

THE AIRBORNE REMOTE SYSTEMS FOR OFFSHORE OIL SEEPAGE DETECTION

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Keys:offshore, seepage, remote systems, ALF

Abstract

The paper presents an analysis of the airborne remote detection systems and their capabilities for the offshore petroleum exploration programs. Airborne and spaceborne sensors are reviewed and evaluated in terms of usefulness in responding of oil spills. The sensors are optical (visible, infrared, ultraviolet), ALF, hyperspectral mapping, microwave sensors (radiometers, radars, scatterometers), sonar systems, LURSOT system.

The paper shows the efforts towards detection and mapping of offshore oil seepage.

Remote sensing is useful in several modes of oil spill detection, including large area surveillance, site specific monitoring and tactical assistance in emergencies. It is able to provide essential information to enhance strategic and tactical decision-making, decreasing response costs by facilitating rapid oil recovery and ultimately minimizing impacts. For ocean spills, remote sensing data can provide information on the rate and direction of oil movement

Remote sensing from an aircraft is still the most common form of oil spill tracking. Attempts to use satellite remote sensing for oil spills continue, although success is not necessarily as claimed and is generally limited to identifying features at sites where known oil spills have occurred. For open ocean spills, there is less need for rapid changes in flying speed, direction and altitude, in these instances the use of low altitude, fixed-wing aircraft have proven to be the most effective tactical method for obtaining information about spills areas.

Airborne visual observations of spilled oil from the air, along with still and video photography, are the simplest and most common method of determining the location and extent (scale) of an oil spill. GPS and aircraft inertial systems allow pinpointing the oil's location. Photography, particularly digital photography, is also a useful recording tool and allows others to view the situation on return to base. Many devices employing the visible spectrum, including the conventional video camera, are available at a reasonable cost. Digital single-lens-reflex (SLR) cameras and camcorders are now available at reasonable prices. Dedicated remote sensing aircraft often have built-in downward looking cameras linked with a GPS to assign accurate geographic coordinates.

Oil has an increased surface reflectance above that the water in the visible (380 to 700 nm) but shows limited non-specific absorption tendencies to allow to use to the visible spectrum as an oil detection means. In the visible band, oil has no sharp spectral features. Heavy oil appears brown showing up to the 600 to 700 nm region. Mousse shows up in the red-brown or closer to 700 nm. Sheen appears silvery and reflects light over an wide region up to the blue. 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. This is the component than contains the information on surface oil (**Fig.1**) [12].



Fig.1. Scattered patches of heavy fuel oil spreading to brown and silver sheen in warm ambient conditions (air temp $\sim 30^{\circ}\text{C}$, water temp $\sim 25^{\circ}\text{C}$). Viewed from 300 m

Spills detection by visual observation is limited to favorable sea and atmospheric conditions and is inoperable in rain, fog, or darkness; visual observations are restricted to documentation of the spill because there is no mechanism for positive oil detection. Very thin oil sheens are also difficult to detect especially in misty or other conditions that limit vision. Oil can be difficult to see in high seas and among debris or weeds where it can blend in to dark backgrounds such as water, soil, or shorelines. Sun glint and wind sheens can be mistaken for oil sheens. Biogenic material such as surface weeds or sunken kelp beds can be mistaken for oil. Oil on shorelines is difficult to identify positively because weeds look similar to oil and oil cannot be detected on darker shorelines [1].

Airborne Hyperspectral Mapping

The multispectral data sets provided from LandSat allowed us to see the earth in colors not accessible to the human eye. Technology has progressed and it is now possible to view the earth not only in a few, but hundreds, of different spectral channels over a wide wavelength range -hyperspectral sensing and despite some attempts with satellite systems, airborne instruments are leading the way. The hyperspectral airborne sensor records a digital image of the earth's sunlit surface underneath the aircraft, the hyperspectral sensor records images different wavelengths of reflected light.

