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Oil Slick Thickness Measurement: A Possible Solution to A Long-Standing Problem

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Abstract

The measurement of oil slick thickness has long been a relative science, with absolute measurement eluding the remote sensing community. Knowledge of oil slick thickness would significantly benefit both the spill response and scientific research communities. The effective direction of oil spill countermeasures such as *in situ* burning and dispersant application depends on knowledge of slick thickness and volume. Without accurate thickness information, application of these technologies in a spill response is a hit-and-miss scenario at best. In the research community there remains a great deal to be learned about oil slick spreading, and dispersant effectiveness. A remote sensor which can provide an absolute measurement of oil thickness, could begin to unravel some of the mystery surrounding the dynamics of oil slick spreading and provide a real method of measuring dispersant effectiveness. One of the most exciting roles for the slick thickness measurement sensor would be the calibration of other pieces of remote sensing equipment. Some of the most economical and commonly used airborne remote sensors are the ultraviolet/infrared (UV/IR) scanners and cameras. The UV portion of the sensor responds to the entire area of the slick including the thin sheen areas. The thermal IR portion of the sensor provides information on the thicker portions of the slick. The integration of data from the UV and IR provides an indication of the thick and thin portions of the slick. This is however a relative picture with little known about the actual thicknesses involved. Calibration of these economical instruments with a sensor capable of absolute slick thickness measurement would be a boon to the response community.

Environment Canada, in conjunction with Imperial Oil Resources Limited, the United States Minerals Management Service and the Industrial Materials Institute of the National Research Council Canada are pursuing the development of a novel laser-based technique for the remote measurement of oil thickness on water. The demonstration system, referred to as the Laser Ultrasonic Remote Sensing of Oil Thickness (LURSOT) sensor has been assembled and successfully tested in a laboratory environment. The LURSOT sensor is presently being modified following participation in a recent airborne remote-sensing field trial and evaluation of the recommendations presented in the report "*Study into the Feasibility of Constructing an Operational Sensor for Laser-Ultrasonic Remote Sensing of Oil Thickness*". This paper will summarize the need for the type of information provided by the LURSOT sensor, and the present status of the system.

1.0 Introduction

There has long been a need to measure oil slick thickness, both within the oil spill response community and among academics in the field. There are presently no reliable methods, either in the laboratory or in the field to provide an accurate measure of oil-on-water slick thickness. The ability to measure oil slick thickness would provide significant advances to the basic understanding of the dynamics of oil spreading and behaviour. Knowledge of slick thickness would allow for more effective oil spill countermeasures including dispersant application and *in situ* burning. Indeed, the effectiveness of individual dispersants could be determined quantitatively with accurate measurements of the oil remaining on the water surface following dispersant application. Indeed when referring to the measurement of dispersant effectiveness, Mackay and co-workers concluded, "*There is an incentive to devise better methods of measuring oil slick thickness before and after dispersion for effectiveness assessment purposes, and as a guide to those applying dispersants. A remote sensing system is preferred. Measurement of effectiveness by taking water samples alone is unlikely to give reliable data. The aim should be to measure the amount remaining on the surface*" (Mackay *et al*, 1986). Finally, there is a need to calibrate some of the more economical and readily available pieces of remote sensing equipment. Several of these sensors provide relative, ie. thick or thin, indications of slick thickness. Calibration of these wide field-of-view sensors would provide a reliable method of estimating the volume of rogue oil slicks.

2.0 Slick Thickness Sensors

Optically thick oil will absorb solar radiation and re-emit a portion of this energy in the thermal infrared (IR), 8 to 14 μm, region of the electromagnetic spectrum. This oil is then detectable by infrared remote sensing. The thicker portions of oil appear to be warmer than the surrounding water. Oil of intermediate thickness appears to be cooler than the water, since although they possess the same physical temperature, oil is a weaker emitter than water in the thermal IR. Thin sheen patches of oil are undetectable in the thermal infrared. Attempts to calibrate the thickness appearance of IR imagery have not been successful (Belore, 1982, 1983). The reflectivity of oil at ultraviolet (UV) wavelengths is very high and therefore even thin sheens of oil (< 0.01 μm) can be detected. Infrared and ultraviolet sensors used in combination can provide an indication as to the location of the thicker and thinner portions of a slick. This combination of sensors is available commercially at reasonable cost and as such provides a useful means for the location of the thicker patches of oil targeted for clean-up operations. The laser fluorosensor, which is an active ultraviolet sensor, is able to measure slick thickness to a limited degree (Kung and Itzkan, 1976; Hoge and Swift, 1980). An ultraviolet laser pulse is used to excite the OH stretching vibration in water. Stimulation of this vibrational mode leads to a phenomenon known as Raman scattering. When a XeCl laser emitting at 308 nm is used for excitation, the Raman scattering is observed at 344 nm. The presence of oil on the water surface depresses this Raman signal in a manner proportional to the thickness of the oil provided the oil is not optically thick (up to ~ 20 μm depending on the absorption properties of the oil). This method requires knowledge of the absorption coefficient of the oil at the excitation and Raman wavelengths. Since oils absorb strongly in the ultraviolet, this method is applicable to only thin layers of oil . In the microwave region, oil is a much stronger emitter than water (O'Neil *et al*, 1983). Thus oil appears bright against the dark sea background. Microwave radiometers can detect this emissivity difference and provide a detection means for oil. In theory, there is a change in this microwave signal with thickness that would allow the instrumentation to be used for slick thickness measurement. In practise however, the signal return depends on signal strength in a cyclical fashion (Hurford, 1989). Therefore, a given signal strength can imply any one of two or three oil film thicknesses within a given slick. To overcome this cyclic redundancy, sensors have been developed which employ several different microwave frequencies. Compounding this problem is the fact that signal strength is dependant on many other environmental factors. Spatial resolution is also a problem since the spatial resolution of these sensors is often less than the spatial size of the oil homogeneities.

