Avoiding errors in cave surveying

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Summary

The evaluation of loops and resurveying in some large cave systems in the Bernese Oberland have shown that many unexpected errors in surveying are caused by incorrect or careless handling of the instruments and also in violating the basic rules of surveying. The following article will try to draw your attention towards the major principles and sources of errors while surveying a route. For a regular control of surveying instruments and the individual eyesight we will introduce the test area of the HRH on the Chromatte later in this article.

Introduction

The first extensive article about the reliability of SUUNTO measuring instruments (Hof 1988) was published about ten years ago in the "Stalactite". The author came to the conclusion that these robust and easy to handle instruments meet all requirements of cave surveying if a few important basic rules and preliminary controls are obeyed. The immensely time-consuming analysis of misreading, particularly in the large cave systems of the Sieben Hengste – Hogant region, have clearly shown the necessity of reminding surveyors to call these principles to mind from time to time. All too often we rely blindly on the "incredible accuracy" of the instruments as claimed by the manufacturers. More often rudimentary errors occur because of ignorance, poor choice of route, incorrect handling of the instruments, misunderstandings whilst recording data and also insufficient concentration or lack of motivation.
The aim of this article is to point out the manifold traps a surveying team has to avoid. We refrain from quoting scientific information as far as possible and refer to the article of HOF (1988). More detailed information on surveying techniques are found in GROSSENBACHER (1991). Also the problematic nature of drawing plans which is just as important as the route, will not be mentioned in this article.
One last remark: paper is patient and computer programmes too sometimes, but the best programme never alters incorrect data, it only works it out incorrectly. Whoever blindly trusts electronics and forgets the basic principles may please refrain from surveying. Any survey with errors is worse then no survey at all, because the search for the errors is more difficult and time consuming then a complete resurvey.

General remarks on measuring errors

The method of cave surveying with a succession of routes has, in comparison to the direct coordinate survey, the disadvantage of errors being carried along over all the routes following. Control functions are very limited and for time reasons are often not carried out: these being, consequent reverse bearings, analysing errors in loops, resurveying.
Random errors have less effect on a lot of succeeding routes, for there is some kind of static correction. The exception are rudimentary errors on long routes. A precise and quickly reproduced drawing at home should bring out rudimentary errors (deviation of 30° or more), but experience shows that this is seldom the case.
Systematic errors have the same effect on all routes and mount up over the whole length. Even small deviations of a few tenths of a degree falsify the results in long caves considerably (e.g. the connection F1 - Sieben Hengste with 80 meters difference in height). The correction of systematic made errors is possible if they can be estimated.
There is a wide range of more or less random errors, which have a systematic

character, depending on the direction of the cave and measuring habits. As the errors in the bearings are always different, they cannot be corrected automatically. As a practical guide this article will centre on the different sources of errors. Almost all variations of the here mentioned errors may be random or systematic.

Choosing the survey points

The system most commonly used in Switzerland, to mark the survey points directly on the rock with nail varnish has proved to be convenient for reference and accuracy. It requires the absolute obedience of the basic rules:

Long routes (over 20m) should be avoided, to achieve full accuracy in the final drawings. Small reading errors (even accidental) have a unusually strong effect on the accuracy of any measurement. Consequently care should be taken concerning rudimentary errors: avoid poor visibility due to protruding rocks, illuminate the survey point (e.g. hold the helm lamp close – illumination from a distance is insufficient), find a convenient position when taking the bearings, second bearings, reverse bearings.

Routes which do not allow convenient readings is one of the main sources of errors. An additional survey point in the middle often helps to reduce the possibility of making errors.

Sometimes it isn't possible to set the measuring instrument directly on the survey point. In this case the surveyor has to offset parallel to the route. The value of the offset has to be pointed at by the second surveyor at the other end of the route (and not guessed by the instrument reader), in order to avoid rudimentary bearing errors.

The method of surveying, mostly used around cave entrances, by aiming at the eyes of the second surveyor is very unreliable especially when it involves long routes. Survey points in surface survey should be marked with paint, nail varnish is not lightproof.