There are a number of research systems available [13] (eg. AVIRIS), and some first generation commercial systems (CASI, DAIS, etc). Most past and current hyperspectral sensors have been airborne, with two recent exceptions: NASA's Hyperion sensor on the EO-1 satellite, and the U.S. Air Force Research Lab's FTISI sensor on the MightySat II satellite. Several new space-based hyperspectral sensors have been proposed recently. AIG during 1995 using the AVIRIS instrument as a first attempt to broaden the use of hyperspectral data. A hyperspectral AIG/HyVista Group Shoot has been organised in the USA during 1999 using the commercial HyMap sensor.

The AVIRIS sensor allows more specific spectral analysis with wavelengths from 380 nm to 2500 nm, in 224 spectral channels, spectral resolution of about 10 nm. The 2001 AVIRIS scene of the Santa Barbara coastal zone is obtained from the NASA Jet Propulsion Laboratory (JPL) in California. AVIRIS data allow the study of different types of oil spills in the ocean, oil spill classification, and quantitative measurements for apparent oil spill.

HyMap airborne hyperspectral scanner developed by Integrated Spectronics in Sydney, Australia is affordable, high quality hyperspectral data on a commercial basis. The HyMap scanner provides 126 spectral channels spanning the wavelength range from the 0.4 to 2.5mm (visible to shortwave infrared) spectral region over a 512-pixel swath. To minimise distortion induced in the image by aircraft pitch, roll and yaw motions, the HyMap is mounted in a gyro-stabilised platform Zeiss-Jena SM2000 augmented with a Boeing C-MIGITS GPS/INS, the spatial resolution achieved with the HyMap is in the range of 3 to 10m. The key features are: hyperspectral sensors offer a number of advantages over current airborne oil sensing systems; fully developed for aircraft use, with signal processing to correct for aircraft position and movement; lightweight and compact, so that they can be fitted into small survey aircraft; the sensors are proved capable of defining the shape of slicks with high contrast and spatial resolution; can penetrate to depths of 20-30 m in clean water to see the submerged oil. The sensors are also reportedly successful under a wide range of sea conditions;

HyMap measuring capability in the Short-Wave Infra-Red (SWIR) offers the additional possibility of properly separating an effect called 'sunglint' from any data over open water, as water will absorb almost 100% of radiation at these wavelengths. Due to the same effect, it is also possible to discriminate seepage with strong surface expressions from other seepage. This is not possible with sensors lacking SWIR measurements.

Disadvantage include the high cost. Unlike other geophysical airborne sensors where the calibrated units can be used directly in the data interpretation stage, post-processed reflectance data from hyperspectral sensor are only the first step in the information extraction process.

Airborne Infrared sensors, which detect infrared radiation levels given off surfaces, have been developed into relatively inexpensive sensors for ship-board and aerial observation of oil slicks. These sensors are capable of detecting thicker parts of a slick only ($> 100 \mu\text{m}$) so are useful for guiding response to

the thicker parts of oil. They must be combined with an ultraviolet sensor, which shows the thin oil sheens, for complete imaging of both the thick and thin portions of a slick. The combined image provides a useful guide to where to direct response efforts [9,2].

Oil, which is optically thick, absorbs solar radiation and re-emits a portion of this radiation as thermal energy, primarily in the 8 to 14 μm region (8000 to 14000 nm). The nature of infrared signatures on water is depending on thickness of the oil, its weathering and the water temperature. For slicks of thicknesses between 50-500 μm , the oil appears to be at a lower temperature than the surrounding water. When the oil thickness is greater than 500 μm the oil appears warmer [6]. In infrared (IR) images, thick oil appears hot or white in infrared data, the middle thicknesses of oil appear cool and black, and thin oil or sheens are not detected.

