Oil Spill Remote Sensing: A Brief Review of Airborne and Satellite Sensors*

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Abstract

The Emergencies Science Division (ESD) of Environment Canada, (Canadian government department), is responsible for remote sensing during oil spill emergencies along Canada's three coast lines, vast system of inland waterways, as well as over the entire land mass. In addition to providing operational remote sensing, ESD conducts research into the development of airborne oil spill remote sensors, including the Laser Environmental Airborne Fluorosensor (LEAF) and the Laser Ultrasonic Remote Sensing of Oil Thickness (LURSOT) sensor. ESD's Remote Sensing Group has vast experience in the remote sensing of oil spills. One of the tools which can be used for strategic planning when responding to an oil spill are satellite images. These images cover large areas of terrain and are available at several wavelengths across the electromagnetic spectrum. Environment Canada has used multi-spectral Landsat and SPOT satellite data in response to two recent oil spill emergencies; the 1989 Exxon Valdez oil spill and the recent pipeline spill in the Komi Republic (1994). In the visible region of the spectrum, oil has no specific characteristics distinguishing it from the background water. Thus visible techniques are generally restricted to documentation because of the lack of a positive oil detection mechanism. On land the situation is not quite as bad, however water can again complicate the issue. In the case of the oil spill in the Komi Republic, before and after images indicate changes following heavy rainfall and the bursting of oil retaining dams. We have however been unable to distinguish between several new features in the later image. These new features may be oil, water or a mixture of the two. Without ground truthing activities, the nature of these new features can only be speculative.

In addition to a discussion of Environment Canada's experience with satellite imagery in response to oil spills, this paper will briefly review airborne and satellite sensors used by the oil spill remote sensing community. The benefits and disadvantages of each type of sensor will be outlined.

1.0 Introduction

Remote sensing is becoming an increasingly important tool for the effective direction of oil spill countermeasures. Spill cleanup personnel have recognized that remote sensing can increase spill cleanup efficiency. The general public expects that the government and/or the spiller know the location and extent of the contamination. Recent advances in electronics have made instrumentation more capable and less expensive.

By definition, remote sensing implies that a sensor, other than the eye, is used to detect the target of interest at some distance. The most common form of remote sensing as applied to oil spills is airborne remote sensing - that is using aircraft as a platform. Visual observation - regardless of the platform used, is by definition, not remote sensing.

2.0 Optical Techniques

2.1 Visible Sensors

The most common means of remote sensing is by optical techniques. Cameras, both still and television, are common because of their low price. Several cameras are commercially available (O'Neil, Neville and Thompson, 1983; Bercha, 1984). In recent years, visual or camera observation has been enhanced by the use of GPS (Global Positioning Systems) (Lehr, 1994).

In the visible region of the electromagnetic spectrum (approximately 400 to 700 nm), oil has an increased surface reflectance above that of water, but also shows limited non-specific absorption tendencies. Oil has a general

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manifestation throughout this spectrum. Sheen shows up silvery and reflects light over a wide spectral region down to the blue. There is no strong information in the 500 to 600 nm region, so this region is often filtered out, to improve contrast (Sherman, 1992). Overall, however, oil has no specific characteristics which would help distinguish it from the background. Taylor (1992) studied oil spectra in the laboratory and in the field and observed flat spectra with no useable features distinguishing it from the background. Therefore, techniques of separating specific spectral portions provides no increased detection capability. It has been found that high contrast in visible imagery can be achieved by setting the camera at the Brewster angle (53 degrees from vertical) and using a horizontally-aligned polarizing filter which passes only that light reflected from the water surface. It is this component that contains the information on surface oil (O'Neil, Neville and Thompson, 1983). This technique has been reported to increase contrast by up to 100%. Filters having band-pass below 450 nm may also be used to improve contrast.

Television cameras are often used in conjunction with filters to improve the contrast, in a manner similar to that noted for photographic cameras. This technique has had limited success for oil spill remote sensing because of poor contrast and lack of positive discrimination. New light-enhancement technology (low lux) permits television cameras to operate even in darkness.

