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098 Simple Remote Sensing System for the Detection of Oil on Water

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Simple Remote Sensing System for the Detection of Oil on Water

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Summary

This report describes the development of a simple remote sensing system suitable for use in aircraft of opportunity. The sensing techniques are described, and the basic principles of detection outlined. Examples of the operational use of the system are given.

Le present rapport decrit la mise au point d'un systeme de teledetection simple pouvant etre utilise dans les aeronefs auxiliaires occasionnels. Les techniques de detection sont decrites en detail et les principes de base de la detection sont enonces. Des exemples de l'utilisation pratique du systeme son egalement donnes.

1. Introduction

When large super tankers were first used more than twenty years ago, it was realized that there was a probability that one would encounter a problem and a large oil spill incident would occur. The grounding of the Torrey Canyon off Cornwall in 1967 heralded a new era in oil spill clean-up. It was soon realized that aerial observations were an essential component of an oil spill response. With the rapid development of remote sensing in support of the new generation of satellites, there became available sensor technology that would be useful in augmenting visual observations of oil on water. Problems related to the inability to detect oil through clouds, or at night or to provide a large area surveillance using visual techniques resulted in the development of a number of sensors operating in various parts of the electromagnetic spectrum. Experiments have been conducted around the world to test the ability of this equipment to detect oil. In North America, most of the early studies were undertaken by NASA and the Coast Guard, in the United States and in Canada, by the Canada Centre for Remote Sensing and Environment Canada.

Since the number of controlled releases of oil is severely limited due to environmental and cost factors, there have been only a few large experimental programs (Hawkins et al., 1979). These employed a variety of aircraft and sensors observing the same slick. While most of the early experiments were directed at the establishment of sensor capability to detect oil on the water, in more recent times, remote sensing programs were an adjunct to oil spill experiments on dispersant effectiveness: St. John's (Interra 1982, Gill and Ross, 1982); Halifax (Goodman et al., 1984) and the Canadian Beaufort (McColl et al., 1986 and Swiss et al., 1987).

2. Selection of Operating Frequency

The initial phase of the investigation of remote sensing systems was the development of sensor packages and the characterization of the electromagnetic properties of oil. Since the atmosphere has only a few windows,which are reasonably free from attenuation, it is in these bands of the electromagnetic spectrum that much of the oil parameter studies have occurred. As shown in Figure 1, the atmosphere is transparent in the microwave region (from 1-100 GHz [30cm - .3cm]); in two bands in the infrared (the thermal between 8-14 microns and the near infrared between 3-5 microns (Cateo and Maclean, 1979); in the visible between 0.4-0.8 microns,and in the near ultraviolet between 0.3-0.4 microns. In the X-ray region, there is little attenuation by the atmosphere, but there are no unique properties of oil in this band.

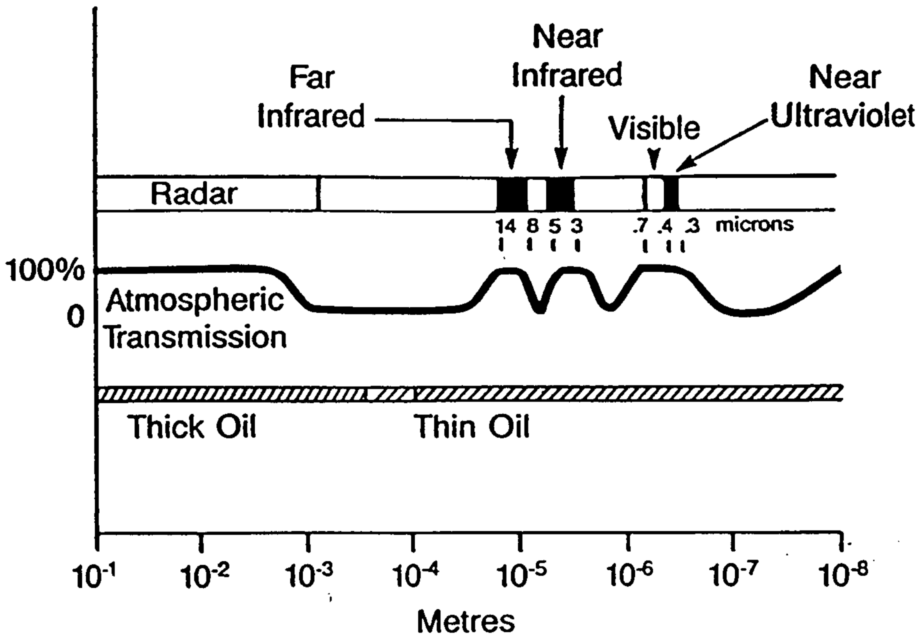

Figure 1. Atmospheric Transmission Bands

3. Active Radar Systems

A number of different forms of active radar systems have been developed and tested for oil spill detection. All of the active systems rely on the fact that the presence of oil on the water surface dampens the development of high frequency capillary waves (Pronk, 1975 and VanKuilenburg, 1975). Since the wavelength of these ocean waves is of the same order as the wave length of many radar systems, the damping effect is clearly visible in the radar return.

The ability to detect oil by radar systems is a sensitive function of wave height. If the sea in calm or has low wave heights, there are not enough capillary waves present, and the slick cannot be distinguished from the surrounding water (Hurford and Martinelli, 1982). If the sea state is too high, the oil is dispersed into the water column and does not suppress the capillary waves, and hence cannot be seen by radar.

3.1 SLAR and SAR imaging radar

The various forms of active radar include: downward looking radar, SLAR (Side Looking Airborne Radar) and SAR (Synthetic Aperture Radar). It was found that the sensitivity of oil was a strong function of polarization, (Guinard, 1971) while the operating frequencies and resolutions of these systems vary by an order of magnitude from L-band (1-2 GHz) to K-band (18-27 GHz), all work on the same principal to detect oil and all have the same advantages and disadvantages (Figure 2).

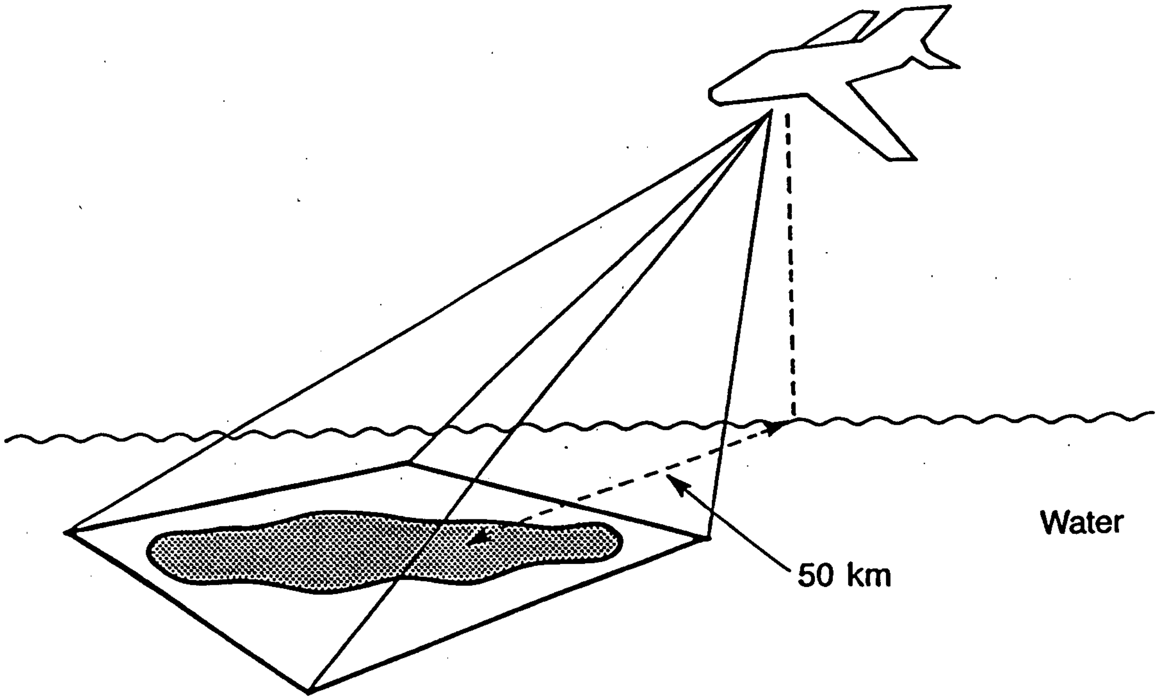

Figure 2. SLAR radar for Oil Spill detection.

3.1.1 Advantages.

Radar sensors are active systems and are not affected by the presence of cloud. They can operate both day and night. The aircraft generally fly at high altitudes, and thus provide an effective means of surveillance.

3.1.2 Disadvantages.

Until recent times, the SLAR and SAR images could not be processed in real time, and this limited the application of these radar to experimental programs, with subsequent post-trail analysis of the data. In the past few years, imaging radar systems have been equipped with real-time processing capabilities which enable these units to produce geometrically corrected images in real time. Such systems hence are suitable for strategic response to a spill situation.

The interpretation of the radar images is difficult and requires a trained operator. Many other oceanographic features such as wind slicks, ice and plankton mats cause a dampening of the capillary waves and could be confused with an oil slick.

The systems are generally heavy and require a large amount of power and a complex antenna system. This means that a dedicated aircraft is required.

3.2 Radar Scatterometer

Another form of radar system is the radar scatterometer (Hawkins et al., 1979). The radar scatterometer measures the microwave albedo of the surface, using a narrow beam at nadir. Since the transmitted energy is constricted into a narrow beam, the power required is low. Typical units operate at 13.3 GHz, with a beam width of 3^{0}, and 2 watts power.

