

## Oil-spill Remote Sensors: New Tools that Provide Solutions to Old Problems

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### Abstract

Remote sensors used for oil-spill slick detection and monitoring are reviewed, and new technologies and developments are highlighted. At the present time, the most commonly employed sensor is an infrared (IR) camera or combination infrared/ultraviolet (IR/UV) system. This sensor class can detect oil under a variety of conditions, discriminate oil from some backgrounds and has the lowest cost of any sensor. The inherent weaknesses include the inability to discriminate oil on beaches, among weeds or debris, through fog and at dawn and dusk (due to solar radiation conditions), oil is not detected. Furthermore, water-in-oil emulsions are sometimes not detected in the infrared. Older IR systems required cryogenic cooling of the detector element(s) in order to function adequately. This cooling requirement added to the size and cost of the system. New technology employing room temperature micro-bolometers has made IR technology more practical and economical, so despite its limitations, it will be a very important tool in the future. Recent results have provided some long sought after answers related to the thickness detection limits of infrared sensors.

The laser fluorosensor is an instrument of the future because of its unique capability to identify oil on backgrounds that include water, beaches, soil, ice and snow. It is the only sensor that can positively discriminate oil on most backgrounds. Radar offers the only potential for large area searches and foul weather remote sensing. Radar systems are costly and require dedicated aircraft. Radar is prone to many interferences, where false targets can be as high as 95%.

Equipment operating in the visible spectrum, such as cameras and scanners are useful for documentation or providing a basis for the overlay of other data. They are not useful beyond this because oil shows no unique spectral characteristics in the visible region. In the future, it is anticipated that less use will be made of equipment operating in the visible band.

The use of satellite imagery for the tracking of oil spills is reviewed. Sensors employing detectors in the visible region of the electromagnetic spectrum offer only marginal utility to the oil-spill response worker. Radar satellite imagery can provide useful overviews on known spills. One important new trend will be the use of a radar satellite for wide-area searching.

### 1.0 Introduction

Remote sensing is an accepted tool in the arsenal of oil spill response personnel. The minimum expectations of society are that the government and the

spiller know the location and extent of the oil contamination. Spill cleanup personnel have recognized that remote sensing can increase spill-cleanup efficiency. Recent advances in electronics have made instrumentation more economical and more capable. Despite this, the operational use of remote sensing lags the technology of sensor design.

By definition, remote sensing implies the use of a sensor, other than the human eye to detect a target at some distance. The most common tools employed for documenting oil spills are simple still or video cameras. The most common form of remote sensing as applied to oil spills is aerial remote sensing - that is employing an aircraft as a platform. Attempts to use satellite remote sensing for oil spills continue. Success is not necessarily as claimed, and generally applies to identifying features at sites where "known" oil spills have occurred.

This article focuses on reviewing oil spill remote sensors from an operational point of view. Other papers from the present authors have reviewed the technology of these sensors (Fingas *et al.*, 1994, 1995, 1996).

## **2.0 Optical Techniques**

### **2.1 Sensors Operating in the Visible**

Optical techniques are the most widely used means of remote sensing. Cameras, both still and video, are commonplace due to their low price and the fact that they are commercial-off-the-shelf (COTS) readily available items. Digital single-lens-reflex (SLR) cameras and camcorders are now available at reasonable prices. Oil has an increased surface reflectance above that of water in the visible (~400 to 700 nm), but shows limited non-specific absorption tendencies. In the visible band, oil has no sharp spectral features, and hence appears black, brown or gray to the observer. Sheen appears silvery and reflects light over a wide region up to the blue. There is no characteristic information in the visible region between 500 and 600 nm, so this region is often filtered out, to provide increased contrast. In general, oil has no spectral characteristics in the visible band which distinguish it from the background. Taylor (1992) examined the visible spectra of oil in the laboratory and the field and observed flat spectra with no spectral features that could be employed to distinguish it from the background. Neville has proposed that contrast between oil and background increases with increasing wavelength (Neville, 1994). Experimentally it has been found that the use of a horizontally-aligned polarizing filter which passes only that light reflected from the water surface and setting the camera at Brewster's angle (53 degrees from vertical) improves the contrast in visible imagery. It is this component that contains the information on surface oil (O'Neil *et al.*, 1983). This technique is said to increase contrast by as much as 100%. Filters that have band-pass below 450 nm can also be used to improve contrast. One should recognize the likelihood that the recognition of oil in the visible spectrum may be more related to human pattern recognition than colour.

