A LOW-COST, COMPACT, MOORED SPECTRAL RADIOMETER

by M. Maccio, J. Marra

LDEO TECHNICAL REPORT
LDEO-98-4

Department of the Navy
Office of Naval Research
Contract #
N-00014-93-1-0347

JULY 20, 1998

Lamont-Doherty Earth Observatory
Columbia University

ABSTRACT

A new type of spectral irradiance meter is described, that offers compact operation, 32 wavelengths of downwelling irradiance, and low cost. The unit is currently configured to be attached to a mooring to measure the change in spectral irradiance over time at prescribed depths. Data from a mooring in the Arabian Sea are presented, and clearly show the change in spectral quality after the onset of the SW monsoon. The operation of the moored spectral radiometer (MSR) agrees closely with the data from an MER-2040, once a correction for the cosine response is applied.

INTRODUCTION

The spectral distribution and flux of irradiance in the upper ocean affects all aspects of oceanography, including energy budgets (Zaneveld et al. 1981, Lewis et al. 1990, Morel and Antoine 1994, Siegel et al. 1995), photon budgets (Smith et al. 1989), primary production (Bidigare et al. 1987), and the distribution of plankton populations (Bricaud and Stramski 1990, Bidigare et al. 1990). The use of satellite sensors (Hovis et al. 1980) has demonstrated the importance of understanding the relationship between plankton and the color of the ocean.

For primary production studies, the spectral properties of the irradiance field are often ignored in favor of broad-band measurements of PAR, photosynthetically active radiation (Marra et al. 1993). PAR sensors must be calibrated against a known spectral distribution, and since the irradiance spectrum changes with depth, PAR sensors will never accurately measure the irradiance, especially near the surface where the spectrum changes most dramatically (Booth, 1976).

PAR sensors, although perhaps less accurate, have had the advantages of low-cost, compactness, and ease of use. Here we present a similarly low-cost, simple, compact and easy-to-use spectral irradiance meter. In its current configuration, it is best used on ocean moorings, however it can be adapted for profiling. We describe the design of the sensor, laboratory tests involved in its evaluation, data collected during a six-month deployment during the Forced Upper Ocean Dynamics Experiment in the Arabian Sea (Trask et. al., 1995), and a comparison test with a MER-2040 (Biospherical Instr., San Diego, CA).

DESCRIPTION OF INSTRUMENT

Linear optical filter: The instrument uses a linear interference filter (Oriel M/N 57480), or LIF, to separate the different components of the incoming light by wavelength. The principle of operation is similar to multiple-cavity interference filters, where multiple reflections from partially reflecting mirror surfaces lead to constructive and destructive interference, thus causing transmittance of bands of light with center wavelengths proportional to the width of the cavity of the layers. The transmittance wavelength of these linear filters varies with position along the length of the filter. The out-of-band blocking is 0.1% as measured by early tests with the filter. The filter is mounted on a rectangular lens holder that permits adjusting its position longitudinally with respect to the light sensing element.

Photodiode array, multiplexer and amplifier: The sensing element is a blue-enhanced photodiode array (LDA) (Centronics, LD35-5), with 35 diodes embedded in a 40 pin DIP ceramic package. The linear filter is mounted over the photodiode array. Since transmittance wavelength in the LIF varies with the longitudinal position, each photodiode effectively measures a specific spectral wavelength. The electrical currents of 32 photodiodes are multiplexed using a low "ON" impedance CMOS integrated circuit. A LM11-C operational amplifier is used to amplify the signal in an inverter configuration. The amplifier gain is controlled by switching different feedback resistors to maximize dynamic range (Fig. 1). Together with the LIF, the MSR records irradiance at 32 wavelengths.

Pressure case and light diffuser: The underwater unit is contained in a PVC pressure case (5.5 in. O.D. and 0.4 in. thick) (Fig. 2). The optical pressure window is made of clear acrylic "G" type plastic (Rohm and Haas). At 1 inch thick, it is strong enough to withstand pressures up to 250 m depth. Scratches on the outside face will not produce major deviations in the ray path since the refractive index of the acrylic is very close to that of the water.

Covering the clear acrylic pressure window are the light diffuser and its holder. They are externally mounted to the instrument so that only a negligible differential pressure is present on its faces, simplifying the mechanical design. The diffuser is made of a core of clear Acrylite GP disc inserted into a piece of concave white Acrylite GP type 020-4, following the design and construction procedure described in Smith (1969).

Optics and spectral system: The optics system has an infrared (IR) filter (Oriel M/N 48040) which is used to avoid over-exposure when the unit is under direct solar light.

The LIF and LDA are mounted on a custom designed printed circuit board. The linear filter position is adjustable through miniature nylon screws to permit wavelength calibration. The board holding the multiplexer and amplifier is connected through a flat ribbon cable to the computer system. The computer, an ONSET Tattletale Model 2B, establishes the sampling time using a DS1216E IC (Dallas Semiconductors) as an independent real-time clock (RTC) and for memory back-up. The computer sets the optimum gain for the amplifier using an automatic gain control algorithm based on an initial sample, and then digitizes the analog signal of the multiplexed output from the diode array. The A/D conversion is repeated 20 times and averaged to improve the measurement signal-to-noise ratio. Finally, each of the 32 averaged outputs from the diode array, representing one wavelength each, plus the time and date from the RTC are stored in 279 Kbytes of memory, yielding a capacity of 3100 samples, equivalent to 17 daily samples over 6 months. In addition to the DS1216 memory back-up, the model 2B computer has its own battery providing redundancy in memory back-up. The computer performs a complete measurement at irregular intervals of 0, 3, 6, 9, 10, 10:30, 11, 11:30, 12, 12:30, 13, 13:30, 14, 15, 16, 18, and 21 hours local time, to have higher resolution around local noon and only a few samples during night hours for reliability, in case of RTC failure, and to obtain dark current values.

Since this version of the spectral-radiometer is designed to be moored rather than used in profiling mode, we decreased the wavelength range from 400-700 nm to 400-600 nm. Irradiance at wavelengths above 600 nm virtually disappears below 20 m in the clearest ocean water, thus this limitation does not diminish the sensor's capabilities for our use. In fact, better wavelength resolution is gained in the more penetrating range from 400-600 nm. For other applications, the wavelength range can be adjusted or extended.

Software: The spectral radiometer uses the ONSET Tattletale Model 2B TTBASIC language to implement all its subroutines and main program, together with the real-time clock (RTC) mentioned above.

The software handles all relevant functions to control the diode multiplexer, to set the gain controlled amplifier, for A/D conversion and filtering and to establish optimum gain for the amplifier based on the previous measurement and to handle all the RTC subroutines.

LAB TESTS

A calibration bank was constructed around the Optical Radiation Calibrator from Li-Cor (Model 1800-02) which was modified to allow movement of the sensor relative to the light source, and to permit the use of color filters in the light path. Table 1 shows Calibration data obtained with the above calibration bank.

Previous to deployment, several types of diffusers were tested in a lab tank following the procedure described in Smith (1969) to establish the optimum structure for cosine response.

A calibrated light from the modified Li-Cor 1800 radiometer is vertically and perpendicularly projected against the surface of the water in which the radiometer is immersed at 10 in. of depth. This setup is also used to obtain the immersion coefficients following the procedure described by Mueller and Austin (1995, Sect. 4.1.6). Several readings were taken at different angles. Figure 3 shows the units response at 531 nm and is compared to the ideal cosine response.

We discovered that the diffuser response introduces an error in the irradiance that depends on the radiance angular distribution. For shallow waters (<10 m), where most of the light energy is located near the zenith (small angles), the overall error is relatively small (less than 5%). For deeper waters (65 m), assuming a uniform distribution and using Eq. (1) from Mueller and Austin (1995, Sect. 4.1.3) correction factor, the error is 35%, i.e. the unit is measuring 0.65 of the true value.

We believe that this cosine distribution is due the material used in the construction of the diffuser and not the geometry. The diffusing properties for white Acrylite GP type 020-4 are slightly different and apparently not as good as the Rohm & Haas Plexiglass

II-UVT used by Smith (1969). Unfortunately, this was not noticed in time to replace the material for the Arabian Sea Mooring deployment. On the other hand, it is a problem that is easy to correct by replacing the diffusing material by one with a higher particulate content (Smith, 1969).

