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Using the seawifs profiling multichannel radiometer to determine water-leaving radiances

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**USING THE SEAWIFS PROFILING MULTICHANNEL RADIOMETER TO
DETERMINE WATER-LEAVING RADIANCES**

A Thesis

Presented to

The Faculty of Moss Landing Marine Laboratories

San Jose State University

In Partial Fulfillment of the Requirements for the Degree

Master of Science

By

Darryl Wayne Peters

August 2002

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Abstract

USING THE SEAWIFS PROFILING MULTICHANNEL RADIOMETER TO DETERMINE WATER-LEAVING RADIANCES

By Darryl Wayne Peters

The Satlantic Profiling Multichannel Radiometer (SPMR) and Marine Optical System (MOS) were used to measure water-leaving radiances (L_w) during the MOCE 5 through MOCE 8 cruises. Five sets of multiple profiles were used to evaluate the capability of three smoothing techniques at reducing the high frequency noise in SPMR upwelled radiance (L_U) and downwelled irradiance (E_D) profiles. A modified version of the Smith and Baker (1984) method proved to be most effective at decreasing the variability in L_U and E_D profiles caused by surface waves. Under ideal conditions, SPMR L_w values were repeated to within 1.5%. SPMR solar normalized water-leaving radiances (L_{wN}) were generally 10 to 20% greater than MOS in clear water suggesting possible calibration errors. Limitations in the deployment strategy and processing design in pigment rich coastal water caused the SPMR to under estimate L_{wN} by as much as 10 to 25% compared to MOS.

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INTRODUCTION

In the late 1960s it was recognized that the color of natural waters contains information about their composition (Clarke *et al.*, 1970). The oceans contain a mixture of dissolved and suspended materials whose absorption and scattering properties determine the color of the sea. Early fluorometric measurements of phytoplankton abundance in the ocean showed exceedingly complicated variations in space and large temporal variability, indicating that a limited number of widely spaced ship track fluorescence profiles could not possibly represent global phytoplankton distributions.

In the open ocean, suspended material is primarily composed of phytoplankton (Siegel and Dickey, 1987). The primary photosynthetic pigment in phytoplankton is chlorophyll *a*, which absorbs light in the blue and red portions of the visible spectrum, and little in the green. Ocean color is related to pigment concentration with a shift from blue to green as pigment concentration increases (Gordon and Morel, 1983).

Ocean color remote sensing is used to estimate pigment concentrations by direct measurement of the amount of visible light leaving the ocean surface. Satellites have the capability of providing a synoptic view of the ocean that could not be accomplished by shipboard sampling alone. The Coastal Zone Color Scanner (CZCS, 1978 to 1986) was the first ocean color instrument to be flown aboard a satellite and provided useful imagery on the global phytoplankton distribution. Following atmospheric correction, CZCS quantitatively measured spectral "water-leaving radiance," L_w , at five bands in the visible

spectrum. Near-surface chlorophyll concentrations are determined by the ratios of L_w in two or more bands. One of the difficult tasks in satellite mapping of ocean chlorophyll distributions is the accurate removal of path radiance. This is the light scattered from air molecules and aerosol particles. The path radiance may contribute 90% of the total radiance measured by the satellite. Thus, it was doubtful that an atmospheric correction scheme could be applied to CZCS imagery having the required accuracy to yield meaningful phytoplankton distributions.

NOAA/NESDIS initiated an extensive oceanographic program in 1976 to gather surface truth data from 72 ocean stations of varying chlorophyll, suspended sediment, and dissolved organic matter concentrations. Spectral downwelled irradiance, E_D , and upwelled radiance, L_U , were measured at these stations. These data formed the first large data set from which atmospheric corrections and in-water plankton pigment algorithms could be determined (Gordon, *et al.*, 1983).

The CZCS mission lacked an adequate calibration plan to cope with the change of the satellite sensors over time (Evans and Gordon, 1994). For the generation of ocean color satellites following CZCS, NASA adopted a vicarious calibration plan to fine tune the post launch satellite calibration (Mueller and Austin, 1995). These satellites include the Sea-viewing Wide Field-of-view Sensor (SeaWiFS) and the Moderate Resolution Imaging Spectroradiometer (MODIS). A plan developed to provide continuous daily surface measurements of ocean color using a moored marine optical buoy (MOBY) and to take ship-based measurements of the ambient light field and oceanographic properties

including total suspended materials and phytoplankton pigment concentrations (Dennis Clark, pers. comm.). The daily MOBY observations are taken at the time of SeaWiFS and MODIS satellite overpasses. Shipboard observations are taken during Marine Optical Characterization Experiment (MOCE) cruises and during MOBY refurbishment cruises. MOBY was first deployed near the island of Lanai in Hawaii in 1997 and continues to be used as a primary source of in-water optical calibration data.

Radiometric measurements of ocean color taken from the Marine Optics System (MOS) radiometers are shown in Figure 1. The upper panels show downwelled irradiance, E_D (left) and upwelled radiance, L_U (right) measured near the surface. These show that the “color” of downwelled light near the surface is white, having nearly equal intensities across the spectrum. The upwelled light, through a spectral transformation at the sea surface and below, has color. In Hawaiian waters the upwelled radiance is rich in the blue portion of the spectrum (400 to 450 nm) and poor in the yellow to red portion of the spectrum (550 to 700 nm). The reason for this is seen in the lower panels, the diffuse attenuation coefficients for irradiance (K_E) and radiance (K_L) show strong attenuation in the red portion of the spectrum and variable attenuation in the blue. The low blue attenuation in Hawaiian waters results from low absorption by phytoplankton pigments, but in coastal waters off Mexico chlorophyll in the abundant phytoplankton pigments absorb blue wavelengths strongly.

The spectral diffuse attenuation coefficient for the clearest natural waters, K_w , has been related to absorption (a) and scattering (b) for pure water in the visible spectrum

(Smith and Baker, 1981). Mueller (2000) adopted the most recent measurements of pure water absorption by Pope and Fry (1997) to calculate $K_w(490)$. Pure seawater attenuation (mainly by absorption) increases dramatically above 500 nm and is about an order of magnitude greater in the red than the blue (Fig. 2). K_w represents the lower limit for light attenuation in the ocean and observations based on *in situ* radiometers. The difference between observed K_E and K_L spectra and that of pure water is attributed to the presence of dissolved and particulate materials. It is through these measurements that algorithms are developed that link phytoplankton pigment concentrations to measurements by surface and satellite radiometers.

In-situ match-up data are obtained from a variety of geographic areas covering the range of observable chlorophyll concentrations to validate satellite derived products (Mueller and Austin, 1995). The goal of the MOCE program is to collect in-situ oceanographic and radiometric data, from a variety of optical water types in the California Current, Gulf of California and the Hawaiian Islands, to characterize the bio-optical properties of the upper water column, and to collect meteorological data pertinent to the atmospheric path radiance correction (Feinholz and Broenkow, 1993).

Three radiometric profilers (Marine Optical System (MOS), Fiber Optic System (FOS) and the SeaWiFS Multichannel Profiling Radiometer (SPMR)) are used to measure the water leaving radiance at each bio-optical station during MOCE cruises, as well as to compliment MOBY measurements during routine refurbishments (Clark, 2002). The MOS and the SPMR radiometers are shown in Figure 3.

The present study focuses on a comparison of measured apparent optical properties and derived products between MOS and the SPMR from four MOCE cruises and one MOBY refurbishment cruise (Figs. 4 and 5). MOS is the cornerstone instrument used in bio-optical algorithm development and sea truth validations. The primary goal is to determine *accurate* water leaving radiances, L_w . This requires extrapolations of near-surface upwelled radiance values, L_U , to just below the air-sea interface. Because radiometric measurements cannot be made directly, subsurface L_U measurements are used from two or more depths, then the value closest to the surface is extrapolated to the surface by estimated values of the diffuse upwelled radiance attenuation coefficient, K_L . MOS and MOBY are used to make repeated high spectral resolution scans at three depths, and K_L is computed from pairs of observations. These K_L estimates are noisy due to surface wave effects on the ambient light field. The SPMR, however makes low spectral resolution, high depth resolution (sub-meter) profiles of L_U at seven wave bands. Thus the purpose of this work is to evaluate the use of SPMR for determining K_L to compare water-leaving radiances determined by both instruments, and to develop computer routines to process the raw SPMR data and to compute L_w .

Prior to and during the MOCE 5 cruise, a standard software package was used to process the data from the SPMR. Several problems were identified and new processing code was written to reduce the variability between successive casts. A data format was adopted to comply with MLDBASE (Broenkow and Reaves, 1993) which is currently used for both the MOBY and MOS data sets.

RADIOMETRY BACKGROUND

Precise and accurate measurements of electromagnetic radiation are central to the science of radiometry. Radiation is defined as energy in the form of electromagnetic waves. Oceanographic radiometers measure radiant flux from the sun altered by the ocean's surface and by in-water properties. Radiant flux is defined as the time rate of flow of radiant energy. The International System (SI) of units is used to express these quantities. The unit of radiant energy is the joule (J) and the unit of radiant flux is the watt (W) or joules per second (J s^{-1}).

Two fundamental radiometric quantities in ocean optics are radiance and irradiance. Radiance, L , is defined as the radiant flux (W) projected on to a given surface area (m^2) and collected through a given solid angle (sr) in ($\text{W m}^{-2} \text{sr}^{-1}$). Spectral radiance, $L(\lambda)$, is radiance measured over a given wavelength range, or spectral band, (nm) in ($\text{W m}^{-2} \text{sr}^{-1} \text{nm}^{-1}$). The wavelengths of interest to ocean optics cover the visible region of the electromagnetic spectrum from 400 to 700 nm. Irradiance, E , (W m^{-2}) is the radiant flux (W) projected on to a given surface area (m^2) from all angles above the surface. Spectral irradiance, E , ($\text{W m}^{-2} \text{nm}^{-1}$) is irradiance measured over a given wavelength range (nm). Examples of each spectral quantity are given in Figure 1 (upper left and right). The two quantities are geometrically related by

$$E = \int L \cos(\theta) d\omega \quad (1)$$

Irradiance is obtained by summing the incremental radiances, L , weighted by the cosine of

their angular direction normal to the detector surface, $\cos(\theta)$, through the solid angle, ω , from all directions usually either above (downwelled irradiance) or below (upwelled irradiance) the surface. Because all quantities are spectral, hereafter, the wavelength subscript (λ) will be omitted unless it is required for clarity.

Once sunlight penetrates the sea surface, the difference between the index of refraction of air and water reduces its speed and alters its direction. As refracted light penetrates downward it can be absorbed by both the water and its constituents and scattered by particles in suspension. Summing the effects of absorption and scattering defines light attenuation. These properties are independent of the ambient light and thus are termed inherent optical properties. Both water and its constituents selectively absorb and scatter light at specific wavelengths which affects the spectral distribution, or color, of light. Downwelled light scattered back towards the sea surface has the ability to leave the water column and be measured remotely.

Radiometers are designed to be orientated vertically with sensors at the top and bottom ends. Sensors facing upward measure spectral downwelled radiance or irradiance, L_D or E_D , and sensors facing downward measure upwelled spectral radiance or irradiance, L_U or E_U . An irradiance sensor placed above the sea surface measures incident irradiance, E_s , which is used as a reference for the amount of light entering the ocean.

Profiling radiometers measure the vertical distribution of light (Fig. 6, upper row). The reduction of measured light with increasing depth is expressed using the diffuse attenuation coefficient, K . This quantity is influenced by the ambient light and thus termed

an apparent optical property.

The change in the amount of downwelled irradiance with increasing depth can be described by a first-order approximation:

$$dE_D = -K_E E_D dz \quad (2)$$

where dE is the incremental change of irradiance E_D over an incremental change in depth, dz . Equation 2 states that the decrease in irradiance with depth is directly proportional to irradiance, to the first power. The first-order approximation can be applied between any two depths in a profile where it is assumed that K_E is uniform. In the ocean this equation is valid in the upper mixed layer where suspended materials have a homogenous distribution. Integration of Equation 2 through a region of constant attenuation yields:

$$E_{D2} = E_{D1} e^{-K_E (Z2-Z1)} \quad (3)$$

where E_{D2} is the downwelled irradiance at depth $z2$, E_{D1} is the constant of integration which is downwelled irradiance at the upper boundary, $z = z1$, and K_E is the irradiance diffuse attenuation coefficient over the depth range $z2 - z1$ (where z is positive downward). The diffuse attenuation coefficient, K_E , is determined by rearranging Equation 3 and solving for K_E :

$$K_E = -\ln(E_{D2} / E_{D1}) / (z2-z1) \quad (4)$$

where $z2 - z1$ is the distance over which irradiance is attenuated. The same principle applies to upwelled radiance and its diffuse attenuation coefficient, K_L ,

$$L_{D2} = L_{D1} e^{-K_L (Z2-Z1)} \quad (5)$$

K_E and K_L have units of m^{-1} . Because small changes in irradiance can lead to large

changes in K_E , the practical determination of K_E is made difficult by small differences in the radiance field caused by capillary wave refraction (Smith and Baker, 1984). The difference between Equations 3 and 5 is in the direction of estimation with respect to depth. K_E propagates E_D downward and K_L propagates L_U upward. It is important to note that these equations assume that K_E and K_L are constant over the depth interval, $z_2 - z_1$, and measurements are free of boundary effects, for example surface and bottom reflections.

