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A COMPARISON OF OBSERVED AND ANALYTICALLY
DERIVED REMOTE-SENSING PENETRATION DEPTHS
FOR TURBID WATER

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SUMMARY

The depth to which sunlight will penetrate in turbid waters was investigated during field tests at Kerr Reservoir in Clarksville, Virginia. These tests were conducted in water with a single scattering albedo range of 0.6 to 0.85, values typical of turbid coastal water, and over a range of solar elevation angles. Two different techniques were used to determine the depth of light penetration, one was experimental and the other employed an analytical model. The diffuse attenuation was derived from experimental data at three bandwidths over the visible spectrum using a submarine photometer. These values were used to compute the corresponding light penetration depths. These depths were then compared with depths computed using a quasi-single scattering analytical relationship to determine the diffuse attenuation coefficient from the inherent optical properties and the in-water incident irradiance angle. The results showed little change in the depth of sunlight penetration with changing solar elevation angle. A comparison of the penetration depths indicates that the best agreement between the two methods was achieved when the quasi-single-scattering relationship was not corrected for solar angle. For these tests, sunlight penetration appeared to be dependent on inherent water properties only. Secchi disk depths are shown for comparison.

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INTRODUCTION

The depth to which the sunlight penetrates the water surface is a major factor in controlling many marine processes, and as such, is of interest to those dealing with marine problems and systems. The amount of light available determines the depths at which phytoplankton and zooplankton can live and grow, and thus, is a key to the productivity of a region. In addition, the light that is backscattered from beneath the water's surface contains information about the water properties and the material in the water that can be observed by a remote sensor. This information can be interpreted by users of the data, but it is only applicable to the depth to which the light can penetrate and return to the sensor. A number of methods have been developed to determine the depth of light penetration, among them are the use of an underwater photometer, analytical modeling techniques based on the water properties, as well as by use of the traditional Secchi disk.

The decrease in intensity of sunlight as it penetrates the water surface, can be described by use of irradiance-attenuation coefficient (also called the diffuse attenuation coefficient) (Tyler et al., 1972, Preisendorfer, 1976, and Jerlov, 1968). The coefficient decays exponentially with depth and is expressed in per unit depth. Gordon and McCluney (1975) were able to show that for the purpose of remote sensing the effective penetration depth of light in water was equal to the inverse of the diffuse attenuation coefficient. This is the depth for homogeneous ocean water above which 90 percent of the diffusely reflected radiance originates. The shape of the radiance distribution also changes with depth, even in a homogeneous body of water (Tyler et al., 1972). As the light enters the water, it is both absorbed by the fluid (reducing its energy) and scattered by the particulate matter. The scattering causes a

redistribution of the radiant energy to that of a more uniform distribution. At a depth below which the angular distribution does not change, the distribution is considered asymptotic (Tyler et al., 1972). The distribution function D (Smith and Tyler, 1978) gives a qualitative indication of the shape of this light field. If the light field is highly collimated, or like a single vertical vector, the values approach 1. For larger values, approaching 2 the light field is more sphere-like or uniform from all directions.

The diffuse attenuation coefficient can be computed from underwater irradiance values as in Tyler et al., 1972. Both the decay rate of sunlight intensity with depth and with wavelength can be observed by using underwater cosine collectors at two or more depths (Tyler and Smith, 1970). The diffuse attenuation coefficient thus determined is a function both of the depth at which the observations are taken and the wavelength. Experimental values are presented in Tyler and Smith, 1970 for various lake, coastal, and open ocean waters. The diffuse attenuation coefficient can also be computed from the inherent optical properties of the water as suggested in Gordon, Brown, and Jacobs, 1975. Preisendorfer (1961) defined two classes of optical properties for water, the inherent and apparent properties. The inherent properties are those properties which are independent of the light distribution in the water and include the absorption and scattering coefficients. The apparent properties are those which are dependent on and vary with the light distribution in the water. The irradiance is considered an apparent property, as are the derived properties, diffuse attenuation and distribution function. Gordon, Brown, and Jacobs (1975) using the quasi-single scattering approximation to the radiation transfer equation defined the diffuse attenuation coefficient in terms of the inherent water properties--absorption, scattering, and the

in-water incident light angle. They showed that the ratio of the normalized diffuse attenuation coefficient and the distribution function could be considered a quasi-inherent optical property of the water.

As a quasi-inherent optical property, the diffuse attenuation coefficient has been shown to be relatively insensitive to changes in the solar elevation angle. Baker and Smith (1979) were able to demonstrate this invariance for wavelengths across the visible spectrum range for water in the San Vicente Reservoir. The reservoir water was representative of productive ocean water, with a chlorophyll concentration of $7 \mu\text{g}/\ell$ and attenuation length of $1/3 \text{ m}$.

