



Article Water Temperature and Salinity Measurement Using Frequency Comb

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Abstract: Water temperature and salinity are key parameters in many fields such as industry, forestry and agriculture. In this paper, we, theoretically and experimentally, demonstrate a method which is capable of water temperature and salinity measurement based on a laser frequency comb at 518 nm. We have developed a simple Michelson interferometer system. By scanning a mirror on a precision displacement platform, a pair of cross-correlation patterns can be obtained. The real-time optical distance information from these cross-correlation patterns can be used to calculate the optical distance difference changes. Temperature and salinity can be measured via these changes, aided by the empirical formulas. Compared with the reference values, our results show the differences of below 0.12 °C for temperature measurements, and 0.06‰ for salinity measurements. The obtained results indicate that our method can offer a powerful scheme for future temperature and salinity measurement.

Keywords: water temperature and salinity; frequency comb; empirical formulas

1. Introduction

Water temperature and salinity are essential to many aspects, such as industry, agriculture, aquaculture, forestry, potable usage, sailing, entertainment, and scientific research. In aquaculture, water temperature and salinity are significant parameters for fish growth, survival, reproduction and disease resistance [1,2]. In nuclear power plants, the water temperature should be well and precisely controlled during the nuclear reaction [3]. Besides, the spent nuclear fuel which is full of dissolved ammonium salt with radioactivity should be seriously monitored to prevent severe environmental pollution. For chemical research, some bio-colonies are usually cultivated in a solution. On this occasion, a suitable amount of salinity and a proper temperature are the premise of the experiment. These two physical parameters also mean a lot to oceanography, ocean dynamics, ocean-atmosphere interactions, and underwater communication [4]. The specific phenomenon, such as the internal wave, which can not only improve energy and nutrient exchange, but also affect marine facilities, is related to water temperature and salinity. In a word, the temperature and salinity measurements are imperative and worthwhile.

On account of many aspects mentioned above, the temperature and salinity measurement have received increasing interest in recent years. Scientists and engineers all over the world have come up with multiple methods to measure these two physical quantities. The current methods can be mainly regarded as two groups, direct measurement and indirect measurement. In the perspective of direct measurement, the initial temperature sensor, which is still used in marine surveys nowadays, is the reversing thermometer [5], whose measurement principle is similar to the mercury thermometer. The accuracy can be up to $0.02 \,^{\circ}$ C; nevertheless, its disadvantage lies in long response time and non-continuous measurement. In addition, the other direct temperature measurement sensors are

electrical sensors, such as the thermocouple, resistance temperature device (RTD), and thermistor. The thermocouple [1,6] has a good stability, but large thermal inertia, low sensitivity and poor accuracy. The thermistor [7] is very sensitive to temperature and has a short response time, but its stability is poor. The RTD [6,8] represented by platinum resistance is most commonly used in water temperature measurement, and it can be strictly calibrated before leaving the factory. Nevertheless, the contact measurement principle will accelerate the metal corrosion, which will influence the experiment results. For salinity measurement, the conductivity meters [9,10] are the most widely used and two electrodes are exploited to detect the water conductivity, related to the concentrations of the dissolved salt. However, this method can easily cause water polarization [11]. Besides, when the electrodes are covered by a dirty substance, the length and area of the electrodes will change. Hence, the electrodes should be kept clean. Additionally, the invasive scheme can lead to the oxidation and corrosion of the electrodes, and the changes in electrode geometry will influence sensor performance. Therefore, regular recalibration is required.

