HYDROLEVELING OF VERY DEEP CAVES, WITH AN EXAMPLE FROM VORONJA (KRUBERA) CAVE

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This interesting article on a technique for measuring the depth of a deep cave with high accuracy appeared in Svet (The Light)*, magazine of the Ukrainian Speleological Association, number 29, 2006. It has been revised and rearranged by the editor based on a translation for AMCS from Russian by Tatyana Nemchenko, who also kindly provided some clarifications by e-mail. Authors and translator are Moscovites.*

An expedition to Voronja Cave was held in October 2005. It was organized by the Ukrainian Speleological Association under the leadership of George Kasjan, now president of the association. Cavers from the Russian Geographical Society in Moscow and the Bulgarian Speleological Federation also took part. One of the aims was to measure the depth of the cave by the hydroleveling method. This goal was partly fulfilled. Leveling was done downward and upward between the entrance and 916 meters depth and downward only from –916 meters to –1195 meters, at Camp 1200. The work was done by two people, Alexander Degtjarev and Tatyana Nemchenko of Moscow, supported by Vladimir Solomentzev of Moscow, Fory Kolov of Plevna, Bulgaria, and Svet Stanichev of Sofia, Bulgaria.

Hydroleveling is used in building construction for finding two points with the same height, as in leveling a floor. In the simplest case, a tube with both ends open is used, attached to a strip of wood.

In Russia, measuring the depth of caves by the hydrolevel method began in the beginning of the 1970s. The device was a vinyl-coated fabric tube 30 to 50 meters in length with a manometer with fine scale divisions at one end. Such manometers were 25 centimeters or more in diameter. They were inconvenient and often broken. The water bottle that was used to keep the tube filled overturned, and bubbles appeared in the tube. Nevertheless, the method was used and considered the most accurate method of determining depths at the time. The accuracy was estimated to be about 2 percent. Cavers from the Krasnoyarsk' club used the method in some caves. In Forelnaja, in the Bzybsky Ridge area of the Caucasus, hydroleveling of a narrow passage about 1 kilometer in length gave a level difference that was 5 meters different than the one determined by the conventional method with a clinometer and tape. The depth at the time of Sneznaya Cave in the same area went from 720 to 700 meters when measured by hydroleveling, and Kievskaya Cave in the Zeravsanksij Ridge, Central Asia, went from 1030 to 980 meters deep. Hydroleveling was also used for other purposes, such as water-supply work in expeditions to Central Asia.

The method was revived in 2000, when Eugene Snetkov made a new model of the device in which the bulky and unwieldy manometer was replaced by a diver's depth gauge. Metallic parts of the device were made by Constantin Mukhin. The water-bottle reservoir was replaced by a rubber glove, an idea borrowed from Australian wine-makers, who packaged wine in plastic bags with a cock at the bottom. A buyer could drink from a package that did not leak when upset, and the wine did not oxidize when the container was partly empty. The new model was used for vertical measurements in Mchishta Cave in the Bzybsky Ridge. The length of a river passage from the resurgence sump at the entrance, called a gryphon by Russian cavers, to the terminal sump is about 1.5 kilometers, and the elevation difference is only 20 meters. Gena Somokhin of Ukraine did a hydroleveling in V. Pantjukhina Cave in the same area, and the depth of the cave changed from 1508 to 1488 meters. New interest in the method appeared after discovery of the deepest cave, Voronja, in the Arabica Massif in the Caucasus. There was a lot of interest in the true depth of the cave. In the summer of 2005 Gregory Shapoznikiv and Larice Pozdnykova, both of Ekaterinburg, Russia, hydroleveled the cave to the dry bottom at –2080 meters, according the conventional tape survey. However, the difference between their downward and return levelings was quite large, 8 meters, and errors in the method were discovered. A new hydroleveling was made in the cave in October 2005. The results are discussed in this article. The influence of atmospheric pressure on the readings was discovered, the high accuracy of the method was proved, and the method of measurement by intervals was introduced. Alexis Shelepin and Martha Rushechka, both from Moscow, took part in the development of the method, and Alexis Gurjanov took part in the mathematical justification. The authors could not find any mention of this method in non-Russian publications.

A hydrolevel device is made of a 50-meter transparent tube filled with water, on one end of which a rubber glove is placed, and on the other a metal box with a transparent window. An electronic diver's depth gauge or watch with a depth-gauge function is submerged in the box. The tube is

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coiled or on a reel. If the rubber glove is placed on one station and the box with the depth gauge is placed on a lower one, then the hydrostatic pressure between the two points, according to Pascal's law, depends only on the difference in heights and the liquid density. The route of the tube does not affect the pressure in the box. Adding readings of the gauge from consecutive pairs of stations gives us the depth of the cave in relative units. They are relative because depth gauges are calibrated for sea water, and we fill the hydrolevel with fresh water. Therefore we determine a coefficient to recalculate the measurement in meters. For this purpose a measuring tape is hung on a free drop, with the 0 on the tape and the glove of the hydrolevel at the top point. The gauge reading is taken with the box at several vertical locations, according to the tape, for example, at 5, 10 ,15, 20, and 25 meters. The Casio watch with depth gauge that we used works from 1 to 30 meters sea water. The relative values read are plotted on a graph against the tape values. The points should lie on a straight line, and the parameters k and b, describing the line $h = kx + b$, are determined by mathematical methods. h is the true difference in station heights in meters and x is the reading of the hydrolevel in relative units. The parameter b is not necessarily equal to 0 because of air pressure.

