DistoX and TopoDroid

Calibration, precision, accuracy

Version 2020.03.20

Marco Corvi - 2020

DistoX basics

DistoX is an integrated electronic device for cave surveying. With DistoX you can measure distance, azimuth and inclination at once. The measured values can be transferred via bluetooth to a Palm (PocketTopo or Auriga), or an Android device (TopoDroid, CaveSurvey, Qave, or SexyTopo). It has been designed and produced by Beat Heeb.

The first version, DistoX, was presented at Vercoors in 2008. It consists of an extension board to be installed inside the Leica DISTO A3. The software on the board intercepts the commands of the user, measures azimuth and clino, displays the values on the screen together with the distance, and transfers them all via bluetooth. The measured data remain in a circular memory buffer that can hold slightly over 4000 data. This board remained in production for about one and half year, after which it went out of production due to a component that was no longer available.

After three years, at the end of 2013, Heeb was able to create a new model, the DistoX2, for the Leica DISTO X310 (E7400x in US). The DistoX2 board replaces one of the original Leica boards. An amagnetic rechargeable battery can be installed, making the use more convenient. The memory buffer of the DistoX2 can hold only about 1000 data, but the device has more functions than the first model. The DistoX2 is going out of production (end of 2019).

One important feature of the DistoX2 is the possibility to upgrade the firmware, thus adding new functions. Firmware 2.3 was released in August 2014, firmware 2.4 in February 2015, and firmware 2.5 in August 2016.

References

Documentation on the DistoX website paperless.bheeb.ch

Documentation on souterweb.free.fr

Video tutorials and pages on derekbristol.com

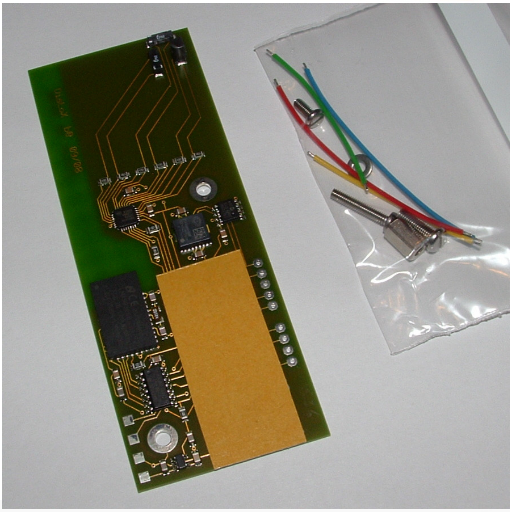
DistoX (version 1)

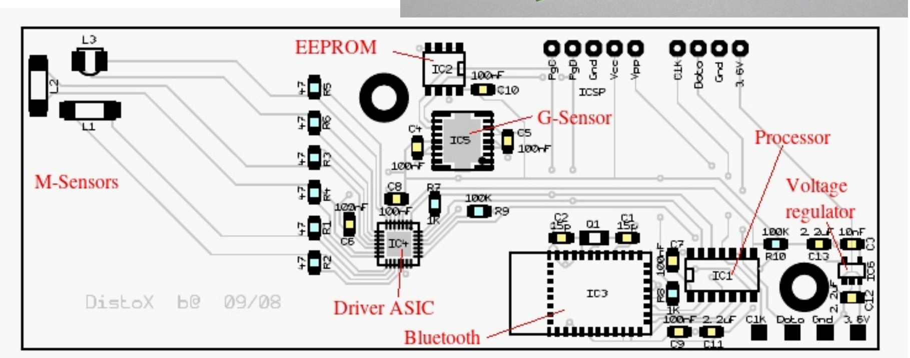
The DistoX is an extension board for the Leica DISTO A3.

The DistoX board has the following sensors:

- M X/Y sensor PNI corp. 12683
- M Z sensor PNI corp. 12779
- G sensor VTI tech. 647361

The spec sensitivity of the magnetic sensors is about 15-50 nT at best, which means 0.03°-0.1°.





DistoX keys

DIST/ON turns on the device/laser, takes reading
PLUS and MINUS
AREA
MEM (storage)
REF toggles reference between "rear" and "front"
UNITS selects distance and angle units
CLEAR/OFF turns off laser, switches off the device

DistoX screen

The display on the DistoX shows
[1-3] the data values azimuth, inclination, and distance, with their units
[4] the reference icon (either "rear" or "front"). When the laser is on it has a blinking '*' on top .
[5] the bluetooth icon (in enabled), blinking when the DistoX is connected.
[6] the number of untransmitted data in memory, 1 to 19, or "In" (for "infinite"). If there is no data to transmit nothing is displayed. In silent mode it displays 0.

In calibration mode the screen displays "CAL" with the number of calibration data.

DistoX functions

To switch on the DistoX press DIST/ON. The laser is turned on at the same time. To take a shot press again DIST/ON: the display shows the values of azimuth (top), inclination (middle), and distance (bottom). To take another shot start the laser by pressing DIST/ON anew. To interrupt a measurement press CLEAR, and the laser turns off.

To switch off the device press CLEAR for two seconds. The DistoX switches off by itself after 90" of inactivity.

If you press either PLUS or MINUS the laser turns on. Pressing DIST after that the measurement is taken and the distance is added to or subtracted from the previous value, respectively. The result is shown on the display stored in memory, and transmitted.
This behaviour comes from the original Leica board. The DistoX reads the display of the distance and measures the angles. When the Leica board displays the distance summed with the previous value, the DistoX takes that as "distance" of the shot. Care must be taken not to start a measurement by pressing accidentally PLUS or MINUS.

A short press of the UNIT key switches the illumination of the screen on/off.
A long press (2 seconds) on the UNIT key, with the reference at "rear", changes the distance unit cycling through m to 3 decimals (mm), m to 2 decimals (cm), ft to 2 decimals, ft-inches and fraction, inches with decimals, inches with fraction. The distance unit is shown after the value.
A long press on the UNIT key with the reference at "front" cycles through settings of compass, bluetooth and angle units:

compass off, bluetooth off
compass on, bluetooth off, angle unit degree
compass on, bluetooth off, angle unit grad
compass on, bluetooth on, angle unit degree
compass on, bluetooth on, angle unit grad.

The angle unit, either 'o' (degree) or 'g' (grad), is displayed after the azimuth and inclination values.

When the bluetooth is on, the bluetooth icon is shown on the screen, and the DistoX bluetooth is *discoverable,* ie, it can be discovered by a bluetooth scan. All the DistoX devices have bluetooth name "DistoX". The DistoX bluetooth pairing PIN is 0000 (four zeros).

MEM shows the data in memory. A "mem" icon is shown near the data

number in memory. Pressing MEM repeatedly you can view the other data in memory.
To switch the calibration mode on/off, go to the tenth data in memory and press UNIT for two seconds.

Pressing CLEAR and PLUS for 5 seconds turns the beep sound on/off.

To turn on silent-mode press the sequence AREA AREA REF REF CLEAR. In silent mode measurements are stored in memory but the data are immediately marked as "transferred". Other unsent data present in memory are also marked as "transferred". In silent mode '0' is shown instead of the number of data in memory.

Pressing AREA turns on test-mode. In this mode the compass keeps running. With "rear" reference, the screen shows azimuth and inclination. With "front" reference it shows roll and dip angles. You must not take readings in test-mode: data are neither stored nor transferred, and the memory display may become inconsistent.

AREA AREA shows the firmware version (top) and the board serial number (bottom). In this mode switching the reference to "front" or "rear" with the REF key turns the silent mode on/off.

Error codes

When there is a problem with the measurement, the DistoX displays an error code:

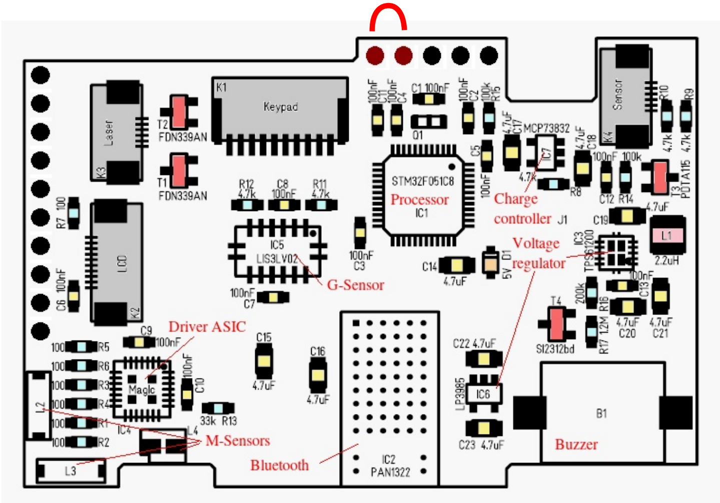
252: temperature too high
253: temperature too low
255: signal too weak
256: signal too strong
257: too much background light
260: laser beam interrupted

These codes are the error codes of the original Leica instrument. Other (unusual) error codes can arise from a measuring module error. Make sure the lens glass is clean. A module error raised by mistake may go away by switching off and on the DistoX.

References

B. Heeb, DistoX user manual, 2008.08.14
B. Heeb, DistoX advanced informations - Firmware v. 1.3 1nd 1.4, 2010.12.12
B. Heeb, Inside DistoX - DistoX version 1.3, 2008.10.10

DistoX2



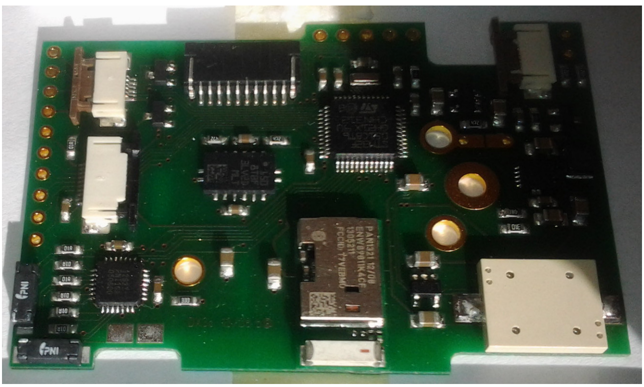
The DistoX2 is a replacement board for one of the Leica DISTO X310 boards.

The DistoX2 board has the following sensors:

- M X/Y sensor PNI corp. 13104
- M Z sensor PNI corp. 13101
- G sensor ST Microel. 497-841501-ND

The spec sensitivity of the the magnetic sensors is like that of the DistoX (0.03°-0.1°). That of the G sensors is 1‰ at best, that is 0.06°.

Jumping the two red pins (marked with a arc) hardware resets the board and boots the DistoX2 in bootloader mode, so that a firmware can be uploaded.



DistoX2 keys

ON/DIST: turns on, takes readings

PLUS and MINUS: navigates in memory, screens, setting values

FUNC: diaplays device informations

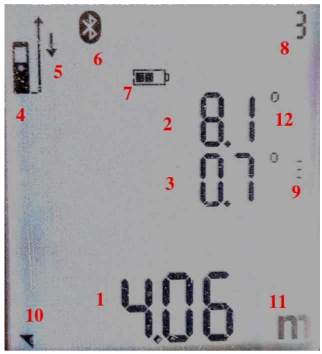
SMART: details about the data

UNITS (MEM): memory, units

REF: reference point

TIMER

CLEAR/OFF: switches laser, or DistoX2 off



DistoX2 screen

[1-3] The DistoX2 screen displays the data values: distance, azimuth, inclination, and their units [11,12].

[4] The reference icon shows the current reference setting.

[5] A downward arrow at its right indicates that backsight is enabled.

[6] The bluetooth icon is visible if bluetooth is enabled, and blinking while connected to another device.

[7] The battery icon shows the battery level; this can be checked with the info as well. During recharges it cycles through three positions.

[8] The number of data to transmit is shown on the top-right. Two dashes are shown if the DistoX2 is in silent mode.

[9] When a triple shot is detected, three short lines are displayed to the right of the inclination value.

[10] A small triangle at the bottom-left if the triple-shot is enabled.

The label "2nd" appears when one of the two sets of acceleration sensors is out of order.

In calibration mode the screen displays the label "CAL" [1] with the number of calibration data [2].
The number of data that have not been transmitted yet is shown on the top-right corner [3].

Switching on and off

To turn on the DistoX2 press DIST. If the device was switched off with block on keys, press MINUS to unblock them (as shown on the screen). When you turn on the DistoX2 the laser is automatically on, press CLEAR to turn if off, or DIST again to take a reading.
To switch off the DistoX2 press CLEAR for a couple of seconds. To switch it off with the key-block press CLEAR and MINUS together for a couple of seconds.
The DistoX2 switches off after 90" if no key is pressed, and no bluetooth connection is established.
The key block is useful to prevent the DistoX2 turning on accidentally and measuring during the transport.

Measuring

To take a shot press the DIST key to turn the laser on. Then press it again to measure and turn the laser off. You can also press and hold the DIST key.
The measured values are displayed on the screen: azimuth at the top, inclination in the middle, and distance at the bottom. Additional data can be seen with the SMART button.
If the timer is set, the DistoX2 waits for the set time, before measuring.

Shots can be taken also with the timer. After pressing TIMER, with the laser off, you can set the time with PLUS or MINUS. Then pressing DIST the laser

turns on and the countdown starts. When it is finished the reading is taken. If you want to interrupt the measurement, press CLEAR to exit the timer.
Pressing TIMER with the laser on, the countdown starts immediately and the reading is taken when it expires.
The timer is helpful for taking a precise shot since the DistoX2 will be shaken inevitably when a key is pressed.

With firmware 2.3 and up it is possible to switch the laser on/off and to take measurements via bluetooth.
Controlling the DistoX2 remotely is useful for accurate measurements, but it requires good coordination between the instrument person and the book person.