Tests of a mid-band IR system MIR (3.4 to 5.4 μm) over oil spill showed no detection in this range, however, ship scars were visible. Studies in the thermal infrared TIR (8 to 14 μm) show that there is no spectral structure in this region. Tests of a number of infrared systems show that spatial resolution is extremely important when the oil is distributed in windrows and patches, emulsions are not always visible in the IR, and cameras operating in the 3 to 5 μm range are only marginally useful [1]. Oil detection in the infrared is not positive, however, as several false targets can interfere, including weeds, shoreline, and oceanic fronts. Infrared is reasonably inexpensive, however, and is currently the prime tool used by the spill remote sensor operator. A disadvantage of any type of infrared detector, however, is that they require cooling to avoid thermal noise, which would overwhelm any useful signal.

Airborne Laser Fluorosensor (ALF) [13] seepage detection system is a seep detection system that uses a sophisticated, solid state laser to generate UV light which is pulsed from a low flying aircraft (**Fig. 2**). The laser induces fluorescence in any fresh hydrocarbons on the sea surface, which satellite or other airborne techniques would have difficulty in detecting. Oils are complex mixes containing typically about 10,000 hydrocarbon compounds that fluoresce. Due to the differences in the composition the fluorescence spectra of different oils show variations with respect to the spectral form and the intensity of the fluorescence observed. So the natural oils fluorescence when are illuminated by ultra violet (UV) light. Flying height is typically 80 m (to 600 m) and flying speed is typically 270 km/hr. A surface swath width is 100 m at 300 m flight altitude conical scanner for two-dimensional mapping of sea surface.

The ALF acquisition system is performance by excimer laser at 308 nm for the analysis of oil and organic pollutant (MkII system, Barringer's Fluoroscan) and the newest MkIII with NdYAG laser at 266 nm with 176 recorded channels and records fluorosensor data at the 50 Hz acquisition rate. A telescope collects any fluorescence signal which is passed through a diffraction grating to produce a spectrum which is sampled using a diode detector array. Each laser pulse has a duration of 7ns, the delay increases with increasing flying height (533ns at 80m height). Detectable oil film thickness in the field: 0.01 to 0.05 μm .

Most laser fluorosensors used for oil spill detection employ a laser operating in the ultraviolet region of 300 to 355 nm. There exists a broad range of fluorescent response for organic matter, centered at 420 nm referred to as Gelbstoff or yellow matter, which can be easily cancelled. Chlorophyll makes a sharp peak at 685 nm. Cruid oil fluorescence return is within 400 and 650 nm with peak centered in 480 nm. The Raman signal occurs at 344 nm for laser wavelength is 308 nm-XeCl laser and excitator of MkII. The MkIII laser Raman peak occurs at 293 nm and can be used for oil layer thickness estimation because the strong absorption by oil on the surface will suppress the water Raman signal in proportion to thickness.

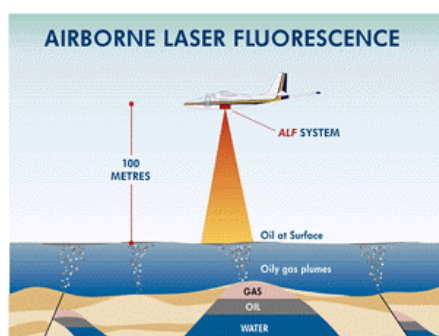


Fig.2

The new generation of the Laser Environmental Airborne Fluorosensor (LEAF), which was developed in Canada in 1992 now is the Scanning Laser Environmental Airborne Fluorosensor (SLEAF) operating aboard a DC-3 aircraft based in Ottawa. The key features are: ALF detects oil sea surface films that may be too thin for satellite or other airborne methods and detects oil spills below the sea surface; ALF estimates the oil volume- quantity and type of oil- e.g. heavy crude oil with a probability of 98% on the water surface, identification of the oil through its spectral form; ALF can be used during day and night if the visibility is sufficient and within certain limits is practically independent of the sea state; ALF gives information about hydrocarbon source, charge rates, trap integrity and oil degradation, helping reduce risk in further exploration

of the area; ALF is a fast and cost effective method of covering large areas prior to further exploration; The ability of the ALF to determine even very small quantities of oil quantitatively and to identify the type of oil makes it an indispensable sensor of sensor equipment for aerial marine surveillance.

