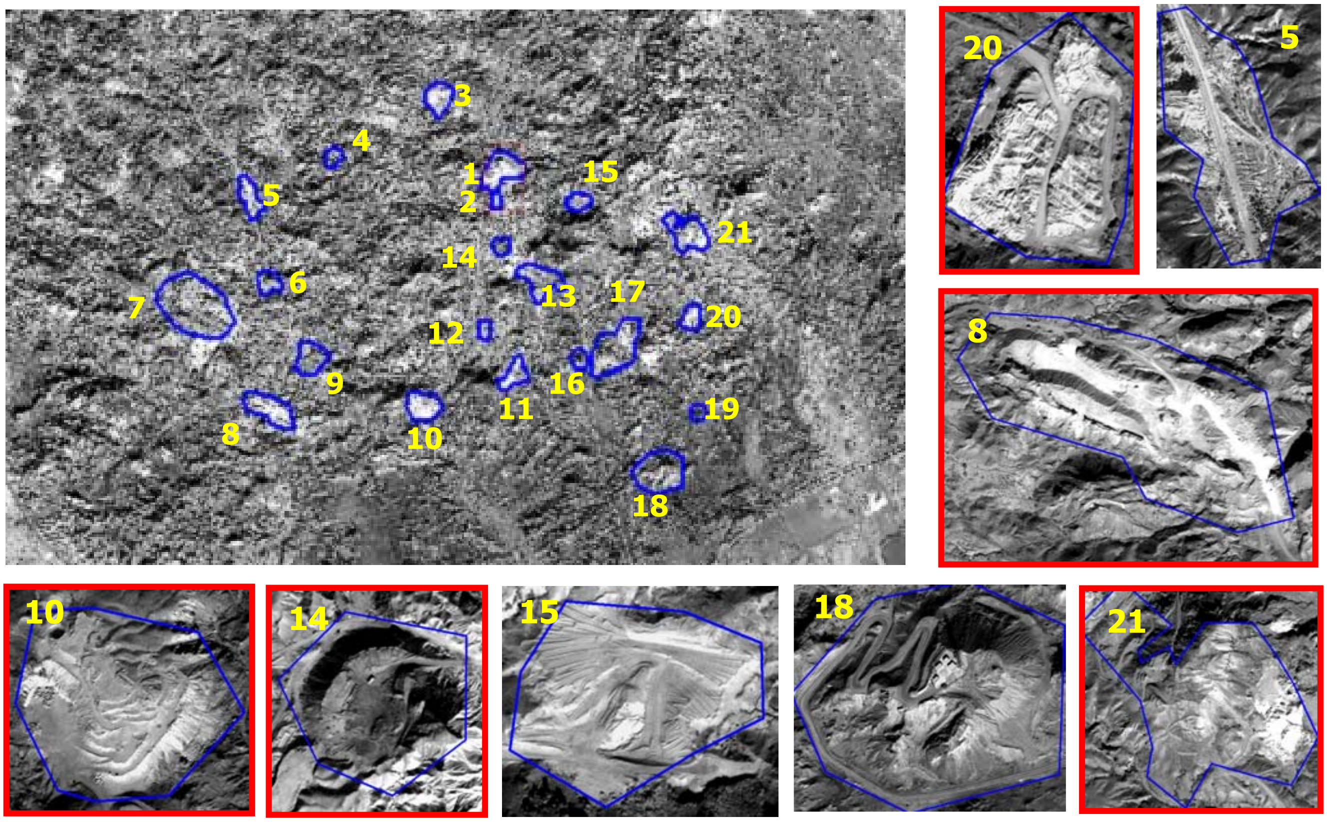

Figure 5. *Large image:* November, 2004 Quickbird scene over study area, with blue polygons indicating sites showing physical signs of human disturbances. *Small images:* Close-ups of selected polygons from the overview image. Red outlines indicate areas showing spectral properties characteristic of the rhyolite mineral group identified in Figure 6.

