

Issue 38



# COMPASS POINTS

July 2007



BCRA



**Hydrolevelling of very deep caves**

**Bosch laser range finder review**

**Hand-held GIS for cavers**

## COMPASS POINTS INFORMATION

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courtesy of Doug Dotson, Speleotechnologies.

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  - Hydrolevelling is a method for measuring cave depths that can potentially give very high accuracy. This article discusses the calibration procedure and experimental techniques that are required to minimise errors and thus obtain the best possible results.

*Cover image: Using a hydrolevelling device in Voronja (Krubera) cave. Left: Tatyana Nemchenko holding the glove reservoir on the higher station. Right: Alexander Degtjarev reading the depth gauge at the lower station to obtain the apparent relative depth change between the two stations. [Photos: Alexander Degtjarev (left) and Tatyana Nemchenko (right)]*

## Editorial

Issue 37 was largely devoted to projects to design and build electronic compasses and clinometers. This theme is continued in this issue with articles about a hand-held GIS system for caves and a review of a laser range finder. Luc Le Blanc has also offered to support various electronic instruments in his Auriga software for PDAs running PalmOS. As he states, such integration is a natural progression after switching to electronic instruments. Maybe in the not-too-distant future we will all be heading underground armed with PDAs containing a database of everything we could wish to know about the cave, hooked up to our electronic instruments such that the line survey practically draws itself?

### Hidden Earth 2007

The UK's national caving conference and exhibition – Hidden Earth – will take place on 21-23 September at Tewkesbury school, Gloucestershire. Full details can be found on the conference website at <http://www.hidden-earth.org.uk/>. BCRA's Arthur Butcher award for excellence in cave surveying will be presented at the conference. All work displayed at the conference will automatically be considered for the award. If you will not be present and wish to nominate someone for the award, you should contact the conference manager in advance. Full details of the rules and nomination procedure can be found on the Hidden Earth website.

As developer of the Auriga cave survey freeware (<http://www.speleo.qc.ca/Auriga>), I would like to mention that I would be more than happy to implement support for additional electronic survey instruments in Auriga such as those featured in issue 37 of Compass Points. I have already done so for France's Toposcan/Easytopo, the Leica Disto and the TNT Revolution module. It is only a matter of agreeing on a simple serial and/or Bluetooth data protocol (such as NMEA) before an affordable PalmOS device can be used as a display interface or a storage device for the acquired data. Going digital all the way is only a natural evolution after switching to electronic instruments.

Version 1.05 of Auriga was released last March 29. It enhances the sketching aids by offering a zoom to scale feature that provides a scaled screen representation of the line plot as it should appear on the sketching paper (i.e. a mm on screen corresponds to a mm on paper). This feature takes into account the current sketching scale as well as the dot pitch of the specific PalmOS device.

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## A hand-held GIS for navigation in caving

Emma White

*This article concerns a project to develop a Geographic Information System (GIS) tailored for cave information that can be used on a hand-held device. Cave entrance locations can be shown on a base map, and the system integrated with a GPS receiver to aid navigation to the entrances. Information about each cave, such as entrance photographs, passage descriptions and equipment requirements, can be stored in a database and retrieved by selecting the appropriate entrance. Such a device could be used as a replacement for a guide book in well established caving areas, or as a prospecting aid.*

### Introduction

Today PDAs (Personal Digital Assistants) are getting smaller and more rugged and so can be adapted for use down most caves. This study examines the possibilities of their use as a navigation tool as well as a possible trip planning tool. The basis of the project is to integrate a Global Positioning System (GPS) receiver with a Geographic Information System (GIS) that allows information about caves, such as passage descriptions and equipment requirements, to be stored and displayed on a map. Although its purpose as a navigation tool inside the actual caves will be limited (as GPS does not work underground) the route to the cave entrances can be examined. This system was designed in order to replace the guide book down caves, but it could have possible uses as a prospecting tool in less well established caving areas.

It was important to choose an area in which many caves were located, and due to this the Ease Gill cave system was chosen. It was also decided that, due to the amount of work involved, only a set few entrances would be recorded; however more could be added later as an option to add new cave entrances to the map would be provided.

### GPS and GIS

The GPS was considered to play a key role in the development of this system: in order to enhance the capabilities of a standalone map the integration of GIS and GPS is important. A GPS device would be able to provide the user with real-time positioning on a detailed GIS map without the need to translate between mediums.

Today GPS systems are much more precise with the development of 3D positioning (the use of additional height information as opposed to 2D GPS where only Eastings and Northings parameters are used) as well as DGPS (Differential Global Positioning System). In many

cases the relative accuracy of a simple hand-held Garmin Etrex was found to be within 20m in the study area which is more than sufficient to find the entrance of a cave. It was also decided to include photographs of the cave entrances to make cave location even easier for the user.

The purpose of the GIS system is to provide the user with a detailed map which can be edited to suit the user's needs from simple pan and zoom to more complex functions. For example, different types of information could be stored on different layers, with the user given the choice of which layers should be displayed. Also, information connected to individual objects could be displayed on request. Large volumes of data (maps) can also be stored on relatively small devices using a GIS.