Measuring with the help of a hydrolevel is today the most exact way of determining the depth of a cave. Its correct application allows an average accuracy of 0.2 percent, or 4 meters for a cave depth of 2000 meters. For comparison, geometric measurement with a tape and slope measurement gives an error not less than 2 percent, 40 meters for a 2000-meter-deep cave, hydroleveling with the old manometer method gives about 2 percent, and barometric leveling can give an accuracy of 15 meters, regardless of the depth of the cave, but has a number of methodological difficulties.

Let's consider separately errors that are random and systematic.

Random errors. There is an error due to the discrete scale divisions of the gauge device or calibration tape. Each measured value, on average, differs from a true one by one quarter of the scale division. For the tape, it is 0.25 centimeters, and for the depth gauge used, with a display reading to 0.1 meters, is it 2.5 centimeters. However, there are ways to reduce the reading uncertainty for the depth gauge, as described later.

Frequently, flow of liquid in the tube, expansion of the tube under pressure, and possible slow equilibrium of pressure due to such causes is suggested as sources of errors. This is completely incorrect. Pressure in a liquid is transmitted with the speed of sound in the liquid, in times less than a tenth of a second in our case. Pressure drop in the tube due to flow would only significantly affect the pressure in the box for high speeds. Expansion of the tube under pressure does not influence the hydrostatic pressure reading.

There will also be random error due to placement on the stations, most often a rigging anchor bolt. The gauge of the hydrolevel was placed on the bottom station with an accuracy of about 1 centimeter. The water-reservoir glove was laid on the palm of a hand with the top of the glove aligned on the top station. On average, the position error of the glove was also about 1 centimeter.

It is possible to estimate the error due to these random deviations. Random errors partly cancel according to the formula $R = x$ ÖN, where R is the total expected error in N measurements, each of which differs from the true value by x on average. For example, in our case of 80 stations to a depth of about 1200 meters, errors in placing the device on station of a total of 2 centimeters each time would add up to 2 Ö80 = 18 centimeters. Assuming 160 stations to a depth of 2000 meters, the error from this source would be about 25 centimeters. As noted above, errors due to the discrete scale of the depth gauge will be about the same size, and they will therefore contribute about the same amount to the expected random error, and random errors are expected to add up to no more than half a meter in 160 stations to a depth of 2 kilometers, considerably less than the claimed error of 0.2 percent for the method, or 4 meters at 2000-meter depth.

There could also be random errors in the operation of the depth-gauge sensor itself, due to, for example, inertness (stickiness) or random inaccuracies. We can estimate this only by examining actual results of repeated measurements, that is, closure errors. In our case, as we were attempting to pin down the world depth record, we carried out the measurement from 0 to 916 meters depth twice, both going down through part of the cave and then returning upward through it the same day. Of this depth, 712 meters was measured by the hydrolevel in 46 shots each way. (The

Alexander Degtjarev and Tatyana Nemchenko at the camp at –1200 meters with the hydroleveling equipment. Alexander is holding the depth gauge in its chamber, and the water-reservoir rubber glove is lying on the rock. *Vladimir Solomentzev*.

true vertical drops were taped.) The vertical closure error turned out to be 5 centimeters, which, for a total of 92 measurements, implies by the square root formula an average random error of only 0.8 centimeters. Generally the closure error in a single day's series of measurements was 5 centimeters; it was only once 10 centimeters. The worst day gave an average random error of 4 centimeters, and the typical day gave 1.25 centimeters. Overall, the average vertical measurement was 15 meters, of which the average error of 0.8 centimeters is 0.05 percent. (All the figures in this paragraph are uncalibrated depths, as read directly from the depth gauge. All the data are in Table 1.)

Systematic errors. Such phenomenal reproducibility of the results indicates the absence of significant random errors. But this is only one aspect of the problem. It is possible to have a random closure error of 5 centimeters to the kilometer and still have an error in the true depth of 20, 40, or more meters. There may still be systematic errors due to errors in calibration of the gauge or mistakes in applying the method. These are more sneaky and difficult to detect, and they do not tend to cancel, but are cumulative, reaching perhaps unacceptably great values.