There is a great deal of indirect methods for salinity and temperature, which can be classified as the water density method, acoustic method, and optical method. As is known, atmospheric pressure, temperature and salinity are three fundamental physical parameters related to water density [12]. When atmospheric pressure is constant, a densimeter can be used to measure the results, which can be converted to the temperature or salinity by the empirical formula. However, when salinity and temperature change together, it is hard to distinguish the source. Acoustic method is also used in temperature and salinity measurement, because sound speed is related to temperature and salinity [13–15]. In general, the sound speed can be measured by the pulse flight time method [13,14]. However, the roughly measured distance value and the multi-path effect will result in measurement error. The means of planer laser induced fluorescence [16,17] has realized the real-time observation of water temperature. The fluorescence dye serves as an indicator, which can be excited by laser source and has a high sensitivity to water temperature. However, the premise of the experiment is that the dye concentration and laser intensity should be constant and stable, which is hard to satisfy. In recent years, optical fibers [18–22] are widely used in temperature and salinity sensing. However, this type of fiber is not appropriate to be applied in harsh circumstances. Besides, it is hard to eliminate the cross-sensitivity influence among strain, temperature and salinity. The water refractive index can also be a reflection in the essential optical feature of water, including salinity and temperature. The instruments for water refractive index measurement can be mainly divided as refractometer and interferometer. Based on the principle of light refraction, the refractometer can measure the refractive index of water by recording the beam deviations angle [23,24]. Nevertheless, the beam deviation can be easily affected by the plankton and suspended sediment [25]. In order to solve this problem, the abbe refractometer based on the Snell law has been used. The critical angle of total reflection and the refractive index can be converted to salinity by an empirical formula [25]. However, the refractive index of the auxiliary prism is necessary and the accurate measurement of the angle value is required, which makes the measurement system complicated, and the measurement uncertainty is only at the order of 10^{-4} . Besides, Michelson interferometers can also be used in temperature and salinity measurements [26,27]. However, the geometry of the water container needs to be accurately measured, otherwise the thermal expansion of the water container itself can produce considerable measurement uncertainty. An adaptive measuring device [28] can be used to compensate the thermal expansion of the water container, and the measurement uncertainty can be better than 10^{-5} . However, the existing reports are based on the fringe counting principle of a continuous wave (Cw) laser source to measure the optical path difference, which requires continuous movement of the mirror, and the procedure cannot be interrupted. An optical frequency comb as a measuring light source can solve this problem. Optical frequency combs have been used to measure the refractive index of air [29], the thickness and refractive index of glass [30], etc. However, refractive index measurements for water have rarely been reported.

In recent years, since the frequency combs were invented, scientists all over the world have been searching for its application field. The underwater application is a brand-new area for frequency combs, which has rarely been reported on before. Recently, our group has realized underwater distance measurement by frequency comb in both time domain and frequency domain [31]. The experiment results show a difference of 100 μ m in the range of 8 m. In this paper, we adopt the frequency comb to realize the detection of water temperature and salinity. The experiments are carried out in a water tank. We adopt a simple Michelson interferometer, in which two measurement arms are designed. A pair of cross-correlation patterns can be obtained to detect the distance between the water arm and air arm, which can be converted to the temperature and salinity by empirical formulas. In particular, our configuration can eliminate the effects of water tank thermal expansion. Meanwhile, a salinity sensor and temperature sensor are involved, whose results can be used to evaluate our measurement results. The experimental results show that our method can precisely measure temperature and salinity.

2. Measurement Set-Up

2.1. Temperature Measurement Setup

As shown in Figure 1, the experiment setup is presented. Above all, the whole experiment configuration can be considered as two sections. One section is used for sensing the optical distance variations caused by temperature; the laser source we employ in this section is frequency comb FC (Menlo system orange, FC1000, 518 nm, 100 MHz, 500 mW), links to the frequency reference, Rb clock (Microsemi 8040). In the picture above, the frequency comb sends out a laser beam, which is split from the Beam splitter 1 BS1 (Thorlabs, BSW10R) into two parts. One is reflected by mirror 1 M1 (Thorlabs, PF10-03-P01) fixed in a precision displacement PDP (PI, M521.DD1), which serves as Reference arm RA. The other is divided by BS2. The transmission beam is traversing part of a quartz glass water tank full of water, and reflected by M2, leading into a measurement arm 1 (MA1). The reflection beam is going through the empty part of water tank, and reflected by M4, which introduces the measurement arm 2 (MA2). Three arms meet at the output of BS1, and detected by PD1 (Thorlabs, PDA36A-EC), and waveforms can be observed from the Oscilloscope Scope (LeCroy, WaveRunner9000-MS). The second section is led by a Cw laser (Spectra-Physics, Excelsior-532-300-CDRH, 532 nm), which is used to get a precise position of the scanning mirror M6 by counting the quantity of fringes. This whole section works as a Cw laser interferometer. Please note that M1 and M6 are connected and scanned together. In addition, in this configuration, temperature is measured as a reference by temperature sensor TS (Seabird, SBE56 Temperature Logger) in real time. Besides, the water tank is divided into two partitions: one is full of water, the other is empty. Lastly, the laser beam should be perpendicular to the glass wall to minimize measurement uncertainty, and the distance L_1 in Figure 1 are set very close to make sure the glass temperature of the empty part is almost the same with the water part.