TABLE 1

Wavelength (nm)	Sensitivity ($W\ m^{-2}\ nm^{-1}$)	Background Noise ($W\ m^{-2}\ nm^{-1}$)
550	0.5×10^{-5}	3.5×10^{-5}
500	0.8×10^{-5}	5.6×10^{-5}
400	1×10^{-5}	70×10^{-5}

FIELD TESTS

We describe two tests of the instrument. The first is a deployment on an Multi-Variable Moored System (MVMS) used as part of the Forced Upper Ocean Dynamics Experiment in the Arabian Sea. The deployment lasted 6 months from April 22 to October 20, 1995. Immediately after recovery the unit was prepared and used with a MER-2040 on the Process-6 cruise of the U.S. JGOFS Arabian Sea Program.

Moored Observations: The unit was attached to a planned deployment of an MVMS to support the radiometer to the mooring cable and for comparison with data from other MVMS sensors. The MVMS powers and samples a suite of sensors that includes PAR, Lu(683), fluorescence, beam attenuation, conductivity and temperature. Useful for the comparison are the PAR and fluorometer because these sensors should provide environmental information that can be used to interpret the spectral irradiance.

Fig. 4 shows the Lu(683) and PAR signals from the MVMS instrument, and the E(550), E(493) and temperature from the MSR for comparison purposes.

There is a sharp drop in E(550) and E(493) after July 4, the drop coincides with a decline in temperature, and is also mirrored in the other optical sensors, PAR and Lu(683). The declines in all these signals can be seen as the advent of the SW monsoon (Yentsch and Phinney, 1993). The surface buoy on the mooring recorded an increase in wind from 4 to above 10 m s^{-1} from about day 155 through day 235 (Aug. 23) (R. Weller, personal communication). The increase in mixing driven by the wind leads to an increase flux of nutrients to the surface layer and, consequently, increases in primary production and chlorophyll a. By this point in the deployment, the fluorometer and transmissometer became fouled, however, the Lu(683) signal, as presented here, will be inversely proportional to chlorophyll a (See Kiefer et al., 1989).

Further evidence that the spectral radiometer is recording an increase in phytoplankton biomass is from an examination of the behavior of the irradiance of different wavelengths, E(λ). As the total irradiance declines, the spectrum shifts from blue to green, consistent with an increase in phytoplankton (Fig. 5, Morel and Prieur. 1977). E(450)/E(550) also declines (Fig. 6), indicating "greener" water during the SW monsoon. Figure 12 shows the noon values of irradiance for the 32 wavelengths at 65 m.

Comparison to a MER-2040 instrument: On the cruise immediately following the mooring recovery, Process-6 of the U.S. JGOFS Arabian Sea Program, four casts were made using the MSR attached to the frame of an MER 2040 instrument for comparison. The frame containing the instruments was stopped at different depths to sample for about 5 min. at each depth. The instrument sensitivity is within the range of the MER 2040 (10^{-5} W m^{-2} nm^{-1}).

For each cast with the MER-2040 clear skies prevailed and the sun altitude above the horizon was 50°-60°. The Spectroradiometer software was modified to sample at a higher rate to increase the number of samples taken at each depth. The data shown in the Figs. 7 through 10. are the averaged values at each depth (1800 samples MER and 20 samples MSR)

The two instruments, the MER-2040 and the MSR deviate from an equal response as a function of depth (Fig. 7 through 10) . The deviation results from the inadequate cosine response discussed in the previous section, and if we apply the correction determined in the laboratory, the output from the MSR is indistinguishable from the MER-2040 (Fig. 11).

Further work on the MSR will involve improvements in several areas. First, the out-of-band blocking (now 0.1%) needs to be improved, especially if the MSR is to be used in a profiling mode

(Siegel et al., 1986). According to the manufacturer, the out-of band blocking in the LIF can be improved to at least 0.01% depending on demand for such a device. Second, the photodiode array could be re-designed for different applications, depending on the spectral range. Third, we plan to incorporate a sensor for upwelling radiances. Finally, the sensor, electronics and data acquisition systems can be made more compact to ensure against self-shading (Gordon and Ding, 1992).

CONCLUSIONS

We have developed a spectral radiometer capable of measuring irradiance at 32 wavelengths for periods of up to 6 months. The unit is lightweight and small, which is ideal for mooring applications. The instrument has been successfully deployed on a mooring with 100 % data return. The software used is simple and robust and which allows adjustments to the sampling mode and rates in the field. At $500 each, the LIF and the LDA are the most expensive components, but the device can be fabricated for less than $2500. The low-cost, size, and easy of use will make this spectral sensor attractive to a broader range of ocean scientists than heretofore.

The materials used in the diffuse collector have to be re-specified to eliminate errors associated with the distribution of angular radiance, and we suggest other improvements to some components.

ACKNOWLEDGEMENTS

We thank C. Trees who kindly allowed the use of his MER-2040 radiometer. Dan Sullivan who helped us process the MER data, and C. Kinkade who operated the radiometer during Process 6. This research was supported by the Office of Naval Research Contract N00014-93-1-0347. This is Lamont-Doherty Earth Observatory contribution XCXXX.

REFERENCES

Bidigare, R.R., J. Marra, T.D. Dickey, R. Iturriaga, K.S. Baker, R.C. Smith, H. Pak. 1990. Evidence for phytoplankton succession and chromatic adaptation in the Sargasso Sea during spring 1985. Mar. Ecol. Progr. Ser. 60, 113-122.

Bidigare, R.R., R.C. Smith, K.S. Baker, J. Marra, 1987. Oceanic primary production estimates from measurements of spectral irradiance and pigment concentrations. Global Biogeochem. Cycles 1, 171-186.

Bricaud, A. and D. Stramski, 1990. Spectral absorption coefficients of living phytoplankton and nonalgal biogenous matter: A comparison between the Peru upelling and the Sargasso Sea. Limnol. Oceanogr. 35, 562-582.

Gordon, H.R. and K. Ding. 1992. Self-shading of in-water optical instruments. Limnol. Oceanogr. 37, 491-500.

Hovis, W.A., D.K. Clark, F. Anderson, R.W. Austen, W.H. Wilson, E.T. Baker, B. Ball, H.R. Gordon, J.L. Mueller, Y. El-Sayed, B. Sturm, R.C. Wrigley and C.S. Yentsch, 1980. Nimbus-7 Coastal Zone Color Scanner: system description and initial imagery. Science 210, 60-63.

Hooker, S.B., W.E. Esaias, G.C. Feldman, W.W. Gregg and C.R. McClain, 1992. An overview of SeaWiFS and Ocean Color. NASA Tech. Memo. 104566, Vol. 1, S.B. Hooker and E.R. Firestone, Eds. NASA Goddard Space Flight Center, Greenbelt, MD, 16pp.

Lewis, M.R., M.-E. Carr, G.C. Feldman, W. Esaias, C. McClain, 1990. Influence of penetrating solar radiation on the heat budget of the equatorial Pacific Ocean. Nature 347, 543-545.

Morel, A. and L. Prieur. 1977. Analysis of variations in ocean color. Limnol. Oceanogr. 22, 709-722.

Morel, A. 1980. In-water and remote measurement of ocean color. Boundary-layer Meteorology 18, 177-201.

Morel, A. and D. Antoine, 1994. Heating rate within the ocean in relation to its bio-optical state. J. Phys. Oceanogr. 24, 1652-1665.

Mueller, J.L. and R.W. Austin, 1995. Volume 25, Ocean Optics Protocols for SeaWiFS Validation, Revision 1, SeaWiFS Technical Report Series. NASA Tech. Memo. 104566, Vol. 25, 67pp.

Siegel, D.A., C.R. Booth and T.D. Dickey. 1986. Effects of sensor characteristics on the inferred vertical structure of the diffuse attenuation coefficient spectrum. Proc. SPIE, Ocean Optics VII, vol. 637, 115-123.

Siegel, D.A. J. C. Ohlmann, L. Washburn, R.R. Bidigare, C.T. Nosse, E. Fields, and Y. Zhou, 1995. Solar radiation, phytoplankton pigments and the radiant heating of the equatorial Pacific warm pool. J. Geophys. Res. 100, 4885-4891.

Smith, R.C., 1969. "An underwater Spectral Irradiance Collector, Journal of Marine Research, 1969".

Trask, R.A., R.A. Weller and W.M. Ostrom. 1995. Arabian Sea Mixed Layer Experiment: Mooring deployment cruise report, R/V Thomas Thompson Cruise Number 46, 14-29 April 1995. WHOI Technical Report WHOI-95-14, Woods Hole Oceanogr. Inst., Woods Hole, MA, 88pp.