In this report, a comparison is made between these methods of determining light penetration for water which is representative of highly productive, near-shore coastal conditions. These tests were conducted at different solar elevation angles for similar water types. The results showed little change in light penetration with changing solar elevation angle. The computed results indicated good agreement between the different techniques for high solar elevation angles only. The best comparison was achieved by using only the inherent water properties to compute the diffuse attenuation coefficient, and not correcting for solar elevation angle.

SYMBOLS

a	absorption coefficient, m^{-1}
b	scattering coefficient, m^{-1}
b_b	backscattering coefficient, m^{-1}
c	= a + b, attenuation coefficient, m^{-1}
D_o	distribution function
E_d	downwelling irradiance $\text{w}/(\text{m}^2\text{-nm})$
F	forward scattering fraction

K_d	downwelling diffuse attenuation coefficient, m^{-1}
Z	depth, positive downward, m
Z_{90}	depth above which 90% of the total radiance originates, m
$\beta(\theta)$	volume scattering function, $m^{-1}sr^{-1}$
θ	scattering angle, degree
θ_0	the in-water angle with respect to the inward normal of the beam of incident irradiance, degree
λ	wavelength, nm
μ_0	$\equiv \cos \theta_0$
ω_0	$= b/c$, single scattering albedo

EXPERIMENTAL FIELD AND LABORATORY MEASUREMENTS

The field measurements of light penetration were made on March 24 and 26, 1981 in the Kerr Reservoir, Clarksville, Virginia, for similar water types and over several solar-elevation angles. The measurements were made using a submersible cosine collector. (A Kahlsico recording High Sensitivity Universal Submarine Photometer Model No. 268WA390 lowered on a wire supported tripod). The collector was equipped with three color filters, blue, green, and red, (420-480 nm, 490-570 nm and 620-680 nm, respectively). Irradiance readings were taken for each bandwidth at selected depth intervals of 20, 40, 60, 100 and 120 cm (up to approximately twice the Secchi disk depth). The instrument and support were lowered from a boom which extended 1 meter off the bow of the boat. The boat and boom were oriented toward the Sun to minimize shadowing.

The tests were conducted at two sites within the reservoir. The first site was used for low and moderate Sun angles with clear skies and very low wind conditions. This relatively open body of water site had to be abandoned on the last day when wind conditions increased, and required moving to a more

protected site in the reservoir. Sky conditions were again totally clear during the tests which were conducted for the highest solar elevation angle. The solar angle was read from solar altitude tables (Kodak Publ No. R-10, 1970) for the first test, and by use of an inclinometer for the last two tests. Secchi disk depths were also read for each test. Water samples were pumped onboard for optical analysis at a portable dockside lab and for chemical analysis at the main Langley laboratories. These large-volume samples (approximately 40 gallons) were taken from just below the water's surface (20 cm).

The optical analysis was performed within an hour of sampling to obtain the beam-attenuation coefficient, c , the volume scattering function, $\beta(\theta)$, and the absorption coefficient, a . Measurements for c and $\beta(\theta)$ at small angles ($\theta = 0.37^\circ, 0.75^\circ, \text{ and } 1.5^\circ$) were made at 50 nm intervals from 450 nm to 800 nm using the Langley Small Angle Scattering Meter (SASM) (Usry et al., 1981). Large-angle $\beta(\theta)$ measurements were made using a Brice-Phoenix (BP) light-scattering photometer which had been modified to give spectral data (Whitlock et al., 1980). The absorption measurements were made at wavelengths and resolutions identical to those of the SASM using the Langley Spectral Absorption Coefficient Instrument (SPACI) (Friedman et al., 1980).

ANALYTICAL RELATIONSHIPS

The decrease in the intensity of sunlight as it penetrates the water column is described by the diffuse attenuation coefficient, K_d , as follows:

$$K_d = \frac{1}{(Z_2 - Z_1)} \ln \left[\frac{E_d(Z_1)}{E_d(Z_2)} \right] \quad (1)$$

where E_d is the downwelling irradiance at depths Z_1 and Z_2 respectively (Tyler et al., 1972). The depth of sunlight penetration as determined from the experimental data is then the inverse of K_d .

The analytical expression developed by Gordon et al., 1975 (page 419, eqn. 12) which relates the diffuse attenuation coefficient to the inherent water properties and the in-water solar zenith angle is as follows:

$$K_d = \frac{c[1 - \omega_0 F(\mu_0)]}{\mu_0} \quad (2)$$

where,

$$\mu_0 = \cos \theta_0$$

$$\omega_0 = b/c$$

F = forward scattering fraction

c = a + b, attenuation coefficient.