### Hardware and software

There are many hardware and software options available on the market today for developing an integrated GPS and GIS system. These range from the simple hand-held GPS unit to a more complex Pocket PC design. Due to the harsh environment that the device would be used in larger devices such as laptops were deemed to be unsuitable for the job even though the hardware capabilities were sufficient to handle large datasets and complex functions.

Hand-held GPS devices such as the Garmin Etrex are a relatively cheap option and simple maps can be uploaded onto them. Cave entrances and routes could also be added using the track logs and waypoints system. However this system is not able to handle more complex functions such as text files, detailed maps, photographs and simple databases.



An Ipaq PDA with a GPS attachment could be a viable option as they are able to handle more complex functions and they can support many different file types as well as being able to handle large datasets.

There are various software options available, most of which are associated with some kind of licensing and would incur some cost for any potential user. The DNR Garmin extension for the ArcView software offers a link-up between the hand-held GPS device and the GIS modelling software. The Garmin GPS uses a proprietary data format for internal maps so the software enables point features to be uploaded to the GPS device as Waypoints and the Shape Files as Tracklogs. Simple textual information such as the names of the caves for example can also be uploaded. This system is however too simple and any additional information could not be used.

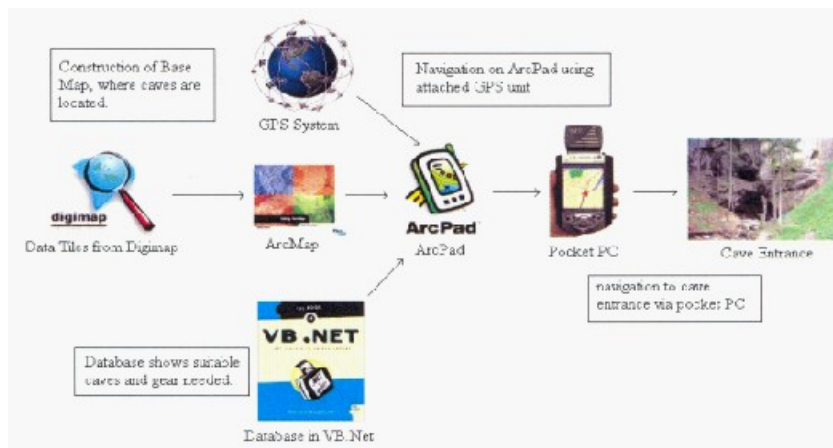
The ArcPad software in conjunction with Esri's ArcGIS range is able to capture analyse and display information on a compatible PDA. It is able to provide support to various industry-standard vector and raster image display as well as various other image formats such as JPEG and Windows Bit Map. This is a distinct advantage as it allows photographs of the cave entrances as well as potential aerial imagery of the area to be used. Automatic integration with GPS data is also provided and the user is able to choose between the options of using 2-dimensional, 3-dimensional or DGPS as well as having the advantage of on-the-fly datum conversions where the input GPS data is automatically converted to the datum of the projected map. Map navigation tools such as pan, zoom and spatial book marking is also provided.

In order to incorporate a trip planning tool into the system it was decided that a database of caves was to be created. This was done using VB.Net as it is a simple easy to use object oriented programme.

For the purpose of this study an Ipaq with a GPS attachment was therefore deemed most suitable. This was ruggedised using an Otterbox. The ArcPad software option was also chosen as it was able to offer GIS functionality of an increased complexity compared to much of the other available software. Figure 1 demonstrates the procedures involved in bringing the whole system together from where the data is obtained to how it is integrated into the system.

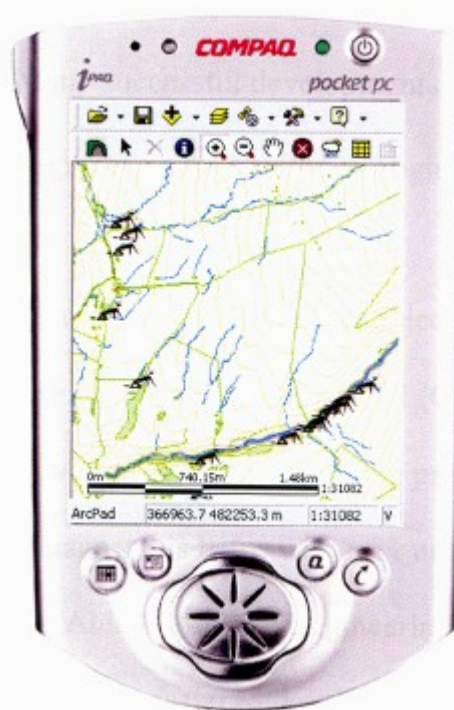
## The map

The map of the area was downloaded from Digimap and split into layers (different features) to make viewing a lot easier; this included layers for features such as contours, rivers and boundary data. It was also hoped I would be able to add a layer which showed the survey data for the actual cave system but due the unavailability of proper data this was not possible in the end. (As GPS obviously won't work underground it would have been useful to have the survey data so cavers could navigate underground themselves just by simply reading the survey). This was then first displayed on ArcMap.