Scanners are often used as sensors in the visible region of the spectrum. A rotating mirror or prism sweeps the field-of-view and directs the light to a detector. Prior to the advent of CCD (charge coupled device) detectors this sensor provided much more sensitivity and selectivity than a television camera. Another advantage of using scanners is that signals can be digitized and processed before display. Recently, newer technology has evolved and similar digitization can be achieved without scanning by using a CCD imager and continually recording all elements, each of which is directed to a different field-of-view on the ground. This type of sensor is known as a push-broom scanner. The advantages of this technology over the older scanning types are many. Several types of aberrations and errors can be overcome, the units are more reliable than mechanical ones, and all data are collected simultaneously for a given line perpendicular to the direction of flight of the aircraft. Several types of scanners have been developed recently. In Canada, the MEIS (Multi-spectral Electro-optical Imaging Scanner) was developed (O'Neil, Neville and Thompson, 1983) and the CASI (Compact Airborne Scanner Instrument) (Palmer, Borstad and Boxall, 1994) and in Holland the Caesar system (Wadsworth, Looyen *et al.*, 1992). These instruments do not offer a distinct advantage over cameras for oil spill work.

The use of visible techniques in oil spill remote sensing is, to a great extent, restricted to documentation of the spill due to the lack of a positive oil detection mechanism. Furthermore, many interferences (false alarms) exist. Sun glint and wind sheens can be mistaken for oil sheens. Biogenic material such as surface weeds or sunken kelp beds can be mistaken for oil. Oil on shorelines is difficult to identify positively because weeds can have similar appearance and oil on darker shorelines cannot be detected. In summary, utility of the visible spectrum for oil detection is limited. It does, however, offer economical means of documenting spills and means of providing baseline data on shorelines or relative positions.

2.2 Infrared Sensors

Optically-thick oil absorbs solar radiation and re-emits a portion of this radiation as thermal energy largely in the 8-14 μm region. Thick oil appears hot in infrared images, intermediate thicknesses appear cool, and thin oil (sheen) is not detectable. The thicknesses at which these transitions occur are not known, but evidence indicates that the transition between the hot and cold layer lies between 50 and 150 microns and that the minimum detectable layer is between 10 and 70 microns (Hurford, 1989; Goodman, 1989; Belore, 1982; Neville, Thompson *et al.*, 1979). The reason for the appearance of the "cool" slick is not fully understood. One theory is that the evaporative cooling of the slick exceeds its radiative heating at a certain thickness and thus appears cool compared to the surrounding water. Another and more plausible theory, is that a moderately thin layer of oil on the water surface causes destructive interference of the thermal radiation waves emitted by the water, or in some other way attenuates this signal, thereby reducing the amount of thermal radiation emitted by the water.

Infrared cameras are now very common and commercial units are available from several manufacturers. In the recent past, scanners with infrared detectors were largely used. Infrared detectors of any type suffer from the disadvantage that their detectors require cooling to avoid thermal noise, which would overwhelm any useful signal.

The traditional method of cooling the detector was by using liquid nitrogen. This generally gives about 4 hours of service. New, smaller sensors use closed-cycle coolers or Joule-Thompson coolers which take advantage of the cooling effect realized when a gas is expanded. This type of cooling implies that a gas cylinder or compressor can be transported with the sensor but refills or servicing may not be required for days at a time (Goodman 1988).

Most infrared sensing of oil spills takes place in the thermal infrared (8-14 μm). One sensor which is designed as a fixed-mounted unit uses the differential reflectance of oil and water at 2.5 and 3.1 μm (Seakem, 1988). Tests of a mid-band IR system (3.4-5.4 μm) over the TENYO MARU oil spill showed no detection in this range, however ship scars were visible (Rogne and Smith, 1992; Rogne, Macdonald *et al.*, 1992, Kennicutt, MacDonald *et al.*, 1992). Specific studies in the thermal infrared (8-14 μm) shows there is no spectral structure in this region (Salisbury, D'Aria and Sabins, 1993). Tests of a number of infrared systems show that spatial resolution is extremely important when the oil is distributed in windrows and patches; that emulsions are not always visible in the IR and that 3-5 μm cameras have marginal utility (Hover, 1994).