This expression is derived from the radiative transfer equation assuming a homogeneous water mass and using the quasi-single-scattering (QSS) approximation. Use of QSS approximation forces perfect forward scattering for all photons not backscattered. Thus, the only loss of irradiance, when using this relationship, will be due to absorption or backscattering. The above relation appears to be a good approximation of the diffuse attenuation coefficient for all water with single scattering albedos of less than 0.95 (Gordon et al., 1975).

In terms of the inherent optical properties that can be measured in the optical lab equation 2 becomes

$$K_d = \frac{a + b_b}{\cos \theta_0} \quad (3)$$

where,

a = absorption coefficient

b_b = backscattering coefficient = $b(1 - F)$

θ_0 = the in-water angle with respect to the inward normal of the beam of incident irradiance.

RESULTS AND DISCUSSION

The tests, conducted at three different solar elevation angles, were for water which displayed relatively consistent chemical and optical properties, as shown in table 1. The most important chemical properties in terms of the effect on light penetration are the total-suspended-solids (TSS), chlorophyll a (Chl a), and dissolved organic carbon (DOC). The TSS and Chl a have strong effects on the scattering of the light while the DOC level affects the light absorption. For all three tests, these results are very similar, with test number 3 being slightly higher in TSS and Chl a. Test number 2 was the lowest in DOC of the three tests. The attenuation coefficients for all samples were very similar and characteristic of coastal waters.

The results of the three tests are presented in figures 1 to 3 as a comparison of the observed and computed penetration depth variation with wavelength. The Secchi depths are also presented for comparison.

The penetration depths are presented for bandwidths associated with each of the color filters on the submarine photometer that was used in making the irradiance observations. The distribution with wavelength for the blue, green, and red penetration depths relative to each other is very consistent.

This indicates little change in optical properties with site, which would be expected from a homogeneous water body.

The small changes in penetration depth between test 1 and test 2 are within the estimated accuracy to which the tripod depth could be read (+5 cm). The 5-to 6-cm change noted for test 3 may be the result of the slightly higher level of TSS and Chl a for that site. No consistent increase in penetration depth was noted as the solar elevation angle increased indicating that the depth of sunlight penetration was relatively insensitive to the solar elevation angle over the range tested.

The green bandwidth corresponds most closely with the bandwidth sensitive to the eye which is the remote sensor for the Secchi disk. As anticipated, the Secchi disk depths (SDD) were always greater than the corresponding penetration depths as determined from the photometer or the inherent water properties. The changes in SDD, however, observed by eye for the different tests correlated very well with the changes observed by the green band filter on the underwater photometer. That is, a 3-cm change in SDD between test 1 and 2 was also recorded as a 3-cm change by the photometer. An 8-cm change between 2 and 3 was recorded as a 10-cm change. The close correlation between the change in SDD and the change in observed values indicated SDD may be a better measure of changes in transparency than one would normally anticipate.

The light penetration depths computed from the inherent water properties are shown in figure 4 for values computed at 50-nm increments. These are in comparison with penetration depths computed by Gordon and McCluney (1975) from Jerlov's oceanic and coastal water types. The Roman numerals refer to Jerlov's oceanic water and the Arabic numerals to coastal water types. The curve for the Kerr Reservoir water follows the same trend as Jerlov's type 9 coastal water,

with the maximum penetration depth of approximately 50 cm at 650 to 700 nm. This shift toward the red end of the spectrum is due to the increasingly higher concentrations of decaying organic material available in the rivers that absorbs strongly in the blue (Gordon and McCluney, 1975).

A comparison of all three computed penetration depth curves for each solar elevation angle (figures 1-3) indicates that the higher solar-elevation test agrees better with the depths computed from the observed values than do those for lower solar elevations. The comparison also indicates that using the Gordon et al. (1975) QSS relationship without correcting for solar elevation angle (or by assuming $\cos \theta_0 = 1$), provides the best comparison with observed data for all tests. This agrees with the findings of Baker and Smith (1979) that the depth of sunlight penetration in natural waters is relatively insensitive to the solar-elevation angle. Gordon's QSS relationship is for a collimated beam of incident light. It appears that as the direct light from the Sun decreases that the skylight becomes a greater part of the total available light. In fact, the skylight always appears to be a major part of the available light. This decreased influence due to direct Sun is further strengthened by the compressing effect of the light entering the water and being restricted to a 48° half-angle cone. This compression of light due to the air-water interface reduces the effect of any changes in the solar elevation angle, so that any change in lighting level would become a smaller percentage of the total available light.

The comparison, based only on the absorption and backscattering coefficients, implies that a good estimate of the sunlight penetration for these waters can be determined solely on the basis of these inherent water properties for the range of solar-elevation angles encountered. This would allow definition of sunlight penetration for stable bodies of water, regardless of the light conditions when the water samples were taken.

