

EXPERIMENTAL REMOTE SENSING OF SUBSURFACE TEMPERATURE
IN NATURAL OCEAN WATER

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Abstract. A remote sensing laser Raman backscattering technique has made the first field measurements, from a boat, of subsurface temperature in natural ocean waters. These results and the measurement systems rapidly developing from them open wide areas of exploitation. The technique utilizes the observation of the 3400 cm^{-1} O-H stretching Raman band of liquid water. The spectral data were analyzed to obtain the subsurface water temperature in accordance with previous laboratory studies. The importance of such a measurement by the Raman scattering technique is that it now enables depth resolved profiles of ocean water temperature to be obtained by remote sensing from airborne platforms that can be adapted for application to many problem areas of physical oceanography, meteorology, climatology, ocean technology, and thermal discharge management. An accuracy of $\pm 2^\circ\text{C}$ has been obtained in the initial field experiments. A more refined system has been designed which will permit accuracies of better than $\pm 1^\circ\text{C}$ in the first one or two optical attenuation lengths of depth.

The purpose of this communication is to report the first successful depth resolved remote sensing measurements of subsurface ocean water temperature in a boatborne field experiment. Such measurements have strong implications for research and technology in the general areas of ocean and coastal physics, oceanography and weather and climate prediction and in thermal pollution management. The temperature measurement was obtained by spectral analysis of the 3400 cm^{-1} O-H stretching Raman band of liquid water in accordance with previously reported laboratory experiments [Walrafen, 1961; Schwiesow, 1971; Chang, et al, 1974].

The physical basis of the measurement is the fact that (a) liquid water exists in at least two forms, monomers and dimers; (b) the two forms are in chemical equilibrium as a function of temperature; (c) the O-H Raman stretching frequency is significantly different for the monomer and dimer forms; (d) the relative concentration of monomer vs. dimer can be determined from the Raman spectrum and, thus, the temperature can be inferred.

The major advantage of the Raman scattering remote sensing technique, especially when adapted to airborne versions, is that it can rapidly and economically measure subsurface water temperature profiles over large areas.

As such it has direct application to the elucidation of such specific temperature related problems (among others) as input to sea-air interaction modeling, the physics of oceanic meso-scale systems, behavior of ocean fronts and other mixed layer dynamics, synoptic behavior of sound propagation, monitoring of thermal discharges and validation of thermal discharge models, etc.

A laser Raman lidar system was assembled and operated to obtain Raman spectra of ocean water aboard the Computer Genetics Corporation research vessel Makai. The purpose of the effort was to demonstrate remote subsurface temperature measurements in natural waters. Although laboratory experiments had been performed previously, Raman temperature measurements of natural ocean water had never before been obtained under in situ conditions and there were unanswered questions as to the extent to which naturally occurring interferences, such as fluorescence, would place a limit on the accuracy and the resolution of the laser Raman technique especially in coastal zones. An experimental program has been designed to answer these questions. This paper reports initial results.

The block diagram of the laser Raman system that was operated aboard the Makai is shown in Figure 1. The laser source was a pulsed nitrogen laser operating at a wavelength of 337.1 nanometers and producing pulses of 100 kilowatts peak power with an effective pulse duration of 10 nanoseconds at a pulse repetition rate of 500 Hertz.

The output from the laser is passed through an interference filter which passes the 337.1 nm laser line with high efficiency but blocks spontaneous emission occurring in the laser gas discharge in the O-H Raman spectral region near 3800 Å. An attenuator is also placed in the laser beam to provide a beam power attenuation of the order of X100 so that a photon counting detection system previously employed in atmospheric Raman measurement applications system could be used in the liquid water studies.

As shown in the block diagram a bistatic arrangement of the transmitter and receiver optics functions to define a volume of subsurface water from which the laser Raman scattering is detected. Operation in such a bistatic mode is adequate for experimental studies in the first few tens of meters of depth. This configuration is being modified for deeper penetration application by utilizing electronic range gating techniques and a more suitable blue-green laser wavelength.

The photons collected by the receiver optics

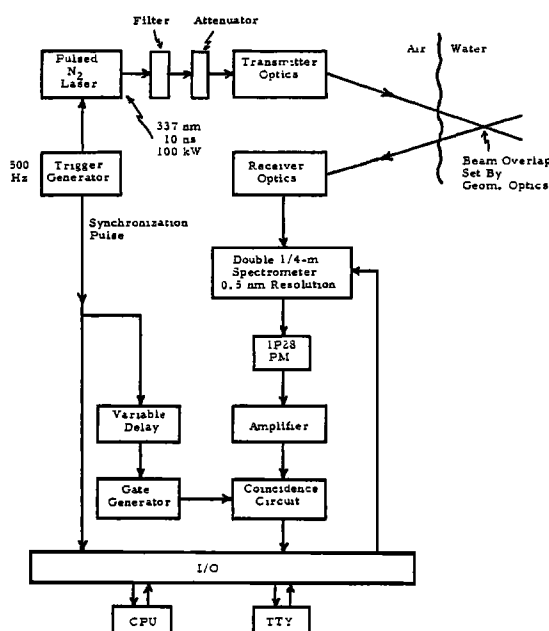


Fig. 1. Block diagram of laser Raman system currently operational on research vessel Makai.

are passed through a double 1/4 meter focal length scanning spectrometer having a 0.5 nanometer spectral resolution. The wavelength scanning of the spectrometer is controlled by the computer. The function of the spectrometer is to produce a spectral scan of the liquid water Raman O-H stretching band with sufficient resolution so that the monomer and dimer components can be resolved and a temperature determined.