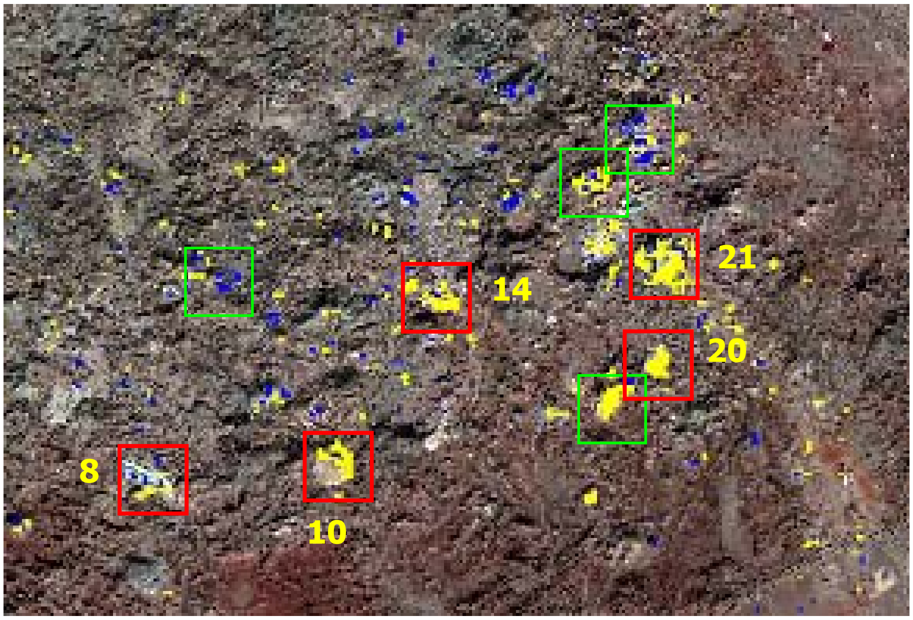

Figure 6. Results of hyperspectral analysis, showing the distribution of two spectral classes of a mineral group identified as rhyolite, sandstone and/or hemimorphite, overlaid on the Quickbird scene from Figure 5 (here displayed in colour). Blue classified pixels were darker and, based on the Quickbird image, tended to be natural undisturbed locations of the mineral, whereas yellow pixels were brighter, the majority showing evidence of human activity. Red boxes indicate areas of mineral concentration where human disturbances were observed in the Quickbird scene. Green boxes are areas where human disturbances were not observed.

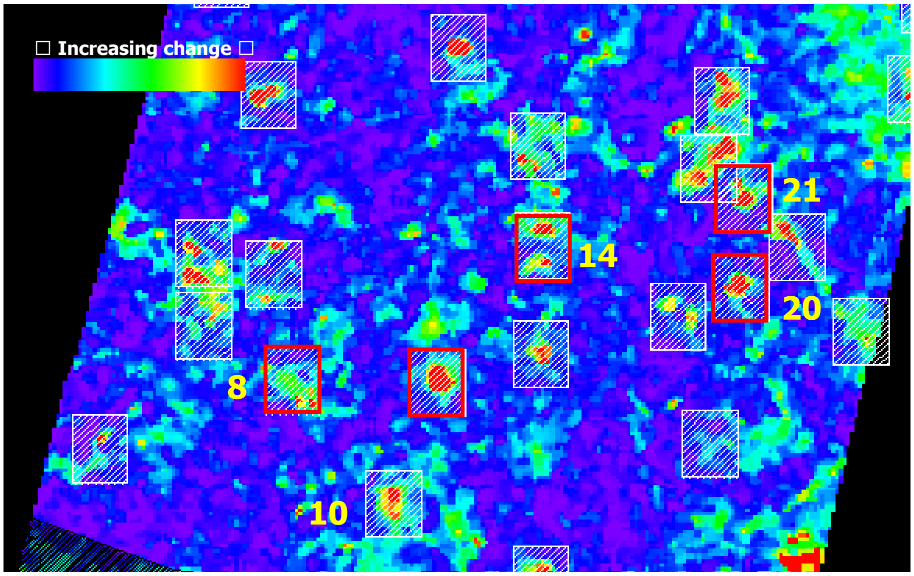

Figure 7. 2003-2007 MAD change detection: areas showing the greatest change are highlighted by rectangles; those also selected in previous analyses are indicated by red rectangles.