ALF is the active sensor capable of remotely measuring oil in the sea surface. Disadvantages include the large size, weight and high cost.

Airborne microwave sensors (MWS)

MWRadiometers. Oil on the ocean emits stronger microwave radiation than the water and thus appears as a bright object on a darker sea. The emissivity factor of water is 0.4 compared to 0.8 for oil [12]. A passive device can detect this difference in emissivity and could therefore be used to detect oil. In addition, as the signal changes with thickness, in theory, the device could be used to measure thickness. The line scanning microwave radiometer (MWR) enables quantitative assessments of detected oil slicks by analysing the radiant emission from the sea surface and oil slicks at two or three frequencies for avoidance of interference (18.7- thickness and volume determination for thicker layers with reduced geometrical resolution (22 m), 36.5- all-weather capability and best-possible geometrical resolution (11 m) and 89 GHz- sensitive detection of thin layers and high geometrical resolution (5 m), see **Fig.3**) [1].

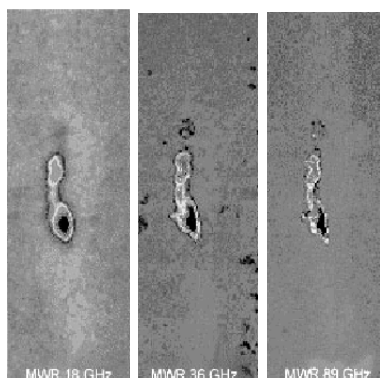


Fig.3 Example of an crude oil field with approx. 5m 3 oil impact; maximum layer thickness 1.8mm

The modular multiple-frequency radiometer allows the unambiguous determination of film thicknesses in the extended range from 0.05 to 2.5 mm with an improved geometrical resolution of 5 m at a flight level of approx. 300 m.

This detection method has not been very successful in the field, however, as several environmental and oil-specific parameters must be known. In addition, the signal return is dependent on oil thickness but in a cyclical fashion. A given signal strength can imply any one of two or three signal film thicknesses within a given slick. Microwave energy emission is greatest when the effective thickness of the oil equals an odd multiple of one quarter of the wavelength of the observed energy. Biogenic materials also interfere and the signal-to-noise ratio is low. In addition, it is difficult to achieve high spatial resolution [14].

MWRadars. The two basic types of radar that can be used to detect oil spills and for environmental remote sensing in general are Side-Looking Airborne Radar (SLAR) and Synthetic Aperture Radar (SAR).

The Side-looking Airborne Radar (SLAR) is the primary sensor for long-range detection of oil pollution on the sea surface. SLAR sends out short pulses in the X-band perpendicular to the flight direction to left and right side of the aircraft and receives their reflection from small gravity and capillary waves up to a distance of typically 30 km, depending on wind conditions and aircraft altitude.

A number of other conditions can lead to false returns that are difficult to distinguish from that of oil on the water, among them algae blooms, freshwater fronts, sand banks and wind shadows. It is, however, also possible that other phenomena, like natural substances floating on the sea surface, local changes in the wind field or variations of the bottom topography smooth the water surface making it impossible to distinguish these areas from oil slicks. This procedure is, to a large extent, independent of weather and visual conditions and allows the detection of oil pollution through a cloud cover [14].

An airborne surveillance system to monitor the German territorial waters in the North Sea and Baltic Sea for oil discharges and marine pollution. A SLAR unit will cost between \$700,000 to \$1,000,000.

Satellite Synthetic Aperture Radar (SAR) systems are able to sense through cloud and darkness and to function day and night. This "all-weather" operation and the wide swath width provided by the available SAR satellites have been the major reasons why satellite-based SAR has been most commonly promoted for operational detection of oil slicks.