3.2.1 Advantages

The radar scatterometer has all the capabilities of the imaging radar systems since it can be used at night and with cloud cover. An additional advantage is that the signal is obtained from directly beneath the aircraft, and hence can be used in conjunction with various optical sensors which are generally nadir devices

3.2.2 Disadvantages

The radar scatterometer as it is normally used is a line scanning device and does not produce an image of the slick. It is possible to use a fan-beam which scans in a direction perpendicular to the aircraft. This signal when combined with the motion the aircraft produces a two-dimensional map.

3.3 Marine Radar

The use of marine radar has been recently investigated during an offshore experimental oilspill (Tennyson, 1988). The experimental slicks, consisting of about 800 liters, of a medium weight crude oil, were detected at ranges up to 19km. This required adjustments of the radar to reduce the effects of the anti-sea clutter circuits and to select the correct gain settings. These are front panel adjustments and did not require any modification to the radar. The range of detection is much greater than the 1 km reported by Axelsson (1974). The low angle of incidence of the radar signal indicates that some other mechanism is being detected than the simple reduction of the capillary waves, since these cannot be detected at angles of incidence less than about 20^{o} (Simonett, 1983)

4. Passive Microwave Systems

The ocean is a natural emitter of microwave radiation, and oil on the surface will absorb some of this radiation. This forms the basis for passive microwave systems (Troy and Hollinger, 1977). In the microwave region, water has an emissivity of 0.4, whereas oil has a value of 0.8. Thus the oil appears "hot" with respect to the water. The signal to noise ratio, since the noise is the signal, is very low, and a quiet region of the microwave spectrum must be chosen (Kendall et at., 1985). Much experimentation has been done using a two band system at 22.4 and 31 GHz, and a single channel system operating at 37 GHz has been used in some experiments (Fast, 1986). Under ideal conditions, the oil can be detected, and an estimate made of the oil thickness. Thickness measurements cannot be made absolute, since the absorption characteristics of oil are highly dependant on the state of the oil and its water content. Relative values of thickness can be determined using this method.

No suitable technology has been found to calibrate such a sensor. The broad beam width of most systems result in a large footprint. This means the oil thickness is integrated over a large area, within which then can be an order of magnitude of thickness variation. There is some experimental evidence that the apparent microwave temperature is linearly related to oil thickness over the range of 0.1 - 1mm. At a greater thickness the oil absorption prohibits the determination of oil thickness.

4.1 Advantages

The system is passive and does not require a large power source, and is quite small. The microwave radiometry provides complementary information to other sensing systems.

4.2 Disadvantages

The passive microwave systems have a low signal to noise ratio and are subject to interference from a variety of sources. They are complex electronically, and some systems operate in a line scan rather than image mode. This however is largely a function of electronics and has been easily changed if the basic sensor was useful.

For the more complex fan-beam system a special antenna is required, which implies the use of a dedicated aircraft.

Passive microwave systems are expensive and have limited commercial availability. There is one system built by the Swedish Space Corporation which has been used in several experimental spill situations (Fast, 1987).

There is little available technology above 100 GHz and shorter wave lengths. The region is known as the extreme infrared, and the earth's atmosphere is a good absorber in this region. The next window is in the thermal infrared from 8 to 14 microns.

5. Thermal Infrared

The low atmospheric attenuation band between 8-14 microns is known as the thermal infrared, since the predominate radiation is thermal in origin. The measurement of the radiative flux in this band can be expressed in terms of "apparent" temperature.

In this spectral band, the emissivity of oil is .94-.97 (Munday et al., 1971; Horvath et al., 1971 and Buettner and Kern, 1965) and of water is .988 (Wolfe, 1965). This is one component of the signal source, and gives a temperature difference of about 0.6^{O}K for a reflectivity difference of 1 percent between oil and water. Thus an apparent difference for material in thermal equilibrium could be as large as 3^{O}K, with the oil appearing cooler. The initial observations of oil on water under field conditions show a temperature difference of a few degrees K, and the oil was warmer than the water. There must be a physical source of temperature difference, not related to the emissivity difference (Neville et al., 1979). It was noted in the early experiments that the thicker patches of oil had a different temperature than that of the sheen, and in most cases the sheen was not readily detected in the infrared. One reason for this is that the thin film of oil does not absorb the radiation from the water, and hence there is no contrast between the oil and water. The causes of these temperature differences have been ascribed to the increased absorption of oil due to its lower albedo, and the low thermal conductivity of the oil, which allows a real temperature difference to be maintained. Since the heat flux is a function of temperature, there will be a thickness below which there will be an undetectable thermal difference. A typical IR image in shown in figure 3. The best evidence would indicate that this is at a thickness of about 100 to 150 microns (O'Neil et al., 1983).

Since the actual temperature difference is a complex function of incident solar radiation density, the thermal properties of the oil and the oil thickness, it is not possible to use the intensity (apparent temperature difference) to measure oil thickness (Thomson and McColl, 1972).

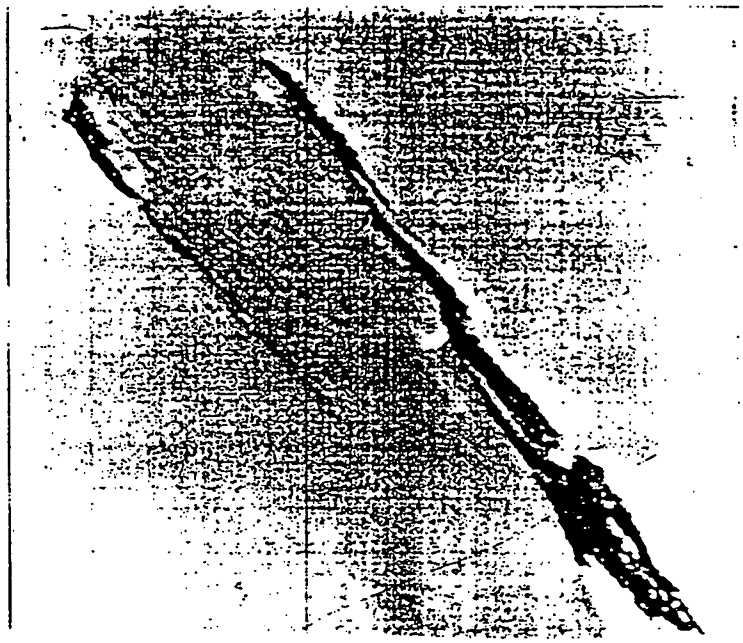

Figure 3. Oil Slick in Thermal Infrared

Several experimenters have noticed a region around the thick oil patches, which appear at a temperature lower that the surrounding water (figure 4). This may simply reflect the emissivity difference between the oil and water, but there may be physical reasons for this temperature. The most consistent with existing evidence would seem to be that the lowering of temperature is caused by evaporative heat loss. No surface observations are available to confirm this theory.

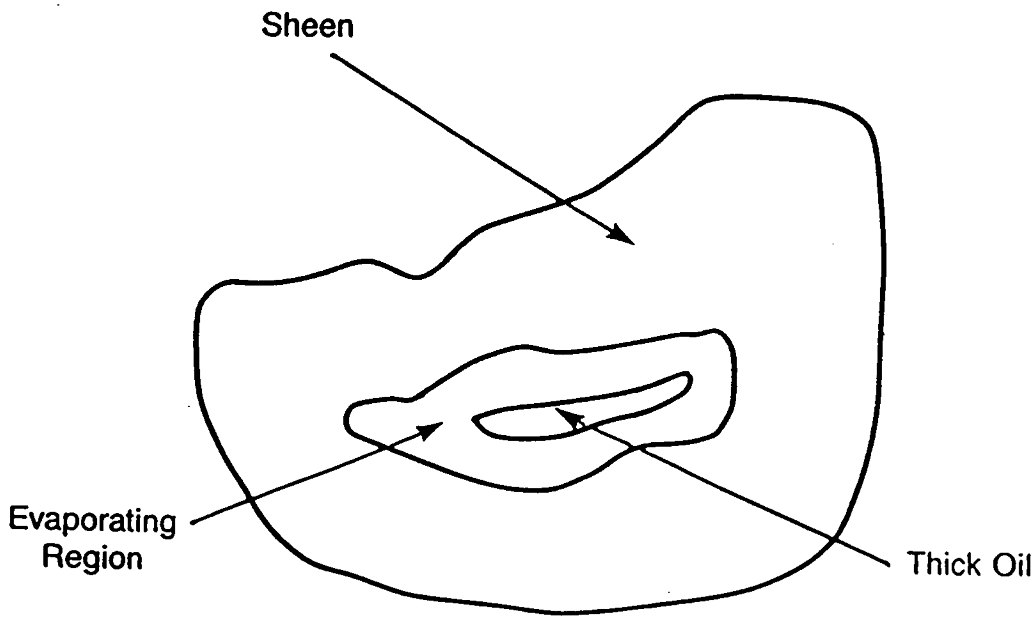

Figure 4. Regions of a typical slick.

An alternate interpretation of IR imagery is given by LeGuen et al., 1987. They identify three levels of infrared returns, one with a temperature greater than the surrounding water and two with temperatures less than ocean (Figure 5). The warmer oil is assumed to be very thick material (>500 microns) and can be either oil or an emulsion (chocolate mousse). The region with the slightly lower temperature than the water is postulated to be thin oil (<50 microns), and the region of lowest temperature, is assumed to be thicker oil (100-300 microns). These assignments are based on expected values of radiation and have not been confirmed by observations at the ocean surface.

