Non-Traditional Surveillance Systems and their Application to Safeguards

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Abstract:

The term "surveillance" is most often associated with images or videos captured in the visible region of the electromagnetic spectrum – approximately 400 to 750 nanometers, as this is where the human eye can see. However, the electromagnetic spectrum is vast and possibly other information can be extracted using systems that are sensitive to other wavelengths or techniques that could exploit what has been non-traditional information. This additional information might be useful in applications where lighting is low or obscured; for heat detection or analysis; to detect particular chemicals, effluents, or materials; to detect objects through-the-wall; to determine polarimetric behaviors of light with materials; or for general improvement in discriminating an object of interest. For instance, thermal cameras can detect emitted heat, which may allow for better material or object discrimination in an image, or even for determining density variations in materials. Other imaging techniques, even in the visible region, can be exploited to process information in atypical ways. This paper will look at commercial or academic, non-traditional imaging systems and evaluate possible safeguards applications.

Keywords: surveillance; non-visible imaging; electromagnetic spectrum

1. Introduction

Containment and Surveillance (C&S) methods in safeguards contribute to "continuity of knowledge" regarding nuclear materials and inspection equipment. Surveillance has traditionally relied upon imaging systems sensitive to the visible region of the electromagnetic spectrum. However, imaging systems are available which exploit other regions of the electromagnetic spectrum as well as other physical quantities associated with an optical field, and exploring these other regions and quantities has the potential to strengthen safeguards activities by offering additional information for improved surveillance measures.

The Next Generation Safeguards Initiative [1], or NGSI, is meant to strengthen international safeguards, coordinate the U.S. safeguards technology programs, and revitalize the U.S. safeguards technology and human capital base. NGSI has five pillars: (1) policy development and outreach, (2) concepts and approaches, (3) technology development, (4) human resources development, and (5) international infrastructure development.

The goal of the 3rd pillar, "technology development", is to enable the IAEA to optimize the use of limited human and financial resources. Its three objectives are to develop advanced tools and methods to detect diversion of declared nuclear materials, develop advanced tools and methods to detect undeclared production or processing of nuclear materials, and provide information analysis solutions to improve state level assessments. It is within this technology development pillar that non-traditional imaging could be added as a new tool set.

From the European perspective, specific tasks from the ESARDA C&S Compendium [2] that warrant exploration of non-traditional imaging are task (1) advise the European Commission and IAEA on new and improved instruments and methods and on areas where R&D effort is still needed, and task (10) study technical characteristics of instruments and devices from other domains (e.g., physical protection) and investigate the possible transfer of technology from these domains to the safeguards area.

So what is non-traditional imaging? The answer crosses multiple physical domains – spatial, spectral band, spectral resolution, time, and direction, to name a few, and thus this introduction will begin with a brief explanation of the limitations of visible imaging.

The visible region of the electromagnetic (EM) spectrum (Figure 1) ranges approximately from 400 to 750 nm. What humans perceive as color is the wavelength dependence of the radiation reflected from an object within this region. Under bright illumination, the human eye has three classes of cone photoreceptors – one for long visible wavelengths (red), one for medium visible wavelengths (green), and one for short visible wavelengths (blue). The limited variations of color that humans see are combinations from those three cones. Conventional visible region digital cameras[1] measure the intensity of optical radiation reflected from a scene on a detector. The source of optical radiation often is broad spectrum, meaning that it contains radiation outside of the visible spectrum. Many detector materials within digital cameras are sensitive to the radiation outside of the visible band as shown in Figure 2; however, filters are often placed on the camera to eliminate this radiation as it causes unwanted effects in the imagery. To image just outside the visible region of the EM spectrum, the filters used on digital cameras are removed. Further away from the visible region, new detector materials and technologies are required – as well as new illumination sources for some EM bands.

