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THE FORMULATION OF ECHO SOUNDING CORRECTION TABLES

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Abstract

The 'Echo Sounding Correction Tables' (formerly Matthews' Tables) are of important practical use to hydrographers, and are convenient to use. In case that there is not any oceanographic data available, the actual depth is derived from the tables with the observed depth from the echo sounder. With the recommendation of the International Hydrographic Organization (IHO) and the Hydrographic Offices of some countries, the tables have been widely used in recent years.

Matthews' tables are suitable for the manual correction of sounding velocity, but not for use by computers. In this paper, the tables are formulated by using the method of the least squares approximation on the basis of the orthogonal system of polynomials. So that only a few simple coefficients need to be entered into the computer, and then the true depth can be calculated directly on the basis of the observed depth data. These correction formulas are very easy and efficient to use, and their accuracy is equivalent to that of the 'Echo Sounding Correction Tables'.

INTRODUCTION

At present, depth soundings are usually measured with echo sounders (fathometers). The transducer of the echo sounder emits downward-directed pulses of high frequency sound, which are reflected from the seabed and return back to the transducer, and the depth can be calculated according to the recorded time. This depth is only an approximate depth of water, or so-called observed depth, because it is calculated by using the product of the designed sounding velocity of the echo sounder and the one-way travel time of the sound pulse. In practice, because sea water is not an even medium, and both the physical properties and

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the chemical properties in each layer of sea water are different, the travel velocity of the sound wave in sea water becomes a variable which is different from the designed sounding velocity in each layer. Therefore, in order to obtain the true depth, corrections for sound velocity have to be added to the observed depth.

To calculate the correction value of sound velocity, the temperature and salinity of each layer in sea water have to be measured. In many cases it is very difficult to obtain these oceanographic data. Therefore, how to obtain the correction data for sound speed in a simple and convenient way without any oceanographic data and to meet the requirements of accuracy is of basic importance in improving the accuracy of depth soundings.

Tables of world-wide application for the correction of echo soundings for the varying speed of sound in sea water were first prepared for the Hydrographic Department of the U.K. by D.J. Matthews in 1927, and published as 'Tables of the Velocity of Sound in Pure Water and Sea Water for Use in Echo Sounding and Sound Ranging' (Matthews' Tables). A second edition, extensively revised by the same author, appeared in 1939 and was recommended by the Vth International Hydrographic Conference in 1947 to all hydrographic offices. Much new information was added in the late twenty years, and the second edition of Matthews' tables was extensively revised again. The computation of the tables was carried out by D.J.T. Carter at the Institute of Oceanographic Sciences of U.K. The third edition of 'Echo Sounding Correction Tables' was published in 1980 by the Hydrographic Department of the Ministry of Defence of U.K. and its use recommended in 1982 by the XIIth International Hydrographic Conference to all hydrographic offices. At present, the tables have been adopted by many countries for the correction of sound speed, and this offers a great convenience for hydrographic surveying and charting.

GENERAL SITUATION OF 'ECHO SOUNDING CORRECTION TABLES'

The new edition of the 'Echo Sounding Correction Tables' is compiled on the basis of the analysis and calculation of numerous historical oceanographic observations from 195,000 oceanic stations. Its accuracy is much higher than that of the second edition. Generally, the mean square error of the true depth from the tables is ±3 to ±4 metres, no more than ±5 metres. Due to the lack of data, it is estimated that the mean square error of the true depth below 5,000 metres is about±10 metres. The accuracy of the tables can completely fulfil the requirements for practical use.

When the tables are used, in order to select the corresponding table, the figures in the tables should be first used to determine which sea area the position being measured belongs to. Then, the observed depth must be reduced to metres and rounded to the number of 10 metres. Finally, the true depth will be obtained by consulting the table with the observed depth.

Eighty-five ocean areas are delineated in the tables. The limits of the areas have been drawn at whole degrees of latitude and longitude. Starting from the depth of 200 metres the true depth data obtained from the observed depth will be given continuously at the interval of 10 metres up to the sea bottom in each area.

However, the use of the tables has limitations. The way which the table is used to consult correction data is suitable for manual operation and is not suitable for computers. If the correction data for every depth measured with the echo sounder is consulted from the tables manually, it will be proved to be inconvenient and slow. If these tables are entered into the computer directly and the computer consults the tables, then much memory space will be occupied, and it will also increase difficulty for programming and data input. In order to solve this problem, it is necessary to establish formulas which can replace the correction tables. When the formulas are used, only a few simple parameters of the formulas need to be entered into the computer, and the true depth will be conveniently calculated. Based on this assumption, the Matthews' tables are formulated in this paper. In order to meet various requirements, two correction formulas are given for each sea area.

