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Progress in Achieving Airborne Oil Slick Thickness Measurement

C.E. Brown and M.F. Fingas
Emergencies Science Division, Environment Canada
Ottawa, Ontario, CANADA K1A 0H3
Brown.Carl@etc.ec.gc.ca

R.H. Goodman
Imperial Oil Resources Limited
Calgary, Alberta, CANADA T2L 2K8

J.V. Mullin
Technology Assessment & Research Branch
US Minerals Management Service
Herndon, Virginia, USA 22070-4817

M. Choquet and J.-P. Monchalin
Industrial Materials Institute
National Research Council of Canada
Boucherville, Québec, CANADA J4B 6Y4

Abstract

The ability to accurately measure the thickness of an oil slick on water by remote sensing has just recently become a reality. A laboratory sensor has now been developed to provide this absolute oil slick thickness measurement. A joint project between Environment Canada, the US Minerals Management Service, Imperial Oil Resources Ltd. and the Industrial Materials Institute of the National Research Council of Canada has led to the development of a prototype slick thickness measurement system, known as the Laser Ultrasonic Remote Sensing of Oil Thickness (LURSOT) sensor. This laboratory sensor was the initial step in the ultimate goal of providing an airborne sensor with the ability to remotely measure oil thickness on water. The LURSOT sensor employs three lasers to produce and measure the time-of-flight of ultrasonic waves in oil and hence provide a direct measurement of oil slick thickness. The successful application of this technology to the measurement of oil slick thickness will benefit the scientific community as a whole by providing information about the dynamics of oil slick spreading and the spill responder by providing a measurement of the effectiveness of spill countermeasures such as dispersant application.

This paper will provide initial results from laboratory testing prior to a second round of airborne test flights of the modified LURSOT system.

1.0 Introduction

Scientists and spill response personnel have long been searching for a precise way to measure oil-on-water slick thickness. Until recently there was no reliable laboratory or field method to provide an accurate measurement of oil slick thickness. Knowledge of slick thickness will result in more effective direction of oil spill countermeasures including dispersant application and *in situ* burning. In reality, the effectiveness of specific dispersants could be determined quantitatively by the accurate measurement of the oil remaining on the water surface following dispersant application. Furthermore, the ability to measure oil slick thickness should provide significant advances to the fundamental understanding of the dynamics of oil slick spreading.

2.0 The LURSOT System

LURSOT system development has been conducted under contract by the Industrial Materials Institute of the National Research Council of Canada in Boucherville, Québec. Complete details of the LURSOT system are outside of the scope of this paper, however a brief summary of the development is presented below. The LURSOT sensor is a three laser system with one of the lasers coupled to an optical interferometer to accurately measure oil slick thickness. The thickness measurement process begins with the absorption of a powerful infrared laser (CO_2) pulse which induces a thermal pulse in the oil layer. Rapid thermal expansion of the oil occurs near the surface where the laser beam was absorbed. This leads to a step-like rise of the sample surface and the creation of an acoustic pulse. The acoustic pulse moves down through the oil layer until it reaches the oil-water interface where it is partially transmitted (~85 %) and partially reflected back (~15 %) towards the oil-air interface where it causes a minute displacement of the oil surface. The amount of time required for the travel of the acoustic pulse through the oil and back to the surface again is a function of the acoustic velocity of the oil and the thickness of the oil layer. The displacement of the oil layer is measured by a probe laser beam (Nd:YAG) aimed at the surface. Motion of the surface causes a phase or frequency shift (Doppler shift) in the reflected probe beam. The modulation of the probe beam is subsequently demodulated with an optical interferometer (either a confocal Fabry-Pérot interferometer or a photo-refractive crystal). The absolute oil slick thickness can be determined from the time of propagation of the acoustic wave between the upper and lower surfaces of the oil layer. The LURSOT system uses a third laser (a continuous wave HeNe laser) to examine the water surface and generate a trigger pulse when the correct surface geometry for measurement exists. The minimum detectable oil thickness layer that can be measured with the present LURSOT configuration is 700 µm and the maximum is 38 mm. Signal processing techniques such as adaptive filtering could be used to measure oil thicknesses below 700 µm.

The initial attempt to test the LURSOT system in an airborne environment was unsuccessful for several reasons (Brown *et al.*, 1994). Briefly, the extreme operating environment provided by a moving platform was radically different from the laboratory setting in which the prototype LURSOT was developed. The intense vibrations experienced in the airborne environment lead to the elimination of the confocal Fabry-Pérot interferometer in favour of a photo-refractive crystal detector for probe laser phase demodulation. The Photo-Refractive Optical Ultrasonic Detector (PROUD) was developed by IMI to provide a demodulation device that is insensitive to vibrations. The PROUD detector is however, sensitive to frequency changes caused by motion of the target relative to the laser source (in the aircraft). To compensate for these frequency (Doppler) shifts, an optical frequency compensation device (OFCD) was devised and tested. In order to employ the OFCD on board an aircraft, a measurement of vertical velocity must be provided. This was accomplished

through the development of a vertical velocity sensor (VVS) by the Institute for Aerospace Research at the National Research Council of Canada, in Ottawa. The VVS couples a Differential Global Positioning System (DGPS) receiver with an accelerometer in order to provide accurate real-time vertical velocity measurement. The VVS was tested onboard the DC-3 and found to operate satisfactorily when isolated mechanically from the floor of the aircraft and filtered appropriately (Brown *et al.*, 1997). A decision was made to construct a device to measure the instantaneous optical frequency of the returning target laser beam. This device provides a diagnostic as to how well the optical frequency compensation device is working. Also, this device will provide data on the severity of the Doppler shift induced on the probe laser during normal test conditions of the LURSOT. The broad range of temperatures encountered in the aircraft, were found to induce differences within the optical beam path of the probe laser (Nd:YAG) that were outside acceptable limits. To correct this, a novel compact laser system was developed and mounted on a zero thermal expansion carbon-epoxy optical breadboard.

In addition to the known problems associated with operation in the airborne environment, there were concerns about the possible loss of co-linearity of the laser beams employed in the LURSOT system. A complete theoretical analysis of the support structure which houses the optical and laser components was undertaken at the University of Toronto's Aerospace Institute in order to understand the effect of vibrations on the co-linearity of the optical system. The investigation uncovered several shortcomings with the initial structure and provided the information required to design a structure which provides the stability required to ensure co-linearity of the laser beams at the operating altitude of 300 feet. The structure was subsequently constructed under contract by Aérotech Incorporated, Laval, Québec.

In order to better visualise the level of misalignment, if any, in actual flight conditions, a system has been developed to measure the in-flight co-linearity of the generation and detection beams employed in the LURSOT system. The system employs a mirror to image the two laser beams onto a thin plate of blackened aluminum. The laser beams in turn, heat a spot on the aluminum plate, and an infrared camera (sensitive in the thermal infrared) captures an image of these "hot" spots. A suitable delay is added so that each beam can be observed sequentially. The image sequences of the IR camera are digitized and stored for processing in a computer. During flight, a mirror is moved into position to divert the laser beams onto the aluminum plate at any time (if required for verification of colinearity). The positions of the two beams are subsequently determined through data analysis of the infrared camera images and beam co-linearity/overlap are confirmed.

The redesigned LURSOT system was assembled at IMI and extensively tested in a large-scale laboratory environment to confirm functionality of individual components and the successful measurement of actual oil slick thickness. Individual components of the LURSOT system in the new support structure are shown in Figures 1 and 2.

3.0 Flight Test Program

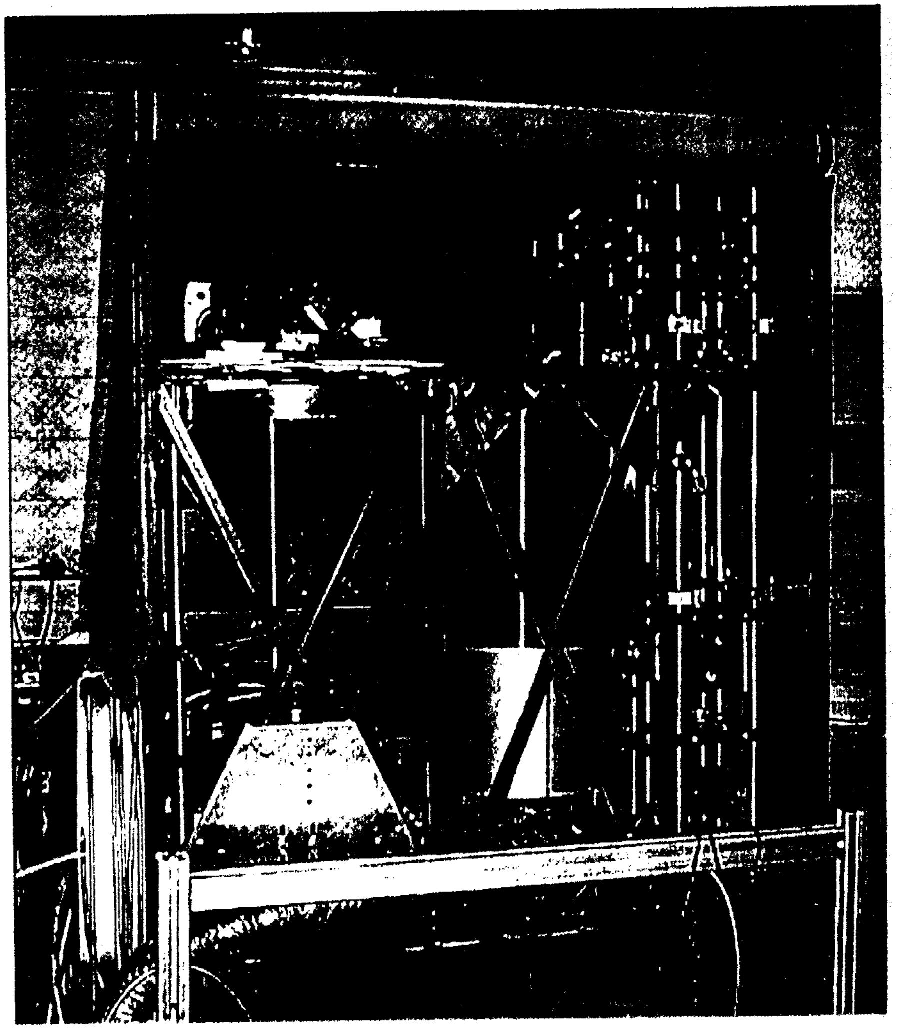
The re-engineered LURSOT has now been transported to the Emergencies Science Division's (ESD's) hangar facilities in Ottawa where it is being installed on ESD's DC-3 and undergoing a final certification process. Following installation, the

LURSOT will undergo the following four sets of flight tests.

Flight Test 1: Verification of Individual Components

The first set of tests will verify that each individual component of the LURSOT system operates appropriately under normal flight conditions. For these tests, no laser beam will exit the aircraft during flight. The following items will be addressed:

- Verify that the in-flight laser output power (each of the three lasers) is equal or close to the nominal values measured on the ground
- Verify the in-flight performance of the photo-refractive device for the measurement of a phase modulation of the detection laser (equivalent to a laser-ultrasonic modulation). For these tests, an optical phase modulator will be used to induce a known phase variation of the detection laser output. The output of the detection laser will then be directly injected in the collection telescope of the LURSOT, bypassing the focussing optics



- Verify the in-flight co-linearity of the 3 laser beams at the output of lasers, i.e., that the generation and detection lasers are within the overlap criteria (distance between the beam spots less or equal to the beam spot sizes at 300 feet) for normal flight conditions.