Scanners have frequently been employed in the visible region of the spectrum. A rotating mirror or prism sweeps the field-of-view (FOV) and directs the light to a detector. Prior to the advent of charge-coupled detectors (CCDs), scanner technology provided enhanced selectivity and sensitivity compared with video cameras. The primary advantage of scanners is that the signals can be digitized and enhanced before display. Similar digitization can now be achieved without scanning by using a CCD

imager and continually recording all array elements, each of which is directed to a different FOV on the surface. These sensors are known as push-broom scanners. Several types of aberrations and errors can be overcome through the use of CCD technology. CCD units are more reliable than mechanical scanners, and all data are collected simultaneously for a given line perpendicular to the direction of flight. Several types of scanners have been built (Fingas *et al.*, 1994). These instruments, however, do not offer a distinct advantage over cameras for oil spill response work.

The use of visible techniques is generally restricted to that of documentation because the lack of a positive oil-detection mechanism. In addition many interferences or false positives exist. Sun glint and wind slicks can be mistaken for oil sheens. Biogenic material such as surface vegetation or sunken kelp can be mistaken for oil. Oil on shorelines is difficult to identify positively because vegetation can have a similar appearance. Oil on dark shorelines cannot be detected. In summary, utility of the visible spectrum for oil detection is limited. It does, however, provide an economical means of documenting spills and providing baseline data on shorelines or relative positions. Visible techniques are routinely used for oil spills, primarily because of the low cost and the ability to employ them on aircraft-of-opportunity.

## 2.2 Infrared Sensors

“Optically thick” oil absorbs solar radiation and re-emits this radiation as thermal energy mainly in the 8-12  $\mu\text{m}$  spectral region. Thick oil appears hot in infrared images, intermediate thicknesses appear cool, and thin oil or sheen is not detectable. At night the reverse is observed. The thicknesses at which these transitions occur are not known accurately, however scientific evidence indicates that the transition between the hot and cool layers lies between 50 and 150  $\mu\text{m}$  and the minimum detectable layer lies between 10 and 70  $\mu\text{m}$  (Fingas *et al.*, 1994). When the oil and water are at the same actual temperature, the oil will have an apparent lower temperature due to the differences in emissivity between oil (0.94-0.97) and water (0.98).

Infrared cameras in the 8 to 12  $\mu\text{m}$  range are now very common. In the past, infrared scanners were commonly employed. These older generation infrared detectors required cryogenic cooling to eliminate thermal noise, which would otherwise overwhelm any useful signal. The earliest method of cooling the detector was by filling a cryogenic dewar with liquid nitrogen. This generally provided about 4 hours of service. More recently, smaller sensors have employed thermo-electric or Joule-Thompson coolers which use the cooling effect realized when a gas is expanded. In the past year, a new type of infrared detector - a silicon based micro bolometer array - has entered the marketplace (Kreider *et al.*, 1997). These micro bolometer arrays can be operated uncooled and therefore are much cheaper, smaller and require much less power to operate. Each bolometer in the array measures temperature changes induced by incident thermal radiation. The array is packaged in a small vacuum package to provide thermal isolation. The output signals can be controlled externally to provide signals that adhere to NTSC or PAL video standards. Currently the noise equivalent temperature difference (NETD) of micro bolometer focal plane arrays is  $\sim 0.1$  K at 30 Hz frame rates. It is anticipated that this will be reduced to between 0.03 and 0.05 K in the near future. This will then be comparable

to cooled PtSi arrays (NETD 0.05 K) or cooled HgCdTe or InSb arrays (NETD 0.025K) (Kreider *et al.*, 1997). One of these uncooled microbolometers has recently been integrated into a remote sensing package that can be flown on aircraft-of-opportunity (Brown *et al.*, 1998a).