METHODS

Data Sets

Data sets for this study incorporate both coastal and oligotrophic waters covering a wide range of water leaving radiance spectra. Profiles of radiometric and oceanographic data were taken in varying physical and biological settings during four MOCE cruises and one MOBY refurbishment cruise. MOCE 5 covered the coastal waters off Baja California, Mexico, both on the Pacific side and in the Gulf of California, as far north as Stations 12 through 15 and as far south as Stations 7 and 8 (Fig. 4). MOBY L51 and MOCE 6 through MOCE 8 occurred near the Hawaiian Islands (Fig. 5). During these cruises a wide array of atmospheric, biological and physical parameters were measured in support of MOCE. Only radiometric and oceanographic profile data were used to evaluate the performance of the SPMR processing routines.

Station locations were generally determined by satellite overpass or in cloud free areas. Ambient conditions most favorable for stable radiometric measurements are clear skies, calm seas and winds, weak surface currents and optically deep waters free of bottom reflection. Radiometric data used in this study were obtained from two different types of instruments with different deployment methods.

Table 1. Cruise Dates and Station Locations

Cruise	Dates	Stations	Location
MOCE 5	1-21 Oct 1999	20	Pacific side off Baja California and Gulf of California
MOBY L51	18 Nov 1999	1	MOBY site
MOCE 6	9-16 Apr 2000	8	MOBY site, around Lanai and south of Oahu
MOCE 7	3-10 Dec 2000	8	MOBY site, around Lanai and west of Oahu
MOCE 8	28 Feb-9 Mar 2001	8	MOBY site, south of Lanai and west of Oahu

CTD Profiler

Oceanographic and optical data (salinity, temperature, dissolved oxygen, beam attenuation, chlorophyll fluorescence) were obtained from a standard Sea-Bird Electronics CTD/rosette system fitted with 17-liter samplers required for total suspended matter analysis, a C-Star transmissometer and Chelsea Aquatracka III fluorometer. A detailed description of standard CTD processing procedures is given in Broenkow *et al.* (1995). CTD profiles contain information about the vertical distribution of physical and biological properties in the upper water column which influence light attenuation. These data were used to assess profiles of the diffuse attenuation coefficient.

SPMR/SMSR

The SPMR system, designed by Satlantic, Inc., Halifax, Nova Scotia, uses two instruments: the profiling radiometer (SPMR) and the surface reference radiometer (SMSR). The profiler measures both $E_D(z)$ and $L_U(z)$ while the reference measures E_S only. The SPMR/SMSR radiometers measure light using low fluorescence interference

filters with silicon diode detectors; the center wavelengths for each of the seven channels are 412, 443, 490, 520, 555, 665, and 683 nm. The filters were designed to match the SeaWiFS bands and meet the 10 nm half-pass bandwidth required by the SeaWiFS calibration/validation protocols (Mueller and Austin, 1995). $E_D(z)$ and E_s are measured using seven small cosine collectors with individual detectors, while $L_U(z)$ is measured with separate detectors behind seven entrance apertures having 10° (half-angle) fields of view in water. This particular system is equipped with an automatic gain switch to amplify the signals at low light levels (SPMR User's Manual, 1996).

The SPMR is a free-falling radiometer which was allowed to drift away from the stern of the ship to avoid ship shadowing or reflection. Additionally, proper ship orientation required the back deck of the ship to face the sun to minimize these effects. A preliminary 50 m cast was taken to allow for temperature equilibration of the optical sensors as well as a depth offset for the pressure transducer. A stable free-fall, with desired velocity (~ 0.75 to 1 ms^{-1}) and low tilt ($< 5^\circ$), was usually achieved within the top 2 m. This was accomplished using a 2 kg ballast weight attached to the front (bottom) end of the profiler and syntactic foam fins attached to the back (top) end.

The SMSR was designed to attach to a float and drift away from the ship at a rate similar to the SPMR. The purpose of the design was to enable near-surface measurements closest to the light field to be sampled by the profiler without shadow contamination. Since waves induce a highly variable near surface light field, the SMSR was alternatively secured to the ship about 10 m above the sea surface. This allowed the reference to be

free of shadows or reflections from the ship's superstructure. Since the SMSR was not gimbaled, E_s spectra show variations associated with ship pitch and roll, but these perturbations were usually less than ten percent. Both the SPMR and SMSR sample simultaneously at 6 Hz resulting in 7-8 samples per meter. Raw SPMR and SMSR data were recorded directly on a computer using Satlantic data acquisition software.

MOS

The Marine Optical System (MOS) is the primary radiometer used to determine in water E_D and L_U spectra. It is identical to the instrument in the Marine Optics Buoy (MOBY) which also measures E_D and L_U over the visible and near IR portion of the electromagnetic spectrum (Clark, 2002). MOS has two collectors at opposite ends of the pressure housing similar to the design of the SPMR. The top collector is a cosine collector for E_D measurements. The L_U collector at the lower end of the pressure housing uses a narrow entrance aperture, less than 5° (full-angle) field of view in water. Unlike the SPMR filter instrument, the E_D and L_U signals are split into blue and red components by a dichroic mirror. The "water mirror" reflects blue-green light into one spectrograph while transmitting red and the near infrared into the other. Each spectrograph contains a single holographic grating which diffracts the incoming beam to produce spectra that are imaged on 512 by 512 channel CCD arrays. The combination of the two spectrographs yields high resolution (0.6 nm) spectra from 350 to 950 nm.

The Surface Irradiance Sensor (SIS) is used with MOS to measure incident irradiance only. These data are used to normalize underwater data to common lighting

conditions. The 38-channel SIS spectra are lower resolution (9 nm) and range from 370 to 700 nm. Data from 370 to 448 nm do not have sufficient sensitivity and are not used in the normalization (Flora, 2001). SIS is mounted shipboard on a gimbaling mechanism about 10 m above the sea surface. Spectral scans are collected continuously at 1 to 10 minute intervals during daylight hours.

MOS is deployed to ensure sampling at or near the time of a satellite overpass, or near local apparent noon, in an area usually free of clouds. Similar to SPMR deployment, MOS deployment minimized the effects of shadows by floating the instrument on a tripod away from the ship. MOS was lowered by electric winch to desired discrete depths usually 1, 11 and 21 m in oligotrophic waters and 1, 5 and 11 m in coastal waters. Thus the deployment methods of MOS and the SPMR, which takes continuous profiles, are fundamentally different. A set of MOS E_D and L_U spectra are typically taken at each depth, with the number of scans controlled by the operator (typically five). Two dark scans were taken before and after each set to account for the dark current of the instrument. A complete MOS profile typically takes about an hour.

While the SPMR and MOS instruments require similar conditions for successful deployment and data acquisition, radiometric measurements could not be taken simultaneously due to cable entanglement and instrument shadowing problems. Therefore, the SPMR was generally deployed before and after MOS, which was deployed near the time of satellite overpass. Both data sets provide measurements of downwelled irradiance, $E_D(z)$, and upwelled radiance, $L_U(z)$, and are accompanied by simultaneous

surface irradiance, E_s . Surface irradiance was measured to account for changing sky conditions during subsurface acquisition.

Data Processing

Conversion

Both the MOS and SIS data sets are composed of spectral scans. The valid scans in each set are averaged before the average dark current is subtracted from the light measurement. For a complete description of MOS processing procedures see Feinholz and Broenkow (1993). Satlantic, Inc. provides calibration coefficients to convert raw SPMR data from binary counts to radiometric units. The calibration files consist of dark counts, system responses and immersion factors for both high and low gain settings.

Radiometric units are produced through application of the following:

$$L(z) = [ADU(z) - A_0] A_1 I_m$$

where $L(z)$ is the converted radiance in radiometric units ($\mu W \text{ cm}^{-2} \text{ sr}^{-1} \text{ nm}^{-1}$), $ADU(z)$ is the raw 12-bit Analog Digital Unit (counts), A_0 is the instrument dark current (counts), A_1 is the spectral response function ($\mu W \text{ cm}^{-2} \text{ sr}^{-1} \text{ nm}^{-1} \text{ count}^{-1}$) and I_m is the spectral immersion factor (unitless). Once the data have been converted, they are quality checked to remove invalid values in a profile. Examples of invalid data include: profiler tilts greater than 5° ; profiler descent rates less than 0.2 ms^{-1} ; above-water collection (E_D head only); and measurements at extremely low light levels. A depth offset is applied to each sensor head to account for the distance between the collectors and the pressure transducer. Clouds can alter the underwater lighting conditions and contaminate the

ambient light field. Since SPMR profiles require just over a minute to complete, profiles influenced by clouds are quickly terminated and restarted. Therefore, cloud contaminated casts were rejected in the final data set.

Normalization

The diffuse attenuation coefficient, K , between two depths is calculated for MOS as:

$$K = -\ln[(L_2 R_2)/(L_1 R_1)] / (Z_2 - Z_1) \quad (6)$$

where L_2 and L_1 are the average light measurements at depths Z_2 and Z_1 respectively. R_1 and R_2 are the SIS surface irradiance ratios which account for changing solar angles and sky (i.e. cloud) conditions computed as:

$$R_1 = E_{sr} / E_{s1} \quad (7)$$

$$R_2 = E_{sr} / E_{s2} \quad (8)$$

E_{sr} is the surface reference irradiance taken at the time when the near surface spectra are acquired. E_{s1} and E_{s2} are surface irradiances taken at the times when spectral scans are made at depths Z_1 and Z_2 respectively. R_1 and R_2 are average values over the SIS E_s spectrum due to the fact that SIS's spectral range does not completely cover that of MOS (Mike Feinholz, pers. comm.). Final derived products (L_{U0} , L_w and L_{wN}) are computed in the same manner as those for the SPMR. A normalization is not required for SPMR measurements since solar angles do not change significantly in one minute.

Smoothing

High frequency, in-water light field fluctuations are caused by focusing of light due to surface waves (Schenck, 1957). The effects of refraction and reflection at the sea surface on radiometric profiles are quite evident. The SPMR sampling rate allows these high frequency fluctuations to be resolved. The highly variable light field exhibits quasi-periodic fluctuations around a mean distinct from random fluctuations (Smith and Baker, 1984). SPMR profiles must be smoothed to remove the variability associated with surface processes before light attenuation can be attributed to in-water properties and before the diffuse attenuation coefficient and the water-leaving radiance are calculated.. SPMR radiometric profiles were log transformed before they were smoothed to account for the approximately exponential decrease of light with increasing depth, consistent with Beer's Law.

Three different smoothing methods were applied to a subset of data and their capability of reducing the effects of waves was examined. The first is a boxcar filter designed to preserve only the low frequency components of a signal. The second method is a least squares method introduced by Smith and Baker (1984) and the third a modified version of the Smith and Baker technique.

The boxcar function applies an N-term equally weighted filter in which observations are cumulatively multiplied by these weights as:

$$X_T = \sum W_K X_{T-K} \quad (9)$$

where X_T is the smoothed value computed from raw observations $X_{T-N/2}$ through $X_{T+N/2}$,

and W_k is an individual weight in the function. The weights have values equal to $1/N$ where N is the number of elements in the filter (Holloway, 1958). This filter preserves the mean while the high frequency component of the signal is removed. The length of the resulting smoothed signal is decreased by N elements, the length of the boxcar, $N/2+1$ at the top of the profile and $N/2-1$ at the bottom. This filter was applied in MATLAB using the “convolve” function. For example a 5-point boxcar filter is accomplished by the MATLAB code:

```
>> Y = conv(X,[1/5 1/5 1/5 1/5 1/5])
```

This function produces additional elements at both ends of the profile which are removed before subsequent passes are conducted. The amount of data removed from both ends of the profile is proportional to the length, N , of the boxcar. Optics data were averaged in 1 m depth bins prior to boxcar smoothing.