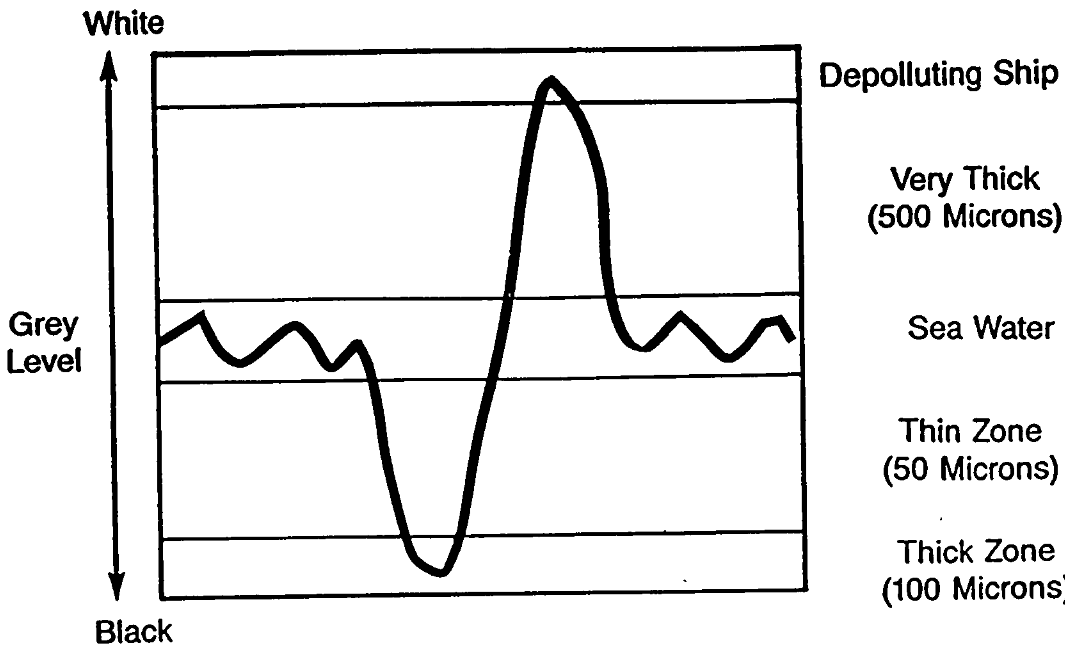

Figure 5. Line transit across a slick (Leguen et al., 1987)

The apparent temperature difference changes between day and night; the temperature of the oil is greater during the day and lower at night. At dawn and dusk the temperature difference may be very small. This is consistent with solar heating and thermal insulating of the oil as the cause of the temperature differences observed in the infrared.

5.1 Advantages

The main advantage of the IR system is that it is simple to operate, and can be installed in a small aircraft. Both line scanner and imaging systems are commercially produced and available. The interpretation of the data is relatively simple, and leads to easily understandable results.

The infrared systems are moderately priced.

5.2 Disadvantages

The infrared sensors cannot penetrate clouds, and thus must be used under clear conditions. There is some differences in the literature as to the detectability of oil at night, but some experiments have been successful.

The detector of the system operates at liquid nitrogen temperatures, and this requires the use of liquid nitrogen, or a high-pressure air Stirling cycle cooling system.

When used with dispersant applications, the understanding of the image is more complex due to various oceanographic process which give similar images in the infrared. Due to the complexity of the processes which determine the apparent relative temperature of the oil and water, quantitative measurement of oil thickness is not possible using infrared systems.

6. Near Infrared Systems

The next window of low atmospheric transmission is between 3 to 5 microns. In this region, the difference of the emissivity of oil and water is the primary source of signal. Observations using passive systems have shown that there is an inadequate source of natural radiation in this region to provide a suitable signal. Therefore, the systems that operate in this band are generally active systems, and use an infrared source to illuminate the water surface.

6.1 Oil Film Monitor

One such system operates in two narrow bands centered at 2.5 and 3.1 microns, since the emissivity differences between water and oil are greatest in these two regions (Wright and Wright, 1973) as shown in Figure 6.

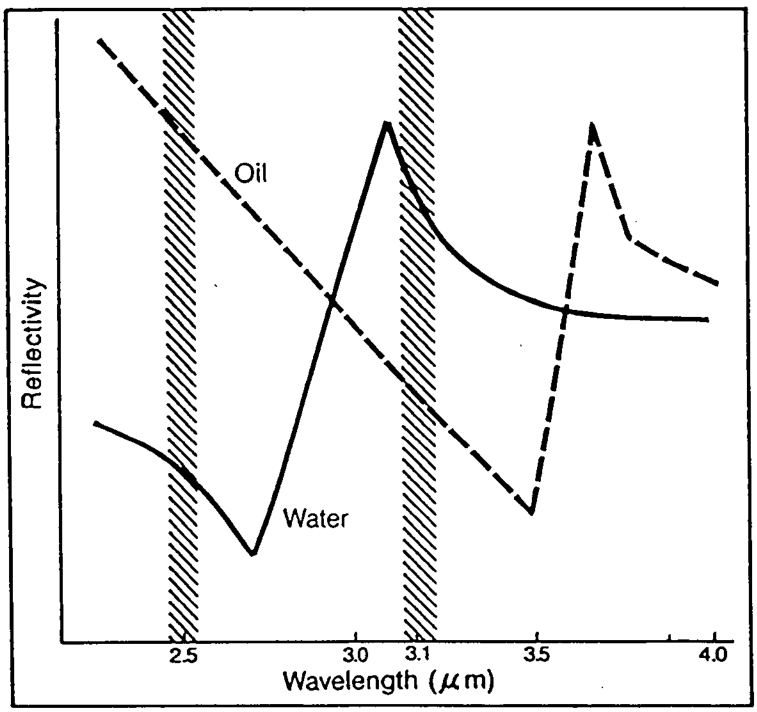

Figure 6. Reflectivity of oil and water in the near infrared.

While there is some atmospheric absorption in this region, the range limit is not critical this the system has been designed to operate a short distances in a fixed location, such as at refinery sites.

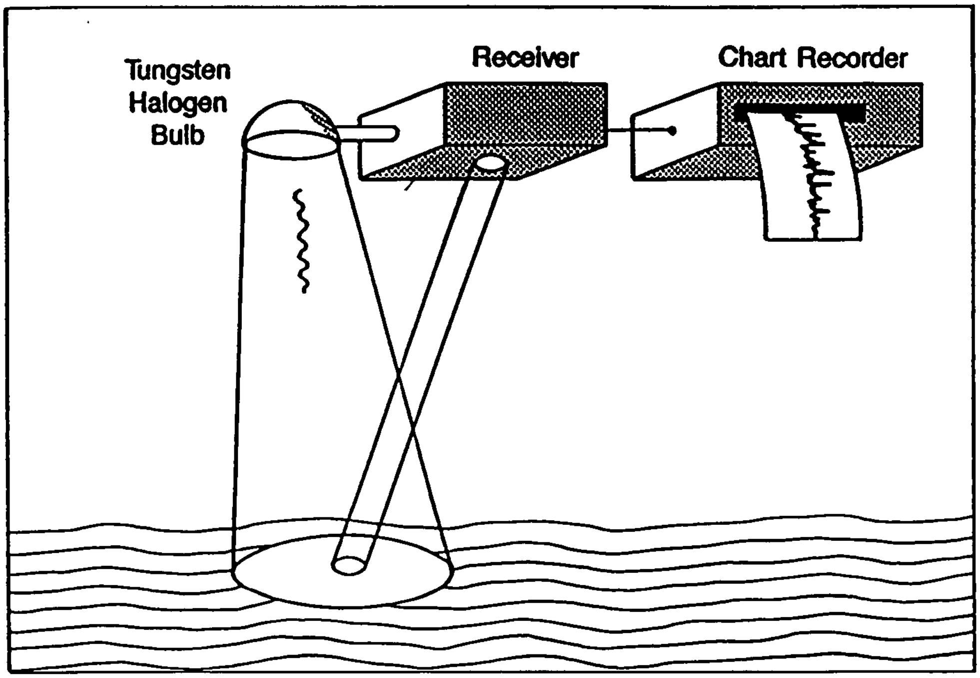

Figure 7. Active near-Ir oil film detector.

There has been a study conducted by Environment Canada to study the use of a near-infrared system to detect chronic emissions of hydrocarbons from offshore platforms. The main problem with this application is the limited range of less than 20 meters (Garrett el al., 1985). An improved system using better optics and more complex signal processing has been developed which has a useful range of 30m (Seakem, 1988)

6.1.1 Advantages

These systems are sensitive to thin films of hydrocarbon (in the order of 1 micron), and provide a high signal-to-noise ratio. The output is quite stable and is suitable for unattended operation. Since it is an active system, the presence of oil can be determined both day and night. The interpretation of the results in simple and unambiguous.

The system is inexpensive.

6.1.2 Disadvantages

The range of about 30 meters is a severe limitation for airborne applications, as is the slow response time of a few seconds. At extreme ranges, the sensitivity of the detector is reduced under even moderate wave conditions. This system has been developed for fixed monitoring sites.

6.2 Gaspills/Oilspills Monitoring System

A novel oil slick detection system which detects the presence of oil vapour above a slick has been developed which operates in the near infrared. The system is passive, and detects the absorption of the naturally occurring background radiation due to the presence of hydrocarbon vapours. This system is a modification of a unit

(Gaspills) initially developed for the detection of low carbon number gas vapours. Tests have shown that this unit does not have adequate sensitivity to detect vapour clouds above a spill, and it is unlikely that a suitable instrument can be developed (Garrett et al., 1986)

The next band in which the atmosphere to transparent is the visible band from 0.4 to 0.8 microns. The human eye is most sensitive to radiation in this band and has a peak sensitivity at about .54 microns (green light).