Most commonly, infrared remote sensing has taken place in what is known as the thermal infrared region at wavelengths between 8 and 12  $\mu\text{m}$ . Tests of mid-band IR systems (3 to 5  $\mu\text{m}$ ) have indicated that these sensors may have some utility (Hover, 1994; Hover and Plourde, 1994). Specific studies in the thermal infrared (8-12  $\mu\text{m}$ ) shows there is no spectral structure in this region. Tests on several infrared systems show that spatial resolution is important especially when the oil is distributed in patches and windrows. In addition, emulsions are not always detectable in the infrared (Hover, 1994).

The relative thickness information that can be provided in the infrared is useful since it can be used to direct oil recovery equipment to thicker portions of the slick. Contrary to popular opinion, recent experiments have shown that there is no direct correlation between oil slick thickness and brightness in infrared imagery (Brown *et al.*, 1998b). Oil detection in the infrared is not foolproof, since several false targets can interfere - including vegetation, shorelines, and oceanic fronts. Infrared is, however, reasonably economical and is currently the prime remote sensor employed by the spill responder. Due to the recent advances in detector technology, the use of infrared sensors will become commonplace in the future.

### 2.3 Ultraviolet Sensors

Oil is highly reflective of ultraviolet (UV) radiation even at thin layers (<0.01  $\mu\text{m}$ ) (O'Neil *et al.*, 1983). Ultraviolet sensors can therefore be used to map thin sheens of oil. Ultraviolet and infrared images are often overlapped to produce a relative thickness map of oil slicks. Ultraviolet data are subject to many interferences or false positives including, wind slicks, sun glint and biogenic materials. Since these interferences are often different than those observed for infrared sensing, the combination of IR and UV can provide a more positive indication of oil than the use of either technique alone. UV sensors are not commonly used in an operational response mode and will not have a strong role in the future except in conjunction with IR techniques.

### 3.0 Laser Fluorosensors

Laser fluorosensors employ the property that certain compounds (primarily aromatic hydrocarbons) in the oil absorb ultraviolet light and re-emit a portion of this energy in the visible region of the spectrum. Few other compounds show this tendency, hence fluorescence emission is strongly indicative of the presence of oil. Naturally-occurring substances such as chlorophyll, fluoresce at sufficiently different wavelengths to avoid confusion. Different classes of oil yield slightly different fluorescent spectral signatures and intensities. One can therefore differentiate between different classes of oil under ideal conditions (Hengstermann and Reuter, 1990; Brown *et al.*, 1994a,b, 1995b, 1996a,b,c).

The majority of laser fluorosensors used for oil detection employ a laser operating in the ultraviolet between 300 and 340 nm. At these wavelengths of excitation, there exists a broad organic matter fluorescent return, centred at 420 nm.

This fluorescence signal is known as Gelbstoff or yellow matter, which can be easily annulled. Chlorophyll yields a sharp peak at 685 nm. Oil fluorescence is typically in the region between 400 and 650 nm with peak intensities in the 480 nm region. There exists a phenomenon known as Raman scattering. The water molecules can absorb the incident laser pulse and return the incident energy minus some rotational-vibrational energy. The water Raman signal occurs at 344 nm when the incident wavelength is 308 nm (XeCl laser). The water Raman is useful for maintaining wavelength calibration of the fluorosensor, but had also been proposed as a way to estimate oil thickness, because oil on the surface will suppress the water Raman signal in proportion to thickness (Hoge and Swift, 1980). This technique is by no means operational and would in any case only be usable for very thin slicks (between 1-10  $\mu\text{m}$ ).

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 vegetation and detecting oil in a variety of environments including beaches and on snow and ice. Tests on shorelines have shown this to be highly successful technique (Dick *et al.*, 1992). Fluorosensors have recently been used operationally however only by a pair of agencies. It is anticipated that the use of fluorosensors will increase in the future because of their unique capability to positively identify oil.