The relative thickness information in the thermal infrared can be used to direct countermeasures equipment to thicker portions of the slick. Oil detection in the infrared is not positive, since several false targets can interfere - including weeds, shoreline, and oceanic fronts. Infrared is, however, reasonably inexpensive and is currently the prime tool used by the spill remote sensor operator.

2.3 Ultraviolet Sensors

Oil slicks display high reflectivity of ultraviolet (UV) radiation even at thin layers (<0.01 μm). Therefore, ultraviolet sensors can be used to map even sheens of oil. Overlayed ultraviolet and infrared images are often used to produce a relative thickness map of oil spills. Ultraviolet cameras, although inexpensive, are not used to a great extent because it is difficult to overlay camera images (Goodman, 1988). Infrared scanner data and that derived from push-broom scanners allow for the easy superimposition of data and the production of IR/UV overlay maps. Ultraviolet data are also subject to many interferences (false images) such as wind slicks, sun glints, and biogenic material. Since these interferences are often different than those for infrared sensing, the combination of IR and UV can provide a more positive indication of oil than the use of either technique alone.

3.0 Fluorosensors

Laser fluorosensors are active sensors which take advantage of the fact that certain compounds in petroleum oils absorb ultraviolet light and become electronically excited. This excitation is rapidly removed through the process of fluorescence emission, primarily in the visible region of the spectrum. Since very few other compounds show this tendency, fluorescence is a strong indication of oil presence. Natural fluorescing substances such as chlorophyll, fluoresce at sufficiently different wavelengths to avoid confusion. Different types of oil yield a slightly different fluorescent intensities and spectral signatures. It is possible to differentiate between classes of oil under ideal conditions (Hengstermann and Reuter, 1990; Fruhwirth, Fingas and Brown, 1994; Brown, Fruhwirth, Wang, *et al.*, 1994; Brown, Wang, *et al.* 1994).

Most laser fluorosensors used for oil spill detection employ a laser operating in the ultraviolet region between 300 and 355 nm (Diebel, Hengstermann, *et al.*, 1989; Geraci, Landolina *et al.*, 1993). With this wavelength of activation, there exists a broad organic matter fluorescent return, centred at 420 nm. This is referred to as Gelbstoff or yellow matter, which can be easily annulled. Chlorophyll yields a sharp peak at 685 nm. Crude oil fluorescence return is in the region between 400 to 550 nm with peak centres in the 480 nm region. There also exists a phenomenon known as Raman scattering, which involves energy transfer between the incident light and the water molecules. The water molecules can absorb some of the energy as rotational-vibrational energy and return the light as the incident energy, less this energy of rotation or vibration. The water, the Raman signal occurs at 344 nm when the incident wavelength is 308 nm (XeCl laser). The water Raman signal is useful for maintaining calibration of the fluorosensor in operation, but has also been used in a limited way to estimate oil thickness, because the strong absorption by oil on the surface will suppress the water Raman signal in proportion to thickness (Hoge and Swift, 1980). The point at which the Raman signal is entirely suppressed depends on the oil type, since each oil has a different absorption strength.

It is also possible to use oil fluorescence on a person-portable scale. Work has been undertaken to develop a hand-held UV light to detect oil spills at night at short range (Fingas, 1982). Another related instrument is the "Fraunhofer Line Discriminator" which is essentially a passive fluorosensor using solar irradiance instead of laser light (O'Neil, Neville and Thompson, 1983). This instrument did not attain great success because of the limited discrimination and the low signal-to-noise ratio. Laser fluorosensors are thought to have significant potential for the future because they may be the only means to discriminate between oiled and un-oiled weeds and detecting oil on a variety of beach types. Tests on shorelines show that this technique has been very successful (Dick, Fruhwirth and Brown, 1992). Additionally, the sensor offers the only means of reliable detection of oil in certain ice and snow situations.