Yentsch, C.S. and D.A. Phinney, 1993. The effect of wind direction and velocity on the distribution of phytoplankton chlorophyll in the western Arabian Sea, pp. 57-66. In: Oceanography of the Indian Ocean, ed. by B.N. Desai. A.S. Balkema, Rotterdam.

Zaneveld, J.R.Z., J.C. Kitchen and H. Pak, 1981. The influence of optical water type on the heating rate of a constant mixed layer depth. J. Geophys. Res. 86, 6426-6428.

FIGURE CAPTIONS

Fig. 1. Circuit-board design used in the MSR.

Fig. 2. Schematic of the MSR

Fig. 3. The cosine response of the MSR (+) compared with a perfect cosine response (solid line)

Fig. 4. Properties measured on the mooring of the Forced Upper Ocean Dynamics Experiment in the Arabian Sea in 1995. The mooring was deployed on April 20 (day 118) and recovered on October 20, 1995. Beginning on or about day 160, the MSR records differential decreases in Ed(550) and Ed(493). The PAR sensor also records a decrease. Natural fluorescence, Lu(683), is normalized to PAR. We used the square of the Lu(683) value to prevent division of one small number by another. The Lu(683) sensor became fouled at about day 186, as indicated by the arrow.

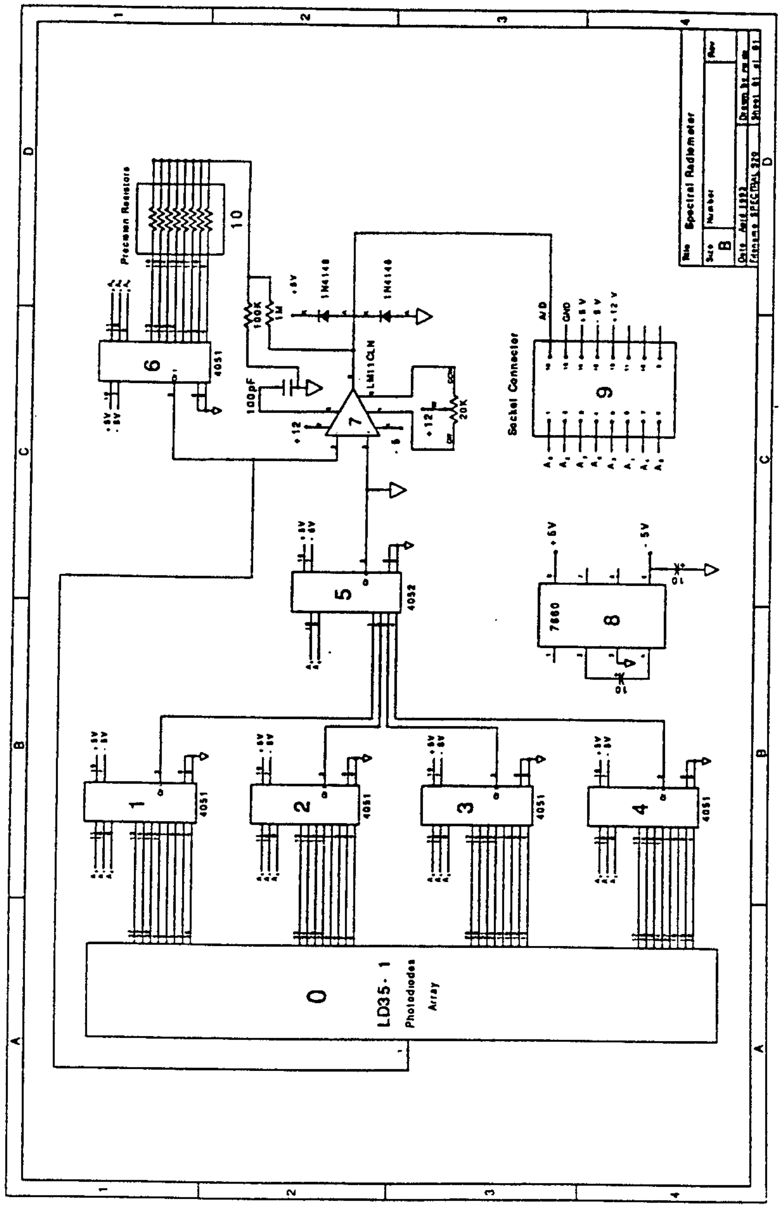
Fig. 5. Irradiance spectra from selected days during the deployment, showing the shift toward longer wavelengths, indicating an increase in the quantity of chlorophyll at 65 m.

Fig. 6. Ratio of Ed(450)/Ed(550) as a function of time. The decrease in this ratio means the water is becoming greener during the SW monsoon period.

Fig. 7 - 10 Comparisons of the MSR with an MER-2040 during the Process-6 cruise of the Arabian Sea JGOFS program, November, 1995. The MER and MSR were stopped at selected depths for five minutes: (a) 10 m, (b) 35 m, (d) 65 m.

Fig. 11. A comparison of the MER and MSR without (a) and with (b) the corrected cosine (see Fig. 3).

Fig. 12. Noon values of irradiance for the 32 wavelengths at 65 m.



Spectral Radiometer
Precision Resistors
Socket Connector
LD35-1
Photodiodes
Array
4051
4052
7660
LM11CLN
1N4148
100pF
100K
1M
20K

Figure 1

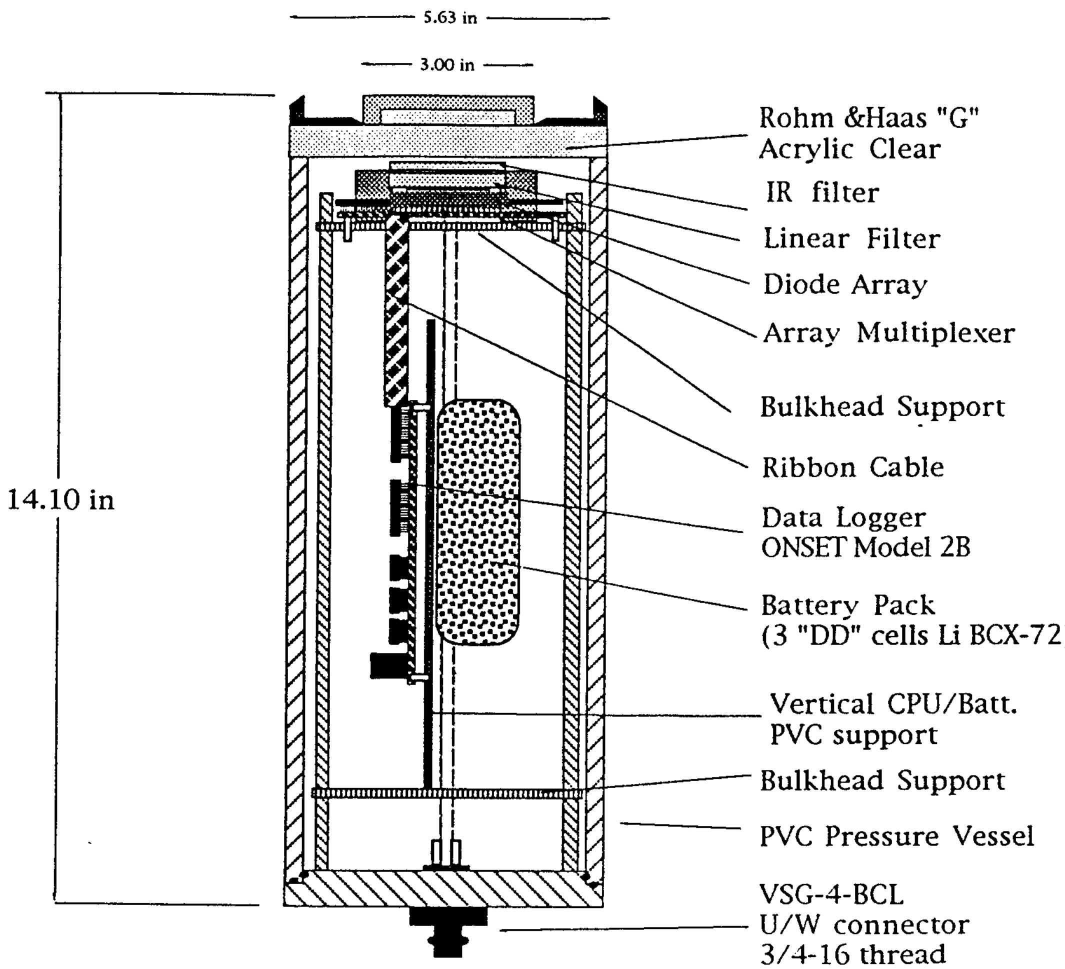

5.63 in
3.00 in
14.10 in
Rohm &Haas "G"
Acrylic Clear
IR filter
Linear Filter
Diode Array
Array Multiplexer
Bulkhead Support
Ribbon Cable
Data Logger
ONSET Model 2B
Battery Pack
(3 "DD" cells Li BCX-72)
Vertical CPU/Batt.
PVC support
Bulkhead Support
PVC Pressure Vessel
VSG-4-BCL
U/W connector
3/4-16 thread