With the SMART key you can cycle through additional information of the data (the distance is always shown):
• azimuth, horizontal distance, vertical distance
• roll angle and magnetic dip angle
• magnitude of magnetic field (µT) and acceleration (unit of "g", 9.81m/s2)
• raw XYZ values of on-board acceleration sensors
• raw XYZ values of the separate acceleration sensors
• raw XYZ values of the magnetic field sensors

The last three are shown only for the last reading, not for the data in memory.
If the laser is on, the SMART key gives access to the last five pieces of additional information only, while the distance is replaced by three dashes.
This additional information is usually not important. It may become useful if one thinks that the DistoX2 is behaving in a strange way, and suspects that there is something wrong with the sensors or there is magnetic disturbance.

Memory

The data in memory can be viewed pressing the UNITS key. The last data will be shown. Pressing PLUS or MINUS you can navigate through older data. The order of the data in memory is shown at the top-right, starting with 001.

When a data is displayed you can see additional information of the data pressing the SMART key as described above.

Pressing CLEAR and UNITS for two seconds clears the "transmit" flag of all the data in memory, so that no data will be transmitted.
This is useful when you want to take some shots but do not want to download them. Alternatively you can enable silent-mode, take the shots, and disable silent mode.

Reference

The reference point can be at the "rear" (this is the default), at the "front", or at mounting point for a "tripod". The current reference is shown with an arrow in the reference icon on the top-left of the screen.
Pressing REF the reference is set to "front" temporarily for the next measurement, after which it reverts to "rear". Pressing REF twice in a row the reference is set to "tripod". This setting is permanent. To return to "rear" press REF again. Pressing REF for two seconds sets the reference at "front" permanently. To revert this setting press the REF key.
The temporary reference at "front" is necessary for very short splay shots, about 20 cm or less, provided the DistoX front can be placed on the station.

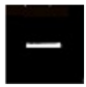
REF and FUNC for two seconds toggles the rear-reference between "extended" and "back". This is useful when the DistoX has a tail to position the reference point more precisely on the station. With this reference the length of the tail is add to the distances; this value can be set through the device information screen. With "extended" rear-reference, pressing REF cycles through "front", "tripod" and "extended" reference.

Backsight

With backsight enabled the DistoX2 takes the readings in the opposite direction: 180° is added to the azimuth and the sign of the inclination is reversed. A downward arrow is shown near the reference icon when readings are taken backsight, or a backsight data is displayed from memory. Backsight is set on/off by pressing UNITS and MINUS for two seconds.

Backsight is a dangerous feature of the DistoX2. It must be disabled before splays are taken, otherwise they are reversed (like the legs). It is better to leave the task of marking the backward shots to the application that manages the data (and the sketches). TopoDroid has a setting to revert the DistoX2 backsight data. With this setting active, the app switches the TO and FROM stations when they are assigned to the shots.
The real problem with backsight is that, having it, the instrument can operate in two different ways, one opposite to the other. This requires more attention and care from the instrument person and the book person as well during the survey.

Triple-shot

With the triple-shot enabled the DistoX2 emits a double beep when you take three consecutive shots that differ less than 3 cm in distance and 1.7° in angle. A symbol made of three horizontal bars is also displayed near the inclination value.
Triple-shot is enabled by pressing SMART and MINUS for two seconds. When enabled, a triangle is shown at the bottom-left of the screen.

Triple-shot is very useful because it gives the instrument person a feedback that the leg measurement is complete. However it can happen that all three shots are bad. A check of the values on the display, especially the distance, is always a good habit.

Units

The distance unit is selected pressing UNITS for two seconds. The unit cycles through meters to three decimals (mm), meters to two decimals (cm), decimal feets, decimal inches, feets with inches and fraction, inches and fraction.

Pressing UNITS and SMART for two seconds toggles the angle unit between degree and grad.

Silent mode

With the DistoX2 in silent mode, the data are recorded in memory, but they are not transmitted. Actually they are recorded as already transmitted. Pressing UNITS and FUNC for two seconds toggles between silent mode and normal mode. When silent mode is enabled two dashes are displayed on the top-right instead of showing the number of data to transmit.

Silent mode can be used to take a measurement that you don't want to be in the survey. Beware that switching silent mode on clears the "transmit" flag of the data in memory.
When you take survey shots or calibratin data you must make sure that the silent mode is not enabled: the number of data to transmit must increase.

Calibration mode

The DistoX2 toggles between calibration mode and normal mode by pressing the CLEAR and SMART for two seconds. In calibration mode the distance is not measured (there is no need of a target to take a shot), and the raw sensor values are recorded and transmitted. These data are used to compute the calibration coefficients that can be uploaded into the DistoX2. These coefficients are used to transform the sensor values to XYZ values in the "ideal" frame of reference of the DistoX2, from which azmiuth, inclination

and roll are computed,
In calibration mode the screen displays "CAL" and the number of calibration data. The calibration data stored in memory can be analyzed: press the UNITS key to see the last data and PLUS or MINUS to navigate the memory. When a data is displayed, you can cycle through additional information using the SMART key

• combined acceleration XYZ sensor values
• magnetic field XYZ sensor values
• on-board acceleration XYZ sensor values
• separate acceleration XYZ sensor values

The last two are available only for the last reading.

Beep, Backlight, and Bluetooth

Pressing REF and MINUS two seconds toggles the beep sound on and off. *The beep is useful for the instrument person to have a feedback sound, therefore it is advisable to keep it on.*

REF and PLUS switches the screen backlight on/off. *Switching off back illumination saves power. The screen backlight is not really necessary and it is safe to keep it off, and save battery power. When the laser is off, the backlight doubles the power consumption.*

Pressing CLEAR and FUNC turns the bluetooth on/off. When bluetooth is on the DistoX2 is always *discoverable*. The device bluetooth name is DistoX-AAAA where AAAA is the serial number. The DistoX2 bluetooth pairing PIN is 0000 (four zeros). While the DistoX2 is connected to a bluetooth device, it does not switch off even if it is inactive. The bluetooth is necessary to transfer the data to the Palm/Android.

Device information

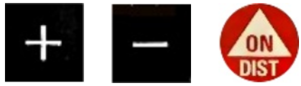
The FUNC key shows the device information. You navigate forward in the set with FUNC and backward with SMART. As usual CLEAR exits this mode.

The first screen shows the battery voltage and type ("LI" for LiPo, "AL" for alkaline). The voltage is about 4.2 V when the battery is fully charged. It discharges to 3.2-3.5 V, but most of the energy is used before 3.8 V. The battery type can be changed pressing FUNC and SMART for five seconds. The setting must be consistent with the battery in use (rechargeable installed inside or AAA cells respectively).
The second screen shows the hardware and firmware versions, and the device serial number.
The third screen displays the illumination level (between 1, dark, and 10, bright). To change the level press PLUS and MINUS for two seconds to enter editing and use PLUS or MINUS to increase or decrease the value. Confirm the setting with FUNC.
To switch the illumination completely off, disable it pressing REF and PLUS for two seconds. *Switching off the illumination saves battery power.*
The fourth screen displays the endpiece offset in mm, between -128 and 127. The default value is 27 mm. To change the value press PLUS and MINUS for two seconds to enter editing, then PLUS to increase, MINUS to decrease. The endpiece value is added to the distance when the reference is "extended".

Continuous mode

The continuous acquisition mode is available only with firmwares 2.4c and 2.5c. In the second info screen the firmware number has a small 'C' nearby. The continuous acquisition is started pressing PLUS and DIST for two seconds. In this mode the DistoX2 takes readings continuously until CLEAR is pressed. It is useful if you want to take really many splays, to construct a coarse 3D model.

Firmware upgrade



To upgrade the firmware on the DistoX2 it must be turned on in bootloader mode: press PLUS, MINUS and DIST at the same time. The screen remains empty. When the DistoX2 is in bootloader mode a firmware can be transferred to it via bluetooth. After the firmware has been upgraded switch it off pressing CLEAR.

A wrong firmware upgrade can damage the DistoX2. Read the proper documentation carefully before you upload a firmware.

Factory reset

Pressing CLEAR, FUNC and UNITS for five seconds resets the DistoX2 to the factory state. The memory is cleared, the settings are set to default values, and the calibration coefficients are reset to a neutral calibration.

Error codes

The DistoX2 error codes are the same as those of the DistoX version 1.

References
B. Heeb, DistoX2 user manual - Firmware version 2.4, 2015.01.22
B. Heeb, The next generation of the DistoX cave surveying instrument, CREG, 88 2014
B. Heeb, Inside DistoX2 - Leica Disto X310 based DistoX, Firmware version 2.1 - 2.3, 2014.07.30

In the following we use the term "DistoX" to refer to the DistoX (version 1) and to the DistoX2 (version 2) indistinguishably.

TopoDroid display has a black background to save battery during surveys. In this document TopoDroid screenshots have been inverted to false colors for better readability.

DistoX2 main functions (single press and release)

Power ON / Turn laser ON / Take reading

Cancel operation / Turn laser OFF

Change distance reference (Front - Tripod - Rear/Endpiece)

Set timer duration (with laser OFF) / Start timer (with laser ON)

Enter Memory mode - Show saved readings

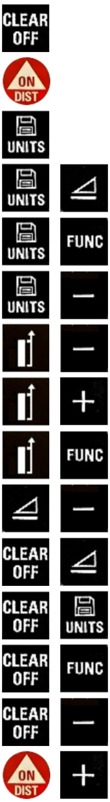
Scroll to previous reading (Memory) / Increase setting (Timer, Backlight, Endpiece)

Scroll to next reading (Memory) / Decrease setting (Timer, Backlight, Endpiece)

Show device information (Battery V, Serial Nr., Fw/Hw, ...)

Show extended measurement information

DistoX2 secondary functions (press and hold for 2 seconds)



Power OFF

Take reading (with laser ON)

Change distance units

Change angle units (degrees / grads)

Turn silent mode ON/OFF (---)

Turn backsight mode ON/OFF

Turn beep ON/OFF

Turn display backlight ON/OFF

Change distance reference (Rear / Endpiece)

Turn triple-shot check ON/OFF

Enter/Exit calibration mode

Clear unsent reading from memory

Turn bluetooth ON/OFF

Power OFF with button lockout

Take readings in continuous mode

DistoX bricolage and gadgets

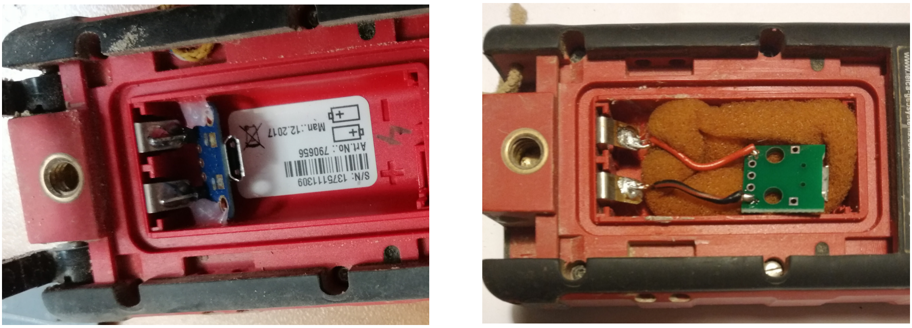
A problem with the DistoX version 1 is the loss of calibration due to the batteries moving in their slots. A solution, suggested by Heeb on his website is to put a piece of paper between the two batteries so that they cannot move.

Another problem was the necessity to calibrate it any time the batteries are replaced. To avoid this people have tried to use external batteries connected to the DistoX with an electric wire.

Piece of paper between the batteries (B. Heeb)
External batteries (clan.des.tritons.free.fr - 2009)

With the amagnetic internal battery the DistoX2 has solved the problems of the batteries.

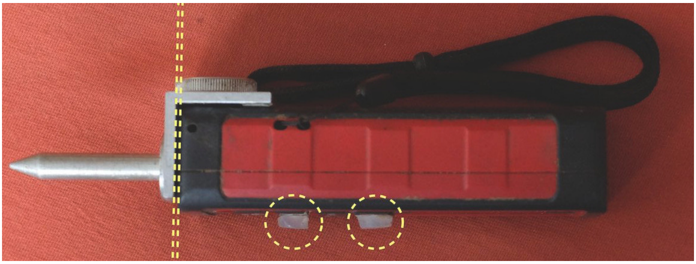
A weak point of the DistoX2 is the USB breakout board soldered to the battery contacts. The solderings are usually not strong enough to hold the board after repeated plug and unplug in the USB socket. The common solution is to hold the board in place with a drop of hot glue. Alternatively the USB board can be connected to the contacts with a couple of wires, either soldered or with two fastoms. This makes replacing the USB board simpler in case the USB socket breaks off the board.



USB board fixed in place with two drops of glue (Photo G. Cergol), or connected with two wires. The padding prevents the USB board from moving freely.

An important gadget for precise surveys is the tail extension. This allows a more accurate positioning of the reference point on the station. The DistoX2 reference must be set to "extended rear", and the correct length of the tail must be set. The tail should be on the line of the laser beam, but small deviations have negligeable effect because the length of the tail is smaller than the (usual) minimum shot length. Suppose that the tail is 5 cm while the minimum shot is 1 m. A misalignment of 5 degrees amounts to 5 mm. An offset error is moreimportant for the precision.

Othe useful gadgets are the two button extensions glued on the DIST and TIMER keys, to help recognize them by the touch.