#### **4.0 Microwave and Radar Techniques**

##### **4.1 Radar Sensors**

Oil on a sea surface dampens some of the small capillary waves that are normally present on clean seas. These capillary waves reflect radar energy producing a "bright" area in radar imagery known as sea clutter. The presence of an oil slick can be detected as a "dark" area or one which has an absence of sea clutter. Unfortunately oil slicks are not the only phenomenon which can be detected in similar manner. There are many potential interferences including, fresh water slicks, calm areas (wind slicks), wave shadows behind land or structures, vegetation or weed beds which calm the water just above them, glacial flour, biogenic oils, whale and fish sperm. Despite these limitations, radar is an important tool for oil spill remote sensing since it is the only sensor capable of doing large area searches (approximately 50,000 square kilometres per hour for airborne systems). Radars are one of the few sensors that can "see" at night and through clouds or fog.

Two basic types of radars have application to oil spills and general environmental remote sensing, Synthetic Aperture Radars (SARs) and Side-Looking Airborne Radars (SLARs). SLARs are an older technology, but are more economical to purchase and employ long antennae to improve along-track resolution. SARs use the forward motion of the sensor (aircraft or spacecraft) to synthesize a very long antenna, thereby achieving along-track resolution (which is range independent). Sophisticated electronic processing is needed to extract images from a SAR signal. SARs are more costly, but are capable of more range and greater resolution than SLARs. Comparative tests show that SAR is vastly superior (Mastin *et al.*, 1994). Radar systems developed for search and rescue roles have little, if any, application to oil spills because they are designed to located hard targets. Such radar systems contain complex circuitry to remove sea clutter, which is the primary signal of interest for oil-spill detection.

Experimental work on oil spills has shown that X-band radar yields better data than L- or C-band radar (Fingas and Brown, 1996). In addition, it has been shown that antenna polarizations of vertical for transmission and vertical for reception (VV) also yield better results than other configurations (Madsen *et al.*, 1994). Recent investigations have found that C-band HH polarized imagery such as that collected by the Canadian Radarsat satellite does an extremely good job on delineating oil slicks. Radar detection of oil slicks is limited by sea state, low sea states 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. This limits the application of radar for oil slick detection.

In summary, radars optimized for oil spills can provide useful information to spill response personnel, in particular for large area searches and for night-time or foul weather work. The technique is susceptible to false targets and is limited to a narrow range of wind speeds. A number of agencies employ radars for operational remote sensing. Airborne radar may not be as popular in the future, however, the use of satellite radar data will be useful for large scale work where positive identification is not a prime consideration.

#### 4.2 Passive Microwave Sensors

The ocean is an emitter of microwave radiation. Oil on the ocean is a strong emitter of microwave radiation compared to water and thus appears as a "bright" area on a darker sea. Water has an emissivity factor of 0.4, whereas oil has an emissivity factor of 0.8 (Ulaby *et al.*, 1986). A passive device can detect this difference in emissivity and could provide a detection means for oil. In addition, there is a change in signal with thickness, therefore in theory, the device could be used to measure slick thickness. This technique has not met with great success. First, the methodology relies on prior knowledge of several environmental and oil specific parameters and 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 film thicknesses within a given slick. Emission of microwaves is a maximum when the effective thickness equals an odd multiple of a quarter wavelength of the observed energy. In addition, biogenic materials cause interference and the signal-to-noise ratio is poor. High spatial resolution is difficult to achieve (Goodman, 1994a). New wide-band techniques may offer potential however the work has progressed slowly (McMahon *et al.*, 1995).

In summary, passive microwave radiometry may offer potential as an all-weather oil sensor. Its potential as a reliable slick thickness measurement device is questionable. Currently, microwave radiometers are not widely used operationally and these sensors may not be common in the future.