**Figure 1: The system.**

(This is a desktop version of ArcPad, from where more complex editing functions can be performed). From this, downloading the maps of the area onto the Ipaq was pretty simple. The layers were simply transferred onto ArcPad so they could be displayed and then the data was downloaded onto the Ipaq. Figure 2 shows the map displayed on ArcPad. The symbols of the cavers represent the cave entrances.



**Figure 2: The map displayed on the pocket PC.**

## The trip planning tool

A trip planning tool was created on VB.Net, a simple object oriented programming language. The purpose of this tool was to help a party in planning the trips that they would like to do as well as giving rope lengths and an estimated duration for the trip for any given cave included within the study. Figure 3 shows the tool. Inputs such as the number in the party and the number of riggers are input first, error messages appear if the number in the party is less than three or if there are more riggers than members of the party. The preferred grade and whether or not SRT is involved are then entered and the suggested caves appear as a list. When one is selected the details of that particular cave are then displayed in the "Output" box.

Alternatively the user could search by the cave name. Any warnings associated with the cave (as from Northern Caves 3) are also displayed in the "Extras" box.

## Adding cave entrances

In order to be able to insert cave entrances an ArcPad applet was used. Ready-made applications can be downloaded for free from the Esri website and the ArcPad XML and associated VBScript file can be edited manually in a simple text editor to suit your own application. In my case a programme for logging trees was edited so it logged caves instead. This application also allows you to add your own menu icons on ArcPad and buttons to add new cave entrances, select existing cave entrances, a trip planner tool and a link to the Met. Office website were added.

**Figure 3: The trip planning tool.**

On adding new cave entrances the entrance photos as well as descriptions of the caves are entered. These can be then retrieved later when the user clicks on the cave entrance symbol which had been added as a new layer of the map. This could also be edited so other JPEG files could also be displayed, such as any rigging guides for the caves.

Figure 4 shows the various tabs available when the user clicks on a certain cave entrance symbol. When the user adds a new cave information is inserted into the tabs and saved. This appears in a “read only” format when the entrance is clicked on for a second time.

Code was added to the VBScript file to bring up the Met. Office web page for the area (provided the device is fitted with an internet connection) when the user clicked on the “Weather” button. Likewise code was added for the “Trip Planner” button so the trip planner tool was displayed.

## Testing

The device was put through a variety of testing procedures, from testing to see if the actual code worked to testing the device in the field. When testing the device in the field it was decided just to test its use as a navigational tool outside the caves as there would be various liability issues if the device became damaged when testing it inside the caves. The device was used to plan a trip and it was suggested that it would probably have been useful to include the amount of maillons needed, but in all it managed to hold up. It was then used to navigate to some cave entrances and this was done with great success. New cave entrances were then logged onto the device and the users were able to navigate back to them again. It would have been useful to test it properly underground as it would need to rival the use of a hand-held GPS and a guidebook if it was to be of any use.

## Conclusion

Using the tools created on the ArcPad application the user can now plan a trip (view the amount of gear needed and the estimated duration of the trip) and navigate to the cave entrance using the GPS attached on to the Ipaq and the cave entrance photographs. Once inside the cave the written guides and possible survey data could be used for navigation. In using an Ipaq large amounts of information can be stored on a relatively small device eliminating the need to carry down large amounts of surveys and guide books on a given trip. There are also still some problems however as to whether the device will actually stand up to the rigours of the average caving trip as well as if the batteries will actually hold out, but as hand-held devices become cheaper, smaller, more durable and more advanced their uses can be extended into a wider range of applications and situations.

## Acknowledgements

This article is based on the dissertation “Handheld GIS for Route Planning and Navigation in Caving” presented for the degree BSc. Hons. GIS at the University of Newcastle upon Tyne, May 2006.

**Figure 4: The cave entrance log forms.**

# Bosch DLE 50 Laser Range Finder

Ben Cooper

*Laser rangefinders have dropped in price over the last few years, with the classic Disto now retailing at under £300. This is still, however, a significant investment for most of us. But over the last year Disto, Stanley and Bosch have all launched “consumer” models at the £100 price point. In this article, Ben Cooper reviews the use of the Bosch DLE50 in surveying the new discoveries in Mendip’s Upper Flood Swallet.*

Bosch offers two models in its “professional” tool range, the DLE50 that retails for £115[1] (Figure 1), and the DLE150 that retails for about £270 (prices checked as of May 2007). The primary difference is the measurement range: the DLE50 can measure distances of up to 50m, while the DLE150 can, you guessed it, measure up to 150m. This compares with Leica’s Disto A2 (£115), A3 (£185) and A5 (£275) models at 60m, 100m and 200m respectively. But for most domestic users and cave surveyors, 50m is more than adequate. Indeed, the typical cave survey tape measure is rarely longer than 30m (100ft).