4.0 Radar and Microwave

4.1 Radar

Capillary waves on the ocean reflect radar energy producing a "bright" image known as sea clutter. Oil on the sea surface damps some of these capillary waves. Thus, the presence of an oil slick can be detected as a "dark" sea or one which has an absence of this sea clutter. Unfortunately oil slicks are not the only phenomenon which is detected in similar manner. Interferences (false targets) are many and include fresh water slicks, wind slicks (calms), wave shadows behind land or structures, weed beds which calm the water just above them, glacial flour, biogenic oils, whale and fish sperm (Frysinger, Asher *et al.*, 1992; Alpers and Hühnerfuss, 1987; Poitevin and Khaif, 1992; Hühnerfuss, Alpers and Witte, 1989). Because of the number of these interferences, radar can be ineffective in locations such as in Prince William Sound, Alaska where the dozens of islands, fresh water inflows, ice, and other features produce hundreds of false targets. Despite these limitations, radar is an important tool for oil spill remote sensing because it is the only sensor which can be used for large area searches, and because it is one of the few sensors that can "see" at night and through clouds or fog. Radars have strong disadvantages because of the many false targets and the high cost of the sensor.

There are two basic types of radars that have application to oil spills and environmental remote sensing in general, Synthetic Aperture Radars (SARs) and Side-Looking Airborne Radars (SLARs). The latter is an older technology, less expensive, and employs a long antenna to achieve spatial resolution. The synthetic aperture radar uses the forward motion of the aircraft to synthesize a very long antenna, thereby achieving very good spatial resolution (which is range independent) at the expense of sophisticated electronic processing. SARs are inherently more expensive, however they are capable of more range and greater resolution than SLARs. Comparative tests show that SAR is vastly superior (Mastin, Mason *et al.*, 1994). Search radars such as those frequently employed by the military have no application to oil spills because they usually remove the clutter signal. Thus, the primary signal of interest is deleted. Furthermore these radars have signal processing optimized to pinpoint small, hard (to radar signals) objects such as periscopes. This signal processing is very detrimental to oil spill detection.

Experimental work on oil spills has shown that X-band radar yields better data than L or C band radar (Intera, 1984; C-CORE, 1981). It has also been shown that antenna polarizations of vertical for transmission and vertical for reception (V,V) yields better results than other configurations (Bartsch, Grüner *et al.*, 1987; Macklin, 1992; Kozu, Umehara *et al.*, 1987; Madsen, Skou and Sorenson 1994). Radar is limited by sea state as well, sea states which are too low will not produce sufficient sea clutter in the surrounding sea to contrast to the oil and very high seas will scatter radar sufficiently to block detection inside the troughs. Indications are that wind speeds of at least 1.5 m/s (~3 knots) are required as a minimum to allow detectability and a maximum of 6 m/s will again remove the effect (Wisman, Alpers *et al.*, 1993; Hielm, 1989). This limits the environmental window of application of radar for oil slick detection.

Ship radars suffer from similar limitations and have the additional handicap of low altitude that restricts their range to between 8 to 30 km, depending on antenna height. Ship radars can be adjusted to reduce the effect of sea clutter de-enhancement. Ship-borne radars were successfully used at 8 km to detect a surface slick in the Baltic Sea and during a trial offshore Canada at a maximum range of 17 km (Tennyson, 1985). The technique is very limited by sea state and, in all cases where it was used, the presence and location of the slick was already known.

In summary, radars optimized for oil spills can fulfill a useful role in oil spill remote sensing, in particular for large area searches and for night-time or foul weather work. The technique is highly prone to false targets and is limited to a narrow range of wind speeds.

4.2 Microwave Scatterometers

A microwave scatterometer is a device that measures the scattering of microwave or radar energy by a target. The presence of oil reduces the scattering of the microwave signals just as it does for the radar sensors and thus suffers from the large number of interfering factors noted above. One radar scatterometer was flown over several oil slicks and employed a low-power transmitter operating in the Ku band (13.3 GHz) (O'Neil, Neville and Thompson, 1983). The "Heliscat", a device with four frequencies has been used to investigate capillary wave damping (Wisman, Alpers *et al.*, 1993). The advantage of this type of sensor is that it has a similar aerial coverage to optical sensors and operates in a nadir geometry (looks straight down). The main disadvantages of microwave scatterometers include the lack of discrimination for oil and the lack of imaging capability.