Figure 1. Temperature and salinity measurement experiment setup. FC: Frequency Comb; Rb: Rubidium clock; BS1: Beam Splitter 1; M1: Mirror 1; RA: Reference Arm; PDP: Precision Displacement Platform; BS2: Beam Splitter 2; MA1: Measurement Arm 1; MA2: Measurement Arm 2; M5: Mirror 5; PD1: Photodetector1; Cw Laser: Continuous wave Laser; BS3: Beam Splitter 3; PD2: Photodetector 2; Scope: Oscilloscope; TS: Temperature Sensor; SS: Salinity Sensor; *d* is the thickness of the glass tank; *D* is the geometric distance of water; PD: Photodetector; L_0 , L_1 , L_2 , L_3 , L_4 is the geometric distance of the optical path marked in the schematic.

2.2. Salinity Measurement Setup

The salinity measurement setup is arranged as in Figure 1, which is the same with the temperature system. Please note that the salinity sensor (Mellter Toledo, Seven2go Pro) is used here to measure salinity as a reference, which will be compared with the measurement results. Meanwhile, the temperature sensor serves as a temperature monitor. The water used here is also distilled water in order to get a larger salinity measurement range. Considering the temperature also contributes to the refractive index, the environment should be constant. The experiment photograph is shown in Figure 2.



Figure 2. Experiment photography.

3. Materials and Methods

Theoretically, the optical path length of MA1 L_w and MA2 L_a can be expressed as:

$$L_w = (L_0 + L_2 + L_3)n_a + 2dn_g + Dn_w$$
(1)

$$L_a = (L_0 + L_1 + L_2 + D + L_4)n_a + 2dn_g$$
⁽²⁾

Among these Equations, n_g is the group refractive index of glass. n_w stands for the group refractive index of the water. n_a represents the group refractive index of air. Please note that the MA1 optical path distance L_w is slightly longer than MA2 L_a . Therefore, the optical path difference (*OPD*) between MA1 and MA2 can be calculated as:

$$OPD = L_w - L_a = (L_3 - L_4 - L_1)n_a + D(n_w - n_a)$$
(3)

When water temperature or salinity changes respectively, the variation of water group refractive from n_w to n_{w1} will change the optical length of MA1 from L_w to L_{w1} , which results in *OPD* changing into *OPD*1.

$$L_{w1} = (L_0 + L_2 + L_3)n_a + 2dn_g + Dn_{w1}$$
(4)

$$OPD1 = L_{w1} - L_a = (L_3 - L_4 - L_1)n_a + D(n_{w1} - n_a)$$
(5)

$$L_{w1} - L_w = OPD1 - OPD = D(n_{w1} - n_w)$$
(6)

$$n_{w1} = \frac{L_{w1} - L_w}{D} + n_w = \frac{OPD1 - OPD}{D} + n_w$$
(7)

3.1. Temperature Measurement Principle

There are various formulas that exclaim the relations of temperature and salinity. In this presented work, we adopt the Quan-Fry formula [32]:

$$n(S,T,\lambda) = n_0 + (n_1 + n_2T + n_3T^2)S + n_4T^2 + \frac{(n_5 + n_6S + n_7T)}{\lambda} + \frac{n_8}{\lambda^2} + \frac{n_9}{\lambda^3}$$
(8)

In this empirical Equation, *S* is the salinity in ∞ , *T* is the temperature in degrees Celsius and λ is the wavelength in nanometers. Here are the coefficient values:

 $n_0 = 1.31405, n_1 = 1.779 \times 10^{-4}, n_2 = -1.05 \times 10^{-6}, n_3 = 1.6 \times 10^{-8}, n_4 = -2.02 \times 10^{-6}, n_5 = 15.868, n_6 = 0.01155, n_7 = -0.00423, n_8 = -4382, n_9 = 1.1456 \times 10^{-6}.$

With this formula, the phase refractive index *n* can be obtained.