The Industrial Materials Institute (IMI) of the National Research Council of Canada has recently developed a novel measurement technique called Laser-Ultrasonics for the non-destructive evaluation of materials. This technique has shown considerable promise as a method to provide an accurate measurement of oil slick thickness on the surface of water from a considerable distance. The Laser-Ultrasonic Remote Sensing of Oil Thickness (LURSOT) sensor employs a short laser pulse for the production of ultrasonic waves in an oil layer in conjunction with a second laser coupled to an optical interferometer for the remote detection of ultrasonic surface movement. The development of this technique, which provides valuable oil slick thickness and hence oil volume information, is outlined in the following section.

3.0 Laser Ultrasonic Remote Sensing of Oil Thickness (LURSOT) Sensor

The LURSOT sensor is a three laser system with one of the lasers coupled to a Fabry-Pérot interferometer to accurately measure oil thickness (Choquet *et al*, 1993, Brown *et al*, 1994a). The sensing process is initiated with a thermal pulse created in the oil layer by the absorption of a powerful CO_2 laser pulse. Rapid thermal expansion of the oil occurs near the surface where the laser beam was absorbed. This causes a step-like rise of the sample surface as well as an acoustic pulse of high frequency and large bandwidth (~ 15 MHz for oil). The acoustic pulse travels down through the oil until it reaches the oil-water interface where it is partially transmitted and partially reflected back towards the oil-air interface where it produces a slight displacement of the oil surface. The time required for the acoustic pulse to travel through the oil and back to the surface again is a function of the thickness and the acoustic velocity of the oil. The displacement of the surface is measured by a second laser probe beam aimed at the surface. Motion of the surface induces a phase or frequency shift (Doppler shift) in the reflected probe beam. This phase or frequency modulation of the probe beam is then demodulated with a confocal Fabry-Pérot interferometer (Monchalin, 1986). The Fabry-Pérot interferometer behaves as a very narrow optical filter which directly demodulates the light when the laser probe frequency is set on one of the slopes of the filter response (~ half height). The technique is very sensitive to the high frequency surface displacement caused by the ultrasonic pulse, and is insensitive to low frequency motions such as vibration. Figure 1 illustrates the surface displacement, as a function of time, of a 2 mm layer of oil on water, induced by a 100 mJ laser pulse with a 100 ns rise-time. Also shown in the upper portion of Figure 1 is the signal produced by the Fabry-Pérot system following some additional electronic filtering. The high sensitivity of the system allows for the clear observation of the second echo which is barely visible in the surface displacement curve. The LURSOT system uses a third laser (a continuous wave HeNe laser) to interrogate the water surface and generate a trigger pulse when the correct surface geometry for measurement exists.

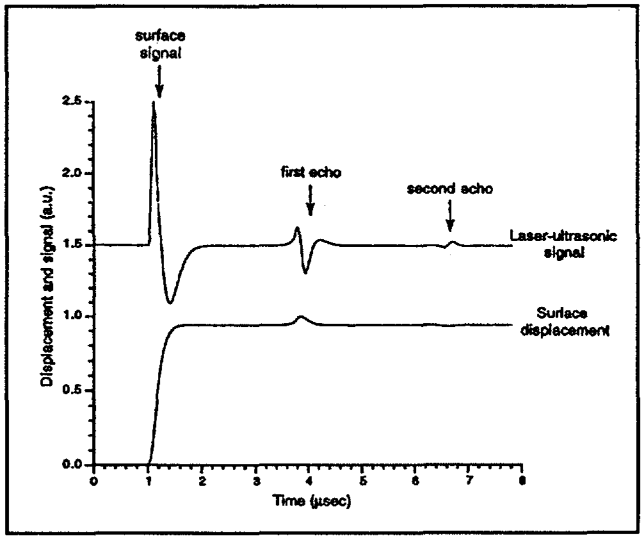

Figure 1. Theoretical displacement observed at the surface of an oil layer on top of water following laser excitation and corresponding laser-ultrasonic signal