7. Visible systems

The most commonly used method for observation is the visible in a trained human observer (Horstein, 1972). Using this technique it is possible to detect the presence of oil on the surface, and to estimate its thickness, since the colour of the oil is related to its thickness (ITOPF, 1981). Table 1 is taken from this bulletin.

TABLE 1

Appearance	Oil Type	Approximate Thickness (Microns)	Approximate Volume (m^3/km^2)
Brown/Orange	Water in Oil Emulsions (Mousse)	1000	1000
Black/dark Brown	Crude or Fuel Oil	>100	100
Iridescent	Oil Sheen	>.3	0.3
Silvery	Oil Sheen	>.1	0.1

From ITOPF, 1981

Such visual observations can be recorded on a log sheet with sketches. The use of either monochrome or colour photography and video techniques gives the same information as an observer, but can be recorded in a form more suitable for subsequent analysis and briefing.

7.1 Advantages

One of the main advantages of observation in the visible band is the ease of interpretation of the data. This coupled with simple and familiar equipment makes this method the most commonly used in oil spill surveillance.

If flying at a suitable altitude, large areas of the ocean can be quickly scanned for the presence of oil.

7.2 Disadvantages

It is not possible to observe oil at night or through cloud cover in the visible part of the spectrum.

It is difficult to determine the presence of oil uniquely from typical surveillance altitudes, and the aircraft must continuously change altitude to verify the presence of oil. With a variable focal length lens and either a TV or standard camera, this problem can be greatly reduced.

There are difficulties in distinguishing between oil and other natural occurring features such as windbreaks, bottom features and cloud shadow, especially under poor light conditions.

8. Ultraviolet systems

Three very different types of oil spill detection systems have been developed which operate in the ultraviolet. One system depends on the difference in reflectivity of oil and water in the ultraviolet, and is a passive system (Horvath, 1970). Another uses visual detection of UV induced fluorescence (Fingas, 1982), and the third a laser operating in the ultraviolet (.337 microns) to excite the fluorescence of the oil, which is detected in the visible (.37-.69 microns) (O'Neil et al., 1980).

8.1 Passive Ultraviolet System

Hydrocarbons, even as a thin sheen, have a high degree of reflectivity in the near ultraviolet, where the atmosphere is transparent. The transmission band of the atmosphere is very narrow and only extends from 0.3 to 0.37 microns. The differences in the reflectivity are small, and hence the image contrast is low. This system can only operate when there is adequate ultraviolet illumination from the sun to provide an image.

8.1.1 Advantages

The ultraviolet system is very sensitive to the presence of a small amount of hydrocarbon on the water surface, and there is little effect from other materials on the sea surface expect for oil generated in the decay of plant and animal material, and in some cases the chlorophyll from a large accumulation of plant material. Such features are rarely concentrated in slicks, but are generally spatially diverse.

8.1.2 Disadvantages

The system can only operate in the day, when there is adequate solar illumination in the ultraviolet.

8.2 UV Fluorescence System

An active system using a commercial ultraviolet light to induce the natural fluorescent of the oil was developed by Environment Canada (Fingas, 1982). This is a simple hand held unit which can be constructed from readily available components. Field tests have shown that this equipment can readily detect oil at night.

8.3 Laser Fluorosensor

The laser fluorosensor is an active system which induces fluorescence in the oil with a narrow beam ultraviolet source. The resulting fluorescence is detected in the visible, and provides not only a unique signal for oil, but different type of oil can be differentiated from the return signal (Rayner and O'Neil, 1979. This capability is very useful for surveillance operations and pollution detection (Figure 8).

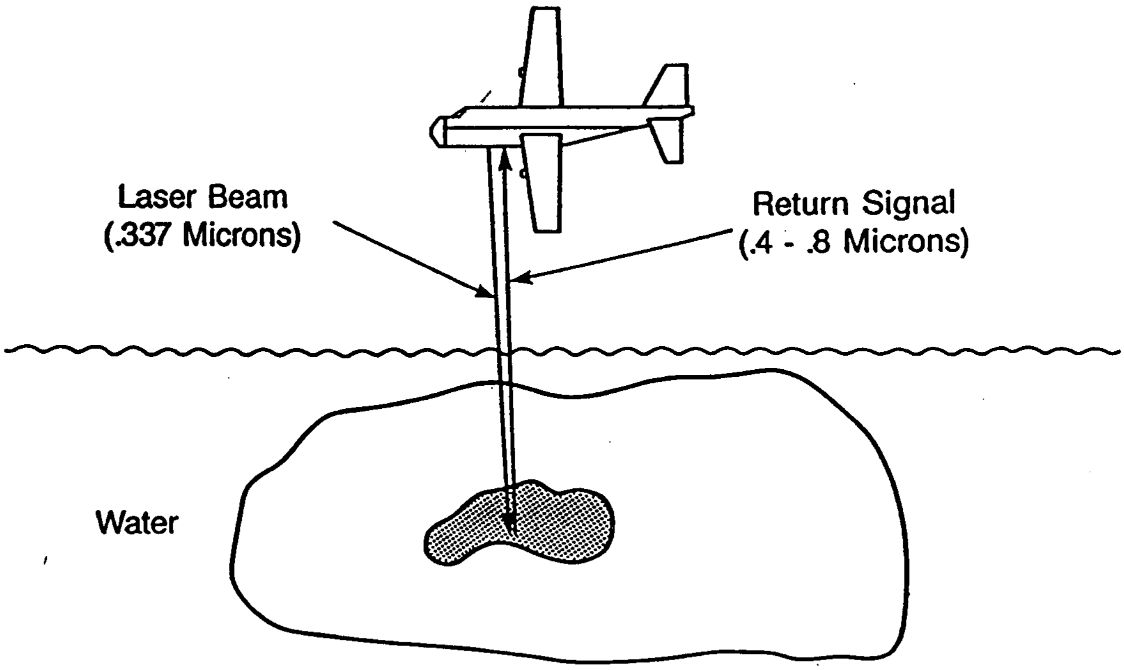

Figure 8. Diagram of Laser Fluorosensor.

8.3.1 Advantages

The main advantage of the laser fluorosensor is that it can operate both day and night, and provides a unique return for oil, thus eliminating the problem of false returns. This is especially important at night, where the feature cannot be visually examined.

8.3.2 Disadvantages

The laser fluorosensor, as it is presently designed, is a line scanning device and does not present a map of the surface.

The unit is expensive, has complex electronics and requires a highly trained operator to run the equipment. A dedicated aircraft is required.

The size and weight of the CCRS Mark III sensor was such that this instrument required the use of a dedicated aircraft. A study was undertaken by the Canadian oil industry to investigate the development of a small, lighter system that could be used from an aircraft of opportunity. A variety of different detectors, including CCD imaging systems, were studied, and both Xenon flash systems and solid state lasers were considered as light sources. It was concluded that such systems had an inadequate signal to noise ratio and would only be useful under a very limited set of operating conditions (Green, 1985)

8.4 Operational Example of a Remote Sensing System using dedicated aircraft.

8.4.1 AOSS

A operational radar system has been developed for the United States Coast Guard (Meeks et al., 1977). This unit known as AOSS (Airborne Oil Surveillance System) is installed in a Lockheed C130B (Hercules) four engined transport aircraft. The sensor package consists of the following:

1. A 45 kw X-band SLAR with a range of 27km and a resolution of 30m.
2. A line scanner operating at .32-.38 microns in the near ultraviolet and at 8-13 microns in the infrared channel.
3. A passive microwave imager at 37 Ghz.

8.4.2 AIREYE

A next generation system, also used by the U.S. Coast Guard, is the AIREYE, which consists of a similar instrumentation package to AOSS. This system is mounted in a Falcon 206 Executive Jet aircraft. The sensor package includes:

1. A 200 kw X-band SLAR with a range of 128 km.
2. A line scanner operating at .32-.4 microns in the near ultraviolet and at 7.6-13.8 microns in the infrared channel.
3. A high sensitivity active gated television operating in the visible

No similar systems have been developed in Canada, although a number of systems concepts have been developed by various government agencies (O'Neil et al., 1980). The main method of surveillance in Canada remains overflights using trained observers. In order to make remote sensing more readily available for oil spill response, a new remote sensing system has been developed which can be used in aircraft of opportunity.

9. Sensor Selection

It is clear from the above review that there are many systems available which can be used to the surveillance and tracking of oil spills. The main problem with most of these systems is not in their technical limitations, but rather in their availability on short notice in the event of any incident. Most of these units require a dedicated aircraft due to the need for external mounting on antennae, or the integration of the imaging equipment with the aircraft navigation. Since oil spills rarely happen, the cost of having a dedicated aircraft is very high compared to the benefits, and the trend has been to use trained observers and not the more complex remote sensing equipment. The need therefore is to develop a system which can be fitted in a readily available aircraft of opportunity, and function as an extension of the human observer. Such a system should meet the following criteria:

1. Small size

2. Light weight-each piece should be less than 30kgs, and have total linear dimensions of less than 150cm. so that it can be shipped as accompanying checked baggage.

3. Require no external mounting of sensors required on aircraft. It is assumed that a standard camera port is available.

4. Operate using its own power, or a standard 28v aircraft system.

5. Have a mission life compatible with air fuel limitations.

6. The output of the system should be readily available in real time.

These criteria severely limit the selection of sensing systems. The SLAR/SAR systems are eliminated on the basis of the need for an external antennae configuration, weight and operating power. All the line scanning imaging systems require a connection to the aircraft electronics in order to provide information on the scale of the one component of the image. This eliminates the IR/UV line scanner, the laser fluorosensor and the microwave radiometer. The selection of sensors is therefore limited to image producing systems. The most commonly used real-time image producing systems are based on television technology. A review of available equipment which had a standard NTSC video output indicated that cameras were available which operate in both the thermal infrared and the near-ultraviolet.