ESTABLISHMENT OF ECHO SOUNDING CORRECTION FORMULAS

In fact, the establishment of calculating formulas based on the correction tables is a problem of curve fitting. We may take the observed depth x measured with echo sounder as an independent variable and the correction of sound speed h as the function of x. The functional relation between these two physical values is unknown, but from the tables we can get several sets of corresponding x and h and find out their functional relation, then the calculation formulas could be obtained. The method of curve fitting used most extensively is the least squares approximation, that is to select the square sum of residual error of all pairs χ^2 as objective function and reduce χ^2 to a minimum:

$$\chi^2 = \sum_{i=1}^{\bar{n}} \delta_i^2 = \sum_{i=1}^{\bar{n}} [H(x_i, C) - h_i]^2 = min \tag{1}$$

Where δ is the residual error, h is the correction of sound speed obtained from the tables, C is the coefficient of the fitting formulas and H is the correction of sound speed obtained from the fitting formulas.

In order to avoid a poor condition of the coefficient matrix of the normal equation and to improve stability in calculation, the orthogonal system of polynomials is selected as the fitting function in this paper. The least squares fitting is done by a generalized polynomial of degree m:

$$H(x) = \sum_{k=0}^{m} A_k F_k(x) \tag{2}$$

Where, A_k is the coefficient, $F_k(x)$ is a polynomial of degree k which satisfies the orthogonal condition:

$$\sum_{i=1}^{n} F_j(x_i)\, F_k(x_i) = 0 \qquad (j \neq k) \tag{3}$$

$F_k(x)$ can be established on the basis of the improved Gram-Schmidt orthogonal method in linear algebra, A is calculated in the following equation:

$$A_k = \langle F_k, h \rangle / \langle F_k, F_k \rangle \qquad (k = 0, 1, \dots, m) \tag{4}$$

where, $\langle\, \rangle$ means inner product.

Equation (2) can be written to the power polynomial form:

$$H(x) = \sum_{k=0}^{m} C_k x^k \tag{5}$$

Equation (5) is equivalent to equation (2), and thus we have got the final equation of the correction formulas.

THE PRACTICAL CORRECTION FORMULAS

In theory, the orthogonal system of polynomials to carry out fittings may be used to approximate the correction tables with arbitrary accuracy. But, since the length of the computer's characters is limited and some other errors may happen during the time of calculation, the tables can only be approximated to a certain degree. Our calculation shows that the mean square error of the difference between the true depths from the formulas and that from the tables generally is 0.2 to 0.3 metre and the maximum error is 0.5 to 0.6 metre, when the polynomial degree m amounts to 14 to 16. Because the listing data of the original correction tables is only within the accuracy of a metre, the precision of the true depth calculated with the orthogonal system of polynomials of degree 14 to 16 is equivalent to that of the true depth obtained from the tables. It is not necessary to use the correction formula with very high fitting precision, because the actual precision of the tables is ±3 to ±4 metres. The use of the orthogonal system of polynomials which has a lower degree and can meet a certain requirement of accuracy is suitable, in this way it is possible to reduce the amount of work for calculation and input of coefficients. In this paper, the orthogonal systems of polynomials of which the fitting mean square error is ±0.3 to ±0.4 metre and the maximum error is below 1.0 metre are selected as the practical echo sounding correction formulas. In general, the polynomial degree is 5 to 8, and the degree of 2 to 4 or 9 is in the minority. The coefficients of the polynomials C_k for each sea area are shown in Table 1.

As long as each coefficient C_k in Table 1 is substituted into equation (5), the correction data for sound speed can be obtained. The x in equation (5) is the observed depth which is in kilometre, and the result obtained is the correction value of sound speed in meter. If we want to get the true depth, the correction value of sound speed should be added to the observed depth.

THE APPROXIMATE CORRECTION FORMULAS

In some cases, the requirements of the accuracy for the depth data are not very high. For example, to calculate the Bouguer gravity anomaly in marine gravity, the depth data are required. If the increase of the depth error is 10 metres, then the error of the Bouguer anomaly would increase about 0.5 mgal. Therefore, if the error of the depth is within the range of 10 metres, that will be enough to meet the requirements of the marine gravity. For these purposes the polynomial degree could be even lower than above. In this paper, the polynomial of degree 2 to 3 is selected as the approximate correction formula, and its fitting mean square error is less than ±2m, and the maximum error is normally less than 5m and only a few of them are slightly larger than that. The coefficients are shown in Table 2.