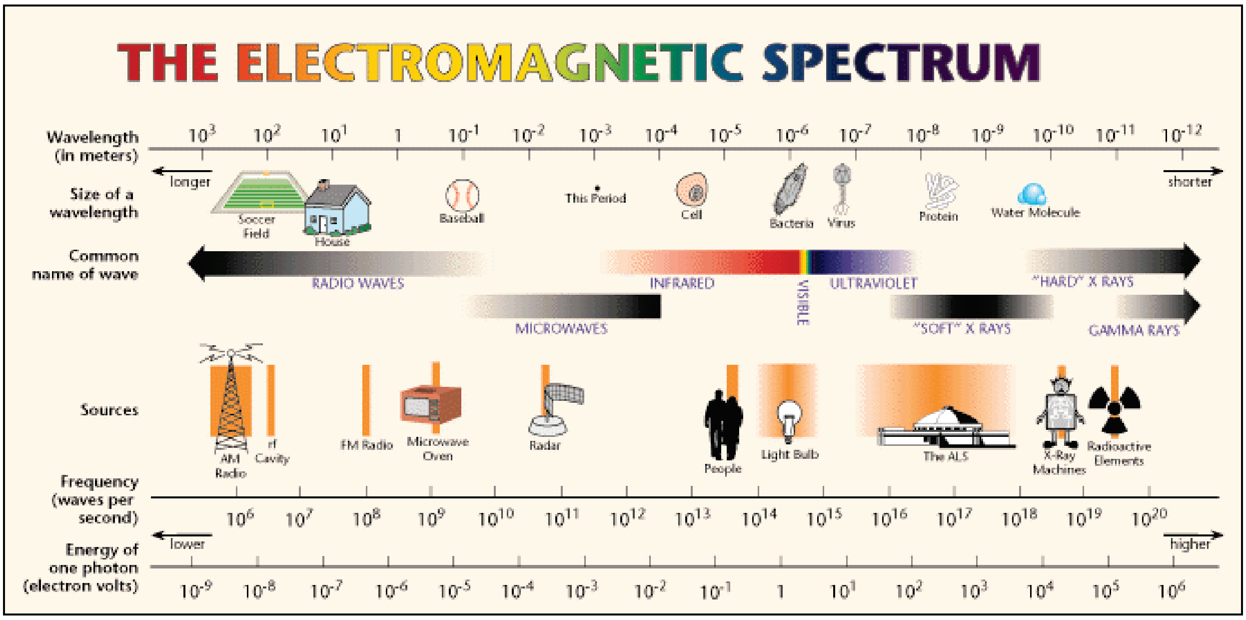

Figure 1: The electromagnetic spectrum (Courtesy: Remote Sensing Tutorial [3]).

[1] Common visible region digital cameras as systems will simply be referred to as digital cameras, although other types of imaging systems use digital technology as well. Detectors for each type of imaging system will be specified in more detail.

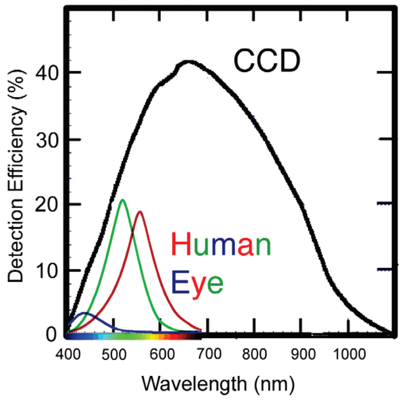

Figure 2: Human eye detection efficiency versus Charge Coupled Devices (CCD) commonly found in digital cameras [4].

2. Imaging Systems across the Electromagnetic Spectrum

2.1. Reflective Infrared

Cameras that provide images in the near infrared (NIR) are sensitive to light just beyond visible red light – wavelengths in the range of 750 to 1000 nm[2]. NIR camera images require some means of illumination either from broad spectrum natural sources such as sunlight, moonlight, night sky light or from active NIR illuminators.

Two detector technologies are most commonly employed to capture images in the NIR – Charge Coupled Devices (CCDs) used in digital cameras and Indium Gallium Arsenide (InGaAs). CCD cameras are sensitive to light in the 350 to 1000 nm range, which overlaps the ultraviolet, visible, and NIR bands. InGaAs cameras are sensitive to radiation in the 900 to 2500 nm (0.9 to 2.5 micron) ranges, but are more common to approximately 1700 nm (1.7 microns).

The performance of a CCD camera in NIR applications is affected by the quantum efficiency (QE) or sensitivity of the imager at NIR wavelengths. Imager relative QE's can range from 0 to 85% in NIR wavelengths as compared with on the order of 100% in the visible spectrum. When selecting a CCD camera for NIR imaging, choosing a camera with high NIR QE provides the best NIR images at the lowest NIR illumination. The QE of CCD cameras tends to be high at the low (visible) end of the NIR spectrum and significantly decreased at the high end of the NIR spectrum. InGaAs cameras exhibit low QE at the low end of the NIR spectrum and higher efficiency at the high end of the spectrum. Figure 3 shows the QE curves of the silicon detector used in CCD cameras versus the InGaAs detector.