2.4. Concluding Remarks: Optical

Improvements in the spatial resolution of optical sensors during the last ten years have made commercial satellite imaging a valuable tool for safeguards use. New satellites being launched this year or planned for 2009 will increase both the capability and availability of high resolution imagery: GeoEye-1, launched September 6 of this year, offers 0.5m panchromatic and 1.6m multispectral resolution, improving on the previously highest commercially available resolution at 0.6m/2.4m panchromatic/multispectral available with Quickbird. RapidEye, with a constellation of 5 satellites, offers 6.5m multispectral with a one day revisit time. WorldView-2, to be launched in 2009, will provide 0.5m panchromatic and 1.8m multispectral with 8 spectral bands, an improvement on the 4 bands (red, green, blue, near infrared) available with most current multispectral satellites.

WorldView-2 in particular is exciting because it widens the possibilities for spectral analysis of high resolution imagery. For safeguards, the analysis of materials will likely continue to benefit from hyperspectral however, due to the high spectral resolution required to see the narrow features used in mineral identification. Techniques such as image coregistration and fusion will remain powerful tools for combining the information contained in the high spatial and high spectral resolution imagery.

What does need to be improved upon is the availability of safeguards specific spectral libraries to provide standards for hyperspectral analysis. Case studies at well known facilities such as Olympic Dam will enable us over time to build up this type of reference resource.

3. Radar

Recent advancements in Synthetic Aperture Radar (SAR), such as higher resolutions and polarimetric capabilities, are provided by several new satellite systems. TerraSAR-X operated by Germany's DLR was launched in June 2007 and has a best resolution of 1 meter. RADARSAT2 operated by Canada's MDA was launched in December 2007 and is fully polarimetric with a best single polarized resolution of 3 meters. In addition to increased resolution and polarimetric modes, these new satellites have better orbit information and maintenance which is important when performing coherent and interferometric techniques discussed in the following sections. Previous to these new satellites, the best space-borne SAR resolution was approximately 8 meters from RADARSAT-1.

Several analysis techniques and methods used in the current investigation are presented in the following sections.

3.1 Object Detection & Infrastructure Analysis

SAR is well suited for nuclear safeguards because of its all weather, 24 hour a day imaging capability. Due to the physics of radar imaging and acquisition geometry, SAR is particularly useful for identifying objects such as fences, power towers, ships on the water, airplanes on a runway, and cars in a parking lot.

The increased resolution of the recently launched SAR satellites have made it possible to identify smaller objects and has improved the detail of objects in the image. Using 1 meter TerraSAR-X imagery, it was possible to count the number of hatches on cargo ships and identify if the ship has onboard cranes.

The CNSC has acquired CV-580, RADARSAT-1, RADARSAT-2 and TerraSAR-X imagery of many Canadian nuclear generating stations. In addition, 1 meter TerraSAR-X imagery has also been acquired at open pit, underground, and in-situ leaching mines.

It has been shown that under very dry conditions it is possible for the radar waves to penetrate the surface and image features below. In 1981, the SIR-A SAR was able to penetrate approximately 10 feet of sand and produce an image of the bedrock [1]. RADARSAT-1 was also able to see the current Amundsen-Scott Station in Antarctica, and the older station that is buried by 30 meters of snow [2].

Another unique ability of SAR is that the radar will penetrate the fabric roof of domed sports arenas and see the interior features, as shown below in **Error! Reference source not found.**. The stands of the BC Place arena in Vancouver, Canada are clearly visible around the oval of the football field. The radar is not able to penetrate the concrete roof of the hockey arena in the top right of the images, which is why it appears different in the TerraSAR-X image. Any equipment or vehicles in these types of fabric roofed structures would be hidden in optical imagery, but would potentially be seen in high resolution SAR imagery.

