Caveatron Calibration Instructions

Version: 2018-04-25

Introduction

After assembling the Caveatron, it needs to be calibrated before use and the calibration coefficients and other parameters must be loaded into the system's EEPROM memory. With one exception, these parameters are a onetime calibration that is done when the hardware is first assembled and do not need to be updated unless something physically changes about the system. The exception is the Hard & Soft Iron Magenetometer Calibration which must be redone from time to time, however, it is simple and quick to do and is fully carried out onboard the Caveatron.

Calibration Parameters

Calibration parameters are stored in the Caveatron's EEPROM, which is a non-volatile memory that is retained when power is removed and is separate from the SD card data storage. In Hardware Revision A, the EEPROM is located on the Real-Time Clock module (the one with the coin cell battery). The table below is a list of the parameters stored on this EEPROM, their starting address, and the size of the memory block it occupies.

Table 1. List of Caveatron calibration parameters stored in EEPROM with their type, address, and size.

<table>
<tr><th colspan="2">Calibration Parameter</th><th>Data Type</th><th>EEPROM Address (Hex bytes)</th><th>Data Size (# Pages)</th></tr>
<tr><td colspan="2">Serial Number</td><td>5 characters</td><td>0</td><td>1</td></tr>
<tr><td colspan="2">Hardware Code</td><td>11 characters</td><td>20</td><td>1</td></tr>
<tr><td colspan="2">Touchscreen Calibration</td><td>3x1 character array</td><td>80</td><td>3</td></tr>
<tr><td colspan="2">Accelerometer Calibration</td><td>3x4 float array</td><td>200</td><td>4</td></tr>
<tr><td rowspan="4">Magnetometer Alignment Calibration</td><td>No LIDAR Installed</td><td rowspan="4">8x1 float array</td><td>300</td><td>2</td></tr>
<tr><td>XV LIDAR</td><td>340</td><td>2</td></tr>
<tr><td>SWEEP LIDAR</td><td>380</td><td>2</td></tr>
<tr><td>Future Use</td><td>420</td><td>2</td></tr>
<tr><td rowspan="4">Magnetometer Hard & Soft Iron Calibration (User Calibration)</td><td>No LIDAR Installed</td><td rowspan="4">3x4 float array</td><td>500</td><td>4</td></tr>
<tr><td>XV LIDAR</td><td>580</td><td>4</td></tr>
<tr><td>SWEEP LIDAR</td><td>660</td><td>4</td></tr>
<tr><td>Future Use</td><td>740</td><td>4</td></tr>
<tr><td rowspan="3">LIDAR Orientation Calibration</td><td>XV LIDAR</td><td rowspan="3">1 float</td><td>820</td><td>1</td></tr>
<tr><td>SWEEP LIDAR</td><td>840</td><td>1</td></tr>
<tr><td>Future Use</td><td>860</td><td>1</td></tr>
<tr><td colspan="2">LRF Range Calibration</td><td>1 float</td><td>880</td><td>1</td></tr>
</table>

*A page is the smallest block of data that can be written to this EEPROM. It is 32 bytes (20 Hex bytes) in size.

In the sections below, each of the Calibration parameters that the Caveatron requires are described along with instructions on how to perform the calibration. Some of these calibrations require a special program sketch to be loaded onto the Caveatron, some use an Excel spreadsheet to perform the computations, and some require a special calibration setup to be prepared. These are listed at the start of each section.

Serial Number

Special Requirements: None

This is an alphanumeric code to identify the unit and must have 2 letters followed by 3 numbers. The second character identifies the hardware code and must be an 'A' at this time.

Hardware Code

Special Requirements: None

This is an 11 digit numeric code that defines the specific hardware components inside the Caveatron allowing for different electronics modules to be used with the same software. The Hardware Codes are defined in a separate Hardware Code Description document.

Touchscreen Calibration

Special Requirements: "Caveatron Touchscreen Calibration.ino" sketch uploaded to Caveatron

This defines the mapping of touch positions to screen positions and varies from screen to screen so each one needs an initial calibration. No change of these values over time has been observed.

