The Application of LIF to Study the Dispersion of a Surface Film Due to Wave Breaking Using a Two Camera System

T. Schlicke[1], A. D. Arnott[1], J. M. Buick[2], C. A. Greated[1] and N. H. Thomas[2,3]

[1] Department of Physics and Astronomy, JCMB, The University of Edinburgh, Mayfield Road Edinburgh EH9 3JZ, UK
[2] CEAC, Aston University, Birmingham, B4 7ET, UK
[3] FRED Ltd., Birmingham, UK

Abstract

In this paper we report on the application of laser induced fluorescence (LIF) to study the dispersion of a surface layer due to wave breaking. The technical aspects of the experiment are described; in particular we consider the production of a ``wide screen" image using an extended light sheet of length up to 2 m, and a double camera system which was used to obtain the images. The technique employed to produce surface films with a thickness of the order of a few microns is also described. Details are given of the normalisation of the LIF images due to intensity variations in the light sheet and the calibration method which was applied.

1 Introduction

Surface films in the ocean can be formed in a number of ways ranging from the large-scale pollution which can be produced by, for example, by an oil-spill; to small-scale naturally occurring slicks [1,2] due to biological processes. It is also possible that surface layers can be formed by marine rains containing high levels of dissolved free amino acids [1,3], although it is unclear whether this constitutes a source or a sink for the surface film. Naturally occurring slicks are a complex mixture of the organic materials found in the ocean, such as fatty acids, esters, carbohydrates and hydrocarbons which are mostly the exudes and decay products of various marine life [4]. Due to their complex composition, which may be constantly changing due to chemical processes occurring in the film, they are not fully understood in detail. Despite this, it has long been established that surface layers, even if only a few molecules thick, can have a significant effect on damping water waves [5,6]; indeed in laboratory experiments it can be necessary to follow a lengthy cleaning procedure to ensure that no film is present [7,8]. Short gravity waves are damped due to the Marangoni Effect [9,10]. When a viscoelastic film covers the water surface, two types of waves can be supported: surface waves and Marangoni waves. The Marangoni waves are produced by the compression and dilation of the surface film due wave motion. The viscous tangential stress at the water surface does not vanish but is balanced by the tangential stress exerted on the surface by surface tension gradients in the film. The tangential force associated with the surface tension gradients provides a restoring force for the Marangoni waves which are strongly damped due to the large velocity gradients in the boundary layer. When the frequency of the surface waves and the Marangoni waves

coincide, a resonance occurs which causes a strong dissipation of energy. Significant wave damping has also been observed at longer wavelengths. This has been explained [10] by energy transfer from the longer wavelengths to shorter wavelengths were the energy dissipation occurs by the Marangoni Effect. The damping produced by the surface films has important consequences for Synthetic Aperture Radar (SAR) [11,12].
In this paper we are concerned with the development of an LIF system to study the dispersion of such slicks due to wave breaking which has environmental implications concerned with the dispersion after an oil spill or leak and also in determining when a surface can be considered clean with respect to SAR imaging [11,12]. This has recently become increasingly important due to growing awareness of the issues of global climate change and the damage to the environment due to pollution, and hence the increased need to monitor the ocean. An earlier investigation of this problem was performed by Rapp and Melville [13] using a non-fluorescent dye. The application of LIF gives two main advantages: firstly it is possible to detect lower dye concentrations; and secondly we obtain qualitative concentration measurements at each point giving a more detailed description of the mixing process.