Figure 2

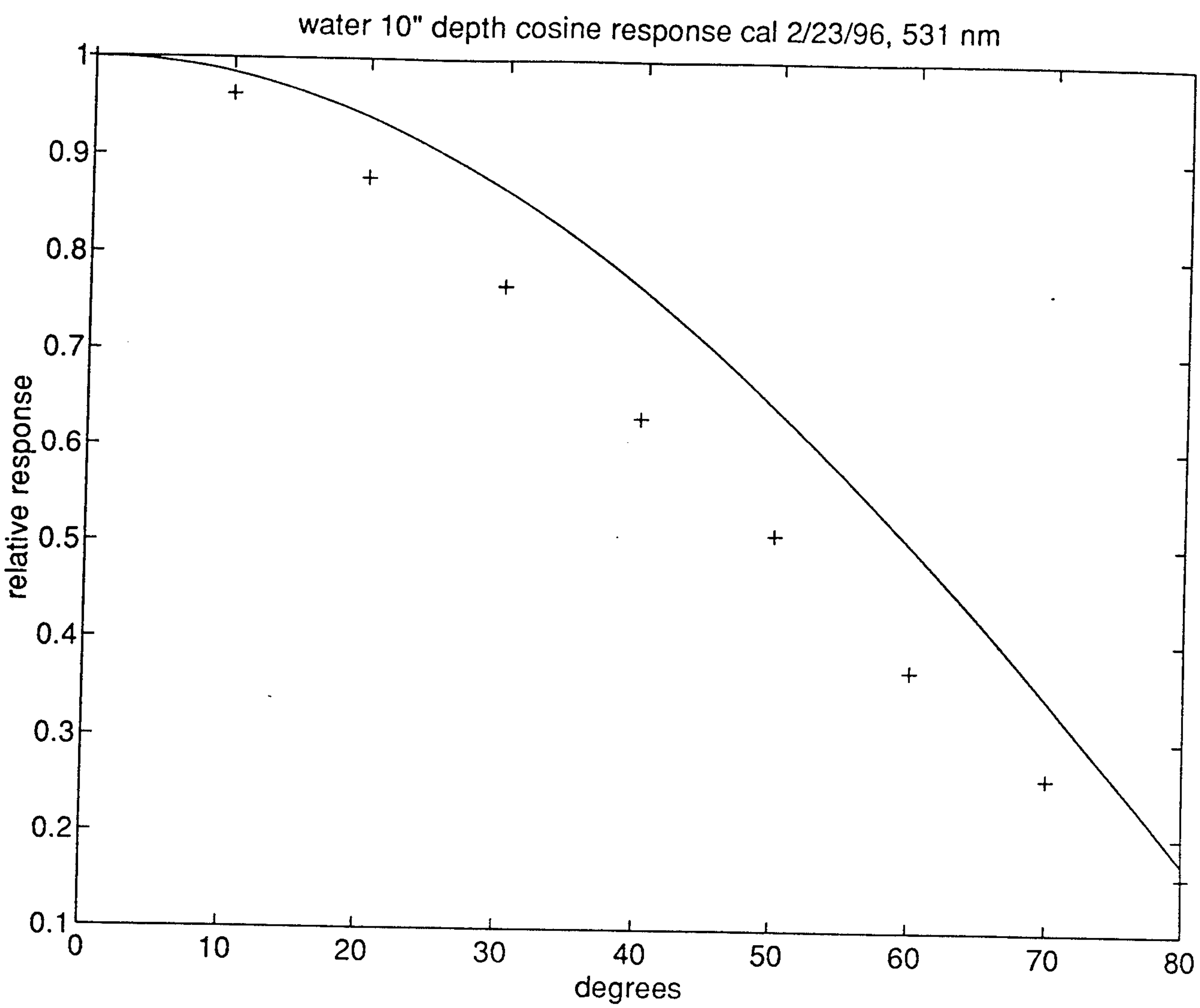
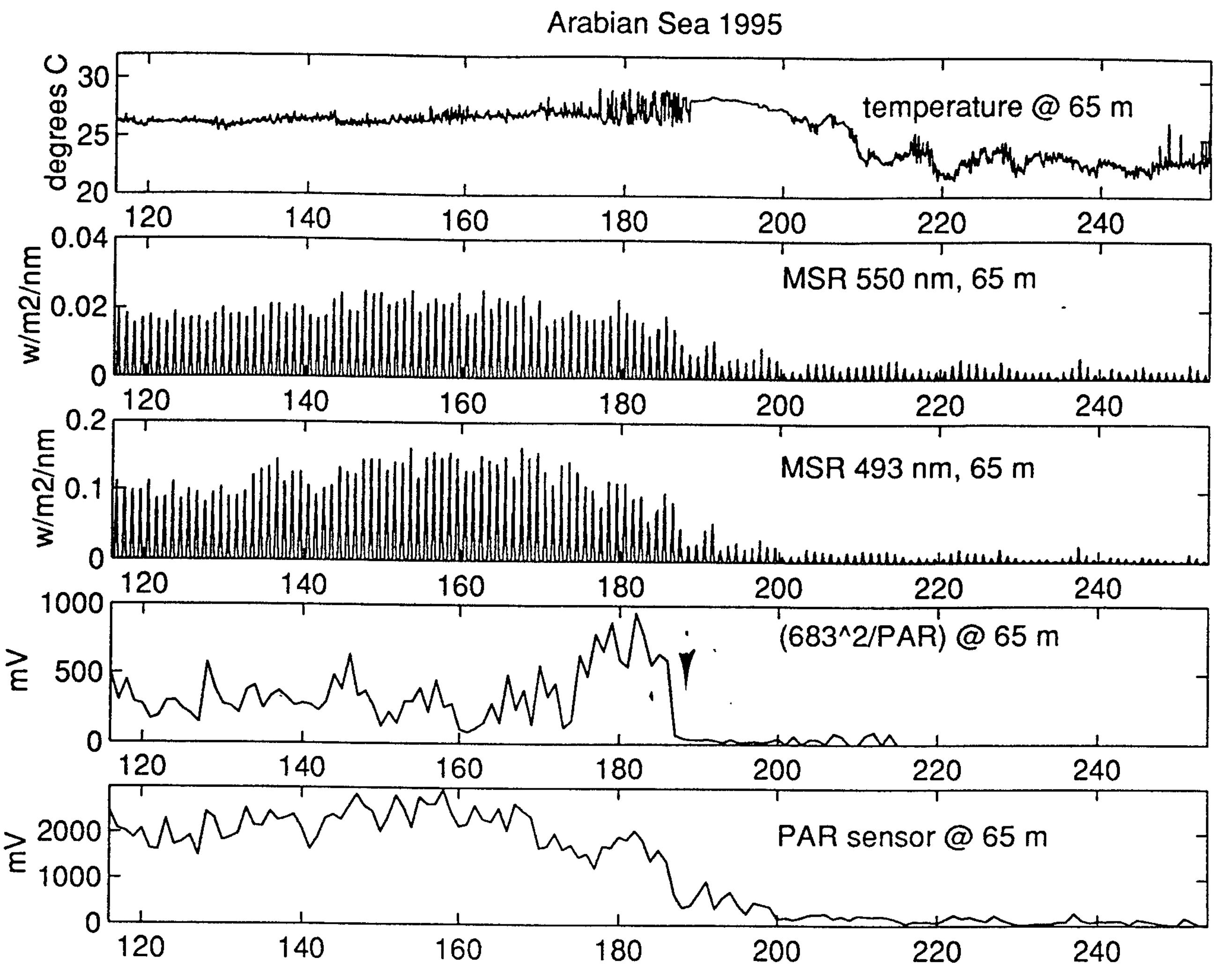

water 10" depth cosine response cal 2/23/96, 531 nm
relative response
degrees
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
10
20
30
40
50
60
70
80