Bubbles in the system will lead to systematic underestimates of the depth. Bubbles are of two sorts, gas and vacuum. The first comes from degassing of the water. It is especially great if chlorinated water is taken from the faucet. Solubility of gasses falls with rise in temperature, so if we fill the tube with cold water and put it in the sun, we will get bubbles in the tube. Fine bubbles stuck to the walls do not influence the reading. But they come off the walls and merge to form large bubbles that fill the cross-section of the tube. A bubble 10 centimeters in length will cause a regular error of 10 centimeters in each measurement. Bubbles should be expelled by flicks of the fingers when the tube is filled. It is best to prepare the tube on the surface, not in the cave, having unwound the tube on a steep slope. During use, the tube, which must be transparent, should be examined visually for bubbles once a day. They usually do not appear after proper initial preparation, especially if the tube is filled with warm, boiled water. Fine bubbles that do appear later migrate quickly to the glove during work on vertical drops. Large bubbles, at least, should be released from the glove, but bubbles in the glove influence the result much less, as the glove is laid horizontally, with little thickness, during the measurement.

Vacuum bubbles are formed if the device is prepared in the wrong order. For example, if the device is filled with water and then the box, at a lower level, is opened, for example to insert the gauge, water from the glove will flow downward, and if the glove is emptied, a vacuum bubble can appear in the tube. Such a device will be impossible to use. Another possible source of vacuum bubbles is a leak in the box under pressure.

The reader should try to understand this example of an actual case. The depth gauge was zeroed in air. The box was opened in a saucepan of water and the gauge was inserted in it, while the tube was run 10 meters above up a slope to its reel. After that, the depth gauge showed 0.0 under 10 meters of water. Why?

The glove can be a source of systematic errors. It should be strong but thin and should at all times be flabby, not full and stretched tight. A stretched glove creates additional pressure, hopelessly spoiling the result. We recommend that the glove be approximately half to one-third full of water, but empty of air. But even a half-filled glove will cause errors if compressed, for example trapped within the reel of tube or bent backward upon itself. We recommend laying the glove out on open palm for each measurement.

The glove must hold enough water that it never becomes empty due to either leaks or expansion of the tube under pressure. A shriveled-up glove can allow an error of up to 10 meters, even without producing a vacuum bubble.

Another source of error could be nonlinearity of the depth gauge. The test values obtained when calibrating the device against a tape should lie on a straight line. It might happen that the device is linear only, for example, from 5 to 20 meters, and that the data above 20 meters depart from a straight line. Such things need to be determined for every specific depth gauge. Plot the points on graph paper. We used a Casio diver's wristwatch with a depth-gauge function. It was good enough and gave a linear response in the range from 2 to 25 meters. At 30 meters it turned off. In the range from 0 to 1 meter it showed 0, and indications were unstable and slow to settle in the range from 1 to 2 meters.

In our project, we used a tape to measure the free drops. We recognized that on such a drop a measurement by the hydrolevel cannot be more accurate than one by the tape against which the level was calibrated, so hydroleveling in those cases was not done. It is difficult to achieve an absolutely vertical position of the tape. The cosine of 1 degree is 0.998, and the cosine of 3 degrees is 0.9986, and these would create an error of only 0.02 or 0.14 percent, more exact than the general accuracy of our method, 0.2 percent. But such errors always have the same sign, always overestimating the depth, and are systematic, so they must be taken into account. In our project, ten tape measurements were a total of 211 meters, 18 percent of the measured depth. In two cases, where the bottom station was displaced horizontally less than 2 meters from true vertical, we measured the hypotenuse of the triangle with the tape and calculated the depth using the Pythagorean Theorem.

Another source of error, either in taping the vertical shots or calibrating the device against the tape, is possible stretching of the tape under its own weight. But a tape gives an error of no more than 1 centimeter on a 25-meter drop, as indicated by comparison with a laser range finder on a free entrance drop. This possible error was not considered further.

An important source of systematic errors is change in atmospheric pressure after the depth gauge is zeroed. During past years, when hydroleveling was carried out by manometers with an elastic spiral, the influence of the atmosphere was not taken into account. That was correct, because the atmosphere pressed on the outside and the inside of the spiral tube equally. In our case the situation is completely different. The depth gauge is reading absolute pressure, the sum of the hydrostatic pressure and the atmospheric pressure. When the Casio watch is functioning as a clock, it continuously zeros the depth gauge for ambient pressure. When it is submerged and functioning as a depth gauge, that calibration is retained. But if the atmospheric pressure subsequently changes, this will inevitably be reflected in the readings. Ordinary daily fluctuations in pressure influence the gauge very little. For example, usual daily fluctuations of 2 millimeters of mercury equal 27 millimeters of water. In practice. over the course of a day, such fluctuations cancel out almost completely.

But major weather fronts or changes in surface temperature can occur. Under such conditions, air pressure can change during a day by 0.2 meters of water. For the control of such phenomena, we advise carrying a barometer with you. Record the air pressure at each calibration of the system, at each zeroing of the depth gauge, and from time to time during the survey. With these readings it will be possible to calculate the barometric offset (parameter *b*) precisely enough.