In figure 5, the normalized diffuse attenuation coefficients for the Kerr tests are shown as a function of the single scattering albedo, ω_0 , and the forward scattering fraction, F . These results are compared with Monte Carlo simulations for downwelling irradiance computed by Gordon et al., for both a pure Sun and a pure sky illumination case. Attenuation values based on the inherent optical properties were used to examine the effect of solar-elevation angle. The high elevation in test 3 corresponds closely with the Sun case, and the low solar-elevation angle of test 1 matches closely with that of the sky case. The moderate solar angle of test 2 falls between these two examples, as expected. The attenuation coefficients were also computed from the observed irradiance values, but the three sets of values were insufficient for meaningful comparison.

Using the Monte Carlo simulation technique, Gordon et al. (1975) were able to show that the ratio $K_d/(cD_0)$ was dependent on $\omega_0 F$ only and independent of the incident radiance distribution. In table 2, this ratio has been computed from the inherent optical properties for each solar angle. As indicated by the simulation technique used by Gordon et al., little change is seen with changing solar angle, and $K_d/(cD_0)$ can be considered a quasi-inherent optical property.

Using this quasi-inherent property, the distribution function D_0 was computed for each solar angle and is also shown in table 2. The values ranged from approximately 1.08 for the high solar angle to 1.39 for the lowest solar angle. The distribution function also appears to be invariant with wavelength which is not consistent with Tyler et al. (1972). According to Smith and Tyler, 1978, the distribution function varies with depth as does the radiance distribution. The value approaches 2 for the uniform diffuse radiance of the

asymptotic light field and approaches 1 for a single collimated incident beam of light normal to the surface. The values for the Kerr test approach 1 for the high solar angle test which would be similar to the single incident beam of light, and become larger for the low solar-angle cases where the sky radiance becomes a larger part of the overall light available. The values observed were on the order of 1 to 1.5 which is typical of natural waters in the blue-green region of the spectrum (Wilson and Austin, 1978), but did not approach the values predicted for the asymptotic light field. Distribution functions computed using the observed diffuse attenuation coefficients also fall in this range.

CONCLUDING REMARKS

Comparative light penetration tests were conducted for several solar elevation angles at the Kerr Reservoir in Clarksville, Virginia. Although location within the Reservoir changed, the water remained chemically and optically similar. Light penetration depths predicted for high solar-elevation angles by using the inherent water properties in the quasi-single-scattering approximation were in close agreement with those observed using a submarine photometer. The agreement lessened as the Sun angle became lower when corrected data were used. In all three cases, the quasi-single-scattering approximation relationship, uncorrected for solar angles, gave better agreement than when corrected. The uncorrected results suggest that within the solar limits tested, the sunlight penetration is independent of solar elevation angle and can be determined by the inherent water properties of absorption and backscattering alone.

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TABLE 1.- WATER QUALITY AND OPTICAL PROPERTIES

Property	Test Number		
	1	2	3
Solar elevation angle (deg)	23°	48°	60°
Secchi disk depth (cm)	72	75	65
Attenuation coefficient (c) at 550 nm (m^{-1})	11.0	10.9	10.6
Scattering coefficient (s) at 550 nm (m^{-1})	9.2	9.0	8.8
Absorption coefficient (a) at 550 nm (m^{-1})	1.8	1.8	1.8
Total suspended solids (mg/l)	13.9	14.4	17.4
Chlorophyll <u>a</u> ($\mu g/l$)	13.5	10.4	15.8
Dissolved organic carbon (mg/l)	4.2	2.4	3.4
Particulate organic carbon (mg/l)	0.8	0.6	1.1
NTU (turbidity)	--	15	18
Iron (ppm)	0.34	0.47	0.44
Nitrates (mg/l)	1.4	1.6	1.5

TABLE 2.- SPECTRAL VARIATION OF DIFFUSE ATTENUATION AND DISTRIBUTION FUNCTION WITH SOLAR ANGLE

Solar Elevation Angle (deg)	Parameter	Wavelength, (nm)							
		450	500	550	600	650	700	750	800
23°	K_D/cD_0	0.251	0.243	0.218	0.209	0.207	0.231	0.360	0.393
	D_0	1.386	1.387	1.385	1.383	1.377	1.381	1.383	1.384
48°	K_D/cD_0	0.268	0.274	0.219	0.210	0.200	0.225	0.347	0.371
	D_0	1.156	1.156	1.156	1.158	1.155	1.155	1.156	1.156
60°	K_D/cD_0	0.251	0.231	0.220	0.217	0.218	0.255	0.387	0.399
	D_0	1.080	1.100	1.082	1.088	1.078	1.086	1.083	1.083