Figure 8: BC Place, Vancouver, Canada. GoogleEarth image of BC Place dome (left) and see-through capability of high resolution SAR image, TerraSAR-X (right).

3.2 Sublook Analysis

Sublook refers to the generation of two or more images from a single SAR image. In a traditional SAR image, the satellite (or airplane) is transmitting and receiving signals as it progresses along a flight path. These signals are then processed into a SLC (single look complex) image. The sublook technique uses the same received data as in the SLC case, but produces multiple images of reduced resolution that are essentially taken from slightly different angles along the flight path. Analysis of the sublook images can be used to discriminate between targets and speckle.

Sublook coherence is a technique that is performed on two sublook images. Coherence is discussed in greater detail in section 3.5, but in this case it is basically a measure of similarity between the two sublooks. Since the sublook images are taken from slightly different angles, the sublook coherence will identify those areas where the backscatter has remained the same. Noise from speckle and clutter will vary at different angles and will have low coherence [3]. The left panel of **Error! Reference source not found.** shows a RADARSAT1 fine beam mode image of the Beverley uranium mine in Australia, acquired on 11 May 2008. The right panel shows the result of the sublook coherence, which has been inverted to more clearly show the identified targets (points of interest) in black. As can be seen in Figure 9, there are many targets at the mine site and a few to the north. This type of analysis can be used on a coarser resolution image with a larger footprint to help identify areas for further investigation with high resolution imagery with a smaller footprint.

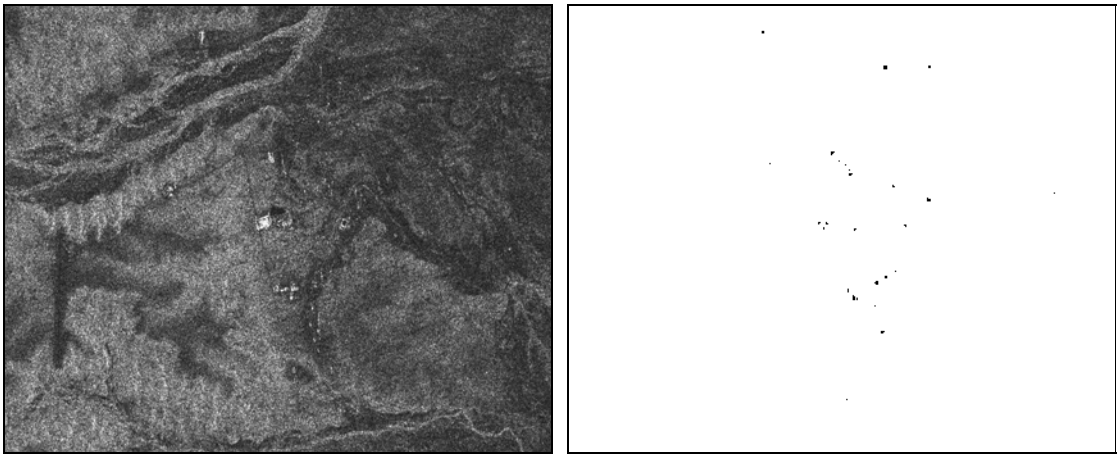

Figure 9: The RADARSAT1 fine beam mode image (left) shows the Beverley Uranium Mine in Australia. The sublook coherence (right) was generated by first creating two sublook images from the original, then calculating the coherence of the sublooks. The result was then inverted so that the targets identified appear black.

3.3 Polarimetric Synthesis

Fully polarimetric SAR sensors, such as RADARSAT2, can generate four images acquired at different transmit and receive polarizations, whereas traditional SAR sensors only acquire in one polarization. The four polarizations are HH, HV, VH, and VV, where HV stands for a horizontally transmitted signal and a vertically received signal. From these four polarimetric images it is possible to calculate any transmit and receive polarization. By analysing many of these calculated polarization images, targets and objects that scatter only in a particular polarization can be located. It is also possible to decompose and classify polarimetric data in terms of the basic scattering mechanism, typically defined as surface scattering, volume scattering, and double bounce.