THE ADVANTAGE OF THE FORMULATION OF THE CORRECTION TABLES

When the formulas are used for correction of sound speed, only a few data need to be entered into the computer to replace a large number of data in the tables. In the original tables, the total number of data points is 55,645, but there are 541 coefficients in the practical correction formulas and 303 coefficients in the approximate correction formulas, they are about 1/103 and 1/184 of the data of the original correction tables respectively. This not only saves the space of the memory in the computer, but also decreases the possibility of making mistakes. In the second place, the forms of the correction formulas are very simple, it is very easy for programs design. The arbitrary observed depth can be directly substituted into the formulas to calculate the true depth, and it is not necessary to round the depth to whole ten metres before using the tables. For accuracy there is not much difference between the use of the correction formulas and that of the correction tables. If the accuracy of the tables is specified for ±5m, then the overall accuracies of the correction of the sound speed which is carried out by using the practical correction formulas and the approximate correction formulas should be ±5.01m and ±5.2m respectively after considering the fitting error. The effect of using the approximate formulas on the Bouguer gravity anomaly is about 0.3 mgal.

In addition, when we handle the observed depth data of the joint sections of two or more than two sea areas, as long as the appearances of the correction curves of sound speed are similar, we may fit a unitary formula for the correction of sound speed. This is a more original advantage for using the correction formulas. In this way it is not necessary to distinguish which sea area every observed depth belongs to and to determine which correction table is to be used, and this will greatly raise the working efficiency. Let us take No. 52 and No. 53 sea areas of the Northwest Pacific Ocean for example, through unitary fitting the polynomial of degree 6 is given as the practical formula and the polynomial of degree 3 as the approximate formula. The fitting mean square error of the former is ±1.3 metres and its maximum fitting error is 2.5 metres and those of the latter are ±1.8 metres and 8.9 metres respectively. These results are enough to meet the requirements of accuracies.

However, the above-mentioned formulas are only suitable for the echo sounders which have the designed sound velocity of 1,500m/sec. (i.e. 820 fathoms/sec.). If the designed sound velocity of the echo sounder which is used is another value V′, then the x in the formulas has to be replaced by 1,500 x′/V′ before the formulas are used, where, x′ is the observed depth obtained from the echo sounder which is being used.

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Table 1

Practical formulas of echo sounding correction for observed depth

No	C_0	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9
1	–1.63	–32.05	3.929	.182						
2	–.26	–26.05	–1.23	1.447	–.101					
3	1.31	–38.04	5.65							
4	1.11	–22.19	–7.8	5.802	–1.217	.0979				
5	.1	–10.26	–16.39	8.953	–1.789	.1384				
6	–6.26	25.21	–65.4	39.85	–10.805	1.127				
7	–.86	–43.53	10.4							
8	.2	–2.87	–1.31	.633						
9	–1.25	.06	–8.57	3.924	–.5267	.02743				
10	1.78	–13.83	7.543	–7.417	3.8555	–.8863	.096344	–.40252E-2		
11	–1.86	3.021	–44.72	54.43	–33.1437	11.43308	–2.215443	.224532	–.92548E-2	
12	–2	–19.61	9.31	–5.737	2.3013	–.383	.022963			
13	–1.61	33.63	–33.314	13.07536	–2.36716	.2179	–.00794			
14	–2.28	30.97	–20.002	–2.22	6.2097	–2.41313	.4408883	–.398924E-1	.143888E-2	
15	–1.09	9.2	–10.6012	3.638	–.4025	.01795				
16	–.37	6.66	–5.215	1.499	–.0717					
17	2.43	–3.26	11.07	–7.189	2.0466	–.24282	.010632			
18	.84	14.77	–13.562	4.591	–.5613	.02766				
19	2.66	9.83	–12.698	4.6184	–.57292	.028				
20	.96	25.59	–31.199	14.571	–3.38243	.45066	–.0316219	.9043E-3		
21	3	2.305	–7.138	2.674	–.26885	.0108				
22	4.51	–1.48	–11.275	6.68	–1.6338	.24129	–.019421	.6516E-3		
23	2.59	3.9	–21.545	13.877	–4.0288	.648	–.053568	.17769E-2		
24	1.98	7.15	–26.725	17.351	–5.3875	.94834	–.087326	.32663E-2		
25	5.32	–5.11	–10.834	7.9583	–2.26696	.35375	–.027876	.86515E-3		
26	.33	23.35	–46.879	28.931	–8.7497	1.457614	–.1261166	.44423E-2		
27	–1.18	38.454	–74.663	55.483	–22.4874	5.45562	–.780975	.607909E-1	–.198114E-2	