2 Experimental Description

21 Apparatus

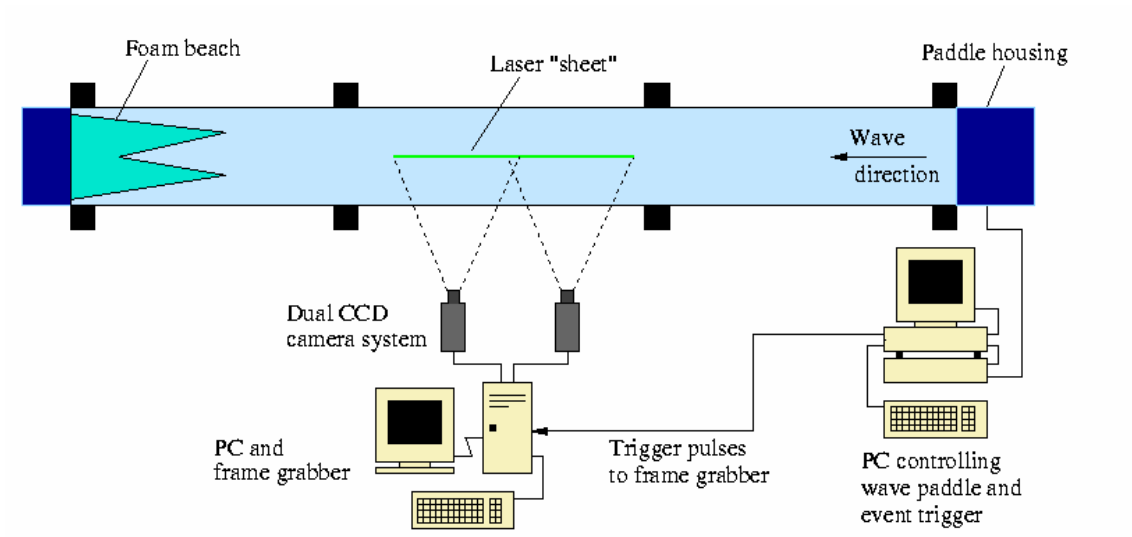


Figure 1: Plan view of the experimental set-up

A plan view of the LIF apparatus is shown in figure 1 and the details of the illumination system are shown in figure 2. The wave experiments were performed in a wave flume 9.7 m long and 0.4 m wide with a still water depth of 0.75 m. The breaking wave is generated using the superposition of a number of sinusoidal waves which are generated by the computer controlled wave paddle with frequencies in the range 0.5 Hz to 1.5 Hz. These waves are focused at a specified distance downstream of the paddle to produce a breaking event which is just inside the measurement region. The extent of the measurement region is determined by two factors: the area of the fluid which can be illuminated by the laser light and the area which is in the field of view of the cameras. It was found that after the wave breaks the surface film is dispersed further horizontally (corresponding to the direction of propagation of the wave) than it is in the vertical direction. For this reason it is necessary to use a measuring region which is greater in the horizontal direction than the vertical. Figure 2 shows the illumination system. A laser beam is directed onto an octagonal mirror; each face of the mirror reflects the beam, as shown in figure 2, producing a pseudo light ``sheet'' through the centre of the tank. At the free surface the length of the light ``sheet'' is approximately 2 m. A ``wide screen'' camera system was set up using two Pulnix TM9701 cameras with 28 mm Nikkon lenses positioned 3 m from the tank and 1 m apart such that their fields of view overlap slightly as shown in figure 1. Both cameras were triggered at 20 frames per second and were initialised by the computer controlling the wave paddle. The images were captured using a Coreco Viper Quad frame grabber and stored in RAM. 2000 images were stored for each experiment before each pair of images from the two cameras were combined to give the final ``wide screen'' image. The use of the two camera system enables a measurement region of the required shape to be used. If a single camera had been used to image the same area, there would have been a reduction in the resolution and there would have been large areas of the image which contained no information.

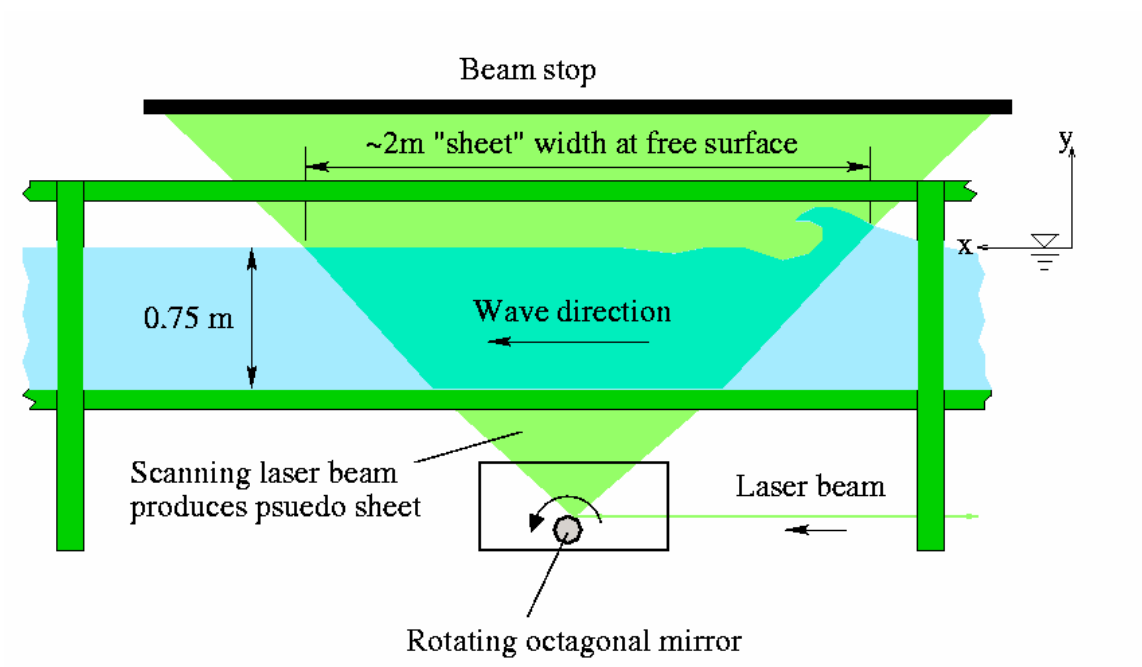


Figure 2: Details of the illumination system

2.2 LIF

LIF is a full field, non-intrusive, optical technique for obtaining concentration

measurements of a material within a fluid. A photon of frequency ν, colliding with an atom will either be absorbed or scattered. The probability of absorption is greatest when the energy of this photon, hν (where *h* is Planck's constant), matches one of the atom's excitation energies. If the photon is absorbed, its energy is transferred to one of the atom's electrons. The atom is now excited and therefore unstable. In liquids the energy is dissipated by intermolecular collisions, resulting in the emission of a band of photon frequencies. If these photons have frequencies within the visible spectrum, the material will appear to glow.
In the experiments described here we use Rhodamine B, a highly fluorescent dye [14]: concentrations of the order of parts per billion can be seen with the human eye. Rhodamine B is soluble in water, producing a pink solution but when illuminated, it glows a bright orange colour. A filter is placed in front of each camera lens to remove the Argon-ion laser light (512.5 nm), leaving only the fluorescence (~ 610 nm) which is captured by the camera system.

2.3 Application of the Surface Film

In order to investigate the factors affecting its dispersion, the film should be as uniform as possible. Ideally, the film would lie entirely on the surface of the water and have constant thickness. In addition the application of the film should be repeatable so the initial concentration distribution is not a variable. The method of application that was adopted involved the float shown in figure 3.

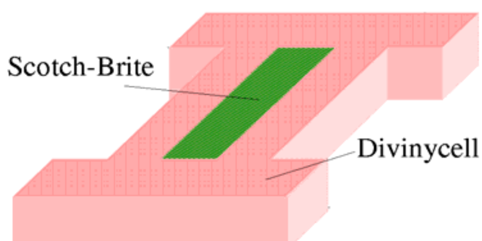


Figure 3: Film applicator

The float consists of an `I' shaped section of divinycell, a lightweight, high strength foam material, with a central strip removed. This gap contains Scotch-Brite, a brand of cleaning wool. The Scotch-Brite is soaked in water until saturated, and then the Rhodamine solution is added. A flow of water on to the Scotch-Brite flushes out the Rhodamine solution and spreads it over the surface, see figure 4. Care must be taken when removing the floats to avoid drips which disturb the film. In the experiments undertaken, the film volume was 5 ml and the Rhodamine B concentration was 1g per litre of methanol. This was found to be the smallest quantity that did not produce a patchy film. The 5 ml was divided equally between two floats, positioned approximately 1 m apart. This resulted in a film approximately 3 m long with a mean thickness of the order of several microns. The surface of the water was skimmed prior to the application of the Rhodamine to remove dust and other particles that would interfere with the spreading of the film.

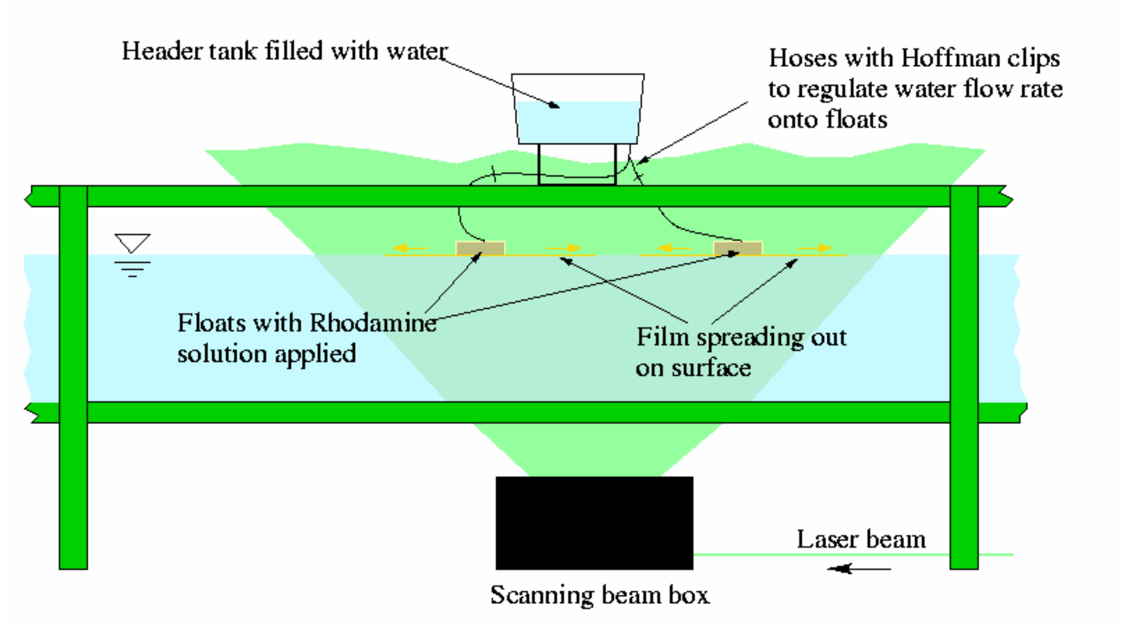


Figure 4: Application of surface film

3 Preparation of LIF images

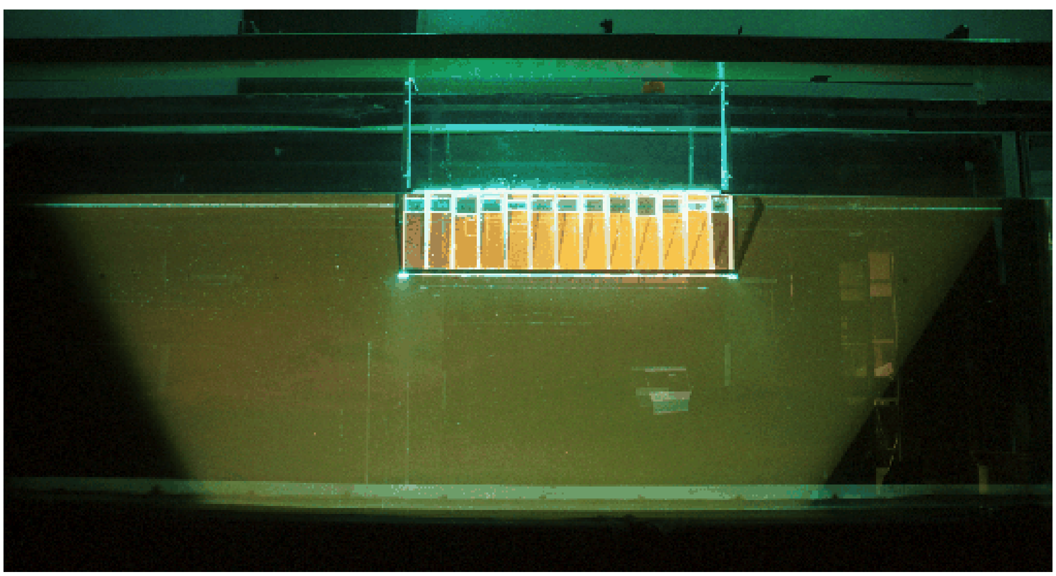


Figure 5: Calibration vessel

On completion of the experiment, the image data in the system memory is written to the hard disk. Before information from the images can be extracted, each image must be processed in two ways: to correct for light sheet variations and to obtain the Rhodamine B concentration. Due to the form of the scanning beam system the light ``sheet'' is not evenly illuminated, the light intensity is reduced as a function of r, the distance from the rotating mirror. This was observed by taking a normalisation image at the end of the experiment. The Rhodamine B which is present in the tank is thoroughly mixed until its concentration is approximately uniform before the normalisation picture is taken. Each pixel of the images taken during the experiment is then normalised by its value in the normalisation image. This procedure also acts to negate any differences in the sensitivity of the two cameras or of individual elements