While major changes in the weather may be rare, loss of zero calibration in the gauge is absolutely inevitable while moving deeper into the cave. The density of air at 1 atmosphere pressure and 0° Celsius is 1.293 kilograms per cubic meter. At the average height of our measurements, 1500 meters, it is 15 percent less. Pressure of the air column from our entrance to our maximum depth of 1200 meters, under a linear approximation and the formula D*P* = *r g h* = 1.293×0.85×9.8×1200 = 12940 Pascals or 1.32 meters of water column. It is possible to add additional corrections for temperature (factor 0.98 for 4° Celsius) and humidity. The total effect is about 1.3 meters.

Practice confirmed these theoretical calculations. Having zeroed the depth gauge at the entrance to the cave, we did not open the box up until the depth of 1200 meters. After having been opened to the air, the gauge showed a stable water depth of 1.2 meters instead of 0, a displacement of 10 centimeters per 100 meters of depth. (At other elevations above sea level and other temperature this value will differ somewhat.) Thus is turns out that the calibration parameter *b* need not be calculated from a calibration, but can be determined from the depth at which the gauge was last zeroed and the approximate depth of the current station. For example, after we zeroed the device at the surface, then for measurement taken at 360

TABLE 1
HYRODLEVELING OF KRUBERA CAVE
by Alexander Degtjarev and Tatyana Nemchenko, October 2005

station	hydrolevel data				atmos. corr.	tape	depth (m)	
	up	down	ave.	scaled			hydro	conven.
entrance to Mozambique								
0-1	18.90	18.85	18.875	18.2903	0.01		19.28	
1-2	12.25	12.30	12.275	12.5451	0.015		31.81	
2-4						24.23	56.04	
4-5	16.15	16.10	16.125	16.4798	0.06		72.46	
5-6	6.50	6.50	6.500	6.6430	0.07		79.03	
6-7	12.80	12.80	12.800	13.0816	0.085		92.03	93
7-8	23.00	22.95	22.975	23.4805	0.1		115.51	
8-9						32.62	148.03	
9-10	29.20	29.20	29.200	29.8424	0.16		177.71	
10-11						3.14	180.85	
11-12	18.50	18.55	18.525	18.9326	0.19		199.60	205
12-13	22.50	22.55	22.525	23.0206	0.21		222.41	226
13-14	3.45	3.50	3.475	3.5515	0.22		225.74	
14-15	17.05	17.10	17.075	17.4507	0.23		242.96	
15-16						23.35	266.31	
16-17	21.15	21.00	21.075	21.5387	0.28		287.57	
17-18						14.10	301.67	
18-19	19.75	19.70	19.725	20.159	0.31		321.52	
19-20	9.60	9.60	9.600	9.8112	0.315		331.01	
20-21	6.75	6.80	6.775	6.9241	0.33		337.61	
21-22	2.70	2.70	2.700	2.7594	0.34		340.02	340
Mozambique to Camp 500								
22-23	9.30	9.30	9.300	9.5046	0.34		349.19	
23-24						33.18	382.37	
24-25	7.05	7.05	7.050	7.2051	0.385		389.19	
25-26						27.37	416.56	
26-27	15.05	15.15	15.100	15.4322	0.42		431.57	
27-28	19.50	19.50	19.500	19.9290	0.44		451.06	
28-29	20.85	20.85	20.850	21.3087	0.46		471.91	
29-30						14.04	485.95	
30-31	3.40	3.40	3.400	3.4748	0.49		488.93	490
Camp 500 to Camp 700								
31-38	12.35	12.35	12.350	12.6217	0.495		501.06	
38-39	20.10	20.10	20.100	20.5422	0.51		521.09	
39-40	14.10	13.95	14.025	14.3336	0.53		534.90	
40-41	1.50	1.55	1.525	1.5586	0.53		535.93	
41-42	10.70	10.75	10.725	10.9610	0.54		546.35	
42-43	6.70	6.70	6.700	6.8474	0.55		552.64	
43-44	22.75	22.75	22.750	23.2505	0.56		575.33	572
44-45	5.25	5.25	5.250	5.3655	0.575		580.12	
45-46	25.00	25.05	25.025	25.5756	0.59		605.11	
46-47	20.75	20.70	20.725	21.1810	0.61		625.68	
47-48						15.24	640.92	
48-49						23.49	664.41	
49-50	27.30	27.30	27.300	27.9006	0.68		691.63	693
Camp 700 to –916 meters								
50-51	21.55	21.55	21.550	22.0241	0.7		712.96	
51-52	15.35	15.35	15.350	15.6877	0.72		727.92	
52-53	19.15	19.10	19.125	19.5458	0.74		746.73	
53-54	26.85	26.85	26.850	27.4407	0.76		773.41	
54-55	23.90	23.90	23.900	24.4258	0.78		797.06	
55-56	21.15	21.15	21.150	21.6153	0.81		817.86	
56-57	18.15	18.10	18.125	18.5238	0.825		835.56	