The drawback for fully polarimetric data is that in order to acquire four images per scene, the resolution of each image is lower than if only a single polarized image is acquired. RADARSAT2, for example, can acquire a single polarized image with 3 meter resolution, or the four polarimetric images with approximately 7 meter resolution. For some applications this loss in resolution might be acceptable while other applications may require the increased resolution.

3.4 Coherent Change Detection

Coherent Change Detection (CCD) is a radar specific technique for measuring the degree of correlation, or similarity, between two SAR images [4]. CCD is performed on two repeat pass single-look complex (SLC) data sets and identifies any changes that occurred between the two SAR acquisition dates. A CCD image is a gray scale image where perfect correlation is given a value of 1 and represented by white, complete de-correlation is given a value of 0 and represented by black, and partial de-correlation is represented by gray tones. Low coherence can also result from the movement and growth of vegetation, erosion and other types of weathering, and from changes in moisture content. As a result of these natural sources of decorrelation, CCD is most effective in dry, arid areas. CCD can be used for the detection of clandestine activities, but it is important that supporting information from optical imagery and ground truth data is used to identify changes that result from natural phenomena, allowing CCD to focus on human activity.

Error! Reference source not found. shows the result of CCD analysis at the Beverley In-Situ Leaching (ISL) uranium mine in Australia. In-Situ Leaching is a low surface impact mining method where a liquid is injected into the ore body and the dissolved ore is the extracted for further processing. As a result, there are no large pits or tailing piles that would traditionally indicate mining operations. The left panel of **Error! Reference source**

not found. shows a TerraSAR-X 1 meter resolution spotlight mode image acquired on 16 May 2008. The right panel shows the coherence image calculated from the TerraSAR-X image and a second image acquired on 27 May 2008 (not shown). Many of the roads around the mine are clearly visible in the CCD image, as well as disturbances around individual wells, as indicated by the arrows.

These results match previous results from RADARSAT-1 [4], although the eight times increase in resolution of TerraSAR-X allows for better interpretation of the CCD results. Furthermore, the disturbances around the wells were visible in the RADARSAT1 CCD image, but the level of resolution was not sufficient to distinguish them from the noise. The fact that they were actually the changes around the wells were only identified when compared to the TerraSAR-X CCD image.