#### 5.0 Slick Thickness Sensors

There has long been a need to measure oil slick thickness. No reliable field or laboratory methods exist to measure oil on water slick thickness. The ability to measure slick thickness would, no doubt, result in significant advances in the basic understanding of the dynamics of oil slick spreading, and improve our ability to deal

with them. There is motivation to develop a slick thickness sensor so that the effectiveness of certain countermeasures such as dispersants can be measured. The volume of oil remaining on the water (an absolute measurement of dispersant effectiveness) cannot be measured without such a device. Finally, there is strong motivation to determine the amount of oil in fugitive slicks. Airborne surveillance of slicks with present sensors often results in erroneous estimates of oil quantity.

There have been several attempts at developing sensors for slick thickness measurement in recent years. The most promising technique involves "laser acoustic" detection (Brown *et al.*, 1994a, 1995a). A high-powered CO<sub>2</sub> laser is used to heat the oil layer. This creates thermal and acoustic waves in the oil. The acoustic waves can be detected using a second laser (Nd:YAG) and an optical interferometer. Slick thickness can be determined from the time-of-flight (TOF) of the acoustic wave between the upper and lower surfaces of the oil slick. This is an absolute means of measuring oil thickness and offers great potential. A consortium of agencies including Imperial Oil Resources Limited, Environment Canada and the United States Minerals Management Service is pursuing this technology. Laboratory tests have confirmed the viability of the method and a test unit has been flown to test the operation of the sensor in an airborne environment. The unit will have operational capabilities once completed but will likely remain a "scientific research instrument" rather than an operational tool.

## **6.0 Real-Time Displays and Printers**

An often overlooked requirement for operational remote sensing is the need for prompt delivery of data products that response personnel can quickly interpret and use. Real-Time displays are important so that sensor operator(s) can adjust sensors in-flight and so that they can provide rapid information on the location and state of the spill. A major concern of the client (responder) is that the data be readily available (Goodman, 1994b). COTS equipment are not always available for direct production of sensor data. At the present time modification of hardware and software is often necessary.

## **7.0 Satellite Remote Sensing**

There is an impression that satellite remote sensing could replace airborne remote sensing in the near future. Although it is likely that space borne sensors will increasingly be used for oil spill remote sensing, there remains a niche that only airborne sensors can fill. The need for prompt data delivery will keep airborne systems busy for the foreseeable future. At best, present satellites can provide one or two images per day. The use of satellite remote sensing for oil spills has been attempted several times. The massive Exxon Valdez slick was detected on LANDSAT satellite data (Dean *et al.*, 1990). Oiled ice in Gabarus Bay resulting from the KURDISTAN spill was detected using LANDSAT data (Dawe *et al.*, 1981; Alfoldi and Prout, 1982). Several workers were able to detect the Arabian Gulf War Spill in 1991 (Fingas *et al.*, 1994). The HAVEN spill near Italy was monitored. It is significant to note that in all these cases the position of the oil was known and in all cases, data had to be processed to see the oil. Data processing with these visible sensors usually required several weeks.

There are several problems in reliance on optical satellite remote sensing. The

first is the frequency with which satellite overpasses occur. The second is the absolute reliance on clear skies when collecting optical images. These two factors combined, result in a very low probability of "seeing" an oil spill in optical satellite data. The case of the Exxon Valdez spill illustrates this point well (Noerager and Goodman, 1991). Although vast amounts of sea surface were covered by the spill for over a month, there was only one clear day when a satellite overpass occurred (April 7, 1989). The third disadvantage of optical 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. Optical satellite imagery does not offer much potential for oil spill remote sensing.

The European (ERS-1,2) and Canadian (Radarsat) radar satellites offer some potential for large offshore spills, however limited testing with the ERS-1 has shown that many false signals are present in a large number of scenes (Wahl *et al.*, 1993; Bern *et al.*, 1993). These false targets will hopefully be reduced through the use of advanced signal processing. Radarsat produced useful data on the Sea Empress spill near Wales, the Nakhoudka spill in the Sea of Japan and during the raising of the Irving Whale oil barge north of Prince Edward Island (see for example, Hodgins *et al.*, 1997). Although, in all three cases "false slicks" were observed over much of the imagery and knowledge of actual slick locations was required to use the data. In the next couple of years a new generation of radar satellites will be launched with improved sensor capabilities. In particular, Envisat, Radarsat 2 and the Earth Observing System (EOS) will incorporate a variety of polarimetric and interferometric capabilities. Design specifications for these sensors have not been finalized at this time however preliminary information is available (Skøelv *et al.*, 1996; Sardar, 1997). Radar satellites are not currently being used for operational work however, the overview potential for known slicks will be increasingly exploited.