I had never used a laser rangefinder before, but I intuitively felt that the use of a laser beam had to be better than dragging the end of a tape through awkward passages. Furthermore, the stated accuracy of the DLE50 is  $\pm 1.5\text{mm}$  (see below), which has to be significantly better than a sagging tape measure stretched at unknown tension. The unit is small, compact, lightweight and rated at IP54 (dust and splash water protected). (By comparison the Disto A3 is also IP54, but the A2 is not IP rated.) It runs off four AAA batteries (Figure 2), and its stated life is 30,000 measurements. In other words, it met all of the criteria to make it a viable cave surveyor’s tool.

I was not disappointed when the unit arrived. It is very compact and light, is easy to use above ground, and has some fun features, such as area, volume and height measurement. The unit has four measurement modes, i.e. from the front of the unit; from the back; from a recessed tripod mount on its underside; and from the end of a handy probe that flips out of the unit at the back to reach into awkward corners. However, it was obvious from the start that some of the features might not be quite so convenient underground. The unit’s IP54 rating excludes the battery compartment. The flip-out probe is fragile, and the recess for this and for the tripod screw are vulnerable to clogging with mud. There are two lenses on the front that are obviously in danger from mud and scratches, although these are cleverly recessed which I found afforded them a remarkable level of protection.

My first approach to these problems was to enclose the entire unit in a clear plastic bag, bound tightly around it using insulation tape. Surprisingly, the laser measurement seemed to work as accurately through a plastic bag as through air, and thinking I had it cracked, I set off underground.

Initially the unit worked fine, but muddy water found its way onto the plastic bag over the lens, and the unit failed to measure. Risking it all, I tore the bag from over the lens and as I continued found to my surprise that the recessed lens stayed mud-free compared to the not-recessed plastic bag that I had been forced to remove. However, muddy water then found its way inside the torn plastic bag, obscuring the LCD screen and making reading the display very hard. But overall the unit showed promise, and use of the laser beam had indeed exceeded my expectations compared to a tape measure.

For my next trip, I cut-up a plastic bag to make a window for the controls and LCD screen, and then sealed this onto the unit with insulation tape, and used more tape to seal around the battery compartment and other annoying holes. This works – the LCD is protected from dirt scratches, dirt can be wiped off, the LCD remains visible, and the battery compartment remains dry. This covering is not intended to provide full immersion waterproofing, simply to protect the unit from wet and muddy hands. The laser lens remains exposed, though with only a little care I find this can be kept completely mud-free. This is helped by keeping the unit in a moderately-sized Peli case when moving from station to station, only removing it to take readings. The insulation tape is of course time-consuming to remove and re-apply, but this only needs to be done to change the batteries (or dry the unit if moisture has penetrated the covering). In truth, tape is really only needed to seal the battery compartment, and I imagine once the unit is a little older and more beaten up, I will be less fussy about keeping it clean!



Figure 1: Front view of the Bosch DLE 50, showing its dimensions.

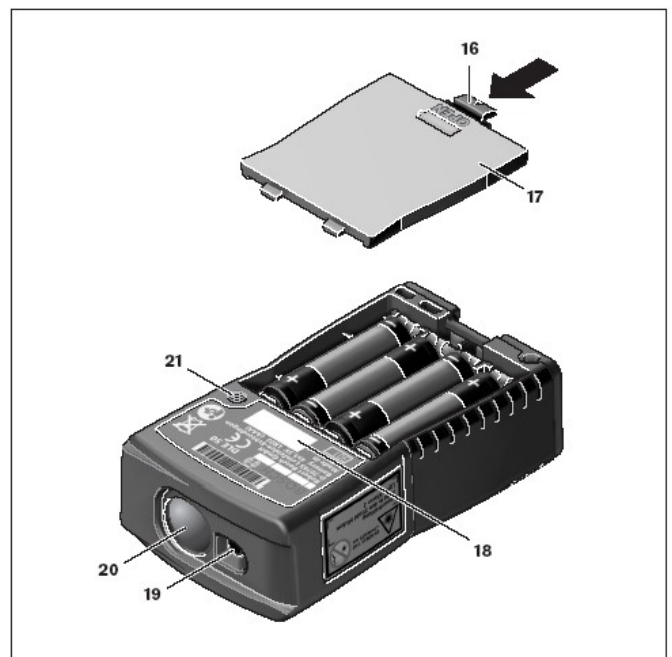


Figure 2: Back view of the Bosch DLE 50.

Battery life is supposed to be very good (30,000 readings), but on my second trip, after only about 500 measurements, the battery warning lit, and readings started to take a very long time. (It takes typically less than 1 second from the time the button is pressed for the unit to make a measurement, but this can rise to 4 seconds for low battery conditions or unfavourable reflectance, etc.) I managed to complete the survey, but when back above ground I found the batteries had recovered. I suspect that the lower temperature underground (11 °C) was enough to weaken the alkaline batteries sufficiently to affect the unit's performance. Nevertheless, I didn't want to risk battery failure underground so changed the batteries ready for my next trip.