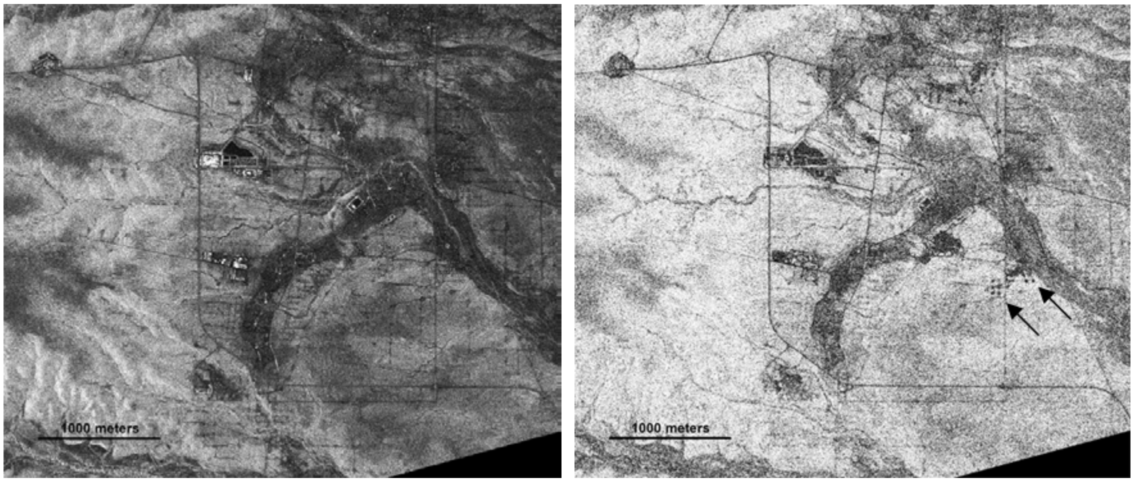

Figure 10: TerraSAR-X spotlight mode (left) of Beverley Uranium Mine in Australia, acquired on 16 May 2008. The coherence image (right) was calculated from the TerraSAR-X image and a second image acquired on 27 May 2008. Dark areas in the coherence image indicate change, and light areas indicate no change. It is possible to identify surface disturbances around the individual wells, as show by the arrows.

3.5 Interferometry

Interferometry is another SAR technique that is related to CCD but instead of identifying surface disturbances it can quantitatively measure centimetre-scale ground subsidence between repeat pass SAR images.

Ground subsidence is an important quantity to measure because it could be evidence of underground nuclear tests [5] or tunnelling [6]. Subsidence at nuclear material storage sites, tailings piles, pipelines, or other infrastructure related to nuclear materials could also indicate that these areas are unstable and that containment issues could occur.

The increased orbit maintenance and more accurate satellite location information of the newer satellites are an important factor for interferometry. The measurement of small levels of subsidence requires knowledge of the satellite orbit and location during imaging.

3.6 Concluding Remarks: Radar

The recent advances in commercially available SAR imagery has a direct impact on the use of SAR satellites for nuclear safeguards. In terms of object detection and infrastructure analysis, the increased resolution allow for better interpretation of the SAR images and identification of smaller objects.

It should be noted that increased resolution comes at the sacrifice of the scene footprint. RADARSAT1 can acquire an 8 meter resolution image with a footprint of 50 km range by 50 km azimuth. The 1 meter TerraSAR-X image has a footprint of 10 km range by 5 km azimuth. In some situations where there is not a well defined area of interest, or when trying to identify an area of interest it makes more sense to use a larger footprint. Once the area of interest has been defined, analysis with higher resolution imagery can begin.

CSSP investigations have confirmed our speculation that SAR sensors can see though certain materials. However, there were some surprises during our analysis. One was the capability of radar to identify much better than optical imagery for certain situations. Actually, this is not really a surprise and should be considered as an encounter that goes against our expectation that optical is always better than radar imagery. The second was that certain objects were clearly shown in a RADARSAT-1 image, which was confirmed by an optical image from Google Earth, at the Ranger mine site in Australia. Two higher resolution TerraSAR-X were acquired to confirm this finding. However, we have not been able to find those objects on the TerraSAR-X images.

4. Acknowledgements

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5. References

[1] McCauley J.F. *et al.,* 1982. "Subsurface valleys and geoarcheology of the Eastern Sahara revealed by Shuttle radar", Science 218, 1004-1020, 1982.

[2] E. M. Choi, "The Radarsat Antarctic Mapping Mission", IEEE AES Systems Magazine, May 1999, pp. 3-5.

[3] R. Meth, "Synthetic Aperture Radar Vehicle Detection via Subaperture Coherence", 2002.

[4] Q.S. Bob Truong, R. Saper, D. Kump, G. Parsons, M. St-Hilaire, and J. Mulvie, "Coherent Change Detection (CCD) for Safeguards Applications," INMM 48th Annual Meeting, Tucson, USA, July 2007.

[5] Q.S. Bob Truong, G. Parsons, M. St-Hilaire, R. Saper, and J. Mulvie, "CSSP Investigations using SAR Imagery for Safeguards Applications" ESARDA Symposium on Safeguards and Nuclear Material Management, Aix-en-Provence, France, May 2007.

[6] Le Mouelic, S., Raucoules, D., Carnec, C., King, C., Adragna, F., "Ground uplift in the city of Paris (France) revealed by satellite radar interferometry," IGARSS '02, IEEE International, Vol 2, 24-28, June 2002, pp. 1222-1224.