Table 1 (following)

No	C_0	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9
28	1.42	5	–22.935	12.568	–2.85535	.31666	–.01353			
29	.09	15.954	–34.74	19.0977	–4.679	.5594	–.02576			
30	3.15	–17.49	15.532	–17.879	9.648	–2.4522	.29936	–.14134E-1		
31	1.93	–21.53	3.675	.1213						
32	–1.5	–36.26	11.292	–4.4366	1.5164	–.26542	.023331	–.812E-3		
33	–1.985	–20.13	–8.7252	13.0433	–6.67465	1.865	–.2849	.223904E-1	–.70851E-3	
34	–1.51	–27.18	3.762	.1528						
35	–1.77	–28.95	2.71	.6445	–.06612	.00287				
36	1.04	–23.88	3.9736	.1176						
37	–1.76	–28.18	4.39	.104						
38	–2.07	–22.28	–18.55	32.2	–23.3186	9.12671	–1.930037	.207744	–.89296E-2	
39	.86	–46.51	19.34	4.052	–11.0393	5.79458	–1.38027	.157627	–.70043E-2	
40	2.83	18.66	–28.64	14.086	–3.0857	.3458	–.015497			
41	2.37	14.46	–29.31	16.293	–3.9681	.48357	–.023169			
42	1.98	24.34	–33.808	17.4426	–4.3949	.63605	–.048965	.15518E-2		
43	.836	11.4	3.12	1.06						
44	.73	3.4	5.666							
45	2.3	4.13	5.744	.02						
46	.33	–22.2	6.02							
47	–2.88	–18.641	.041	1.2649	–.1481	.009406	–.0002408			
48	–.53	–22.15	2.879	.3634	–.0129					
49	2.14	–18.08	–2.078	2.7835	–.5456	.05386	–.002043			
50	2.94	–15.21	–.843	1.3917	–.1468	.006445				
51	2.87	–4.48	–8.972	4.342	–.7127	.06187	–.002169			
52	3.51	9.304	–25.511	14.5088	–4.30748	.828626	–.101612	.763505E-2	–.31934E-3	.56809E-5
53	5.36	5.343	–17.331	8.3845	–1.85184	.251499	–.0202687	.88879E-3	–.16324E-4	
54	3.195	19.607	–37.179	21.0304	–6.19745	1.123893	–.1258994	.847674E-2	–.313382E-3	.48651E-5
55	2.45	24.8	–49.327	33.917	–13.322	3.329086	–.520366	.4899715E-1	–.253355E-2	.55164E-4

Table 1 (following)

No	C_0	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9
56	–.526	26.02	35.479	16.7579	–3.9983	.55184	–.040482	.12209E-2		
57	3.8	–4.06	–5.663	2.272	–.2111	.00778				
58	1.32	15.19	–27.934	12.986	–2.6875	.27969	–.011447			
59	2.55	–1.92	–10.429	4.7958	–.7662	.06158	–.001921			
60	–.234	–3.52	–8.599	3.701	–.4588	.02183				
61	.321	–5.61	–6.359	2.752	–.293	.01227				
62	.75	–16.94	1.4847	.4844	–.01677					
63	.18	2.91	–10.624	3.945	–.4734	.02238				
64	.88	8.968	–16.617	7.124	–1.357	.150387	–.0087955	.2094E-3		
65	.41	–3.72	–6.475	2.77	–.317	.01455				
66	1.11	7.66	–15.74	5.867	–.7647	.03794				
67	.015	9.51	–22.3385	11.25	–2.48357	.274456	–.0117826			
68	–2.14	26.13	–27.644	11.4074	–2.2642	.23546	–.009793			
69	1.43	18.75	–24.203	9.775	–1.7659	.16407	–.006041			
70	3.23	5.55	–9.848	3.354	–.36474	.01627				
71	2.95	6.27	–14.152	6.0117	–1.0496	.09661	–.003543			
72	1.53	10.17	–10.847	3.384	–.3514	.01515				
73	.25	17.49	–12.565	2.972	–.1713					
74	3.72	2.02	–7.88	3.405	–.3					
75	.31	21.8	5.99							
76	–1.61	–29.55	5.69							
77	2.25	–34.85	5.48							
78	5.72	–28.88	–2.591	4.66	–1.2	.1143				
79	4.46	–.65	–8.91	3.228	–.249					
80	2.9	–4.66	–8.621	4.0907	–.63439	.51113	–.0016408			
81	5.03	–.87	–.72	2.454	–.3987	.02414				
82	5.32	–.72	–11.96	6.833	–1.4738	.16944	–.008081			
83	5.71	–2.264	–9.779	5.2424	–.9695	.09284	–.00353			
84	4.18	2.46	–12.982	5.8889	–1.0393	.09459	–.003407			
85	7.25	–7.17	1.82	.78						