9.1 The Ultraviolet Camera.

Since the near-ultraviolet band lies immediately adjacent to the visible band, a study was made of the sensitivity of standard TV cameras in the region from 0.3 - 0.4 microns. From the point of view of the television industry, it is desirable to reduce the sensitivity to ultraviolet light since this tends to wash-out skies and render fresh tones grey. The spectral response on some vidicon and most CCD detectors is such that there is an appreciable sensitivity in the ultraviolet. A typical response can be seen in Figure 7. If a suitable band pass filter is used with such a detector, the frequency response can be adjusted to only detect near-ultraviolet radiation (Figure 9).

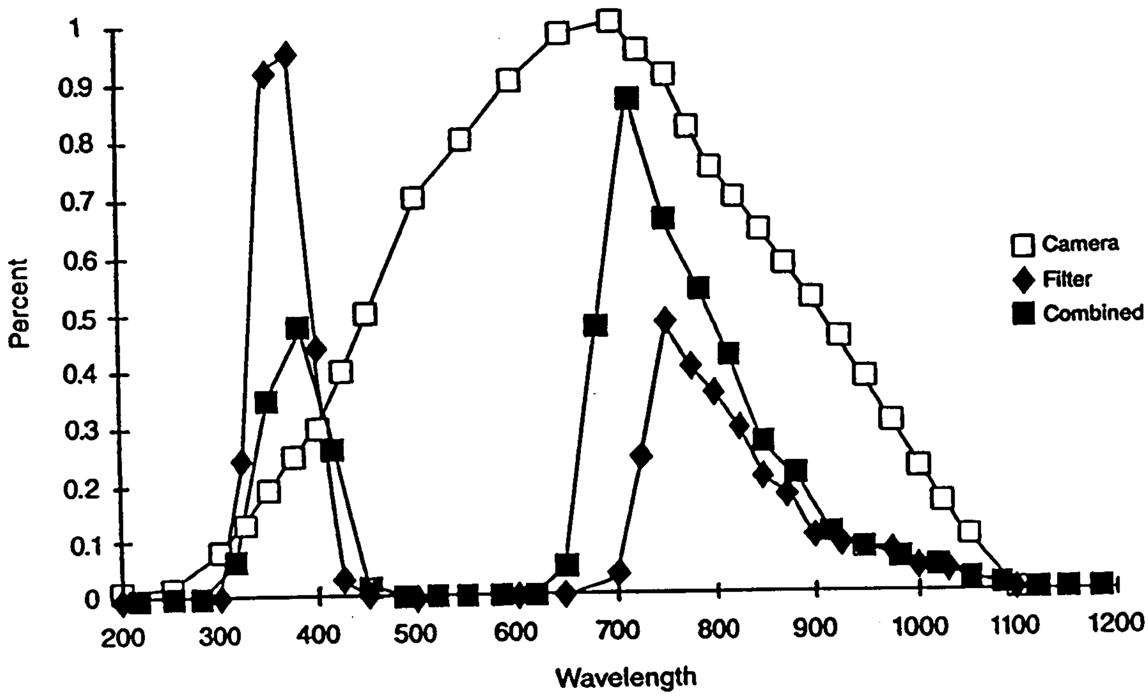

Figure 9. Spectral sensitivity of camera and filter system for UV sensor.

In order to reduce the effects on sun glitter, especially at low sun angles, a polarizing filter is added to the filter package. Within the addition of these two filters, there is considerable adsorption in the 0.3 - 0.4 micron region. This requires a camera with a sensitivity of at least 1 lambert. Such units are readily available and are known as a LLLTV (low Light Level Television). The particular camera chosen was a standard industrial unit, the Cohu Model 5200 SVC Silicon Target image system and a ZION Auto Iris Zoom lens (16 - 160mm). A Cohu model 5800 Lens Control Unit (LCU) is used to operate the camera (Figure 10).

Figure 10. Picture of Cohu camera and filter system

The two filters used were a Corning 7-51 with transmission from .310-420 and .7 to 1.1 microns and a Polaroid HNP'B (240-740). These are the same filters as used by O'Neil et al (1983). This camera and filter package produces high quality, albeit low contrast images in the UV, as shown in Figure 11).

Figure 11. Typical image of a spill in the Ultraviolet

9.2 The Infrared Camera

Since detectors operating in this region of the electromagnetic spectrum are measuring thermal radiation, a suitable signal-to-noise ratio can only be achieved if the detector is cooled. There are a variety of techniques used to achieve this cooling, including thermoelectric coolers, liquid nitrogen and high-pressure air Stirling cycle engines. Since it was envisaged that this remote sensing system for oil spills would operate in remote areas, the use of liquid nitrogen would not be possible.

A number of imaging systems are commercially available which produce television images in the far infrared (8-14 microns). The simplest of these is the pyroelectric vidicon. This unit was designed for high-temperature contrast situations, and did not have an adequate sensitivity for the oil spill situation where is total temperature contrast is in the order of a few degrees centigrade.

A number of IR imaging systems have been developed to survey heat losses in houses. These systems have sufficient sensitivity, but lack spatial resolution since they a constructed using a matrix of individual IR detecting elements.

A system based on SPRITE detector technology was chosen for its high sensitivity (0.2^{o}C), and its long term stability. The unit chosen is a Barr and Stroud IR18 (Figure 12).

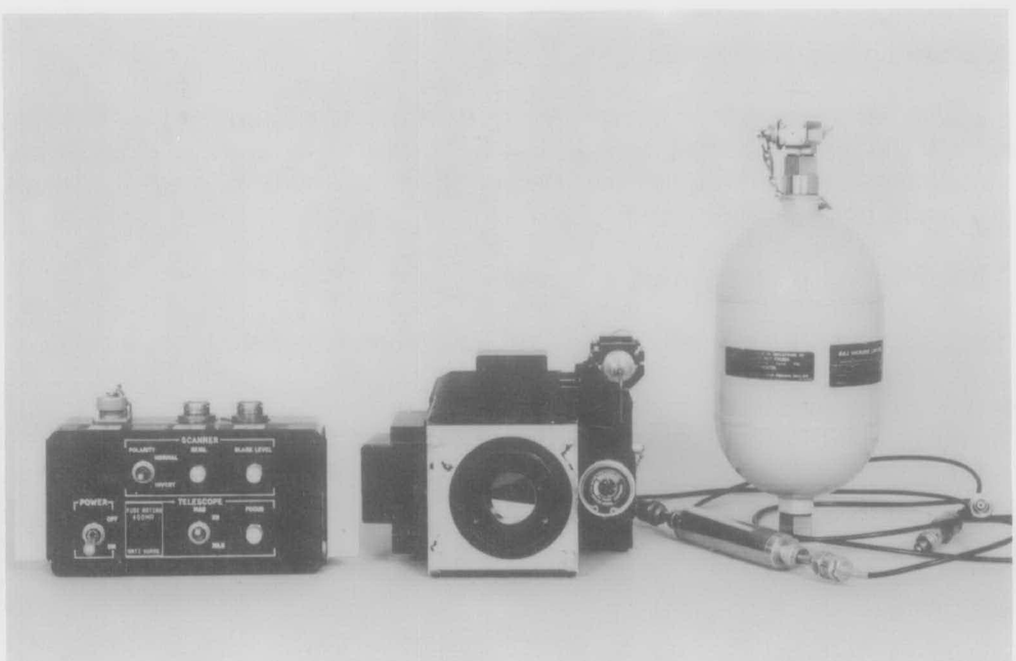

Figure 12. Picture of Barr and Stroud Thermal Infrared Camera

This camera uses a high pressure air cooling system based on a Stirling cycle engine. Either high-pressure air bottles or a electrically powered high pressure pump can be used to provide energy for the cooling system. In order to achieve a long mission time, and to minimize operational problems, the self-contained high pressure pump option (Figure 13) was chosen for the simple remote sensing system.

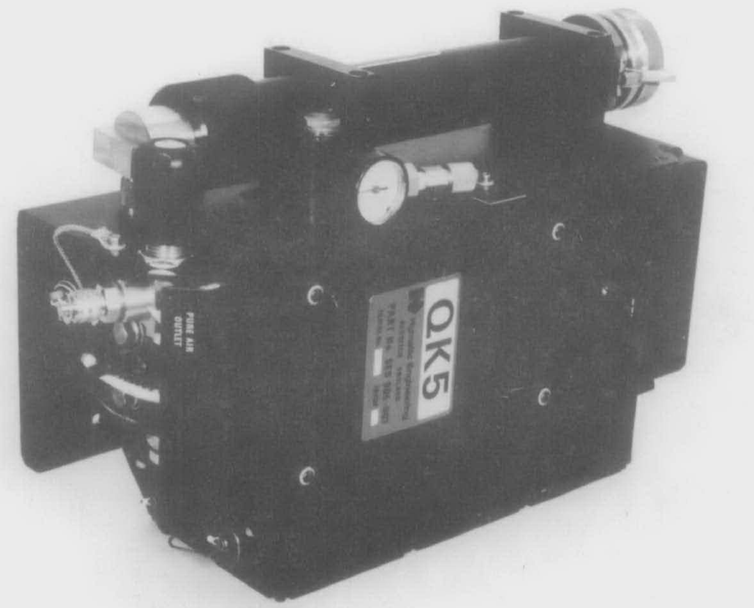

Figure 13. High pressure electrically operated pump for cooling IR detector

9.3 Positioning and Navigation

Since it was not desirable, or in many cases possible, to obtain a direct connection to the aircraft navigation system, a small low-light level monochrome camera with a wide angle lens was mounted so that the navigational and flight instruments of the aircraft could be recorded.