Smith and Baker (1984) applied a first-order least squares fit to binned, natural-logarithm transformed irradiance data. The independent values are the integer depths at the center of the bins and the dependent data are the natural-log transformed and binned irradiances. From this method the slope is the diffuse irradiance attenuation coefficient, K_E (m^{-1}) and offset, $\ln(E_0)$, is the natural-log of the modeled irradiance at the upper depth:

$$\ln(E_D) = \ln(E_0) - K_E Z \quad (10)$$

Coefficients from this model are used to compute smoothed values representing the mean irradiance which are obtained at each depth bin Z' by:

$$E_D(Z') = E_0 e^{-K_E Z'} \quad (11)$$

Smith and Baker (1984) suggested an initial fit to their *irradiance* data over 5 m intervals and then additionally smoothing the K_E profile five times over 3 m intervals. In the current work the radiance data were treated in the same manner. Bins were set to integer depths at 1 m intervals. Again, there is a trade-off to this approach. Noisy profiles require greater smooth intervals to reduce the effects of waves, yet as the smooth interval and/or the number of passes is increased, information with respect to K_E is lost at both ends of the profile.

The Smith and Baker smoothing method was modified and incorporated into the processing scheme presented here. The following section, and the remainder of this paper, refers to the custom computer routines as "MLML," listed in Appendix B. The radiometric data were passed through the least squares fit N times (usually 2 to 3 for $L_v(z)$ and 3 to 4 for $E_D(z)$) to produce a mean light profile from which $K_L(z)$ and $K_E(z)$ were then determined. Attenuation profiles were not additionally smoothed. Preserving the original length of the raw profiles while creating the mean light profiles requires two steps. First, only half intervals were used at the ends of the profiles. Following this, the slope and offset from the mean depth of the least square fit were applied at original raw depths. The surface most depth to start the fit was visually determined, usually near two meters depth. The smoothed radiometric and attenuation profiles were then interpolated to integer depths at 1 m intervals.

The interplay of interval size and the number of passes for the boxcar and MLML methods was investigated to determine which technique would best represent an

uncontaminated profile. It has been recognized that “noisy” profiles require a greater interval size (Mueller and Austin, 1995; Siegel et. al., 1995) and may require more passes through each smoothing procedure. A sensitivity test was also performed to help determine the depth ranges over which to compute the most repeatable surface K_L and K_E . The different methods were evaluated for both $E_D(z)$ and $L_U(z)$ profiles. Examples of each smoothing method for both $E_D(490)$ and $L_U(490)$ profiles are shown in Figure 7.

A series of MATLAB programs were written to determine acceptable data smoothing techniques. The method which was most successful at reducing the effects of wave noise on L_U and E_D profiles would be included into the new processing routines. Results between the different smoothing methods will be separated into two categories:

- 1) The near-surface attenuation coefficients and extrapolated products from each method.
- 2) Normalized root mean square (RMS) deviations were computed on attenuation profiles, K_L and K_E , from the three smoothing methods on casts with depths greater than 100 m.

The first category addresses the repeatability of the near-surface attenuation coefficients and extrapolated estimates from each smoothing method. The variability for a set of profiles was examined by calculating both the individual deviations about the set mean and the standard error of the set. The variability associated with individual profiles was examined using confidence intervals for the near-surface attenuation coefficients. The confidence intervals were used to estimate the uncertainty associated with each method's extrapolated products (L_{U0} and E_{D0}). The confidence interval, CI, of the linear regression

slope was computed by:

$$CI = K \pm t S_b$$

where t is the t -value from a lookup table for $p < .05$ with $n - 2$ degrees of freedom and s_b is the standard error of the estimate of the regression slope, K . From CI the upper and lower limits of K , K_{hi} and K_{lo} , are used to calculate the range of extrapolated products. The uncertainty was computed as the ratio of the range of the extrapolated values, K_{hi} minus K_{lo} , to the extrapolated value using K , multiplied by 100 to express it as a percentage.

Five sets of casts from MOBY L51 and MOCE 8 were used for the comparison of surface products for each method. These stations were chosen because they contained at least four casts per set, were free of cloud contamination and exhibited plenty of wave noise. The MOBY-L51 data set consists of 11 repeated casts taken over a 25 minute period. Two of the casts were contaminated by ship shadow and were not included. The MOCE 8 data set consists of four sets of casts from two stations. The top 50 m of the water column was sampled which was sufficient for the retrieval of the near surface diffuse attenuation coefficient in clear waters. This is based on the fact that 90% of the diffusely reflected irradiance originates from depths of $1/K_E$ (Gordon and McCluney, 1975). Ninety percent of the light available for remote sensing is confined to depths shallower than 50 m when K_E values are greater than $0.02 \text{ (m}^{-1}\text{)}$, which is just above the K_w minimum in the blue region.

The second category focuses on the entire attenuation profile. RMS deviations were computed at 5 m intervals from 10 to 100 m to examine the difference between each smoothing method throughout the attenuation profiles. This exercise is similar to the SeaWiFS Data Analysis Round Robin Experiment in 1994 (DARR-94), however, the DARR-94 only considered the RMS differences between K_E profiles (Siegel, *et al.*, 1995). The DARR-94 analysis examined different methods involving complete processing of radiometric profiles, some of which have the capability of correcting contaminated sections of a profile.

Calculating K_L

A log-linear least square fit of L_U between two near- surface depths of a smoothed profile was used to obtain a slope and offset directly. The slope of the least squares fit is the diffuse attenuation coefficient, K_L .

Because of the effects of surface waves and profiler attitude, the shallowest reliable measurements can be as deep as 2 to 10 m. It is therefore necessary to extrapolate the shallowest values, using the diffuse attenuation coefficient, to just beneath the sea surface, $z = 0^-$. Assuming a well mixed near surface layer with uniform attenuation, the extrapolated value of upwelled radiance just below the sea surface is determined from:

$$L_{U0^-} = L_U(z) e^{K_L z} \quad (12)$$

where z denotes the depth beneath the surface, $L_U(z)$ is the upwelled radiance at depth z , and K_L is the diffuse upwelled radiance attenuation coefficient from the least square fit between the near-surface depths. $E_D(z)$ is extrapolated up to a depth just below the sea

surface to compute E_{D0} , in the same manner using K_E . All quantities are spectral and apply equally to the SeaWiFS bands used in SPMR.

The calculation of the water leaving radiance, L_w , involves propagating L_{U0} up through the sea surface. L_w is obtained through:

$$L_w = L_{U0} (1-\rho) / n_w^2 \quad (13)$$

where ρ is the Fresnel reflectance, which is approximately a 2% loss due to internal reflection, and n_w is the refractive index which is 1.34 for sea water at 35 PSU and 16° C. The n_w^2 term accounts for the increase in solid angle as light exits the sea surface, which decreases radiance by 54.3% (Austin, 1974).

The water leaving signal is “solar normalized” so that surface comparisons can be made with satellite observations. The effects of the standard atmosphere are accounted for as well as variations in solar angle and earth-sun distance. This is accomplished by:

$$L_{wN} = L_w / F_n \quad (14)$$

where F_n is the solar normalization factor (Gordon, 1988) computed as:

$$F_n = t(\theta_0) (1-\rho(\theta_0)) \cos(\theta_0) / r_{es}^2 \quad (15)$$

where θ_0 is the solar zenith angle, $t(\theta_0)$ is the diffuse atmospheric transmittance, $(1 - \rho(\theta_0))$ describes the reduction of solar illumination as the radiance crosses the air-sea interface, $\cos(\theta_0)$ normalizes the sun angle to zenith, and r_{es}^2 accounts for the adjustment in earth-sun distance (Flora *et al.*, 1997). The diffuse atmospheric transmittance is a function of Rayleigh and ozone scattering and the solar zenith angle (Gordon and Clark, 1981).

Radiometric Calibrations and Stability

To ensure the quality and consistency of the data, all radiometers are calibrated on a routine basis. Satlantic calibrates the SPMR and SMSR sensors approximately once per year. SPMR and SMSR stability was monitored using RS series lamps, monitors and controls provided by Gamma Scientific. Stability measurements were taken before, during and after MOCE 5 and before each of the MOCE 6 through MOCE 8 cruises.

Calibrations of MOS are conducted before every cruise with National Institute of Standards and Technology (NIST) traceable light sources.

MOS Comparison

MOS files contain high spectral resolution data of L_U , E_D and their associated derived products, K_L , L_{WN} and K_E . To compare the SPMR derived products to MOS derived products, MOS spectral data, M_{λ_p} , were band-weighted to SPMR spectral bands 1 through 5 by:

$$M_{sw}(\lambda_b) = \int M_{\lambda_p} R(\lambda_b) d\lambda / \int R(\lambda_b) d\lambda \quad (16)$$

where $M_{sw}(\lambda_b)$ are the five SPMR weighted MOS values, $R(\lambda_b)$ are the five SPMR normalized band responses over each SPMR filter wavelength range $d\lambda$ (Fig. 8). This process parallels the steps in weighting MOS spectral normalized water-leaving radiances by SeaWiFS responses to simulate SeaWiFS determined radiances (Broenkow *et al.*, 1993). Multiple values of SPMR L_{WN} values taken from a set of casts were averaged before comparison with MOS. The values from a set taken before MOS were compared separately with those taken after MOS. L_{WN} will be used in the comparisons rather than

L_w since L_w values for each instrument should be different due to the difference in time between sampling. Sub-surface irradiance data will not be included the comparisons because it is not used in satellite validation.

For the sake of brevity, only data from channels 3 (490 nm) and 5 (555 nm) will be shown in the figures for the smoothing and MOS comparisons. The 490 nm channel was chosen to represent the “blue-green” group composed of channels 1-3 and the 555 nm channel was chosen to represent the “green-yellow” group composed of channels 4-5. Results from the representative channels are typically characteristic of their respective group, both in time and throughout a profile. Also, only data from the first five channels will be used in both the smooth comparison and MOS comparison. Light levels at wavelengths greater than 600 nm are very low below the top meter due to strong seawater absorption. SPMR attitude and velocity reach stability usually at or below two meters limiting the ability to detect the red signal. A shallower depth range than available is required to successfully compute K_L to avoid linear regression through an inflection, and to extrapolate the surface-most measurement. This is not accounted for in the MLML processing routines which do not process each channel individually. Additionally, at wavelengths greater than 600 nm, instrument self-shading becomes important, especially at low sun angles and with wider housing diameters (Gordon and Ding, 1992).

RESULTS

Prosoft Comparison

The purpose of this work was to examine the precision of SPMR derived near-surface products from multiple SPMR casts in an optically stable environment. The Satlantic processing software, "Prosoft," derives near surface data (Level 4 Processing) containing only SPMR radiance data. Irradiance data are not processed because their software assumes the surface irradiance meter, SMSR, is underwater. Their software does not provide regression statistics from the least squares fit to compute associated errors of extrapolated products. Lack of these features and other problems resulted in more robust programs being written in MATLAB and to automatically form MLDBASE files.

Prosoft and MLML mean deviations from nine stations during the MOBY L51 cruise are shown in Figures 9 through 11. The range of Prosoft K_L mean deviations are at least five times greater than those obtained using MLML software. The MLML mean K_L values are around 4% greater than Prosoft for channels 1 through 3, about 2% greater for channel 4 and about 2% less for channel 5. The standard errors for Prosoft K_L values are 7 times greater than MLML for channels 1 through 3, and 9 to 10 times greater for channels 4 and 5. The range of Prosoft L_{u0} mean deviations are at least 2 times greater than MLML deviations. MLML mean L_{u0} values are about 1.5% less than Prosoft values for channels 1 through 3, about 3% and 5.5% less for channels 4 and 5 respectively. The standard errors for MLML L_{u0} values are from 52 to 60% less than Prosoft for channels 1

through 4, and 33% less for channel 5. The situation is similar for the solar normalized water leaving radiances. The range of Prosoft L_{WN} mean deviations are at least 30% greater. MLML mean L_{WN} values are just over 5% greater than Prosoft values for channel 1, almost 4% greater for channels 2 through 4, and almost 2.5% less for channel 5. Results of the standard errors for L_{WN} values are nearly identical to those for L_{U0} .

Profile Smoothing Methods Comparison

Surface Products: K_L , L_{U0} and K_E , E_{D0}

A sensitivity analysis was performed to determine which combination of smoothing interval, number of smoothing passes, and the depth range to compute near-surface K would lead to the smallest range of L_{U0} and E_{D0} values. Optimum results were achieved for the Hawaiian data set by smoothing L_U profiles three times over 9 m intervals and E_D profiles four times over 11 m intervals for the MLML regression and boxcar methods. L_U profiles were smoothed once over a 9 m interval and E_D profiles were smoothed once over a 11 m interval for the Smith and Baker method. Both attenuation profiles were additionally smoothed five times over 5 meter intervals. The depth range 7 to 12 m was selected for the regressions to compute surface K_L using the MLML and Smith and Baker methods, and 10 to 15 m was used for the boxcar method since the surface-most depth of 10 m is available using a 9 m interval. A depth range of 12 to 17 m was used to compute K_E for all three methods.

Tables 2 (MOBY L51) and 3 (MOCE 8) summarize the results of the near-surface K 's along with their respective L_{u0} and E_{D0} estimates from each of the smoothing methods compared. The tables show the mean $\pm$ the standard error of K_L , L_{u0} , K_E and E_{D0} from each set for channels 1 through 5. The standard error for the sets of MLML surface products were slightly lower than or equal to the other two methods 90% of the time.

