HYPERSPECTRAL IMAGERY FOR SAFEGUARDS APPLICATIONS

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ABSTRACT

High-resolution black-and-white satellite imagery is becoming more common as a cost-effective tool for nuclear safeguards inspectors and regulators, and is now used routinely to provide information to validate or confirm state declarations – primarily through photo-interpretation of cues such as shape, size, pattern, texture, shadows and site associations. Multispectral and thermal imagery can provide valuable supplemental information on the nature and composition of the material in a target to assist in interpretation. Recent advances in remote sensing technology are now providing additional tools that might be used to confirm operations, scheduling, movement of materials and other reported details. Hyperspectral sensors, having hundreds of spectral bands, provide the real possibility to 'do chemistry from space', by allowing very subtle measurements of narrow spectral absorption features that reflect the chemical makeup of the target material – distinguishing between ore types, for example.

As part of a co-operative project between the Canadian Safeguards Support Programs, Canada Centre for Remote Sensing, and the International Atomic Energy Agency, we are investigating the use of hyperspectral imagery for remote examination of operating uranium mines and other facilities, with the objective of developing methodologies that can be used for safeguards verification of declared and undeclared activities. This paper introduces the concept of hyperspectral remote sensing, discusses the current 'state of the art', and presents examples of the use of satellite and airborne hyperspectral imagery to demonstrate classification, identification and differentiation of terrain, materials, water and vegetation in locations of interest to the safeguards community.

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SAFEGUARDS APPLICATION OF REMOTE SENSING

Facilities of interest to the safeguards community are often located in remote areas far from built up areas and are difficult or expensive to access. Satellite imagery is the only tool available that provides synoptic, wide-area spatial coverage of remote or inaccessible areas without administrative restrictions. Trans-boundary analyses can be repeated at intervals to provide temporal monitoring and change analysis. Commercially available high resolution satellite imagery is now becoming a common tool of safeguards inspectors, and allows production of up-to-date, independently produced maps that can be used to evaluate member state declarations and monitor reactor or mine operations.

In 2004, a wide variety of satellite data is available

- very high resolution panchromatic (black and white) imagery similar to aerial photography that is taken on demand. These systems (IKONOS, Quickbird, EOS) have recently been introduced commercially and are replacing aerial photography for many applications.
- lower spatial resolution multispectral (many colours – usually 4-10 spectral bands) imagery; with more spectral resolving power. IKONOS and Quickbird offer 2-4m pixels; Landsat Thematic Mapper, while only having 30m resolution also has thermal capability and a 30 year archive of the entire earth. These systems are very widely used in biology, geology, meteorology and other fields of science.
- hyperspectral (very many colours, currently 200 spectral bands with 30m pixels from HYPERION) imagery capable of detecting very subtle colour variations. Currently in research, hyperspectral holds great promise for detailed identification and classification of surface materials.
- more recent radar imagery that can see through cloud and darkness (not discussed here)

In general, the panchromatic sensors allow an analyst to use photo-interpretative techniques to recognise *structures and objects* by the their shape, texture, shadows, orientation, context. The more common multispectral sensors generally have lower spatial resolution, having traded spatial detail for spectral resolving power. Unlike panchromatic systems, multispectral and hyperspectral systems permit identification of *material, composition or surface chemistry* by their spectral signature or colour, not by their shape. They thus offer the safeguards community a new data dimension with considerable promise.

THE HYPERSPECTRAL CONCEPT

Figure 1 illustrates the spatial and spectral properties of panchromatic, multispectral and hyperspectral imagery. With panchromatic imagery, very detailed spatial patterns can be resolved, but the only spectral information is brightness. Structures such as buildings or industrial components are readily identified from their shape and size. With multispectral, broad colour information is available, at a cost of some loss of spatial resolution. Although buildings are less clear, other features such as vegetation or water that can be ambiguous in panchromatic imagery are clearly identifiable based on their colour. With hyperspectral, there is further degradation of the image spatially, but now details of the spectral properties of the scene may be resolved, permitting the identification of materials.

From a safeguards standpoint there are applications for all three types of imagery. The selection of which to use in any situation is a function of the type of information to be extracted. Are buildings and other structures of primary interest? Is there information to be derived from vegetation or water properties? Is the composition of mine waste of interest, for example?

Since panchromatic imaging is well known in the safeguards community our focus in this paper is the applications of multispectral and in particular hyperspectral imagery. We present examples of these and discuss the types of information that can be obtained from their interpretation.