Fig. 1: Compass SUUNTO

Fig:1: SUUNTO Compass with mounted Plexiglas cylinder. The light received from the opposite survey point shows as a vertical line in the Plexiglas cylinder and enables a correct bearing, even in steep sections. This system eliminates inexact guesses of the vertical extension when taking the compass bearing. Such errors can be unbelievably huge on steep routes (over 30° inclination). Detailed description and how to assemble this system are found in Weissensteiner und Trüssel (1991) or www.speleo.ch /equipment. Photo M. Trüssel.

Steep routes (over 40°) cause more problems when taking the bearing. It is very difficult to keep the compass level and to guess where the survey point exactly is. It often leads to blockage of the compass disc. The eye can be easily tricked by rock structures slightly out of vertical. This problem can be solved with the aid of a perpendicular (e.g. cord with clinometer) or a optical aid mounted on the compass (Plexiglas cylinder, Weissensteiner und Trüssel 1991, see Fig. 1). Steep routes should be avoided if possible and replaced by vertical sections.

Repeated misbearings cause massive errors in a survey network which are later difficult to define. They can only be reduced by precise drawing and consequent marking and labelling of the survey points. Apart from the discreet marks with nail varnish the marking with fluorescent strips has proved to be effect full, especially in larger systems. They are discreet too, can be seen from a distance of 10m and the number is written directly onto the strip with a waterproof marker. (In small caves however they are annoying. A.r.) Also recommendable are Synthosil notice pads placed by important survey points, e.g. a turn off, chimneys etc. holding all the necessary information.

Influence of iron

It is common knowledge that iron influences the compass needle. Unfortunately cavers gear consists lot of iron parts and not everything can be replaced by plastic, aluminium or brass. The manufacturers of caving gear do not take enough notice of the demands of a survey team. Survey teams are a minority of all cavers and many otherwise experienced cavers are unaware of this fact. The amount of inaccurate cave plans affected by iron is estimated at 20 – 30%! This unsatisfactory situation enforces the replacement of all iron parts in the near vicinity of the compass needle by the cavers themselves. Unbelievable but true, the widely spread Petzl lamps have a iron spike to protect the nozzle which is only 2cm above the compass needle when taking a bearing! Errors of 10° or more are guaranteed (but never mentioned in any warranty). The construction of the helm lamp however makes it rather easy to replace almost all iron parts. A list of the nuts and bolts needed is shown in Fig. 2 and can be ordered at Spelemat, Bussigny. The SGHBern has the parts needed in stock and will send them on demand.

Fig. 2. List of replacement parts to modify the Petzl helm lamp (Laser) for surveying purposes

Article	Number	Size	Replaced part
Brass bolt Cylindrical	1	M 5/35	Iron spike near nozzle, Fixing of nozzle holder
Brass bolt Cylindrical	1	M 3/60	Fixing of the reflector, (rear side)
Brass bolt Cylindrical	1	M 3/30	Axle of Piezo
Brass bolt Cylindrical	2	M 3.5/6	Fixing of the electric light
Brass nut self-locking	2	M 3	Fixing of the reflector and Axle of Piezo

The replacement of the Piezo lighter is not so easy. The springs can be replaced with rubber bands, the hammer inside is irreplaceable and is, depending on how it is mounted on the helmet directly above the instrument. It causes errors of approximately 5° with a systematic character but they are still too variable and correction afterwards is hardly possible. Because the Piezo is usually located on the right side of the nozzle, it improves the results if the bearing is taken with the left eye. It also helps to mount the Piezo higher up to enlarge the distance between the hammer and the instrument (Authors comment: the Piezo can be mounted so it can be removed when needed. Maybe somebody will find a simple solution). If the surveyor is not sure of the helmets influence, it is better to take it off while surveying. The rest of the, sometimes massive, iron parts are normally far enough away from the instruments to have any significant influence. One should be aware that equipment such as the carburettor, may get too close when pushed ahead in narrow passages, the jumar on the rope or the sack full of iron material on the back (on surface survey even the carburettor), electrical lamps, spectacle frames and many other things may have an influence. Fences and iron gates can cause errors on surface survey.