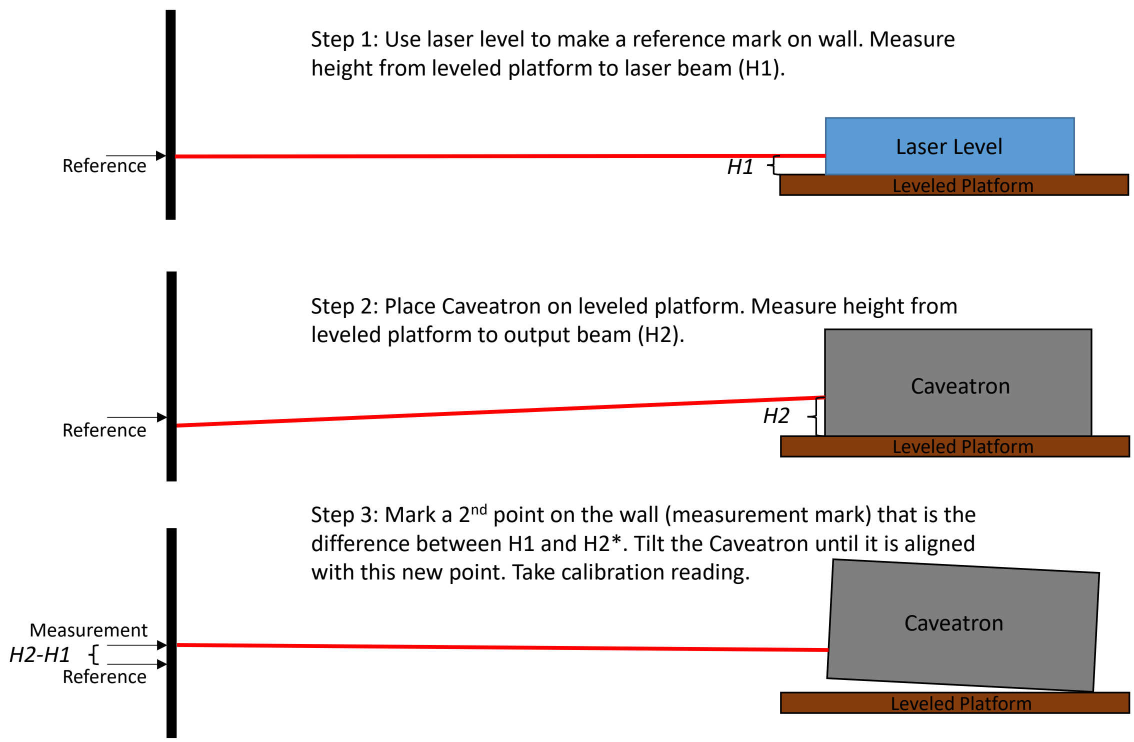
The calibration is performed by uploading the "Caveatron Touchscreen Calibration.ino" sketch using the Arduino IDE. (This sketch originates from the URTouch Calibration example sketch from the URTouch library with modified parameters for the Caveatron.) Once loaded you will see instructions. Touch the screen to begin and you will see 8 boxes with small crosshairs in the center of each. Use an object with a fine point for best results but do not use an object made of something that will damage the screen like metal or something too sharp. (For example, a touch stylus or a slightly rounded wooden toothpick would be suitable but a mechanical pencil would not.) Touch and hold the pointer on the highlighted crosshairs while the text in the screen says "HOLD" until it is says "SUCCESS". Continue with each successive highlighted box until all boxes are complete after which a screen appears with the calibration parameters. Record these values for later uploading.

Accelerometer Calibration

Special Requirements: Laser level or inclinometer, vertical surface to place marks, mm-precision ruler, level-able surface and/or a tripod, "Caveatron Accelerometer Calibration Calculator.xlsx" Excel spreadsheet.

This is probably the most critical calibration since it is not only used to calculate inclination and roll angle but is also used to compensate for tilt in the azimuth measurement. It should only need to be done once after assembly is complete. However, if you disassemble and reassemble the unit, you might consider repeating it if you think the calibration may have been affected. This purpose of the calibration is actually to correct for the misalignment between the accelerometer and the laser rather than the enclosure, since the dot of the laser is what is actually used in measurements. However, the enclosure is used as a reference since it is relatively square and has flat surfaces.

This calibration can be performed anywhere, just so long as there is enough distance between the Caveatron and wall or other target surface, preferably at least 3 meters. You will need a leveled surface and/or tripod, a ruler, a pencil and a good quality laser level. Instead of a laser level you could also use your cave survey inclinometer, but is a bit more challenging to do. It is preferable to attach the Caveatron to another plate to make the process easier, but is not necessary. Before starting, carefully level the level-able surface (or tripod) in both perpendicular directions. Figure 1 illustrates the steps. Start by using the laser level (or inclinometer) to make a level reference spot on your target surface or wall and mark it. Now measure the height from the leveled surface to the point where the laser emits from the laser level (*H1* in the illustration), or where the viewing port is on your inclinometer. Next, remove the laser level, place the Caveatron on the leveled surface, turn on its laser (can be done by entering Manual mode or going to the calibration function screen described below) and measure the height of the laser above the leveled surface (*H2*). On the wall, mark a 2nd spot (the measurement mark) that is a distance above or below the reference mark that is equal to the difference between *H2* and *H1*. Finally tilt the Caveatron up or down until the laser is exactly hitting the measurement mark. This can be done using shims, a tilt stage, adjusting the tripod, or other means. If the Caveatron has been mounted on another plate, check that this plate is still level in a direction perpendicular to the laser beam.