There were some difficulties using the laser rangefinder, which will be common to all makes. I wear glasses, but underground these get muddy and steamed up, and worse, the small screws by the nose pads affect compass readings. I now wear contact lenses underground, but these only partially correct my eyesight. It's better than with steamed up glasses, but it does mean that for survey stations more than about 8m away, I struggle to see the target clearly. This is not a problem for sighting the compass, as the angular resolution of my eyesight is better than the 0.2° or so precision needed for the compass. However, the laser beam needs to accurately hit the target. A target at 30m distance with a diameter of 5cm requires a pointing accuracy of 0.1°, and that needs sharp eyesight. Similarly, the slightest hand-shake is amplified over such distances. I quickly learnt to steady the laser rangefinder against the rock, but unless the unit was actually resting on a boulder, some hand-shake was inevitable. Furthermore, to activate the measurement, the large red button needs to be pushed. Even though I generally kept my thumb over the button, I often found that while concentrating on the target, my thumb had moved so that when I pressed, either nothing happened at all, or more annoying, I pushed one of the other closely-situated buttons. Also, a surprising amount of effort is required to push the button. This is not noticeable above ground, but when standing awkwardly, the slightest movement translates to movement of the laser beam off target. These problems were all solved with practice and team-work. I now ask the station "spotter" to hold a flat target (such as the back of his hand) at the station, and guide me verbally about whether or not the beam is on target. In fact the plastic cover of my survey notebook acts as a good target, and professional laser surveying targets can also be purchased. I also take two readings (except for very short legs). If both readings are within about 1cm, I mentally average the two and call the result out to the "recorder", to 1cm precision; otherwise I keep taking measurements until I get consistency. A word of caution: laser light must not be shone into the eyes, and this is a real risk for the station spotter, particularly at the longer distances and when working at head-height stations. I quickly learnt to keep the laser beam pointing safely at the walls, floor or ceiling, especially when I was shuffling about to get into a more comfortable position and not particularly concentrating on my friends in the distance!

The benefits of laser range finding are as follows.

1. Unlike a tape measure, the laser beam does not have to be dragged across the passage, making progress through the cave much faster. While of marginal benefit in large walking passage, this is invaluable in tight passages or exposed traverses and climbs.
2. The laser beam is a useful pointer, enabling the surveyor to point at candidate stations in the distance for colleagues to "mark" (I used a compact red LED bicycle light as a station marker, providing obvious benefits over the traditional white cap-lamp which can be confused with other helmet lights in the vicinity).
3. It is very quick to measure Left-Right-Up-Down (LRUD) station data, especially as LRUD measurements by tape always conflict with the need to drag the end of the tape measure to the next station (or require two tapes).

4. Enables accurate "Up" measurements. In fact, estimating ceiling height and then measuring it with the laser became a fun and competitive game during our survey! (We decided to only record LRUD to 10cm precision, especially as there is some debate about whether to record passage dimensions exactly at the station position, or as perceived by the cavers, which typically corresponds to the maximal width and height).
5. It eliminates uncertainty about sagging tape and tape tension, although this is partially offset at larger distances by the difficulty of accurately aiming the laser beam.
6. The DLE50 in particular is compact, moderately easy to use and moderately cave-proof.

#### Notes

[1] Online from CPC Farnell. I can currently source the Bosch DLE50 for £105. Please contact me for details at [ben@caver.plus.com](mailto:ben@caver.plus.com)

## DLE 50 Specifications

Measuring range (A) 0.05 - 50 m

Measuring accuracy

- typical  $\pm 1.5$  mm
- maximum 3 mm (B)

Measuring duration

- typical <0.5 s
- Maximum 4 s

Lowest indication unit 1 mm (precision)

Operating temperature -10 °C - +50 °C

Storage temperature -20 °C - +70 °C

Relative air humidity, max. 90%

Laser class 2

Laser type 635 nm, <1 mW

Laser beam diameter (at 25 °C), approx.

- at 10 m distance 6 mm
- at 50 m distance 30 mm

Batteries 4 x 1.5 VLR03 (AAA)

Rechargeable batteries 4 x 1.2 VKR03 (AAA)

Battery service life, approx. 30000 individual measurements

Automatic switch-off after approx.

- Laser 20 s
- Measuring tool (without measurement) 5 min

Weight according to EPTA-Procedure 01/2003 0.18 kg

Protection class (excluding battery compartment) IP 54 (dust and splash water protected)

Specification notes:

(A) The working range increases depending on how well the laser light is reflected from the surface of the target (scattered, not reflective) and with increased brightness of the laser point to the ambient light intensity (interior spaces, twilight). In unfavourable conditions (e.g. when measuring outdoors at intense sunlight), it may be necessary to use the target plate.