There are presently three SAR satellites in orbit with global coverage: RADARSAT, ERS-2 and ENVISAT. These provide revisit times for most places on the globe that are impractically long and irregular for operational sensing of a given spill. RADARSAT has a repeat cycle of 24 days for coverage of a given area of latitude, while ENVISAT and ERS-1 have revisit frequencies of 35 days and have the ability to image surface oil seeps remotely with wide swath coverage (typically 100 x 100km scenes for ERS and 165 x 165kms for Radarsat Wide1) [9,10].

The versatile RADARSAT satellite, operated and managed by the Canadian Space Agency (CSA), is equipped with a Synthetic Aperture Radar (SAR) which transmits its C-band microwave energy in a horizontal orientation (polarisation), the energy which returns to RADARSAT's sensor is captured using the same polarisation (HH polarisation). SAR obtains strips or swaths of HH polarized imagery from 50 to 500 kilometers in width with selectable resolutions from 10 to 100 meters. Variations in the returned signal (backscatter) are a result of variations in the surface roughness and topography as well as physical properties.

A number of limitations with Satellite SAR for oil spill detection have been recognised for some time. SAR systems rely on the detection of surface roughness, with rougher surface returning more of the microwave signal. Detection is difficult or impossible for some oil types. Satellite SAR systems also suffer from significant limitations for operational slick sensing. Principal obstacles have been coverage, limitations due to wind and sea state as well as the limited resolution that is provided by SAR images. First, wind speed value has to be between 2-3 to 10-14 m/s. Secondly, it is rather hard to distinguish oil spill from other phenomena which analogously to oil spills have negative radar contrast (look dark on SAR images) relative the surrounding waters and commonly referred to as "look-alikes" films of surface active substances observable particularly at wind speed < 5-6 m/s, wind shadow areas near the coast, heavy rains damping small scale roughness, upwelling zones and grease ice. Thirdly, the SAR image allows detecting oil on the ocean surface only, before it goes down in sub-surface layer as a result of dispersion. SAR images are also known to return many "false positives" for oil slicks caused by natural phenomena which generate patches of similar appearance (Fig.4)[5].

Automatic analysis of SAR images is not applied routinely yet. Several algorithms based on application of different approaches are suggested, realized and tested. After preprocessing (converting the original SAR data to a common format and geographical projection) and masking (to mask away all land areas, including small islets, and their innermost water areas where wind-dampening shadows often appear) the main task is detection of dark patches and bands in the image. SAR is the preferred radar technology and a unit cost between \$2,000,000 to \$4,000,000.

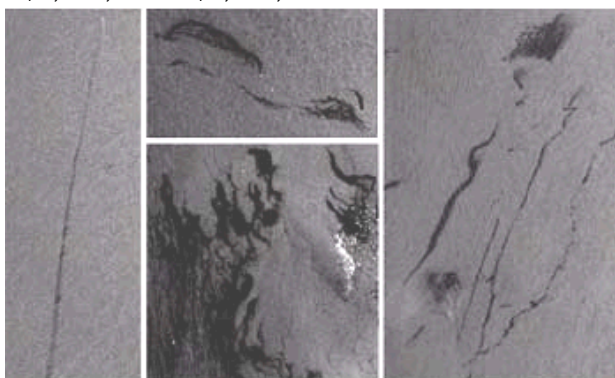


Fig.4 . Examples of various oil slicks on ERS SAR images:left- a long linear slick from a moving ship; middle up- slicks from offshore oil rigs; middle down- slicks probably from natural seepage; right- slicks along a major shipping route

The NASA/JPL airborne SAR (AIRSAR) system operates in two modes. In the first mode (POLARSAR), polarimetric radar data were collected at P-, L-, and C-bands. In the second mode (TOPSAR), cross-track interferometry data were collected at C- and L-bands. The original navigation system of AIRSAR consisted of a Honeywell Integrated GPS/INS (IGI) installed on the DC-8 aircraft with a ring laser gyro that determined the attitude of the aircraft and a new Motorola Six-Gun 6-channel GPS receiver that provided the positioning information of the aircraft and positioning accuracy of 100 m (CA code).