Instrument handling

To establish the survey data intense concentration and experience is always needed under bad conditions of light, dirt, blocking compass disc, inverse scale etc. In training the error rate of beginners and surveyors with little experience was sometimes up to 50%. But even experienced surveyors are not immune to making errors. Tiredness and lack of motivation are the main reasons of reduction in accuracy of the bearings taken (reading to fast, no verification of data, aiming at the wrong survey point, etc). It has been established that the accumulation of errors does not proportionally grow with the length of the survey, but rather after a certain point of tiredness is reached on long-time survey tours. The trick is to recognise the right moment to break up a survey tour.

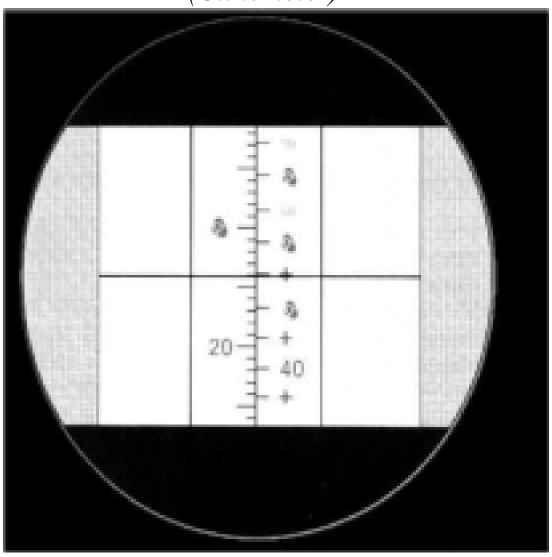
Usually we advise to take the bearings with only one eye. First the eye does not tire so fast and secondly, the optical incorrectness of the readers eye, which is quite common, has less effect on the results (growing tiredness, waning concentration).

The correct handling of the instruments needs to be trained. If the compass is not held absolutely horizontal, while the surveyor is in a twisted position, the disc will not rotate freely and the bearing will be inaccurate. 30° and more are often noticed. As there is no water level, the free rotation of the compass disc must be checked before every reading. The steeper the route, the more complicated is the handling. Taking the bearing too fast will not allow the disc to settle in position. The clinometer doesn't usually block when held at an angle. However it is recommended to hold it vertical. Holding it at a slight angle can lead to systematic errors of approximately 1° (reasoning see HOF 1988). Inclination values that are systematically too high lead to unrealistic depths of the caves. The best example is the connection of F1 with the Sieben Hengste system. The error of 80m equals a error value of less then one percent per route.

Reading and counting the fine lines on the scales of the instruments is difficult even in daylight, even more so with poor lightning or a twisted and uneasy position of the body. Instruments with fluorescent markings made of tritium, with built-in illumination, an extra hand torch (check the effect on the compass needle!) or simply using the hand as a make-shift reflector improve the visibility through the optic. Time and again errors are made by reading the wrong scale mainly by beginners or inexperienced cavers.

Fig. 3. Reading the instruments

(Clinometer)



(Compass)

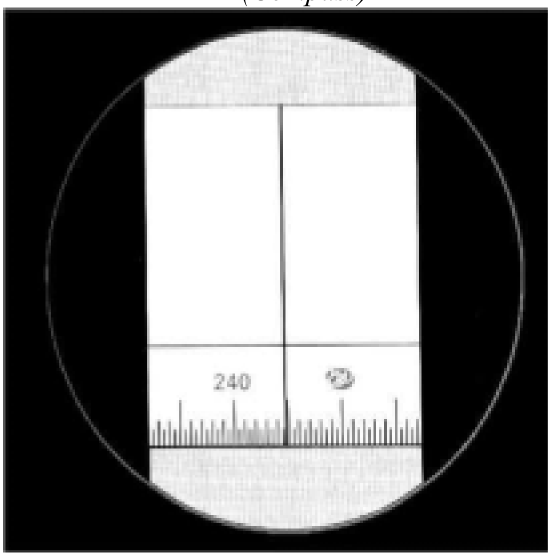


Fig. 3: Reading the scales of instruments in poor lighting conditions and an uneasy body position often causes problems and leads to misinterpretations. The scale is usually seen but the numbers are often blurred. The bearing is taken by counting the fine lines from the last recognised number on the scale. In the picture above is a typical view through the compass (left) and the clinometer (right). What are the values of the declination and the inclination?
See the end of this article.