For MOBY L51, the differences between mean K_L values for each method are within 3%; the differences between mean L_{u0} values for each method are within 1%; the differences between mean K_E values for each method are within 6%; and the differences between the mean E_{D0} values are within 4%.

Table 2. Results of surface products for each smoothing method from MOBY L51.

MOBY L51	412 nm	443 nm	490 nm	520 nm	555 nm
ML K_L	0.035 ± 0.001	0.034 ± 0.001	0.032 ± 0.001	0.046 ± 0.001	0.066 ± 0.002
SB K_L	0.035 ± 0.001	0.034 ± 0.001	0.033 ± 0.001	0.047 ± 0.002	0.067 ± 0.002
BC K_L	0.035 ± 0.001	0.034 ± 0.001	0.033 ± 0.002	0.046 ± 0.002	0.065 ± 0.003
ML L_{u0}	1.86 ± 0.06	1.62 ± 0.05	1.27 ± 0.03	0.70 ± 0.02	0.28 ± 0.01
SB L_{u0}	1.87 ± 0.06	1.63 ± 0.05	1.28 ± 0.04	0.71 ± 0.03	0.28 ± 0.01
BC L_{u0}	1.86 ± 0.07	1.63 ± 0.05	1.28 ± 0.04	0.70 ± 0.03	0.28 ± 0.01
ML K_E	0.033 ± 0.002	0.033 ± 0.002	0.032 ± 0.002	0.055 ± 0.002	0.079 ± 0.002
SB K_E	0.035 ± 0.002	0.034 ± 0.002	0.034 ± 0.003	0.057 ± 0.003	0.081 ± 0.003
BC K_E	0.034 ± 0.003	0.034 ± 0.004	0.034 ± 0.004	0.056 ± 0.003	0.081 ± 0.004
ML E_{D0}	105.99 ± 5.35	109.79 ± 5.70	117.99 ± 5.86	112.07 ± 5.47	102.32 ± 5.16
SB E_{D0}	108.53 ± 7.44	113.42 ± 7.17	122.17 ± 5.96	116.33 ± 5.94	105.66 ± 4.69
BC E_{D0}	107.85 ± 5.24	112.52 ± 5.85	121.42 ± 6.60	115.80 ± 6.57	105.51 ± 6.83

MOCE 8 results are the averages of four sets of profiles from Stations 5 and 6.

The mean K_L values for each method are within 4%. The mean L_{U0}^- values for each method are nearly within 1%. The mean K_E values for each method are within 3%, The mean E_{D0}^- values for each method are nearly within 1%.

Table 3. Results of surface products for each smoothing method from MOCE 8.

MOCE 8	412 nm	443 nm	490 nm	520 nm	555 nm
ML K_L	0.029 ± 0.002	0.027 ± 0.002	0.027 ± 0.002	0.039 ± 0.002	0.059 ± 0.003
SB K_L	0.029 ± 0.002	0.027 ± 0.002	0.027 ± 0.002	0.039 ± 0.003	0.060 ± 0.004
BC K_L	0.030 ± 0.002	0.028 ± 0.002	0.028 ± 0.002	0.039 ± 0.002	0.059 ± 0.003
ML L_{U0}^-	2.82 ± 0.36	2.38 ± 0.29	1.69 ± 0.19	0.92 ± 0.10	0.34 ± 0.04
SB L_{U0}^-	2.82 ± 0.36	2.38 ± 0.28	1.69 ± 0.18	0.92 ± 0.10	0.34 ± 0.04
BC L_{U0}^-	2.85 ± 0.36	2.40 ± 0.29	1.71 ± 0.19	0.92 ± 0.11	0.34 ± 0.04
ML K_E	0.022 ± 0.002	0.022 ± 0.002	0.025 ± 0.002	0.047 ± 0.002	0.070 ± 0.003
SB K_E	0.022 ± 0.002	0.022 ± 0.002	0.024 ± 0.003	0.047 ± 0.004	0.070 ± 0.004
BC K_E	0.022 ± 0.003	0.022 ± 0.004	0.024 ± 0.004	0.046 ± 0.004	0.070 ± 0.004
ML E_{D0}^-	127.87 ± 14.85	131.43 ± 15.07	139.14 ± 16.86	132.32 ± 16.91	121.50 ± 15.12
SB E_{D0}^-	128.49 ± 15.52	132.62 ± 16.03	139.79 ± 17.28	132.91 ± 16.85	123.02 ± 16.73
BC E_{D0}^-	127.15 ± 14.98	131.47 ± 15.85	138.67 ± 17.62	131.68 ± 17.17	121.71 ± 16.26

Mean Deviations

The individual percent deviations about their mean value stated below are expressed as the absolute difference (in percentage) between the minimum and maximum deviations. The values given are the best and worst cases among channels 1 through 5. Percent difference from the mean for individual K_L , L_{U0}^- , K_E and E_{D0}^- values from MOBY

L51 are shown in Figures 12 through 15 and MOCE 8 are shown in Figures 16 through 19. Set means and standard errors are included in the lower left and right of the figures respectively.

MOBY L51

MLML smoothed K_L values have the smallest range about the mean value, 9 to 11%, followed by Smith and Baker, 10 to 13%, and the boxcar, 11 to 15%. MLML L_{U0} values have the smallest range about the mean value, 6 to 8%, followed by Smith and Baker, 8 to 10%, and the boxcar, 9 to 13%. Smith and Baker K_E values have the smallest range about the mean value for channels 1 and 2, 17 and 20%, followed by MLML, 20 and 21%, and the boxcar, 35 and 39%. MLML K_E values have the smallest range about the mean value for channels 3 through 5, 8 to 17%, followed by Smith and Baker, 9 to 19%, and the boxcar, 16 to 35%. The boxcar E_{D0} values have the smallest range about the mean value for channels 1 through 4, 12 to 14%, followed by MLML, 14 to 15%, and Smith and Baker, 18 to 23%. MLML E_{D0} values have the smallest range about the mean value for channel 5, 16%, followed by both Smith and Baker and the Boxcar, 17%.

MOCE 8

MLML smoothed K_L values have the smallest range about the mean value, 13 to 22%, followed by the boxcar, 16 to 25%, and the Smith and Baker, 21 to 29%. The range of L_{U0} deviations are nearly identical between the methods, MLML are 27 to 34%, Smith and Baker are 28 to 33%, and the boxcar are 29 to 34%. MLML smoothed K_E values have the smallest range about the mean value, 15 to 32%, followed by Smith and Baker,

16 to 40%, and the boxcar, 20 to 52%. The MLML E_{D0} values have the smallest range about the mean value, 32 to 39%, followed by the boxcar, 38 to 44%, and the Smith and Baker, 40 to 48%. It should be recognized that these results for MOCE 8 are higher than MOBY L51 because they are the mean of four sets of profiles. Individual set results are all lower than MOBY L51 which is evident in the figures. However, the average of the sets were used for the sake of brevity.

Confidence Intervals

The 95% confidence intervals of least squares regressions were computed to show the uncertainty of extrapolated products from a smoothed profile associated with the uncertainty in computing K. This type of analysis focuses on uncertainties associated with individual casts versus the uncertainty associated with a set of casts addressed in the previous section. Results for each cast from MOBY L51 are shown in Figure 20, and from MOCE 8 in Figure 21.

MOBY L51

All of the MLML individual L_{U0} uncertainties for channels 1 through 5 are below 1%. Excluding the sixth cast, individual boxcar L_{U0} uncertainties are lower than 2% for channels 1 through 4, and 3% or lower for channel 5. Excluding the eighth cast, individual Smith and Baker L_{U0} uncertainties are 3% or lower for channels 1 through 4, and 5% or lower for channel 5. The mean MLML L_{U0} uncertainties for channels 1 through 5 are the lowest, followed by the boxcar and last Smith and Baker. All of the MLML individual E_{D0} uncertainties for channels 1 through 5 are below 2%. Excluding

the fifth cast, individual boxcar E_{D0} uncertainties are 3% or lower for channels 1 through 5. Excluding the fifth cast, individual Smith and Baker E_{D0} uncertainties are lower than 15% for channels 1 through 5. The mean MLML E_{D0} uncertainties for channels 1 through 5 are the lowest, followed by boxcar and last Smith and Baker.

MOCE 8

All of the MLML individual L_{U0} uncertainties for channels 1 through 5 are below 1%. Excluding the last cast, individual boxcar L_{U0} uncertainties are lower than 3% for channels 1 through 5. Excluding the fourteenth cast, individual Smith and Baker L_{U0} uncertainties are lower than 3% for channels 1 through 4, and lower than 6% for channel 5. The mean MLML L_{U0} uncertainties for channels 1 through 5 are the lowest, followed by the boxcar, and last Smith and Baker. All of the MLML individual E_{D0} uncertainties for channels 1 through 5 are below 3%. Excluding two of the casts, individual boxcar E_{D0} uncertainties are 7% or lower for channels 1 through 5. Individual Smith and Baker E_{D0} uncertainties are 22% or lower for channels 1 through 5. MLML mean E_{D0} uncertainties are the lowest while Smith and Baker are the highest. MLML L_{U0} and E_{D0} uncertainties also show the least amount of variability for each of the data sets. MLML L_{U0} and E_{D0} individual uncertainties are consistently lower than the other methods for both the MOBY L51 and MOCE 8 data sets.

Attenuation Profiles

Attenuation profiles were computed using the method of least squares following Smith and Baker (1984), on L_U and E_D profiles smoothed with each of the three methods.

Figure 22 shows an example of the K_L and K_E profiles considered for the RMS analysis, from Station 1 of MOCE 5. Profiles contaminated by clouds or ship shadowing were not included. Due to the nature of the Smith and Baker and boxcar methods, and the increased smoothing interval required in clear water, the surface-most binned depths of attenuation profiles are deeper than 5 m. Therefore, RMS differences at 5 m intervals start at 10 m. Eighteen casts from MOCE 5 and twenty-one casts from MOCE 6 through MOCE 8 were used to assess differences between attenuation profiles.

The DARR-94 analysis considered good agreement between methods to be RMS values less than 5% (Siegel *et al.*, 1995). Most of the K_L profiles from MOCE 5 have RMS values below 5%. K_E profiles from MOCE 5 begin to show good agreement below 35 m. The percentage of K_E profiles that have consistent RMS values less than 5% above 35 m, increases with the longer wavelength channels. All of the K_L profiles (all channels) from MOCE 6 through MOCE 8 show slightly better agreement than MOCE 5 with RMS values below 3%. $K_E(412,443,490)$ profiles begin to show good agreement below 30 m from MOCE 6 through MOCE 8. $K_E(520,555)$ profiles from all MOCE cruises, begin to show good agreement below 20 m. Similar to MOCE 5, the percentage of K_E profiles that have consistent RMS values less than 5% above 30 m from MOCE 6 through MOCE 8, increases with the longer wavelength channels. The average RMS values for all of the K_L and K_E profiles from each of the MOCE cruises are shown in Figure 23. Mean K_L RMS values from MOCE 6 through MOCE 8 are slightly lower than MOCE 5 in the upper 50 m, and markedly lower between 65 to 90 m for $K_L(555)$ (Fig. 23, upper right). Mean K_E

RMS values from MOCE 5 are slightly lower than MOCE 6 though MOCE 8 in the upper 40 m. Mean RMS deviations among the methods in the top 20 m are lower for K_L , below 2%, compared to K_E which are generally between 5 to 12%.

MOS Comparison

An important aspect of analyzing surface truth data concerns determination of solar normalized water-leaving radiances. Comparison of MOS and SPMR values for near surface K_L and L_{WN} data are shown in Figures 24 through 27. Data from 51 mean SPMR casts and 38 MOS casts were used to assess differences between the two radiometers. Twenty eight comparisons were made using MOCE 5 data, 15 SPMR averages before the MOS profiles were acquired, 13 after. Twenty three comparisons were made using data from the MOCE 6 through MOCE 8 cruises, 11 SPMR averages before MOS, 12 after.

MOCE 5

MOS K_L values are greater than SPMR in clearer waters where attenuation was low, at Stations 5, 10, 11 and 17. SPMR K_L values are greater than MOS for 85% of the comparisons from MOCE 5. These differences are greatest in areas of strong attenuation such as Stations 7, 8, and 12 through 14 (Figs. 24 and 25, top row). No apparent trend seems to exist with the comparisons from SPMR data collected before or after MOS (Fig. 24, top row). MOS band weighted $K_L(520,555)$ are below $K_w(520,555)$ nine times at (Stations 4,5,6,9,11) compared to SPMR $K_L(520,555)$ values which are below $K_w(520,555)$ only once at Station 10 (Fig. 25, upper right).