The Raman photon output from the spectrometer is detected by a RCA 1P128 photomultiplier and amplified by an Ortec Model 454 timing filter amplifier. The conditioned Raman photon signal and a gate pulse suitably synchronized and delayed with respect to the laser firing are combined in a coincidence circuit the output from which is recorded using direct memory access (DMA) techniques with a Data General NOVA 1200 computer. The number of pulses occurring during the same data taking interval is also recorded. The ratio of the Raman photons to laser pulses recorded over a given time interval is the basic data obtained.

The data taking is fully automated. The computer can be directed through the teletype (TTY) to specify the number of laser pulses over which to record data at each wavelength and the maximum and minimum wavelengths and the wavelength increments of each spectral scan. The data obtained are printed on the TTY in tabular form listing "wavelength", "data", "cumulative data" and "drift". Successive rapid spectral scans to construct a "cumulative data" record allows the spectral information to be added coherently, thus, increasing the signal to noise ratio. The "drift" data record is a real time diagnostic that allows the operator to easily recognize during an experiment the occurrence of large error signals as soon as they may occur.

Initial Raman spectral data have been obtained from the research vessel Makai on November 3, 5 and 6, 1976 and March 26, 27 and 30, 1977 at various depths from the surface to 10 meters below the surface in the Annisquam River, a tidal estuary in Massachusetts. A typical sample of such data obtained at a depth of 1 meter below the surface is shown in Figure 2. The measurements were made under a high tidal flow condition in waters polluted by industrial and other urban runoff. It was estimated that the diffuse absorption coefficient was of the order $K=0.3 \text{ m}^{-1}$. The range limitation in this prototype bistatic experiment was a geometrical one due to the inability to spatially resolve the intersection of the focussed spectrometer slit on the laser beam at depths greater than 10 meters.

Figure 2 is a plot of the number of Raman photoelectrons collected per 0.5 nanometer spectral interval per 10,000 laser pulses as a function of wavelength. Shown are two sets of data, the dashed curve obtained as an instrument calibration in the laboratory with a water sample at 22°C and the solid curve obtained in the Annisquam River water at 6°C, according to "ground truth" temperature readings obtained with a pair of calibrated mercury thermometers.

A temperature can be obtained from the Raman spectra by comparing the height of the band contour at the peak, which corresponds to mostly monomer contributions, to the height of the contour at the inflection point on the short wavelength side which corresponds to mostly dimer contributions. These spectral features

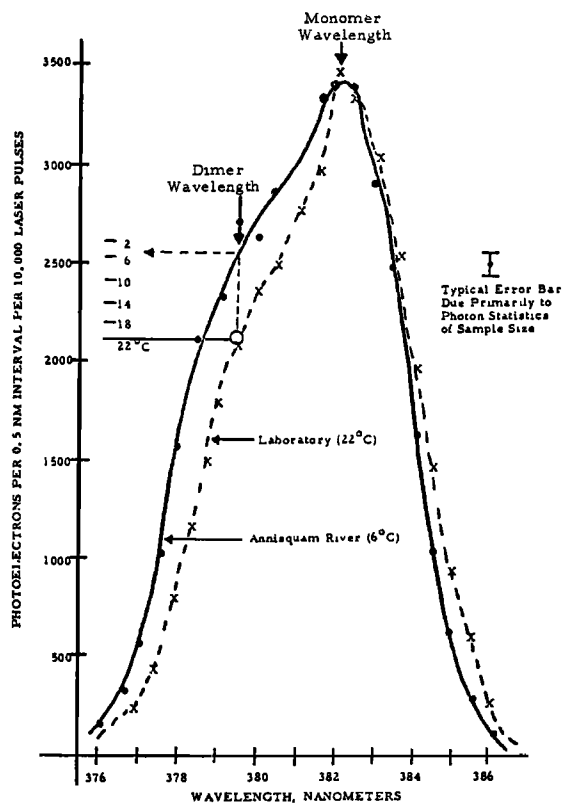


Fig. 2. Raman spectral data for liquid water.