*Technically, you should measure H2 after you have tilted the Caveatron and fine tune the point on the wall, but in practice the tilt is not as much as shown here so is probably not necessary.

Figure 1. Illustration of the setup for the Accelerometer calibration.

To take the calibration reading for this position, use the *ADVANCED CALIBRATION* function in the Caveatron's Calibration menu (Figure 2). Then select the first function on the list called *1000 RAW MAG & ACC POINTS FOR ACCELEROMETER CALIBRATION*. This will record 1000 consecutive readings of the raw accelerometer and magnetometer values into a file that you name. Name the file something you will remember like "TopUp" to note the orientation of this reading. Gently tap "Start" so as to not misalign the Caveatron. A beep indicates the start of the calibration measurement and a few moments later a slightly longer beep indicates the calibration measurement is complete.

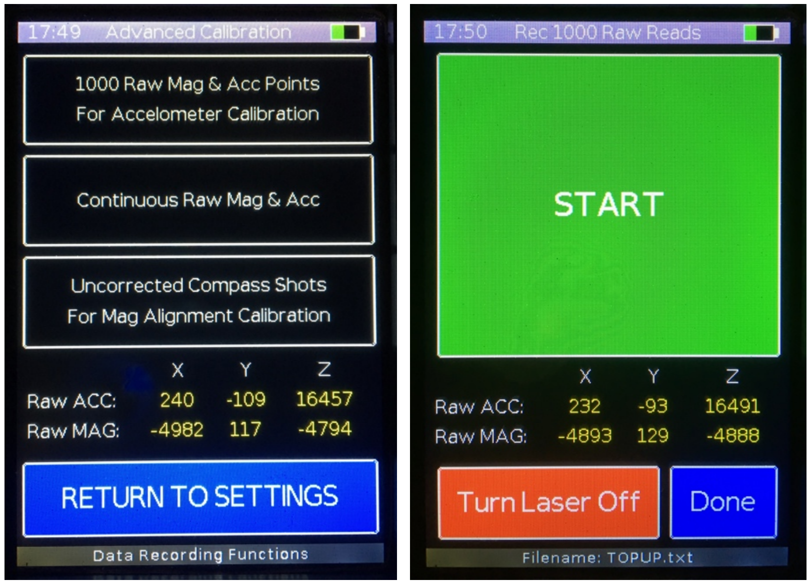


Figure 3. ***ADVANCED CALIBRATION*** **menu screen on the Caveatron and the start screen for** ***1000 RAW MAG & ACC POINTS FOR ACCELEROMETER CALIBRATION*****. The bottom portion of each screen displays live raw accelerometer and magnetometer values.**

Now repeat this process for each of the 6 orientations, labeling each file according to which side is facing upward as seen from the rear of the unit. For the Front and Rear Up measurements, the tripod is especially helpful or else you will need to mount the Caveatron so that its laser can hit the floor and ceiling. Place the Caveatron as far from the floor or ceiling as possible (i.e. for the Rear Up measurement, you would put the Caveatron as high above the floor as possible.) Find the vertical points on the ceiling or floor using the laser level or laser level and measure the offset from the Caveatron's laser in a manner similar to Figure 1. Mark the same offset from the laser level's reference point on the ceiling or floor and realign the Caveatron's laser to this measurement mark and perform the Calibration reading as described above.

After the calibration data is gathered, use the "Caveatron Accelerometer Calibration Calculator.xlsx" Excel spreadsheet to compute the calibration constants. Open each of the 6 calibration files (one for each orientation) in Excel – you may need to use the Import Wizard to be sure the comma delimiters are recognized and separate the data into individual cells. Copy and paste all the data into the appropriate sheet for that orientation, overwriting the sample values. Return to the Results sheet and the bordered box contains the 12 calibration coefficients that you will need in a 4x3 matrix. These are already in the correct order for loading into the Caveatron as the accelerometer calibration parameters.

Magnetometer Calibration

Special Requirements: See sections below

This calibration determines the coefficients that correct for various magnetometer errors caused by internal magnetic fields and misalignments. There are two types of magnetometer calibrations that must be performed. The first is the physical misalignment calibration. This one determines the 3-axis angular offset of the magnetometer chip on the compass board from the Caveatron's laser beam. This calibration should only need to be done once after assembly is complete. However, if you disassemble and reassemble the unit, you should consider repeating it if you think the calibration may have been affected. The second part of the calibration involves removing the effects of what are called hard and soft iron. The hard iron distortions are those that result from permanently magnetized ferromagnetic objects within the Caveatron (such as steel screws, buzzers, the LIDAR scanner motor, etc.) that create their own magnetic fields near the compass. The soft iron distortions are those created by the induction of a temporary magnetic field into normally un-magnetized components such as a battery or a time varying current traveling through a wire. Various factors can cause these distortions to change or drift or time - especially the soft iron distortions. As such, the hard and soft iron calibration must be occasionally updated and a simple routine is built into in the Caveatron to perform this calibration.