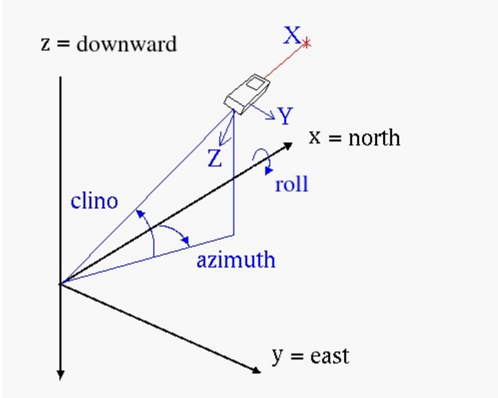
Precision gadgets (M. Sluka)

A DistoX case is useful to protect the device during transportation as well as during the survey.

DistoX2 waterproof case (Facebook page)

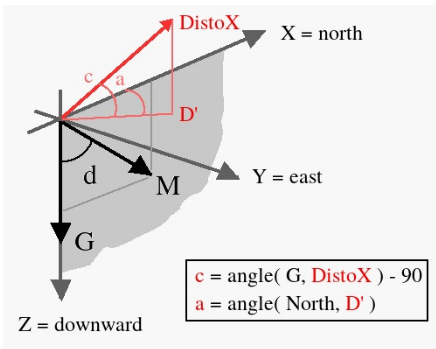
Calibration

DistoX mathematics



The triaxial sensors inside the DistoX are not perfectly aligned to the ideal reference frame of the DistoX (with the X axis in the direction of the laser beam). Furthermore the sensors have differences in gain and offset. Finally the magnetic field is affected by the hard-iron (resident fields) and soft-iron effects (induced fields) in the components inside the device.
The conversion from the values of the magnetic field and acceleration measured by the sensors to the components of these fields in the ideal frame of the DistoX can be sufficiently approximated by a linear transformation (with possibly a non-linear term for the acceleration). The calibration coefficients are the parameters of this transformation, and the "calibration" of the DistoX amounts to computing these numbers.

Knowing the values of the fields in the DistoX frame, it is easy to compute the direction of the X-axis in the world frame.
In the world frame (with Z vertical downward, X towards the magnetic north) **G**=(0,0,1) and **M**=(sin(d),0,cos(d)), where *d* is the angle between **M** and the Z-axis (d=90°-dip). If the DistoX has azimuth *a*, inclination *c*, and roll *r*, the DistoX frame is obtained from the world frame with a rotation of *r* about X, *c* about Y, and *a* about Z (world axes). Therefore, a vector **V**=(V_x, V_y, V_z), in DistoX frame, has components $R^t \cdot (V_x, V_y, V_z)$ in the world frame, where R is the rotation matrix $R_x(-r)R_y(-c)R_z(-a)$ that transforms a vector W=(W_x, W_y, W_z**)** in the world frame to R·W in the DistoX frame.
In particular G=(-sin(c), sin(r)cos(c), cos(r)cos(c)) in the DistoX frame. Therefore $tg(c) = - G_x/\sqrt{(G_y^2+G_z^2)}$.
To compute the azimuth consider the vector in the north direction, N=G^(M^G)/|M^G|. In the DistoX frame its X component is cos(a)cos(c).



The complete rotation matrix is shown on the right. The entries are $R_{ij}=\mathbf{e}^D_i \cdot \mathbf{e}^W_j$: the columns are the unit vectors of the world frame in the DistoX frame, the rows are the unit vectors of the world frame in the DistoX frame.
Below are the fomulas used to compute azimuth, inclination and roll.

$$R = \begin{vmatrix} cc\ ca & \boxed{cc\ sa} & \boxed{-\ sc} \\ -\ cr\ sa + sr\ sc\ ca & \boxed{cr\ ca + sr\ sc\ sa} & \boxed{sr\ cc} \\ \boxed{sr\ sa + cr\ sc\ ca} & \boxed{-\ sr\ ca + cr\ sc\ sa} & \boxed{cr\ cc} \end{vmatrix}$$

sin(r) sin(a) + cos(r) sin(c) cos(a) **n=G^M** **G**

In the DistoX frame:

- $\mathbf{G} = R_x(-r)\ R_y(-c)\ (\ 0, 0, 1\ )$
- $\mathbf{M} = R_x(-r)\ R_y(-c)\ R_z(-a)\ R_y(d)\ (\ 0, 0, 1\ )$

- $r = \mathrm{atan2}(\ G_y\ ,\ G_z\ )$
- $c = -\ \mathrm{atan2}(\ G_x\ ,\ \sqrt{(\ G_y^2 + G_z^2\ )}\ )$
- $a = \mathrm{atan2}(\ (G_yM_z - G_zM_y)|\mathbf{G}|,\ |\mathbf{G}|^2 M_x - G{*}M\ G_x\ )$

DistoX calibration

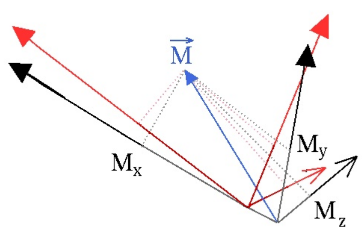
The purpose of the DistoX calibration is to find the coefficients of the linear transformation that maps the values Gs,Ms measured by the sensors to the calibrated fields Gr,Mr in the ideal DistoX frame,

$$Gr = Bg + Ag\ Gs$$
$$Mr = Bm + Am\ Ms$$

The offset vectors Bg, Bm and the 3x3 matrices Ag, Am are the coefficients of the calibration. If a non-linear term for Gs is used there are three more coefficients.

The calibration algorithm minimizes the total error, *E*, between Gr,Mr and the corresponding true values Gt,Mt, for orientations of the DistoX covering all directions, and rotations around the laser axis.

Components of the vector M, in the DistoX frame of reference, and in the sensors' frame of reference



$$E^2 = (1/n) \sum (Gt - Gr)^2 + (Mt - Mr)^2$$

where the sum is over many directions. The coefficients of the calibration enter the error through the expression of Gr,Mr in terms of Gs,Ms.

The algorithm repeatedly follows three steps until the variations of the calibrated fields Gr,Mr are very small:

1) minimize *E* with respect to azimuth, inclination, and roll
2) estimate the angle, *d*, between **G** and **M**
3) minimize *E* to find the calibration coefficients Bg,Bm and Ag,Am

The hypotheses (constraints) are that |G|, |M| and the angle between **G** and **M** are independent of the orientation and rotation of the DistoX. Furthermore the values of azimuth and inclination must be independent of the rotation (roll). Therefore the data that differ only by the roll form a group and they must yield the same values of azimuth and inclination.

Beat Heeb calibration algorithm

This calibration algorithm has been developed by B. Heeb for PocketTopo. The same algorithm is implemented also in TopoDroid and Auriga.

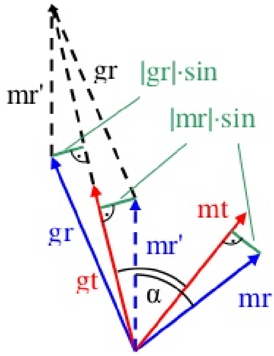
The minimization of the error function is carried out iteratively, under the hypothesis that the starting point is close enough to the global minimum. All the computation is done in the DistoX frame, In the linear algorithm, the calibrated values of gravity and magnetic field Gr,Mr are assumed linearly related to the sensor values Gs,Ms as described above.
For the non-linear algorithm instead of Gs a linearized value Gs' is used in which to each component of Gs a term proportional to its square minus 1/2 is subtracted. The coefficients of proportionality are the non-linear parameters N of the algorithm. N must be computed together with the linear coefficients. Here only the linear algorithm is described.

The minimization with respect to the parameters Bg,Bm and Ag,Am results in a linear system. This can be solved algebraically, provided the pairs of vectors Gs,Ms are evenly distributed over all directions.

Further unknowns are the rotation angles a,c,r of each direction. They enter the error through the true vectors Gt,Mt. The minimization of the error with respect to the roll r leads to the equation (for each direction)

$$Gr \wedge Gt \cdot x + Mr \wedge Mt \cdot x = 0 \qquad [1]$$

From this the roll angle can be computed.



Similar equations hold for y and z (minimization with respect to c and a, respectively). Therefore we have the vector equation

$$Gr \wedge Gt + Mr \wedge Mt = 0 \qquad [2]$$

which says that Gt,Mt lie in the same plane as Gr,Mr. This equation is solved "geometrically" as shown in the figure (copied from Heeb's paper).

The last requirement is that the laser beam is aligned to the X-axis of the DistoX frame. The minimization of the error for sets of measurements with common a,c but varying r (unidirectional groups) gives equations [1] for each roll, but the similar equations for a,c contain the sum over the data of the group,

$$\sum Gr \wedge Gt + Mr \wedge Mt = 0 \qquad [3]$$

We define the group average vector Gp = Rz(-c)(0,0,1) and similar for Mp. Then Gt=Rx(-r)Gp.

Define Ga=Rx(r)Gr, the calibrated vector that corresponds to zero roll. Then equation [3] becomes

$$(\sum Ga) \wedge Gp + (\sum Ma) \wedge Mp = 0 \qquad [4]$$

which is similar to equation [2], but involves the average calibrated vectors at zero roll, and Gp,Mp. This is solved geometrically like equation [2]. It effectively uniformizes the data at varying roll.

There is one more unknown: the angle d between G and M. At each iteration it is computed by minimizing the error with respect to d. Then tg(d) is the ratio between the averages of |Gt^Mr| and Gt·Mr.

Finally there remain an overall roll ambiguity. Any rotation about the X-axis of a calibrated pair Gr,Mr is also a calibrated pair because it yields the same values of azimuth and inclination. This ambiguity is resolved by imposing that the yz and the zy components of Ag are equal.

The linear algorithm steps are
[1] pre-compute the average of the sensor vectors and of their outer product matrix (for G and for M)

$$B^0 = E[\ Gs\ ]$$

$$A^0 = E[\ Gs \times Gs\ ]$$

Then precompute the matrix G^0 which is used in the step [9] to solve a linear system for the calibration parameters

$$G^0 = (A^0 - B^0 \times B^0)^{-1}$$

[2] estimate the angle a between G and M
[3] Initialize Bg = 0, Ag = 1, and same for Bm and Am.

[4] Compute Gr=Bg+Ag Gs, where Gs are the sensor values. Similarly for M
[5] For each group "adapt" the Gr.Mr vectors to those of the first data, rotating their plane to fit that of the first data
[6] Get the "true" group vector Gp,Mp
[7] Estimate sin(d) and cos(d) averaging the angles of the data
[8] Estimate the roll angles and the "true" data vectors
[9] Update Bg and Ag solving the linear system obtained from the minimization of the error function with respect to the calibration coefficients. Similarly for Bm and Am.
[10] repeat steps [4] through [9] until the change in the computed real values is small enough (success) or the algorithm has gone through too many iterations (failure)

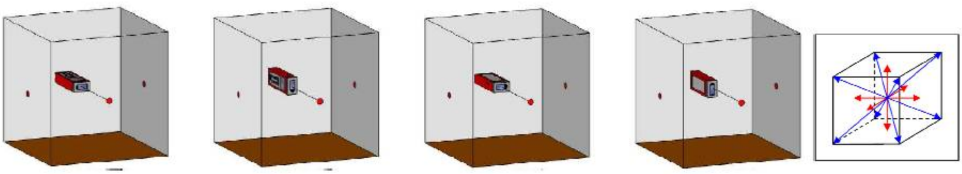
Reference

B. Heeb, A general calibration algorithm for 3-axis compass/clinometer devices, CREG Journal

Calibration in practice

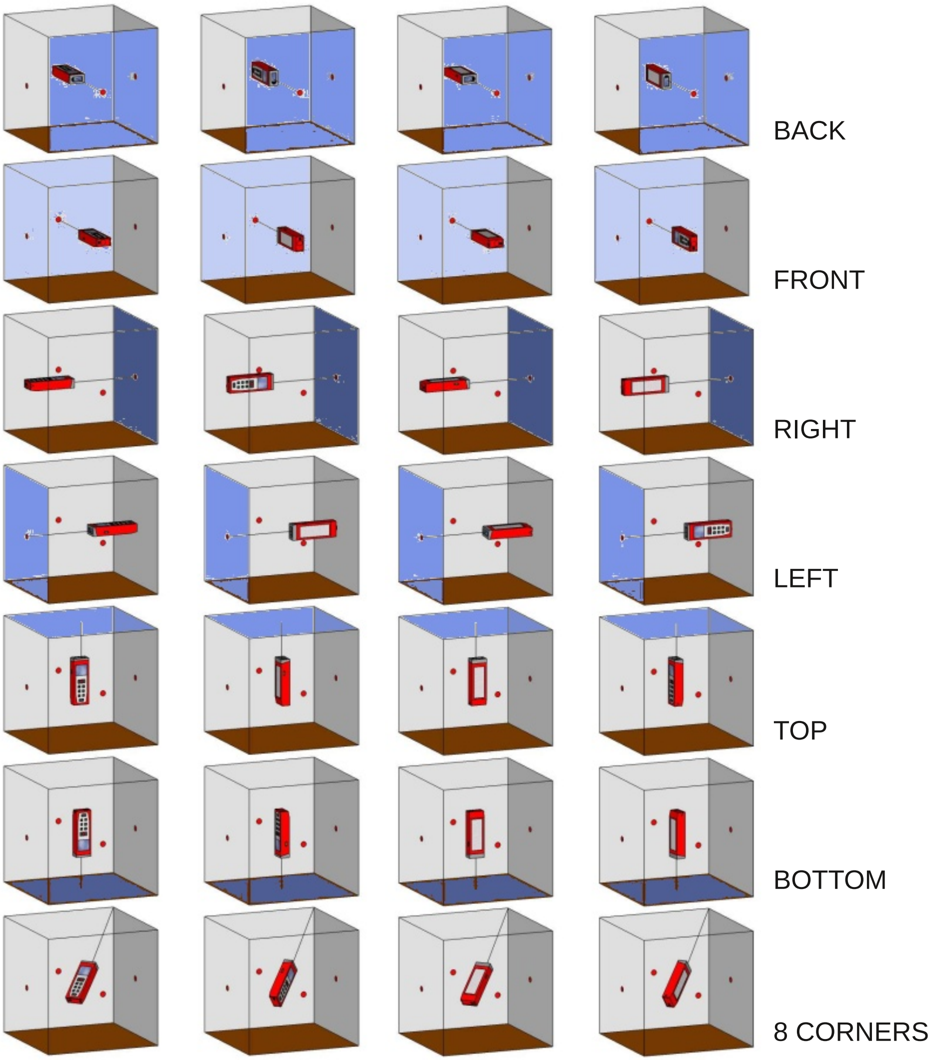
To calibrate the DistoX you need to take calibration shots in several directions at different angles of rotation about the laser beam. The suggested number is 14 directions and for each direction four shots with the DistoX screen facing up, left, right and down. To get the direction evenly distributed think of them as taken from the center of a cube to the center of the six faces, and to the eight corners. It is possible to take more data, ie, use additional directions.
As a minimum the four data forming the four unidirectional groups in the horizontal directions should be taken. They must be taken with care, using fixed points for the position of the instrument and the target.
The four rotations in the other 10 directions may not form a group. It is enough that their directions are close, but do not need to be "exactly" the same. In this case it is not necessary to use fixed points, and the shots can be taken in midair. Using groups for the other 10 directions as well, slightly improves the calibration, but requires more care and it takes a little longer to take the shots.
The uncertainty in the calibration data of a group must be at least as small as that expected in the survey. The calibration shots of a group should be taken with the target point at 3-5 m. A 5 cm error at 5 m makes a 0.6° difference among the shots. The DistoX must be accurately placed on the point. To avoid shaking the DistoX on pressing the DIST key, you can use the TIMER or the remote control when you take calibration shots.