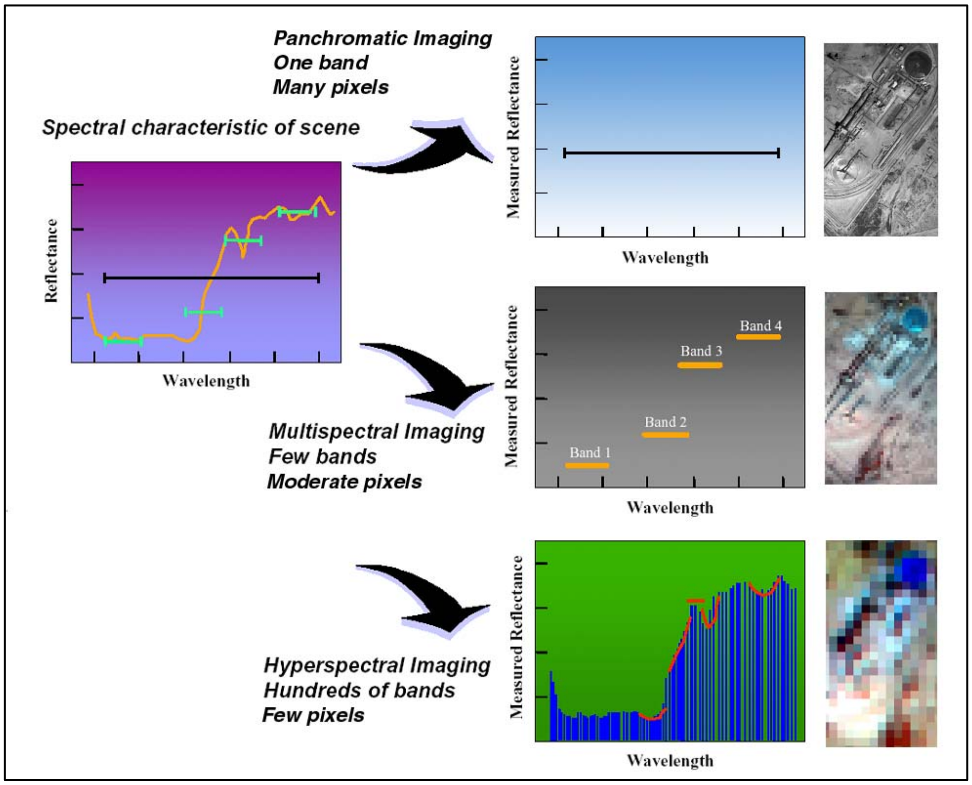


Figure 1. Comparison of spectral and spatial properties of panchromatic, multispectral and hyperspectral imagery. Adapted from http://eo1.gsfc.nasa.gov/overview/Workshop/06.pdf

HYPERSPECTRAL DETECTION OF INDUSTRIAL MATERIALS

If the spectral properties of materials of interest are known, hyperspectral imagery can be used to locate those materials in a satellite scene. We used laboratory spectral measurements of samples of raw phosphate ore and phosphate fertilizer to locate these materials in imagery from the American hyperspectral satellite sensor HYPERION. Figure 2 shows samples of the ore and fertilizer obtained from the site, laboratory spectra of the two materials, and their localization in imagery from HYPERION. We see the main ore stockpile located in the lower half of the image, and fertilizer scattered around the processing facility.