4.3 Microwave Radiometers

The ocean is an emitter of microwave radiation. Oil is a strong emitter of microwave radiation compared to water and thus appears as a bright object on a darker sea. Water has an emissivity factor of 0.4 whereas oil has one of 0.8 (O'Neil, Neville and Thompson, 1983; Ulaby, Moore and Fung, 1989). A passive device can detect this emissivity difference and could provide a detection means for oil. In addition, there is a signal change with thickness and, in theory, the device could measure thickness. This detection method has not resulted in great success in the field. To begin with, the methodology depends on knowing several environmental and oil specific parameters. Secondly, the signal return is dependant on oil thickness but in a cyclical fashion. A given signal strength can imply any one of two or three signal film thicknesses within a given slick. The emission of microwave energy is a maximum when the effective thickness of the oil equals an odd multiple of one quarter of the wavelength of the observed energy. Biogenic materials also interfere and the signal-to-noise ratio is low. In addition, high spatial resolution is difficult to achieve (Goodman, 1994). The Swedish Space agency has done some work with different systems, a dual band, 22.4 and 31 GHz, device, and also with a single band 37 GHz device (Fäst, 1986). Skou, Sorensen and Poulson (1994) describe a 2-channel device with 37.5 and 10.7 GHz. Mussetto, Yujire *et al.* (1994) described the tests of a 44-94 and 94-154, 2-channel devices over oil slicks. They showed that correlation with slick thickness is poor and suggest that other factors other than thickness also change surface brightness. They suggest that a single channel device might be a useful instrument just to give an all-weather relative-thickness instrument. Literature describes the tests of single-channel devices over oil slicks, 36 GHz (Zhifu and Wiesbeck, 1988) and an 90 GHz device (Süss, Grüner and Wilson, 1989).

In summary, passive microwave radiometers may offer potential as an all-weather oil sensor. Its potential as a reliable slick thickness measurement device is questionable.

5.0 Slick Thickness Sensors

There has long been a need to measure oil slick thickness, both within the oil spill response community and among academics in the field. There are presently no reliable methods, either in the laboratory or in the field to provide an accurate measure of oil-on-water slick thickness. The ability to measure oil slick thickness would provide significant advances to the basic understanding of the dynamics of oil spreading and behaviour. Knowledge of slick thickness would allow for more effective oil spill countermeasures including dispersant application and in situ burning. Indeed, the effectiveness of individual dispersants could be determined quantitatively with accurate measurements of the oil remaining on the water surface following dispersant application (Goodman and Fingas, 1988). Finally, there is a need to calibrate some of the more economical and readily available pieces of remote sensing equipment. Several of these sensors provide relative, ie. thick or thin, indications of slick thickness. Calibration of these wide field-of-view sensors would provide a reliable method of estimating the volume of rogue oil slicks. Aircraft surveillance of slicks often results in erroneous oil quantity estimates.

The suppression of the water Raman peak in laser fluorosensor data discussed above has not been exploited or tested fully. This technique may work for thin slicks, but not for thick ones, at least not with a single excitation frequency. Attempts to calibrate the thickness appearance of infrared imagery have been made, but also have not been successful. It is suspected that the temperatures of the slick as seen in the IR are highly dependent on oil type, sun angle and weather conditions. If this is the case, it may not be possible to use IR as a calibrated thickness measurement tool. Accurate surface methods do not exist, therefore the calibration of existing equipment is very difficult (Brown and Goodman, 1986). The use of sorbent techniques to measure surface thickness yields highly variable results (Goodman and Fingas, 1988). As noted in the section on microwave radiometers, the signal strength as measured by these instruments can imply one of several thicknesses. This methodology does not appear to hold promise for other than relative oil thickness measurements.