MOS $L_{WN}(412,443,490)$ data are greater than SPMR at the lower end of measured values (pigment rich water), with one exception at Station 14. SPMR $L_{WN}(412,443,490)$ data are greater than MOS at the upper end of measured values (clearer water), except for three cases at Stations 6, 10 and 11. $L_{WN}(520,555)$ values do not vary as much as $L_{WN}(412,443,490)$. This region of the visible spectrum is known as the “hinge point” because L_w and L_{WN} show the lowest amount of variation with changes in pigment concentration. There appears to be a trend with respect to before and after MOS collections at the upper end of measured $L_{WN}(555)$ values (pigment rich water). SPMR data collected before MOS are lower and SPMR data collected after MOS are greater, with one exception at Station 7 (Fig. 25, lower right).

MOCE 6, 7, 8

SPMR K_L values are much more repeatable than MOS K_L values. The range of MOS $K_L(412,443)$ values are nearly twice that of SPMR, and $K_L(490,520,555)$ values are more than three times greater (Figs. 26 and 27, top row). Most of the variability in the comparisons occurs in MOCE 6 where MOS values fluctuate above and below SPMR (Fig. 27, top row). The SPMR K_L values measured before and after MOS appear to be equally spread about the 1:1 line (Fig. 26, top row). None of the SPMR $K_L(412,443,490)$ values are below their respective $K_w(412,443,490)$. However, 74% $K_L(520)$ and 48% of $K_L(555)$ are below their respective K_w values (Fig. 27, upper row). Interestingly, most of the values below K_w are from MOCE 6 and MOCE 8 which occurred during the spring. All of the MOS band weighted $K_L(490)$ values below $K_w(490)$ are from MOCE 6 and

MOCE 8. Forty-eight percent of MOS $K_L(520)$ and 68% of MOS $K_L(555)$ values are below their respective $K_w(520,555)$, again mostly from MOCE 6 and MOCE 8.

SPMR $L_{wN}(412)$ values are all greater than MOS, mostly between 10 to 20%. Only two MOS $L_{wN}(443)$ values are slightly greater than SPMR, again SPMR values are mainly 10 to 20% greater. One MOS $L_{wN}(490)$ value is slightly greater than SPMR from MOCE 7. SPMR $L_{wN}(490)$ differences are even greater than the $L_{wN}(412,443)$ comparisons. SPMR $L_{wN}(520)$ values range from 35 to 74% greater than MOS. With the exception of one point, $L_{wN}(555)$ comparisons have a distribution similar to the $K_L(555)$ comparisons, with the range of MOS $L_{wN}(555)$ values more than twice that of SPMR. Seven MOS $L_{wN}(555)$ values are greater than SPMR, five are from the MOCE 7 cruise which occurred during the winter.

DISCUSSION

Prosoft Comparison

If profiles have been smoothed sufficiently and attenuation is nearly constant, log transformed L_U and E_D profiles should appear as a straight line in the upper mixed layer. The range of Prosoft K_L and L_{U0} mean deviations was unacceptably large suggesting an inadequate smoothing. The Prosoft User's Manual states that they incorporate the Smith and Baker smoothing method into their processing scheme. However, the depth range over which their routines smooth E_D and L_U profiles is too small, and it is applied only one time through the profile. These limitations, coupled with the fact that Prosoft extrapolation depths are quite often too shallow (they use the surface most L_U values from their binned files for extrapolation by default) lead to highly variable derived products. Figure 28 shows the insufficient smoothing in an L_U profile from MOBY-L51 by Prosoft compared to MLML. MLML routines allow the processor to choose the top depth and range over which to compute surface K_L and K_E values as well as the number of times to repeat the smoothing operation. Therefore, SPMR data processed with Prosoft were not suitable, and a new set of processing routines were developed.

Profile Smoothing Methods Comparison

The primary goal of re-writing the SPMR processing software was to increase the repeatability of L_{U0} and E_{D0} estimates for successive casts. Comparison of three different smoothing methods was done to determine the most effective technique in removing

wave-noise for the new processing routines. This ensures that the most precise measurements for repeated casts increases the confidence of the SPMR mean K_L and L_{U0} data to be used later for comparison with MOS measurements. L_U profiles are not affected by waves as much as E_D profiles as explained in Siegel *et al.* (1995). Downwelled light is restricted to a cone due to refraction. The area of the cone increases with increasing depth and the probability of focused and de-focused light cancel. At great depth the effects of wave focusing are nil. Upwelled radiance is backscattered downwelled light which has entered the sampled volume from a region much larger than the radiance sample volume. The radiance sample volume is a narrow (about 20°) solid angle extending downward from the radiance port. Because E_D is measured over the upper hemisphere, random tilts in the profiler affect E_D profiles more than L_U profiles. This explains the large degree of variability associated with E_{D0} estimates compared to L_{U0} .

Irradiance fluctuations can penetrate to depths greater than 50 m in clear waters where most of the measurements in this study were taken. The amplitudes of the fluctuations tend to decay exponentially with increasing depth, and the fluctuation frequency is reduced with increasing depth as well (Snyder and Dera, 1971). Siegel and Dickey (1988) characterized downwelled irradiance fluctuations in the North Pacific Ocean and showed that this decay can be modeled using an exponential function. They calculated the mean (smoothed) profile and computed the absolute difference from the raw (unsmoothed) profile to illustrate the decay process. In coastal waters, light attenuation

by pigment absorption and particle scatter can greatly reduce this effect (Gordon and Dera, 1968). These characteristics can be seen in $E_D(443)$ profiles from MOCE 5 Stations 4 and 12 (Fig. 29). At Station 4, strong fluctuations exist in the mixed layer down to about 25 m. The fluctuations disappear below 35 m, in the pycnocline, and attenuation of the irradiance signal increases below 60 m where fluorescence and beam attenuation are at a maximum. At Station 12, only slight fluctuations are present in the top 4 m and no longer exist below 6 m. Attenuation is strongest in the upper 6 m and exhibits a uniform decrease below this depth. Fluorescence and beam attenuation are at a maximum at about 3 or 4 m and abruptly decrease down to about 7 or 8 m. Therefore, smaller intervals and one smoothing pass were used in processing some casts from MOCE 5, Stations 7 and 8, and in the Gulf of California, Stations 12 through 15. Most SPMR profiles at sites off Hawaii are terminated above the pycnocline. Thus wave focusing effects are evident throughout the entire profile, and the exponential decay in the irradiance and radiance profiles are clearly evident (Fig. 3, left column).

The Smith and Baker method produces smooth K_E profiles rather than smooth E_D profiles, since E_D profiles are smoothed only once while K_E is smoothed five times over a smaller interval. This approach to processing radiometric profiles has a different purpose. By increasing the length of the smoothing interval and the number of smoothing passes, more data are lost at each end of the profile. In contrast, smaller intervals preserve details of the profile in regions of sharply defined layers, which reflect changes in the inherent optical properties. Their objective was to retain information regarding the true variability

in K_E with depth, avoiding over-smoothing regions of stratification and sub-surface maxima. However, their method fails to remove the high degree of wave noise seen in every E_D profile from MOCE 6 through MOCE 8 and MOBY L51. This is evident by the large amount of uncertainty associated with their method's E_{D0} estimates (Figs. 21 and 22).

The intention of the MLML method is to reduce the effects of waves in the mixed layer in E_D and L_U profiles. This is critical for the retrieval of precise L_U and surface K_L values used to compute L_{U0} . The idea behind this approach involves removing as much of the wave noise in L_U or E_D profiles rather than directly focusing on the attenuation profiles. Mean deviations of K_L , K_E , L_{U0} and E_{D0} demonstrate that the MLML modification of the Smith and Baker method produces the most repeatable results. MLML mean deviations and standard errors were either the lowest or second lowest among the three methods. The MLML method produced the lowest mean L_{U0} and E_{D0} values for each of the sets which suggests over-estimation by the other two methods. The MLML method also best minimizes the uncertainty associated with the extrapolation for individual casts (Figs. 21 and 22). MLML uncertainties associated with individual L_{U0} estimates were 2 to 5 times lower than the boxcar and Smith and Baker uncertainties and 2 to 10 times lower than the other two methods for uncertainties associated with E_{D0} estimates. MLML uncertainties were consistently below 1% for L_{U0} and below 2% for E_{D0} . Tighter confidence intervals are associated with regressions least affected by wave noise.

Because K_L and K_E are derivatives, their estimate is sensitive to small changes in L_U and E_D respectively. However, L_U and E_D are the variables which have the greatest effect on the precision of L_{U0} and E_{D0} estimates. Using Equation 12 a sensitivity analysis was performed, first varying K_L by 5, 10 and 15%, keeping L_U from the depth of extrapolation constant and noting the effects on L_{U0} . Then K_L was held constant, letting L_U vary by the same percentages, again noting the effects on L_{U0} . Results in Table 4 show that variations in L_U have a greater effect on L_{U0} than variations in K_L .

Table 4. Sensitivity of L_{U0} when varying K_L compared to varying L_U
Step 1. Vary K_L by 5, 10 and 15 percent, holding $L_U(5\text{ m}) = 0.25$

% Change	K_L	L_{U0}	% Change
0	0.03	1.492	0
5	0.0315	1.503	0.75
10	0.033	1.514	1.51
15	0.0345	1.526	2.28

Step 2. Vary $L_U(5\text{m})$ by 5, 10 and 15 percent, holding $K_L = 0.03$

% Change	$L_U(5\text{ m})$	L_{U0}	% Change
0	0.25	1.492	0
5	0.2625	1.511	1.26
10	0.275	1.530	2.53
15	0.2875	1.549	3.82

Boxcar smoothing was applied to profiles in a manner similar to the MLML method. It was included in the comparison, even though it results in a loss of data at the

beginning and end of the data sequence, because it employs different smoothing. Because the boxcar method does not provide near surface L_U data, the depth from which L_U is extrapolated is greater than that of the MLML method. The near-surface K_L was computed between 10 and 15 m, compared to 7 to 12 m for the MLML and Smith and Baker methods. Recall that the MLML regression method does not result in data loss from the ends of the profile. In addition, the boxcar filter is applied using the MATLAB “convolve” function which adds numerical artifacts to each end of a profile. These artifacts are usually removed before subsequent passes are carried out. The boxcar method did not increase the precision of L_{U0} and E_{D0} estimates from smoothed L_U and E_D profiles. However, the boxcar usually did a better job of removing the wave noise in individual casts compared to the Smith and Baker method because of the greater number of passes through the profile. This is evident from the uncertainty analysis, especially for E_{D0} estimates (Figs. 21 and 22). With the exception of one cast the boxcar E_{D0} uncertainties are consistently below 3%, Smith and Baker E_{D0} uncertainties are consistently above 5% and as high as 15%.

Attenuation Profiles

All attenuation profiles were calculated using least squares regression. Smith and Baker (1984) concluded this was their best method for smoothing and directly obtaining attenuation profiles. Other methods have also been developed (Petzold, 1988; Mueller, 1991). This section addresses the effects of over-smoothing sub-surface features below the mixed layer as a result of intense smoothing to handle the fluctuations above. Over-smoothing takes place during each pass with a particular smoothing filter. In effect, areas

with sharp inflections are continually straightened with each pass. If the interval is too large, K is misrepresented where L_U or E_D are changing on scales smaller than the interval. This is the intention in the case of reducing surface fluctuations which are solely attributed to wave focusing. However, this is not desired below the mixed layer where the goal is to best represent the optical properties associated with sub-surface maxima. Low RMS values throughout the profile (Fig. 23) suggest that the increased interval used with each of the methods still over-smooths sub-surface features. Disagreement between the smoothing methods in the top 30 m of K_E profiles is attributed to surface wave noise and failure to completely remove edge artifacts created by Matlab's convolve function. The profiles were not reprocessed in the attempt to resolve particular features. Results are only given from processing with the goal to remove wave effects for the retrieval of precise water-leaving radiances.

MOS Comparison

One of the primary goals stated in the SeaWiFS protocols was the retrieval of water-leaving radiances whose uncertainties are within 5% (Mueller and Austin, 1995). The comparison of MOS and the SPMR data in this study shows that this goal was not achieved. The MOCE 5 comparisons were only slightly better than their Hawaiian counterparts. Only 5 out of 28 met the 5% requirement for channels 1, 2 and 4, while 7 and 11 met it for channels 3 and 5 respectively (Fig. 25, bottom row). For this cruise, differences in the comparisons can be attributed to the different water types encountered. The SPMR tended to be greater than MOS in clearer water with the opposite being true

for pigment rich water (Fig. 27, bottom row). The comparisons from MOCE 6 through MOCE 8 show that the SPMR over-estimates L_{WN} by 10 to 20%, especially in the blue channels 1 through 3 (Fig. 27, lower left). Only 2 out of 23 comparisons met the 5% requirement for channels 1 and 3, 3 out of 23 for channel 2, and 8 out of 23 for channel 5. None of the comparisons for channel 4 were even close, SPMR values are mainly 40 to 80% greater. This points to calibration problems which will be discussed later on. Questions concerning radiometric accuracy cannot be addressed by the comparison of only two radiometers. Two related questions which arise from this comparison are:

1. Why are SPMR K_L 's more repeatable than MOS K_L 's, especially from MOCE 6 through MOCE 8?
2. Why are the SPMR L_{WN} values consistently much higher than those for MOS in channels 1 through 3 during MOCE 6 through MOCE 8 and lower than MOS during MOCE 5 in channels 1 through 3 at the lower end of measured values?