## **8.0 Sensor Recommendations**

Recommendations for oil spill remote sensing systems are based on the above discussions with cost being a primary consideration. The first sensor recommended for oil spill work is an infrared camera. Present day cameras that employ micro bolometer technology are small, economical and require only a small amount of power to operate. These cameras are readily adaptable for use in almost any aircraft. An infrared camera and ancillary equipment can be purchased for approximately \$50,000. This is the only piece of equipment that can be purchased off-the-shelf. All other sensors require special order and in many cases actual sensor development. The laser fluorosensor offers the only potential for discriminating between oiled and un-oiled vegetation, for positively identifying oil contamination on ice or snow, and in a variety of other environments. These sensors are however, large and expensive. A production unit could cost in excess of \$500,000 and weigh 200 kg or more. 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 between \$700,000 to \$1,000,000. SAR is the preferred radar technology and a unit will cost between \$2,000,000 to \$4,000,000 and 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, and a data down- or side-link.

## 9.0 References

Alfoldi, T.T. and N.A. Prout, *The Use of Satellite Data For Monitoring Oil Spills in Canada*, Environment Canada Report Number EPS 3-EC-82-5, Ottawa, Ontario, 1982.

Bern, T-I, T. Wahl, T. Anderssen and R. Olsen, "Oil Spill Detection Using Satellite Based SAR: Experience from a Field Experiment", *Photogrammetric Engineering and Remote Sensing*, Vol. 59, No. 3, pp. 423-428, 1993.

Brown, C.E., Z. Wang, M. Fruhwirth and M. Fingas, "May 1993 Oil-Spill Sensor Test Program: Correlation of Laser Fluorosensor Data With Chemical Analysis", in *Proceedings of the Seventeenth Arctic and Marine Oilspill (AMOP) Technical Seminar*, Environment Canada, Ottawa, Ontario, pp. 1239-1261, 1994a.

Brown, C.E., M. Fruhwirth, M. Fingas, R. Goodman, M. Choquet, R. Héon, C. Vaudreuil, J-P. Monchalain and C. Padioleau, "Laser Ultrasonic Remote Sensing of Oil Thickness: Absolute Measurement of Oil Slick Thickness", in *Proceedings of The First International Airborne Remote Sensing Conference and Exhibition*, ERIM Conferences, Ann Arbor, Michigan, pp. I567-I578, 1994b.

Brown, C.E., M. Fruhwirth, M.F. Fingas, R.H. Goodman, G. Vaudreuil, J-P. Monchalain, M Choquet, R. Héon, C. Padioleau and J. Mullin, "Absolute Measurement of Oil Slick Thickness: Why Do We Need to Know and How Can We Achieve It", in *Proceedings of the Third Thematic Conference on Remote Sensing for Marine and Coastal Environments*, Environmental Research Institute of Michigan, Ann Arbor, Michigan, pp. I491-I500, 1995a.

Brown, C.E., M. Fruhwirth, and M.F. Fingas, "Scanning Laser Environmental Airborne Fluorosensor: Progress on an "Exciting" Development", in *Proceedings of the Third Thematic Conference on Remote Sensing for Marine and Coastal Environments*, Environmental Research Institute of Michigan, Ann Arbor, Michigan, pp. I1-I5, 1995b.

Brown, C.E., M.F. Fingas and R. Nelson, "Airborne Laser Fluorosensors: Valuable Tools for Response to Marine and Terrestrial Oil Spills", in *Proceedings of Ecoinforma '96, Global Networks for Environmental Information*, Environmental Research Institute of Michigan, Ann Arbor, Michigan, Vol. 10, pp. 459-464, 1996a.