TABLE 1
continued

station	hydrolevel data				atmos. corr.	tape	depth (m)	
	up	down	ave.	scaled			hydro	conven.
57-58	1.35	1.35	1.350	1.3797	0.825		836.11	827
58-59	16.85	16.85	16.850	17.2207	0.84		852.50	
59-60	19.05	19.10	19.075	19.4947	0.86		871.13	
60-61	5.65	5.65	5.650	5.7743	0.87		876.03	
61-62	21.55	21.55	21.550	22.0241	0.89		897.17	
62-63	19.75	19.75	19.750	20.1845	0.91		916.44	
–916 meters to Camp 1200								
63-64g	6.40		6.400	6.5408	0.92		922.06	
64g-64d	12.25		12.250	12.5195	0.93		933.65	
64d-64c	10.70		10.700	10.9354	0.94		943.65	
64c-64b	7.75		7.750	7.9205	0.95		950.62	
64b-64a	18.15		18.150	18.5493	0.96		968.21	
64-64a	4.75		4.75	4.8545	0.97		972.09	
64-65	5.10		5.100	5.2122	0.97		976.34	
65-66	9.70		9.700	9.9134	0.98		985.27	
66-67	16.20		16.200	16.5564	0.99		1000.83	
67-68	16.10		16.100	16.4542	1.01		1016.28	
68-69	8.95		8.950	9.1469	1.02		1024.41	
69-69a	11.60		11.600	11.8552	1.03		1035.23	
69a-70	6.45		6.450	6.5919	1.04		1040.78	
70-71	6.70		6.700	6.8474	1.04		1046.60	
71-72	15.50		15.500	15.841	1.05		1061.39	
72-73	11.20		11.200	11.4464	1.065		1071.77	
73-74	4.90		4.900	5.0078	1.07		1075.71	1109
74-76*	35.00	35.10	35.050	35.8211	2.17		1109.36	
76-77	24.90		24.900	25.4478	1.12		1133.69	
77-78	23.80		23.800	24.3236	1.14		1156.87	
78-79	23.65		23.650	24.1703	1.17		1179.87	
79-80	15.55		15.550	15.8921	1.19		1194.58	1211

Notes on Table 1.

While time permitted, gauge readings were recorded both going down and then going back up through the area. The two readings were averaged. The scaled value is the average multiplied by the factor $k = 1.0220$.

The atmospheric correction is derived from the reading obtained when the gauge chamber was opened to air at Camp 1200, scaled by the relative depths of the stations.

A tape was used to determine the vertical distance on some strictly vertical drops.

The hydrolevel depth is determined by either adding the taped distance or by adding the scaled hydrolevel average and subtracing the atmospheric correction.

For comparison, depths from the conventional survey are listed for some stations.

*The area between stations 74 and 76 is complex, and the gauge data were taken twice, with different intermediate stations. The two values in the table are the sums of the pairs of measurements. Because the line contains two measurements, the atmospheric correction is double.

meters depth, the correction *b* will be –0.36 meters. Similarly, if we zeroed the device at –500 meters, the correction at –930 meters would be 10cm×(500–930)/100 = –0.43 meters.

Errors caused by not taking this correction into account can be significant. Say that 300 vertical meters are surveyed downward in a day, after zeroing the gauge at the start. The atmospheric correction increases from 0 to 30 centimeters, with an average of 15 centimeters. If there were twenty measurements, then ignoring the correction would lead to an accumulated error of 0.15×20 = 3 meters. If the process is repeated each day for seven days to the bottom of a 2-kilometer-deep cave, the total error would be 20 meters, or 1 percent, five times as high as the accuracy claimed for hydroleveling done correctly. The situation will be even worse if there are long nearly horizontal stretches of cave, so that each measurement gives only a small increase in depth, but still the (now relatively larger) barometric error.

It is possible that omitting the atmospheric correction will cause an opposite error to accumulate on the way back up, if measurements are repeated on the way out after rezeroing the gauge at the bottom, and averaging will cancel out the error to some extent. Where?

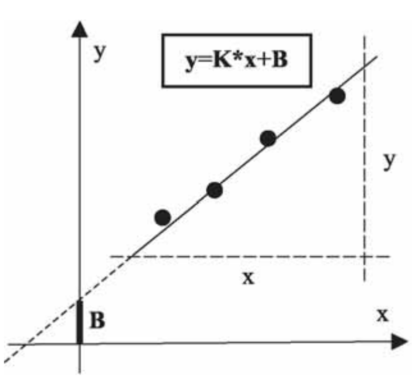
The temperature dependence of the density of water, 0.0053 percent per degree, is insignificant. In Voronja (Krubera), the temperature varies only from 2°C at the entrance to 7.5° at the bottom, and this does not give cause for anxiety. However, the difference from 22° on the surface and cave temperature gives a density change of 0.2 percent, similar to the accuracy claimed for the method, and cannot be ignored. Calibration should be done only after the water in the hydrolevel has cooled to cave temperature.