9.4 Television Based Integration of sensors

The three sensors, IR, UV and navigation have been integrated into a single data recording system suitable for the remote sensing of oil. Since all three sensors produce a video output, the first stage of integration was to combine these three signals into a single composite colour image, with the IR being red, the UV being blue and the navigation or annotation being green. The original system design is shown in Figure 14.

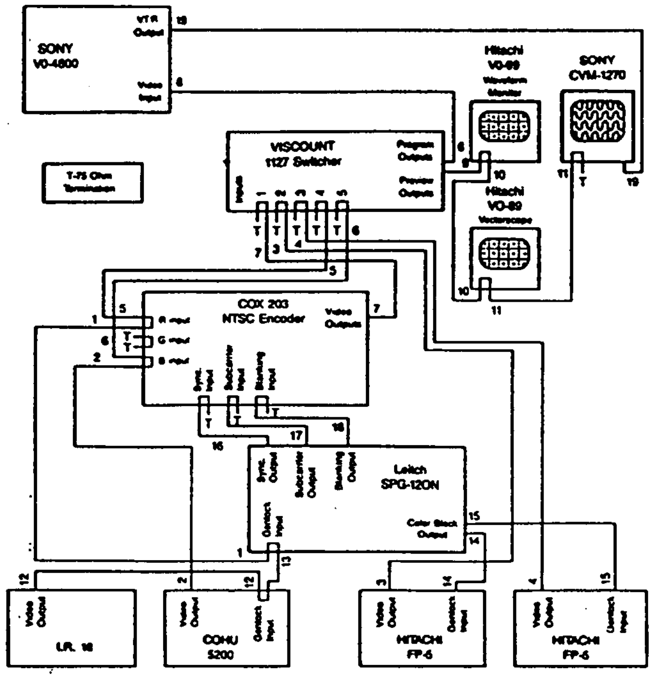

Figure 14. Video based image processing and display system

The concept was to combine the IR, UV and navigation images as one overlapping colour composite image. The outputs of the individual sensors could be viewed by adjusting the input signal levels, and the three sensor output would be available for recording on a single industrial tape recorder. Since the generation and display of television images is highly dependant on synchronization or timing of the signals, only one sensor could be used as a timing generator, and the other two must be slaved in time to this master unit. The Barr and Stroud IR18 generates an artificial television image, using a scanning mirror driven by a high-speed motor. The inherent inertia of this system was such that it could not operate as a slave unit, and must be the master unit, with the UV and Navigation cameras being slaves. The quality of the synchronization pulses available from the IR camera were poor and required regeneration using an external sync-generator.

In order to control the nature of the display, and to provide the ability to combine the three signals in a variety of formats, a television switcher was incorporated in the system. This allowed the viewing of each image separately or combined. Half and quarter screen images can be generated by the video system. For example, the quarter screen image allows monitoring, albeit at a reduced scale, the three input signals and the composite video signal.

Initial tests of the system indicated that synchronization was a problem, and the three images could not be overlapped and maintain a steady picture. Each individual image was satisfactory, but the composite was not. The cause of the problem was traced to a vertical frame instability in the IR camera. The time jitter associated with this camera was larger than the timer jitter that could be tolerated by the two slave cameras.

This approach to the problem was abandoned, and a new system for integration was developed.

Since the data are available in digital form, a number of images enhancement techniques can be implemented before display. These include contrast stretching, density slicing and geometrical corrections. The contrast stretching is especially valuable for the UV image which is inherently low contrast. The areas of the images, from either the UV or IR can be computed since the camera configuration and altitude are known. Such a number is needed for some experimental situations, but for operational situations the area of the slick is not a very useful number.

The system has been built using the following components:

1. Tandy 3000 computer with two 20meg hard discs
2. Sharp XM 1300 Monitor
3. Targa 16 video to digital and digital to video convertor
4. Cox Model 203 RGB to composite video convertor
5. Merrick 800 watt UPS invertor for conversion from 28VDC to 110vac for computer
6. Panasonic Model 3248 with 12mm lens for annotation
7. Barr and Stroud IR18 Thermal Infrared camera
8. Cohu LLLTV 5200 camera with Corning 75-1 and Polaroid HNP'B filters.

The electronic component of the unit is housed in a single air transportable case . The power requirements are:

1. Electronics - 340 watts
2. IR camera - 36 watts at 28VDC
3. High pressure Pump - 60 watts at 28VDC A higher starting current, up to 20 amps depending on temperature is required.
4. UV Camera 24 watts at 28vdc

The system and various components have been tested in a number of experimental situations and in an actual spill incident.

10. System Test and Evaluation Program

A number of test programs were undertaken to evaluate the effectiveness of the simple remote sensing system, and to develop methodology for the interpretation of the resulting images. Three levels of testing were carried out: in the Esso wave basin, in experimental field situations and in an actual spill situation.

10.1 Wave Basin tests

The initial testing of the system was conducted as part of a dispersant effectiveness study undertaken using the large Esso Resources wave basin. The infrared and ultraviolet cameras were mounted on a tower located adjacent to the boom containing oil. A horizontal bar, mounted on the tower was used place the camera or camera over the center of the slick. Since this was an experimental program, the results were recorded on an industrial grade video recorder during the experiments. The results were analyzed later using a Spectral Data VIP image analysis system.

These tests showed that both the sensors performed as expected. The effectiveness of the polarizing filter in reducing sun glitter was limited, mainly due to reflections from the mounting tower. When operated from an aircraft, this problem would be greatly reduced.

The data from the infrared camera was analyzed to determine the area of the thick components of the oil slick and to examine the effectiveness of the dispersant spay pattern. This data has been used for a number of studies (Brown and Goodman, 1988)

10.2 Dartmouth Refinery Trials

A program to test the use of various sensors in the detection on chronic oil spills was initiated by Environment Canada in 1985. One of the initial tests was the evaluation of the IR and UV sensors (Garret et al 1985), developed for the simple remote sensing system, under controlled conditions at the API separator of the Esso Dartmouth refinery. Two cameras worked well once the problem of obtaining clean high pressure air for the IR had been resolved.

The slicks associated with the API seperator output are very thin, and thus were not readily detected by the IR camera. This is consistent with the experience of other studies. The UV camera work well, but had low contrast and was subject in sun glitter. Neither sensor was judged suitable for the detection of chronic spills. This is not inconsistent with other studies in this area.

10.3 Freshwater Dispersant Trials

The first field use of this equipment was during the 1985 freshwater dispersant trials conducted near Athabaska, Alberta. (Quaife et al, 1986). The basic purpose of this experiment was to determine the effectiveness of dispersants in a freshwater environment. This was the final component of a five-year, disciplinary study on the use of dispersants in a freshwater situation.

The experimental program was based on the use of three sloughs with similar characteristics. On slough would be used as a control and the other two would have oil spilled on them. The one oil slough would remain untreated, and the other would be sprayed with Corexit 9550. On the two oiled sloughs, a number of hydrocarbon samples, both surface and sub-surface were taken to determine the effectiveness of the dispersant.

The remote sensing component of the program used a Cessna 411 twin engined aircraft. The UV camera and simple video based system were used for these experiments. Flight lines were flown over both sloughs, which were located about 12 km from each other. The information was collected about every 15 minutes for a period of eight hours, with one break for aircraft refueling. The equipment operated on its internal batteries, and functioned well even under severe turbulence conditions. The same could not be said for the operator! The data from these flights was used to determine the location of the oil, and its motion (Goodman et al, 1986). Two days after the initial spill, an other flight was made using both the IR and UV cameras, together with the video data acquisition system. It was found that oil trapped in the floating vegetation, and on the shoreline could be readily identified in the infrared images.

The results of the freshwater trials have been published in a number of reports over the past few years(Brown and Goodman, 1987; CPA 1986).

10.4 Minuk Incident

In mid September 1985, a severe storm of long duration caused damage to the Esso artificial island, Minuk, located in the Canadian Beaufort at 69^{o} 42` 7" N and 136$^{o}$ 27` 7" W. Among the problems this event caused, some 388 m^3 of Arctic Diesel P50 was spilled into the ocean. Esso response personal were alerted, and the simple remote sensing system, together with the video based data system were mounted in an Esso twin-Otter. This equipment was used for regular surveillance flights and tracked the spill until it **dissipated five days after the initial incident. Both the ultraviolet and infrared systems worked as expected. After four days, there is not signal from the IR, but the slick could be followed using the UV for a further day. The images were recorded on a standard video recorder and analyzed later.

This incident proved the concept of using an aircraft of opportunity as a sensing platform and the flexibility of the simple remote sensing system under operational conditions.

10.5 Beaufort Sea Trials

In 1987, the system was used in conjunction with a major dispersant trial conducted in the Canadian Beaufort. The two cameras were mounted in a Twin Otter belonging to Borek Aviation of Inuvik. No problems were encountered in mounting the equipment and making it operational. This was the same set of equipment as had been used previously, expect the electrical pump was used instead of the air bottle used in the two other experiments. The pump worked well and significantly increased the mission time of the system.

The equipment worked well and there were no operational problems. The data was again recorded on video tape for subsequent analysis, and was also displayed and analyzed in real time using a prototype commercial system. The data from the post analysis and the real time system were in agreement on the areas of the slick as a function of time.