Even more counting errors happen because of inverse scales of both the compass and the clinometer (see Fig. 3). Even if this error isn't systematic, a 10° error on a 20m route (75° instead of 85°) causes an error of 3.8m! Trainings with beginners have shown that the inexperience of counting from right to left or down to up leads to error rates up to 50%. But also experienced surveyors are not always aware of this fact and the errors increase with tiredness and waning concentration, especially the difference between small positive and negative inclination values.

Data recording

The third person on a survey is the one who notes all the data from the others and at the same time does the drawings and estimates the height and width of the cave. Comprehension in such an environment can be affected by clay on the walls which muffles the voice, running water, numbers that sound almost the same and all the different dialects and languages which can lead to errors. With tiredness the numbers get mixed up (e.g.76 instead of 67) and can add up to 10% of wrongly noted values. It is essential to say the values loud and clear and have them repeated by the drawer and again reconfirmed by the instrument reader.

A dangerous source of errors are interpretations and conversions on reverse measured routes. Instruments with a 400° scale are in this case easier to read. It's an absolute must to agree and write down on the survey sheet which instrument scales 360° or 400° are used (some clinometers have a percent scale), the number of the instruments and who does the conversions (danger of double conversions). We recommend to record the data as read by the instrument reader and mark the conversions on the survey sheet (can be important for corrections later on). To avoid interpretation errors we recommend to refrain from rounding distances to 5cm or even 10cm. Often a value gets forgotten in the hassle of drawing and estimating and is put in later by guesswork. Sometimes the recordings are almost unreadable and at home are defined with the flip of a coin. One more rule for the drawer is to keep clean hands!

Treatment and care of the instruments

SUUNTO survey instruments look robust but have relatively delicate parts inside. They are easily affected by dampness, dirt and impacts. Through a tour the instrument reader has no means of detecting such caused errors and the instrument gives wrong bearings throughout the following years. Errors like this can only be detected with calibrations on a periodical basis. The instruments are not waterproof and should not be submerged. Water will carry fine dust into the instruments. Cleaning is done with a damp cloth only. As a basic rule the instruments should be kept clean, transported by hanging around the neck inside the overall and in their leather cases, handled without both gloves and clean hands. Special care has to be taken when wearing wetsuits. The high dampness leads to too much condensation and sometimes affects the reading.

Replacing the rubber gasket with a thicker one or sealing with silicon improves the water resistance, but the latter dims the light for the reading (changed angle of the light). Opening the instruments for cleaning is possible, but is delicate and requires calibration.

Impacts, even minor ones can damage or shift the axle which causes systematic errors or the disc inside catches and takes a long time to settle. Not big impacts, as most people think, but many minor impacts such as banging two instruments together inside the overall cause more problems. Most damage is caused by the careless transport from one survey point to another without storing the instruments away properly (surface survey). Gluing both instruments together reduces the risk of impacts.

Its not so much the defects from age that is a problem, but finding the errors caused by it. The only way is correct treatment and care, control and calibration measurements. Small bubbles obstruct the free rotation of the disc. If bubbles are not a effect by air pressure (change of altitude) they are a clear sign of an aging instrument. A refill with white spirit is difficult to do and extends the life span usually only for a few months.

The measuring tape needs only minimum care. The numbers must be clearly readable, especially the zero point. A rivet at zero removes all doubt. We recommend not to cut or shorten measuring tapes, not even for 10m. Conversion errors occur more often than with whole tapes. Some dealers sell replacement tapes which are considerably cheaper then a complete new roll.

Instrument errors and optical eye correction

No warranty with a brand new instrument gives guarantee of accuracy. Systematic errors of 2° are common and add up on long routes to several dozens of meters. On top of that come the errors from ageing or defects (bent axle). Some of these can be neutralized by an instrument specific correction factor but the problem is in finding the right value and the exact time when they occur.