The calibration coefficient *k* must be accurately determined. This is very important, as it is a source of systematic errors, and different results can be gotten from the same raw data by using different values. For example, the data taken by Gregory Shapoznikiv and Larice Pozdnykova during their hydroleveling were processed four times using different ways of estimating *k*. For Camp 1200, four different depths, ranging from 1160 to 1187 meters, were calculated. From the data in Table 1, taken by Alexander Degtjarev and Tatyana Nemchenko, Degtjarev calculated a depth of 1194 meters for the same place. Such a dispersion of values is inadmissible. It is necessary to choose one proven method of calculation. In fact, calculating *k* and *b* is a matter of choosing an average straight line through test points gotten when calibrating the hydrolevel device against a tape.

One method is graphical. Place the test data on graph paper and draw a straight line over them. The graph may enable you to reject some points as defective. If three test points are on a straight line and the fourth is located to one side, it should not be taken into account in calculating k. Such an approach, however, can sometimes lead to unreasonably rejection of some points, since the rejection is done just by sight. After defective points are rejected and the drawn straight line adjusted to pass through the remaining points, it is possible to calculate k by the formula $k = (y_n-y_1)/(x_n-x_1)$; see the figure. The graphical method is very simple to use, but it is difficult to estimate accurately the position of the straight line and the error in the result. We advise using the graphical method only in field conditions for quality control and to afterward calculate the coefficient *k* mathematically.

If points are not on a straight line, as will certainly be true to some extent, it is possible to calculate a straight line by the least-squares method, that is, calculate the line such that the sum of squares of the distances of the points from the line is the least. The great fault of this method is that we cannot automatically determine which points are simply small random deviations from the line and which should rejected due to poor quality of the reading. Therefore the calculated line can be different in both *k* and *b* from the line calculated from just the good points. [A description, with formulas, of the method for calculating the least-squares linear fit and estimating the confidence limits on the result has been omitted from this version of the article. Interested readers can find it in any elementary statistics book.—ed.]

It is possible to carry out calculations



by Student's criterion. It differs from the previous method in that it mathematically rejects as defective some points, calculates parameters of a straight line, and estimates the accuracy of the resulting *k* and *b* based on the size of the deviations of the remaining points.

The difference in the coefficient *k* calculated by A. Degtjarev by the geometrical method and by Student's criterion was in the third digit after the decimal. That would give a difference in depth at –1194 meters of 0.45 meters.

Opinions differ about how to calculate the correction *b*. One opinion holds that *b* should always be 0. That is obviously incorrect for our method, where changing atmospheric pressure with depth since the device was zeroed affects the reading. Another opinion is that we should use the *b* calculated along with *k* by one of the mathematical methods. We claim that the coefficient *b* must be calculated or measured first, because it is possible to calculate it from the barometric formula or carry a barometer and take accurate readings. Then the coefficient *b* should be fixed in the calculation of *k* by one of the methods such as least-squares.

There is one more essential point in the discussion of the calculation of *k*. The first set of data for Voronja, that of Gregory Shapoznikiv and Larice Pozdnykova, were processed in four different ways, giving values from 0.976 to 1.095. Various reasons why there may be systematic errors were discussed above, but in our opinion their calculated coefficients differed because of incorrect methods of calculations. We welcome comments.

We think the coefficient should not be calculated. It should always be equal to 1.022, at least for the depth gauge we used. Significant deviations from this value point to methodical mistakes in calculations. Degtjarev and Nemchenko, for example, found values of 1.0232, 1.0217, 1.0252, 1.0217, and 1.0184 for five different calibrations against a tape at different depths from 0 to 1165 meters (see Table 2). The average was 1.0220. The average dispersion of values from the average was about 0.2 percent. It is necessary to note that the coefficient 1.0220 applies only to the depth gauge we used. Other models, and perhaps other examples of the same model, might be different. And does the sensitive membrane in the gauge change with time? This question is open. It will be necessary to continue experiments and gather statistics.

Even the most inaccurate use of a hydrolevel will not create a closure error in the raw readings of more than 10 or, rarely, 20 centimeters. If closure errors after corrections for *k* and *b* are 0.8, 1.2, or even 1.5 meters, then there is some systematic mistake in the calculations.

In summary, we recommend the following techniques for calibration:

Graph test points and reject defective points. Calculated values of *k* should be very close.

Take a barometer with you to determine *b* from time to time. (Lacking a sufficiently accurate barometer, we did not do this for the data in Table 1. But the barometer we did have showed that there had been no major changes in air pressure.) The value of *b* should vary by about 10 centimeters per 100 meters depth; this depends somewhat on elevation and temperature.