Flight Test 2: Verification of Triggering Mechanism

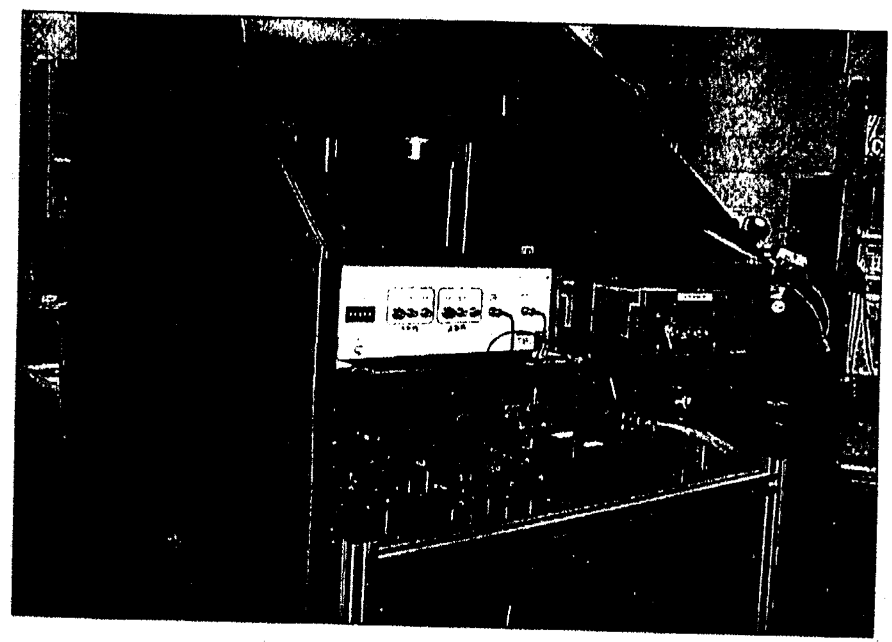
This test will verify the triggering mechanism of the LURSOT system. For this test, only the triggering laser (HeNe) will exit the aircraft. This test will be made over a river or lake environment.

Flight Test 3: Verification of Vertical Velocity Compensation Device

The third set of tests will verify the proper operation of the vertical velocity compensation device (VVDC). During these tests, both the triggering laser and the detection laser light will exit the aircraft.

Flight Test 4: Airborne Test of the Complete LURSOT System

Following verification of acceptable airborne operation of individual LURSOT system components, a final set of test flights will focus on acquiring an airborne measurement of oil slick thickness. Initially, a signal will be collected over a



large body of water, such as a lake, without an oil layer. The laser-ultrasonic signal would consist of the "surface signal" generated by the initial thermal expansion of the water surface, caused by the absorption of the generation laser.

Following the successful collection of a laser-ultrasonic signal over a large body of water, flights over man-made pools of oil-on-water will be undertaken. Laser-ultrasonic signals will be recorded and the thickness of the oil layers will be determined.

4.0 Conclusions

The redesigned LURSOT system provides absolute measurement of oil-on-water slick thickness in the laboratory environment. As such, LURSOT provides the scientific community with a device to study the fundamentals of oil slick spreading. The ultimate goal of this project, the airborne measurement of oil slick thickness, is now imminent. Successful completion of the airborne testing phase of this project will provide the spill response community with an airborne sensor that can provide information required to make effective, well-informed oil spill countermeasure decisions.

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Survey of Technologies A
Trans

Gregory Bearman*, Claude Robins
*Jet Propulsion Laboratory, Cali
‡Alyeska Pipelin
Gregory.H.

Abstract

The Alyeska Pipeline Service
kilometer-long Trans Alaska Pipeline
Propulsion Laboratory (JPL), NASA'
Beyond Earth Orbit, to see whether it
developed for space exploration to de
the pipeline. Migration of technology
to ensure a high level of system integ

JPL examined the following n
thermal sensors, both active and passi
ranging); ground penetrating radar; *in*
remote sensing does not provide adeq
desired. Similar issues also arose for
penetrating radar.

A simple *in situ* system consis
small sensors capable of one-time or n
best future option for a retrofitted leak
economic hurdles can be overcome.

1.0 Introduction

Alyeska Pipeline Service Com
pipeline that moves oil from the North
The pipeline traverses difficult terrain
pipeline is located in an environmental
always been concerned with leak detec

Some facts about the pipeline v
problem facing Alyeska. Of the 1290
ground while the remainder is below g
varying degrees of natural stability. T
and 36 above ground major stream cro
°C to -50 °C with snow cover part of th
sunlight during the year while part of i
sort of visual inspection or optical rem

Alyeska currently relies primar
system to detect any major leak in the
conditions with no "slack" (vapor pock
barrel per hour spill in about 10 minut
for volume balance technology.

In addition, for external leak de
who monitor the line by helicopter. Th