The relation between the group refractive index n_{w1} and phase refractive index n is:

$$n_{w1} = n - \lambda \frac{dn}{d\lambda} \tag{9}$$

By Equations (8) and (9), the group refractive index n_{w1} can be indicated as:

$$n_{w1} = n_0 + (n_1 + n_2T + n_3T^2)S + n_4T^2 + \frac{2(n_5 + n_6S + n_7T)}{\lambda} + \frac{3n_8}{\lambda^2} + \frac{4n_9}{\lambda^3}$$
(10)

Hence, the temperature *T* can be expressed as:

$$T = \frac{-(n_2S + \frac{2n_7}{\lambda}) + \sqrt{(n_2S + \frac{2n_7}{\lambda})^2 - 4(n_3S + n_4) \left[n_0 + n_1S + \frac{2(n_5 + n_6S)}{\lambda} + \frac{3n_8}{\lambda^2} + \frac{4n_9}{\lambda^3} - n_{w_1}\right]}{2(n_3S + n_4)}$$
(11)

In order to avoid the cross-sensitivity influence, we only focus on the situation of distilled water, whose salinity can be considered as 0. Therefore, Equation (11) can be rewritten as:

$$T = \frac{-\frac{2n_7}{\lambda} + \sqrt{\left(\frac{2n_7}{\lambda}\right)^2 - 4n_4 \left[n_0 + \frac{2n_5}{\lambda} + \frac{3n_8}{\lambda^2} + \frac{4n_9}{\lambda^3} - n_{w1}\right]}}{2n_4}$$
(12)

With Equations (7) and (12), we can convert group refractive index n_{w1} into the temperature *T*.

3.2. Salinity Measurement Principle

Based on the Quan-Fry formula mentioned above, with the Equation (11), the salinity can be expressed as:

$$S = \frac{\lambda^3 (n_{w1} - n_0 - n_4 T^2) - 2\lambda^2 (n_5 + n_7 T) - 3\lambda n_8 - 4n_9}{\lambda^3 (n_1 + n_2 + n_3 T^2) + 2\lambda^2 n_6}$$
(13)

When the water temperature is relatively constant, with the Equations (7) and (13), the group refractive index n_{w1} and salinity value *S* can be converted to each other.

3.3. Geometry Distance of the Water

Based on the theoretical analysis carried out above, the measurement of water geometric distance is indispensable. In order to obtain this value, two steps are required.

To the beginning, half part of the water container is full of water, and the other is empty. Thus, a distance value *OPD* can be acquired. This distance value introduces the optical path difference between MA1 and MA2.

Afterwards, both sides of the container should be empty, and the optical distance of MA1 will be changed to L_{w2} . Therefore, a new distance value *OPD2* will be obtained, which stands for the optical distance between new MA1 and MA2. Please note that when one side of the water tank is full of water, L_w is slightly longer than L_a , which has been mentioned above. Hence, when both sides of the water tank are empty, L_a will be longer than L_{w2} . Consequently, the water geometry distance can be calculated by the following Equations:

$$L_{w2} = (L_0 + L_2 + D + L_3)n_a + 2dn_g \tag{14}$$

$$OPD2 = L_a - L_{w2} = (L_1 - L_3 + L_4)n_a \tag{15}$$

$$L_w - L_{w2} = OPD + OPD2 = D(n_w - n_a)$$
(16)

$$D = \frac{L_w - L_{w2}}{n_w - n_a} = \frac{OPD + OPD2}{n_w - n_a}$$
(17)

The group refractive index n_w and n_a can be calculated via the empirical formulas. After the values *OPD* and *OPD*2 are acquired, *D* can be calculated.

3.4. The Initial Refractive Index

In order to get n_{w1} , it is also necessary to get the value of n_{w0} , that is, the initial water group refractive index.

Based on the analysis above, n_{w0} can be calculated as:

$$n_{w0} = \frac{OPD + OPD2}{D} + n_a \tag{18}$$

The air group refractive index n_a can be acquired via the Ciddor formula [33]. Please note that abbreviations we use above are well explained in Appendix A.

4. Results and Discussion

4.1. Measurement of Water Geometry Distance

In this section, we describe the measurement of the water geometry distance. The environment parameters are: temperature 23.2 °C, pressure 1007.06 hPa, and humidity 16.67%. The group refractive index of air n_a can be calculated as 1.00026325 by Ciddor formula.