The only way to define correction factors is by control measurements and calibration of the instruments in periodical spaces of time. The HRH owns a facility where control and calibration measurements can be made with a reasonable effort. A calibration must produce the following results:

- If and how accurate the read values can be reproduced; if reproduction is possible
- The deviation of the instrument from magnetic north (or the horizontal for the clinometer) and
- The deviation from magnetic north (or the horizontal) owing to individual eyesight.

Fig.5. Control measurements

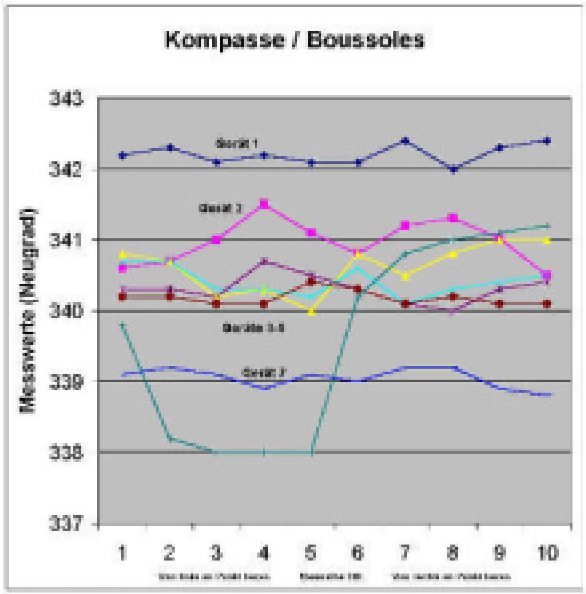


Fig.5: Graph of the results from control measurements with SUNTO compasses. The vertical scale shows the bearings of a fixed survey point for each instrument and measurement. The horizontal scale shows the corresponding ten measurements. In each case the first five measurements were taken with the instrument rotated from left to the survey point, the next five measurements from the right. The values of the instruments 3 – 6 are within a spectrum of 0.5°, rated good or sufficient. As the exact reference measurement is missing, it's assumed that the value is in the same spectrum. The value of instrument 1 is almost +2° offset. Because of the good reproducibility (ca 0.3°) it is easy to find the correction factor. The same applies to instrument 7 with –1° offset. Instrument 2 has a fluctuation in the bearings of 1° and the correction factor is smaller then the fluctuation in the bearings. Instrument 8 with fluctuation of more then 3° should not be used for surveying any more. The big difference between the two measuring series indicates a bent axle which hinders the free rotation of the disc.

Fig.6. Control measurements

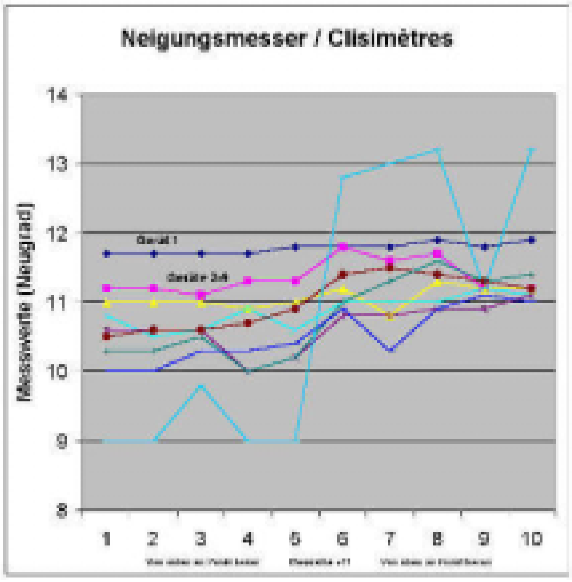


Fig.6: Graph of the results from control measurements with SUNTO clinometers. The format is the same as in Fig.5. In each case the first five measurements were taken with the instrument moving from below to the survey point, the next five measurements from above. Clinometers, in general, have slightly bigger differences compared to compasses. Nearly all instruments show a clear difference between the measuring series. The values are app. 0.5° higher when taken from above! Depending on the habit of the surveyor this may lead to systematic errors. The exact reference value lies probably in between the spectrum of the instruments 2 – 8, which is however more then 1°. Instrument 1 has a good reproducibility, but a correction factor must be determined. Instrument 9 again indicates a bent axle which hinders the free rotation of the disc and should not be used for surveying any more.