The directions do not need to be exact. Approximate directions are good enough.



The four rotations of a unidirectional group and the 16 directions in the cube.

It is the 14 directions that are important, not the "cube". Therefore you can take the first horizontal direction from A to B, and the second from B to A, Similarly the other two could be A-C and C-A. Furthermore A-B can be slightly tilted, ie have a few degrees of inclination. Similarly it's enough that A-C is only roughly at 90° to A-B.



The calibration data must be taken in an environment free of magnetic disturbances. Caves or woods are good places to calibrate the DistoX. Since it is difficult to see the red dot of the laser when there is too much ambient light, it is better to calibrate the DistoX early in the morning or at dusk, or on a cloudy day, if you do it in the woods. In a house, near the buildings or power lines, the calibration is unreliable.
Be careful not to wear gadgets that might influence the magnetic field: watch, glasses, etc. The cave lamp can be disturbing, as any cave gear. Keep the Palm/Android at a suitable distance.

The calibration "degrades" with time. This is probably due to changes in the internal magnetic field (hard iron) or due to exposure to (intense) external fields. Mechanical shock can also affect the calibration. With the rechargeable battery it is recommended to repeat the calibration after a couple of months. With replaceable batteries it is necessary to repeat the calibration every time the batteries are changed.
It is a good practice to check the accuracy of the DistoX calibration before beginning a new survey (see section "Calibration checks"), and even in the middle of a survey if you suspect that there are some problems with the calibration.

References

B. Heeb, DistoX calibration manual, 11.27.2008

B. Heeb, DistoX2 calibration manual, 12.20.2013

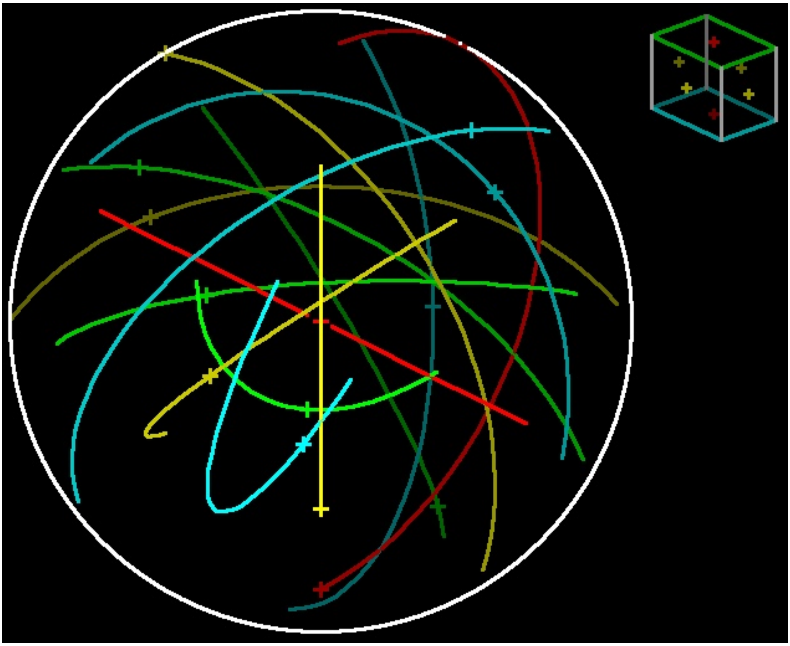
D. Bristol www.derekbristol.com/disto

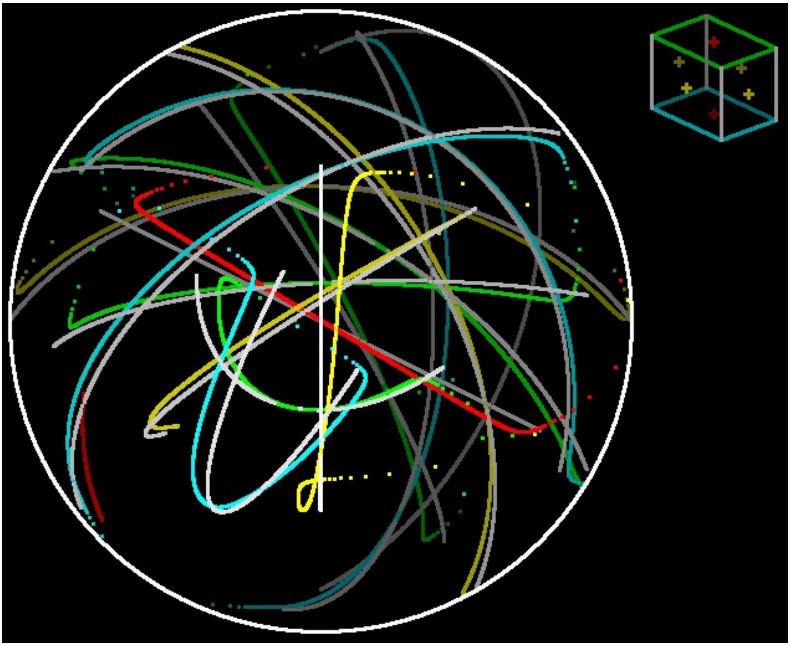
TopoDroid video course

The orientation space

What is the space of the orientations of the DistoX ?
If the calibration data do not include samples from a portion of the orientation space, the sensor readings for those orientations may not be properly compensated by the calibration transformation. An orientation of the DistoX corresponds to the 3D rotation that takes the world frame (East, North, Upward) to the frame of the DistoX.
The space of the 3D rotations is well known to mathematicians; they call it SO3 - O means that the transformations preserve orthonormality, S that they do not invert right handness, and 3 are the dimensions. It can be imagined as a solid unit sphere with diametrically opposed points on the surface identified. The center of the sphere is the zero-rotation. Any other point P=(x,y,z) defines a unit vector **u**=P/|P| and an angle φ = 180 |P|. That corresponds to the rotation of angle φ around the direction **u**.

On the next page there are two images of the orientations of the 14 cube directions in the sphere SO3. The point of view has inclination 30°, and azimuth 45°.
The top image shows the roll curves for the 14 orientations. Each direction orientations describe an arc inside the sphere, going from a point on the surface to the diametricaaly opposite point.
Red: orientations with X pointing up and down, Yellow: centers of four side faces. Green: the upper four corners, and blue the lower ones.
The bottom image shows the roll curves for the 14 orientation as seen by the sensors. The X direction is computed with the inverse of the transformation of G. Z is computed with the inverse of the transformation of M (this is an approximation). Y is computed as the unit vector normal to Z and X (another appproximation). The curves are slightly distorted from the ideal curves (in gray). The purpose of the calibration algorithm is to find the (linear) transformation that maps the dirstoted curves onto the ideal ones, without knowing the precise direction of the 14 orientations.

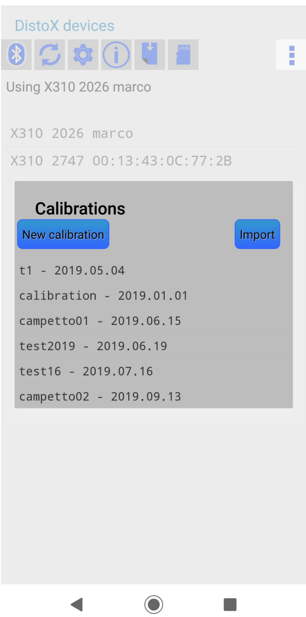




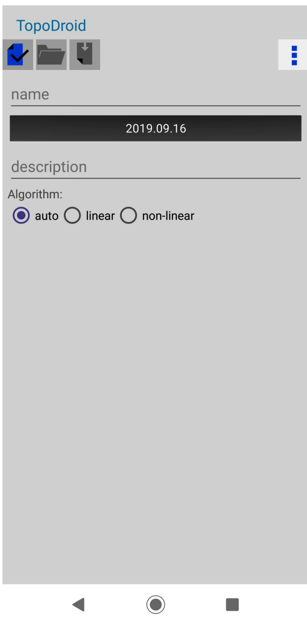
DistoX calibration with TopoDroid

Device Window
Open TopoDroid and go to the Device Window (left-most button of the Main Window).
If necessary, select the DistoX as working device, by tapping its entry.
From the Device WIndow open the calibration list dialog (third button) [1], which displays the list of the calibrations of the work device that are in the database. In this dialog tap the "New Calibration" button to open the Calibration Info Window.

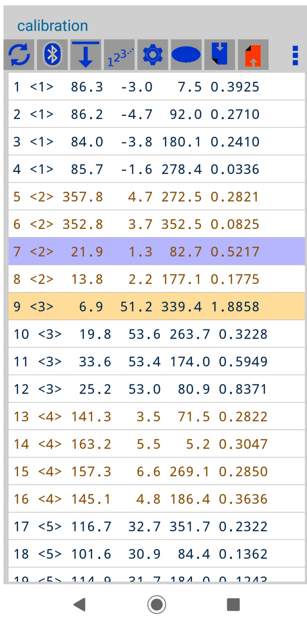
Calibration Info Window [2]
You must enter a name for the calibration, because TopoDroid distinguishes objects by the name. You can set the calibration date (the default is the current date), enter a brief comment to remind you where you did the calibration, and specify which calibration algorithm to use. By default



[1] Calib list dialog



[2] Calib Info Window



[3] Calib Data Window

TopoDroid is set to choose the algorithm automatically according to the DistoX model, so you can safely leave this choice to "auto". In general, the calibration of a recent DistoX2 should use the non-linear algorithm. The difference between "linear" and "non-linear" is often negligeable in normal surveying practices.
Finally save the new calibration (left-most buttom). At this point the other buttons become active, and you can open the Calibration Data Window (second button).

Calibration Data Window [3]
This window will be empty at first because you have not taken neither have you downloaded any calibration data. The buttons on the top are

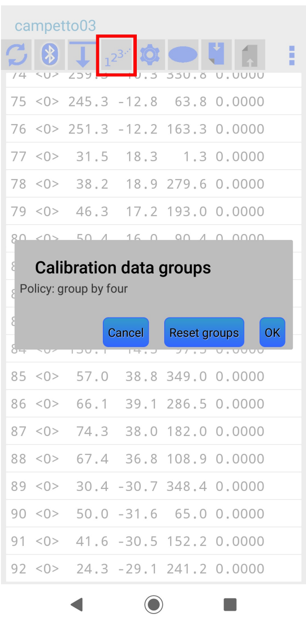
1. calibration mode toggle
2. bluetooth
3. data download
4. group assignment
5. calibration computation
6. distribution of the data directions, and G,M field values
7. calibration coefficients download
8. calibration coefficients upload

Toggle the DistoX to calibration mode. This can be done with the left-most button or with the DistoX keys (CLEAR and SMART for two seconds). The DistoX must be on. The same button is present in the Device Window too.

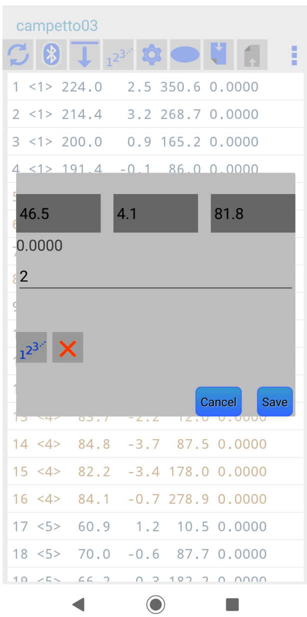
Now take the 56 or more, calibration shots. To take shots more precisely you can use the DistoX TIMER, or TopoDroid remote control (drop-down menu of button 2).
When you are done, download the data (button 3).
Each data entry shows
- the order index
- the group number of the data
- the data values: azimut, inclination, and roll computed without calibration
- the data error in the calibration. 0 if the calibration hasn't been computed yet, or the data is excluded from the computation.

It is possible to display the raw data values as well, either in hex or in decimal. This is useful only for debugging.

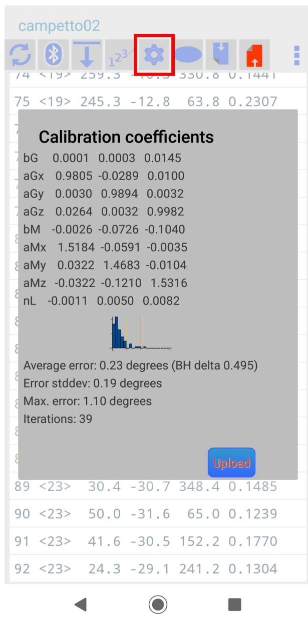
Divide the data in groups of four (fourth button) [4]. You can choose the group policy, either groups of four data (TopoDroid policy), or four groups that represent four horizontal directions, followed by individual data (PocketTopo policy).
The calibration data group is denoted by a positive number. Data with even group number are displayed in orange, those with odd group number in blue.
A group number "0" (zero) denotes a data that must be "excluded" from the computation of the calibration, but still considered in the automatic group assignment.
A negative value (-1) denotes "deleted" data. Data with number 0 are gray. The display of data with negative number is controlled by a menu ("SHOW DELETED"). Deleted data do not enter in the calibration computation, nor in



[4] Data grouping dialog



[5] Calib data edit



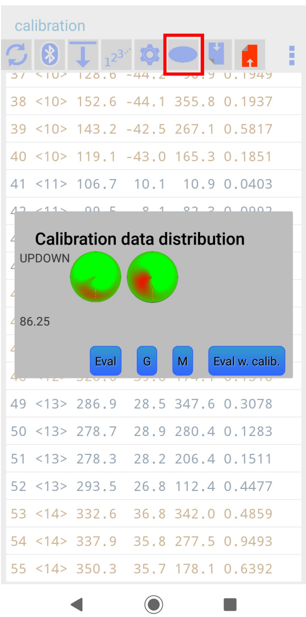
[6] Calib coefficients display

the group assignment. "Excluded" should be used for data poorly taken, for example not holding the DistoX firmly. "Deleted" for data taken by mistake. You should not exclude bad data from the calibration computation for the sole purpose of reducing the calibration error.
Partially received data are violet. They are automatically marked "excluded".

Tapping a data entry opens the data edit dialog [5]. It displays the data values (azimuth, inclination, and roll) and the data error in the calibration. Through this dialog you can change the data group number (entering also 0 or -1), mark the deleted data, and renumber the following data.

Compute the calibration coefficients (fifth button) [6]. The result of the calibration is shown in a dialog displaying the calibration coefficients, the average, standard deviation, and maximum of the residual errors of the data in degree, and the value "delta" as reported by the original algorithm of Beat Heeb. This is the final variation of the data when the algorithm terminates. There is also a histogram of the data errors: the yellow mark is 0.5° and the red mark is 1.0°.
The dialog has a red button to upload the calibration coefficients to the DistoX. The upload can be done from the Calib Data Window with the last button (red up-arrow) as well.
A warning appears when you try to upload a calibration with coverage below 95%.
Finally toggle the DistoX back to normal mode (button 1)

The sixth button displays how the data cover all directions [7]. The dialog shows the coverage on the upper hemisphere (left) and lower hemisphere (right). The vertical direction is at the center of the circles. The horizontal directions are on the border: North at the top, East at the right, South at the bottom and West at the left. The



[7] Data distribution display

circles are green where the directions are covered by the data, and reddish where the coverage is poor.
It is possible to display direction distributions for

- uncalibrated data
- data corrected with the calibration
- data magnetic field in DistoX frame
- data acceleration field in DistoX frame

The numerical value of the percent coverage is also shown.

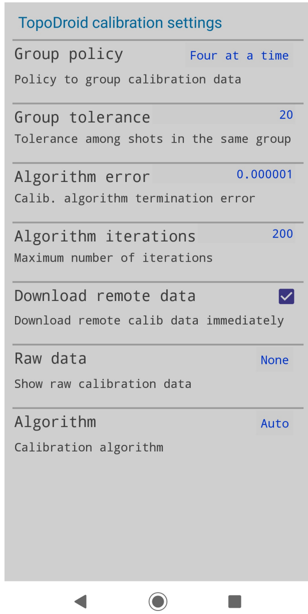
If you find that some directions are not well covered by the calibration data, you can take more data and add them to the calibration. The new data are appended at the end and the automatic group assignment will not change the old data.

The background color of the calibration data is used to highlight

- data with saturated values (magnetic field exceeding the range of the sensors) [orange]
- data that are different from the average of the group more than a set angle [green]
- data with error over 1.0° [red]

TopoDroid calibration settings

The calibration settings are
- algorithm termination error [0.000001]
- maximum number of algorithm iterations [200]
- group automatic assignment policy [either *TopoDroid* or *PocketTopo*]
- off-group highlighting threshold [40°]
- whether to display raw data [default no]
- immediate data download with the remote control [default yes]
- default calibration algorithm ["auto"]



Calibration settings

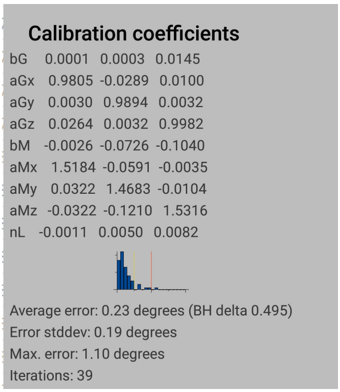
Comparison of group policies

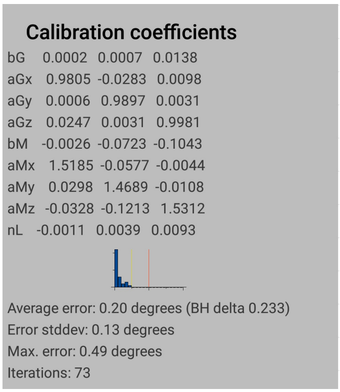
Here we compare the results of the two calibrations on the same set of data, divided in groups following the *TopoDroid* policy (groups of four) and the *PocketTopo* policy (four groups of four followed by individual data).

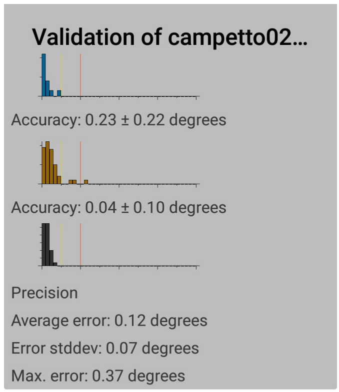
With *TopoDroid* policy there are 23 groups of 4 data. The algorithm takes 39 iterations. The final error is 0.23°±0.19°. The maximum error is 1.10° and the "delta" 0.495.
With *PocketTopo* policy there are 4 groups of four and 76 individual data. The algorithm takes 73 iterations. The final error is 0.20°±0.13°. The maximum error is 0.49° and the "delta" 0.233.
The apparently better results of the second policy (also apparent from the histograms of the errors) are due to the smaller number (16 vs 92) of data involved in the computation of the error. The "delta" takes into account also the final variations of the individual data.

The *TopoDroid* policy terminates in less iterations. The transformation interpolates the data rolls in all the directions. That of *PocketTopo* policy fits more closely to the roll of the individual data off the horizontal plane. This justifies its higher number of iterations.
"Delta" is the final variation of the data when the algorithm terminates. *PocketTopo* policy's smaller delta can be explained by its trasformation being closer to the individual data off the horizontal plane.

The outcome of the validation (see p. 51) between the two calibrations is consistent with this interpretation. The error distribution of *PocketTopo* policy (blue histogram) is closer to 0, because it includes only the horizontal data, while *TopoDroid* policy (orange histogram) is more spread out due to the off-horizontal data. The relative comparison of the two calibrations (grey histogram) show a discrepancy of 0.12°±0.07° with a maximum of 0.37°.
The inspection of the numerical data shows that the average discrepancy increases with the inclination angle. It is 0.09° for the set of "horizontal" data (inclination below 25°), 0.13° for those at intermediate inclination (between 25 and 65°), and 0.20° for data at high inclination.







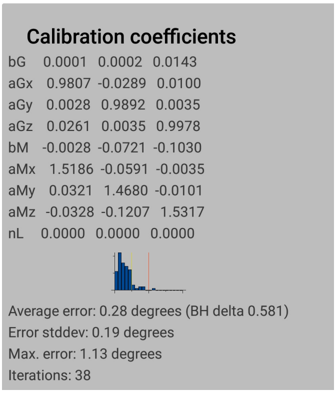
The validation errors between calibrations with the same group policy, done at different times, confirm that the *PocketTopo* policy tends to overfit the data off-horizontal, while the *TopoDroid* policy interpolates among them, and is more stable in time.
The differences are nevertheless rather small, and negligeable in the usual surveying practice.

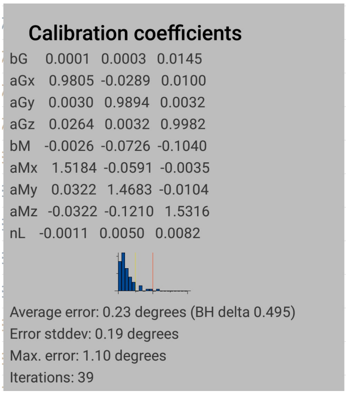
	TopoDroid policy	PocketTopo policy
2 months	0.24±0.15° (max 0.73°)	0.32±0.23° (max 1.15°)
4 months	0.19±0.12° (max 0.61°)	0.32±0.22° (max 1.14°)
8 months	0.25±0.17° (max 0.78°)	0.34±0.22° (max 1.10°)

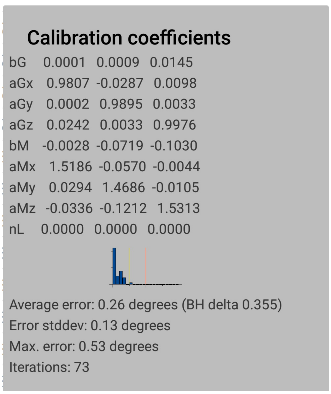
Comparison of calibration algorithms

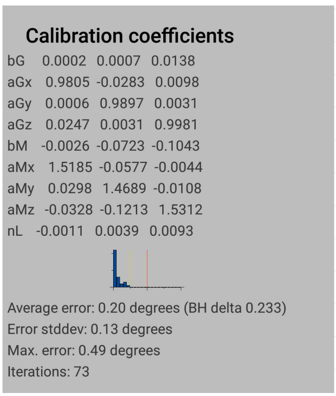
The images below show the results of the calibrations computed with the "linear"(left) and the "non-linear" (right) algorithm on the data. These are divided in groups by the *TopoDroid* policy (groups of four: top) and the *PocketTopo* policy (four groups of four plus individual data: bottom).

Apparently the difference between the non-linear algorithm and the linear one is very small, and it is irrelevant unless a very precise survey is needed..









Calibration rigs

One of the major difficulties with the calibration process is to place the DistoX on the exact spot and aim at the target. Several people have tried to render the process easier using calibration rigs, devices that help taking the calibration shots, either more accurately and more uniformly distributed in all the directions.

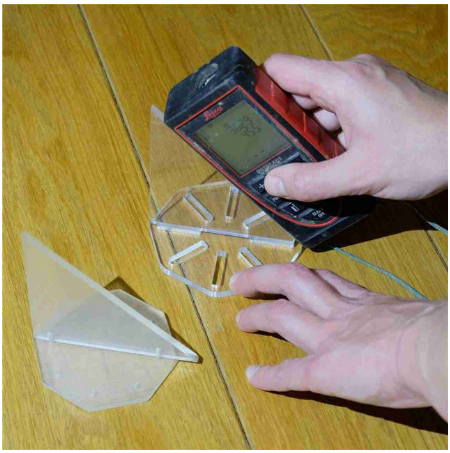
Amatorial calibration rigs are usually personal devices created by the "inventor" for his own use. They are of single-user and remain at the level of prototype, or proof of concept.
Certain devices have been constructed with more care, and the idea and deisgn has even been presented at conferences.
Almost all these rigs assume that the DistoX frame is aligned with the laser beam. Unfortunately this is often not the case as the two can differ even by degrees. This can be compensated either by adding spacers to the DistoX, or by mounting suitable slots on the rig where the four DistoX faces can be placed. In the first case the spacers can worn out during the use of the DistoX in cave. In the second case the calibration rig is good only for one DistoX.

Calibration rig (B. Pease)

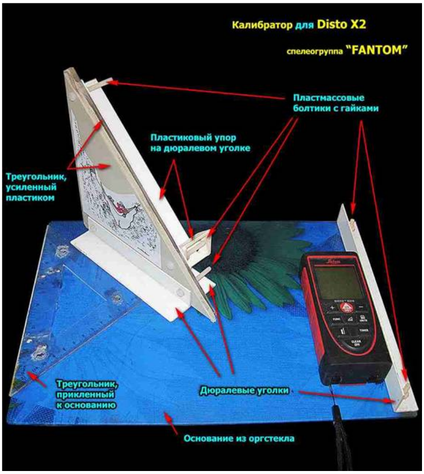
Calibration rig (M. Consolandi)

A calibration rig that addresses and solves this probem is the cube, a cube-octahedron with slots to hold the pole of a DistoX support. Overall there are 26 directions, guaranteeing a good directional distribution. The DistoX support has a three-screw regulator that permits to fine tune the orientation of the DistoX so that the laser axis gets aligned with the pole of the support.
A simpler, yet interesting calibration device is shown in the video youtu.be/_MPIsTRMdlg. A plastic tube holding a support for the DistoX, with a wooden circle glued at either end. The laser beam must come out through a small hole at the center of one circle. The tube can be rotated on a V-shaped wooden support, and the DistoX must be placed so that the laser beam stay fixed while turning the tube. To take the calibration shots the DistoX is controlled remotely.
Szymon Kostka's calibration rig is similar. All parts are aluminum and plexyglass. The screws aer brass. This rig is for the DistoX version 1 and it necessarily has a target for the laser beam.

AESDA (F.T. Regala)



Astrolabio



Fantom

Calibration frame in PVC. Side bars are 60 cm long (Ph. Balister)

Cuboctahedron (W. Formella)

Calibration cube first model (N. Kozlov)

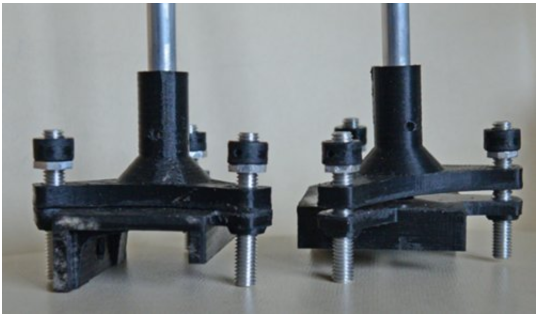
References

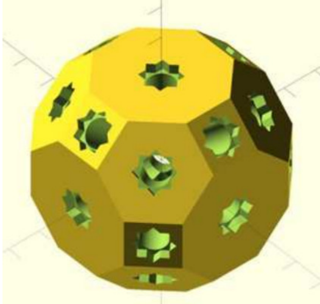
F. Tata Regala, AESDA calib - un calibrador para DistoX/X2, 6 Congreso Nacional de Espeleologia, Federacao Portuguesa de Espeleologia, 2016 77-82

Astrolabio

B. Pease, Paperless surveying update, NSS Convention, 2017

Calibration cube: https://bitbucket.org/ngry/distox2_cube





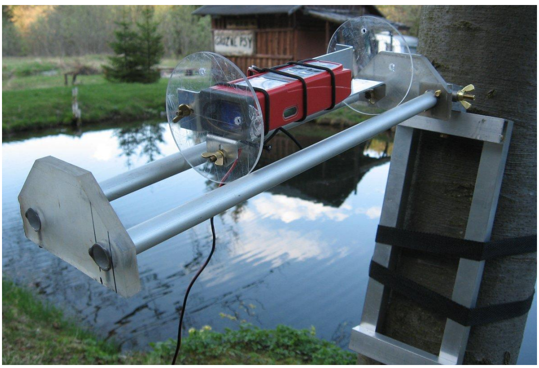
Calibration cube second model.

Details of the tunable DistoX support and the cubeoctahedron.

(N. Kozlov)

Calibration cylinder

(K. MacLeod)

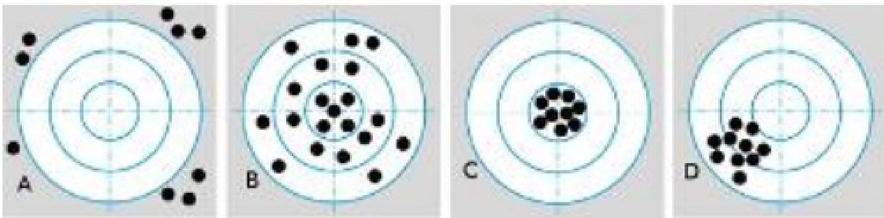


Calibration rig

(S. Kostka)

Accuracy and precision

Precision describes the uncertainty (error) in values taken by repeated readings. If the values are close to one another the measurement is precise. If they are spread out it is less precise. Precision is like the number of significant figures in the measured value; the more the significant figures the higher the precision.
Accuracy has to do with how close the measured value is to the real value. A measurement can be precise and yet inaccurate if the measured value is off-target. A miscalibration of the instrument can result in a poor accuracy.

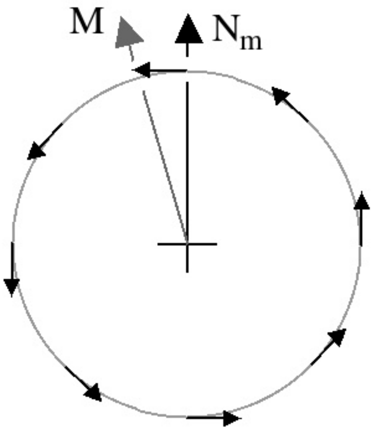


Accurate (B and C) versus precise (C and D).

The calibration of the DistoX is necessary to have an accurate instrument. The quality of the calibration is then the accuracy of the instrument.
However the accuracy and the precision of the data, do not depend only on those of the DistoX. In the measuring process the positioning of the DistoX on the station, and its aiming at the target are also crucial. The precision in positioning and aiming can easily be worse than that of the calibrated DistoX, so the final precision of the data is effectively determined by these two operations.
The accuracy can also be compromised by a sloppy measuring practice. Shooting off-target and false reflections can give a wrong distance. Magnetic influences, especially due to the batteries of the headlight, can result in inaccurate azimuth angles.

The compass and clino set is not intrinsically accurate. It is possible (and easy) to calibrate the clino so that the values of the inclination are "accurate". However there is no way to eliminate an overall declination in the

compass without resorting to an external reference (which is usually not very simple).
The calibrated DistoX, on the other hand, is intrinsically accurate. The calibration procedure of the DistoX does not need any external reference, and still one can get a well-calibrated, accurate, instrument. This is due to the fact that the DistoX has 3-axial sensors and measures all the components of the magnetic field and the acceleration. The compass, on the contrary, "measures" only the horizontal components of the magnetic field.

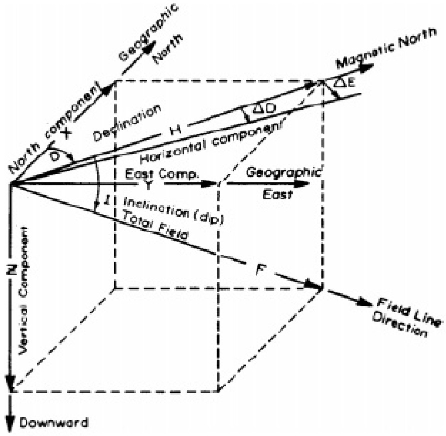


Overall declination for the compass

The accuracy of the DistoX is an intrinsic property which can be proved theroretically. An ideal DistoX is absolutely accurate. If a device is such that for every three points A, B, and C, it measures lengths with zero error, the measured directions A-B and B-A are exacty complementary, and the triangle ABC closes with zero error, then the device is absolutely accurate.

The calibrated DistoX is only an approximation to such an ideal device, It differs from the ideal device by the range of precision of the measurements. Therefore a calibrated DistoX is accurate within the limits of its calibration precision.
The precision of the distance measurements, according to the DistoX user manual is 2 mm, for distances between 0.05 m and 10 m. This figure is from the Leica DISTO User Manual. For angles the root mean squared error is 0.5° (after proper calibration). In practice it is not hard to get an average error of 0.2-0.3° with standard deviation below 0.2°.

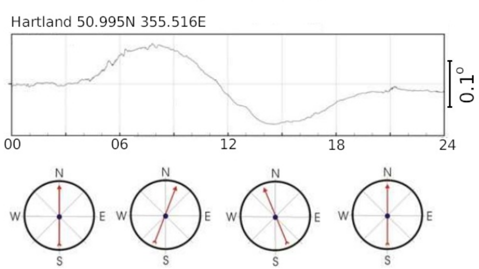
The Earth magnetic field



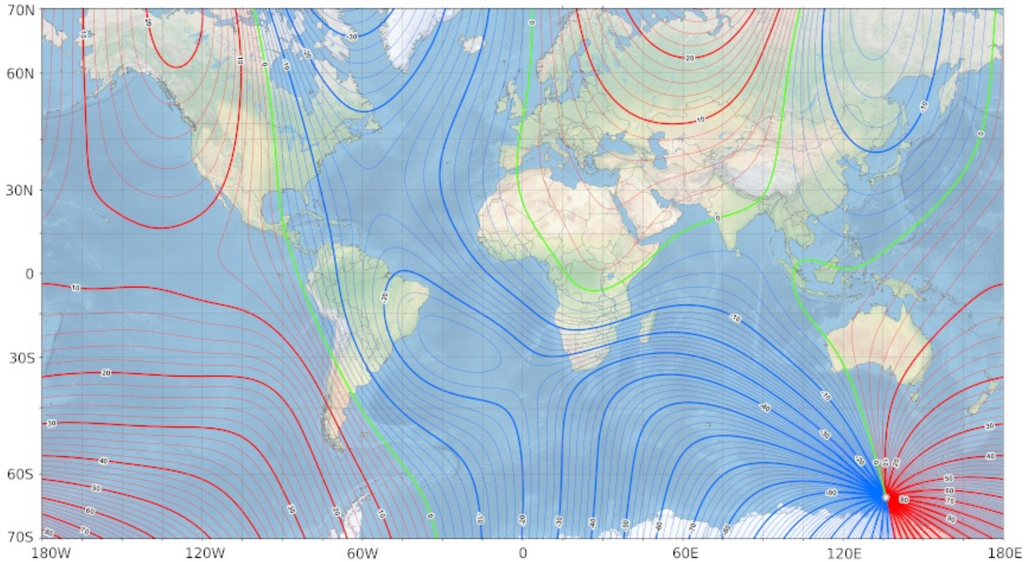
Cave surveying relies, normally, on the absolute reference system provided by the direction of gravity (downwards) and the Earth magnetic field. The precision of the cave surveying instruments is limited by the stability of the magnetic field. This issue was not important for the compass as its range of error (0.5°) is larger than the variations of the magnetic north. With the DistoX that measures all the components of the magnetic field and can be calibrated to 0.1°, the effects of variations in the magnetic field become a limiting factor for the precision of the instrument.

The Earth magnetic field is different at different places and varies in time. It is directed slanting downward in the nortern hemisphere, upward in the southern hemisphere. The plane containing the magnetic field and gravity defines the direction of the magnetic north as the line it intersects the horizontal plane. In cave surveying the azimuth values are usually referred to the magnetic north.

The Earth magnetic field is almost dipolar, its intensity varies from about 30 µT at the equator, to about 60 µT at high latitudes. The magnetic axis is tilted about 11.5° from the Earth rotation axis. Therefore the magnetic north is not aligned to the geographic north, the difference is the magnetic declination. It is positive when the magnetic north points to the east of the geographic north, and negative when it points west. The declination varies with the



Daily variations of the declination (about the average) in solar-quiet times.
Effects on the compass needle (exaggerated)



World magnetic declination map in January 2019.
Green lines are the agonic lines (zero declination isogones), red lines are positive declination isogones, blue lines are negative declination isogones.
Adapted from https://www.ngdc.noaa.gov/geomag/WMM/

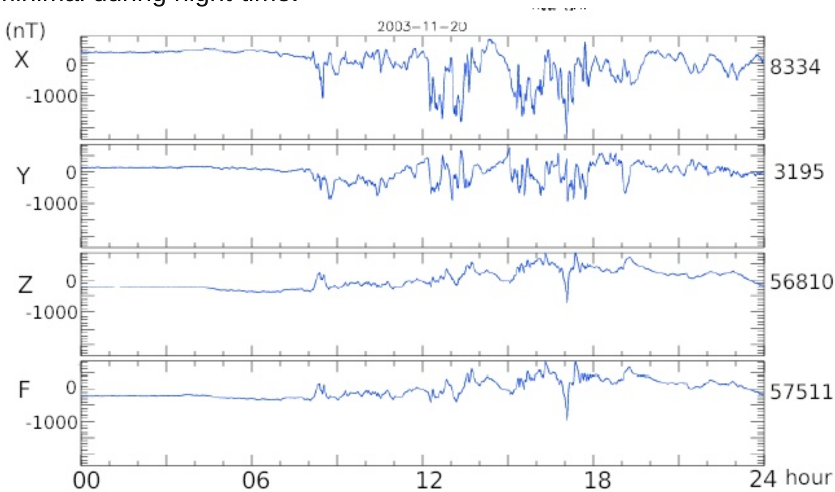
location and in time, and can be rather large, not only near the magnetic poles. The rate of change of magnetic declination depends on the place and is not regular. It can also have jerks.

The major source of the Earth magnetic field is self-sustained dynamo effect in the outer layer of the fluid part of the Earth core. In the core the field is likely multipolar, but at the Earth surface this field is approximately dipolar. The magnetic declination results from the non-dipolar components.

Other sources of the magnetic field (at the Earth surface) are: the magnetic fields in the ionosphere, and in the magnetosphere, and the fields generated by currents induced in the lithosphere (crustal fields) due to time-varying magnetic fields in the ionosphere and magnetosphere.

Long-time variations of the magnetic field are due to the dynamics of the Earth's interior. Their effects are pole migration, and reversal (during the epochs the Earth magnetic field has reversed many times). Secular variations result in changes in the declination.

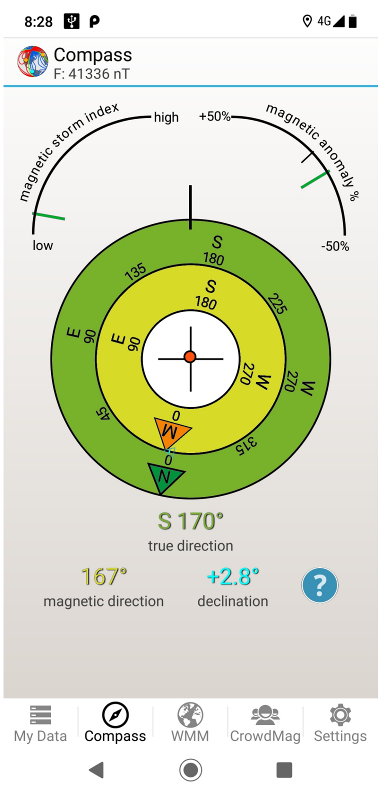
Short-time variations are daily variations due to solar radiation interaction with the ionosphere and magnetosphere, and the induced currents in the lithosphere. During periods of low solar activity (solar quiet) the daily variations are mainly caused by currents in the ionosphere where the solar radiation maintains a certain level of ionization. The ionization depends on the altitude, latitute, time of day, season, and solar activity. In the 80-200 Km range winds driven by the day-night temperature difference, and tides due to the gravity of the Sun and the Moon, produce a dynamo effect. The resulting variations in the magnetic field on the Earth surface are rather regular, with a daily period. The Y (east) field component is the most affected. The magnitude of these variations is about 10 nT, which means at most 0.1° in the measured azimuth. The result is that the magnetic north is turned a bit eastward in the morning and westward in the afternoon. These effects are larger during the summer as well as at high latitudes. The effects are minimal during night-time.



Magnetograms during a solar storm.
From the top: X (north), Y (east), Z (downward) components and F (total intensity).

Other regular variations have a period of 27 days, and are relate d to the solar day (the time of a Sun rotation, as seen from the Earth), and the Moon revolution around the Earth. There are also variations with a 11-year period connected to the 11-year period of the Sun activity.

During sun storms the variations of the magnetic field can be larger. The solar wind magnetic field interacts with the magnetosphere. During a storm the variations in the magnetic field at the Earth surface can reach a couple of 100 nT in temperate regions (in auroral regions they can go over 1000 nT). All components of the magnetic field are affected and their effect on the azimuth can be as large as 0.6°, but for particularly strong events it can be of the order of a few degrees. These effects last from few minutes, to hours and days.



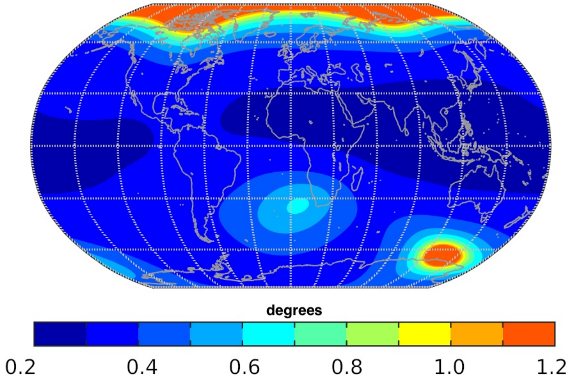
You can use the NOAA app *geomag* to get the local magnetic declination, as well as information about the solar magnetic disturbances.

References

https://www.gncd.noaa.gov/geomag
https://geomag.bgs.ac.uk/education/earthmag.html
J. Love, Magnetic monitoring of Eart and space, Physics Today, Feb. 2008, 31-36
V. Schmidt, Error due to magnetic variations, Compass Point, 2 1993

Geomap app screenshot.
Inverted background color (black).

World Magnetic Model



Declination uncertainty. Geomag website

Changes in the flow of the outer core of the Earth lead to unpredictable changes in the magnetic field. However the system has a large inertia and the changes have time scales of several years. Therefore accurate prevision of the field can be made. The World Magnetic Model (WMM) is a prediction model that can be used to compute the magnetic declination at each location. It is issued every five years by the NOAA, National Center for Environmetal Information. It is very accurate on the release date, and deteriorates with the years. In temperate regions its accuracy stays within 0.4° normally.

The WMM predicts only the long-wavelength (3000 km) portion of the internal Earth magnetic field. The portion of the field generated by crust, upper mantle, ionosphere, and magnetosphere are largely unaccounted for. Therefore spatial and temporal deviations (anomalies) from the WMM can be observed. In certain areas anomalies can exceed 10°. Anomalies of 3-4° are not uncommon, but are usually of smaller spatial extent.
The Enhanced Magnetic Model (EMM) includes crustal fields down to 56 km wavelength.

The WMM model includes uncertainty estimates for every geomagnetic element. This includes both the inaccuracies in the model coefficients, and the missing contributions to the total geomagnetic field, such as the crustal field. The uncertainty is around 100 nT for each component. That of the declination is between 0.2° and 0.4° in temperate regions (see figure).

Reference
https://www.ngdc.noaa.govgeomag/WMM/limit.shtml

IGRF

Declination	
Model Used:	WMM-2020
Latitude:	45° N
Longitude:	9° E
Date	**Declination**
2020-01-07	2.82° E ± 0.36° changing by 0.15° E per yea

Declination	
Model Used:	IGRF2015
Latitude:	45° N
Longitude:	9° E
Date	**Declination**
2019-01-07	2.60° E changing by 0.13° E per year

Declination	
Model Used:	EMM2017
Latitude:	45° N
Longitude:	9° E
Date	**Declination**
2019-01-07	2.59° E changing by 0.15° E per year

The IGRF (Internation Geomagnetic Reference Field) is a standard mathematical description of the Earth's main magnetic field, which is mostly due to the Earth's core (and is 45000 nT on average at the surface). There are also contribution from the crustal fields (200-300 nT).
The IGRF is the obtained from magnetic field data from satellites, observatories, and surveys around the world.
It models the magnetic potential V(r,θ,φ,t) as a truncated series

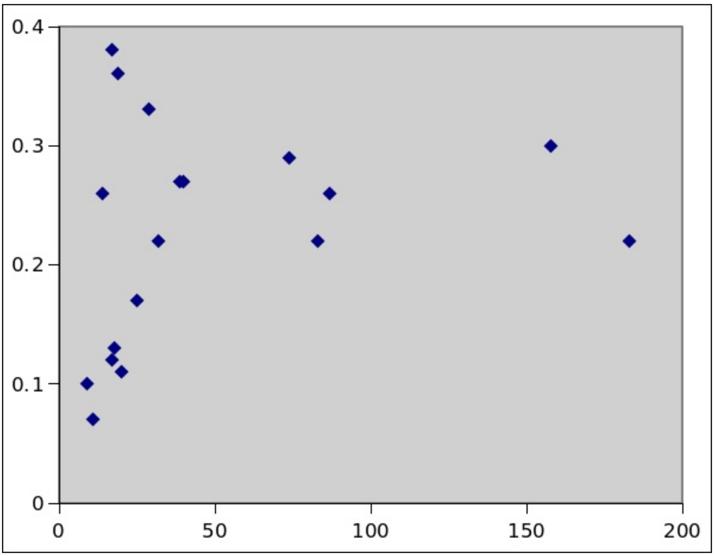
$$V = a \sum (a/r)^{n+1} [\, g(n,m,t) \cos(m\varphi) + f(n,m,t) \sin(m\varphi) \,] P_{n,m}(\cos(\theta))$$

where a = 6371.2 km, and the sum runs over n=1..13, and m=0..n.
The model is inherently approximate. The series expansion is truncated, the series coefficients are obtained from numerical observations, and the observed field has contributions which are not in the IGRF model. The model accuracy can be expected to be 10 nT rms (5 nT rms in the horizontal components), but at places where there are not much data it can be larger. The uncertainty increases typically by 20 nT/year due to the secular variations.

The image above shows the differences between WMM, EMM, and IGRF (www.ngdc.noaa.gov/geomag/calculators/magcalc.shtml)

Survey precision

The precision of survey data depends not only on the precision of the calibrated DistoX, but also on the whole process of taking the survey data. The precision of the DistoX is the lowest bound, below which one cannot expect the data uncertainty to go.
TopoDroid can estimate the precision of the survey data by comparing the direction of each leg shot againt the leg average. For a normal survey this is usually between 0.2° and 0.3° (see figure).
TopoDroid computes the accuracy of the survey from the loop closure errors. The expected closure error is $E = L P / \sqrt{N}$, where L is the length of the loop, N is the number of legs in the loop, and P the data precision (in radians). Inverting this formula one can estimate the data precision. This is normally less than 1°. Compared with the accuracy of compass and clino surveys, which can be expected to be 2.5° (M. Corvi, L'accuratezza del rilievo di Fornitori, Erba in Grotta, 2 2010, 122-127), the use of the DistoX has improved the accuracy of cave surveying.



Survey data precision computed with TopoDroid, as a function of the number of survey legs.

The stability of the reference (the direction of the magnetic north) is a limiting factor to the precision attainable in a cave survey with the DistoX. It combines with the other sources of errors:

- precision of the calibrated DistoX,
- error in positioning the DistoX on the station,
- error in aiming at the target.

These three errors are statistical; their effect is reduced by taking multiple shots for a leg (by a factor $\sqrt{3}$ for the three shots of the leg).

The error due to the reference is "systematic" and time dependent. In principle it can be corrected knowing the time the shots are taken (TopoDroid records the time when the shot is downloaded in the database) and the deviation of the average declination (which can be obtained from the geomagnetic data). Without this knowledge, it can be considered as a statistical error of order 0.1° - 0.2°.

The positioning and aiming errors are typically 5 cm. For a 5 m shot it corresponds to about 0.5°. They can be reduced to 2-3 cm using a DistoX extension (0.3°) and even more with a tripod mounted DistoX (0.1°).

A good calibration can achieve a precision of 0.2° - 0.3°. This is good enough for a typical survey, of precision range 0.5°.

For surveys done with the DistoX extension, a calibration precision of 0.1° becomes important. With much care this precision can be achieved even without a calibration rig. A proper rig would make the job much easier. At this level the declination uncertainty becomes important. The EMM model is necessary. The overall survey precision is still about 0.3°.

If one wants to attain a better precision, say 0.1° - 0.2°, a tripod mounted survey with foresight/backsight legs is necessary, as well as a very precise calibration (0.1°) and the correction for the local instantaneous values of the magnetic declination.

DistoX magnetic sensitivity

The DistoX is more sensitive to magnetic influences than the compass, because it measures the magnetic field in 3 dimensions while the compass measures the horizontal component of the field. Furthermore, the soft-iron internal fields are sensitive to the variations of the external field, which can arise from spontaneous fields (magnetized objects or item producing a magnetic field), or induced fields.

The following is a list of the indicative distances, in cm, from the DistoX at which the magnetic influence of the object produces a variation of 0.1° and 0.5° respectively. You should check the influence of your own gear.

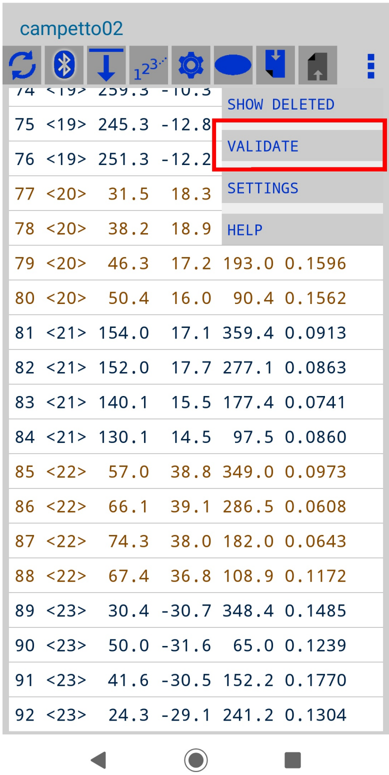
Cell phone/tablet	60 cm - 30 cm
Headlight batteries	40 cm - 25 cm
Fix	35 cm - 25 cm
Wrist watch	15 cm - 10 cm
Zebralight	30 cm - 15 cm
Caving hammer	30 cm - 15 cm
One piece of caving gear	20 cm - 10 cm
Steel carabiner	20 cm - 10 cm
Anchor steel plate	10 cm - 5 cm
Headlight (with batteries on the back of the helmet)	no effect
Aluminum carabiner	no effect

The phone/tablet, should not be kept too close to the DistoX. This is usually a caution only in solo-survey.
The instrument person must pay attention not to take shots with the headlight batteries near the DistoX. While this is not normal in large galleries, it may happen in tight passages and crawlways.
Somehow the fix steel has a strong influence on the magnetic field. Therefore, on pits the stations should be placed at at least 30/40 cm from the anchor.
Caving gear are usually at a safe distance, but you should be aware that it can influence the measurements.

Calibration validation

TopoDroid has a function to validate a calibration.
This function compares the current calibration against another calibration of the same DistoX, and it computes three histograms (distributions); the yellow bar is the 0.5° mark, and the red bar the 1.0° mark. The statistics are displayed also numerically. A calibration validation should compare two independent calibrations of the same DistoX done at about the same time, or not far apart in time. If a long time has passed between the two calibrations the effects due to the variations in the hard iron and soft iron invalidate the calibration validation. From a different perspective the validation function can be used to acertain the drift of calibration coefficients for a DistoX.