Test the hydrolevel against a tape occasionally. Repeated measurement should give minimal differences.

What accuracy is needed in *k*? We believe that it should be accurate to one unit in the third digit after the decimal point. An error of .001 will give an error of 2 meters at a depth of 2 kilometers. When we write of an error of 0.2 percent, or 4 meters at 2 kilometers depth, we are allowing 0.5 meters for random errors such as those caused by the coarseness of the readout scale and errors in positioning the device on station and 3 or 3.5 meters of systematic error in the calculation of *k*. So our estimation of *k* should be mistaken by no more than 0.0015. The tests of Degtjarev and Nemchenko in Table 2 give hope that this number has not been exceeded.

In the earlier measurement by Sapozhnikiv and Pozdnykova, the gauge was rezeroed by opening the box before each calibration against a tape. The atmospheric correction did not grow large. But their coefficients from the various calibrations differed significantly and were not useful for averaging. Degtjarev and Nemchenko, on the other hand, did not allow the device to rezero until all measurements had been completed and they were at a depth of 1200 meters. The change in *b* was, not surprisingly, noticeable to the second group. Their calibration values of *k* did not differ significantly, so the average was used to calculate the results in Table 1.

We think the second method is best, without rezeroing the gauge or changing the water during the entire process. In this case, it is probably enough to carry out one calibration, not far from the entrance to the cave, but with the device already at cave temperature. There the correction *b* should not turn out to be significantly different from 0, because if it is, either the calibration has been done incorrectly or there is something wrong with the system. The coefficient *k* is assumed independent of depth, and is checked only at convenient points against a tape. The correction term *b* is taken to be exactly 0 at the surface and increase monotonically, proportionally to the depth from the entrance.

However, it may be that the device has had to be rezeroed, for example to repair a broken water tube. In this case, after mending the device, it must be carefully recalibrated, and it is important that *b* turn out again to be insignificantly different from 0. It should be possible to average the new *k* with the others, but this should be determined from the actual data. (The Casio watch we used as a depth gauge automatically rezeros itself after 30 minutes with continuously less than 1 meter of water pressure.

TABLE 2

	test data			calculation 1		calculation 2		calculation 3	
	gauge	tape interval		k	b	k	b	k	b
TEST 1	5.0	4.98	5.03	1.0232	0.	1.0248	-0.02	1.0248	0.
depth 30 to 57 m	7.3	7.50	7.60						
stations 2 to 4	9.8	9.97	10.05						
	13.5*	13.95	14.05						
	14.65	14.80	14.90						
	23.7*	24.20	24.30						
TEST 2	5.3*	5.00	5.09	1.0217	-0.36	1.0209	-0.38	1.0204	-0.36
depth 350 to 380 m	10.2	9.98	10.08						
stations 23 to 24	15.1	15.00	15.10						
	20.0	19.95	20.05						
	24.8*	24.92	25.02						
TEST 3	5.6*	4.93	5.03	1.0252	-0.67	1.0263	-0.80	1.0209	-0.67
depth 665 to 692 m	10.6	9.97	10.07						
stations 49 to 50	15.4	14.95	15.05						
daytime	20.3*	19.92	20.10						
TEST 4	5.6*	4.91	5.00	1.0217	-0.67	1.0228	-0.79	1.0157	-0.67
depth 665 to 692 m	10.6	9.96	10.08						
stations 49 to 50	15.4	14.92	15.03						
nighttime	20.3*	19.92	20.03						
TEST 5	6.0*	4.99	5.09	1.0184	-1.15	1.0184	-1.09	1.0258	-1.15
depth 1133 to 1157 m	10.9	9.93	10.03						
stations 77 to 78	15.8*	14.97	15.07						
	17.6**	16.95	17.05						

Notes on Table 2.

The tape interval is the range of distances on the tape over which the gauge gave the indicated reading. The average of the two values was used in all subsequent calculations.

Calculation 1 is from the original paper. These are the numbers cited in the text. The factor *k* was calculated by the graphical method: The points were plotted, two of them (the ones indicated with an asterisk) were selected as typical, and the slope of the line between those two points was calculated. The offset *b* (barometric correction) was not obtained from the test data, but was calculated from the approximate depth of the test. It is the same as the *b* used in Table 1. The average *k* is the 1.0220 used in Table 1.

Calculation 2 is the least-squares linear fit to the test data. Both *k* and *b* are calculated. The average *k* is 1.0226. If the *b* values are taken seriously, a systematic error of about 10 centimeters per station might have occurred in using the data for the day of tests 3 and 4.

Calculation 3 is the least-squares fit for *k*, assuming that the intercept *b* is the same as that under calculation 1. This was done by adding the given *b* to each gauge reading and then doing a fit with no constant term, forcing the line to pass through the origin. The average *k* is 1.0215.

Calculations 2 and 3 are by the AMCS editor.