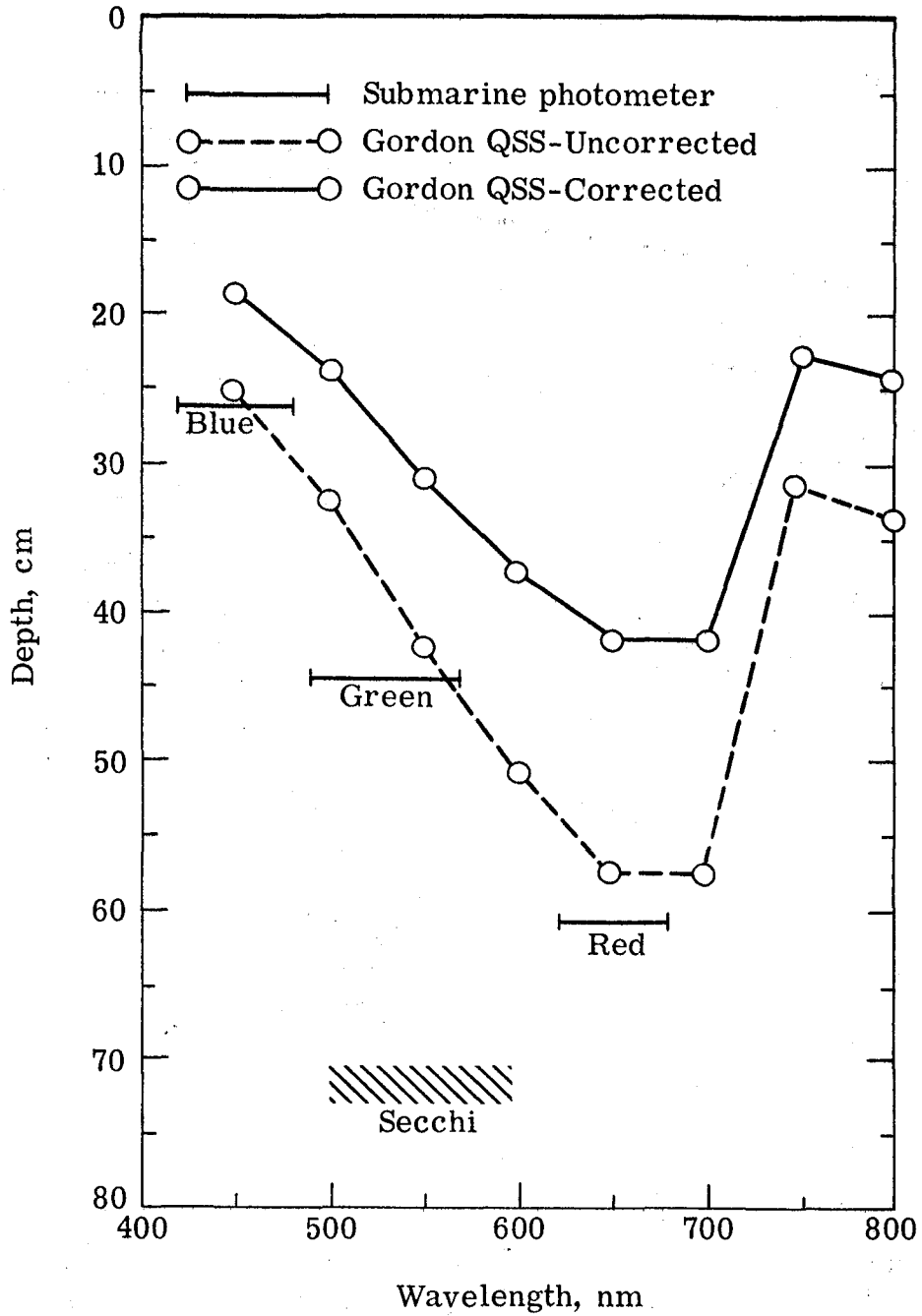


Figure 1.- Comparison of spectral variation in sunlight penetration depths for a solar elevation angle of 23° (Test 1).