within the CCD array. Finally, the normalised pixel values are related to the actual concentration of Rhodamine B. To do this an image of a calibration vessel is taken. This vessel is made of perspex, sealed with silicon and contains 12 compartments containing different, but known, concentrations of the rhodamine/methanol stock solution in water; see figure 5. The image of the vessel is first normalised, as described above. The mean pixel value of each compartment of the calibration vessel is recorded and this is shown in figure 6. The graph is nearly a straight line through the origin, suggesting that in this range of concentrations, the pixel brightness is directly proportional to the Rhodamine concentration. This calibration technique was applied to the images from both of the cameras. It was noted that Rhodamine solutions of significantly higher concentration fluoresced *less* brightly, due to attenuation of the laser beam. In this way Rhodamine concentrations as low as 0.0005 % can be detected.

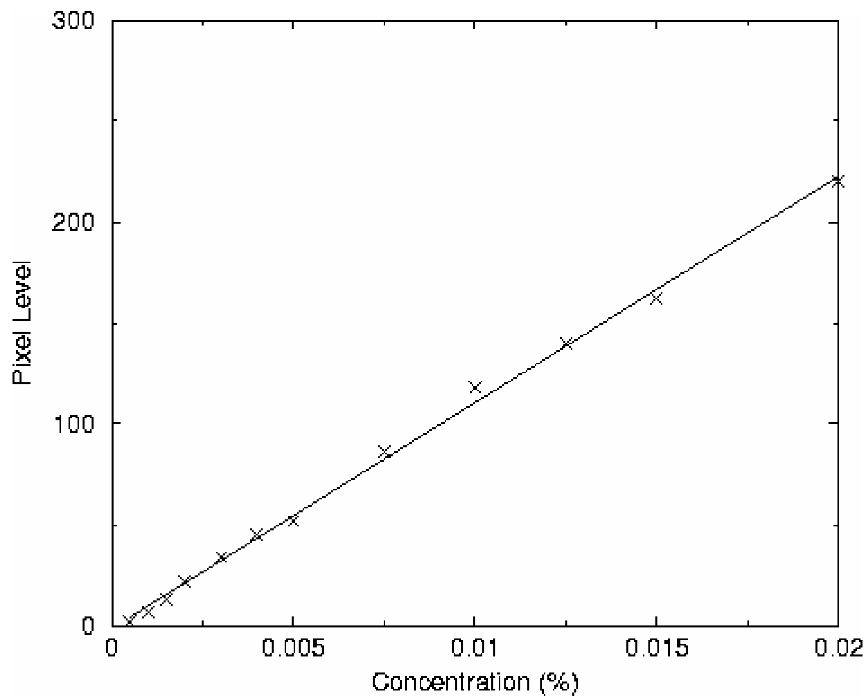
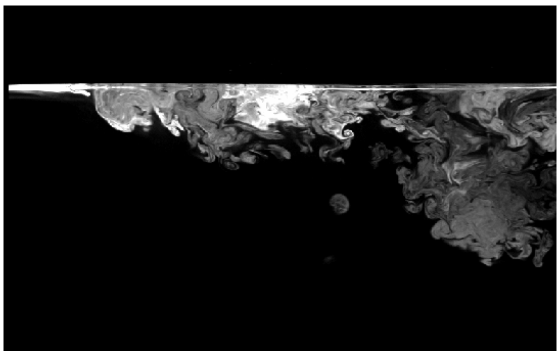