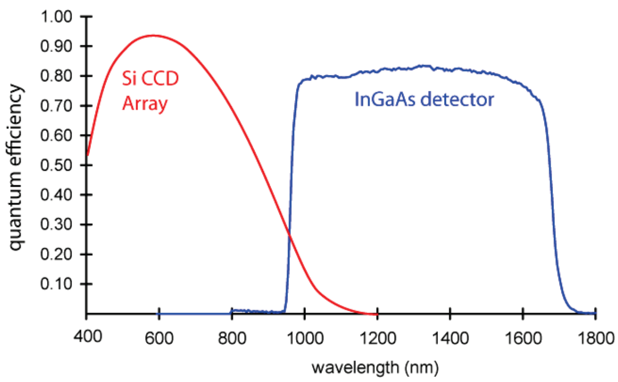

Figure 3: Quantum efficiency (sensitivity) of a silicon detector (CCD) versus InGaAs detector [5].

[2] The numeric values given to regions of the electromagnetic spectrum often depend on the particular application and are both approximate and varied.

NIR sensitive CCD cameras with NIR illuminators are commonly used in physical security applications where discreet observation of a location is required. In interior locations, low power NIR illuminators can provide sufficient illumination to obtain an image similar to that obtained with normal visible room lighting. For safeguards, CCD cameras with NIR illuminators might prove useful in low light applications rather than discreet observation.

Another technology that commonly uses the NIR band is multispectral imaging – particularly for adding NIR capabilities to visible color imagery. One such camera system [6] uses a beam splitter prism to separate light into 4 four CCD sensors, one each for red, green, and blue, and one for the NIR band. The camera is a line scan camera, with 2048 pixels per line requiring image formation by scanning or motion. Applications include fruit and vegetable sorting, food inspection, tiles inspection, print inspection, and PCB inspection. For safeguards, a multispectral line scanner might be useful for item inspection or tamper-indication; a multispectral area camera could be useful for surveillance in low light applications or other applications involving broad differences between visible and NIR (for example, moisture content or seeing through printed material [7]).

The short-wave infrared (SWIR) band ranges from approximately 1000 to 2500 nm. InGaAs cameras can be used above 1.7 microns by varying the fraction of indium in the ternary compound. However, more common detector technologies are HgCdTe (also called MCT) and InSb.

Some applications in the SWIR include low light level imaging, thermal imaging of hot objects (in the 200C to 800C range), vision enhancement, and process control. SWIR is often used for spectral characterization in imaging spectroscopy, which will be discussed later in this paper. These applications may apply to safeguards as well.

2.2. Ultraviolet

The ultraviolet (UV) band extends from 10 to 400 nm, although only the region from 200 to 400 nm is used for imaging because air is opaque below 200 nm. The region from 300 to 400 nm is called the near-UV, and from about 250 to 280 nm the deep-UV. The most common UV illumination sources used for imaging are direct sunlight, gas discharge (black light) lamps, UV LEDs and electronic flash. UV imaging has experienced increased application in recent times due to advances in UV camera hardware technology.

Many CCD cameras used for visible imaging can actually image in the near-UV; however, this is an undesirable feature in visible imagery as the camera cannot simultaneously focus both bands of light and the resulting image would have artifacts such as purple halos around point sources and overall image softening [8]. Because of these effects, CCD cameras employ UV blocking filters. To image in the near-UV, the blocking filters must be removed. The near-UV band can also be transmitted through standard glass lenses; however, the less expensive glass without antireflection coatings has better performance in the near-UV.

Special detectors and lenses are required to image in the deep-UV. The detectors can either use very thin silicon substrates or wave-shifting coatings. Lenses need to be made from quartz (fused silica) or calcium fluorite [8].

There are two approaches for obtaining UV images: reflected UV and UV fluorescence. In reflected UV imaging, the surface of an object is directly illuminated using a UV illumination source. The UV light striking the object’s surface is then reflected or scattered (or even absorbed) and detected by a UV camera. In UV fluorescence imaging, the surface of an object is also illuminated using a UV illumination source. However, the object absorbs the UV excitation and reradiates the light at a longer wavelength for detection by visible or IR cameras.