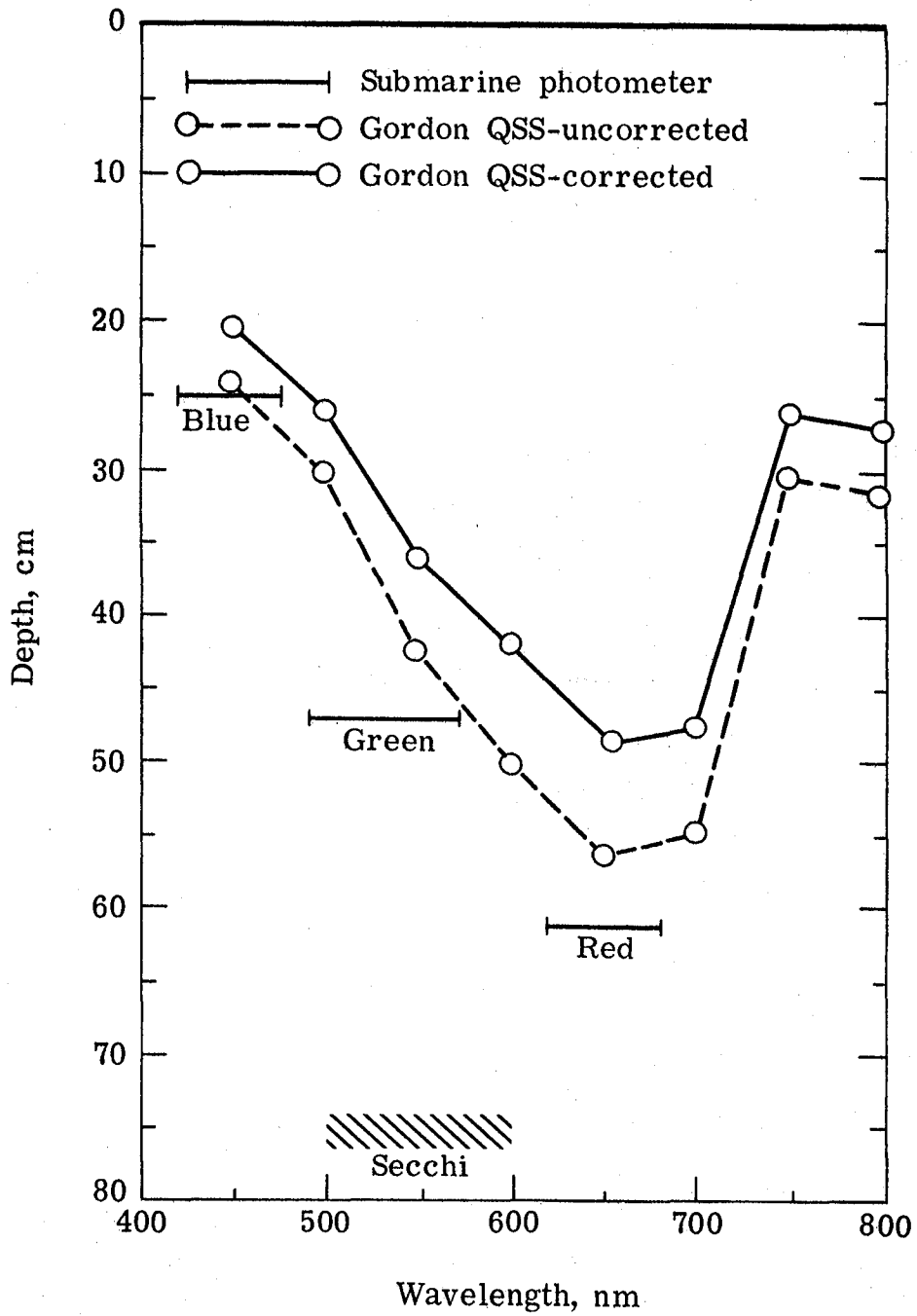


Figure 2.- Comparison of spectral variation in sunlight penetration depths for a solar elevation angle of 48° (Test 2).