** This line declared erroneous by the authors. It was not used in any of the calculations.

During the entire process, it is necessary to keep this from happening. This is most likely to be a problem during breaks or overnight, when the glove should be hung up at least 1.5 meters above the box.)

If data from several tests are available, it is possible to use statistical techniques to estimate how accurately *k* has been determined, based on the scatter of the values. For example, from our data in Table 2, we see that the values are 1.0232, 1.0217, 1.0252, 1.0217, and 1.0184, with an average of 1.0220 and a root-mean-square deviation of 0.0024. While the sample is limited in size, we can estimate that with probability 95 percent the true value of *k* is in the range 1.0220 ± 0.0030. This translates to an error from this source of ± 3 meters at Camp 1200. Adding estimated random errors of 0.4 meters, we get that the depth of Camp 1200 is, with 95 percent probability, 1194.6 ± 3.3 meters. [This statement depends critically on the authors' treatment of the atmospheric correction being appropriate. Not having great confidence in the graphical method, I have also added two methods, varieties of least-squares, to Table 2. My *k*s exhibit a bit more scatter, but the averages do not differ from the authors' by more than 0.06 percent.—AMCS ed.]

Measurement by intervals. The display on the depth gauge gives us discrete numbers such as 1.2 or 24.7. The accuracy of each measurement seems to be half a division, or 5 centimeters. It is actually possible to winkle out of the device much more. The number, say 1.2, on the display actually stands for some interval, such as 1.15 to 1.25. When Degtjarev put the hydrolevel on a station, usually an anchor bolt, he waited for the reading to settle down, and slowly moved the depth gauge upward and downward, looking for where a change in readout occurred. If the reading on the station was 15.7 and it jumped to 15.6 only 2 centimeters higher, he recorded 15.65. But if the reading stayed 15.7 more than 2 centimeters above the station, he recorded 15.7. Thus he reduced the average error in reading by a factor of 2, to 2.5 centimeters.

If the measurements are made twice, as in much of the data in Table 1, the same effect could be gotten by deliberately displacing the box, alternately by plus or minus 5 centimeters, from the stations during the second pass. The averages will reflect the reduced error.

But this is not the limit yet. The real sensitivity of the Casio depth gauge is about 1 to 1.5 centimeters, instead of the 10 that the display shows. Remember that sensitivity is the ability to respond to small changes, whereas the accuracy is the deviation of the displayed value from the true one. A device can be very sensitive, but have low accuracy, either because of limits in reading it or because it needs to be adjusted. The Casio gauge is an example of an inaccurate (or, rather, imprecise) but sensitive device. The result displayed is coarsened artificially by a factor of 10. First, divers don't need to know depth to within a centimeter. And the salinity of the Baltic Sea differs from the salinity of the Pacific Ocean by 30 ppm, so accuracy in the second digit after the decimal point is senseless; without knowing the exact salinity, it means nothing.

When Degtjarev did the test calibrations against a tape shown in Table 2, he recorded the interval on the tape where the device gave a particular reading. For example, the device might show 5.3 at exactly 5.0 on the tape. If it jumped to 5.4 at 5.07 on the tape and 5.2 at 4.97, the interval 4.97 to 5.07 was recorded, and the mid-point 5.02 of that interval was taken to be the point on the tape that really corresponded to a gauge reading of 5.3. This gave an accuracy of reading 5 times greater than that of the numbers on the display. There is no need to make this high-accuracy measurement at every station, as the expected random error is low enough without it. But for calibration and the calculation of *k* and *b*, it is extremely necessary.

It must be noted that the stated sensitivity is characteristic of the particular model of Casio dive watch. For other depth gauges, it might be lower. The sensitivity needs to be determined for each particular case. An insensitive device may make it impossible to attain the desired accuracy, such as 0.2 percent. For example, we tried to use an expensive Swiss depth gauge and totally came to grief. It appeared to have very low sensitivity.

We conclude with some advice and observations that have not been covered already.

Do not use medical IV tubes, but use tougher tubes with an internal diameter of 4 to 5 millimeters. Use transparent tubes, so bubbles can be seen.

The plastic reel for the hose was broken by rocks, and it took seven minutes to reel in 50 meters of tube. Alexander Degtjarev and Tatyana Nemchenko refused to make use of the reel after some practice in the cave. They kept the hose in two loose coils. One, 20 meters, was seldom unwound. The other, 30 meters, was uncoiled and recoiled by one or the other of them, depending on the situation.

Speed of measuring is slow. Degtjarev and Nemchenko could not do more than 300 vertical meters, up and down, in twelve hours. It was very difficult to locate the stations. They should be marked by strips of colored material with large, clear numbers.

The tape for calibrations or measuring free drops must be long. Twenty meters is not enough; use at least 30 or better 50 meters.

Beyond 15 meters, understanding the partner is difficult. Use a few standard, easily understood commands ("ready," "understood," etc.) or whistle equivalents. Write data clearly, on suitable paper.