The strong absorption of 10.6 μm radiation by oil, coupled with the high thermal coefficient of expansion of oil results in the efficient generation of laser-induced ultrasonic pulses. This efficient generation of ultrasound should allow operation of the sensor from an airborne platform since the laser beam does not have to be tightly focussed to produce a sufficient energy density. Problems arises however, with the weak acoustic impedance mismatch between oil and water which results in a weak acoustic reflection coefficient. Observation of the acoustic echoes would be much easier with a strong acoustic reflection at the oil-water interface. Calculations indicate a reflection coefficient of only 14 %, based on typical acoustic parameters of oil and water (see Table 1).

Table 1. Acoustic and Optical Properties of Norman Wells Crude Oil and Water

Property	Norman Wells Crude	Water
Acoustic impedance (Pa s m^{-1})	1.13 x 10^6	1.5 x 10^6
Acoustic velocity (m s^{-1})	1410	1500
Density (g mL^{-1})	0.8	1
Specific heat (J kg^{-1} K^{-1})	1000	4128
Thermal expansion coefficient (K^{-1})	1.0 x 10^{-4}	4.1 x 10^{-5}
Optical penetration depth at 10.6 μm (μm)	100	10
Optical reflectivity at 1.06 μm	0.045	0.02

Certain oil types and energetic seas can lead to the formation of water-in-oil emulsions which have acoustic properties even closer to those of water, reducing the reflection coefficient even further (McClements and Povey, 1989). The low reflection coefficient leads to low amplitude acoustic pulse echoes. Thus, high detection sensitivity is required to observe the small surface deflections. For the confocal Fabry-Pérot interferometer, the detection sensitivity is directly related to the amount of light received by the detector (Monchalin, 1986). Since the probe beam illuminates an essentially flat surface, the reflected beam has low divergence and can be collected with a simple optical telescope of proper aperture. The major loss of probe beam intensity is due to the low optical reflection coefficient of oil at the probe wavelength of 1.06 μm. This low reflection coefficient is compensated by employing a very high-intensity probe laser pulse.

The accuracy of the laser-ultrasonic measurement of oil thickness is dependant on both, the precision of the determination of the time delay between surface displacement echoes and the accuracy of the measurement of the acoustic velocity of the oil. The variation in the acoustic velocities between different hydrocarbon mixtures can be as much as 25 % (Wang and Nur, 1991). This variation is caused by the differing amounts of various components of the different hydrocarbon mixtures. There is also a slight dependence of the acoustic velocity on temperature; however investigations at IMI indicate this variation is < 3 % for a temperature change from 5 to 15 °C. The acoustic velocity of a weathered oil is probably within ~10% of that of the fresh oil. In the case of an emergency response to an oil spill, the type and degree of weathering of the oil may not be known. It is therefore the uncertainty of the acoustic velocity of the oil which limits the accuracy of the remote thickness measurement. This 25 % uncertainty is however more than acceptable for making effective oil-spill countermeasure decisions (Goodman, 1994).

The LURSOT system was set up in the laboratory to make a series of measurements on a range of thicknesses of Norman Wells crude oil on water. The oil had been previously exposed to the environment for more than 16 hours. Oil thicknesses from 250 μm to 35 mm were measured over distances ranging from 2 to 91 metres. In each of the experiments sufficient tap water was placed in the container (at least 4 cm) to prevent any interference echo from the water-container interface.

The temperature of the oil-water combination was 22 °C. A pulsed transversely excited atmospheric CO_2 laser (Laser Science, 200 mJ, 100 ns pulse width) was used for generation of the ultrasound pulses in the oil. The probe laser employed was a frequency-stabilized Nd:YAG (1.06 μm, ~50 μs pulse width) developed by IMI and UltraOptec Inc. The peak amplitude of the probe laser beam was adjusted to nearly saturate the detector, so as to provide maximum sensitivity. A single lens was used to focus the probe laser beam to a spot approximately 4 mm in diameter, equal to that of the unfocussed CO_2 pump laser beam. The pump and probe beams were combined with a germanium dichroic optic. Over short distances (a couple of metres) a 15 cm diameter lens was used to collect the reflected probe beam and focus the light into an optical fiber, which transmits the light to the Fabry-Pérot interferometer. Thirty consecutive signals were averaged to reduce the fluctuations in the probe beam. A typical laser-ultrasonic signal recorded in these experiments is shown in Figure 2. Note that the surface displacement signal just barely saturates the detector. In addition to the surface signal, the first and second echoes are clearly observable. The shapes of the surface displacement and the echoes are different, as expected. The second echo is inverted with respect to the first because of the higher acoustic impedance of water compared to oil, giving an inverted reflection (for displacement). The amplitude of the reflected acoustic pulse is about 12 %, in good agreement with the predicted 14 % based on properties listed in Table 1. Owing to the consistency of the shapes of the echoes, a direct cross-correlation of the estimate of the time delay is possible.