A variety of electrical, optical and acoustic techniques have been investigated in an attempt to measure oil thickness (Reimer and Rossiter, 1987). Two promising techniques were pursued in a series of laboratory measurements. The first technique is known as "thermal mapping" (Aussel and Monchalin, 1989). In this technique, a laser is used to heat a region of oil and the resultant temperature profiles created over a small region near this heating are examined using an infrared camera. The temperature profiles created are dependant on the oil thickness. A more promising technique involves laser acoustics (Krapez and Cielo, 1992; Choquet, Héon *et al.*, 1993). This system, known as the Laser Ultrasonic Remote Sensing of Oil Thickness (LURSOT) sensor, is comprised of three lasers with one of the lasers coupled to a Fabry-Pérot interferometer to accurately measure oil thickness (Choquet, Héon, *et al.*, 1993, Brown, Fruhwirth, Fingas, *et al.*, 1994). The sensing process is initiated with a thermal pulse created in the oil layer by the absorption of a powerful CO_2 laser pulse. Rapid thermal expansion of the oil occurs near the surface where the laser beam was absorbed. This causes a step-like rise of the sample surface as well as an acoustic pulse of high frequency and large bandwidth (~ 15 MHz for oil). The acoustic pulse travels down through the oil until it reaches the oil-water interface where it is partially transmitted and partially reflected back towards the oil-air interface where it produces a slight displacement of the oil surface. The time required for the acoustic pulse to travel through the oil and back to the surface again is a function of the thickness and the acoustic velocity of the oil. The displacement of the surface is measured by a second laser probe beam aimed at the surface. Motion of the surface induces a phase or frequency shift (Doppler shift) in the reflected probe beam. This phase or frequency modulation of the probe beam can then be demodulated with a confocal Fabry-Pérot interferometer (Monchalin, 1986). The thickness can be determined from the time of propagation of the acoustic wave between the upper and lower surfaces of the oil slick. This is a very reliable means of studying oil thickness and offers great potential. A consortium of agencies including Imperial Oil Canada, Environment Canada, and the United States Minerals Management Service is pursuing the technology. Laboratory tests have confirmed the viability of the method and a test unit will be flown to confirm the operability of the concept.

6.0 Satellite Remote Sensing

Although this paper has focussed on airborne remote sensing, a brief discussion of satellite remote sensing is warranted. There exists a strong movement that suggest that satellite remote sensing could replace airborne remote sensing. This myth will be dispelled in this section. The use of satellite remote sensing for oil spills has been attempted several times. The slick from the IXTOC I well blowout in Mexico was detected using GOES and also by the AVHRR (Advanced Very High Resolution Radiometer) on the LANDSAT satellite (O'Neil, Neville and Thompson, 1983). Subsequently a blowout in the Persian Gulf was detected. The massive EXXON VALDEZ slick was detected on SPOT satellite data (Dean, Stringer, *et al.*, 1990); Oiled ice in Gabarus Bay resulting from the KURDISTAN spill was detected using LANDSAT data (Dawe, Parashar *et al.*, 1981; Alfoldi and Prout, 1982). Several workers were able to detect the Arabian Gulf War Spill in 1991 (Cross, 1992; Rand, Davis *et al.* 1992; Al-Ghunaim, Abuzar and Al-Qurnas, 1992; Al -Hinai, Khan *et al.*, 1993). The HAVEN spill near Italy was also monitored (Cecamore, Ciappa and Perusini, 1992). A 'spill' in the Barents sea was tracked using an IR band on NOAA 10 (Voloshina and Sochnev, 1992). It is significant to note that in all cases the position of the oil was known and in all cases, data processing was required to see the oil. This processing usually lasted several weeks.

There are several problems associated with a reliance on satellites for oil spill remote sensing. The first is the frequency with which overpasses occur (Clark, 1989). The second is the absolute reliance on clear skies to perform optical work. These two factors combined can give a very low probability of seeing a spill on a satellite image. This point is well illustrated in the case of the EXXON VALDEZ spill (Noerager and Goodman, 1991). Although vast amounts of ocean were covered by the oil spill for over a month, there was only one clear day that coincided with a satellite overpass, that on April 7, 1989. The third disadvantage of satellite remote sensing is the difficulty in developing algorithms to highlight the oil slicks and the long time required to do so. It took over two months in the case of the EXXON VALDEZ spill before the first group managed to "see" the oil slick in the satellite imagery, although its location was precisely known.

In it's present state, optical satellite imagery does not offer much potential for oil spill remote sensing. New radar satellites including; ERS-1 (and soon ERS-2), RADARSAT-1, and JERS-1 may offer some potential for large offshore spills. Limited testing with ERS-1 has shown that many false signals are present in most scenes (Wahl, Eldhuset and Skoelv, 1993; Bern, Wahl *et al.*, 1993). These satellite systems will not replace airborne remote sensing in the near future.