Brown, C.E., M. Fruhwirth, R. Nelson and M.F. Fingas, "Upgrading the Laser Environmental Airborne Fluorosensor to Provide a Real-Time Response to Oil Spill Emergencies", in *Proceedings of the Nineteenth Arctic and Marine Oil Spill Program Technical Seminar*, Environment Canada, Ottawa, Ontario, pp. 1211-1220, 1996b.

Brown, C.E., M. Fruhwirth, M.F. Fingas, J.V. Mullin and G.L. Hover, "The Scanning Laser Environmental Airborne Fluorosensor: Providing Timely Response in

Complicated Marine Environments”, in *Proceedings of the Nineteenth Arctic and Marine Oil Spill Program Technical Seminar*, Environment Canada, Ottawa, Ontario, pp. 1247-1251, 1996c.

Brown, H., R.H. Goodman, A.B. Markov and H. Hudema, “Development and Testing of an Inexpensive Remote Sensing Package”, in *Proceedings of the Twenty-first Arctic and Marine Oil Spill Program Technical Seminar*, Environment Canada, Ottawa, Ontario, pp. 795-804, 1998a.

Brown, H., J.J. Baschuk and R.H. Goodman, “Infrared Sensing and the Measurement of Oil Slick Thickness”, in *Proceedings of the Twenty-first Arctic and Marine Oil Spill Program Technical Seminar*, Environment Canada, Ottawa, Ontario, pp. 805-810, 1998b.

Dawe, B.R., S.K. Parashar, T.P. Ryan and R.O. Worsfold, *The Use of Satellite Imagery For Tracking The KURDISTAN Oil Spill*, Environment Canada Report Number EPS 4-EC-81-6, Ottawa, Ontario, 31 p., 1981.

Dean, K.G., W.J. Stringer, J.E. Groves, K. Ahlinas and T.C. Royer, “The EXXON VALDEZ Oil Spill: Satellite Analyses”, in *Oil Spills: Management and Legislative Implications*, Eds. M.L. Spaulding and M. Reed, American Society of Civil Engineers, New York, pp. 492-502, 1990.

Dick, R., M. Fruhwirth, and C. Brown, “Laser Fluorosensor Work in Canada”, in *Proceedings of The First Thematic Conference on Remote Sensing for Marine and Coastal Environments*, ERIM Conferences, Ann Arbor, Michigan, pp. 223-236, 1992.

Fingas, M., C. Brown, M. Fruhwirth and L. Gamble, “Assessment of Sensors for Oil Spill Remote Sensing”, in *Proceedings of The First International Airborne Remote Sensing Conference and Exhibition*, ERIM Conferences, Ann Arbor, Michigan, pp. I1-I12, 1994.

Fingas, M.F., C.E. Brown, M. Fruhwirth, and L. Gamble, “Sensors for Oil Spill Remote Sensing: A Review of Performance in Use”, in *Proceedings of the Third Thematic Conference on Remote Sensing for Marine and Coastal Environments*, Environmental Research Institute of Michigan, Ann Arbor, Michigan, pp. I19-I30, 1995.

Fingas, M.F. and C.E. Brown, “Review of Oil Spill Remote Sensing”, in *Proceedings of Ecoinforma '96, Global Networks for Environmental Information*, Environmental Research Institute of Michigan, Ann Arbor, Michigan, Vol. 10, pp. 465-470, 1996.

Goodman, R.H., “Remote Sensing Resolution and Oil Slick Inhomogeneities”, in *Proceedings of The Second Thematic Conference on Remote Sensing for Marine and Coastal Environments: Needs, Solutions and Applications*, ERIM Conferences, Ann Arbor, Michigan, pp. I1-17, 1994a.

Goodman, R.H., "Overview and Future Trends in Oil Spill Remote Sensing", in *Spill Science & Technology*, Vol. 1. No.1, pp. 11-21, 1994b.

Hengstermann, T. and R. Reuter, "Lidar Fluorosensing of Mineral Oil Spills on the Sea Surface", *Applied Optics*, Vol. 29, pp. 3218-3227, 1990.