In reflected UV imaging, features and characteristics of an object can be observed that are not distinguishable using other illumination and camera technologies. UV light is scattered more readily by material surface features than light at longer wavelengths (visible, infrared, and beyond). As shown in Figure 4, a slightly scratched plastic surface will appear smooth when viewed in visible light, but under UV illumination, the scratches become pronounced.

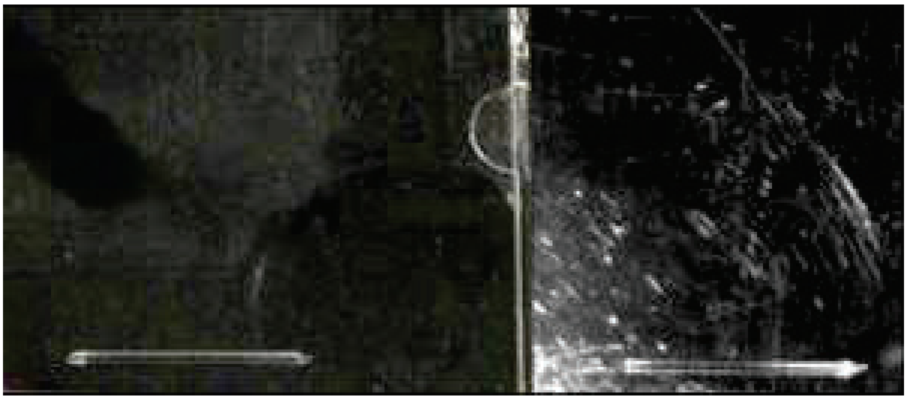

Figure 4: Images of CD jewel case under visible (left) and 365 nm UV light (right) [8].

In a different manner, many materials readily absorb UV light, allowing detection of surface contamination. Furthermore, new and old paints can be distinguished in the UV while appearing identical in the visible spectrum. Figure 5 shows a vehicle that has had its front fender replaced in both visible and near-UV images. The difference in the age of the paint is clear in the UV-image.

Figure 5: The top picture shows a vehicle whose front fender has been replaced imaged in the visible band, and the bottom picture shows the same vehicle imaged in the 320 – 400 nm UV band [8].

UV fluorescence is commonly used in anti-counterfeiting initiatives. Security elements only visible under UV illumination, not in the visible, are incorporated into objects or documents to validate their authenticity. For example, U.S. currency uses UV security threads in its $100 bill [9] which can be verified using a black light, or other UV illumination source. The U.S. state of California has implemented UV photos that fluoresce in the visible band under UV light in their new driver's licenses [10].

For safeguards applications, UV imaging might be useful for tamper indication and equipment authentication. This might be passive or active – scratches can be detected on enclosures, or even organic materials deposited from human contact. Active measures may include embed fluorescent materials into equipment and use UV cameras to detect tampering – perhaps a new approach of more interactive surveilled containment.

2.3. Thermal

The thermal band of the EM spectrum technically ranges from 2.5 to 7 microns for the mid-wave infrared (MWIR) and 7 to 15 microns for the long-wave infrared (LWIR); however, only the regions from 3.3 to 5 microns for MWIR and 8 to 14 microns for LWIR are usable for imaging due to lack of atmospheric transmission in the other regions. Thermal imaging cameras are sensitive to the temperature differences between objects in these regions due to emission of thermal energy.

Thermal imaging has advanced in recent years from a high-cost technology only available to military customers, to ubiquitous detectors available in commercial sectors. In the past, infrared detectors had to be cooled to liquid nitrogen temperatures (77K) to reduce detector noise. New detector materials and other advancements in integrated circuits have allowed for uncooled detectors. Microbolometers are one such type of uncooled detector, and have allowed for small, lightweight, and low power detectors. Uncooled detectors also allowed for large capacity production, and the first commercial applications were for night-time driving aids in BMW vehicles [11].