The magnetometer misalignment and hard/soft calibrations are not fully independent of each other. The measurement for the misalignment calibration can be acquired without the hard/soft iron calibration but the calculation of the coefficients requires the hard/soft iron values and the accelerometer calibration values. The hard/soft iron calibration can be fully performed without the misalignment calibration but cannot be verified without it.

Since the calibration is affected by the presence of the LIDAR module, a separate magnetometer calibration must be performed for each type of LIDAR module and without any LIDAR module present. (Note that if you never intend to use the Caveatron without a LIDAR module, it is not necessary to perform that calibration.) The Caveatron automatically detects if a LIDAR module is attached along with the type of module and the calibration coefficients are stored separately for each condition. Upon startup, it selects the correct calibration coefficients based on what is attached.

The recommended sequence for magnetometer calibration is as follows:

1. Attached the LIDAR to be calibrated or no LIDAR for the non-LIDAR calibration.
2. Perform a User Calibration (Hard/Soft Iron).
3. View the hard/soft iron calibration values and write down the 4x3 matrix values.
4. Take raw data readings for the Magnetometer misalignment calibration on your calibration course using the provided function in the Advanced Calibration menu. Do this for both upward facing and downward facing orientations.
5. Download the file with the recorded Magnetometer misalignment raw data readings. Open the “Caveatron Magnetometer Calibration Calculator.xlsx” Excel spreadsheet and enter the hard/ soft iron calibration coefficients and the accelerometer calibration coefficients.
6. Enter the actual azimuth angles from your calibration course if you have not already done so.
7. Open the Magnetometer misalignment raw data file and copy and paste the up and down orientation values into the indicated sheets of the Excel spreadsheet.
8. Manually adjust the four offset values in the spreadsheet until the misalignment plot is as flat and close to zero as possible.
9. Record the magnetometer misalignment coefficients and load them into the Caveatron.
10. Verify the compass readings. Repeat if significant error remains (> +/- 2 degrees).

Repeat this process for each LIDAR module to be used and for no LIDAR module.

User Calibration (Hard/Soft Iron Calibration) Process

Special Requirements: None

This calibration should be repeated from time to time to update the calibration as these drift over time. Based on experience so far, the calibration is generally stable on the order of several weeks. This calibration is simple to perform and a user-friendly function to conduct this calibration is fully built-in to the Caveatron and the GUI steps are shown in Figure 4. First find an area well away from any buildings or major power lines. Be especially careful to stay far away from any motors such as compressors used in HVAC systems. Remember that roads and sidewalks are not good choices as they often contain rebar.