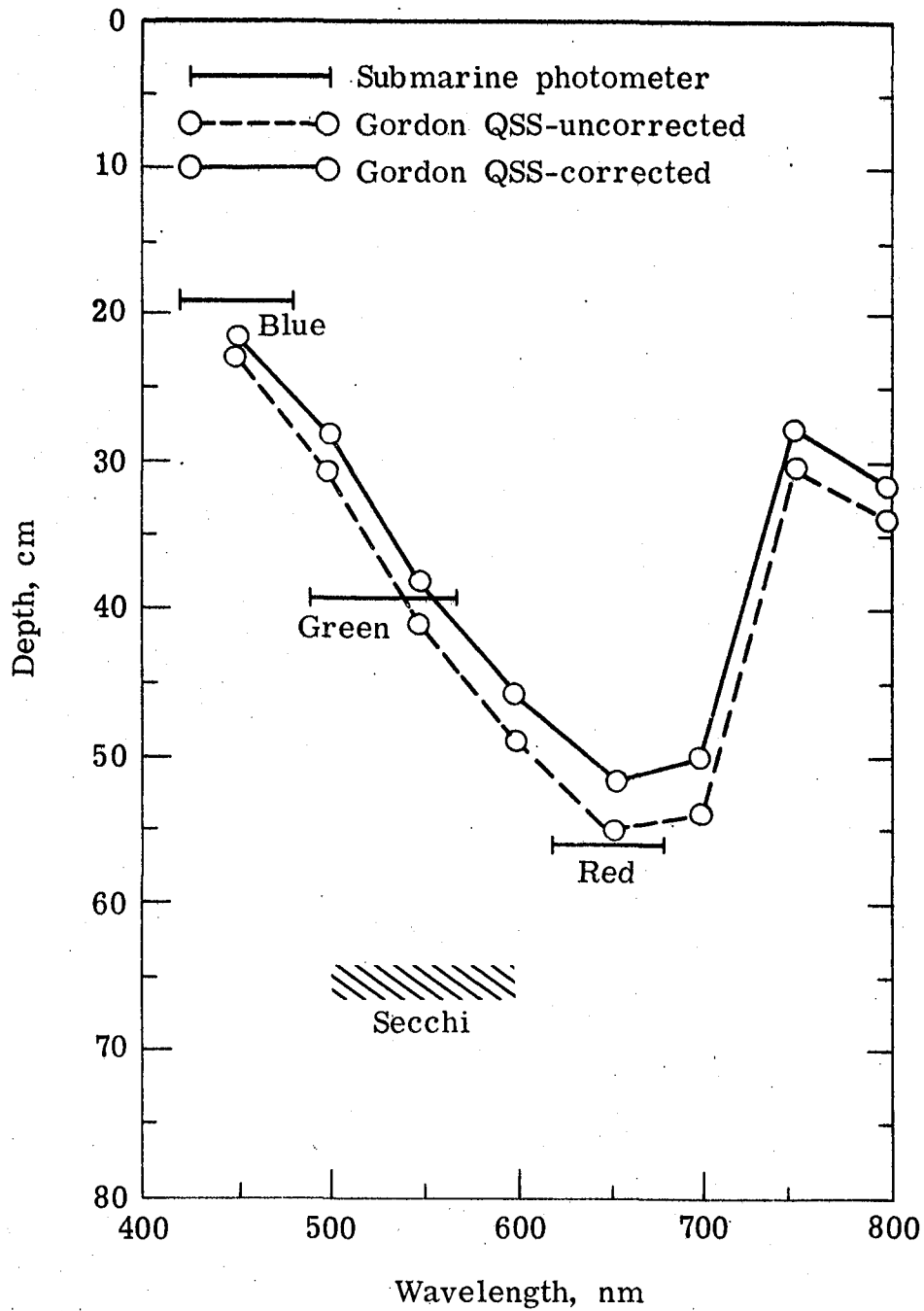


Figure 3.- Comparison of spectral variation in sunlight penetration depths for a solar elevation angle of 60° (Test 3).

