Optical methods for study of sea surface roughness and microscale turbulence

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Abstract

The shape of the ocean surface on a millimeter scale controls the scattering of microwave radiation, hence the measurement of oceanic properties by remote sensing. In addition the micro-turbulence immediately adjacent to the sea surface brings about transfers of momentum, soluble gases such as CO₂, and heat or water vapor through the lowermost layers of air and the water immediately below. Although these processes are of vital importance to our understanding of the oceans and climate, they have not been adequately studied at sea.

Recent developments of optical techniques have greatly simplified measurements of small scale fluid motions and have made them accessible to measurement from a small raft in the open sea. A contributing factor in these developments is the availability of high power, high efficiency visible light diode lasers and high resolution CCD arrays. Optical methods have the advantage that they do not influence the delicate motions of capillary waves at the sea surface, nor are they intrusive in the motions of small turbulent eddies.

Our light source for study of turbulence below the water surface is a diode bar laser array. Light generated by the laser array (4 watts at 680 nm wavelength) is refracted into a fan shaped light sheet of approximate dimensions 50 by 20 by 2 mm to illuminate particles in the water. Sea water is sufficient transparent to this deep red light that particle tracking and particle image velocimetry can be carried out. The laser and a CCD camera in their water proof containers are so compact that they do not materially interfere with the water flow despite being mounted below the sea surface.

KEY WORDS: Seasurface roughness, PIV laser diode

1. Introduction

The scattering of microwaves by the seasurface is influenced by Bragg scattering from very short water waves. For example, back scattering of 30 mm microwaves at glancing incidence is brought about by 15 mm seasurface ripples. Such ripples are called capillary waves because capillarity, that is, surface tension working against the curved water surface, provides most of the restoring force. Capillarity is dominant in waves with wavelengths shorter than 17 mm. The restoring force of longer waves is predominantly provided by gravity. The ocean surface has waves of a wide range of wavelengths extending from long swells down to ripples with lengths of the order of a millimeter. Wavelengths near the transition from gravity to capillarity are critical for microwave scattering and hence the measurement of oceanic properties by remote sensing. The roughness of the seaseface to the flow of wind has also a contribution from these very short waves by creating micro-turbulence immediately adjacent to the sea surface. The capillaries can be very steep with great curvature thus can generate turbulence at and below the surface. Turbulence in the water can also create capillaries. Short surface waves can be generated and modulated by the wind and longer surface waves (Fig. 1).

The ocean is a giant reservoir of heat and green house gases. The top few meters of sea surface water has as much heat capacity as the entire atmosphere. Near sea surface turbulence brings...
about transfers of momentum, soluble gases such as CO₂, and heat or water vapor through the lowermost layers of air and the water immediately below with great impact on the global climate. Although these processes are of vital importance to our understanding of the oceans and climate, they have not been adequately studied at sea due to limitations of instrumentation and the harsh working environment.

Figure 1. Seasurface slope image at a wind speed of 5 m/s. Image size 20cm by 14cm.

The development of particle image velocimetry (PIV) has revolutionized the description of turbulent flows because it provides a two dimensional view of a flow field, and can repeat the process to make possible successive views in time. This is an enormous advance beyond the one- or a few-point techniques ordinarily used to provide the time course of turbulent flows because it shows structure and evolution of turbulent flows. It is a well established fact that coherent structures form the principal mechanisms for the transfer of properties in laboratory flows. For example, lee eddies occur behind obstacles, inclined hairpin vortex lines have been identified in wall turbulence, and rollers have been identified at the crests of short gravity waves.

Although many coherent structures have been identified in idealized laboratory experiments embodying small Reynold’s number flows, the complexities inherent in the broad range of interactions and the high Reynold’s number regime inherent in natural flows have not been so far examined in the detail necessary to identify structural shapes and their time history.

Instrumentation and software for PIV have become well established in the recent past for the laboratory applications, due to the technical developments of modern lasers, Fourier optics, and computers. In the PIV technique a laser is used to make a pulsed sheet of light that is directed into the region of interest in the flow. A photographic or video camera is focused, more or less at right angles to the plane of the sheet, to record the position of particles embedded in the flow. The usual technique of
determining velocity is to pulse the laser twice at a short interval of time so that a single camera image or video frame shows two images for each particle. By allowing both images to be registered on a single video frame the limitation of video framing rate is avoided; the two pulses can be as close together in time as needed.

The size of seeding particles must be kept small in order to have them follow without influencing the flow. A high powered and focused light source is thus needed, which makes the laser an ideal choice. Seawater is not transparent in the infrared so that visible light must be used. However, most visible light lasers are not efficient. For examples, an argon-ion laser consumes 14KW of electrical power to make 5 watts of green light. With this large input energy being turned into heat, a powerful cooling system has to be attached to the laser. This, and the size and complexity argue against use of an argon-ion laser for the field operations. The newly developed diode-pumped NdYAG lasers with output frequency doubled to provide green light would be much superior, but a simpler system is to use diode lasers directly, now that high output power is available in visible light diode lasers.

A PIV system based on a diode bar array type of laser is presented here for use in the ocean and atmosphere above the ocean. Some first test examples also will be shown.