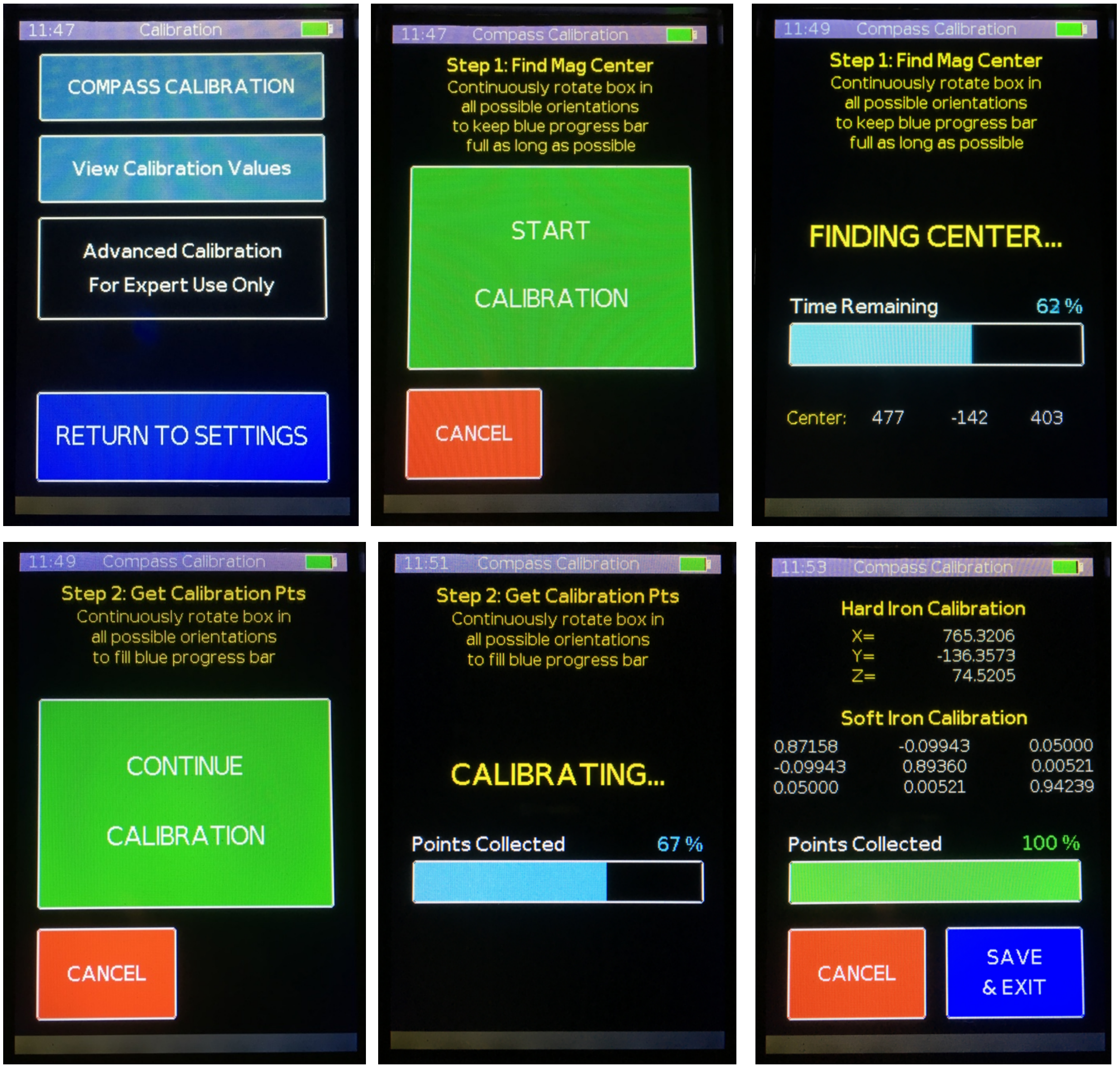


Figure 4. Screens in the User Compass Calibration Process. Start from the *CALIBRATION* menu selecting *COMPASS CALIBRATION* (top left). When ready, press *START CALIBRATION* (top center) to begin step 1 which involves finding the center of the magnetic sphere. Rotate the Caveatron in all orientations continuously trying to keep the progress bar as close to 100% for as long as possible (top right). Once the progress bar reaches zero, the center has been determined and step 2 can begin by pressing *CONTINUE CALIBRATION* (bottom left). Again, rotate the Caveatron in all orientations, but this time trying to increase the progress bar until it reaches 100%. The last few percent may take some time to find orientations that you have missed. Finally, when complete, the computed magnetometer hard and soft iron calibration coefficients are displayed. Press *SAVE & EXIT* to store these with other calibration parameters on the EEPROM or *CANCEL* to keep the current calibration coefficients.

First configure the unit for calibration by attaching or not attaching a LIDAR module, depending on which calibration you wish to perform. Under the *CALIBRATION* menu select the *COMPASS CALIBRATION* function. There are two steps – first determining the approximate center of rotation of the calibration sphere and then calculating the coefficients. Both steps are done in approximately the same way. Hold the Caveatron out in front of you and when you are ready, press *START CALIBRATION* for Step #1 or *CONTINUE CALIBRATION* for Step #2. Continuously rotate the unit in all orientations so that each side points in every direction at some point. One way to do this is to spin the unit several times on one axis while you turn yourself around in a gradual complete 360° rotation and then switch to each of the other two rotation axes while you continue to turn around. Oftentimes the more upward pointed and downward pointed directions get missed, so you may need to spin and rotate the unit in these directions a few more times to complete the calibration. A progress bar is shown on the screen to indicate how many of the required points have been acquired. The unit intelligently acquires points to ensure that a relatively uniform distribution of points are collected around a sphere. If you were to just hold it in one or a few directions, the calibration would never complete as there would be an insufficient distribution of points.

In the Step #1, the goal is to keep the progress bar as full as possible as long as possible while enough points are gathered to get an accurate center position for the magnetic sphere. If you hold it still, the progress bar drops rapidly, but as you spin the Caveatron to different angles, it will jump back up to full. The longer you keep it full, the more accurate the result. Eventually you will have gathered points from every direction and the progress bar will reach zero completing the first step.

In Step #2, the goal it to fill the progress bar to full. As you spin to different angles and new data points are collected, it will gradually fill up. The last few percent may be a bit more difficult to get as you have to find the angles and orientations of the unit you have not yet covered.