Firstly, half part of the water tank is full of water. As is shown in Figure 3a, by scanning the moving stage at the speed of 3.5 mm/s, a pair of cross-correlation patterns can be obtained, which is consistent with the position of M2 and M4. Due to the strong dispersion of water, the cross-correlation

pattern of MA1 compared with the MA2 is distinctively broadened to about 330 μ m (1.1ps). The water temperature is 22.76 °C and the salinity is 0, so the water group refractive index n_w can be calculated as 1.35829166 by Equation (10). We do a Hilbert transform to the patterns in Figure 3a, and the results are shown in Figure 3b. Peak positions are marked in the picture, which are used to acquire the corresponding quantities of fringes in the Cw laser interferometer. Hence, the *OPD* can be measured as 2.424 mm.



Figure 3. (a) Cross-correlation patterns with water in the tank; (b) results of the Hilbert transform.

Secondly, the water tank is empty. By scanning the moving stage at the speed of 30 mm/s, a new pair of cross-correlation patterns is shown in Figure 4a, where the inset is the detailed observation of the patterns. The corresponding Hilbert transform is performed, and the result is indicated in Figure 4b, where the inset is the expansion of the curve. Peak positions are used to acquire the corresponding quantities of fringes. Consequently, the *OPD* can be measured as 76.716 mm.



Figure 4. (a) Cross-correlation patterns without water in the tank; (b) results of the Hilbert transform.

Hence, the geometry of the distance *D* can be calculated as:

$$(76.716 + 2.424)/(1.35829166 - 1.00026325) = 221.044 \text{ mm}$$
 (19)

4.2. Measurement of Water Temperature

We undertook 10-h-long experiments twice from 10:00 p.m. to 8:00 a.m. and from 9:00 p.m. to 7:00 a.m.; during this period, the indoor environments are relatively constant. In the experiment, the water temperature is naturally cooled to environment temperature, which is a very slow procedure. We can regard the water as uniform, and the temperature changes relatively evenly. During the experiment, we use the temperature sensor to detect the neighbor temperature of the water optical beam, which

serves as a temperature reference. Please note that in this experiment, distilled water is used and the initial salinity is 0. The scanning speed for PDP is 3 mm/s.

Figure 5 shows the cross-correlation patterns in 25.33 °C and 24.50 °C. Figure 6 shows the corresponding Hilbert transform, and the measured *OPD* change from 0.389 mm to 0.406 mm. As is shown in Figures 5 and 6, we can find that the *OPD* has enlarged due to the temperature decreasing.



Figure 5. (a) Cross-correlation patterns in 25.33 °C; (b) cross-correlation patterns in 24.50 °C.



Figure 6. (a) Results of the Hilbert transform in 25.33 °C; (b) results of the Hilbert transform in 24.50 °C.

We conducted 10-h-long measurements from 10:00 p.m. to 8:00 a.m. and from 9:00 p.m. to 7:00 a.m., and the results are shown in Figures 7a and 8a. Please note that the data are stored in a short time interval in the former experiment, and the latter in a lager time interval. In Figures 7a and 8a, the red solid circle stands for our experiment results, and the black solid line is indicated as the reference results obtained by the temperature sensor. The corresponding deviations between our method and the reference are shown in Figures 7b and 8b. Compared with the reference values, our results show differences of below 0.12 °C for temperature measurements.



Figure 7. Long-term measurement of water temperature from 10:00 p.m. to 8:00 a.m. (**a**) Results obtained using temperature sensor and our method. Red solid circle: our method results, black solid line: the temperature sensor results; (**b**) the difference between our method and the temperature sensor.



Figure 8. Long-term measurement of water temperature 9:00 p.m. to 7:00 a.m. (**a**) Results obtained using temperature sensor and our method. Red solid circle: our method results, black solid line: the temperature sensor results; (**b**) the difference between our method and the temperature sensor.

4.3. Measurement of Salinity

In the experiment, the ambient environment is constant, and the water temperature is constant at 24.5 °C. A multifunctional salinity sensor is adopted to measure the real-time salinity and temperature. During the experiment, we use an analytical balance to add the sodium chloride 10.00 g each time, and wait for 2 h until the sodium chloride is completely dissolved. Please note that in order to get a large measurement range, distilled water is also used in this experiment, and the initial salinity is 0. The scanning speed for PDP is 3 mm/s.

Figure 9 shows the cross-correlation patterns in 2.15‰, 4.31‰, 6.49‰ and 8.68‰. The corresponding Hilbert transforms are shown in Figure 10, and the measured *OPD* are marked in the figure. We can see the results from Figures 9 and 10. When the salinity increases, the refractive index increases, which results in the optical distance difference enlarging.