2. Light sheet from diode laser

The laser array\(^1\) outputs 4 watts cw of total optical power at 680 nm wavelength. This deep red light can propagate in seawater for a few meters, an adequate distance for our purpose. The absorption coefficient is 0.4 m\(^{-1}\) for pure sea water. The efficiency of conversion of electrical to optical energy is 25% for this device when radiating 4 W. Heat generated by the 12 W not radiated could damage the diode, but in our use of short pulses the heat is easily dissipated into a heat sink and ultimately into the surrounding seawater. A more serious problem is chemical attack by water vapor on the face of the diode. This is conveniently avoided by mounting the diode in a waterproof case that also insulates the electrical leads. The case is backfilled with dry nitrogen. Another critical feature of laser diodes is that they present a low electrical impedance when "on" and a high impedance when "off". The electric pulse drive circuit has to be designed to avoid overstressing the laser, especially when (as in our experiments) the cable transmitting current to the laser is so long that transmission line effects of the cable modify the electrical
wave shape between the driver source and the diode. In effect the rise time of the electrical pulse must be slowed sufficiently to avoid "ringing" at the diode end of the cable. For our 10m cable this slow rise time amounts to a few microseconds and does not materially influence the optical pulses since these are on the order of a millisecond in duration.

The bar array consists of sixteen AlGaNp diode lasers each emitting through a 1 micrometer by 150 micrometer face. They are co-linearly and equally spaced forming a line of 9.2 mm length. Because of diffraction through the very thin, one micrometer dimension, each emits a fan beam of light at a right angles to the bar line (vertical in figure 2). The spreading in this direction is about 40 degrees FWHM. In the horizontal direction the spreading is about 11 degrees FWHM from each diode. To form a horizontal light sheet, the emitted fan beams are collimated in the vertical with a cylindrical convex lens (left lens in figure 2) and then expanded in the horizontal with another cylindrical concave lens forming a fan shaped light sheet of approximate dimensions 50 by 20 by 2 mm to illuminate particles in the water. The first lens determines the thickness of the light sheet, and the second controls the spreading of the fan beam. Figure 3 shows, the diode bar package, holder, and under water case. It is small in size and light in weight. It can be conveniently positioned in the water without additional fiber optics. Figure 4 shows projected light sheet from the diode laser system.

![Figure 3. Diode laser, heatsink, and waterproof case. The dimensions of the case are 57 mm diameter and 141 mm length.](image)

The diode laser in its case is compact, rugged, efficiently powered and comparatively inexpensive, all attributes that make it well fitted for field work. As compared to a NdYAG laser it also has the advantage of simplicity of modulation so that any desired optical pulse string can be generated, subject to the limitation of 4 watt pulse power. This feature may be useful for particle tracking velocimetry (PTV). In principal, higher power can be generated by operation of several arrays in parallel.
3. A high resolution PIV and PTV system for field applications

A high resolution digital CCD camera\(^2\) with image area of 1024 by 1024 pixels is used to capture particle images. The camera has 40% quantum efficiency for deep red light. The scattered light signal from 10 micrometer silver particles illuminated by a millisecond laser pulse can be captured (Figure 5). The digital output from the camera is directly read into the memory of a computer (486 type) through a PCI digital capture board\(^3\) at a frame rate of 30 Hz. The camera is mounted in a waterproofed container for underwater usage.

A programmable counter board\(^4\) is used to generate timing signals for triggering camera operation sequences and laser pulses. The timing signals are programmable, thus reducing the degree of complexity in generating timing signals to one of software control through the PC. The durations and the number of light pulses are adjustable for different PIV or PTV applications.

The power for the whole system must be provided by battery on the raft. We use a lead-acid battery system providing 100 ampere-hours at 24 V. The computer and control electronics are all compacted into one watertight box. In addition, the whole system can be remotely operated by a laptop PC through radio ethernet connections\(^5\) suitable for field applications in which the operator is on a boat at some distance from the raft to avoid influencing the wind and waves at the raft. The transmission range of the bi-directional ethernet connections is approximately 50 m.
4. A raft based platform for optical measurement at the sea surface

Figure 6 shows our raft based optical surface measurement system in operation in Mission Bay. The raft consists of a catamaran, 5.4 m long, with the optical equipment supported by two booms extending beyond the bow of the catamaran (on the left). One boom, extending upward into the air, supports anemometers and a mirror to reflect an image of the water surface to a photographic camera mounted just above the bow of the catamaran (see figure 7 for details). The other boom extends underwater and supports the laser diode array and the CCD camera as well as an optical system to color code water surface slopes as seen by the photographic camera. Under water, the light sheet makes an angle of 45 degrees to the vertical. The CCD camera looks from below at a right angle to the light sheet. Its field of view covers an area of about 20 cm by 20 cm from the water surface downward. An apparatus to spray particles into the water is mounted on the upper boom.

The battery and computer control unit are mounted near the stern (right). The controlling computer is operated through radio by a laptop on the mothership closeby.

The optical apparatus to color code water slopes is shown in figure 7. This surface gradient imager consists of a strobe light source, color screen and beam forming lens underwater, and a
photographic recording camera with mirror to record the wave slopes. This records colored light beams refracted at the sea surface over an area of 300 mm square. The recorded surface color images can be used to recover the shape of the water surface which can be used to study the small scale roughness of the sea surface.

Environmental data and raft motion are also recorded digitally by computer. These include pitch, roll and yaw and accelerations of the platform, wind speeds and directions, surface level from a wave staff, air temperature and humidity.

Figure 6 A raft based optical surface measurement platform in Mission Bay water

The raft is designed to be towed offshore by a launch that also serves as a mothership. During towing, the booms are tilted to bring the underwater parts up into the air, and the entire boom assembly is then stowed inboard on the raft.

5. Conclusions

Progress made to extend PIV and PTV methods from laboratory studies to field applications. High efficiency visible light diode lasers of relatively high power are used to simplify the system. These lasers are small, portable and rugged. Control and drive circuits are conveniently adaptable to battery powered systems.
A raft based system for investigating sea surface dynamics optically has been constructed and tested in Mission Bay and offshore near the coast. Open sea PIV, PTV, and surface slope measurements are in progress. These are designed to further understanding of transfer and scattering processes at the sea surface.

Figure 7. Above and below water booms hold optical instrumentation

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