Once the calibration is complete, the coefficients are immediately calculated and displayed on the screen. If you are satisfied, press *SAVE AND EXIT* and the results are stored in the EEPROM as the new Hard/Soft iron calibration parameters for that LIDAR configuration. They can be updated at any time by repeating the *USER CALIBRATION*. Note if you do not press *SAVE & EXIT*, the new coefficients are not stored and the existing coefficients remain in memory.

Magnetometer Misalignment Calibration Process

Special Requirements: 12 pre-measured azimuth points in a full circle at approximately 30 degree separation, "Caveatron Magnetometer Calibration Calculator.xlsx" Excel spreadsheet.

For this calibration, you need to setup an outdoor calibration range. As mentioned above, it needs to be well away from buildings or other objects that may induce a magnetic field. You will need to establish 12 vectors covering a full 360 degrees that are roughly 30 degrees apart (the exact angles are not important nor is the exact separation.) The vectors should be roughly level without a lot of inclination though it is not important that they be exactly level. The length of the vector should be at least 3 m, though up to 6 m will give more accurate results. Once these are setup, use a reliable compass to measure the vector azimuth values to at least 1 degree accuracy or better. Record these values.

Return with the Caveatron and configure it for calibration by attaching or not attaching a LIDAR module depending on which configuration you are calibrating. (If you do not intend to use the Caveatron without a LIDAR, you do not need to calibrate it in that configuration.) You will perform the calibration readings twice – once with the unit with the screen facing upward and once with the screen facing downward. Try to keep the unit roughly level both in pitch and roll while taking the readings.

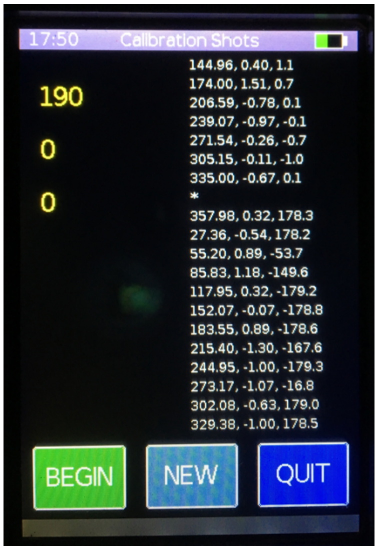


Figure 5. *UNCORRECTED COMPASS SHOTS FOR MAG ALIGNMENT CALIBRATION screen*. The left side shows raw magnetometer values for each axis and the right side shows a scrolling list of recent calibration shots saved to the CALSHOTS.TXT file. Press New to insert a separator into the file to indicate a new set of readings. Press Begin to activate the laser. Tap anywhere on the screen other than the buttons to take a reading which is immediately stored to the file.

To take the calibration readings, go to the *ADVANCED CALIBRATION* menu and select *UNCORRECTED COMPASS SHOTS FOR MAG ALIGNMENT CALIBRATION*. Figure 5 shows the screen for capturing the readings. The left side shows the raw magnetometer readings while the right side shows a running list of measurements saved to the CALSHOTS.TXT file. Although the numbers displayed are corrected azimuth, inclination, and roll (which can be used for verification), the averaged raw values for both the magnetometer and accelerometer are saved as well, along with a timestamp. To start calibration, press *NEW* which creates an asterisk separator in the file to indicate a new set of readings. Then press *BEGIN* which activates the laser. Start by positioning the Caveatron at one end of a vector. For these measurements, you do NOT use the bottom rear corner like in Shot Mode, but instead use a line that is projected back through the enclosure along the path of the laser to a spot on the rear bottom as shown by the yellow dot in Figure 6. Note that you can actually use any point along the dashed line.

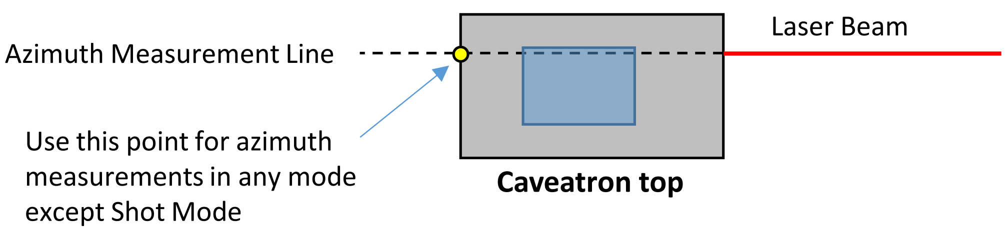


Figure 6. For azimuth calibration, align the Caveatron to the starting point of the calibration vector either at the yellow dot (on the bottom rear of the enclosure) or anywhere along the dashed line.