The difference in acquisition schemes and instrumentation design partially explain the differences between MOS and the SPMR retrieved values. As stated previously, the SPMR has low spectral resolution and high depth resolution. It is much more precise to determine the vertical radiance gradient with the SPMR sub-meter sample interval than by measuring L_U at only three depths as done using MOS. SPMR K_L 's vary by about 30% (worst case between min and max) from MOCE 6 through MOCE 8, whereas MOS K_L 's vary by as much as 75%. No apparent variation seems to exist between SPMR measurements taken before and after MOS (Fig. 26, left column). Since the diffuse

attenuation coefficients are determined by irradiance or radiance ratios they do not require absolute radiometric measurements.

MOS measurements have a high degree of spectral resolution, low depth resolution and are accurately calibrated with NIST radiometric standards. The variable most responsible for determining accurate water-leaving radiances is L_U , though valid K_L values are desired to extrapolate L_U to the surface. Using MOS precise measurements of the light field at each discrete depth are accomplished by taking the average of five acceptable light scans, then subtracting real-time dark scans to achieve signal to noise ratios (SNR) greater than one hundred. The bin factors and integration times for each of the raw scans in a set were equal. A few sets of 5 scans are taken at each depth but only the best (highest SNR) is used in computing the water-leaving radiance. Clouds might reduce the number of possible sets acquired and can potentially decrease the SNR. The relative error of all of the sets of 5 MOS L_U raw scans used from the top depth was calculated as the RMS error normalized to the mean of the scan set. Since the relative errors are spectral, they were band weighted using the SPMR normalized L_U responses using Equation 16. The average weighted L_U relative errors for MOCE 5 are around 2%, and around 1% when one of the stations is removed (RMS of 12%). The average weighted L_U relative errors for MOCE 6 through MOCE 8 are around 1%. Each of the radiometers have the capability of measuring L_U with good precision. However, measurements taken at different depths and times, and calibrated independently, will usually result in different values of K_L and L_{U0} , as shown in both this study and the

SeaWiFS Data Analysis Round Robin study (Siegel *et al.*, 1995).

MOS and SPMR incorporate the same solar normalization function which should, in theory, account for time differences between measurements. The solar normalization factor cannot account for small differences in sky conditions during the two sets of observations. This only points to other factors which contribute to the poor agreement between the instruments.

Other limitations of SPMR acquisition and processing exist, and are especially evident in the coastal, pigment rich waters occupied during MOCE 5. The explanation which follows parallels the reason for not including channels 6 and 7 in any of the comparisons. The SPMR reaches a constant descent attitude at 2 to 3 m below the surface. All data above this depth are rejected before subsequent processing takes place. In green waters with high pigment concentrations there is little, if any, blue light left to detect at these depths, mainly due to strong pigment absorption. L_U was projected to the sea surface in regions of inflections (where K is not uniform) effectively underestimating the water-leaving radiance, which is evident in the L_{wN} comparison (Fig 24, right column). MOS scan depths at these stations were very shallow, just below the sea surface and the second depth was at 2 or 3 m. These shallow depths were achieved because of the ideal conditions experienced at Stations 12 through 15 where the sky was clear and the sea surface was flat calm. However, in the clearer waters of the open ocean with less attenuating material, the conditions most favorable for SPMR casts are not the most favorable for MOS acquisition (Dennis Clark, pers. com.). When the sea surface is flat,

the light field is less diffuse and the effects of capillary wave focusing are more pronounced just below the sea surface (Gordon *et al.*, 1971). This situation causes highly variable MOS K_L values because of the wave effects on MOS L_U at the top depth. MOS K_L values are less than K_w values because of de-focusing and they may be too high when focusing occurs.

The inability to accurately determine L_{wN} involves SPMR calibrations. Satlantic performs the calibrations and they do not provide details of their calibration process. Use of the RS-10 lamp before and following cruises showed that the SPMR was a stable radiometer over the course of the study. The average difference between inspections was less than 0.7% for L_U , and less than 2% for E_D , for channels 1 through 5. However, these inspections are not intended as absolute calibrations, they only provide checks on instrument drift between annual calibrations. L_U and E_D are computed from the instrument's response functions provided in Satlantic calibration files. The large differences between SPMR and MOS $L_{wN}(520)$ from MOCE6 through MOCE 8 raise concerns regarding the accuracy of SPMR calibrations. With MLML and NOAA's experience in making precise and accurate radiometric calibrations for MOS and MOBY, one wonders if the SPMR calibrations provided by the factory are within the required accuracy of absolute uncertainties of less than 3% using NIST traceable secondary standards, and repeated to within 1%, stated in the SeaWiFS protocols (Mueller and Austin, 1995). Finally, an accurately calibrated radiometer requires accurate calibration lamps and precision optical alignment.

Conclusions

The performance of the SPMR in clear waters was improved with the new set of computational algorithms. The modified Smith and Baker method was the most effective in smoothing the fluctuations caused by surface waves. This is evident as seen in the results of the mean deviations and the errors associated with computing a surface K for extrapolation to just beneath the sea surface. Procedures developed here stress the importance to first smooth L_U and E_D profiles, then to compute a near-surface K from the smoothed radiance profiles from which precise water-leaving radiances are calculated.

The SPMR showed the capability of producing highly repeatable water-leaving radiances in clear waters when environmental conditions were favorable. This was the case for both sets of casts from Stations 5 and 6 from MOCE 8 where repeatability was within 1.5% for all five channels (using the normalized RMS). An analysis of the repeatability of the SPMR from the MOCE 5 data set is inconclusive since there were only two casts per set.

Difficulties with SPMR data acquisition at shallow depths in the pigment rich waters encountered during MOCE 5 lead to the under-estimation of water-leaving radiances. A new deployment technique should be developed using this type of profiler in a productive coastal setting. This work on SPMR has led to improvements for processing data from the new Satlantic MICROPRO profiler. The spectral resolution of the MICROPRO is twice that of the SPMR with the addition of seven channels. Each channel

is processed individually to allow for separate smoothing intervals, the number of passes and the depth interval to compute surface K 's in an attempt to avoid over-smoothing and extrapolation through inflections at the longer wavelength channels.

Results from the MOS comparison show that the SPMR is an effective tool is measuring diffuse attenuation coefficients and that MOS is the radiometer of choice for satellite sea surface truth work. MOS is capable of repeating sub-surface upwelled radiances to within 1% in clear water and 2% in coastal water. The ability to provide accurate measurements is the result of painstaking efforts in producing both precise and accurate system responses. This could only be accomplished with the use of NIST traceable calibration sources before each MOCE and MOBY refurbishment cruise.

It would be interesting to see if the agreement between the SPMR and MOS would have improved if the SPMR had been calibrated using NIST traceable calibration sources. It would also be interesting to see if applying SPMR measured K_L values to MOS measured L_U values could make any improvements on the repeatability of MOS water-leaving radiances in clear waters.

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Figure 1. MOS spectral data from Baja and Hawaii. Upper Left: MOS downwelled irradiance, E_D . Upper Right: MOS upwelled radiance, L_U . Lower Left: MOS irradiance attenuation, K_E . Lower Right: MOS radiance attenuation, K_L . Heavy lines show data from MOCE 8, Station 6 in Hawaiian waters (Fig. 5), light lines show data from MOCE 5, Station 3 from the Pacific side of Baja California (Fig. 4).

Figure 2. Attenuation of pure seawater, K_w , * from 400 to 700 nm used by Mueller (2000) using pure water back-scattering, b_b , $\square$ (Smith and Baker, 1981) and the most recent values of pure water absorption, a , $\circ$ (Pope and Fry, 1997).

Figure 3. Upper: The Marine Optical System, MOS, ready for deployment, attached to the floatation tetrahedron on the R/V Moana Wave aft deck. Lower: The SeaWiFS Multichannel Profiling Radiometer, SPMR.

Figure 4. MOCE 5 station locations. 1-21 Oct. 1999.

Figure 5. MOBY L51 and MOCE 6,7,8 station locations. 1999-2001.

Figure 6. SPMR Vertical profiles of unsmoothed, downwelled irradiance, E_D and L_U obtained with the SeaWiFS Multichannel Profiling Radiometer, SPMR at 490 nm. Upper Left: arithmetic plot of E_D . Upper Right: arithmetic plot of L_U . Lower Left: logarithmic plot of E_D . Lower Right: logarithmic plot of L_U . Data from MOCE 8, Station 1.

Figure 7. Logarithmic downwelled irradiance profile for SPMR channel 3, 490 nm (upper left) and channel 5, 555 nm (upper right). Logarithmic upwelled radiance profile for SPMR channel 3, 490 nm (lower left) and channel 5, 555 nm (lower right) at MOCE 8, Station 6. The three smoothing methods (MLML, Smith-Baker, boxcar) are overplotted, but their lines are not distinct at this scale. The extrapolated surface values are: * MLML; □ Smith and Baker; and O boxcar.

Figure 8. MOS spectral and band weighted upwelled radiance. L_U at 1 and 5 m (upper left). MOS spectral diffuse attenuation coefficient, K_L between L_U at 1 and 5 m (lower left). MOS solar-normalized water leaving radiance, L_{WN} (upper right). Normalized SPMR upwelled radiance responses (lower right). * show the SPMR band weighted values. Data from MOCE 8, Station 6.

Figure 9. Percent difference between individual, *, and mean diffuse radiance attenuation K_L values from a nine SPMR profile replication experiment. Prosoft processing is shown in the left column, MLML processing in the right column. Mean K_L values (m^{-1}) are shown in the lower left and standard error of K_L values (m^{-1}), lower right. Data from MOBY L51.

Figure 10. Percent difference between individual, *, and mean subsurface upwelled radiance, L_{U0} values from a nine SPMR profile replication experiment. Prosoft processing is shown in the left column, MLML processing in the right column. Mean L_{U0} values ($\mu W cm^{-2} sr^{-1} nm^{-1}$) are shown in the lower left and standard error of L_{U0} values ($\mu W cm^{-2} sr^{-1} nm^{-1}$), lower right. Data from MOBY L51.

Figure 11. Percent difference between individual, *, and mean solar normalized water-leaving radiance, L_{WN} values from a nine SPMR profile replication experiment. Prosoft processing is shown in the left column, MLML processing in the right column. Mean L_{WN} values ($\mu W cm^{-2} sr^{-1} nm^{-1}$) are shown in the lower left and standard error of L_{WN} values ($\mu W cm^{-2} sr^{-1} nm^{-1}$), lower right. Data from MOBY L51.

Figure 12. Percent difference between individual, *, and mean diffuse radiance attenuation, K_L values from a SPMR profile replication experiment at 490 nm (left column) and 555 nm (right column). Top Row: Smoothing by MLML method; Middle Row: Smoothing by Smith and Baker; Bottom Row: Smoothing by boxcar method. Mean K_L values (m^{-1}) are shown in the lower left and standard error of K_L values (m^{-1}), lower right. Data from MOBY L51.

Figure 13. Percent difference between individual, *, and mean subsurface upwelled radiance, L_{U0} values from a SPMR profile replication experiment at 490 nm (left column) and 555 nm (right column). Top Row: Smoothing by MLML method; Middle Row: Smoothing by Smith and Baker; Bottom Row: Smoothing by boxcar method. Mean L_{U0} values ($\mu W cm^{-2} sr^{-1} nm^{-1}$) are shown in the lower left and standard error of L_{U0} values ($\mu W cm^{-2} sr^{-1} nm^{-1}$), lower right. Data from MOBY L51.

Figure 14. Percent difference between individual, *, and mean diffuse irradiance attenuation, K_E values from a nine SPMR profile replication experiment at 490 nm (left column) and 555 nm (right column). Top Row: Smoothing by MLML method; Middle Row: Smoothing by Smith and Baker; Bottom Row: Smoothing by boxcar method. Mean K_E values (m^{-1}) are shown in the lower left and standard error of K_E values (m^{-1}), lower right. Data from MOBY L51.

Figure 15. Percent difference between individual, *, and mean subsurface downwelled irradiance, E_{D0} values from a nine SPMR profile replication experiment at 490 nm (left column) and 555 nm (right column). Top Row: Smoothing by MLML method; Middle Row: Smoothing by Smith and Baker; Bottom Row: Smoothing by boxcar method. Mean E_{D0} values ($\mu W cm^{-2} nm^{-1}$) are shown in the lower left and standard error of E_{D0} values ($\mu W cm^{-2} nm^{-1}$), lower right. Data from MOBY L51.