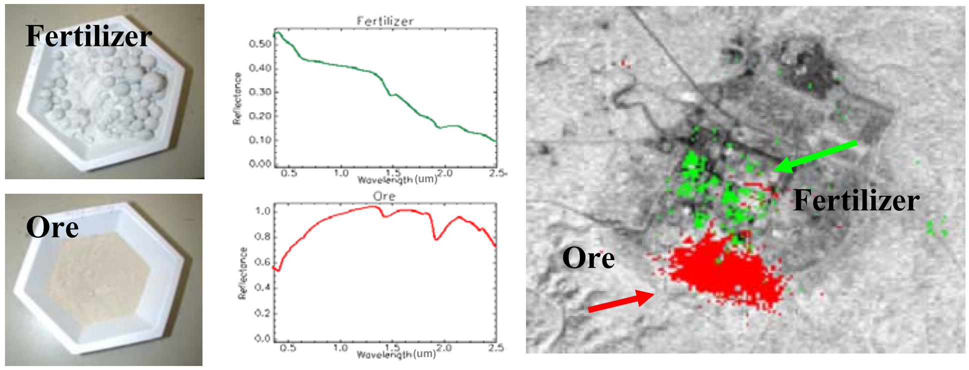
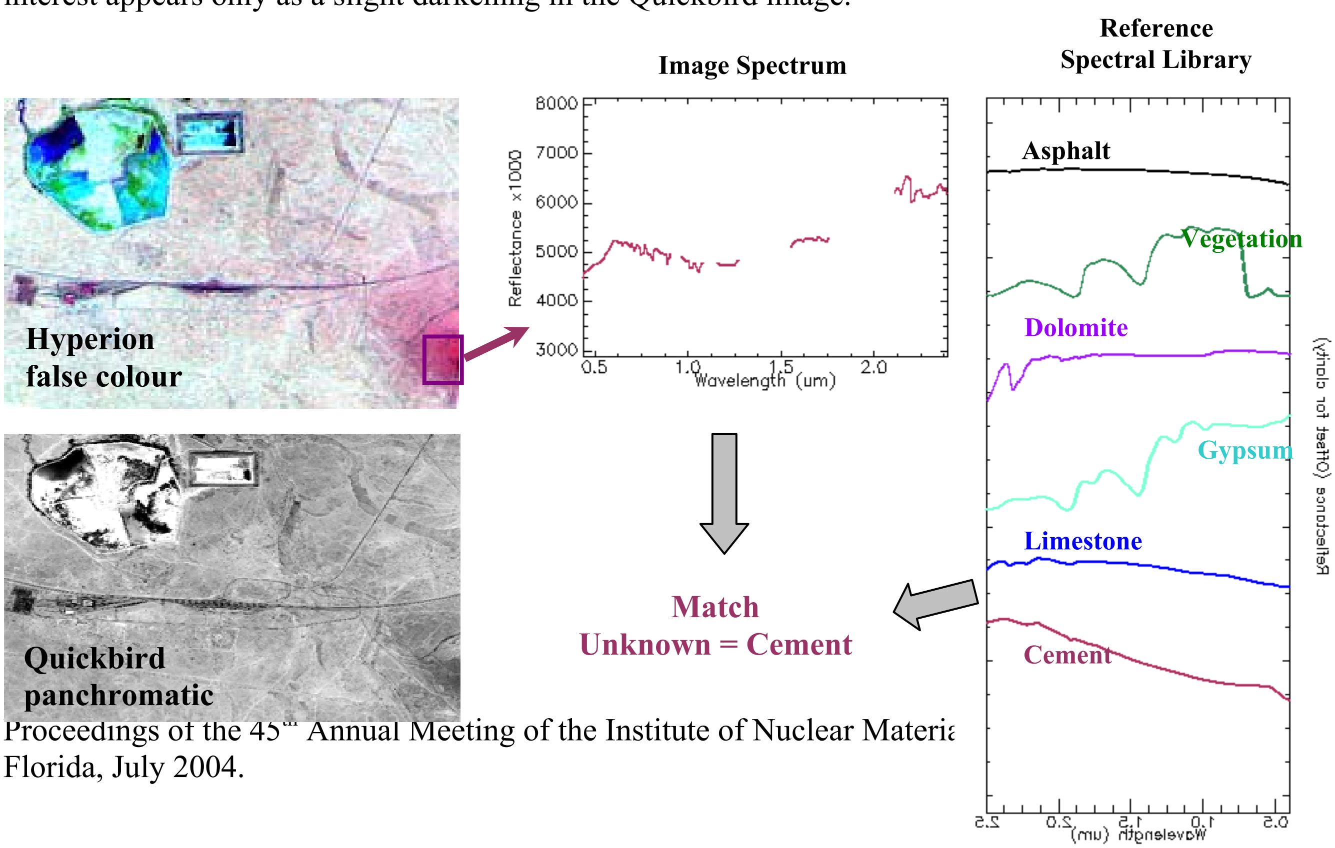


Figure 2. Localization of raw ore (red) and processed fertilizer product (green) in a HYPERION image, based on laboratory spectra of samples. The distributions are shown as red and green overlays superimposed on a black-and-white background image.

HYPERSPECTRAL IDENTIFICATION OF UNKNOWN MATERIALS

Hyperspectral imagery can also be used in an exploratory manner, to highlight materials of potential interest. Using the same HYPERION scene we identified an area with spectral properties that were distinct from those of the surrounding terrain, a fact that was only vaguely evident as a slight darkening in a panchromatic image of the same area (Figure 3). We extracted a spectrum from the image, and by making comparisons with a spectral library, were able to identify the unusual spectrum as cement.