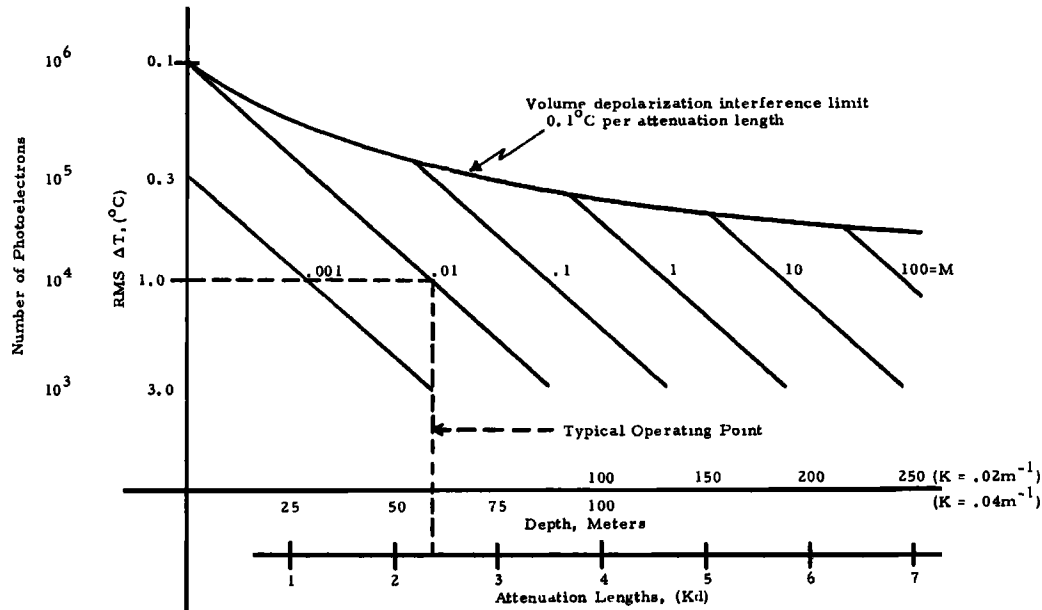


Fig. 3. Typical system operating map (100 meter mixed layer).

are labeled monomer and dimer respectively on Figure 2. A scale showing the height of the dimer inflection point as a function of temperature has been calculated from previously published laboratory data [Walrafen, 1961] and is shown on Figure 2 as a reference. Based on this scale an Annisquam River temperature of 4°C is inferred from the spectra and is consistent with the ground truth temperature of 6°C to within the shot noise limited statistical precision of the Raman measurement which was $\pm 2^\circ\text{C}$.

Based on the results of the initial experimental field measurements, the performance of a fully developed airborne laser Raman water temperature measurement system can now be estimated with a high degree of confidence using standard lidar engineering calculations. The operating map of Figure 3 has been calculated for a typical open ocean measurement situation with a mixed layer depth of 100 meters. The basic parameters on the map are the number of Raman photoelectrons collected as the ordinate with the depth as measured in attenuation lengths displayed on the abscissa. The derived quantities of temperature precision in $^\circ\text{C}$ and the depth in meters as a function of water quality are also shown as alternate ordinate and abscissa quantities respectively. An experimentally measured [Slusher and Derr, 1975] cross-section of $4.5 \times 10^{-29} \text{ cm}^2/\text{molecule-sr}$ was used in the calculations.

The operating lines on the map are drawn for various values of the parameter M where

$$M = \left(\frac{P_L}{20} \right) \left(\frac{\Delta h}{10} \right) \left(\frac{1}{R} \right)^2 T \quad (1)$$

and P_L is the averaged laser power in watts, Δh is the depth resolution in meters, R is the altitude of the aircraft in kilometers and T is the integration time of the measurement in seconds. Thus, for example, for a system with $P_L = 0.2$ watts, $\Delta h = 10$ meters, $R = 1$

kilometer and $T = 1$ second, the map parameter would be $M = 0.01$. This means that with such a system the allowed region of the operating map of Figure 3 is to the left of the line labeled $M = 0.01$. A typical operating point is shown corresponding to a temperature accuracy of 1°C and a depth penetration of 60 meters.

Also shown on the operating map is an upper boundary labeled "volume depolarization interference limit". This represents the most significant interference to the measurement and is caused by depolarization due to transmission of light through natural waters. Analysis of published data [Duntley, 1971] has shown that the depolarization effect will produce an uncertainty in the measurement of 0.1°C per attenuation length.

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References

- Chang, C. H., Young, L. A. and Leonard, D. A., Remote measurement of fluid temperature by Raman scattered radiation, U.S. Patent 3,986,775 filed December 26, 1974.
- Duntley, S. Q., Underwater lighting by submerged lasers and incandescent sources, Scripps Institution of Oceanography Report SIO-71-1, June 1971.
- Schwiesow, R. L., Raman scattering studies of pollutant systems, AIAA Paper 7-1086, November 1971.
- Slusher, R. B. and Derr, V. E., Temperature dependence and cross-sections of some Stokes and anti-Stokes Raman lines in ice, *Applied Optics*, 14, 2116 (1975).
- Walrafen, G. E., *J. Chem. Phys.*, 55, 768 (1961).

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