All the instruments tested by the HRH where classified in the following categories:

- Fluctuation up to 0.3°
  very good instrument (Nr.1 & 7 in Fig.5 and Nr.1 in Fig.6)
- Fluctuation up to 0.5°
  good instrument
- Fluctuation up to 1°
  sufficient to poor instrument (Nr.2 in Fig.5)
- Fluctuation of 1° and more
  useless instrument (Nr.8 in Fig.5 and Nr.9 in Fig.6)

The determination of a correction factor only makes sense in the two first categories. Poor instruments usually have a higher fluctuation value than the correction factor. These instruments should possibly only be used in small caves, certainly not in surface survey.
The comparison of different instruments shows where the real values lie. Experience rates the instruments with a good reproducibility but a systematic value offset of 1° - 2° positive or negative at 10to 20%. To determine the correction factor of other instruments, an instrument with a very good reproducibility and a known correction factor must be used. With it any at random chosen survey point can be given an absolute value. For measuring series with the same fix point over several years the declination must be taken in consideration. Individual eyesight is controlled with the same method. Several cavers make measuring series with the same (if possible) calibrated instrument. the result is a second correction factor for each cavers individual eyesight.
To ensure the determined correction factors to take effect, the instruments must be clearly marked (or the engraved serial number is used). On each survey tour the used instruments (even if not calibrated) and the name of the surveyor (for optical correction) must be declared on the survey sheet and for the survey points. Unfortunately do old plans often lack this information and there is no way of knowing if these plans are accurate. Instruments very often get thrown away when they are out of use without a control measurement ever being made.

Loops, reverse- and resurvey

The principle to close as many loops as possible is still valid, but the possibility of finding errors in the survey should not be overestimated. Only loops with many routes and well spread random errors can stabilize a network of survey routes. This is seldom the case in loops with only a few routes. The actual detection of errors is, as a rule, much more time consuming then a complete resurvey of the whole loop. An error analysis becomes often very difficult and leads to wrong conclusions with:

- Systematic instrument faults. The result is often only a rotation of all

the routes, the wrong value being carried along.
- Single rudimentary errors. Since a loop error may be the total of many errors it is almost impossible to locate one single major error. Such a loop may not be closed as this single error gets split up over the whole routes and does not stabilize but rather distort the survey net.
- Incorrect connection points.

As a basic rule it is recommended not to close the loops in the first stage. If the total of the errors is minimal, the loop may be closed to the endpoint. Otherwise the errors must be searched for (with the assistance of plans, drawings, geological structures) and the faulty routes corrected. Needless to say, the so corrected loops must be resurveyed in the cave.

It's the great disadvantage of the loop method that the errors are not found until at home and because of a single error a complete resurvey is necessary. Under this aspect we always recommend a reverse survey which allows instant control of each bearing. If the difference between the readings is to big, then a third reading will help to find the error. Another method is to use two sets of instruments which slows the team a little, but the drawings in the cave normally take more time.

A resurvey is, after all, a capitulation to the interpretation of measured data or drawings. This kind of work is frustrating but is quite often less time and nerve consuming than trying to interpret missing or incomplete data. In order to avoid a third (or fourth) resurvey, the accuracy of the routes and drawings is essential. This includes:
- No resurvey without a new drawing (except if the old drawing is up to today's standards).
- As many connections to the old routes as possible. The new routes may contain errors too; important if the existing drawing will still be used and for the connection of side passages.
- And most important: accuracy before speed!

Summary

The present article confirms once more that the described techniques become a matter of habit in one survey tour, with a little help from a friend. Again, experience shows they are forgotten just as easily, so instead of a summary we present a table with the most common errors made and the steps to prevent or remove them. The worst errors are separately marked.