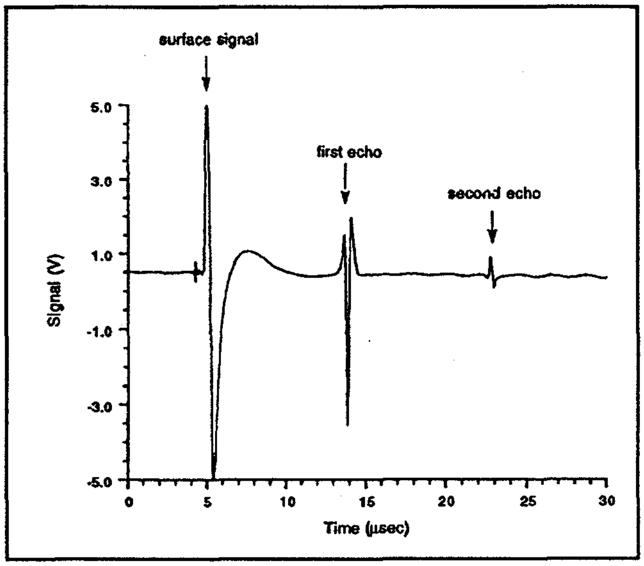

Figure 2. Laser-ultrasonic signal, average of 30 data curves, of an oil layer on water-direct thickness observation: 5 mm (± 50 %), laser-ultrasonic measurement: 6.23 (± 1 %)

Using the measured acoustic velocity of 1410 m s^{-1} for Norman Wells crude, the thickness of oil measured by laser-ultrasonics and cross-correlation of the first and second echoes is 6.23 mm (± 1 %). The 1 % accuracy is in reference to the measurement of the acoustic velocity of Norman Wells crude oil using conventional ultrasonics. Physical measurement of the thickness gives a value of 5 mm (± 50 %), with the 50 % error a result of capillary wicking of the oil on the wall of the beaker. In actual remote sensing operations, the signal-to-noise ratio may be insufficient to allow observation of the second echo. Cross-correlation of the surface signal and the first echo is possible, with a slight error introduced because of the different shapes of the signals. The thickness of the oil layer is determined as 6.26 mm, using the surface signal and the first echo, a difference of 0.5 % with that determined using the first and second echoes. In general, the difference associated with using the surface signal and the first echo is less than 1 % (Choquet, 1990) when compared to use of two consecutive echoes.

The sensitivity of the laser-ultrasonics technique is dependent upon the CO_2 laser beam energy flux at the oil surface and the amount of reflected probe laser beam light that can be collected by the optical system at a given distance. In medium distance laboratory tests, (37 m), there was a reduction in the observed signal-to-noise ratio as a result of the large reduction in probe beam intensity. A series of four inexpensive mirrors were used to produce a path length of 37 m. The mirrors were of low optical quality, with a total round trip reflection of light at the probe laser wavelength measured at just 15 %. The focussing and collecting optics were different than those used in the short range test. A two-lens beam expanding telescope was used to focus the pump and probe beams down to a spot approximately 1 cm in diameter. The collection optics consisted of a 40 cm diameter mirror telescope which focussed the received light into a fiber optic which in turn transmitted the light to the confocal Fabry-Pérot interferometer. The angle of acceptance of the collection lenses was 11 mrad. The probe beam intensity was adjusted to provide maximum signal-to-noise ratio. Figure 3 illustrates a single shot laser-ultrasonic signal from a nominal 5 mm thick layer of oil at a distance of 37 m. The signal-to-noise ratio was sufficiently reduced by the low quality mirrors to prevent observation of the second echo.

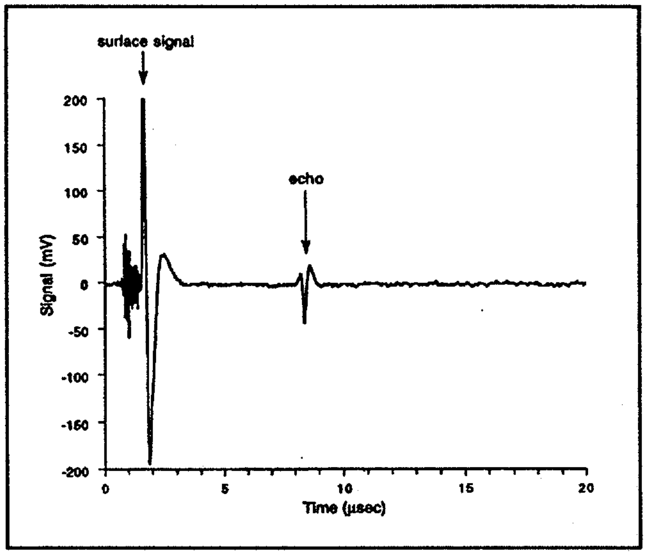

Figure 3. Laser-ultrasonic signal, single shot, of a 5 mm thick oil layer on water; 37 m range