Figure 3. Identification of an unknown material based on its spectral properties. The feature of interest appears only as a slight darkening in the Quickbird image.



AN INTEGRATED APPROACH

For some tasks, the best approach may be to integrate panchromatic, multispectral and hyperspectral imagery. Figure 4 illustrates an investigation aimed at identifying targets in another HYPERION scene, that were selected on the basis of unusual spectral properties not detectable in normal visible/near infrared imagery. We had begun by asking the computer to find 'pure' pixels, that is, targets that were spectrally distinct from everything else in the image. One of the unique spectral signatures found at several isolated locations in the image, was characterized by elevated values only in the long wavelength, shortwave infrared (SWIR) portion of the spectrum. From other work, we speculated that this unique spectrum was blackbody radiation from very hot (over 800 C) material, but we did not know what these targets were.

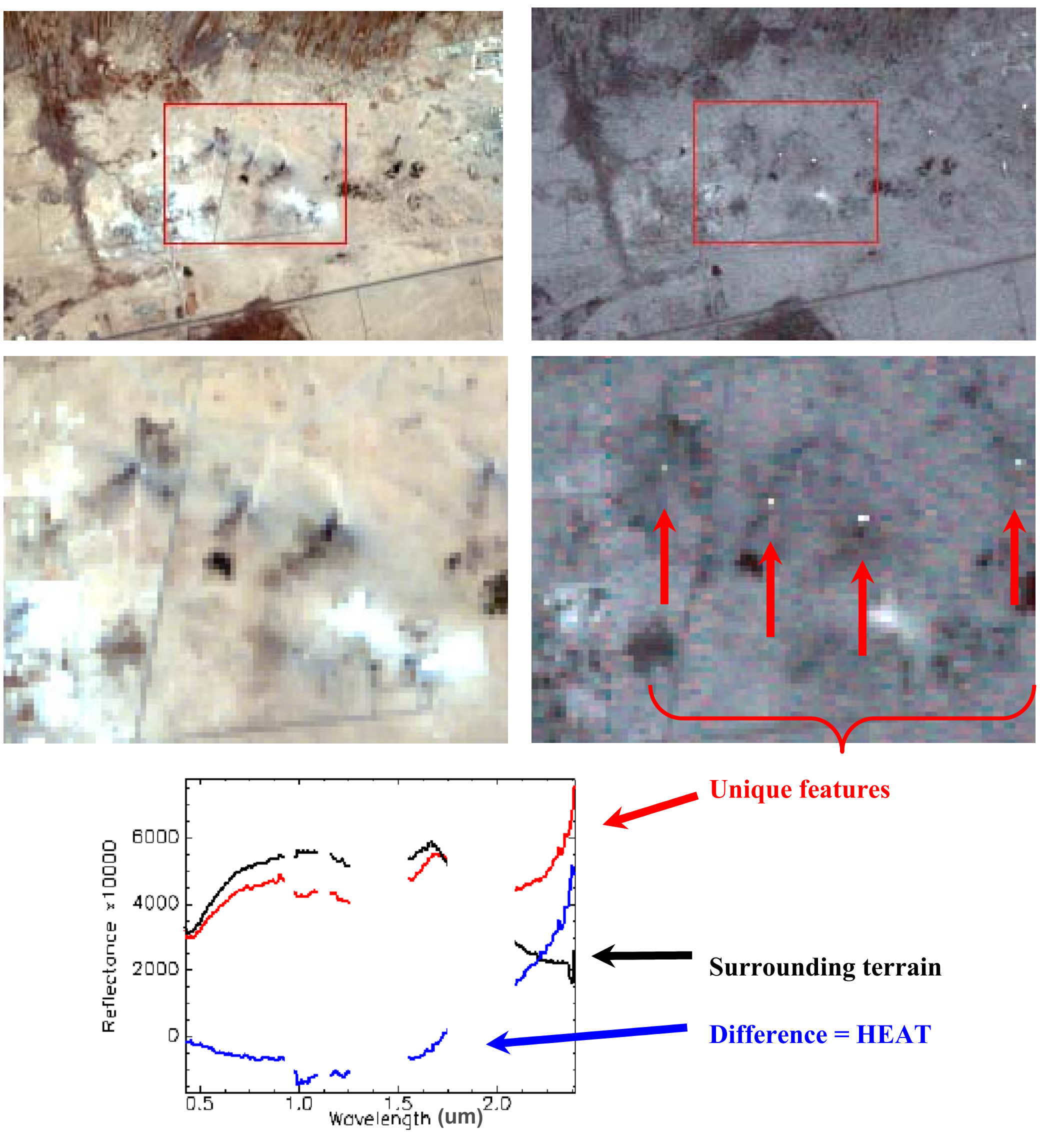


Figure 4. Identification of unique targets from HYPERION imagery as heat sources. *Left,* visible/near infrared, and *right,* SWIR imagery.