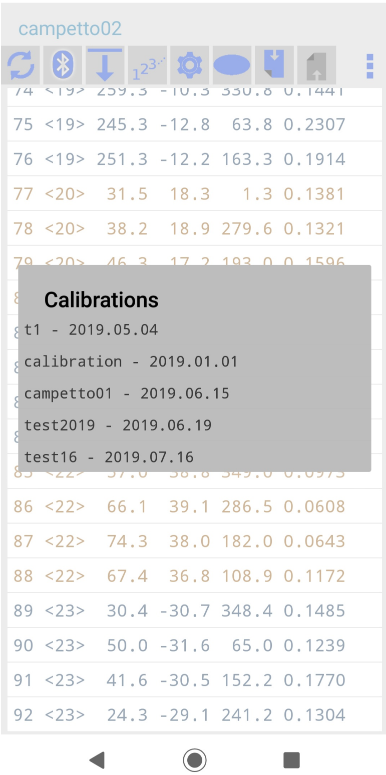
The first histogram (blue) displays the angle difference between each shot of the current calibration and the shot group average, when the data are corrected with the coefficients of the other calibration.
The second histogram (orange) reverses the roles of the two calibrations; it displays the angle differences of the shot of the second calibration corrected with the coefficients of the current calibration.
These first two histograms are indicative of the accuracy of the DistoX calibration process.



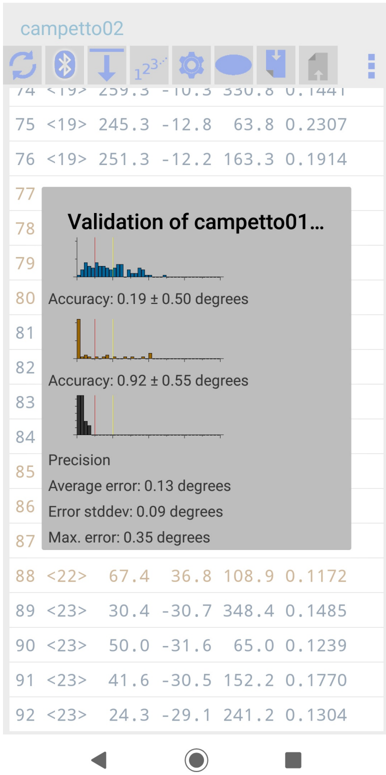
Validation menu

The last histogram (grey) displays, for all the shots of the two calibrations, the angle differences beween the values obtained correcting the shot with the two calibrations. This is indicative of the precision of the calibration, ie, how much a data value can change due to uncertainties in the calibration coefficients.

To validate a calibration tap the menu "VALIDATE" of the Calib. Data Window. In the coming dialog select the calibration against which you want to validate the current one by tapping it. TopoDroid performs the validation and displays the result.



Validation calibration list



Validation result

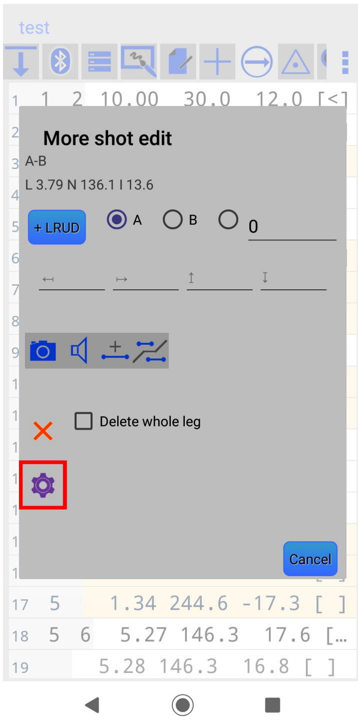
Calibration checks

We have seen that well-calibrated ideal DistoX has: no error between foresight and backsight shots, no error in closing triangles (three leg loops), roll-invariace. Conversely if the DistoX satisfies these conditions it is well-calibrated. Therefore conditions to check a good calibration are:

- foresight/backsight agreement
- triangle loop closure
- roll invariance

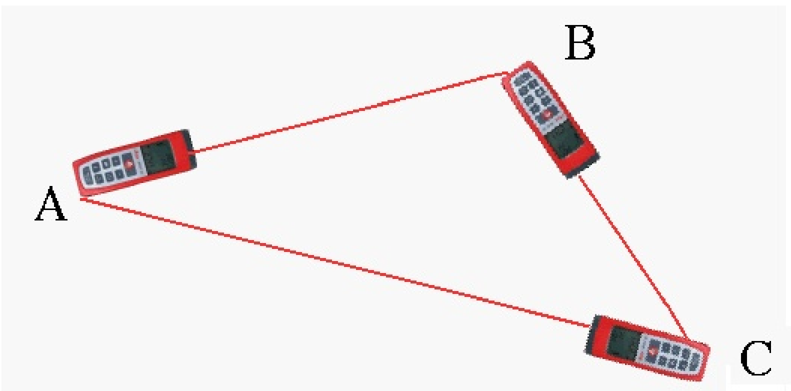
Shots taken to verify these conditions are "calibration check shots".
In TopoDroid (at expert level) you can mark a shot as "calibration check", inspect the extent to which the calibration conditions are satisfied, and save the calibration check shots with the survey data. Calibration check shots are included in Therion, cSurvey, and CSV exports.
This is not a perfect check of the calibration, but it is rather an indication of the uncertainty you can expect on your data, if you take survey shots with the same care as the calibration check shots.

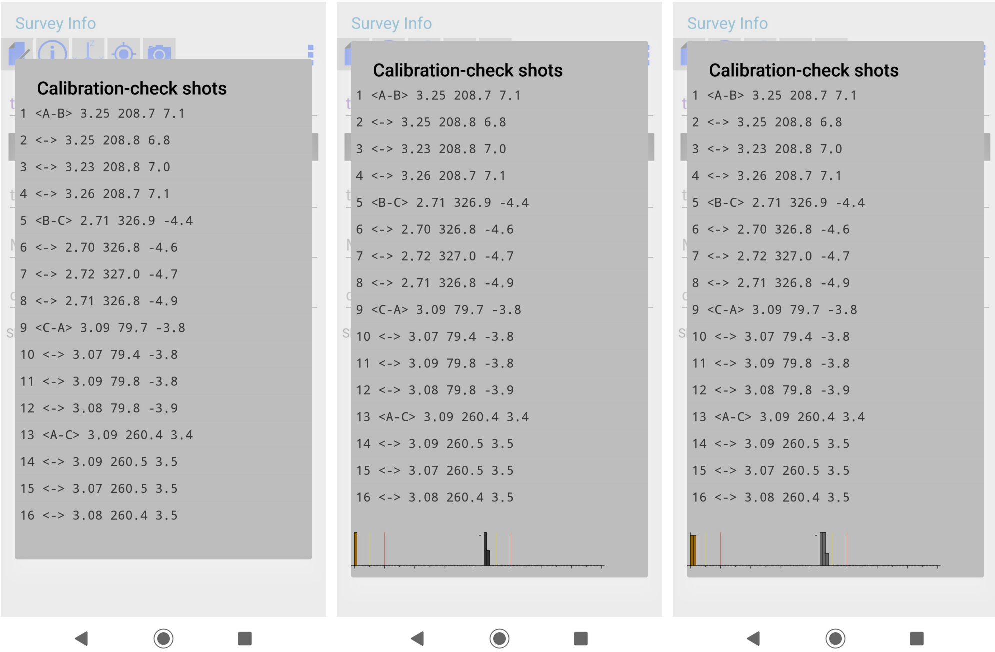
To check the foresight/backsight agreement, you need to take four leg shots A-B, rotating the DistoX around the laser axis, about 90° each time. Next you take four shots for the backsight B-A, again rotating the DistoX. When you download the shots into TopoDroid, it will recognize two legs, say A-B, and B-C. Open the shot edit dialog for A-B, go to the secondary dialog and mark the shot "calibration check" by tapping the green gear button. Next open the shot edit dialog for the B-C shot, rename it B-A and save the name. Then go to the secondary edit dialog and mark it "calibration check".



Now, from the Survey Info Window (accessible from the suitable menu of the Survey Data Window), you can inspect the calibration shots. The menu "CALIB. CHECK" opens a dialog listing the calibration check shots. If you tap on A-B TopoDroid computes the roll-invariance errors, and, since there is a backsight shot, it computes the foresight/backsight agreement. The result is displayed as distribution of the angle differences (in degrees).

To check the closure of triangles you need to take three calibration check legs (each with four data at different angles of roll): A-B, B-C, and C-A. Edit each and mark it as "calibration check" as you did for the foresight/backsight check.
Next in the dialog listing the calibration check shots select one side of the triangle. TopoDroid will automatically recognize the other two sides and compute the triangle closure error for each possible combination of the data of the three sides, and display the distribution of the errors, E, converted to angles according to a = √3 (E/L), where L is the length of the triangle loop (ie, the perimeter of the triangle).





A set of calibration check shots, A-B, B-C, C-A and A-C.

These data have been taken after a calibration with error 0.12°±0.07°.

Left. The dialog listing the calibration check shot.

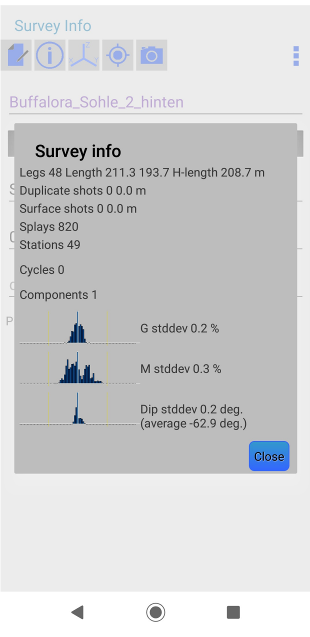
Middle. Tapping data A-C TopoDroid shows the error distribution among the four data of A-C (left histogram) and that of the foresight/backsight A-C/C-A (right histogram).

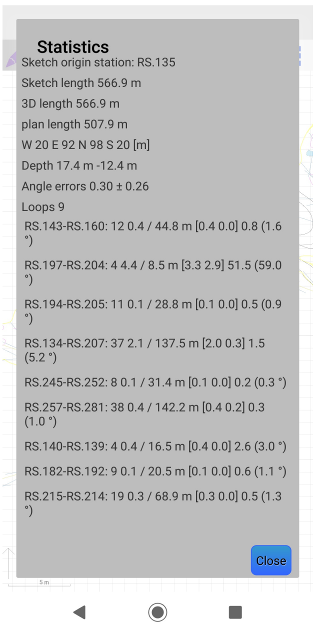
Right. Tapping on A-B (or on B-C) TopoDroid shows the error distribution among the four shots of A-B (left histogram) and that of the triangle A-B-C (right histogram).

TopoDroid survey checks

Other information about the quality of the survey are provided by the histograms of the distribution of: the deviations from the survey average value, the intensities of M and G, the angle between M and G. These histograms are shown in the data statistics dialog of the Survey Info Window. The zero is in the middle of the histogram and the yellow bar mark the tolerance values chosen through the app settings.
Numerical values of the standard deviations of the distribution are also reported.

Another information about the quality of the survey is the loop closure errors. TopoDroid computes the data reduction only for the sketches. Therefore this information is available only from the data statistics of sketches. TopoDroid can compensate the loop closure errors, however it is advisable to leave the loops open so that a possible bad closure is immediately spotted on the sketch (usually on the plan-view).
The sketch stats dialog (menu "STATS") lists the loop closure errors and the statistics of the angle precision of the legs (average and standard deviation).





Other DistoX functions of TopoDroid

TopoDroid has other functions to work with the DistoX:
- remote control to take reading with the DistoX2 - firmware 2.3 up.
- reading the information from the device
- reading the the calibration coefficients from the DistoX
- reading the data stored in the DistoX memory
- changing the "transmit" flag of data in the memory of DistoX version 1
- downloading the firmware from the DistoX2
- uploading the firmware to the DistoX2

DistoX informations

For the DistoX version 1 TopoDroid reads and displays the following information:

- device code
- angle units
- compass/clino on/off status
- mode (normal or calibration)
- silent mode on/off status

For the DistoX2 TopoDroid reads and displays the following information:

- device model
- device code
- firmware version
- hardware version

DistoX memory

TopoDroid can read the data from the memory of both the DistoX (version 1) and the DistoX2.
Each line of the memory dump contains:

- memory address
- letter code to distinguish data

- data values.

The letter codes are:

- 'd' survey shot
- 'b' survey backshot (only DistoX2)
- 'g' accelation values of calibration data
- 'm' magnetic field values of calibration data (only DistoX version 1)
- '?' not recognized.

Upper case is used for data with active "transmit" flag.
Shot data contain distance (meters), azimuth and inclination (degrees). The magnetic field and acceleration values, and the angle between the two fields, available for the DistoX2, are not shown.
For the calibration data, the raw values are shown. Only the 'g' values are shown for the DistoX2.

For the DistoX version 1 it is also possible:

- to read and save the position of the memory cursors
- to clear or set the "transmit" flag of the data in a specified range of memory.

DistoX2 firmware

To upload a new firmware to the DistoX1 one needs a special program, part of the development environment of MicroChip for embedded systems. The DistoX2 bootloader can upgrade the firmware via bluetooth.

When the DistoX2 is in bootloader mode, TopoDroid can

- read and save the DistoX2 current firmware
- upload a new firmware to the DistoX2

Uploading a firmware to the DistoX2 is very simple with TopoDroid.
First switch the DistoX2 in bootloader mode.
Then open the Firmware Dialog with TopoDroid's "FIRMWARE" menu of the Device Window.
Next select the firmware file to upload, and press the "Upload" button.

When it is done, switch off the DistoX2.

TopoDroid has a number of DistoX2 firmware files bundled in:

- firmware 2.1
- firmware 2.2
- firmware 2.3
- firmware 2.4, 2.4c
- firmware 2.5, 2.5c, 2.5t

From v. 5.0 TopoDroid includes the firmwares 2.4c and 2.5c patched for the continuous mode command and the firmware 2.5t patched for the double beep audio feedback every four calibration shots.