Figure 16. Percent difference between individual and mean diffuse radiance attenuation, K_L values at 490 nm (left column) and 555 nm (right column). • Station 5 before MOS cast; x Station 5 following MOS cast; + Station 6 before MOS cast; * Station 6 following MOS cast. Top Row: Smoothing by MLML method; Middle Row: Smoothing by Smith and Baker; Bottom Row: Smoothing by boxcar method. Mean K_L values (m^{-1}) are shown in the lower left and standard error of K_L values (m^{-1}), lower right. Data from MOCE 8. Stations 5 and 6.

Figure 17. Percent difference between individual and mean subsurface upwelled radiance, L_{U0} values at 490 nm (left column) and 555 nm (right column). • Station 5 before MOS cast; x Station 5 following MOS cast; + Station 6 before MOS cast; * Station 6 following MOS cast. Top Row: Smoothing by MLML method; Middle Row: Smoothing by Smith and Baker; Bottom Row: Smoothing by boxcar method. Mean L_{U0} values ($\mu W cm^{-2} sr^{-1} nm^{-1}$) are shown in the lower left and standard error of L_{U0} values ($\mu W cm^{-2} sr^{-1} nm^{-1}$), lower right. Data from MOCE 8, Stations 5 and 6.

Figure 18. Percent difference between individual and mean diffuse irradiance attenuation, K_E values at 490 nm (left column) and 555 nm (right column). • Station 5 before MOS cast; x Station 5 following MOS cast; + Station 6 before MOS cast; * Station 6 following MOS cast. Top Row: Smoothing by MLML method; Middle Row: Smoothing by Smith and Baker; Bottom Row: Smoothing by boxcar method. Mean K_E values (m^{-1}) are shown in the lower left and standard error of K_E values (m^{-1}), lower right. Data from MOCE 8, Stations 5 and 6.

Figure 19. Percent difference between individual and mean subsurface downwelled irradiance, E_{D0} values at 490 nm (left column) and 555 nm (right column). • Station 5 before MOS cast; x Station 5 following MOS cast; + Station 6 before MOS cast; * Station 6 following MOS cast. Top Row: Smoothing by MLML method; Middle Row: Smoothing by Smith and Baker; Bottom Row: Smoothing by boxcar method. Mean E_{D0} values ($\mu W cm^{-2} nm^{-1}$) are shown in the lower left and standard error of E_{D0} values ($\mu W cm^{-2} nm^{-1}$), lower right. Data from MOCE 8; Stations 5 and 6.

Figure 20. Results from regression confidence intervals for each smoothing method for subsurface upwelled radiance, L_{u0} values at 490 nm (top left) and 555 nm (top right) and subsurface downwelled irradiance, E_{D0} values at 490 nm (bottom left) and 555 nm (bottom right). * MLML; O Smith and Baker; □ boxcar. Data from MOBY L51.

Figure 21. Results from regression confidence intervals for each smoothing method for subsurface upwelled radiance, L_{U0} values at 490 nm (top left) and 555 nm (top right) and subsurface downwelled irradiance, E_{D0} values at 490 nm (bottom left) and 555 nm (bottom right). * MLML; O Smith and Baker; □ boxcar. Data from MOCE 8.

Figure 22. Diffuse attenuation profiles computed from a profile from MOCE 5, Station 1. K_L 490 nm (top left) and 555 nm (top right) and K_E 490 nm (bottom left) and 555 nm (bottom right). The three smoothing methods (MLML, Smith and Baker, boxcar) are overplotted, but their lines are not distinct at this scale. Values are: * MLML; + Smith and Baker; o boxcar.

Figure 23. Average root mean square (RMS) profiles, normalized to the mean of the three smoothing methods, from MOCE 5,6,7,8. K_L 490 nm (top left) and 555 nm (top right) and K_E 490 nm (bottom left) and 555 nm (bottom right). * MOCE 5; + MOCE 6; o MOCE 7 and x MOCE 8.

Figure 24. Comparison of MOS (x-axis) and SPMR (y-axis) surface derived products for 490 nm (left column) and 555 nm (right column). Comparisons of K_L (top row) and L_{WN} (bottom row). Black diagonal lines represent the 1:1 line of equality. * SPMR data collected before MOS; • SPMR data collected after MOS. Data from MOCE 5.

Figure 25. Comparison of MOS, *, and SPMR, •, surface derived products, K_L (top row), L_{WN} (middle row) and L_{WN} percent difference from MOS (bottom row) for 490 nm (left column) and 555 nm (right column) during the course of MOCE 5. Black horizontal lines in plots on the top rows represent the clear water attenuation minima $K_w(490)$ and $K_w(555)$ respectively.

Figure 26. Comparison of MOS (x-axis) and SPMR (y-axis) surface derived products for 490 nm (left column) and 555 nm (right column). Comparisons of K_L (top row) and L_{WN} (bottom row). Black diagonal lines represent the 1:1 line of equality. * SPMR data collected before MOS; • SPMR data collected after MOS. Data from MOCE 6, 7, 8.

Figure 27. Comparison of MOS, *, and SPMR, •, surface derived products, K_L (top row), L_{WN} (middle row) and L_{WN} percent difference from MOS (bottom row) for 490 nm (left column) and 555 nm (right column) during the course of MOCE 6 through MOCE 8. Black horizontal lines in plots on the top rows represent the clear water attenuation minima $K_w(490)$ and $K_w(555)$ respectively. Black vertical lines separate MOCE 6 (left), 7 (middle) and 8 (right).

Figure 28. Plots of Prosoft and MLML smoothed L_U at 490 nm (bottom row) profiles and K_L at 490 nm (top row) profiles from MOBY L51 demonstrating the insufficient job of smoothing by Prosoft.

Figure 29. Plots of log transformed E_D at 490 nm (top row) from MOCE 5, Station 4 (left column) and Station 12 (right column) demonstrating the attenuation of irradiance fluctuations. CTD profiles of sigma-theta, σ_θ (middle row) and Chl fluorescence at 670 nm (bottom row) are shown to help explain the irradiance fluctuation decay process.

Appendix A. SPMR Station Listings

Cruise	Station Number	Date	Start Time (GMT)	Latitude	Longitude
MOCE 5	1	1 Oct 1999	21:06:03	32° 26.76' N	117° 21.38' W
	2	2 Oct 1999	17:45:20	29° 41.66' N	116° 06.69' W
	3	3 Oct 1999	18:33:13	27° 25.74' N	114° 57.17' W
	4	4 Oct 1999	18:18:04	25° 09.52' N	112° 59.63' W
	5	5 Oct 1999	18:18:15	22° 47.74' N	110° 08.14' W
	6	6 Oct 1999	18:06:09	22° 48.66' N	107° 10.91' W
	7	7 Oct 1999	16:18:42	22° 02.25' N	105° 46.12' W
	8	8 Oct 1999	18:03:10	21° 47.39' N	105° 45.66' W
	9	9 Oct 1999	17:07:57	24° 04.92' N	107° 45.14' W
	10	10 Oct 1999	18:23:49	22° 30.87' N	109° 35.11' W
	11	11 Oct 1999	19:11:53	25° 48.61' N	110° 46.44' W
	12	12 Oct 1999	18:26:07	28° 35.07' N	112° 26.02' W
	13	13 Oct 1999	18:40:26	28° 35.20' N	112° 31.29' W
	14	14 Oct 1999	17:29:34	28° 34.56' N	112° 32.85' W
	15	15 Oct 1999	17:15:21	28° 34.96' N	112° 33.09' W
	16	16 Oct 1999	17:51:24	25° 54.12' N	110° 07.98' W
	17	17 Oct 1999	16:38:19	22° 58.16' N	109° 29.77' W
	18	18 Oct 1999	16:55:18	24° 26.48' N	112° 01.46' W
	19	19 Oct 1999	17:52:28	27° 12.98' N	114° 37.35' W
	20	20 Oct 1999	17:48:37	30° 17.63' N	115° 55.23' W
MOBY L51	1	18 Nov 1999	22:25:05	20° 48.84' N	157° 12.03' W
MOCE 6	1	9 Apr 2000	20:35:05	21° 12.74' N	158° 07.95' W
	2	10 Apr 2000	21:19:33	20° 37.60' N	157° 01.88' W
	3	11 Apr 2000	20:06:23	20° 48.96' N	157° 12.51' W
	4	12 Apr 2000	21:53:22	20° 51.79' N	157° 09.28' W

	5	13 Apr 2000	19:56:14	20° 33.00' N	157° 02.59' W
	6	14 Apr 2000	21:33:46	20° 59.31' N	156° 46.21' W
	7	15 Apr 2000	20:49:39	21° 16.00' N	158° 15.91' W
	8	16 Apr 2000	20:26:05	21° 01.30' N	157° 58.67' W
<hr/>					
MOCE 7	1	3 Dec 2000	20:30:45	21° 07.73' N	157° 45.96' W
	2	5 Dec 2000	20:35:15	20° 53.87' N	156° 48.46' W
	3	6 Dec 2000	21:00:34	21° 23.98' N	158° 22.41' W
	4	7 Dec 2000	22:20:49	20° 27.63' N	157° 9.46' W
	5	8 Dec 2000	20:59:26	21° 24.59' N	158° 27.95' W
	6	9 Dec 2000	20:16:20	20° 37.36' N	157° 04.86' W
	7	9 Dec 2000	22:19:52	20° 29.36' N	156° 57.78' W
	8	10 Dec 2000	20:43:45	21° 25.50' N	158° 22.92' W
<hr/>					
MOCE 8	1	28 Feb 2001	21:57:31	20° 55.47' N	156° 59.35' W
	2	2 Mar 2001	20:34:11	20° 20.82' N	157° 15.07' W
	3	3 Mar 2001	22:22:23	20° 46.80' N	157° 00.61' W
	4	4 Mar 2001	21:09:55	20° 51.36' N	157° 11.48' W
	5	5 Mar 2001	21:27:43	21° 28.97' N	157° 20.07' W
	6	6 Mar 2001	20:15:36	20° 39.98' N	157° 07.02' W
	7	7 Mar 2001	21:02:19	21° 29.62' N	158° 32.41' W
	8	8 Mar 2001	23:50:05	20° 49.23' N	157° 12.08' W
	9	9 Mar 2001	20:48:58	21° 28.83' N	158° 28.17' W

Appendix B. SPMR Data Reduction Programs

```

function spmrlevel1_(fname)

% SPMRLEVEL1_ - convert raw SPMR\SMSR data into calibrated, physical
%               units.
%
% Use As:      spmrlevel1_(fname)
%
% Input:       fname - filename of raw data *.raw
%
% Output:      Unbinned, calibrated SPMR\SMSR data stored in MLDBASE
%               format.
%
% Example:     spmrlevel1_('stn02a.raw')
%
% Note:        This function must be run in specific data directory
%               to ensure proper cruise calibrations files are used.
%
% See Also:    mlvars_ for MLDBASE information.

% 14 Mar 2000; DP

mlglobal;
[FhdS,SymS,Xdat,poff] = readspmraw_(fname);
fprintf('Raw Data File:      %s\n',fname);
[s,f,d,sizes] = dirlist_([pwd '\'],'*.cal');
fnameP=f(1,:);
fnameR=f(2,:);
[LCal,ACal] = readspmrcal_(fnameP,fnameR);
fprintf('Profile   Cal File: %s\n',fnameP);
fprintf('Reference Cal File: %s\n',fnameR);
refconp=strcmp(FhdS(4,29:31),'DRY'); % get SPMR configuration from FhdS
refconr=strcmp(FhdS(4,41:43),'DRY'); % get SMSR configuration from FhdS
FHDS = FhdS;                          % save File Header, Symbol string
SYMS = SymS;
% Make real MLDBASE variables
chckvar_;
[Xdat,ind]=fltrnan_(Xdat(1:Mpts,1:Nvar),0);
% Make real MLDBASE variables again
chckvar_;
% Check of GAIN setting before conversion
for J = 1:Mpts
    GAIN(J,:) = rem(Xdat(J,:),2);
end
% Apply radiance calibrations, channel by channel
% L = Im*a1*(Counts - a0)
for J = 1:Mpts
    Gain = rem(Xdat(J,:),2); % Gain=0, LCal(:, :, 1) Gain=1, LCal(:, :, 2)
    Gain = Gain + 1;         % Gain is now the index into LCal
    for C = 1:14
        G = Gain(C);
        a0 = LCal(C,G,1);
        a1 = LCal(C,G,2);
        if refconp == 1 % for RS10 stability processing