We then examined Quickbird high-resolution panchromatic imagery of the same area, and overlaid it on the HYPERION image. This allowed us to see that all four targets had similar structure, and tentatively identify the heat sources as brick kilns (Figure 5).

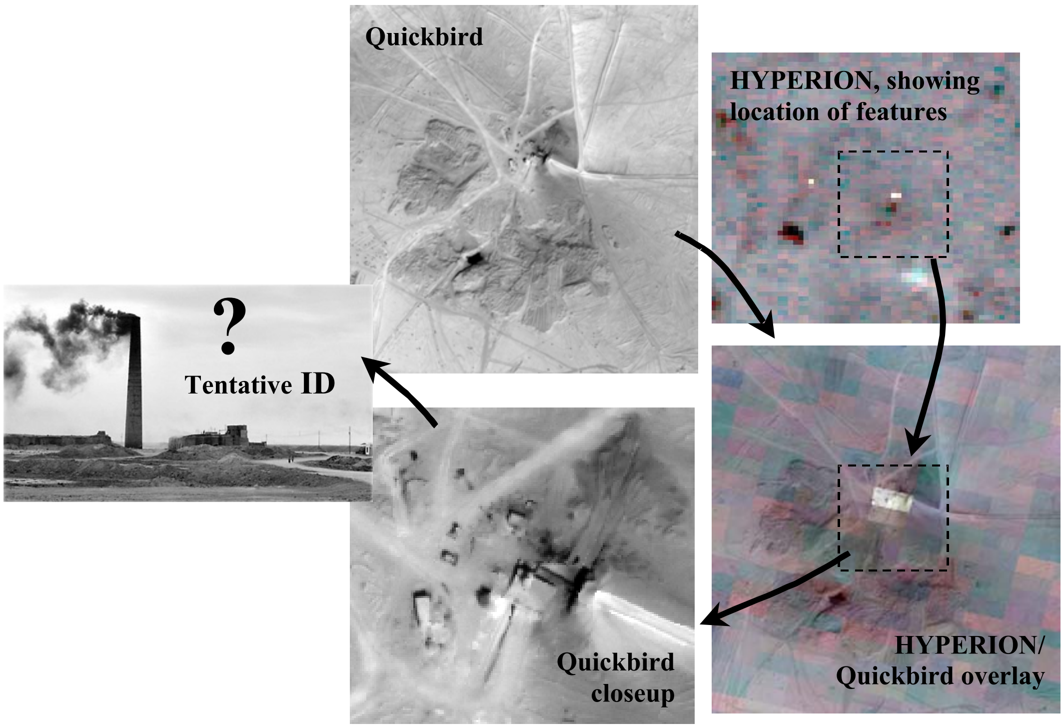


Figure 5. Use of HYPERION hyperspectral imagery in combination with Quickbird high resolution panchromatic to identify heat sources.

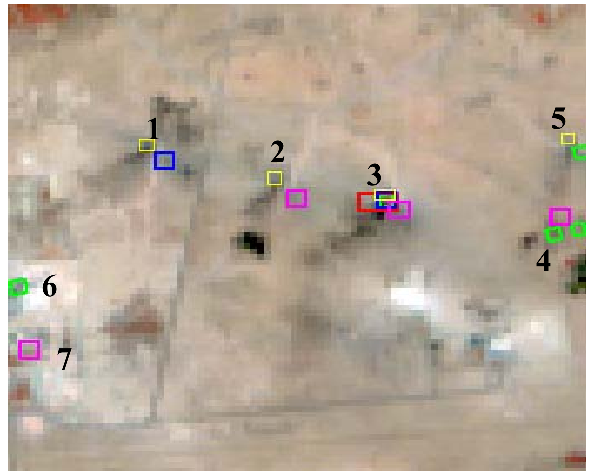
Finally, several examples of thermal imagery from Landsat and ASTER were examined to create a time series of kiln usage. Figure 6 shows the four kilns, plus three additional heat sources found in the thermal images, which were not hot when the HYPERION scene was acquired. Two of these (#6 and 7) were identified from Quickbird imagery as being structurally different from the others, likely stacks from a cement plant located off the left margin of the images. Interpretation of the time series shows that kiln #3 was in use on all dates, whereas the others were in use only occasionally (Table 1).