11.Conclusions

As the result of the use of this equipment in a number of oil detection systems, it has been found that the sensors work well and are reliable. After nearly two years *of operation, and shipping several times across Canada and to Europe, no equipment malfunctions have been experienced except when contaminated air was inadvertently used.

There are some difficulties in the interpretation of the Ir data. These images contain a wide range of gray scale, which would indicate a temperature variation across the slick. One possible interpretation of this is a spatial variation in slick thickness. However, no patterns of the IR images can be correlated with other observations, and it is likely that the IR contrast variations represent a complex mixture of uneven solar heating, the inhomogeneity of the oil and oil thickness variations. With present technology, it is not possible to separate these variables.

11.1 Measurements of Dispersant Effectiveness

One of the basic premises of the Beaufort trial was that the remote sensing system could be used to determine dispersant effectiveness. The interpretation of the IR images in terms of dispersants effectiveness has proven difficult for a number of reasons.

There are a number of process issues at the ocean surface that cause difficulties in the interpretation of the infrared images. The mechanism for the formation of emulsion balls is not well understood and the criteria for formation has not been characterized. These emulsion balls are very unstable and their interaction with the ocean wave spectrum is not known.

There is now substantial experimental evidence that there are a number of processes which interfere with the simple interpretation of the area of the slick as representing the amount of oil on the surface. As a result of these experiments, it is concluded that it is not possible to undertake a dispersant effectiveness experiment based solely on remote observations using current technology.

12.Recommendations

The simple remote sensing system works well, and provides information in a timely and effective manner. It would be nice if the equipment were smaller, and consumed less power, but experience has shown that these are not major limitations to the operational use of the UV and IR systems.

The response of the UV filter, Corning 7-51, when combined with the high sensitivity of the Cohu camera in the visible gives a significant response in the .7-.9 micron region of the visible. This response reduces the contrast available for the UV reflectance. A filter with a higher optical density between .5 and .9 microns would improve the contrast.

Since it may be necessary to fly a low altitudes, a wider angle lens on both the IR and UV camera would be useful. At the time of the initial system design, these were not available, but the manufactures have now added these to their product line.

There is a problem in obtaining suitable images of long thin slicks such as a typical of most spills situations. If adequate detail is obtained in the narrow direction, the slick covers more than one frame. Since there are few features on the ocean surface to use as points of reference, it is difficult to obtain accurate registration from frame to frame.

The problems of aligning the two cameras once they have been mounted in an aircraft can be frustrating. Current practice is to fly over a structure terrain, such as a town, and align the two images. This is time consuming and requires expensive aircraft flight time. A potential solution is using a fixed target on the ground and a 90^{o} mirror to align the two cameras. Once a suitable mirror material has been found, this should be a practical technique.

The major problem is the remote sensing of oil is the lack of a method to measurement slick thickness. A knowledge of the area of a slick is not important, where the volume is critical information both strategic response, dispersant effectiveness or cleanup efficiency measurements. This is the final component needed for the remote sensing of oil spills to become a fundamental information sources at an incident.

12.1 Thickness Measurements

None of the remote sensing techniques has the capability to determine the thickness of the oil on the water surface. Since in most situations, it is the volume of oil that is important, the knowledge of the area of a slick is of little interest. There has been a significant effort devoted to the development of remote oil thickness measurement techniques, but no reliable system has been developed. The microwave radiometer, which measures the microwave temperature of the oil, produces data which is related to oil thickness. This system can detect differences in thickness, but it cannot be calibrated to give absolute thickness since the apparent temperature is highly dependant on the water content of the oil.

The absorption of the water Raman line by an oil film was studied to determine its potential for use in the measurement of oil thickness (Hoge and Swift, 1980). They studied the suppression of the .381 micron Raman line of water due to the presence of oil. While changes in absorption were noted in both laboratory and field experiments when oil was present, it was not possible to quantify the adsorption in terms of oil film thickness. The main interfering factors were the water content and the natural fluorescence of the oil.

There is a general problem with the determination of slick thickness either from the air or water surface. Several surface sampling systems have been devised which use a fixed geometry, and sorbent pads (Belore, 1982). This apparatus has been found to give highly variable results, which are at best an estimate of the thickness within an order of magnitude. In calm water, this technique seems to work well and the results compare favourably with those obtained using a precision micrometer coupled to a detector (Brown and Goodman, 1986). However, on the ocean, such techniques are not useful.

In addition to the problem of obtaining a reliable thickness measurement, there is a sampling problem for a slick even of modest size. The sampling vessel must to small and of shallow draft so as not to disturb the slick, which limits the sampling to modest sea states. It is very difficult from such a vessel to determine the extent or location of the slick and thus obtain a representative sample. Hence an aircraft is required for guidance and positioning of the sampling vessel. In order to obtain a statistically reliable set of data, many samples must be taken, in as short a time a possible. There are no reliable surface sampling techniques available since the thin film of oil on the water surface is always disturbed by the sampling process (Goodman and Fingas, 1988).

12.1.1 Potential Techniques

Since oil thickness is identified as one of the most critical issues in terms of remote sensing of oil, a number of concepts have been investigated in Canada.

12.1.1.1 Propagation of Surface Acoustic Waves

It has been demonstrated that the presence of a film of material which presents an acoustic discontinuity allows the generation and propagation of Lamb waves, the wave length of which is related to the film thickness. Several workers have developed various concepts that use this phenomenon and other acoustic differences between oil and water. (Nawwar et al., 1987).

It order to initiate the process, it is necessary to generate an acoustic delta function. This can be done using radar, an acoustic beam or a laser. The problem is to obtain a reproducible impulse which is independent of the angle of incidence since the system must operate in a wave environment. It would appear that the radar systems, with their large skin thickness are the most suitable candidate. The next problem is the detection of the surface acoustic waves (Reimer and Rossiter, 1987).

One proposal is to use small buoys with acoustic transducers which telemeter the data to the remote sensing aircraft. This is similar in concept to the well developed sonabuoys which are used to detect submarines, but would seem to be a complex and slow method to measure oil thickness.

A second system proposed would use a laser interferometer to detect the acoustic surface wave pattern. While this has been demonstrated in laboratory experiments, it has not been tested on any larger scale (Monchalin, 1985).

12.1.1.2 Laser Induced Thermal Wave

The principal for this system is that the rate of propagation of a thermal shock wave is related to the thermal properties of the oil and the thickness of the film.

The device uses a laser to induce a thermal shock in the surface oil film and an infrared imaging system to measure the rate of propagation of the thermal wave and the damping of the wave.

Initial experiments have shown this to work at a laboratory scale. The rate of propagation and damping give independent measurements of the oil thermal properties, and the film thickness. This system is therefore self-calibrating and provides some information on the thermal properties of the oil. Additional properties of the oil, related to viscosity may be determined from the damping of the surface waves.

The system has only been tested at a laboratory scale and the effects of waves and wind action have not been determined.

12.1.1.3 Broad Band Impulse Radar

The use of impulse radar to measure ice thickness is a well established technology. Most of the ice radars operate in the 100 Mhz band, and measure ice thickness in the order of meters. The oil thickness problem is six orders of magnitude smaller and thus would require a frequency of factor of six greater. This is not practical with existing technology. An alternative is to illuminate the oil and water with a broad band of electromagnetic radiation and look in the frequency domain for the interference patterns at integer values of the wavelength in the film. Initial laboratory experiments were not successful, but this has been attributed to (Rossiter and Reimer, 1987) experimental difficulties and the limitation of the impulse radar employed in the study.

13. References

Axelsson, S., 1974 "Remote Sensing of Oil Slicks--Results form a Field Experiment in the Baltic Sea", September 1974. Saab-Scania AB, Missile Electronics Center.

Belore, R. 1982. "A Device for Measuring Oil Slick Thickness." Oil Spill Technology Newsletter 7(2) pp44-47.

Brown, H.M. and R.H. Goodman 1986. "In-Situ Burning of Oil in Leads." Proceeding of the 9th Arctic Marine Oil Spill Technical Seminar June 1986, Edmonton, Alberta, pp245-256.

Brown, H.M. and R.H. Goodman 1987. "Dispersants in the Freshwater Environment" ASTM Conference Proceedings Dispersants:New Ecological Approach throught the 90's, Williamsburg, VA (in press)

Brown, H.M. and R.H. Goodman 1988. "Dispersant Tests in a Wave Basin--Four Years Experience" Proceeding of the 11th Arctic Marine Oil Spill Technical Seminar June 1988, Vancouver, B.C., pp501-514.

Buettner, K.J.K. and C.D. Kern, 1965. "The Determination of Infrared Emissivities of Terrestrial Surfaces." J. of Geophysical Research 70 pp1329-1337.

CPA, 1986 "Freshwater Oil Spill Research Program Field Trial Final Report", Available through Canadian Petroleum Association, Calgary Alberta.
Cateo, C.E. 1973. "Remote Sensing Techniques for Detecting an Oil Slick." Journal of Petroleum Technology pp267-278.

Catoe, C.E. and J.T. McLean 1979. "A Multispectral Look at Oil Pollution, Detection, and Monitoring and Law Enforcement." CCRS Energy Mines and Resources Ottawa.

Fast, O. 1986. "Remote Sensing of Oil on Water-Air and Space Borne Systems." DOOS-Seminar 1986, Trondheim, Norway.

Fast, O. 1987. "Swedish Coast Guard starts using Third Generation Marine Surveillance System." Proceeding of 1987 Oil Spill Conference, Los Angeles, pp137-141

Fingas, M. 1982. "A simple night-time oil slick detector." Spill technology Newsletter vii(1):21-29

Garrett, B.P., R.M. Gershey and D.R. Green, 1986. "Remote Sensing Chronic Oil Discharges." Environment Canada EE80 p101 + appendices.