Table 2

Approximate formulas of echo sounding correction for observed depth

No	C_0	C_1	C_2	C_3	No	C_0	C_1	C_2	C_3	No	C_0	C_1	C_2	C_3
1	.93	-36.38	5.621		30	8.09	-23.35	4.759		58	11.38	-16.46	2.178	.2703
2	3.97	-36.23	5.208		31	4.55	-25.4	4.985		59	9.1	-19.44	3.239	.1773
3	1.31	-38.04	5.655		32	1.28	-36.62	5.874		60	5.7	-19.2	3.019	.2041
4	5.19	-35.21	5.208		33	2.73	-31.07	5.605		61	5.44	-18.46	2.55	.281
5	7.29	-32.48	4.77		34	3.29	-33.49	5.642		62	6.85	-26.63	5.246	
6	6.12	-26.51	3.035		35	3.56	-36.75	6		63	6.41	-13.5	1.484	.3176
7	-.86	-43.53	10.378		36	3.58	-27.64	5.244		64	13.1	-18.93	3.379	.158
8	5.61	-13.52	3.625		37	-.29	-30.66	5.36		65	4.93	-15.45	2.023	.2784
9	7.36	-20.02	4.994		38	.06	-33.22	5.823		66	9.76	-15.83	2.23	.2613
10	8.39	-23.7	5.444		39	-2.64	-31.79	5.611		67	6.7	-13.38	1.483	.3188
11	3.84	-22.29	5.23		40	12.15	-12.08	2.141	.3601	68	7.72	-3.41	-8.5	.4897
12	.81	-22.85	5.176		41	10.64	-15.06	3.237	.2496	69	11.3	-9.97	.557	.4048
13	13.45	-8.15	1.301	.3203	42	14.93	-14.78	3.733	.1721	70	8.81	-8.76	.353	.4202
14	10.98	-3.49	-.03	.4474	43	2.3	6.46	7.4		71	10.03	-13.01	1.527	.3146
15	5.07	-6.6	.662	.3996	44	.73	3.4	5.666		72	7.32	-4.5	-.548	.4828
16	3.26	-1.58	-.355	.4668	45	2.52	3.72	5.915		73	5.2	4.76	-3.929	.848
17	2.42	3.24	-1.558	.5637	46	.33	-22.2	6.017		74	10.58	-16	4.989	
18	7.34	-2.78	-.207	.4496	47	1.51	-27.18	4.803	.088	75	.31	21.78	5.992	
19	9.49	-8.49	1.146	.3577	48	1.12	-25.2	4.301	.1261	76	-1.61	-29.55	5.695	
20	14.65	-12.45	2.426	.2305	49	8.21	-29.91	5.811		77	2.25	-34.85	5.481	
21	9.28	-12.32	2.223	.263	50	5.56	-21.64	3.544	.1769	78	7.25	-35.14	5.599	
22	10.29	-17.93	3.539	.172	51	8.98	-20.34	3.181	.2095	79	8.21	-11.74	-.046	.6382
23	8.63	-17.5	3.32	.1857	52	17.24	-25.11	4.618	.0983	80	9.81	-21.64	3.643	.1649
24	8.97	-18.01	3.123	.2269	53	17.85	-23.45	4.331	.111	81	7.95	-9.03	6.121	
25	12.23	-22.25	4.996		54	16.88	-20.83	3.631	.1495	82	10.5	-16.96	3.477	.2059
26	10.26	-16.28	2.989	.1678	55	18.01	-22.88	4.297	.1196	83	11.52	-18.34	3.661	.1837
27	11.2	-14.67	2.495	.2099	56	13.22	-14.34	1.847	.3052	84	10.99	-16.35	2.506	.2305
28	8.48	-19.89	3.637	.1421	57	8.32	-15.12	1.703	.3407	85	8.32	-10.81	4.977	
29	8.56	-16.22	2.514	.2393										