Table 1. Summary of thermal output by seven structures identified in Figure 6.

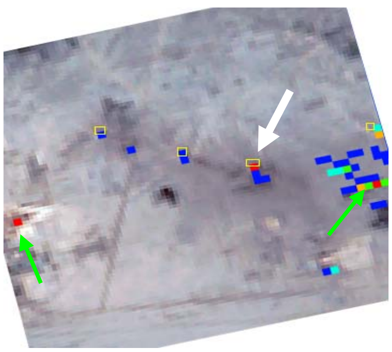
		Brick kilns					Other	
Date	Sensor	1	2	3	4	5	6	7
26 Nov 00	Landsat7			+	+		+	

6 Jun 01	ASTER			+				
24 Jul 01	ASTER	+		+				

HYPERION May 8/02



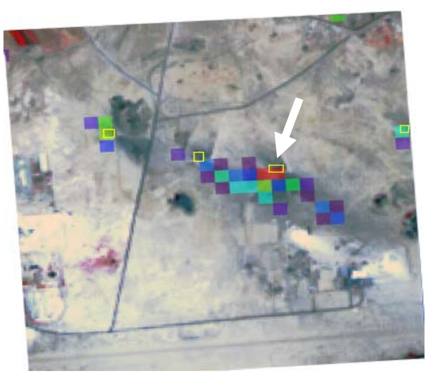
Summary



Landsat7 November 26/00

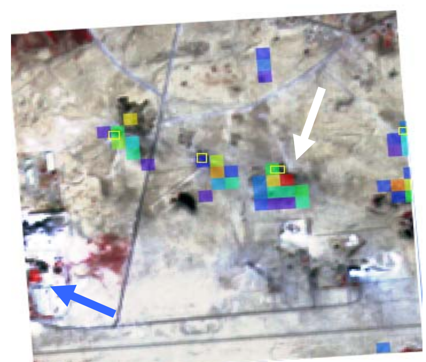
Hyperion image with overlays comparing locations of high temperature pixels from ASTER and Landsat scenes with those identified from HYPERION.

Yellow: HYPERION May 8/02
Green: Landsat November 26/00
Red: ASTER June 6/01
Blue: Aster July 24/01
Magenta: Aster October 24/02



ASTER June 6/01

ASTER July 24/01



ASTER October 24/02

8 May 02	HYPERION	+	+	+		+		
24 Oct 02	ASTER			+				+

Figure 6. Time series of thermal imagery from HYPERION and the multispectral sensors, Landsat ETM7 and ASTER, to show temporal usage of the heat-producing structures. In the Landsat and

ASTER images a colour image is overlaid with coloured pixels showing relative temperature (blue = slightly elevated temperature, red = high temperature; no overlay = "normal" temperature).

Each sensor plays a role in monitoring. HYPERION, ASTER and the commercial high spatial resolution satellites are 'targeting sensors' (that is, they are only turned on over targets of interest), and all have limited archives. They thus cannot be used to produce a long time series. We only used one Landsat example, but we could have taken advantage of its 30-year archive to produce a time series at intervals as short as 16 days.

SUMMARY

Hyperspectral offers a new dimension to satellite imaging being used by the safeguards community. In addition to *identification of structures and objects* in panchromatic images, it is now possible to identify and detect the *composition, material and surface chemistry* of a target using hyperspectral imagery. While the availability of spacecraft hyperspectral sensors is at present limited to HYPERION, Canada and several other nations are currently planning follow-on systems. Most are scheduled for launch before the end of the decade. Hyperspectral science is currently the focus of great attention in the remote sensing community and we can count on soon having several spaceborne hyperspectral systems in wide use.

Hyperspectral imaging is a new tool to add to the image analyst's toolbox along with the panchromatic and multispectral tools already in use. With appropriate use of hyperspectral, multispectral and panchromatic imagery, much more complete, multi-dimensional site descriptions can be built of the structure, composition and temporal variability of targets of interest.

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