(B) +0.1 mm/m at unfavourable conditions, e.g. at intense sunlight



# Obtaining accurate cave depths by hydrolevelling

Alexander Degtjarev, Eugene Snetkov and Alexey Gurjanov

*Hydrolevelling is an alternative to measuring depth with clinometer and tape that has a long history of use in Russia. The method is potentially very accurate – 0.2% is claimed – but in order to achieve this, great care must be taken with calibration and to minimise errors during use. The history of the method and details of the equipment used during a survey of Krubera/Voronja were recently described in Speleology [1]. This article provides a more in-depth treatment of the techniques used during that survey to obtain high accuracy.*

## Introduction

Hydrolevelling is used in building construction for finding two points with the same height, as in levelling 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 hydrolevelling method began in the beginning of the 1970s, and was considered to be the most accurate means of measuring depth despite the difficulties in using the cumbersome equipment of the time. Interest in the method has been revived following the discovery of Voronja on the Arabica Massif in the Caucasus – currently the world's deepest cave.

The hydrolevel device used in recent Voronja expeditions comprises a 50m transparent tube filled with water, which is coiled or placed on a reel. A rubber glove which acts as a reservoir is placed on one end of the tube, and a metal box with a transparent window is placed on the other. A Casio diver's wristwatch with a depth gauge function is submerged in the box. 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 depends only on the difference in heights and the density of the water, i.e. the route of the tube does not affect the pressure in the box. Reading the depth gauge gives the apparent depth change between the higher and lower station (see the cover of this issue for an example of the device in action). Depth changes are "apparent" because depth gauges are calibrated for sea water, and we fill the hydrolevel with fresh water. Therefore we determine a coefficient to convert apparent depth changes to true depth changes. Adding the readings for consecutive pairs of stations gives the total depth of the cave.

In order to obtain the calibration coefficients, 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. Details of the recommended calibration procedure are provided later in this article.

Measuring with the help of a hydrolevel is today the most precise way of determining the depth of a cave. Its correct application allows an accuracy of 0.2% to be achieved, which corresponds to 4m for a cave depth of 2000m. For comparison, geometric measurement with a tape and slope measurement typically gives an error not less than 2% (or 40m for a 2000m-deep cave). However, in order to achieve this accuracy, the hydrolevel must be properly calibrated and care must be taken to avoid errors. These issues are the subject of this article.

## 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 0.25cm, and for the depth gauge used, with a display graduated in intervals of 0.1m, it is 2.5cm. However, there are ways to reduce the reading uncertainty for the depth gauge, as described later.

Flow of liquid in the tube, expansion of the tube under pressure, and possible slow equilibrium of pressure due to such effects are often 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 a 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 1cm. 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 1cm.

It is possible to estimate the error due to these random deviations. Random errors partly cancel according to the formula  $R = x\sqrt{N}$ , 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 1200m, errors in placing the device on station of a total of 2cm each time would add up to  $2\sqrt{80} = 18\text{cm}$ . Assuming 160 stations to a depth of 2000 meters, the error from this source would be about 25cm. 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. Thus random errors are expected to add up to no more than half a meter in 160 stations to a depth of 2km – considerably less than the claimed error of 0.2% for the method, or 4m at 2000m 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 916m depth twice, both going down through part of the cave and then returning upward through it the same day. Of this depth, 712m was measured by the hydrolevel in 46 shots each way. (The true vertical drops were taped.) The vertical closure error turned out to be 5cm, which, for a total of 92 measurements, implies by the square root formula an average random error of only 0.8cm. Generally the closure error in a single day's series of measurements was 5cm; it was only once 10cm. The worst day gave an average random error of 4cm, and the typical day gave 1.25cm. Overall, the average vertical measurement was 15m, of which the average error of 0.8cm is 0.05%. (All the figures in this paragraph are uncalibrated depths, as read directly from the depth gauge. All the data are in Table 1.)



Hydrolevelling data					Atmos	Depth (m)			44-45	5.25	5.25	5.25	5.37	0.58	580.12			
Station	Up	Dn.	Avg.	Scaled	corr.	Tape	Hydro.	Conven	45-46	25.00	25.05	25.03	25.58	0.59	605.11			
Entrance to Mozambique																		
									46-47	20.75	20.70	20.73	21.18	0.61	625.68			
									47-48						15.24	640.92		
									48-49						23.49	664.41		
									49-50	27.30	27.30	27.30	27.90	0.68		691.63		
									Camp 700 to -916m									693
									50-51	21.55	21.55	21.55	22.02	0.70		712.96		
									51-52	15.35	15.35	15.35	15.69	0.72		727.92		
									52-53	19.15	19.10	19.13	19.55	0.74		746.73		
									53-54	26.85	26.85	26.85	27.44	0.76		773.41		
									54-55	23.90	23.90	23.90	24.43	0.78		797.06		
									55-56	21.15	21.15	21.15	21.62	0.81		817.86		
									56-57	18.15	18.10	18.13	18.52	0.83		835.56		
									57-58	1.35	1.35	1.35	1.38	0.83		836.11		
									58-59	16.85	16.85	16.85	17.22	0.84		852.50		
									59-60	19.05	19.10	19.08	19.49	0.86		871.13		
									60-61	5.65	5.65	5.65	5.77	0.87		876.03		
									61-62	21.55	21.55	21.55	22.02	0.89		897.17		
									62-63	19.75	19.75	19.75	20.18	0.91		916.44		
									-916m to Camp 1200									
									63-64g	6.40		6.40	6.54	0.92		922.06		
									64g-64d	12.25		12.25	12.52	0.93		933.65		
									64d-64c	10.70		10.70	10.94	0.94		943.65		
									64c-64b	7.75		7.75	7.92	0.95		950.62		
									64b-64a	18.15		18.15	18.55	0.96		968.21		
									64-64a	4.75		4.75	4.85	0.97		972.09		
									64-65	5.10		5.10	5.21	0.97		976.34		
									65-66	9.70		9.70	9.91	0.98		985.27		
									66-67	16.20		16.20	16.56	0.99		1000.83		
									67-68	16.10		16.10	16.45	1.01		1016.28		
									68-69	8.95		8.95	9.15	1.02		1024.41		
									69-69a	11.60		11.60	11.86	1.03		1035.23		
									69a-70	6.45		6.45	6.59	1.04		1040.78		
									70-71	6.70		6.70	6.85	1.03		1046.60		
									71-72	15.50		15.50	15.84	1.05		1061.39		
									72-73	11.20		11.20	11.45	1.07		1071.77		
									73-74	4.90		4.90	5.01	1.07		1075.71		
									*74-76	35.00	35.10	35.05	35.82	2.17		1109.36		
									76-77	24.90		24.90	25.45	1.12		1133.69		
									77-78	23.80		23.80	24.32	1.14		1156.87		
									78-79	23.65		23.65	24.17	1.17		1179.87		
									79-80	15.55		15.55	15.89	1.19		1194.58		
																1211.4		

- While time permitted, gauge readings were recorded both going down and then going back up, and the two readings averaged. The scaled value is the average multiplied by  $k = 1.0220$
- 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 accumulating the hydrolevel averages (or taped distances) and subtracting the atmospheric corrections.
- For comparison, depths from the conventional survey are listed for some stations
- The area between stations 74 and 76 (marked \*) is complex, and the gauge data were taken twice, with different intermediate stations. The two values in the table are sums of the pairs of measurements. Because the line contains two measurements, the atmospheric correction is double.

**Table 1: Hydrolevelling data from Voronja.**

## 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 5cm 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 drawn from a tap. 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 if they come off the walls and merge to form large bubbles that fill the cross-section of the tube they will cause errors. A bubble 10cm in length will cause a systematic error of 10cm 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 10m above up a slope to its reel. After that, the depth gauge showed 0.0 under 10m 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 shrivelled-up glove can give an error of up to 10m, even without producing a vacuum bubble.

Another source of error could be non-linearity 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 20m, and that the data above 20m 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 25m. At 30m it turned off, and in the range from 0 to 1m it showed 0. 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 hydrolevelling in those cases was not done. It is difficult to achieve an absolutely vertical position of the tape. The cosine of  $1^\circ$  is 0.998, and the cosine of  $3^\circ$  is 0.9986, and these would create an error of only 0.02% or 0.14% - more exact than the general accuracy of our method, 0.2%. However 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% of the measured depth. In two cases, where the bottom station was displaced horizontally less than 2m 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 1cm 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 hydrolevelling 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 2mm of mercury equal 27mm 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 0.2m 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  $0^\circ$  Celsius is  $1.293\text{kg/m}^3$ . At the average altitude of our measurements, 1500m, it is 15% less. Pressure of the air column from our entrance to our maximum depth of 1200 meters, under a linear approximation and the formula  $\Delta P = rgh = 1.293 \times 0.85 \times 9.8 \times 1200 = 12940\text{Pa}$  or 1.32m of water column. It is possible to add additional corrections for temperature (factor 0.98 for  $4^\circ\text{C}$ ) and humidity. The total effect is about 1.3m.

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 1200m. After having been opened to the air, the gauge showed a stable water depth of 1.2m instead of 0, a displacement of 10cm per 100m of depth. (At other elevations above sea level and other temperatures this value will differ somewhat.) Thus it 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 360m depth, the correction  $b$  will be  $-0.36\text{m}$ . Similarly, if we zeroed the device at  $-500\text{m}$ , the correction at  $-930\text{m}$  would be  $10\text{cm} \times (500-930)/100 = -0.43$  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 30cm, with an average of 15cm. If there were twenty measurements, then ignoring the correction would lead to an accumulated error of  $0.15 \times 20 = 3\text{m}$ . If the process is repeated each day for seven days to the bottom of a 2km-deep cave, the total error would be 20m, or 1% - five times as high as the accuracy claimed for hydrolevelling 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 re-zeroing the gauge at the bottom, and averaging will cancel out the error to some extent.

The temperature dependence of the density of water, 0.0053% per  $^\circ\text{C}$ , is insignificant. In Voronja (Krubera), the temperature varies only from  $2^\circ\text{C}$  at the entrance to  $7.5^\circ\text{C}$  at the bottom, and this does not give cause for anxiety. However, the difference from  $22^\circ\text{C}$  on the surface and cave temperature gives a density change of 0.2%, 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.