Figure 6: Graph of normalised pixel level plotted against known concentration

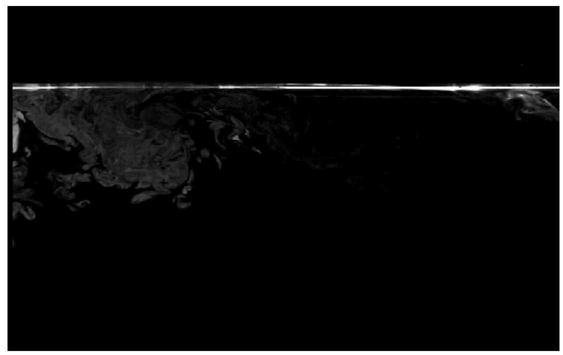
3.1 Combining the Images

Once every image captured from both cameras has been corrected for light sheet variation and calibrated, the images can be combined. The cameras were carefully arranged such that there was a small horizontal overlap between their fields of view. By inspecting the corresponding image from both cameras, this misalignment can be ascertained and used by a program to combine the images. The heights of the cameras were adjusted such that the MWL was at the same position for both. In most of these experiments, the overlap was approximately 8 pixels, resulting in a combined image size of 1528 (768+768-8) by 484. The join between the two original images is generally smooth unless waves are passing. Then, the water height appears to contain a discontinuity at the join, due to refraction at the moving water surface. This is not considered to be a problem since this study is more concerned with long term dispersion.

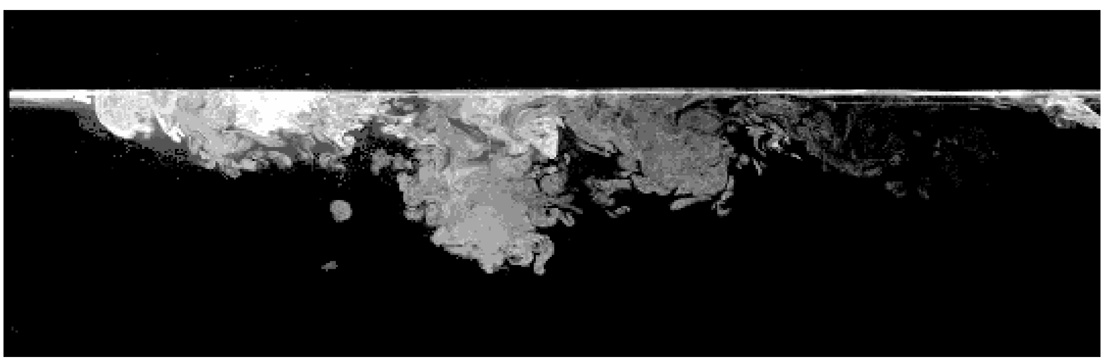
Figure 7 shows the two images obtained by the two cameras and the final ``wide screen" image. The final image is obtained by combining the original two images and performing the normalisation procedure. If the combined image is inspected closely it is possible to make out the join line, however the effect is very small and is not thought to be important when considering the long term motion of the dye. Figure 7 also demonstrates the importance of the normalisation technique. There is a clear difference between the intensity observed in figures 7(a) and 7(b) which has been removed by the normalisation procedure in figure 7(c).