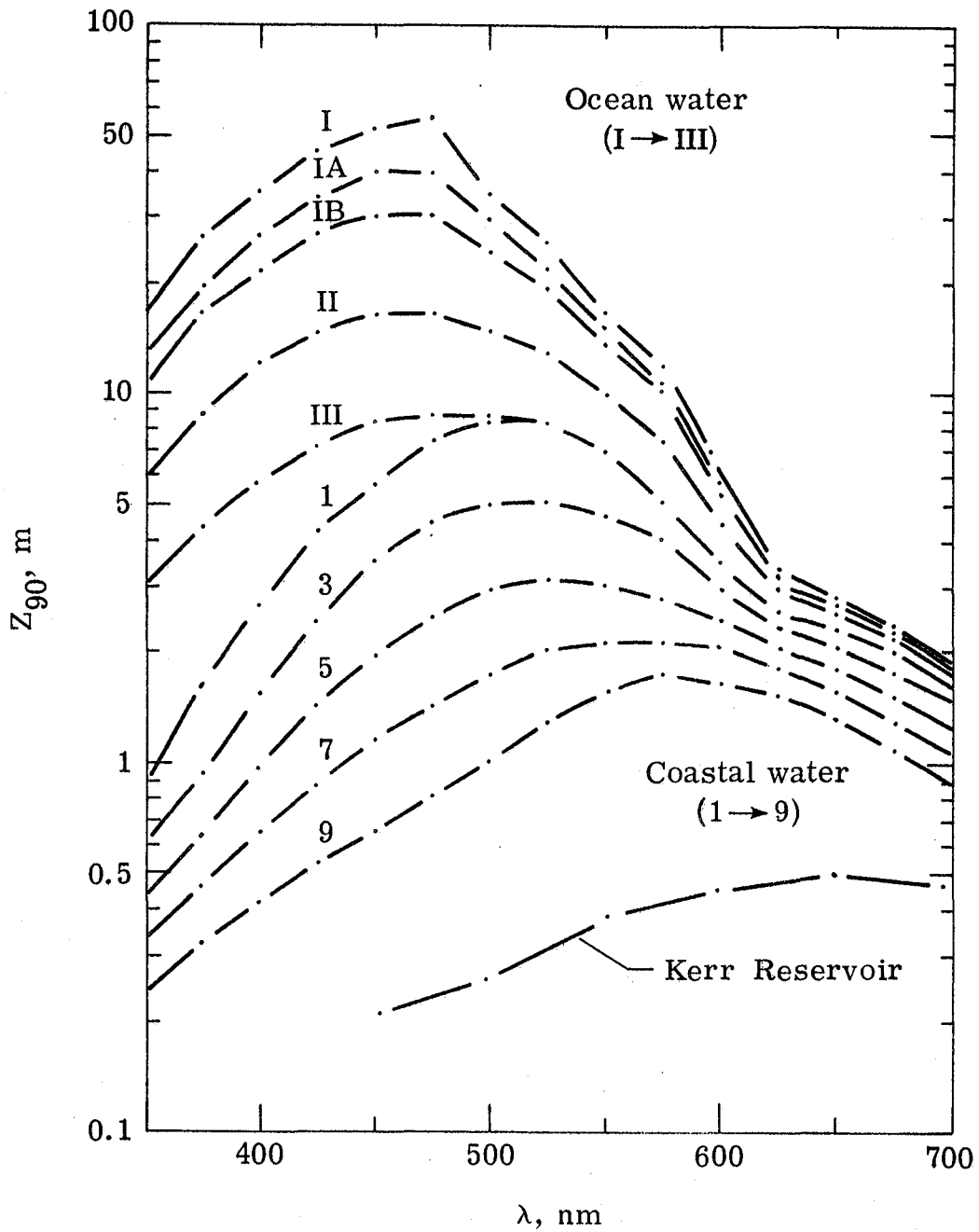


Figure 4.- Spectral variation in light penetration depths (Z_{90}) for various water types from Gordon and McCluney (1975, p. 415).

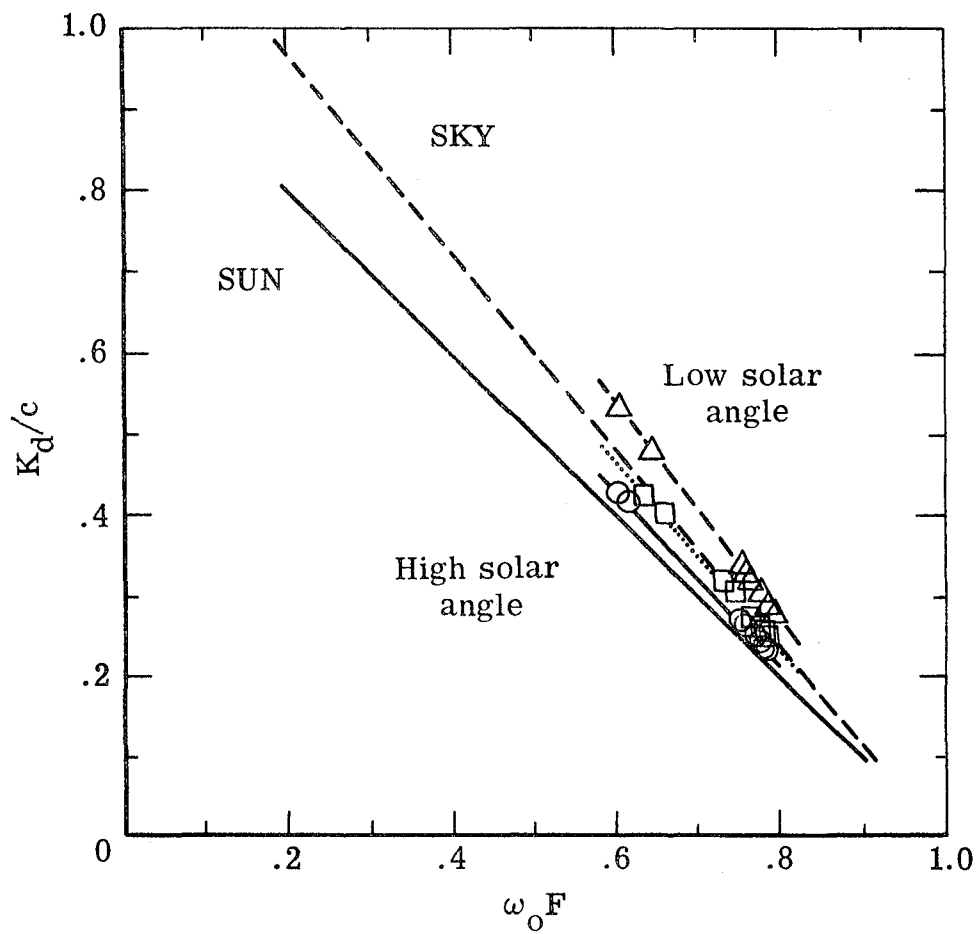


Figure 5.- The effect of solar elevation angle on the downwelling diffuse attenuation coefficient compared with the Monte Carlo simulation of SUN only and SKY only cases from Gordon et. al. (1975).

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