When the laser is pointed at the other end of the vector, tap anywhere on the screen away from the buttons to take the reading. The buzzer will beep indicating the start of the reading and again at the end. The recording process will only take about 1 second. Be sure to hold the Caveatron as still and as accurately on target as possible while the readings are being taken. Move to the next vector and repeat until all 12 vectors have been recorded. Now press *New* to start the second calibration set and repeat the readings for all 12 vectors with the unit oriented upside down.

Download the CALSHOTS.TXT data file to the Caveatron and find your two sets of readings (the most recent are at the end of the file). Each set of readings is separated in the file by a line with an asterisk and each line represents one vector recording. The date and time of each reading is recorded at the end of each line as a long text string to further assist with identifying the correct data.

Open the “Caveatron Magnetometer Calibration Calculator.xlsx” Excel file. First be sure that the current accelerometer coefficients and hard/soft iron magnetometer coefficients are entered in the “Cal Parameters” sheet. Then be sure that the actual azimuth values for each calibration vector that you measured in advance with your compass are entered into the box on the “Plot” sheet. Copy and paste the 12 lines of vector data from the CALSHOTS.TXT file into the correct sheet of the Excel spreadsheet for the screen upward or downward and then repeat for the other orientation.

To find the calibration values, go to the “Plot” sheet and find the X OFFSET, Y OFFSET, Z OFFSET, and ROTATION OFFSET values. Separate sets of values are provided for upward and downward orientation. On the right side is a plot showing the azimuth error for both upward and downward orientation. These will have a sinusoidal shape. The goal is to make these as flat as possible and as close to zero as possible – within +/- 2 degrees or better. Starting with the ROTATION OFFSET, manually enter different values (could be positive or negative) to the nearest tenth of a degree until the sinusoidal curve is roughly centered around zero. Now adjust the X OFFSET value to the nearest 10 until the sinusoid starts to flatten out. Get it as flat as possible and then begin to adjust the Y OFFSET value to flatten it further. I have rarely found it necessary to adjust the Z OFFSET value to anything other than zero, so you can probably ignore it. After the curve is reasonably flat, start fine tuning by adjusting each value in turn until the curve become as flat as possible and centered around zero. You can use the average and RMS values shown to assist with this (average indicates offset from zero and RMS indicates amplitude of the sine wave). Once you are satisfied, repeat for the upside down orientation. Record the four X, Y, Z, and ROTATION OFFSET values for both up and down orientation. These will be loaded into the Caveatron as a 1x8 matrix in the order {X Up, Y Up, Z Up, Rot Up, X Down, Y Down, Z Down, Rot Down}.

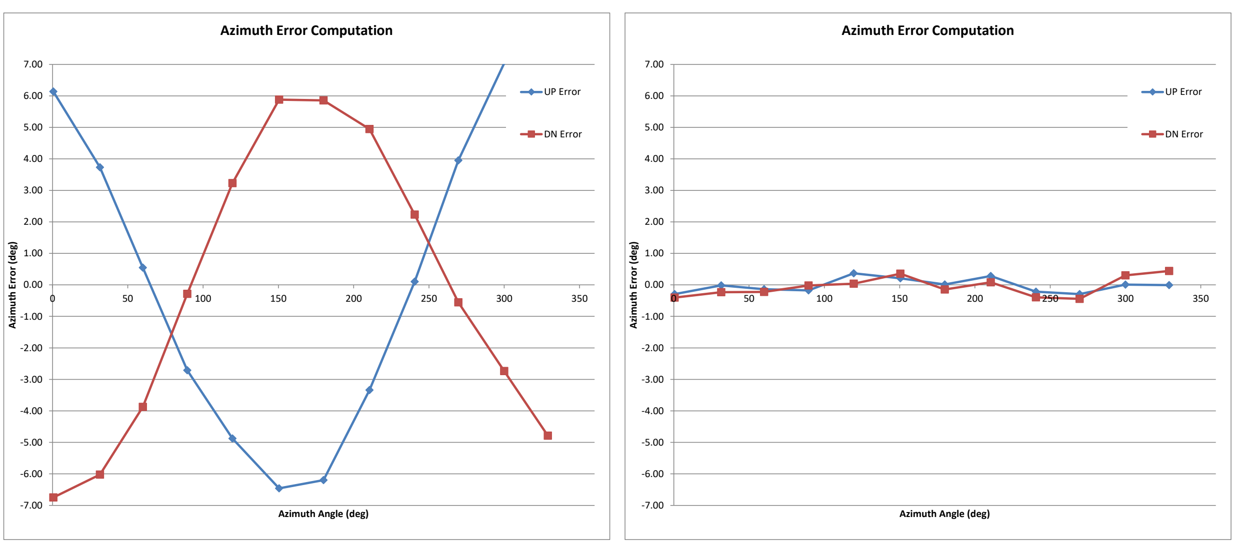


Figure 7. Error plots from the “Caveatron Magnetometer Calibration Calculator.xlsx” Excel spreadsheet. At left is a typical error plot after the data is entered but before finding the misalignment calibration values. At right is a well-calibrated plot with an error of less than 0.5 degrees.