In **Table 1** are shown a comparison of satellite and airborne MW Sensors.

Radar	Spatial Resolution		Swath width	Overpass frequency	Full-earth Rep.Cycle	Typical Time process
	Minimum	Range				
ERS-2	30 m		100-500 km	3 days	35 days	<2 h.
RADARSAT-1	9 m	9-100 m	50-500 km	2 days	7-17 days	<2 h.
Airborne sensors						
SLAR	10 m	10-50 m	10-40 km (single-sided)	As required		Real-time
SAR	1-3 m	1-10 m	10-40 km (single-sided)	As required		Real-time

Table 1. Comparison of Selected Existing Satellite and Airborne Sensors [3]

A microwave scatterometer is a device that measures the scattering of microwave or radar energy by a target. The presence of oil reduces the scattering of the microwave signals just as it does for radar

sensors, however, and this device is adversely affected by the same large number of false targets has flown over several oil slicks and used a low-power transmitter operating in the Ku band (13.3 GHz). The main disadvantages include the lack of discrimination for oil and the lack of imaging capability [1,12] .

The **Laser Ultrasonic Remote Sensing of Oil Thickness (LURSOT)** sensor is developed by IMI of National Research Council, Canada and consists of three lasers, one of which is coupled to an interferometer to accurately measure oil thickness. The LURSOT is installed on DC-3 aircraft of Innotech Aviation INC. at the operating altitude of 100 m. and to a spot approximately 1.5 cm.in diameter. The thickness can be determined from the time of propagation of the acoustic wave between the upper and lower surfaces of the oil slick. The sensing process is initiated with a thermal pulse created in the oil layer by the absorption of a powerful CO₂ laser pulse. The displacement of the surface is measured by a second laser probe beam (Nd:YAG) aimed at the surface. Motion of the surface induces a phase or frequency shift (Doppler shift) in the reflected probe beam. The LURSOT uses a third laser (a continuous wave HeNe laser) to examine the water surface and generate a trigger pulse. The minimum detectable oil thickness layer which can be measured is 700 µm and the maximum is 38 nm [1,9,14] .

Conclusions

Remote sensing equipment mounted in aircraft is being used increasingly to monitor, detect and identify sources of oil spills. Cameras relying on visible light are widely used, and may be supplemented by airborne sensors which detect oil outside the visible spectrum and are thus able to provide additional information about the oil. The most commonly employed combinations of sensors includes Side-Looking Airborne Radar (SLAR) and downward looking thermal infra-red (IR) and ultra-violet (UV) detectors or imaging systems. Other systems such as Forward Looking Infra-Red (FLIR), Microwave Radiometers (MWR), Airborne Laser Fluorosensors (ALF) and hyperspectral imaging. UV, thermal IR, FLIR, MWR, and hyperspectral are passive sensors, measuring emitted or reflected radiation. With the possible exception of MWR, they are unable to penetrate cloud cover, fog, haze or rain. Their use is consequently limited to clear weather periods. SLAR and ALF incorporate an active source of radiation and can be used at night, as can some IR systems in the right circumstances where temperatures are sufficiently high. Radar-based systems can also penetrate cloud and fog and are therefore able to operate under most conditions.

As oil becomes harder to find, pursuit of fractured reservoirs and subtle signs of hydrocarbons at the surface and sea surface will receive increased attention. Airborne ALF system and hyperspectral hydrocarbon mapping are the insights of detection oil seeps source on the sea surface because of their high effectiveness and should be used in conjunction with GPS and aircraft inertial systems which allow pinpointing the oil's location and other airborne geo-data sets.

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