Garrett, B.P., W.G. Tidmarsh and R. Mitchner 1985. "Evaluation of Remote Sensing Technology for Monitoring Low Volume Oil discharges from Offshore Well Sites." Proceeding of the 8th Arctic Marine Oil Spill Technical Seminar June 1985, Edmonton, Alberta, pp303-317.

Gill, S.D. and C.W. Ross, 1982. "1981 Dispersant Application Field Trial-St John's Newfoundland." Proceeding of the 5th Arctic Marine Oil Spill Technical Seminar June 1982, Edmonton, Alberta, pp255-264.

Goodman, R.H., M.R. MacNeill and H. Ripley, 1984. "Remote Sensing Program for the 1983 Offshore Dispersant Trials." Proceeding of the 7th Arctic Marine Oil Spill Technical Seminar June 1983, Edmonton, Alberta, pp488-506.

Goodman, R.H., G. Petersen and R. Fitch, 1986. "The Use of Remote Sensing during teh Freshwater Dispersant Experiments." Proceeding of the 9th Arctic Marine Oil Spill Technical Seminar June 1986, Edmonton, Alberta, pp623-627.

Goodman, R.H. and H.M. Brown. 1987 "A Simple Remote Sensing System for the Determination of Dispersant Effectiveness." In Fate and Effects of Oil in Marine Ecosystems J. Kuiper and W.J. Van den Brink eds. Martinus Nijhoff Dordrecht, The Netherlands pp57-66.

Goodman R.H. and M. Fingas, 1988. "The use of Remote Sensing in the Determination of Dispersant Effectiveness."Proceeding of the 11th Arctic Marine Oil Spill Technical Seminar June 1988, Vancouver, B.C. p377-384

Green, D. 1983 Dome Petroleum Private Communication.

Guinard, N.W. 1971. "Remote Sensing of Oil Slicks." Proceedings of 7th International Symposium on Remote Sensing of Environment Ann Arbor Michigan pp1005-1026.

Hawkins, R.F., A.L. Gray, V. Thomson and R. A. Neville 1979. "Observation of Two Test Spills with a Radar Scatterometer and a Synthetic Aperture Radar (SAR)." Proceeding of Workshop of the NATO-CMMS Pilot Study on the Use of Remote Sensing fora the Control of Maine Pollution: Working Group #1 Spills of OIl and Hazardous Substances Washing D.C. 1979

Hoge, F.E. and R.N. Swift 1980. "Oil Film Thickness measurement using airborne laser-induced water Raman Backscatter." Applied Optics 19(19) pp3269-3281.

Horstein, B. 1972. "The appearance and visibility of thin oil films on water." EPA-R2-72-039 U.S. EPA Environmental Protection Technology Series.

Horvath, R., W.L. Morgan and R. Spellicy 1970. "Measurement Program for Oil Slick Characteristics." Report #2766-7-F ERIM Ann Arbor Michigan.

Horvath, R., W.L. Morgan and S.R. Stewart, 1971. "Optical Remote Sensing of Oil Slicks, Signature Analysis and Systems Evaluation." Willow Run Lab Ann Arbor, Michigan.

Hurford, N. and F.N. Matinelli. "The Use of an infrared line scanner and a side-looking airborne Radar to detect oil discharges form ships (ISOWAKE experiments) Warren Spring Lab PB83-259150 p11.

Intera 1982. "Remote Sensing Analysis of the Oil Spill Dispersant Sea Trial." Environment Canada EE-40 p79.

ITOPF 1981. "Aerial Observation of Oil at Sea", International Tanker Owners Pollution Federation Limited, Bulletin #1, London, England.

Kendall, B.M., H.J. C. Blume and A. E. Cross 1985. "Development of a UHF Radiometer." NASA TEchnical Paper 2504, Langley Research Center, Hampton Virginia.

LeGuen, Y.J.F., M. Brussieux and R. Burkhalter 1987. "Real-time processing of Oil Spill Remote Sensing Data." 1987 Oil Spill Conference API/USCG/EPA Los Angeles, pp71-73

Meeks, D.C., J.J. Bommarito, R.S. Schwantje and A.T. Edgerton. "Transfer, Installation and Flight Testing of the Modified Airborne OIl Surveillance System (AOSS II) in a HC-130B Aircraft, Final Report." United States Coast Guard, Washington, D.C. p160 Coast Guard #D-60-77

McColl, W.D., R.A.E. McGibbon and S.M. Till 1986. "CCRS Remote Sensing of the Beaufort Sea Dispersant Trials, 1986." Proceeding of the 9th Arctic Marine Oil Spill Technical Seminar June 1986, Edmonton, Alberta, pp291-306.

Monchalin, J.P. 1985. "Optical Detection of Ultrasound at a Distance using a Confocal Fabry-Perot Interferometer." Applied Physics Letters 47(1) 14-16.

Munday, J.C. Jr., W.G. MacIntyre, M.E. Penney and J. D. Oberholtzer 1971. "Oil Slick Studies using Photographic and Multispectral Scanner Data." Proceedings of the 7th International Symposium on the Remote Sensing of Environment University of Michigan, Ann Arbor.

Nawwar, A.M., A. Godon, H.W. Jones, E. Yeatman J. Ohuja, M.B. Frish and I. Arvin 1986. "Acoustic Methods for Measuring Thickness of Oil on Water." Environmental Studies Research Funds Report 072 Ottawa.

Neville, R.A., V. Thomson, K. Dagg and R.A. O'Neil 1979. "An Analysis of Multispectral Line Scanner Imagery from Two Test Spills". Proceeding of First Workshop Sponsored by Working Group I of the Pilot Study on the Use of Remote Sensing for the Control of Marine Pollution. NATO Challenge of Modern Society pp15.

O'Neil, R.A., L. Buja-Bijunas and D.M. Rayner 1980. "Field Performance of Laser Fluorosensor for the Detection of Oil Spills." Applied Optics 19(6) pp863-870.

O'Neil, R.A., R.A. Neville and V. Thomson, 1983 "The Arctic Marine Oilspill Program (AMOP) Remote Sensing Study." Environmental Protection Service EPS4-EC-83-3 Ottawa.

O'Neil, R.A., R. Vollmers, H. Parker, F. Gunnegern and R., Spoanoff 1979. " Airborne Remote Sensing of Oil Spills in Coastal Waters-Recommendations of Panels I and II. Proceeding of Workshop of the NATO-CMMS Pilot Study on the Use of Remote Sensing fora the Control of Maine Pollution: Working Group #1 Spills of Oil and Hazardous Substances Washington D.C.

Pronk, A.C. 1975. "Remote Sensing of Oil Pollution at the Sea Surface II: Damping of Water Waves by an Oil Layer as a Possible Indicator for SLAR Observations." NIWARS Technical Publication #22 Netherlands Interdepartmental Working Community for the Application of Remote Sensing Techniques, Delft Netherlands (July 1975).

Quaife, L.R., H. M.Brown, and C. H,. Peabody, 1986. "The Freshwater Oilspill Research Program--Experimental Design" Proceeding of the 9th Arctic Marine Oil Spill Technical Seminar June 1986, Edmonton, Alberta, pp601-622.

Rayner, D.M. and R.A. O'Neil 1979. "Laser Fluorosensors for Remote Environmental Monitoring." Optics News pp5 National Research Council of Canada.

Reimer, E.M. and J.R. Rossiter 1987. "Measurement of Oil Thickness on water from aircraft: A. Active microwave spectroscopy; B. Electromagnetic thermoelastic emission." Environmental Studies Research Funds Report No. 078 Ottawa viii + 82p.

Seakem, 1988 "Remote Sensing--Chronic Oil Discharges" Report to Environment Canada Halifax March 1988 File#KW203-7-1020

Simonett, D., 1983 "manual of Remote Sensing Volume II Interpretations and Applications", American Society of Photography, Fall Church, Virginia

Swiss, J.J., N. Vanderkooy, S.D. Gill, R.H. Goodman and H. M. Brown 1987. "Beaufort Sea Dispersant Trial." Proceeding of the 10th Arctic Marine Oil Spill Technical Seminar June 1987, Edmonton, Alberta, pp307-328.

Tennyson, E.J. 1988 "Shipborne radar as an oil spill tracking Tool" Proceeding of the 11th Arctic Marine Oil Spill Technical Seminar June 1988 Vancouver, British Columbia p385-390

Thomson, K.P.B. and W.D. McColl 1972. "Remote Sensing Survey of the Chedabucto Bay Oil Spill." Environment Canada Scientific Reports #26 p3.

Till, S.M. and R.A. O'Neil 1985. "Development of an Airborne Operational Laser Fluorosensor for use in the Canadian Offshore and Arctic." Proceeding of the 8th Arctic Marine Oil Spill Technical Seminar June 1985, Edmonton, Alberta, pp287-291.

Troy, B.E. and J.P. Hollinger 1977. "Measurement of Oil Spill Volume by a Passive Microwave Imager." NRL Report 3515 DOT-USCG 2-21881 USCG Washington

van Kuilenburg, J., P.W.H. Blansjaar, P.J.F. Geerders, K. Kubik, J. Van Kuilenburg and A. Rosema, 1972 "The Application of Remote Sensing Techniques", Netherlands Interdepartmental Working Community for the Application of Remote Sensing Techniques, Delft Netherlands (June 1972)

Wolfe, W.L. 1965. "Handbook of Military Infrared Technology" Office of Naval Research Washington D.C.

Wright, D.E. and J.A. Wright 1973. "Evaluation of an Infrared Oil Film Monitor." US Coast Guard Report CG-D-51-74 Department of Transportation Washington.