Acknowledgments

This article was made from the experience gathered on numerous survey and frustrating resurvey tours. For lecturing, constructive critics and completion of the manuscript I would like to thank: M. Trüssel, P.-Y. Jeannin, A. Wildberger, Y. Weidmann, A. Hof, and Ph. Häuselmann. Thanks to C. Brandt and B. Freiburghaus for the numerous hours of translation and correction and to A. and B. Dudan for their cooperation in distributing the spare parts necessary to modify the helmet lamp.

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>> Fig. 3: the inclination is + 14° (there are instruments with inverse scales to the one in the picture). The Azimuth is 235°. Whoever had read an azimuth of 245° would have made an error of almost 4m on a 20m route.

	SOURCES OF ERRORS	PREVENTION, REMOVAL
	Survey points	
	Long routes	More survey points; control- and reverse survey; light directly on the survey point;
	Uneasy to read bearings	More survey points
	Parallel offset to the route	As little offset as possible; point at the same offset at the end of the route (to be avoided);
☞	Eye to eye survey	Replace with fixed survey points
☞	Steep routes	Replace with vertical routes; extend survey point with cord and weight; optical cylinder; survey upwards (longer bearing line);
☞	Connection errors	Accurate drawing; clear marks with nail varnish and florescent strips; notes on Synthosil pads at turn off, chimney etc;
	Iron objects	
☞	Helmet	Replace all iron bolts with brass bolts; replace springs with rubber bands; mount Piezo away from instrument or to dismount easily;
	Metal carburettor	Careful in narrow places, especially when carried around the neck;
	Hand held torches	Check influence on compass needle; use stainless steel mirror;
	Spectacle frames	Check influence on compass needle;
	Climbing and descending-equipment	Measuring while descending;
	Kitbag (on back or pushed ahead)	Watch out for iron inside kitbag; take off for measuring;
	Surface survey	Watch out for iron parts like fences, gates;
	Instrument handling	
☞	Tiredness, lack of concen-tration and motivation	Terminate the tour at the right time (individual); reverse bearings; instrument and tape reader change jobs (note on survey sheet);
☞	Insufficient experience	Teachings from experienced surveyors; training in small caves;
	Holding of the instruments	Hold the compass horizontal; hold the clinometer vertical;
	Blocking compass disc	Control the rotation before a measurement; leave enough time to settle into position;
	Badly visible numbers	Fluorescent scale; built-in illumination; hand torch (magnetism) well functioning carbide lamp; reflector (hand or metal plate)
	Wrong scale	Check before the tour; take instrument with right scale;
☞	Inverse scale	Don’t forget the danger while taking the bearings, always compare with the higher and lower numbers visible;
	Data recording	
☞	Misunderstandings	Speak clear and loud; drawer repeats and gets reconfirmation from the instrument reader; control with reverse bearings;
	Distinguish between Inclination / Declination	Inclination always has a plus or minus before the value
	Mixed up numbers	Don’t forget the danger; repeat and reconfirm;
☞	Reverse measured routes	Arrange who does the conversions; mark them on the survey sheet
	Division of scales on instruments	check before the tour;

	Rounding distances	Unnecessary, read to the centimetre;
	Note values later	Should be avoided
☞	Unreadable notes	Take enough time for notes and drawings; keep hands clean;
	Treatment and care of instruments	
☞	Bad visibility because of dirt	Keep instruments clean; never take bearings with gloves; carry instruments inside overall; do not submerge in water;
	Condensation	Careful with wetsuits; dry properly;
☞	Bent axle because of impacts	Protect instruments from banging against each other; transport in leather cases, pullover or overall;
	Bubbles	Check rotation of the disc; refill with white spirit or replace instrument
	Shortened measuring tapes	Should be avoided or replaced (interpretation errors);
	Instrument faults and eye correction	
☞	Bad reproducibility	Periodical calibration; use instrument in small caves only; replace instrument;
☞	Systematic instrument fault	Determine the specific correction value; mark the instrument; declare instrument on the survey sheet;
☞	Systematic eye fault	Determine the specific correction value; declare the name on the survey sheet;

A lot of these errors are unfortunately never detected as comparison surveys only rarely exist. In awareness of all these possible errors we recommend, at least for the main routes, a simultaneous control function through reverse surveying. It is the only method to detect errors on the spot and correct them immediately.