Fig 3



Arabian Sea 1995
degrees C
30
25
20
temperature @ 65 m
120
140
160
180
200
220
240
w/m2/nm
0.04
0.02
0
MSR 550 nm, 65 m
w/m2/nm
0.2
0.1
0
MSR 493 nm, 65 m
mV
1000
500
0
(683^2/PAR) @ 65 m
mV
2000
1000
0
PAR sensor @ 65 m

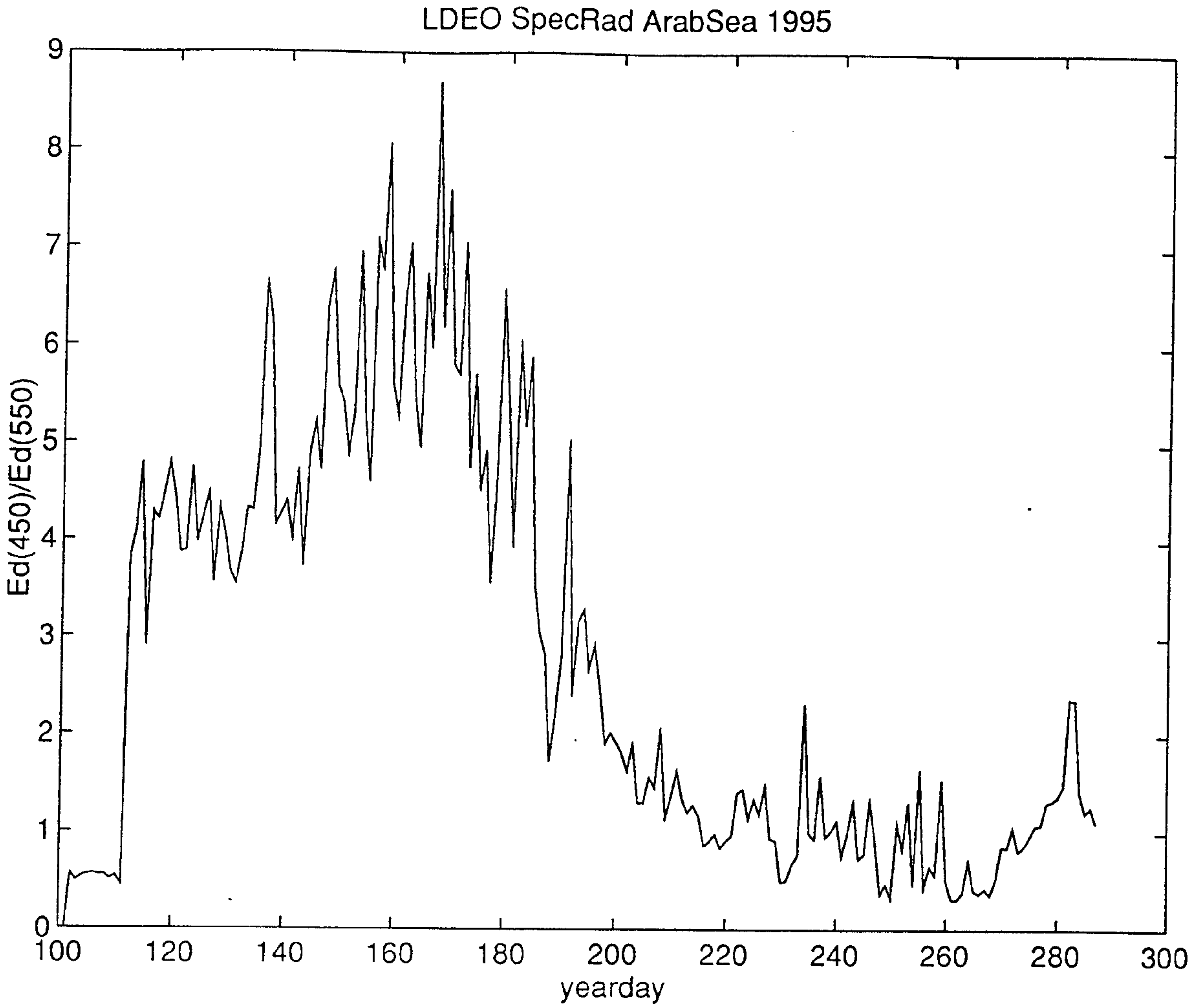
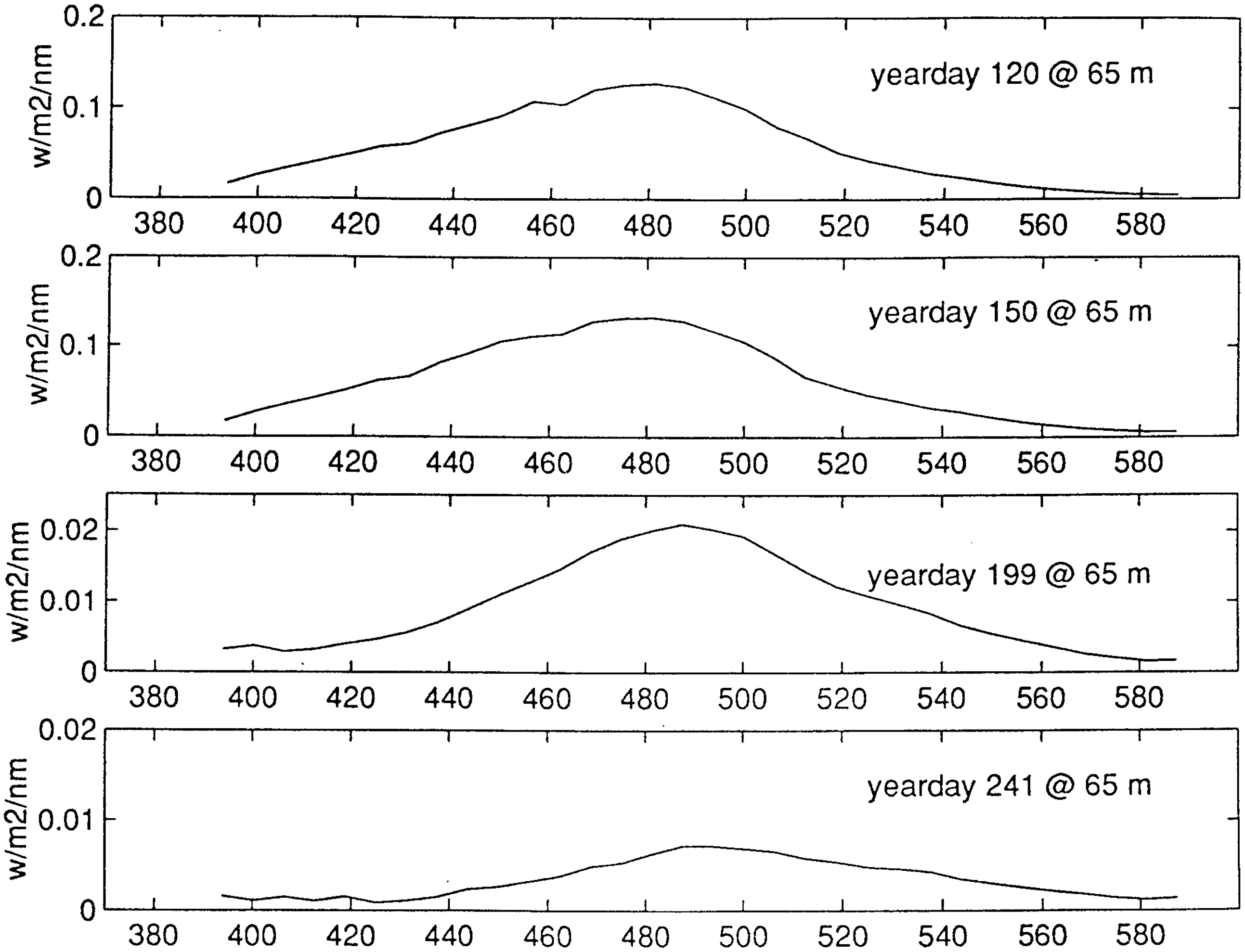
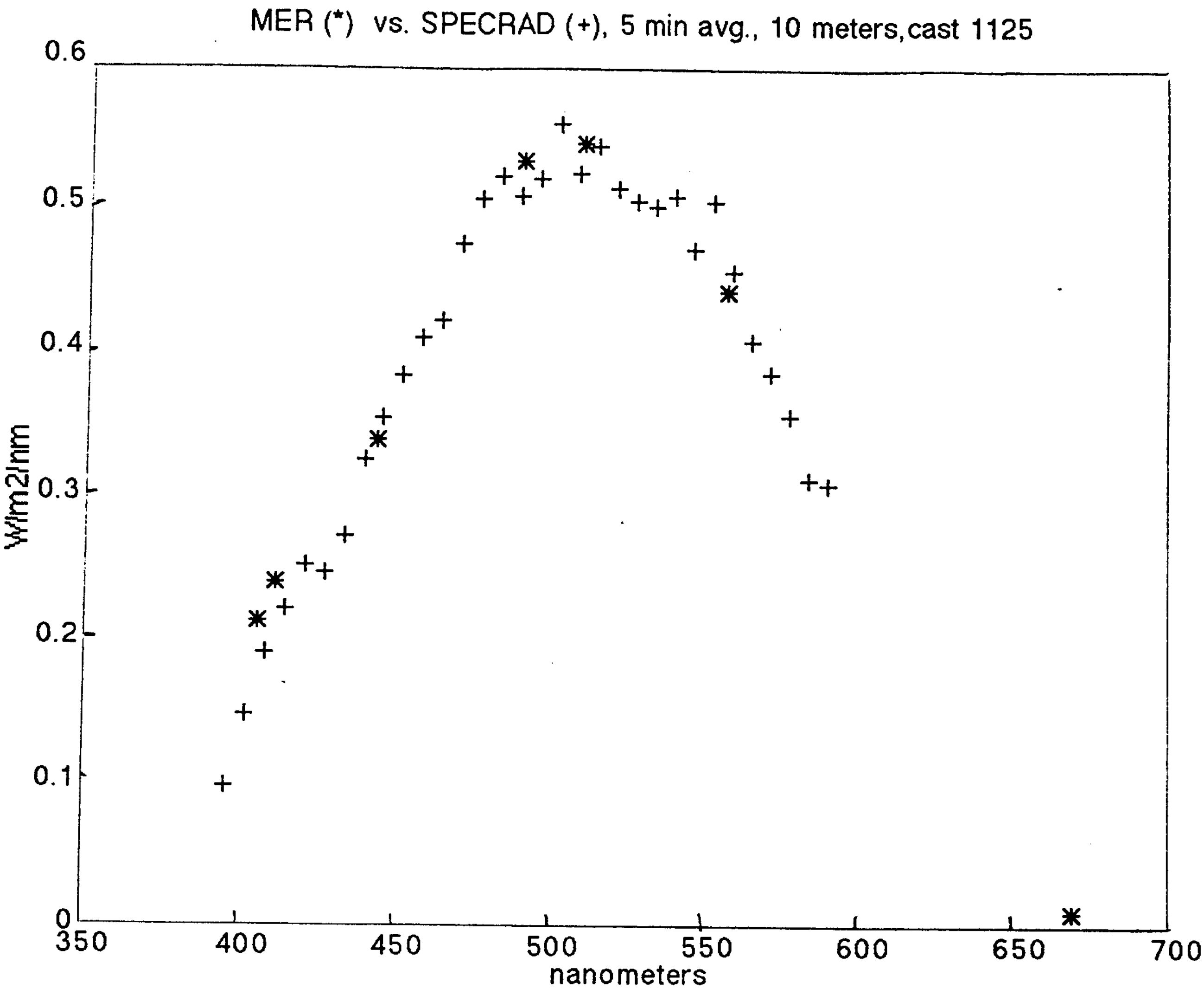
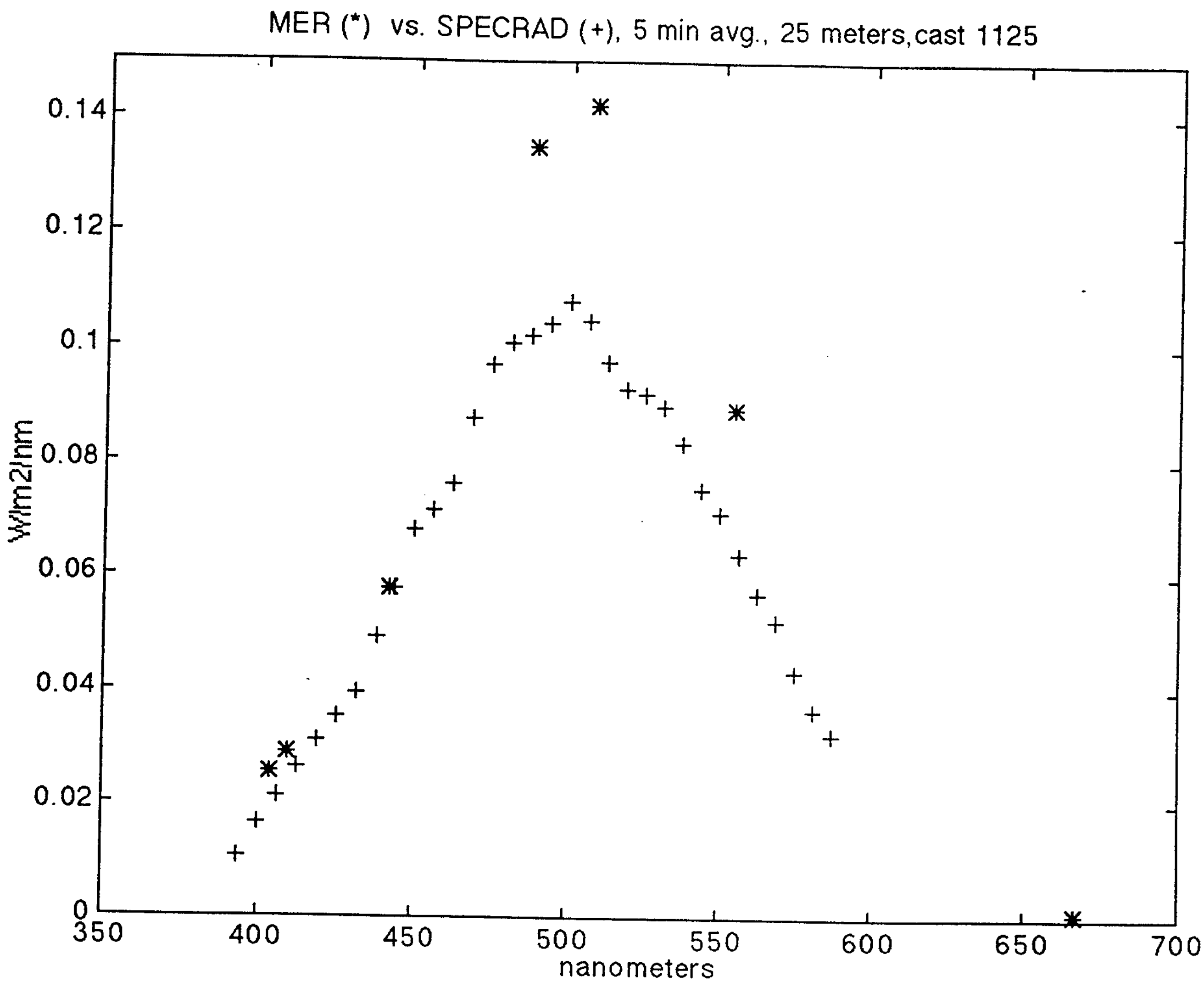