Repeat this process for any other LIDAR modules you wish to calibrate with or with no LIDAR module. Note that until these parameters are loaded, the azimuth results will not be correct.

LIDAR Orientation Calibration

Special Requirements: Protractor or inclinometer

Certain LIDAR modules may need an orientation calibration to ensure that they are aligned to the Caveatron enclosure. This is the case with the XV LIDAR module. This process only needs to be performed once after the system is assembled. To do this calibration, load the default angle of 300 degrees into the Caveatron. Attach the LIDAR and place the unit on a level surface in a room with a flat smooth floor and ceiling. Overhang the LIDAR a bit from the surface so that it can see the floor. Select *LIDAR* in the *SETTINGS* menu to bring up a real-time LIDAR display. Look at the points of the floor and ceiling on the screen. If they are not parallel to the on-screen lines forming the display window, you will need to calibrate the orientation. To do so, tip the unit slightly until the floor and ceiling are parallel to the on-screen lines. Measure this tilt angle using a protractor or using your inclinometer. Depending on the direction of tilt, add or subtract this value from 300 and load the new value into the Caveatron. Double check that the floor and ceiling are now level on the LIDAR live view display.

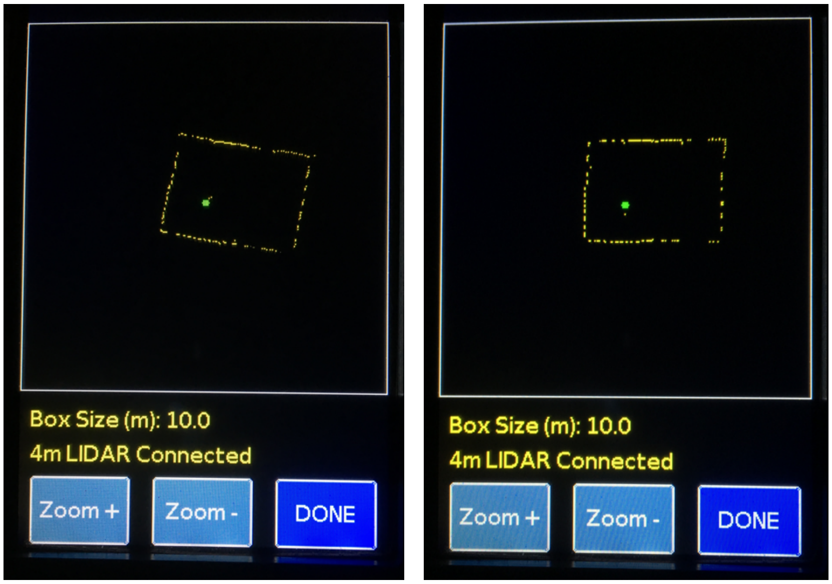


Figure 8. Views of the real-time LIDAR display of a room with the Caveatron on a level table. An improper LIDAR orientation calibration is shown at left while a properly calibrated one is shown a right. In this example, you would subtract several degrees from the initial calibration orientation to obtain the correct value.

LRF Range Calibration

Special Requirements: Tape measure or laser rangefinder

This value is added to or subtracted from the rangefinder value measured by the Caveatron. To date it has not been found to be necessary to calibrate this value. However, you can do so by measuring the distance between two known points with a tape measure or laser rangefinder, then repeat the measurement with the Caveatron. If the values do not agree, enter the difference as the LRF calibration parameter.

Azimuth and Inclination Verification

Verification can be done in a several ways but requires the use of pre-established vectors for which the azimuth and/or inclination is known. (You can use the same vectors you setup for the Magnetometer Misalignment Calibration.) One method is to use Shot Mode and take a shot along the vectors. To do this you will need the retroreflective card at the opposite end of the vector and takes a bit more time since you have to enter a to and from station, but the values are recorded. Manual Mode can also be used for verification and is faster since it does not require the entry of station codes and does not require the use of the retroreflective card, but does not store values – they must be written down. Finally, you can use the *UNCORRECTED COMPASS SHOTS FOR MAG ALIGNMENT CALIBRATION* function under the *ADVANCED CALIBRATION* menu, which not only records the raw uncorrected data but also records the corrected azimuth and inclination angles from the already stored calibration parameters. This is the fastest method and does not require the use of a retroreflective card or entry of station code and the values are recorded to the SD card in a file called “CALSHOTS.TXT” for later download. Note that if you use any method but Shot Mode, you have to align the Caveatron to the start of the vector as per the illustration in Figure 6. Otherwise in Shot Mode you use the rear bottom corner that you select in that mode.