```

```

        Im = 1;                                % DRY SPMR
    else
        Im = LCal(C,G,3);                      % WET SPMR
    end
    Ydat(J,C) = Im*a1*(Xdat(J,C) - a0);
end
for C = 15:21
    G = Gain(C);
    a0 = LCal(C,G,1);
    a1 = LCal(C,G,2);
    if refconr == 1
        Im = 1;                                % DRY SMSR
    else
        Im = LCal(C,G,3);                      % WET SMSR
    end
    Ydat(J,C) = Im*a1*(Xdat(J,C) - a0);
end
end
% Apply polynomial calibrations to auxiliary data
for C = [22:26 28:30]
    Ydat(:,C) = polyval(fliplr(ACal(C-21,:)),Xdat(:,C));
end
% Pressure is a0*(Counts - a1)-pressure tare
Ydat(:,27) = (Xdat(:,27)-ACal(6,2))*ACal(6,1)-poff;
% Remove spikes caused by Gain switch
for J = 1:Mpts
    GAIN(J,:) = rem(Xdat(J,:),2);
end
%Xdat = Ydat;
for C = 1:14
    GS1 = diff(GAIN(:,C));
    ind1 = find(GS1 > 0);
    if ~isempty(ind1)
        ind2 = find(GAIN(:,C) == 1);
        Ydat(ind2(1):ind2(1)+1,C) = NaN;
    end
end
end
mlempy_; % clear all mldbase variables
% Transfer to Xdat to write MLDBASE file for stability files
Xdat = Ydat;

```

```

function spmrlevel2_(fname,SMLZINT,SMEZINT,KZINT)

% SPMRLEVEL2_ - Remove invalid data and apply natural log to optics
%               data. Bin and smooth calibrated data to remove surface
%               effects. Running attenuation coefficients for profile
%               computed.
%
% Use As:      spmrlevel2_(fname,SMLZINT,SMEZINT,KZINT)
%
% Inputs:      fname      - filename of Level 1 file  *L1.mld
%               SMLZINT    - half depth interval for smoothing Lu
%               SMEZINT    - half depth interval for smoothing Ed
%               KZINT      - depth interval for running Kl\Ke calculation  (6m)
%
% Output:      Computed profile products stored in MLDBASE format.
%
% Example:     spmrlevel2_('stn03b11.mld',2.5,4.5,6)
%
% Note:        This function must be run in specific data directory
%               to ensure proper cruise *L1.mld files are used.
%
% See Also:    mlvars_ for MLDBASE information.

% 16 Mar 2000; DP

mlglobal;
fname=lower(fname);
lind=findstr(fname,'l');                % make sure reading L1.mld files
if strcmp(fname(lind(1):lind(1)+5),'l1.mld') ~= 1
    disp('File must be *L1.mld')
    break
end
readmld_(fname);
FHDS = FhdS;
% Make real MLDBASE variables
chkpts_;
chkvar_;
% Normalize using time averaged Eref
Navg = 48;
E0 = mean(Xdat(1:Navg,16:22));
for C = 1:7
    Enorm(:,C) = E0(C)./Xdat(:,C+15);
end
Ptilt = tilt_(Xdat(:,23),Xdat(:,24)); % profiler tilt
pT = Ptilt < 5;                       % indices of valid tilt data
Rtilt = tilt_(Xdat(:,28),Xdat(:,29)); % reference tilt
spd = diff(Xdat(:,1)*6);
LS = find(spd<=0.2);                  % low speeds
Xdat(LS,:) = NaN;                     % loopedit
% Find valid radiances  Lu > 1.5e-4
% pLu(:,C) is logical giving indices of valid samples
for C = 2:8
    p1 = (Xdat(:,C) > 0);
    p2 = (Xdat(:,C) > 1.5e-4);
    p3 = p1 & p2 & pT;                % tilt or no tilt

```

```

    pLu(1:length(p3),C) = p3;
end
% Find valid irradiances Ed > 1e-4
% pEd(:,C) is logical giving indices of valid samples
for C = 9:15
    p4 = (Xdat(:,C) > 0);
    p5 = (Xdat(:,C) > 1e-4);
    p6 = p4 & p5 & pT;
    pEd(1:length(p6),C) = p6;
end
% Select valid data using pLu,pEd: invalid points set to NaN
for C = 2:8
    pl = find(pLu(:,C) == 0);
    Xdat(pl,C) = NaN;
end
for C = 9:15
    pe = find(pEd(:,C) == 0);
    Xdat(pe,C) = NaN;
end
% Depth offset for both Ed and Lu sensors
LUZ=Xdat(:,1)+.924;
EDZ=Xdat(:,1)+(-.313);
% Negative pressures removed
nlz=find(LUZ < 0);
LUZ(nlz)=NaN;
nez=find(EDZ < 0);
EDZ(nez)=NaN;
% Natural log of radiance\irradiance data before least squares fit
for C = 1:7
    LogL(:,C)=log(Xdat(:,C+1));
    LogE(:,C)=log(Xdat(:,C+8));
end
% Optics data at negative pressures removed
LogL(nlz,1:7)=NaN;
LogE(nez,1:7)=NaN;
% Plot Lu data for quality check
figure(1)
set(1,'Position', [442 70 560 420])
plot(LogL(:,3),LUZ,'b'),set(gca,'ydir','reverse'),hold on
xlabel('Ln(Lu490)')
ylabel('Depth (m)')
title(['SPMR ' fname])
Ztl = input(' Enter top integer depth for Lu smooth ');
c = 1;
col = ['r' 'g' 'b' 'm' 'c'];
x = 1;
while ~isempty(x)
    % Apply Least Squares Fit to Lu data (Smith & Baker 1981)
    [flu,bzl]=lsfit_(SMLZINT,LogL(:,1:7),LUZ,Ztl);
    figure(1)
    plot(flu(:,3),bzl,col(c))
    c = c + 1;
    x = input('More smoothings required? yes = 1 no = enter');
    if ~isempty(x)
        Ztl=min(bzl);
    end
end

```

```

LogL = flu(:,1:7);
LUZ = bz1;
disp('Press enter key to keep original depth interval')
tempint = input('Enter depth interval to run fit for next smooth');
if ~isempty(tempint)
    SMLZINT = tempint;
end
else
    break
end
end
close all
% Plot Ed data for quality check
figure(1)
set(1,'Position', [442 70 560 420])
plot(LogE(:,3),EDZ,'k'),set(gca,'ydir','reverse'),hold on
xlabel('Ln(Ed490)')
ylabel('Depth (m)')
title(['SPMR ' fname])
Zte = input(' Enter top integer depth for Ed smooth ');
c = 1;
col = ['r' 'g' 'b' 'm' 'c'];
x = 1;
while ~isempty(x)
    % Apply Least Squares Fit to Lu data (Smith & Baker 1981)
    [fed,bze]=lsfit_(SMEZINT,LogE(:,1:7),EDZ,Zte);

    figure(1)
    plot(fed(:,3),bze,col(c))
    c = c + 1;
    x = input('More smoothings required? yes = 1 no = enter');
    if ~isempty(x)
        Zte=min(bze);
        LogE = fed(:,1:7);
        EDZ = bze;
        disp('Press enter key to keep original depth interval')
        tempint = input('Enter depth interval of fit for next smooth');
        if ~isempty(tempint)
            SMEZINT = tempint;
        end
    else
        break
    end
end
close all
% Calculate running Diffuse Attenuation Coefficient
[Klr,Zlm] = runK(flu(:,1:7),bz1,bz1(1),KZINT,1);
[Ker,Zem] = runK(fed(:,1:7),bze,bze(1),KZINT,1);

```

```

function spmrlevel3_(fname,option,Zopt)

% SPMRLEVEL3_ - Computes surface attenuation for sea surface
%               extrapolation. Solar normalization and weighting for
%               Chl a estimation
%
% Use As:      spmrlevel3_(fname,option,Zopt)
%
% Input:       fname - filename of Level 2 file *L2.mld
%              option - 0 = all point regression
%              Zopt  - bypass interactive plot mode if nargin > 2
%                    input depths for Kl\Ke directly
%                    lz1   - Lu top depth
%                    lz2   - Lu bottom depth
%                    ez1   - Ed top depth
%                    ez2   - Ed bottom depth
%
% Output:      Derived surface products stored in MLDBASE format.
%
% Example:     spmrlevel3_('stn03bl2.mld',0,[2 6 2 7])
%
% Note:        This function must be run in specific data directory
%               to ensure proper cruise *L2.mld files are used.
%
% See Also:    mlvars_ for MLDBASE information.

% 03 Nov. 2000; DP

mlglobal;
CWL=[412;443;490;520;555;665;683];
fname=lower(fname);
lind=findstr(fname,'l'); % make sure reading L1.mld files
if strcmp(fname(lind(1):lind(1)+5),'l2.mld') ~= 1
    disp('File must be *L2.mld')
    return
end
readmld_(fname);
datetime = Vaux(11,1);
Lat      = Vaux(14,1);
Lon      = Vaux(15,1);
yr       = Vaux(25,1);
jday     = Vaux(26,1);
if nargin < 3
    % read in *L1.mld to overplot original L1 for kl and ke depths
    fname1 = [fname(1:6) 'L1.mld'];
    [s1,vaux1,dat1]=readmld_(fname1,0,0,[6 7]);
    % Lu Section
    plot(Xdat(:,4),Xdat(:,1)),set(gca,'ydir','reverse'),hold on
    plot(log(dat1(:,4)),(dat1(:,1)+.924),'k')
    xlabel('Ln(LSF Lu490)')
    ylabel('Depth (m)')
    title('Choose SPMR depths for Kl calculation')
    while ~strcmp(lower(get(gcf,'currentcharacter')),'n')
        zoom on
        waitfor(gcf,'currentcharacter')
    end
end

```

```

end
zoom off
[x,y]=ginput(2);
z11=round(y(1))
z12=round(y(2))
if z11 > z12                                     % make sure z11 = top depth
    z11=round(y(2))
    z12=round(y(1))
end
close all
% Ed Section
plot(Xdat(:,12),Xdat(:,9)),set(gca,'ydir','reverse'),hold on
plot(log(dat1(:,11)),(dat1(:,1)-(.313)),'k')
xlabel('Ln(LSF Ed490)')
ylabel('Depth (m)')
title('Choose SPMR depths for Ke calculation')
while ~strcmp(lower(get(gcf,'currentcharacter')),'n')
    zoom on
    waitfor(gcf,'currentcharacter')
end
zoom off
[x,y]=ginput(2);
ze1=round(y(1));
ze2=round(y(2));
if ze1 > ze2                                     % make sure ze1 = top depth
    ze1=round(y(2));
    ze2=round(y(1));
end
end % if nargin < 3
close all
if nargin >= 3
    z11 = round(Zopt(1));
    z12 = round(Zopt(2));
    ze1 = round(Zopt(3));
    ze2 = round(Zopt(4));
end
% Loglinear Regression (log(Lu\Ed) vs Z) to get Kl\Ke and error stats.
dl1 = Xdat(:,1)-z11;
dl2 = Xdat(:,1)-z12;
il1 = find(dl1==0);
il2 = find(dl2==0);
il = [il1 il2];
for c = 1:7
    [a,b(1,c),r,n,Sb,Sx]= regress1_(Xdat(il1:il2,1),Xdat(il1:il2,c+1));
    kl(1,c)=(-1)*b(1,c);
    Skl(1,c)=Sb;
    SL0(1,c)=Sx0;
    SEkl(1,c)=Syx;
end
mz1=mean(Xdat(il1:il2,1));
Lu0 = exp(Xdat(il1,2:8) + (kl(1,1:7) .* Xdat(il1,1)));
Lw = Lu0 .* 0.543;                                     % 1-rho/N^2
[lat,lon,y,m,d,h,cruise,prof]=spmhdr_(FhdS);
Fn=solnorm_(y,m,d,h,lat,lon);
Lwn=Lw./Fn(1:7);

```



```

del = Xdat(:,9)-ze1;
de2 = Xdat(:,9)-ze2;
ie1 = find(del==0);
ie2 = find(de2==0);
ie = [ie1 ie2];
for c = 1:7
    [a,b(1,c),r,n,Sb,Sx]=regressl_(Xdat(ie1:ie2,9),Xdat(ie1:ie2,c+9));
    ke(1,c)=(-1)*b(1,c);
    Ske(1,c)=Sb;
    SE0(1,c)=Sx0;
    SEke(1,c)=Syx;
end
mze = mean(Xdat(ie1:ie2,9));
Ed0 = exp(Xdat(ie1,10:16) + (ke(1,1:7) .* Xdat(ie1,9)));
% Es Section
fname1 = [fname(1:6) 'L1.mld'];
[s1,vaux1,dat1]=readmld_(fname1,0,0,[6 7]);
for c = 1:7
    Es(1,c)=mean(dat1(:,c+15));
    Esstd(1,c)=std(dat1(:,c+15));
end

```