Figure 9. (a) Cross-correlation patterns in 2.15‰; (b) cross-correlation patterns in 4.31‰; (c) Cross-correlation patterns in 6.49‰; (d) cross-correlation patterns in 8.68‰.



Figure 10. (a) Results of the Hilbert transform in 2.15‰; (b) results of the Hilbert transform in 4.31‰; (c) results of the Hilbert transform in 6.49‰; (d) results of the Hilbert transform in 8.68‰.

We conducted a measurement from 0 to 15.80‰, and the results are shown in Figure 11a. In Figure 11a, the blue solid circle stands for our experiment results and the dashed line is indicated as the reference results obtained by the salinity sensor. The corresponding deviations between our method and the reference are shown in Figure 11b. We can see that our results show differences below 0.06‰ for salinity measurements, compared with the reference values.



Figure 11. (a) Results obtained using salinity sensor and our method. Blue solid circle: our method results, black dashed line: the salinity sensor results; (b) the difference between our method and the salinity sensor.

Based on the results in Figures 7, 8 and 11, it is clear that the two parameters, temperature and salinity, can be precisely measured by our method. The comparisons with the reference values show a difference of within 0.12 °C for temperature measurements, and within 0.06‰ for salinity measurements, respectively. The deviations can be attributed to the measurement accuracy of the corresponding *OPD*, and the accuracy of the empirical formula (i.e., Quan-Fry formula). We consider that several factors can make contributions to the measurement accuracy of *OPD*, including the accuracy of the precision displacement platform, the program of the data process, thermal expansion of the water tank, optical beam alignment, and water inhomogeneity. Additionally and alternatively, other empirical formulas (e.g., Harvey formula [34], Millard [35], McNeil [36]) can be used to calculate the temperature and salinity.

5. Conclusions

In this work, a frequency comb, for the first time, is applied to measure water temperature and salinity. We achieved the target of temperature and salinity measurement, respectively. By a simple Michelson interferometer, based on the optical distance difference change between two arms, the refractive index change can be obtained, which empirical formulas can convert into temperature and salinity. Compared with the reference values, our results show differences of below 0.12 °C for temperature measurements, and 0.06‰ for salinity measurements. Owing to the limitation of our experimental equipment, we performed the experiment in a limited range. However, our method can be applied to a larger range, which provides a powerful scheme for future temperature and salinity measurements.

Author Contributions: B.X. came up with this idea. H.Z. (Haoyun Zhang) designed the experiment. H.Z. (Haoyun Zhang), F.D. and H.Z. (Haihan Zhao) performed the experiment. H.Z. (Haoyun Zhang) and X.X. analyzed the data. H.Z. (Haoyun Zhang) wrote the original manuscript. B.X., X.X. and Z.Q. did the review and editing.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

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Symbols and Acronyms	Meaning
RTD	Resistance Temperature Device
Cw laser	Continuous wave laser
FC	Frequency Comb
Rb	Rubidium clock
BS1, BS2, BS3, BS4	Beam Splitter
M1, M2, M3, M4, M5, M7, M8	Mirror
RA	Reference Arm
MA1, MA2	Measurement Arm
PDP	Precision Displacement Platform
PD1, PD2	Photodetector
Scope	Oscilloscope
TS	Temperature Sensor
SS	Salinity Sensor
<i>L</i> ₀ , <i>L</i> ₁ , <i>L</i> ₂ , <i>L</i> ₃ , <i>L</i> ₄	geometric distance of the optical path in Figure 1
D	geometric distance of water
d	thickness of the glass tank
L_w, L_{w1}, L_{w2}	optical path length of AM1
L_a	optical path length of AM2
OPD, OPD1, OPD2	optical path difference between AM1 and AM2
n_g	group refractive index of glass
n_w , n_{w1}	group refractive index of water
n_{w0}	initial water group refractive index
n_a	group refractive index of air
п	phase refractive index of water
$n(S,T,\lambda)$	phase refractive index in Quan-Fry formula
$n_0, n_1, n_2, n_3, n_4, n_5, n_6, n_7, n_8, n_9$	coefficient values in Quan-Fry formula
S	salinity in ‰
Т	water temperature in °C
λ	optical wavelength in nanometers

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