Hodgins, D.O., S.S. Salvador, S.E. Tinis and D. Nazarenko, "RADARSAT SAR For Oil Spill Response", in *Proceedings of the Twentieth Arctic and Marine Oil Spill Program Technical Seminar*, Environment Canada, Ottawa, Ontario, pp.1031-1041, 1997.

Hoge, F.E. and R.N. Swift, "Oil Film Thickness Measurement Using Airborne Laser-Induced Water Raman Backscatter", *Applied Optics*, 19(19), p. 3269-3281, 1980.

Hover, G.L., "Testing of Infrared Sensors for U.S. Coast Guard Oil Spill Response Applications", in *Proceedings of The Second Thematic Conference on Remote Sensing for Marine and Coastal Environments: Needs, Solutions and Applications*, ERIM Conferences, Ann Arbor, Michigan, pp. I47-58, 1994.

Hover, G.L., and J.V. Plourde, *Evaluation of Night Capable Sensors For The Detection of Oil on Water*, Report of the United States Coast Guard, CG-D-09/94, 1994.

Kreider, J., P. Howard, C. Li and T. Fitzgibbons, "Uncooled Infrared Arrays Sense Image Scenes", *Laser Focus World*, pp. 139-150, August, 1997.

Madsen, S., N. Skou and B.M. Sorensen, "Comparison of VV and HH Polarized SLAR for Detection of Oil on The Sea Surface", in *Proceedings of The Second Thematic Conference on Remote Sensing for Marine and Coastal Environments: Needs, Solutions and Applications*, ERIM Conferences, Ann Arbor, Michigan, pp. I498-503, 1994.

Mastin, G.A., J.J. Mason, J.D. Bradley, R.M. Axline, and G.L. Hover, "A Comparative Evaluation of SAR and SLAR", in *Proceedings of The Second Thematic Conference on Remote Sensing for Marine and Coastal Environments: Needs, Solutions and Applications*, ERIM Conferences, Ann Arbor, Michigan, pp. I7-17, 1994.

McMahon, O.B., E.R. Brown, G.D. Daniels, T.J. Murphy and G.L. Hover, "Oil Thickness Detection Using Wide-band Radiometry", in *Proceedings of the 1995 International Oil Spill Conference*, American Petroleum Institute, Washington, D.C., pp. 15-19, 1995.

Neville, R., Private Communication, 1994.

Noerager, J.A. and R.H. Goodman, "Oil Tracking, Containment and Recovery During The EXXON VALDEZ Response", in *Proceedings of the 1991 Oil Spill Conference*,

American Petroleum Institute, Washington, D.C., pp. 193-203, 1991.

O'Neil, R.A., R.A. Neville and V. Thompson, *The Arctic Marine Oilspill Program (AMOP) Remote Sensing Study*, Environment Canada Report Number EPS 4-EC-83-3, Ottawa, Ontario, 257 p., 1983.

Sardar, A.M., "The Evolution of Space-Borne Imaging Radar Systems: A Chronological History", *Canadian Journal of Remote Sensing*, Vol. 23, No. 3, pp. 276-280, 1997.

Skøelv, Å., S.T. Dokken and T. Wahl, "Up-coming Radar Satellites and Their Potential for Some Marine Applications", in *Progress in Environmental Remote Sensing Research and Applications*, ed. E. Parlow, A.A. Balkema, Rotterdam, Netherlands, pp. 301-307, 1996.

Taylor, S., *0.45 to 1.1  $\mu\text{m}$  Spectra of Prudhoe Crude Oil and of Beach Materials in Prince William Sound, Alaska*, CRREL Special Report No. 92-5, Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire, 14 p., 1992.

Ulaby, F.T., R.K. Moore and A.K. Fung, *Microwave Remote Sensing: Active and Passive: From Theory to Applications*, Artech House Inc., Dedham, MA, 1986.

Wahl, T., K. Eldhuset and Å. Skøelv, "Ship Traffic Monitoring and Oil Spill Detection Using ERS-1", in *Proceedings of The Conference of Operationalization of Remote Sensing*, ITC, pp. 97-105, 1993.