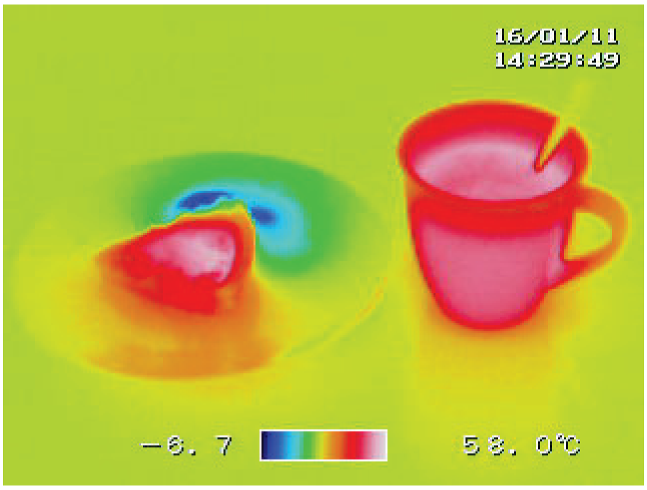

Figure 6: Coffee and apple pie image in the LWIR, using an uncooled detector (microbolometer) commercial thermal imager (Photo courtesy of Pieter Kuiper using an NEC Thermo Shot camera).

Because of the drop in price, thermal imaging is becoming a more affordable option for security and surveillance applications. Standard cameras may rely on auxiliary lighting for illumination, whether from sunlight or active NIR illuminators. Thermal imagers do not require additional illumination as they image differences in temperature from the thermal radiation emission of objects in a scene. This allows for night-time imaging as well as imaging in other poor lighting conditions.

The U.S. Nuclear Regulatory Commission (NRC) has recently required nuclear facilities to provide continuous 24-hour surveillance, observation, and monitoring of their perimeter and control area [12], and thermal imaging is being installed at many facilities for this purpose [11].

Other applications [13] for thermal imaging (including possibly for safeguards) include process control (to monitor quality and safety of plant equipment); analysis of electronics and electrical systems, especially due to overheating or other problems; and analysis of machinery due to heat-producing friction.

Thermal imaging can be used to detect density variations in materials (surface or subsurface non-uniformities or defects to phrase it another way), since continuum heat transfer is impeded by the defects or otherwise affected by density variations [14,15]. Denser materials retain heat longer than less dense materials. Heat can be applied to a scene either through solar loading, or via active means such as brief but intense pulses of light. Infrared cameras are then used to record the surface temperature distribution over time.

For safeguards applications, flash thermography may support safeguards inspections [15] to determine that equipment and facilities are free from tampering and facilities have not been altered.

2.4. Microwave and Millimeter Wave

The microwave and millimeter wavebands have long wavelengths and low energy. The long wavelengths are able to penetrate some materials that visible light cannot since the wavelengths are much longer than the wavelengths of the materials.

The millimeter waveband is defined between 1 and 10 mm. Humans naturally emit enough energy at 3 mm to be detectable, and this energy is able to penetrate clothing. As humans emit this energy through their clothing, any dense objects blocking the energy between the body and a detector will be apparent. Although likely limited for safeguards applications, we mention this as the source of energy is within the long wave bands but still passive.

The rest of this band will require active sources to provide enough energy for detection above terrestrial noise levels. Active microwave sources may generate additional scrutiny by facility operators due to concerns about interference with operator equipment.

The microwave band is from 10 mm to 1 m. Radar technology is within this band, and is well-known for its day/night and all-weather operating conditions. A simple radar system sends out pulses of energy at predetermined intervals. The pulses reflect off of a target, and a portion of the energy is returned to the radar receiver. Geometric and reflecting properties of the target can be estimated from parameters within the returned signal, such as amplitude and frequency. For nonconductive materials, such as vegetation or dry soil, EM waves with long wavelengths are relatively penetrating since their wavelengths are much longer than the material within which they are being transmitted. Ground penetrating radar (GPR) is based on this principle.

There has been discussion about using GPR for Design Information Verification (DIV) in safeguards and thus we provide more detail on this capability [16]. GPR transmits very short pulses into the material, whereupon reflections at dissimilar material boundaries (e.g., steel bars embedded in concrete) return to a collecting/processing system. Generally speaking, GPR operates in the frequency range from 25 MHz (12 m wavelength which falls into radiowaves) to 3 GHz (100 mm wavelength which is in the microwave band). The particular frequency of operation is chosen as a compromise between soil or material penetration depth, object or feature resolution, availability of interference-free frequencies, and antenna and equipment size.

Equipment portability is a key concern when using GPR. Most GPR systems use separate antenna and processing/display systems. This supports multiple frequency ranges, which require different antenna systems, using the same processing unit. For example, a 1600 MHz antenna system provides good resolution of the reinforcing steel in a concrete slab, but a 400 MHz antenna system allows much greater depth of penetration into the material when looking for potential voids below a concrete slab. A separate antenna can also be placed on the material surface, which is needed to couple the maximum amount of energy into and out of the material. Higher frequency systems, i.e., above 800 MHz, are more portable and can be incorporated into a handheld unit. However, these handheld units have a depth of penetration typically less than ½-meter in concrete.

A critical aspect in the practical use of GPR is in the data interpretation. Processed results from current systems are often not intuitive to the novice user, and thus take some training in order to analyze effectively. The processing of a captured time-series of data creates an image on a display that depicts the various layers and objects in the material, subject to the depth and resolution ranges of the frequency and power settings. Figure 7 shows a GPR image of pipes beneath a roadway.

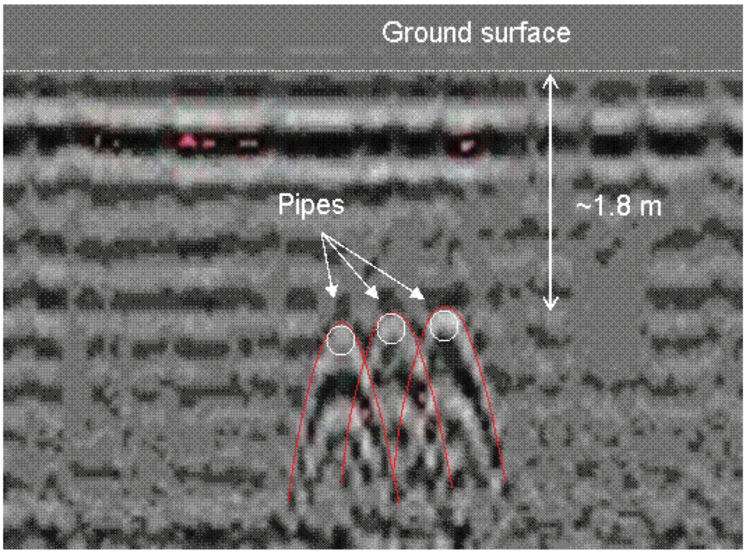

Figure 7: Ground Penetrating Radar (GPR) image of pipes underneath roadway [17].

2.5. X-ray and Gamma rays

X-rays (0.01 – 10 nm) and gamma rays (less than 0.01 nm) are high frequency and high energy, and thus have very short wavelengths. It becomes difficult to measure wavelengths in this region, and thus x-rays and gamma rays are usually referred to by the energy of photons – particles of light that have a particular energy [14].

X-rays and gamma rays can penetrate all materials, and can transfer a significant amount of energy to a localized area producing permanent chemical changes. We saw in section 2.4 that long wavelengths can also penetrate many materials since the wavelength is not on the same order as the material wavelength – however, these long wavelengths cannot image through conductive materials such as water or metals.

X-ray imaging can be used for contraband and anomaly detection – both for imaging through walls and some containers in search of objects as well as human cargo. However, x-ray imaging is typically regulated for human exposure.

Gamma rays occupy the highest energy waveband of the EM spectrum and have highly penetrating properties. They can image where x-rays cannot, such as through steel and other dense materials [14]. Gamma rays are produced by nuclear processes such as radioactive decay.

One method for imaging items inside a steel container [14] is to pass a titanium pellet inside a lead container. The gamma rays are emitted from the lead container through the steel container, and onto x-ray film inside of a light-tight container. Objects from inside the steel container cast shadows onto the x-ray film.

Finally, gamma-ray detectors sensitive to the energy of gamma-ray photons of interest can be used for identification purposes since radioactive materials that emit gamma rays do so at discrete energies. This technique is used in safeguards for identification of different isotopes of radioactive materials for contamination and container contents verification.

3. Acoustic Imaging

Although sound waves[3] are not part of the EM spectrum, we include acoustic imaging due to its ability to image underwater. Under ideal conditions it is difficult to see an object more than 50 m away underwater with visible light [14]. Any deviation from ideal conditions results in drastically worse resolution. High resolution sonar imaging sends an active pulse of sound using a transducer that will also act as the sound receiver. The geometry of the target modifies the shape of the return pulse, while the density of the target affects the strength of the return pulse. The time it takes the pulse to reach the target and return to the transducer determines the distance. The image resolution will depend on the wavelength of the acoustic pulse. One example [14] is a sonar system that uses acoustic pulses with wavelengths of a few millimeters that can resolve features on the order of 20 cm at an imaging range of 100 m.

A search of imaging sonar revealed commercial companies [18] with technologies able to provide high resolution imagery up to 2250 kHz. Figure 8 shows an 11” garden block underwater. The camera is forward-looking, with a slight downward angle.

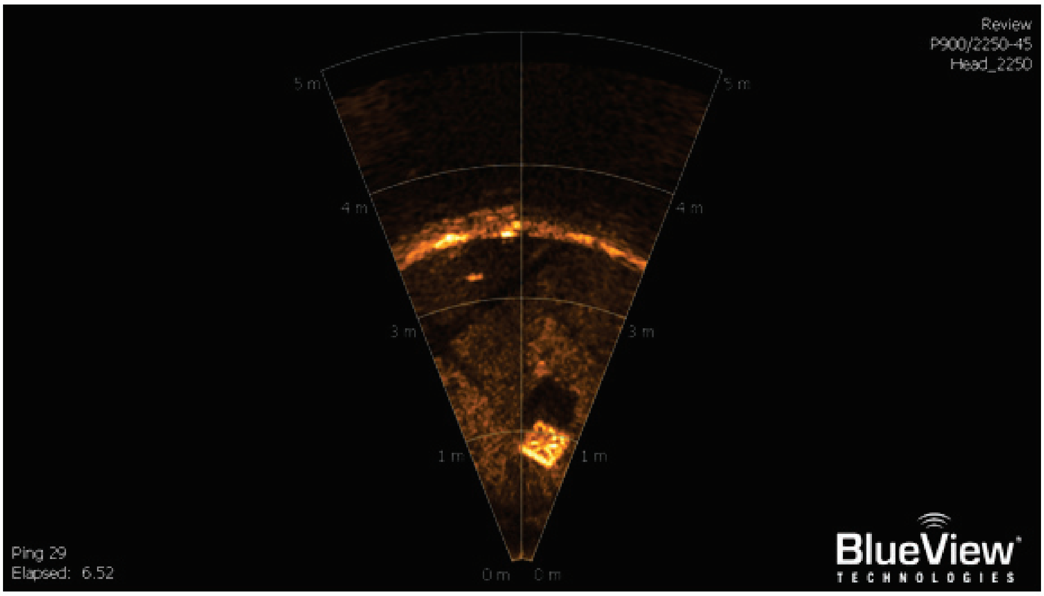

Figure 8: 2D sonar imaging using 2250 kHz sound pulses [18].

Any use of imaging sonar cameras in radiation environments, perhaps such as spent fuel ponds in safeguards applications, would require proper radiation tolerant camera housings. There are many radiation tolerant cameras, housings, and accessories such as lighting available in the commercial sector, including those required for underwater applications.

4. Imaging Spectroscopy

To this point, we have surveyed regions of the EM spectrum, but have not discussed the spectral resolution within these regions. The process by which photons interact with materials (via reflection, scattering, absorption, transmission, and/or emission) varies with wavelength. With enough spectral resolution of a sensor, objects can be characterized by a “spectral signature” – that is the dependence of photons returned to the sensor on wavelength. Figure 9 demonstrates the concept of imaging spectroscopy, or hyperspectral imaging, from a NASA airborne sensor named AVIRIS. A good tutorial on imaging spectroscopy can be found at [19].

[3] Light is composed of transverse waves in an electromagnetic field and requires no medium to travel. Sound is composed of longitudinal waves and requires a sufficient medium (solid, liquid, or gas) to travel.

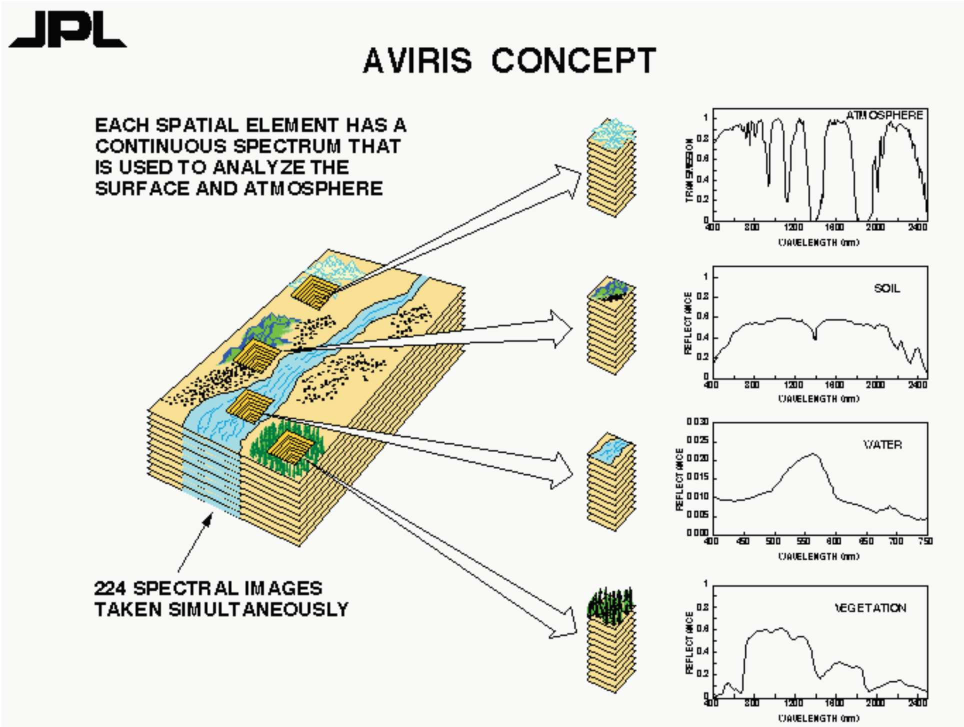

Figure 9: Imaging spectroscopy, or hyperspectral imaging, allows stand-off material analysis. This conceptual figure appears at [20].

Imaging spectroscopy has been used in both laboratory environments as well as remote sensing environments. Commercial applications for interior imaging or surveillance (similar to that of digital camera systems) have not been common due to the high computing and post-processing requirements of hyperspectral image cubes. Hyperspectral images contain not only two-dimensional spatial values, but also hundreds of spectral bands associated with each pixel location. As shown in Figure 9, a separate image can be shown in each spectral band, or spectral analysis can be performed at every pixel. Hyperspectral imaging provides powerful capabilities for analysis, and often is called remote chemistry.

A survey of current commercial spectral cameras returns several companies [21,22] that provide capabilities from the UV through LWIR. These companies list applications as material or chemical identification, color measurement, machine vision, gas and chemical detection, moisture profiling, and counterfeit detection. For safeguards, any of these applications could be considered. Another possibility would be the ability to purposefully embed “tags” into materials and use spectral cameras for tag verification [23], equipment authentication, or tamper-indication.

5. Polarization

Another optical field that is underutilized is polarization. Polarization can provide information about surface features, shape, shading, and roughness [24]. This information is largely uncorrelated with spectral and intensity images, and thus has the potential to enhance features.

One particular use for polarimeters has been for underwater imagery to mitigate the effect of scattering of light by the water. A polarization analyzer can be put in front of a digital camera and the polarization state can be adjusted to maximize the contrast between the object and background [24].

Figure 10: Reflection of cloud removed on water surface using polarizer filter.

In photography, polarizing filters are used to reduce reflections, as well as seeing through windows and water, as shown in Figure 10.

Polarimeters are also used in industry for sample characterization and evaluation. Specifically, polarimeters are used in the glass and sugar industry, the food industry, and in pharmaceuticals to look for chirality of molecules.

For safeguards applications, polarization might be used for tamper indication, equipment authentication, or for imaging through water, windows, high-reflection conditions, or where uncorrelated optical information is beneficial. There are many new research opportunities in polarization, and new applications and capabilities may emerge.

6. Conclusions

Imaging based on radiation from the visible band of the EM spectrum is one of many imaging technologies available. Furthermore, within bands of the EM spectrum, technologies are available to make use of other optical information, such as increasing the spectral resolution to enable imaging spectroscopy and utilizing polarimetric information. Even acoustic imaging, although not part of the EM spectrum, is an available technology for imaging applications.

These technologies are currently and commonly applied in fields other than safeguards. For instance, imaging spectroscopy is common in airborne geological surveys. Physical protection uses NIR illuminators for low-light applications. Thermal imaging is used in process control and now more recently by nuclear facilities for physical protection.

As resource management becomes more critical in safeguards, adaptation of technologies common to other industries could have the potential to provide improved technologies or even complimentary surveillance with less research costs funded directly by the safeguards community.

Not every technology in this survey paper will be applicable to safeguards. It is the hope, however, that this survey paper will provide enough background to spark interest and perhaps focused-research for safeguards applications in these technologies.

7. Acknowledgements

Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

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