(a) Image from left camera



(b) Image from right camera



(c) Combines ``wide screen" image after normalisation

Figure 7: The LIF images captures by (a) the left camera, (b) the right camera and (c) the combined ``wide screen" image after normalisation.

4 Conclusions

LIF has been successfully applied to study the dispersion of a surface layer due to a breaking wave. This has been done using an LIF system which has been modified to allow a ``wide screen" image of the flow to be taken using a double camera system and a wide light sheet. A special technique was also devised for evenly applying a thin film to the water surface with a thickness of a few microns.

5 Acknowledgements

The authors gratefully acknowledge financial support from the Engineering and Physical Sciences Research Council, UK.

References

[1] A. F. Carlucci and D. M. Wolgast. Microbial populations in surface films: Amino acid dynamics in nearshore and offshore waters off Southern California. *Journal of Geophysical Research*, 97:5271-5280, 1992.

[2] P. M. Williams, A. F. Carlucci, S. M. Henrichs, E. S. Van Vleet, S. G. Horrigan, F. M. H. Reid, and K. J. Robertson. Chemical and microbiological studies of sea-surface films in the Southern Gulf of California and off the west coast of Baja California. *Marine Chemistry*, 19:17-98, 1986.

[3] K. Mopper and R. G. Zika. Free amino acids in marine rains: Evidence for oxidation and potential role in nitrogen cycling. *Nature*, 325:246-249, 1987.

[4] J. C. Scott and N. H. Thomas. Sea surface slicks - surface chemistry and hydrodynamics in radar remote sensing. In *Wind-over Wave Couplings Perspective and Prospects*, editors, S. G. Sajjadi, N. H. Thomas and J. C. R. Hunt. Clarendon Press, Oxford, 1999.

[5] J. C. Scott. The historical development of theories of wave-calming using oil. *History of Technology*, 3:163-186, 1978.

[6] J. C. Scott. Oil slicks still the waves. *Nature*, 340:601-602, 1989.

[7] J. C. Scott. The propagation of capillary-gravity waves on a clean water surface. *Journal of Fluid Mechanics,* 108:127-131, 1981.

[8] J. S. Fox. *Transport Dynamics of Marangoni Films*. PhD thesis, University of Birmingham, 1996.

[9] R. Cini and P. P. Lombardini. Experimental evidence of a maximum in the frequency domain of the ratio of ripple attenuation in monolayered water to that in pure water. *Journal of Colloid and Interface Science*, 65:125-131, 1981.

[10] W. Alpers and H. Hühnerfuss. The damping of ocean waves by surface films: A new look at an old problem. *Journal of Geophysical Research*, 94:6251-6265, 1989.

[11] M. Gade, W. Alpers, H. Hühnerfuss, and P. A. Lange. Wind wave tank measurements of wave damping and radar cross sections in the presence of monomolecular surface films. *Journal of Geophysical Research*, 103:3167-3178, 1998.

[12] A. R. Ochadlick, JR., P. Cho, and J. Evans-Morgis. Synthetic aperture radar observations of currents colocated with slicks. *Journal of Geophysical Research*, 97:5325-5330, 1992.

[13] R. J. Rapp and W. K. Melville. Laboratory measurements of deep-water breaking waves. *Philosophical Transactions of the Royal Society of London*, 331:735-800, 1990.

[14] K. H. Drexhage. Structure and properties of laser dyes. In *Topics in applied physics. Vol I*, editor, F.P. Schäfer, pages 145-193. Springer, 1973.