## Calibration method

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 obtained from the same raw data by using different values. For example, the data taken by Gregory Shapozhnikov and Larice Pozdnykova during their hydrolevelling 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 unreasonable 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 afterwards 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 be 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.

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 -1194m of 0.45m.

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 Shapoznikov 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 calculation. 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%. 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. Perhaps the sensitive membrane in the gauge changes 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, 20cm. If closure errors after corrections for  $k$  and  $b$  are 0.8, 1.2, or even 1.5m, then there is some systematic mistake in the calculations.

		<i>Test data</i>				
	<i>Gauge</i>	<i>Tape interval</i>			<i>k</i>	<i>b</i>
TEST 1	5	4.98	5.03	(1)	1.0232	0.
	7.3	7.50	7.60	(2)	1.0248	-0.02
	9.8	9.97	10.05	(3)	1.0248	0.
	*13.5	13.95	14.05			
depth 30-57m	14.65	14.80	14.90			
stations 2-4	*23.7	24.20	24.30			
TEST 2	*5.3	5.00	5.09	(1)	1.0217	-0.36
	10.2	9.98	10.08	(2)	1.0209	-0.38
	15.1	15.00	15.10	(3)	1.0204	-0.36
	20	19.95	20.05			
depth 350-380m						
stations 23-24	*24.8	24.92	25.02			
TEST 3	*5.6	4.93	5.03	(1)	1.0252	-0.67
	10.6	9.97	10.07	(2)	1.0263	-0.80
	15.4	14.95	15.05	(3)	1.0209	-0.67
	*20.3	19.92	20.10			
depth 665-692m						
stations 49-50, daytime						
TEST 4	*5.6	4.91	5.00	(1)	1.0217	-0.67
	10.6	9.96	10.08	(2)	1.0228	-0.79
	15.4	14.92	15.03	(3)	1.0157	-0.67
	*20.3	19.92	20.03			
depth 665-692m						
stations 49-50, night						
TEST 5	*6.0	4.99	5.09	(1)	1.0184	-1.15
	10.9	9.93	10.03	(2)	1.0184	-1.09
depth 1133-1157m						
stations 77-78	*15.8	14.97	15.07	(3)	1.0258	-1.15

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.

Three calculation methods were used to determine  $k$  and  $b$  for each set of test data:

- (1) The two points indicated by an asterisk were selected as typical, and the slope of the line between them calculated to obtain  $k$ . The offset  $b$  was calculated from the approximate depth of the test. The numbers cited in the text were calculated using this method. The average  $k$  of 1.0220 is used in Table 1.
- (2) Both  $k$  and  $b$  are calculated using a linear least-squares fit to the test data. If the  $b$  values are reliable, a systematic error of 10cm per station might have occurred in using the data for the day of tests 3 and 4.
- (3)  $k$  is obtained from a least squares fit to the data assuming that intercept  $b$  is the same as in calculation 1.

**Table 2: Calibration data.**

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 10cm per 100m 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 for  $k$ ? We believe that it should be accurate to one unit in the third digit after the decimal point. An error of 0.001 will give an error of 2m at a depth of 2km. When we write of an error of 0.2%, or 4m at 2km depth, we are allowing 0.5m 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 3.5m 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 Sapozhnikov and Pozdnykova, the gauge was re-zeroed 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 re-zero until all measurements had been completed and they were at a depth of 1200m. 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 re-zeroing 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 re-zeroed, 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 re-zeros itself after 30 minutes with continuously less than 1m of water pressure. 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 1.5m 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% the true value of  $k$  is in the range  $1.0220 \pm 0.0030$ . This translates to an error from this source of  $\pm 3\text{m}$  at Camp 1200. Adding estimated random errors of 0.4m, we get that the depth of Camp 1200 is, with 95% probability,  $1194.6 \pm 3.3\text{m}$ . *[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 ks exhibit a bit more scatter, but the averages do not differ from the authors' by more than 0.06%.—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 5cm. It is actually possible to wrinkle 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 2cm higher, he recorded 15.65. But if the reading stayed 15.7 more than 2cm above the station, he recorded 15.7. Thus he reduced the average error in reading by a factor of 2, to 2.5cm.

If the measurements are made twice, as in much of the data in Table 1, the same effect could be obtained by deliberately displacing the box, alternately by plus or minus 5cm, 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 1.5cm, 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 30ppm, 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%. For example, we tried to use an expensive Swiss depth gauge and totally came to grief. It appeared to have very low sensitivity.

## Summary

Hydroleveilling has the potential to be a very accurate method for measuring cave depths. An accuracy of 0.2% is claimed, which corresponds to 4m for a 2000m deep cave. However, in order to achieve this performance, great care must be taken over calibration of the hydrolevel device, and appropriate experimental technique and data processing must be employed to minimise errors. This article has described the procedures employed during a hydroleveilling survey of Voronja to address these issues and extract the maximum accuracy from the device.

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