7.0 Spot Satellite Imagery From the Komi Region Oil Pipeline Spill

SPOT satellite multi-spectral images were acquired from SPOT Image Corporation for the times prior to and following reported major oil pipeline leaks in the region of the Komi Republic, Russia, north of the city of Usinsk. The images acquired were from July 17, August 22, and November 3, 1994 respectively. These scenes

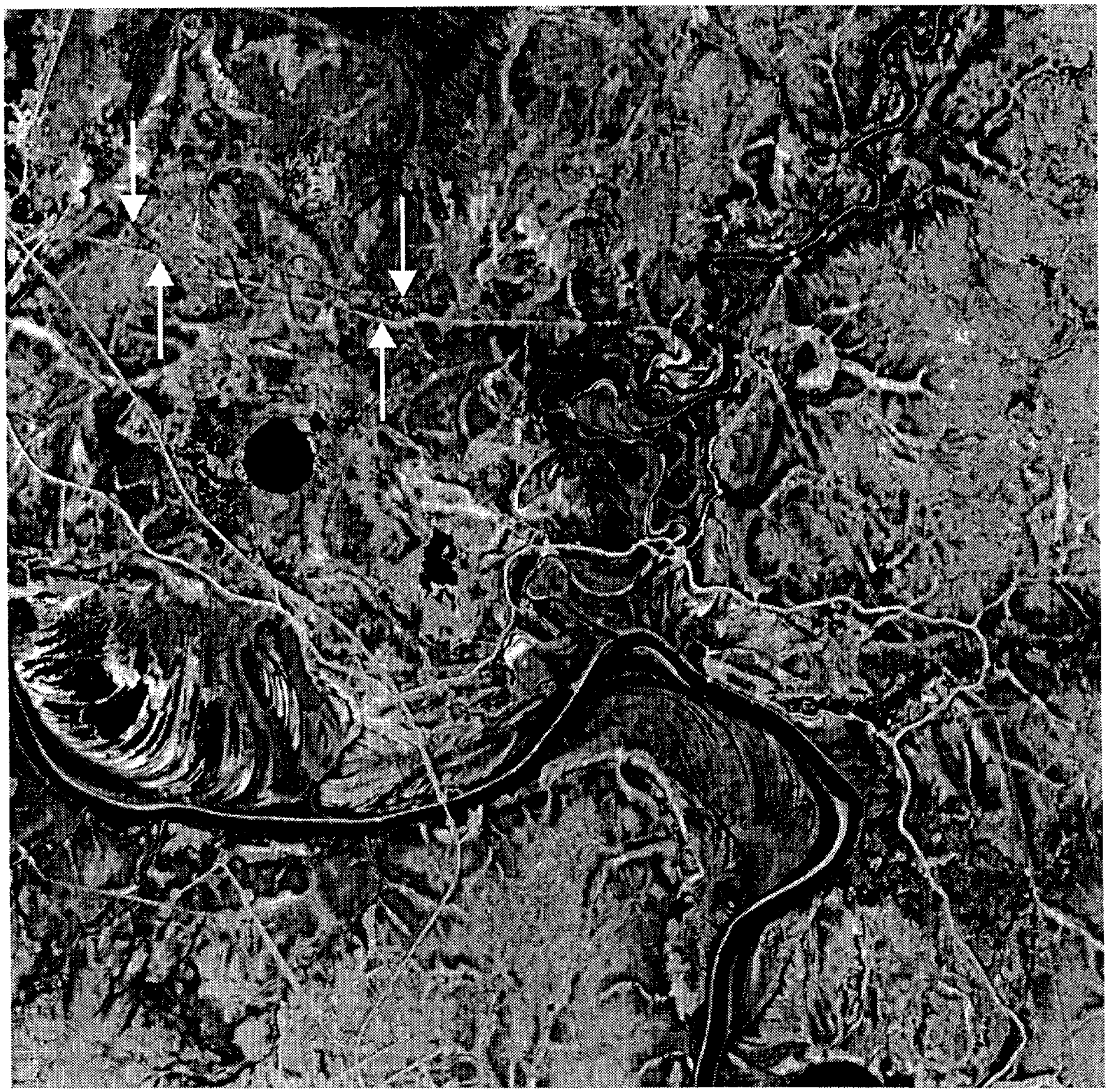

Figure 1. SPOT multi-spectral image of pipeline in Komi Republic, acquired July 17, 1994. Arrows indicate position of two pipelines.