LDEO SpecRad ArabSea 1995
Ed(450)/Ed(550)
yearday
0
1
2
3
4
5
6
7
8
9
100
120
140
160
180
200
220
240
260
280
300

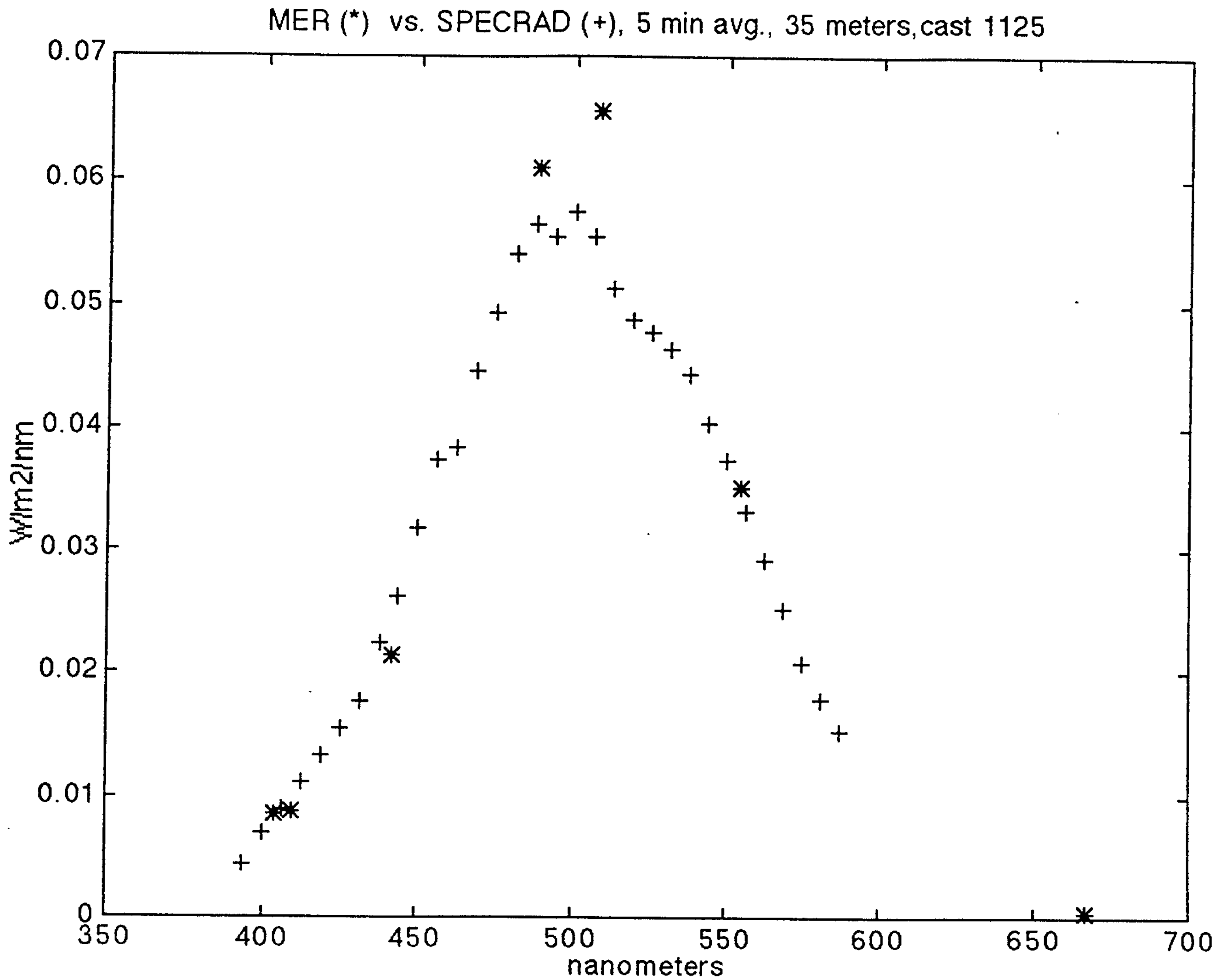
Fig 4

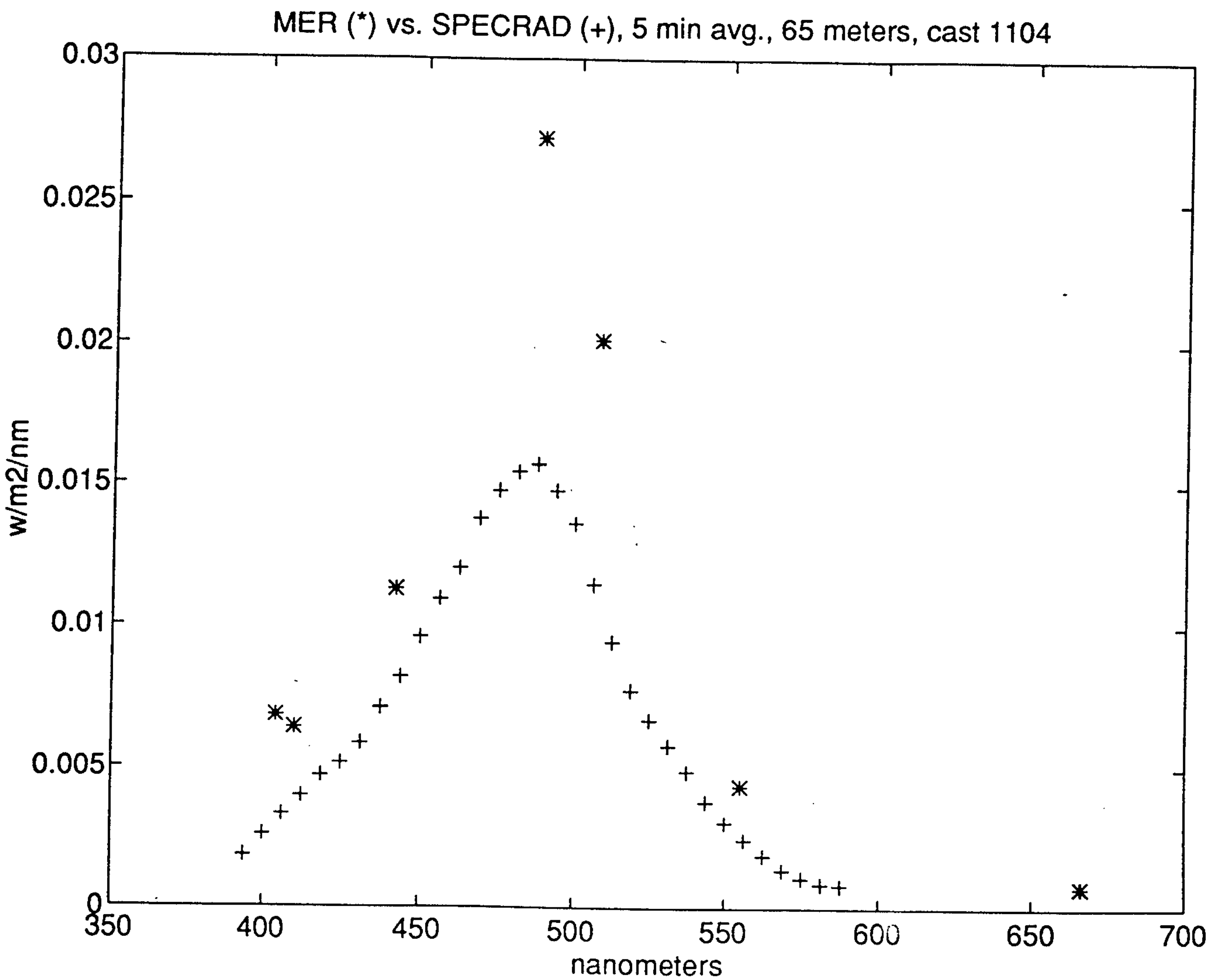

0.2
0.1
0
w/m2/nm
yearday 120 @ 65 m
380
400
420
440
460
480
500
520
540
560
580
0.2
0.1
0
w/m2/nm
yearday 150 @ 65 m
380
400
420
440
460
480
500
520
540
560
580
0.02
0.01
0
w/m2/nm
yearday 199 @ 65 m
380
400
420
440
460
480
500
520
540
560
580
0.02
0.01
0
w/m2/nm
yearday 241 @ 65 m
380
400
420
440
460
480
500
520
540
560
580


MER (*) vs. SPECRAD (+), 5 min avg., 10 meters,cast 1125
W/m2/nm
0.6
0.5
0.4
0.3
0.2
0.1
0
350
400
450
500
550
600
650
700
nanometers