To simulate conditions where the water surface is complicated by wave action, an electrical fan was added to the test set-up. If the surface tilt is greater than 2.75 mrad (one quarter of the acceptance angle of the optical system), the reflected probe beam will not be collected by the optics of the detection system. It was at this point that a third laser, (10 mW HeNe), was added to the system to determine if the water surface geometry is correct for remote sensing of oil thickness by laser-ultrasonics. The HeNe laser beam was directed collinearly to the surface along with the pump and probe beams. HeNe light reflected from the surface was monitored by a detector and used to create trigger signals for the pump and probe lasers when sufficient energy was reflected at 628 nm to indicate proper geometry. When compared with detection on a calm water surface, there is a definite reduction in the observed signal-to-noise ratio. This is a consequence of the water surface possessing a slight curvature as a result of the surface waves. The waves diverge the reflected probe beam, thereby reducing the amount of light collected by the receiver optics. When the intensity/amplitude of the ripples was increased the rate of data acquisition decreased from 1 s^{-1} for light ripples to 0.33 s^{-1} with strong ripples. Note, that the amplitude of the waves was not quantified in this experiment. While one cannot directly extrapolate laboratory observations to actual open ocean conditions, one anticipates that the rapid motion of the aircraft in one direction will provide rapid scanning in this direction, and thereby increase the data acquisition rate.

4.0 Preliminary Test Flight

A preliminary test flight was conducted off the coast of Halifax, Nova Scotia with only the HeNe laser, detector and collection optics to monitor the light reflected from the surface. The stripped-down version of the LURSOT system was mounted in the port-side camera hatch of a DC-3 aircraft operated by Innotech Aviation Ltd. The HeNe laser was focussed, with the same beam expander as in the laboratory experiments, to 91 m (300 feet) with a spot size of ~1.5 cm in diameter. Again the receiving optics consisted of a 40 cm diameter mirror telescope, focussed to 91 m. The acceptance angle of the optical system was 4 mrad. The light collected by the receiver telescope was focussed into a fiber optic which transmitted the light to a photodiode. The data acquisition software used in the test limited the maximum possible data acquisition rate to 3 Hz. Flight lines were flown at a number of altitudes between 91 m (300 feet) and 210 m (700 feet). Data acquisition rates were monitored for the various altitudes, aircraft velocities, and different flight path angles with respect to ocean wave propagation (wind direction). During the flights the amount of reflected HeNe laser light was continuously monitored. When the intensity of the light exceeded a threshold level indicative of adequate surface geometry for thickness measurement, time-registered data were recorded. The rates of data acquisition were higher in the airborne operation than in the laboratory experiments. Average acquisition rates were about 1 Hz at 91 m, and 0.2 Hz at 150 m altitude. These rates were achieved even though the acceptance angle of the receiving optics was reduced to almost one-third of that of the laboratory system. This confirms the suggestion that the forward motion of the aircraft will aid in finding a suitable geometry for thickness measurement. No acquisitions were recorded at an altitude of 210 m, most likely due to inadequate optical alignment for this altitude.

5.0 System Modifications for Airborne Operations

Several modifications to the LURSOT system were made in preparation for the airborne test of the complete system. The preliminary airborne test flight program had shown the time window available for thickness measurement to be about 200 μs. The probe laser had a turn-on time from trigger signal to operational output levels of 160 μs. This leaves only 40 μs for measurement of oil slick thickness which limits the range of measurable oil thicknesses. An optimized flashlamp system was developed to reduce the turn-on time of the probe laser to approximately 120 μs. This extended the amount of time available for thickness measurement to 80 μs, permitting measurement of oil slick thicknesses up to 6 cm (assuming an acoustic velocity of 1500 m s^{-1}).

The DC-3 aircraft could not supply all of the power required for the LURSOT system and the other remote sensing systems on board. To supply the required power for the Nd:YAG probe laser an Uninterruptible Power Source (UPS) was used. The UPS allowed for the operation of the probe laser for several hours, easily sufficient for the proposed test flights. Overnight charging replenished the power supply for the next flight. A special mounting structure was built to permit safe operation of the UPS in the aircraft.

A multiple lens system was designed and mounted in a compact fashion in an attempt to reduce the impact of in-flight noise and vibrations. A replacement lens and optical mount for the probe beam was manufactured. Measurements indicated that a significant amount of light was lost in the CO_2 laser pump beam. To obtain optimum focussing of the CO_2 laser beam at 91 m, an output aperture of at least 10 cm was required. Replacement of this aperture would require substantial modifications to the LURSOT system. The use of the 7.6 cm aperture causes a 50 % reduction in the output power available for ultrasonic pulse generation, however this is more than adequate for generation of pulses of the required amplitude, and therefore the optical system was not modified further.

To provide a rigid structure for the focussing optics that would allow for vertical mounting, a commercially available set-up, the Macrobench system was selected. This system is made from metal optical plates held together by cylindrical rods, which allows for the use of large optics (up to 7.6 cm in diameter) and provides for adjustment in all linear and angular directions. Optical support components required to mount the mirrors and lenses on the Macrobench system were designed and manufactured in the machine shop at IMI. An L-shaped structure was designed to house the lasers and the Macrobench optical alignment system. An separate structure holding the collection telescope optics was mounted in the front starboard sensor bay.

Two additional steps were taken to prepare the complete LURSOT system for the airborne test flight. An optical fiber was installed to provide a reference signal to stabilize the Fabry-Pérot interferometer. With this fiber a small fraction of the probe beam is coupled through the telescope aperture. The light is then transmitted through a large core optical fiber to the confocal Fabry-Pérot interferometer. The length of the Fabry-Pérot cavity is adjusted with a feedback loop to optimum tuning at mid-height of the slope of the optical transmission peak. In the lab a series of mirrors had been employed to re-inject this stabilization beam into the collection telescope, however this was deemed unsuitable for an airborne environment. A commercially available fiber illuminator was employed for the stabilization link. In addition a two-channel data acquisition program was developed to allow for the simultaneous monitoring of the laser-ultrasonic signal from the surface and the low frequency signal from the collected probe beam intensity.

6.0 Airborne Oil Spill Sensor Test Program

To prepare for the airborne oil spill sensor test program, a series of oil thickness measurements were made at a range of 91 m (300 feet) on Alberta Sweet

Mixed Blend (ASMB) crude oil, Hydraulic oil (Esso XD3-10) and Mousse Mix (a 50/50 mixture of ASMB and Bunker C oil), which are three of the four oils chosen for use in the airborne program. These measurements were made on both calm water and in the presence of fan-generated waves. On calm water, the reflected probe beam had to be attenuated to prevent damage to the detector. Periodically, even in the presence of waves, there was sufficient reflected probe beam energy to saturate the detector. Thus the signal-to-noise ratio obtained in these laboratory experiments appears to be more than sufficient for measurement from an airborne platform at an altitude of 91 m.

The Nd:YAG probe laser used in the proof-of-concept LURSOT system can present a possible eye hazard since it operates at a non-eyesafe wavelength (1.06 μm). Although the system fires it's lasers only when the optical axes of all three lasers are known to be safely collected within the aircraft, there was concern that one of the two high powered lasers might be accidentally deflected in an unknown direction. This condition can only occur if there is an accidental firing on a reflective surface on the ground or from a reflection on a smooth surface of the aircraft. These concerns lead to the decision to hold the test program at a controlled access site. The site selected was beside Centre Lake on the grounds of Canadian Forces Base Petawawa, Petawawa, Ontario, 80 nautical miles northwest of Ottawa. This site was 10 km from the nearest highway, and provided controlled access by land and control of the airspace above the site.

A detailed description of the test site construction and Airborne Oil-Spill Sensor Test Program have been reported elsewhere (Brown, 1993, 1994b,c). Briefly, twelve pools of nominal dimensions 12 m wide by 30 m long were constructed with sand berms approximately 30 cm high, lined with 2 layers of polyethylene membrane and filled with fresh lake water to a depth of approximately 15 cm. The overall dimensions of the test pools was therefore 30 m wide by 146 m long. Oil was added to nine of the pools, with the remaining three free of oil to act as controls.

The LURSOT system was again mounted the DC-3 aircraft. In preparation for participation in the airborne remote sensor test program, the alignment of the LURSOT system was verified on the ground. During a pre-test flight, the Fabry-Pérot interferometer was unable to lock itself to a specific level of transmission. In addition, the peak intensity on the stabilization detector of the Fabry-Pérot system was very low, possibly a result of misalignment of either the output lens of the fiber illuminator or of the collection fiber of the Fabry-Pérot.

The system was adjusted on the ground and operation verified by performing an oil slick thickness measurement with the aircraft sitting on the tarmac. This was performed at a range of 91 m using low optical quality folding mirrors which resulted in severe attenuation of both the pump and probe beam intensities. In spite of this, extremely good signal-to-noise ratios were obtained, building confidence that airborne data acquisition was possible. On the first flight, the feedback loop of the Fabry-Pérot interferometer was again unable to lock onto a specific level of light transmission. Vibration and acoustic noise from the aircraft were inducing a scanning of the transmission mode of the interferometer. Thus, there was no transmission of light through the interferometer, and hence no signal was received by the detector. Some triggering of the system did occur over the test pools, (as recorded by event flags on the Laser Environmental Airborne Fluorosensor (LEAF) data recording system), however no definitive laser-ultrasonic signal was observed. While this setback was disappointing, it did indicate that the correct geometry for measurement was found on the surface of the test pools as indicated by the trigger signal initiation. Again, the energy level as viewed on the stabilization detector was low, indicating a possible misalignment of the fiber illuminator or of the collection fiber. Following completion of the first test flight, the aircraft landed to allow adjustment of the fiber illuminator to optimize beam intensity on the stabilization detector. During the second flight, the peak intensity detected was very close to that observed on the ground, however the feedback loop on the Fabry-Pérot interferometer was unable to correct for the vibrations and noise in the system caused by the operation of the aircraft. Upon landing, the Fabry-Pérot interferometer was shielded with sound insulating foam to reduce the effect of acoustic noise on the detection system. A significant reduction in the sensitivity of the system to ambient noise levels was observed.

On the morning of day two of the test program, foul weather prevented operation of the aircraft under visual-flight-rules (VFR), and therefore no flight took place. During the time on the ground, the alignment of the LURSOT system was checked to verify that it had not been altered by several hours of flying time or by the effects of a take-off and landing. The output power of the pump laser was however, lower than expected. This was the result of high temperatures in the cabin of the aircraft. Upon cooling of the laser with a fan, the power output returned to normal. This situation was not considered to be a problem during flight operations since the cabin temperature can be reduced to some extent by introducing cold air from outside the aircraft.

To learn more about the cause of the failure of the LURSOT sensor to acquire thickness measurements, a decision was made to monitor specific signals at the expense of not being able to obtain thickness information. On the next flight, the reflected power of the Nd:YAG probe beam, and the HeNe laser trigger beam intensity collected were simultaneously monitored. This was done to verify the collinearity of the two beams in flight, and to confirm that the time window is sufficiently long to receive the probe beam in spite of the probe laser delay. In this scenario, a long time-scale of acquisition was used to monitor the two beams and observe their temporal shapes. This mode of monitoring did not allow for the acquisition of the high frequency ultrasonic signal. As was the case in previous flights, the system did trigger over the test pools, however no reflected probe beam was collected. The Fabry-Pérot interferometer was still unable to lock onto a specific level of light transmission since the length of the optical cavity was constantly changing, hence no light was transmitted to the detector. During this particular test flight the aircraft experienced periods of severe air turbulence which may have caused a misalignment of the receiver optics. This alignment was checked on the ground with the aid of a retro-reflector and only a slight adjustment of the pump laser was required.

The LURSOT did not operate on the final day of the flight program, as the pump laser output power was again found to be low as a result of misalignment of an internal mirror, possibly a consequence of the rough flight, and the sensitivity of the laser to ambient temperature.

7.0 Discussion and Conclusions

The LURSOT system has demonstrated the accurate measurement of oil slick thicknesses on water, (thicknesses ranging from 250 µm up to 35 mm), at distances of up to 91 m in the laboratory and on the tarmac. The system can provide these measurements to an accuracy of better than 99 % when the acoustic velocity of the oil is known. This accuracy is limited in the case of an unknown oil by the uncertainty in the value of the acoustic velocity which can vary by 25 % between different hydrocarbon mixtures. Even so, this accuracy is far better than the order of magnitude estimates available with present sensors or combinations of sensors. When problems associated with the airborne operation of the LURSOT system have been overcome, this sensor will aid in both spill response operations and oil spreading and behaviour studies. The expected primary role envisioned for an operational LURSOT system is the calibration of other pieces of remote sensing equipment. In particular the thickness response, or lack thereof, of infrared sensors can be re-evaluated in light of the absolute thickness information the LURSOT will provide.

Although the failure to acquire oil slick thickness measurements during airborne operation of the LURSOT system is disappointing, much was learned about the sensitivity of the system to the conditions experienced in an airborne environment. The knowledge gained during this test program is now being applied to remedy the problems experienced by the LURSOT system during it's inaugural airborne operation. In particular, the sensitivity of the system to vibrational and acoustic noise has been evaluated, and measures are being taken to isolate the system from these interferences. The sensitivities of the probe laser to temperature and vibration are also being investigated. In addition, the individual components of the LURSOT system have been evaluated independently by Optech Inc., in a study commissioned by Environment Canada. The recommondations from the study, *"Final Report on a Study into the Feasibility of Constructing an Operational Sensor for Laser-Ultrasonic Remote Sensing of Oil Thickness (LURSOT),"* (Optech, 1994), are being evaluated by the development consortium and may lead to further modifications to the proof-of-concept LURSOT system. Finally, each of the components of the LURSOT system will be tested independently under simulated and actual airborne conditions before the system is reassembled for a future airborne test.

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9.0 References

Belore, R.C., "A Device for Measuring Oil Slick Thickness," *Spill Technology Newsletter*, Vol. 7, No. 2, pp. 44-47, 1982.

Belore, R.C., "Calibration of Infrared Imagery Using a Surface Sampling Device," Environment Canada unpublished report, 1983.

Brown, C.E., Fruhwirth, M., Lambert, P. and Fingas, M.F., "Recent Activities of the Emergencies Science Division's Remote Sensing Working Group," in *Proceedings of the 16th Arctic and Marine Oil Spill Program Technical Seminar*, Environment Canada, Ottawa, Ontario, Vol. 2, pp. 1073-1082, 1993.

Brown, C.E., Fruhwirth, M., Fingas, M.F., Goodman, R.H., Choquet, M., Héon, R., Vaudreuil, G., Monchalin, J.P. and Padioleau, C., "Laser Ultrasonic Remote Sensing of Oil Thickness: Absolute Measurement of Oil Slick Thickness," in *Proceedings of the 1st International Airborne Remote Sensing Conference and Exhibition*, Environmental Research Institute of Michigan, Ann Arbor, Michigan, Vol. 1, pp. 567-578, 1994a.

Brown, C.E., Fruhwirth, M., Wang, Z., Lambert, P. and Fingas, M.F., "Airborne Oil-Spill Sensor Test Program," in *Proceedings of the 2nd Thematic Conference: Remote Sensing for Marine and Coastal Environments*, Environmental Research Institute of Michigan, Ann Arbor, Michigan, Vol. 1, pp. 19-33, 1994b.

Brown, C.E., Fruhwirth, M. and Fingas, M.F., "Airborne Oil-Spill Sensor Field Trial," in *Proceedings of the 1st International Airborne Remote Sensing Conference and Exhibition*, Environmental Research Institute of Michigan, Ann Arbor, Michigan, Vol. 1, pp. 599-611, 1994c.

Choquet, M. and Monchalin, J.P., "Modelling of Thermoelastic Generation of Ultrasound in Oil Upon Water," *Internal Industrial Materials Institute Report*, 1990.

Choquet, M., Héon, R., Vaudreuil, G., Monchalin, J.P., Padioleau, C. and Goodman, R., "Remote Thickness Measurement of Oil Slicks on Water by Laser-Ultrasonics," in *Proceedings of the 1993 Oil Spill Conference: Prevention, Behaviour, Control and Cleanup*, American Petroleum Institute, Publication No. 4580, Washington, D.C., pp. 531-536, 1993.

Goodman, R., "Remote Sensing Resolution and Oil Slick Inhomogeneities," in *Proceedings of the 2nd Thematic Conference: Remote Sensing for Marine and Coastal Environments*, Environmental Research Institute of Michigan, Ann Arbor, Michigan, Vol. 1, pp. 1-6, 1994.

Hoge, F.E. and Swift, R.N., "Oil Film Thickness Measurement Using Airborne Laser-Induced Water Raman Backscatter," *Applied Optics* Vol. 19, No. 19, pp. 3269-3281, 1980.

Hurford, N., "Review of Remote Sensing Technology," in *The Remote Sensing of Oil Slicks*, Lodge, A.E. (ed)., John Wiley and Sons, Chichester, United Kingdom, p. 7-16, 1989.

Kung, R.T.V. and Itzkan, I., "Absolute Oil Fluorescence Conversion Efficiency," *Applied Optics* Vol. 15, pp. 409-415, 1976.

Mackay, D., Chau, A. and Poon, Y.C., "A Study of the Mechanism of Chemical Dispersion of Oil Spills," Environment Canada Report EE-76, Ottawa, 141 p., 1986.

McClements, D.J. and Povey, M.J.W., "Scattering of Ultrasound by Emulsions," *Journal of Physics D: Applied Physics*, Vol. 22, pp. 38-47, 1989.

Monchalin, J.P., "Optical Detection of Ultrasound," *IEEE Transactions on Ultrasonics, Ferroelectrics and Frequency Control*, Vol. UFFC-33, No. 5, pp. 485-499, 1986.

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

Optech Incorporated, "Final Report on a Study into the Feasibility of Constructing an Operational Sensor for Laser-Ultrasonic Remote Sensing of Oil Thickness (LURSOT)," *Environment Canada unpublished report*, 1994.

Wang, Z. and Nur, A., "Ultrasonic Velocity in Pure Hydrocarbons and Mixtures," *Journal of the Acoustical Society of America*, Vol. 89, pp. 2725-2730, 1991.