Figure 2. SPOT multi-spectral scene of pipeline in Komi Republic, acquired August 22, 1994. Horizontal arrow points to fen (lake), other arrows point to dark feature around pipeline which is not observed in the July 17th scene.

were of high quality and free from cloud cover in the areas of interest. Comparison of the July 17th and August 22nd scenes reveals a few changes in the areas immediately beside the pipeline. In the time period between the two data sets, a great deal of rain had fallen in the Komi Republic which may have resulted in large amounts of water being held back in earthen berms built to contain the spilled oil. As indicated earlier in the discussion of airborne optical techniques, there are no spectral features which can be used to distinguish oil from water in the visible region of the spectrum. Thus it would be difficult, if not impossible, to differentiate between oil and water in the SPOT multi-spectral scenes by direct comparison of scenes before and after the major spill. A section of the July 17th image is shown in Figure 1, likewise a section of the August 22nd image is shown in Figure 2. In the August 22nd image one can observe a large dark region to both the north and south of the east-west running pipeline. This new feature is most probably water, oil or a mixture of both. A comparative examination of the intensities of the three spectral bands in the pixels associated with this new feature and the fen (lake) to the southeast reveals essentially no difference between these two features as expected. Comparison of the spectral properties of this feature with other similar looking features in either scene likewise find no great differences. Therefore it is not possible to positively locate oil in the later scene (August 22). Canadian members of a United Nations delegation that travelled to the Komi Republic to observe the spill were not permitted to go near the site of the major spill, therefore the exact coordinates and extent of the spill remain a source of conjecture at this time. Other workers have examined the same images and indicated "Spills were not identified with a high degree of confidence using classification of SPOT imagery due to the overlap in the spectra of oil and water in that region of the electromagnetic spectrum" (Chadwick, Bolus *et al.* 1995). The November 3rd scene was acquired after heavy rains had burst the dams holding back the oil and water, however due to the poor weather and cloud cover in the ensuing time period, the image reveals little new information as the area was blanketed with snow by this time.

8.0 Airborne Systems Developed

Many airborne systems for oil spill remote sensing have been developed. It is important that organizations who are developing new systems consult the literature for summaries of these systems and recommendations (Hurford and Tookey, 1987; Innotech, 1992; Pearlman, Goodman and Galt, 1992; Fäst, 1989; Fäst, Cronstom *et al.*, 1992; Lambert, Schell *et al.*, 1992; Sorensen, Chang and Melhuish, 1994; Schell, 1992, Schriel, 1987; Giammona, Englehardt and Binkley, 1993; Hover, 1992; Hawkins, Gray *et al.*, 1991; Lambert, Bortell *et al.*, 1992; Fingas and Fruhwirth 1992; Fingas, 1992; Geraci and Lolli, 1989; Loostrom, 1987; Sorensen, 1992).

9.0 Recommendations For Airborne Oil Spill Remote Sensing

The following recommendations are based on the above considerations and include cost as a major factor. The primary sensor recommended for oil spill work is a thermal infrared camera. This is the cheapest and most applicable device. A camera and ancillary equipment can be purchased for less than $100,000 and weighs less than 50 kg. This is the only suitable piece of equipment that can be purchased as a stock item. All other sensors require special order and often, actual development. The second sensor recommended is an ultraviolet and visible device. These sensors vary a good deal in price, size and state of development. The laser fluorosensor offers the only potential for discriminating between oiled and un-oiled weeds or shoreline, and for positively identifying oil pollution on ice, among ice/snow and in a variety of other complex environments. This instrumentation is however rather large and expensive. A production unit could cost $500,000 and weigh 200 kg. Radar, although low in priority for purchase, offers the only potential for large area searches and foul weather remote sensing. A SLAR unit will cost around $500,000. SAR is recommended and a unit will cost about $2,000,000 and will require a dedicated aircraft. Most other sensors are experimental or do not offer good potential for oil detection or mapping. Any sensor package should include a real-time printer and display.

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