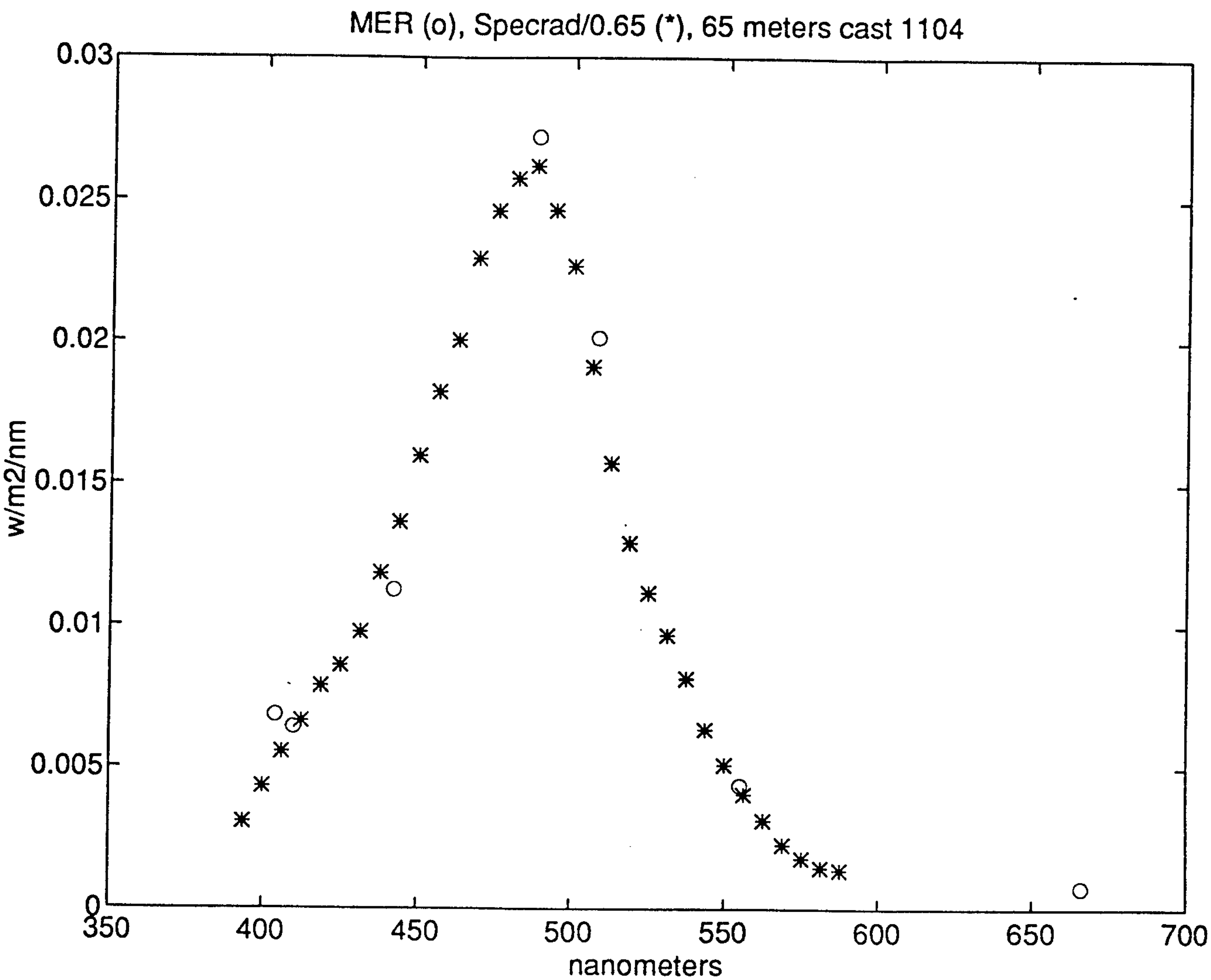


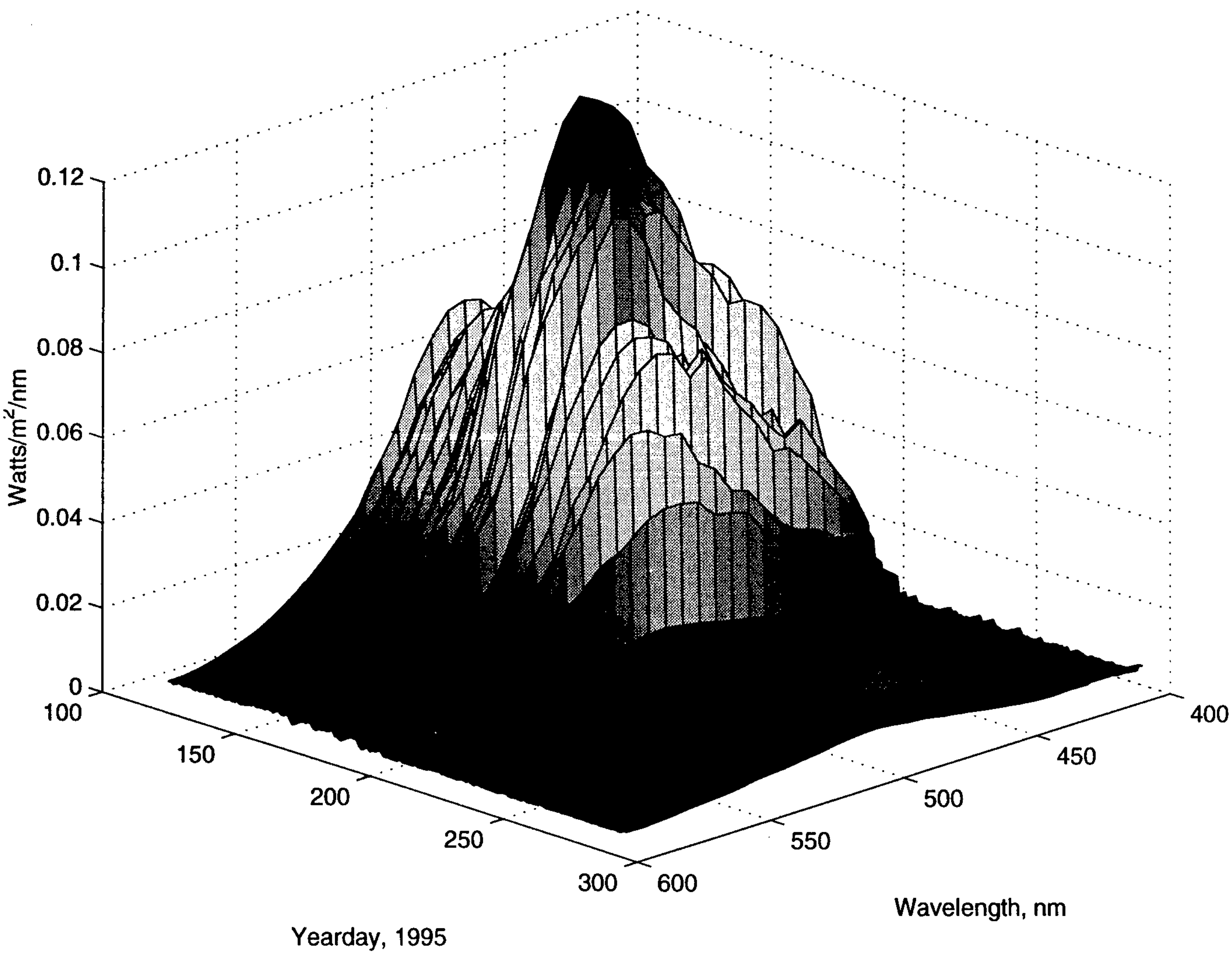
MER (*) vs. SPECRAD (+), 5 min avg., 25 meters,cast 1125
W/m2/nm
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
350
400
450
500
550
600
650
700
nanometers


MER (*) vs. SPECRAD (+), 5 min avg., 35 meters,cast 1125
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
W/m2/nm
350
400
450
500
550
600
650
700
nanometers



MER (*) vs. SPECRAD (+), 5 min avg., 65 meters, cast 1104
w/m2/nm
0.03
0.025
0.02
0.015
0.01
0.005
0
350
400
450
500
550
600
650
700
nanometers


MER (o), Specrad/0.65 (*), 65 meters cast 1104
w/m2/nm
0.03
0.025
0.02
0.015
0.01
0.005
0
350
400
450
500
550
600
650
700
nanometers


0.12
0.1
0.08
0.06
0.04
0.02
0
Watts/m^2/nm
100
150
200
250
300
Yearday, 1995
600
550
500
450
400
Wavelength, nm

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*

2. REPORT DATE
July 1998

3. REPORT TYPE AND DATES COVERED
Final (3/93 - 9/96)

4. TITLE AND SUBTITLE
A Low-Cost, Compact, Moored Spectral Radiometer

5. FUNDING NUMBERS
N00014-93-1-0347

6. AUTHOR(S)
M. Maccio & J. Marra

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Lamont-Doherty Earth Observatory
Palisades, NY 10964

8. PERFORMING ORGANIZATION REPORT NUMBER
LDEO 98-4

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Office of Naval Research
800 N. Quincy Ave.
Arlington, VA 22217

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES
The view, opinions and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy, or decision, unless so designated by other documentation.

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*
The objective of this project was to develop a low-cost, compact, easy-to-use spectral-radiometer for use on ocean moorings. The spectral-radiometer would have use in physical and biological oceanography, as well as in optical oceanography. We describe here the spectral-radiometer prototype, laboratory tests involved in its evaluation and a six months deployment during the Arabian Sea Programme. We have somewhat modified the design from that originally proposed to test trade-offs in specifications and optical configurations.

14. SUBJECT TERMS

15. NUMBER OF PAGES

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL