Caveatron Setup and Calibration Instructions – Rev B

Version: 2020-03-04

Introduction

After assembling the Caveatron, it needs to be initially setup and 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 should not need to be updated unless something physically changes about the system. The exception is the Hard & Soft Iron Magnetometer Calibration which must be redone periodically, however, it is simple and quick to do and is fully carried out onboard the Caveatron.

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 B, the EEPROM is part of the Teensy 3.6 PCB.

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 special parameters including the Hardware Code, and Touchscreen calibration are created using the "*Caveatron_Setup*" firmware that needs to be loaded the first time the system is turned on after assembly. The "*Caveatron_Setup*" program also initializes the other parameters with test values so that the hardware can be checked out. (Note that any previous values in the EEPROM are overwritten.) Those preliminary values will need to be replaced with the calibrations described below or the Caveatron will produce incorrect data. Some of these calibrations 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.

Quick Start Caveatron Setup and Calibration

1. Load the "*Caveatron_Setup"* firmware
2. Wait and it starts the *TOUCHSCREEN CALIBRATION* routine – perform the routine as described below and save the parameters.
3. Restart the Caveatron and tap the screen to enter setup.
4. Run the *HARDWARE SETUP* routine. It will step through a series of screens where you select the hardware used in your Caveatron build. At the end, it will generate the correct Hardware Code which you then save to the EEPROM.
5. Load the "cvfont32.bin" fonts/graphics file onto the microSD card. Restart the Caveatron and run the *LOAD FONTS & GRAPHICS* routine. Step through the instructions to erase and load the file to the SPI flash memory module. If the load was successful, a screen will appear that shows several font sizes, icons, and the Caveatron logo graphic.
6. (Optional) Run the *HARDWARE TEST* routine to check if various modules are functional.
7. Load the main Caveatron firmware
8. Perform the Accelerometer/Gyro calibration and load the parameters to the Caveatron via an IMU file as described below.
9. Perform the Magnetometer calibration and load the parameters to the Caveatron.
10. Perform the other calibrations and load their parameters to the Caveatron.
11. The Caveatron is now setup and ready to go.

Caveatron Setup Firmware

This software needs to be loaded the first time after the Caveatron is fully assembled in order to setup some critical initial parameters, load the fonts and graphics and test the hardware functionality. Note that there are different versions depending on what touchscreen model you are using and you must pick the correct one or the screen will display incorrectly.

On the first run, the touchscreen needs to be calibrated or you may not be able to press the buttons for the other setup functions. Wait 10 seconds after power on and the touchscreen calibration automatically starts. On additional runs, tap anywhere on the screen during the first 10 seconds after power on to start the setup (Figure 1). First select *HARDWARE SETUP* and go through a series of screens that asks about the hardware used in your Caveatron build. Select the box next to the correct answer for each screen. At the end, the hardware code is generated which can then be saved.

Next the Fonts and Graphics are loaded with LOAD FONTS & GRAPHICS. To perform this routine, the file "cvfonts32.bin" must be copied onto the microSD card. Finally, the TEST HARDWARE routine will allow you to try out each major piece of hardware and verify that each is functional.

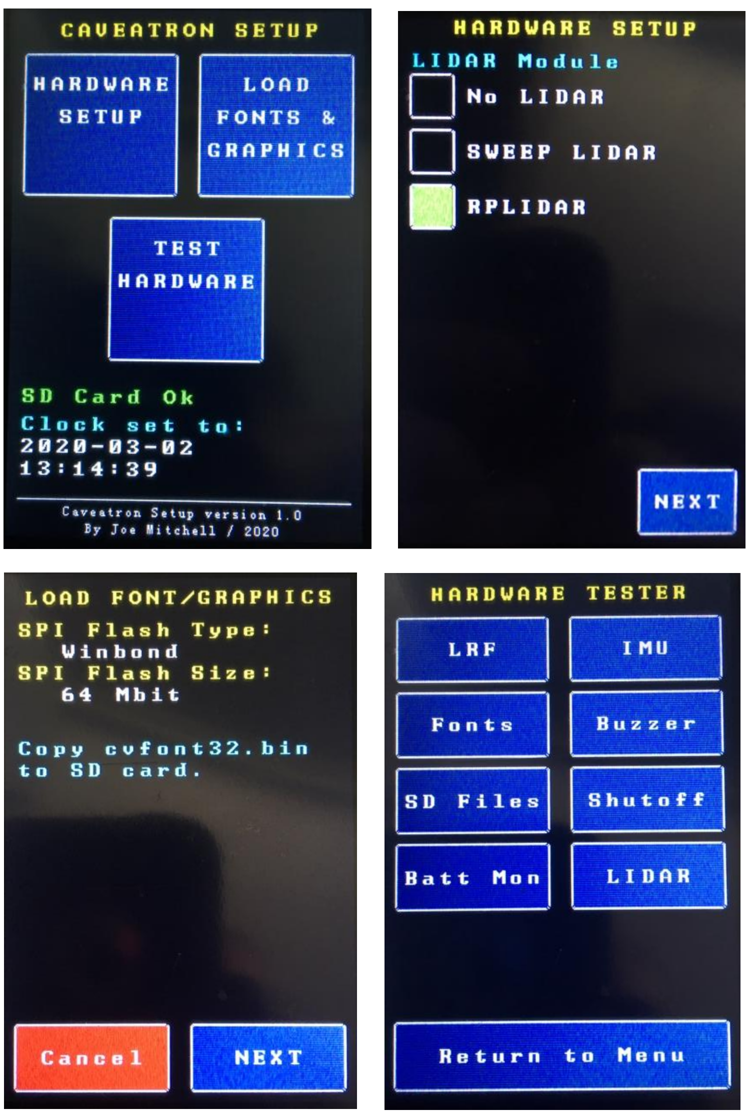

Figure 1. Screens from the "*Caveatron_Setup*" firmware. The main screen (upper left), a screen to select the LIDAR module as part of the *HARDWARE SETUP* routine (upper right), a screen from the *LOAD FONTS & GRAPHICS* routine, and the options in the *TEST HARDWARE* routine.

IMU Calibration Files

Calibration parameters on the Caveatron are loaded and saved via ".imu" files. These are just plain text files with a special format to designate calibration parameters. Each set of parameters is headed by a #x line where the "x" is a character that designates the type of parameters of the next few lines. Each line may have several parameters separated by commas. For a given type of parameters, you must have the correct number of lines of parameters and the correct number of comma-separated values per line. Blank lines and lines starting with ; are ignored. An example is shown in Figure 3 and the format is detailed in Table 1.

There are several ways IMU files are used and some must have specific names:

- With each survey, there is an accompanying IMU file containing the calibration parameters that are used in post-processing. (It does not contain all calibration parameters – just those needed for post-processing.) It has the same name as the other survey and LIDAR files and should be downloaded and kept with those files for later processing when copying the survey and scan data. It is created when a new survey is created. If the Caveatron is recalibrated during a survey, a new survey must be created to save these new parameters.
- A special IMU file can be created that saves all calibration parameters, called "Cal_save.imu". It is created by going to *UTILITIES->CALIBRATE->LOAD/SAVE CALIBRATION->SAVE IMU CALIBRATION* (Figure 2). It can be reloaded from the SD card if necessary (for example if you change the calibration but want to go back to the previous one) by going to *UTILITIES->CALIBRATE->LOAD/SAVE CALIBRATION->LOAD PREVIOUS IMU CALIBRATION*.

Figure 2. Calibration load and save screen.

- To load a new calibration, another special IMU file is used, called "Cal_new.imu". This is generated on a PC and then copied to the SD card on the Caveatron. The file should only contain the parameters you want to change as it will replace every parameter for which there is an entry. For example, if you only want to load a new Accelerometer calibration, the "Cal_new" file should only have the #A line and the subsequent 4 data lines (plus any comment lines you want). Note that the date, screen calibration, and hardware code cannot be loaded in this way but only through the "*Caveatron_Setup"* firmware.

Table 1. Format of ".imu" calibration file

Parameter Type	Code	No. of lines	No. of parameters per line (comma separated)	Note
Date and Time	#D	1	1	Saved value only. Cannot be loaded.
Serial Number	#N	1	1	Saved value only. Cannot be loaded.
Accelerometer	#A	4	3	
Magnetometer Alignment	#L	2	4	
Magnetometer Hard/Soft Iron	#M	4	3	
Gyroscope	#G	1	3	
LIDAR Module Corners	#C	4	2	
Window Distortion Correction	#W	2	2/360 or 2/720	First line has 2 entries. Second line has either 360 or 720 entries.
LIDAR Orientation	#O	1	1	
LRF Range Offset	#R	1	1	
Screen Calibration	#S	1	3	Saved value only. Cannot be loaded.
Hardware Code	#H	1	1	Saved value only. Cannot be loaded.
Comment line	;	1	N/A	";" indicates the line contains a comment that will be ignored. Blank lines are also ignored.

```
;CAVEATRON IMU CALIBRATION PARAMETERS FILE
;Full Parameter User Save

;Date & Time
#D
2019-12-15 22:58:27

;Serial Number
#N
TB001

;Accelerometer Calibration
#A
-6.60394E-03,-6.16834E-03,-8.25826E-02
6.06741E-05,-8.42553E-07,2.03525E-07
2.70245E-07,6.21111E-05,-5.98429E-07
-1.12738E-06,5.84423E-07,6.07884E-05

;Magnetometer Alignment Calibration
#L
-505.0,245.0,0.0,4.0E-01
-370.0,55.0,0.0,9.0E-01

;Magnetometer Hard & Soft Iron Calibration
#M
5615.19580,88.62267,-2809.94727
8.63785E-01,-1.02781E-01,-8.42591E-03
-1.02781E-01,9.20212E-01,1.04588E-02
-8.42592E-03,1.04588E-02,8.72902E-01

;Gyroscope Calibration
#G
-85.69667,-8.72833,117.43167

;LIDAR Module Corners
#C
-1.0,-1.0
124.1,125.5
230.8,232.2
318.0,319.0

;Window Distortion Correction
#W
2,1
0,0,0,0,2,1,2,2,2,2,1,1,0,1,1,3,4,3,3,2,1,0,1,2,1,2,2,1,1,2,1,0,2,1,0,0,0,-1,-3,0,2,1,0,-1,-1,-2,-1,3,2,0,-2,-2,0,2,1,-1,-2,0,1,2,2,2,2,3,3,4,3,4,3,4,4,3,4,4,4,5,6,5,4,6,7,7,5,7,

;LIDAR Orientation Angle
#O
89.0

;LRF Range Offset
#R
0.0

;Screen Calibration
#S
0x0347432AU,0x00BC4E9AU,0x0013F1DFU

;Hardware Code
#H
B212112110-3
```

Figure 3. Example "Cal_save.imu" file

Accelerometer and Gyroscope Calibration

<u>Special Requirements:</u> Laser level or inclinometer, vertical surface to place marks, mm-precision ruler, level-able surface and/or a tripod, "Caveatron Accelerometer & Gyro Calibration Calculator v2.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 4 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.

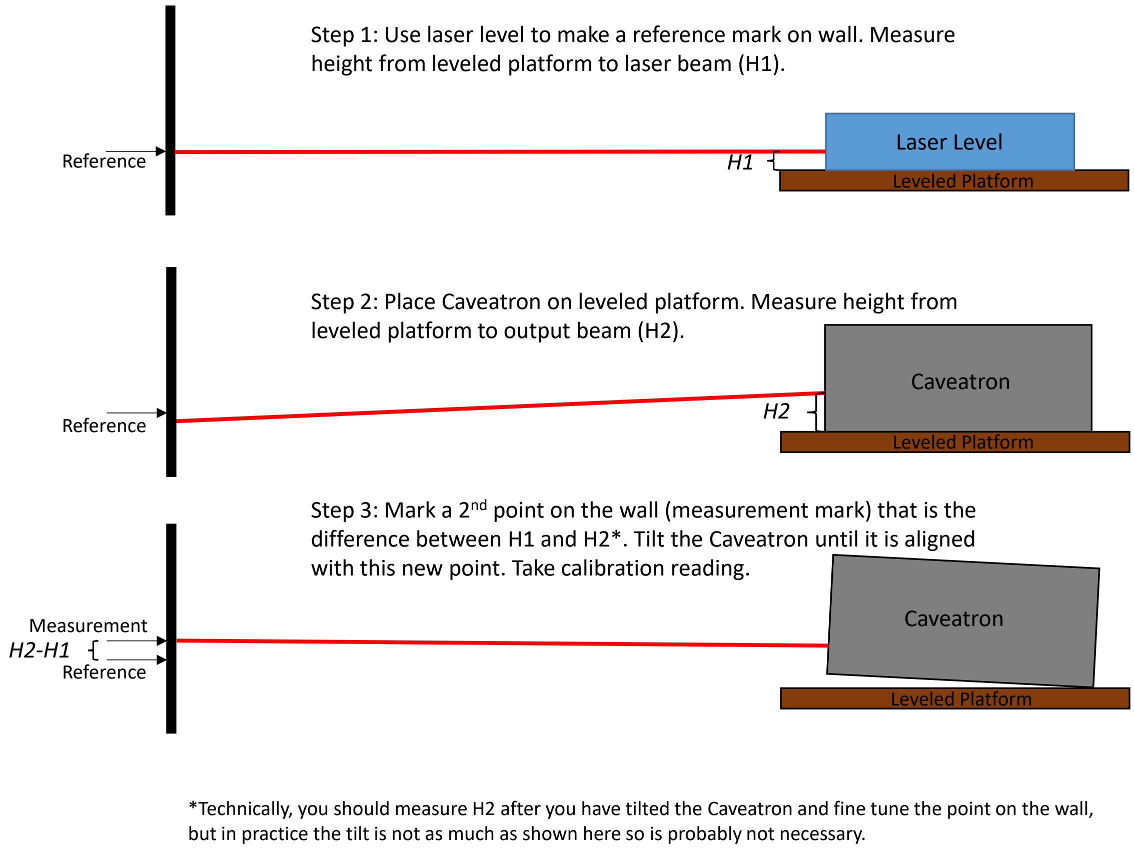

Figure 4. Illustration of the setup for the Accelerometer calibration.

To take the calibration reading for this position, use the *ADVANCED CALIBRATION* function in the Caveatron's Calibration menu (Figure 5). 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.

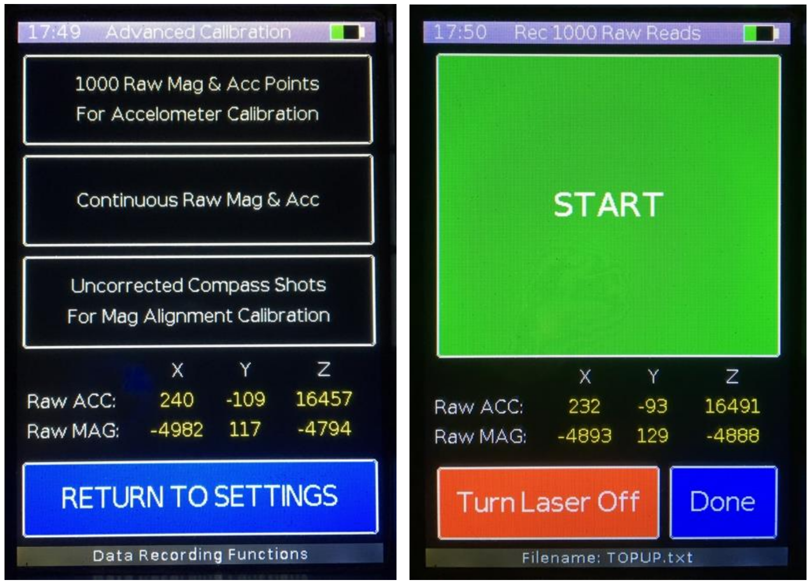

Figure 5. *ADVANCED CALIBRATION* menu screen on the Caveatron and the start screen for *1000 RAW MAG & ACC POINTS FOR ACCELEROMETER CALIBRATION*. The bottom portion of each screen displays live raw accelerometer and magnetometer values.

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. Download each of the 6 calibration files (one for each orientation) from the Caveatron to a PC and open each one 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. One bordered box contains the 12 accelerometer calibration coefficients in a 4x3 matrix and the 3 gyroscope calibration parameters in a 1x3 matrix. Copy these parameters into their respective locations in a "Cal_new.imu" file for loading into the Caveatron EEPROM as described above.

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. Perform a User Calibration (Hard/Soft Iron).
2. 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.
3. Perform a Calibration Parameter Save (*UTILITIES->CALIBRATE->LOAD/SAVE CALIBRATION->SAVE IMU CALIBRATION*). Then connect the Caveatron to a PC and copy the Cal_save.imu file to the PC. Open the file and copy the 4 lines of Magnetometer Hard & Soft Iron Calibration data below the “#M” line. Paste this into the “Caveatron Magnetometer Calibration Calculator.xlsx” Excel spreadsheet “Cal Parameters” sheet in the Magnetometer Hard/Soft Iron section. Repeat for the accelerometer values below the “#A” in the Cal_save.imu document and paste into the Accelerometer section of the same sheet.
4. Copy the file with the recorded Magnetometer misalignment raw data readings from the Caveatron to the PC. Open this file and copy and paste the Up and Down orientation values into the indicated sheets of the Excel spreadsheet.
5. Enter the actual azimuth angles from your calibration course if you have not already done so.
6. In the Plot sheet of the Excel spreadsheet, manually adjust the four offset values in the spreadsheet until the misalignment plot is as flat and close to zero as possible.
7. Copy the magnetometer misalignment coefficients into a “Cal_new.imu” text file.
8. Connect to the Caveatron and copy the “Cal_new.imu” file to the Caveatron. Perform a Calibration Parameter load as described above. (*UTILITIES->CALIBRATE->LOAD/SAVE CALIBRATION->LOAD NEW IMU CALIBRATION*)
9. Verify the compass readings. Repeat if significant error remains (> +/- 2 degrees).

User Calibration (Hard/Soft Iron Calibration) Process

<u>Special Requirements:</u> 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 6. 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.

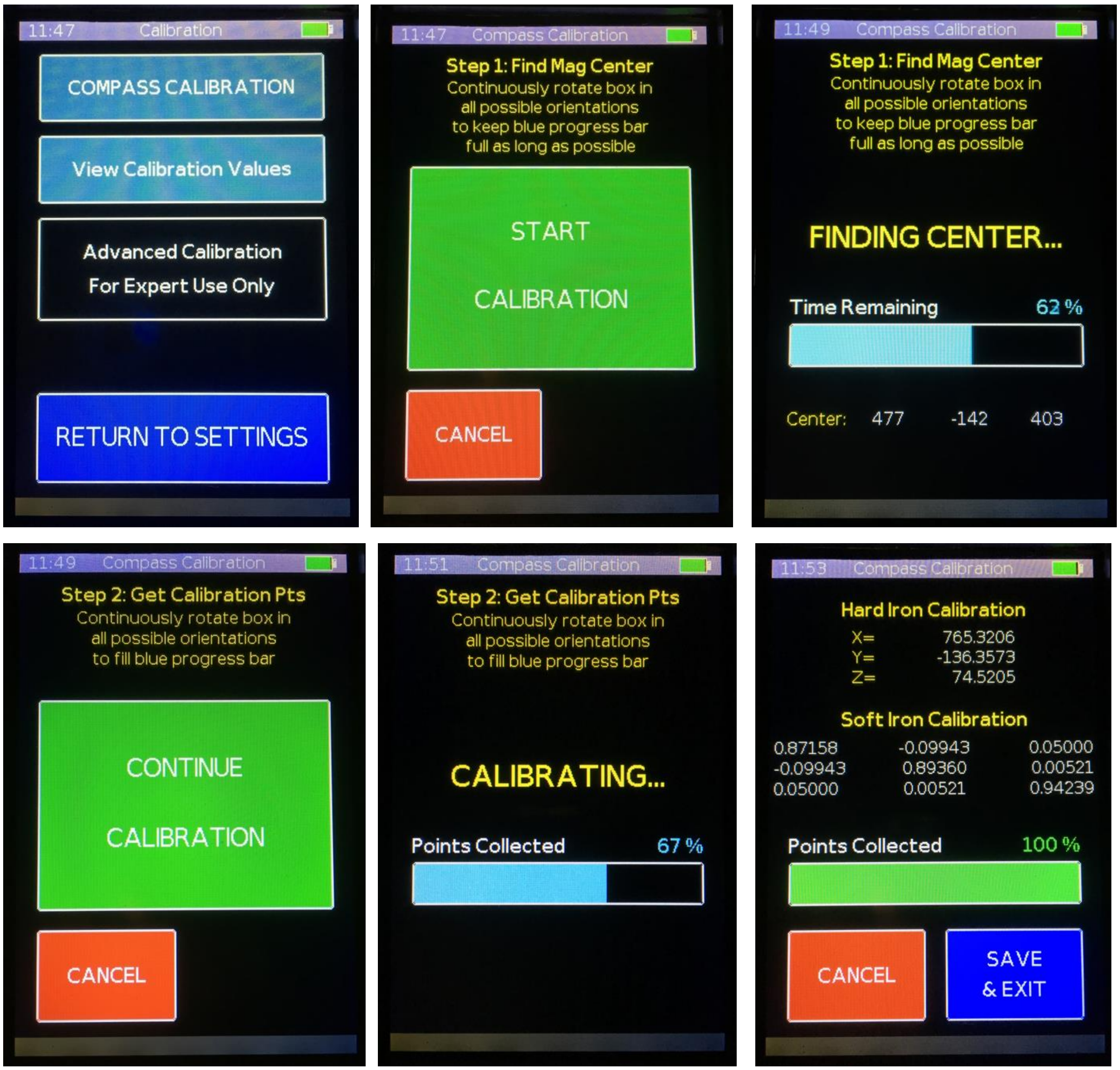

Figure 6. Screens in the User Compass Calibration Process. Start from the *CALIBRATION* menu selecting *COMPASS CALIBRATION* (top left). When ready, press *START CALIBRATION* (top center) to begin step 1 which involves finding the center of the magnetic sphere. Rotate the Caveatron in all orientations 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

<u>Special Requirements:</u> 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.

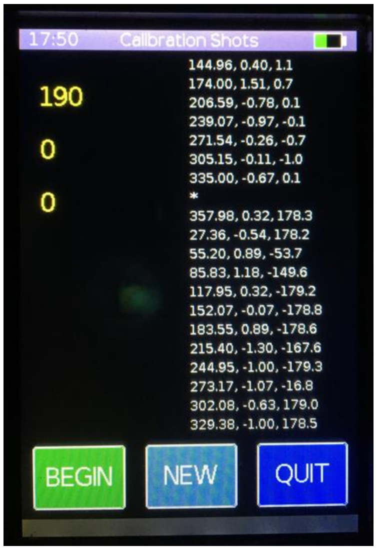

Figure 7. *UNCORRECTED COMPASS SHOTS FOR MAG ALIGNMENT CALIBRATION screen*. The left side shows raw magnetometer values for each axis and the right side shows a scrolling list of recent calibration shots saved to the CALSHOTS.TXT file. Press New to insert a separator into the file to indicate a new set 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 7 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 8. Note that you can actually use any point along the dashed line.

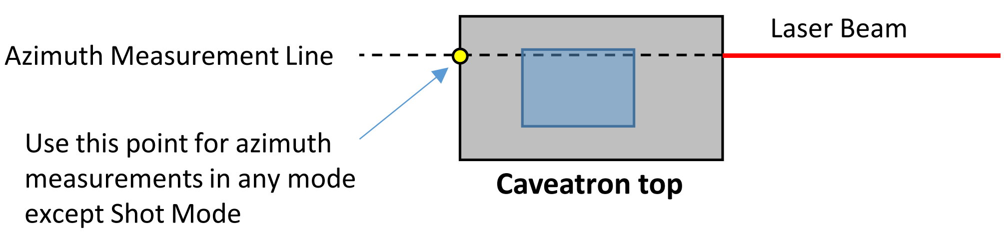

Figure 8. For azimuth calibration, align the Caveatron to the starting point of the calibration vector either at the yellow dot (on the bottom rear of the enclosure) or anywhere along the dashed line.

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}.

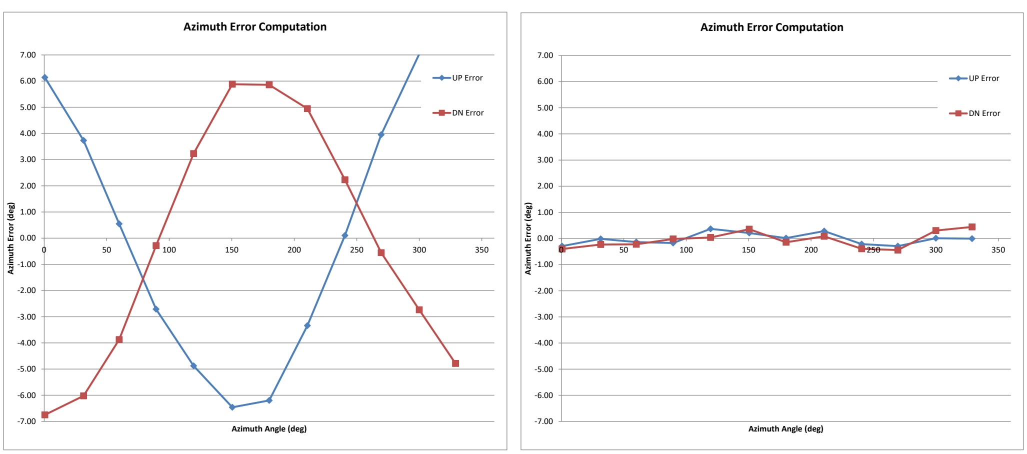

Figure 9. Error plots from the "Caveatron Magnetometer Calibration Calculator.xlsx" Excel spreadsheet. At left is a typical error plot after the data is entered but before finding the misalignment calibration values. At right is a well-calibrated plot with an error of less than 0.5 degrees.

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.

LRF Range Calibration

Special Requirements: Tape measure or laser rangefinder

This value is added to 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.

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 process only needs to be performed once after the system is assembled. 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. Load the new value into the Caveatron. Double check that the floor and ceiling are now level on the LIDAR live view display.

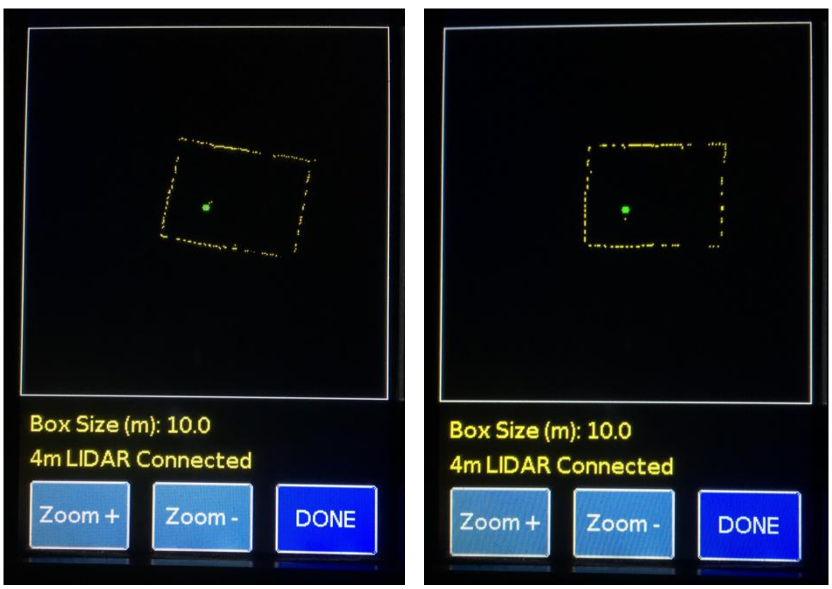

Figure 10. Views of the real-time LIDAR display of a room with the Caveatron on a level table. An improper LIDAR orientation calibration is shown at left while a properly calibrated one is shown a right. In this example, you would subtract several degrees from the initial calibration orientation to obtain the correct value.

LIDAR Module Corners and Window Distortion Correction

Special Requirements: A room from which a cross section can be recorded without significant obstructions to the floors, walls and ceiling. A large box will suffice as well. Also, the “LIDAR Window Correction Calculator.xlsx” spreadsheet is needed to perform the correction calculation.

For LIDARs that use triangulation to measure distance (like the RPLIDAR modules), the corners where the windows come together produce small distortions that should be corrected to ensure the most accurate possible results. In my experience, the error does not exceed 7%, and at most angles is much less than that (Figure 12), so this calibration is not strictly necessary, but is recommended for best results. Furthermore, there are small angles right around the corners that produce highly spurious data that shows up as noise in the data if not removed. This corner noise is more significant and is important to remove. It can be easily filtered out where a LIDAR signal level value is present in the data but at the 4k and 8k data rates of the RP LIDAR, no the LIDAR signal level is not available. So, the angles where the noisy data is present must be identified for removal in post-processing.

To collect the necessary data to perform both the Distortion correction and identify the angles for filtering the LIDAR module corners, set the Caveatron to a position roughly in the center of a room with a clear cross-sectional view to the walls, ceiling and floor. Alternatively, you can put it in the center of a large box. Place the retroreflective card some distance in front of the Caveatron so that the LRF laser will hit it. Be sure the Caveatron is roughly perpendicular to the walls and will not move during the data collection. Remove the LIDAR module lid so there are no windows obstructing the view. Create a new survey file and start a Passage scan, collecting data for about 8-10 seconds. Re-install the LIDAR module lid, being sure not to move the Caveatron at all. Even a small shift will result in an erroneous calibration. Create another new survey file and start another Passage scan, collecting data for about 8-10 seconds. Download the two .cvl files to a PC.

Window Distortion Correction

Open the "LIDAR Window Correction Calibration.xlsx" Excel spreadsheet. The spreadsheet computes the LIDAR module window distortion correction. It assumes you have at least 60,000 points (additional points are ignored), but if you have fewer points, it still appears to work correctly – just be sure to delete any extra points that are not part of your data. First change the extension of the two .cvl files to .txt. Open the files in Excel. Be sure that the proper tab delimited filtering is set so that the angles are in the first column and the distances (in mm) are in the second column. (Do not worry about the header lines, they will be ignored in the spreadsheet.) Select the first two columns of the data where the LIDAR cover was not installed (no windows) and copy them to the first two columns of the NO_WINDOWS green highlighted tab at far left. Then select the first two columns of the data where the LIDAR cover was installed (with windows) and copy them to the first two columns of the WINDOWS_ON green tab.

Now switch to the RESULTS tabs (yellow highlighted). Here you will find a plot showing the measured distance as a function of angle (0-360^{o}). The blue line is the true distance with no window installed. The orange line is the distance after the correction is applied. An example of such a plot is shown in Figure 11. The goal is to have the orange line lie down the center of the blue line as much as possible and the calculator should automatically give a pretty good result. For reference, Figure 12 shows what the uncorrected distance values are for the same data as in Figure 11 illustrating what the distortion actually looks like. You will notice in Figure 11 that at some angles the orange distance falls considerably off of the blue line. These represent the LIDAR module corners which are dealt with in the section below.

Depending on how flat your LIDAR window is, you may need to adjust the scaling factor in the yellow highlighted cell. In general the default value of "1" should be fine which allows for correction values from -127 to +127. A value of -128 indicates that the value is out of range so any data at that angle is ignored.

If the required correction is larger than this, then a higher scaling value is needed to bring it back in range. To find out if you need a larger value, scan down the list in the RESULTS tab looking for places where the Final Correction column (column D) has red highlighted “-128” values. Look at the values in the Base Correction column (column B). If they fall mostly in the range of -254 to +254, then you can use a scaling value of “2” to bring them back in range. If they are in the range of -381 to +381 then use a scaling value of “3” and so forth. However, this will affect all the value and the higher the scaling value, the lower the resolution of the correction. If you only have a few red highlighted -128 values and most of those read “#DIV/0”, then it’s probably best to leave the scaling factor at “1”. The exception is if there are is large percentage red highlighted -128 values and most of them are not “#DIV/0”, indicating that the distortions are much worse than average. In that case, you will need to increase the scaling factor until they number of red highlighted -128 values is minimized.

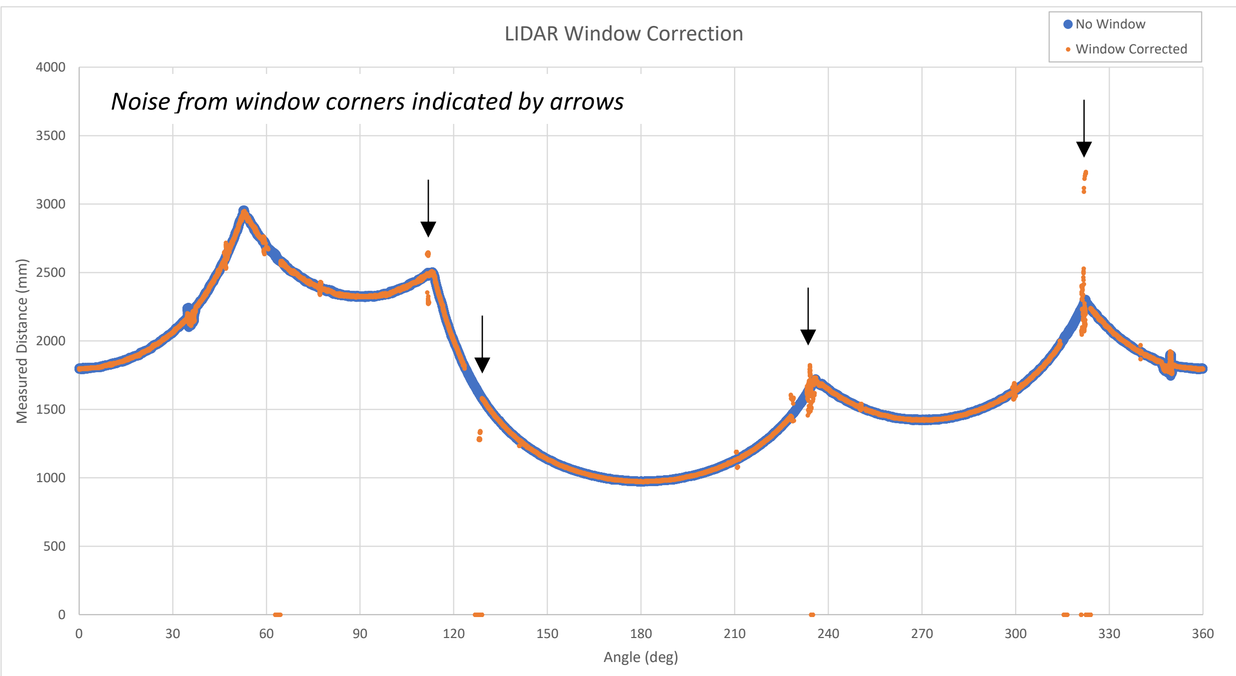

Figure 11. Plot from the RESULTS tab of the “LIDAR Window Correction Calculator” spreadsheet showing the distance as a function of angle for the data with the LIDAR window cover removed (blue line) and with the LIDAR window cover installed and the correction applied (orange line). Locations where noisy data must also be removed due to the window corners are also indicated.

In general the automatic correction should be pretty good, but there may be a few angles where there is a discontinuity that ends up averaging the correction a little bit off of the blue line. You can refine the correction manually by entering values in the green column titled “Manual Adjustment”. These are simply added to the Base Correction column to get the Final Correction column. You will need to zoom in on the plot to see the effect. An example is shown in Figure 13a, where the discontinuity has averaged the correction off of the line. A portion of the data can be moved back onto the line by entering a value of -18 as shown in Figure 13b (this does move a part further off of the line but at least part of it is now corrected.) Note that attempting to apply an adjustment to the 2nd discontinuity in this example only makes things worse as shown in Figure 13c, so it is not appropriate to apply one everywhere. In fact, the residual errors are generally small enough that you do not need to apply any manual adjustments unless you really want to get the correction as good as possible.

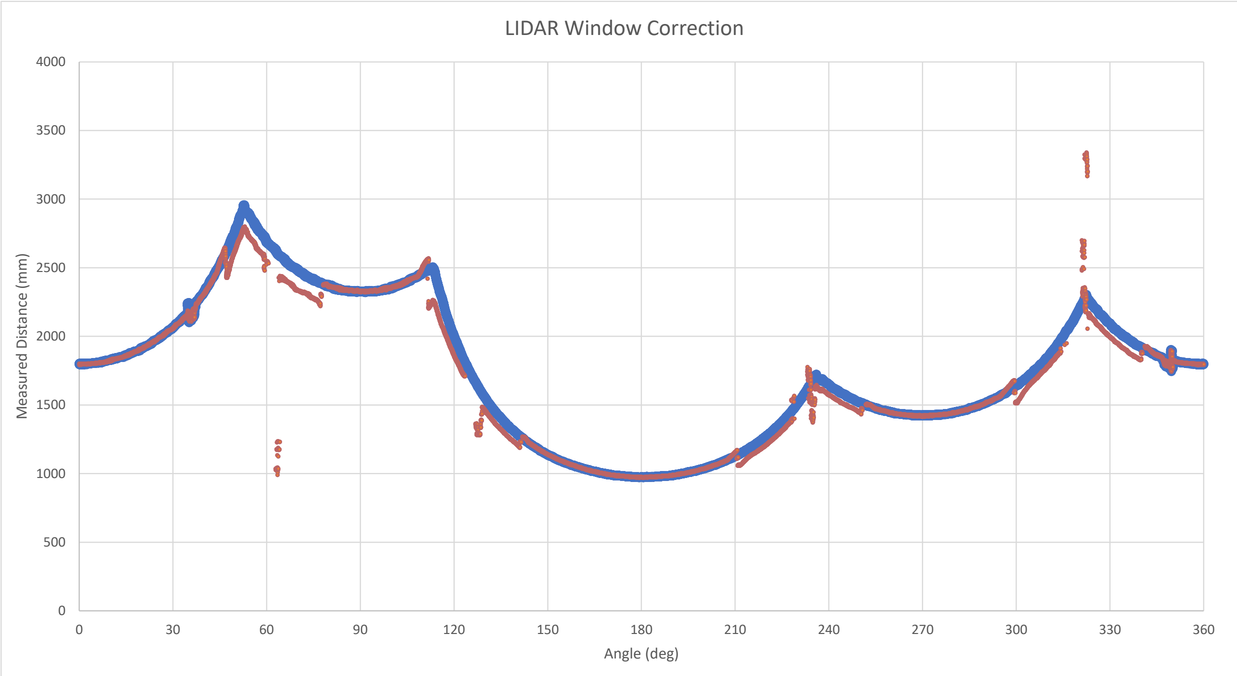

Figure 12. Plot showing the same data as in Figure 11, but without applying any Window Distortion Correction to illustrate the level of distortion. At most angles, the errors are quite small but over some angles the error approaches 7%.

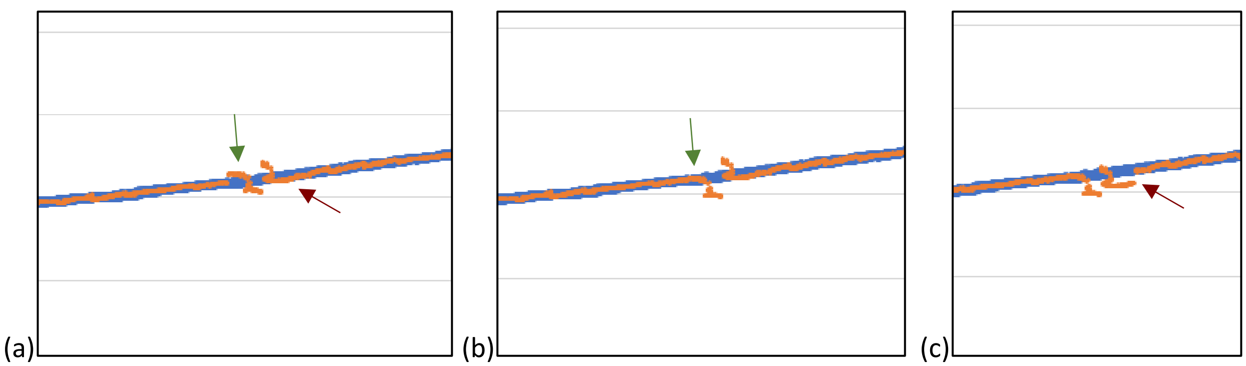

Figure 13. Closeup views of the corrected data (orange line) overlaying the reference data (blue line). (a) The original correction. (b) Applying a Manual adjustment that improves the correction. (c) Applying a Manual adjustment that make the correction worse.

Once you are satisfied with the correction, go to the blue highlight OUTPUT tab (the far right tab after the results tab) where the correction values have been transposed for easy saving to a comma delimited text file. While in this tab, simple Save As and pick .csv for the format. That file can be opened in any text editor and copied and pasted into the .imu file for the calibration upload.

The .imu file has two rows for Window Distortion Correction. The first row has two comma separated values. The first value is the number of corrections. If you are using the spreadsheet calculator, that value must be a “2” for 720 points. 360 points is also support if the first value is a “1”. The second value is the scaling factor from the RESULTS tab on the spreadsheet, which is normally “1” but if you changed it, it will

be a different value. This value can also be "0" in which case no distortion correction will be performed. The most likely entry for the first row will be:
2,1
The second row of the Window Distortion Correction in the .imu file is the actual correction values and are the values copied and pasted from the Excel spreadsheet generated .csv file.

LIDAR Module Corners

Looking back at Figure 11, find the places where the noisy distance values are present that fall considerably off of the blue line. These are the effects of the LIDAR module cover corners and must be removed. This will only be a small range of angles of 1-2 degrees at most. Some corners may not exhibit spurious signals. Expand the horizontal scale of the chart to enlarge these corners and hover the mouse cursor over the first and last points of the noise and pick the next lower and higher values (to the nearest 0.1°) as shown in Figure 14. Record these lower and upper values for the angles to be ignored From this example, one of the four LIDAR corner entries would be 321.1, 322.5, which means all data between 321.1 and 322.5 degrees will be ignored.

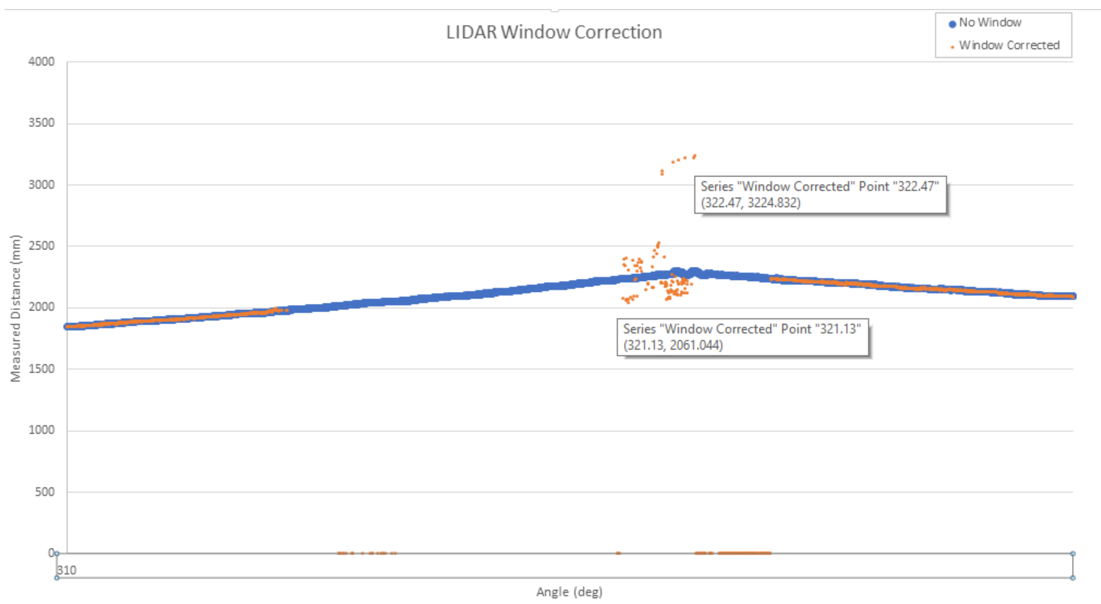

Figure 14. Example of determining the lower and upper limits for the noise created by a LIDAR window corner using a zoomed in portion of Figure 11. By hovering the mouse cursor a pop-up shows the angle of each point which can be used to select the lowest and highest value of the noisy data region.

To enter the data into the .imu calibration file, each row of the four rows represents one corner and there must be four entry lines in the calibration file. Also, the first value in each row must be the smaller of the two and they are separated by a comma. If you do not want to remove values from a particular corner or do not need to remove all four corners, enter the following for that corner:
-1,-1

Note that the data for these angles is still collected by the Caveatron and that these angle removal values are only used by the Caveatron Process post-processing application. A dialog in that application allows you to change these values or not remove any corners at all before applying them to the data.

Touchscreen Calibration

Special Requirements: “*Caveatron_Setup”* firmware loaded to the Caveatron.

This defines the mapping of touch positions to screen positions and varies from screen to screen so each one needs an initial calibration. These should not change over time.

The calibration is performed by uploading the “*Caveatron_Setup”* firmware and waiting for the routine to automatically start after 10 seconds. 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. You can then tap the screen anywhere to save the parameters to the EEPROM.

Hardware Code

Special Requirements: “*Caveatron_Setup”* firmware loaded to the Caveatron.

This is a 12-digit code that defines the specific hardware components inside the Caveatron allowing for different electronics modules to be used with the same software. It is created and loaded through the *HARDWARE SETUP* routine of the “*Caveatron_Setup”* firmware.

Note that a valid hardware code is required or the Caveatron will not function.

Date/Time and Preferences

Special Requirements: None.

These values are initialized with the “*Caveatron_Setup”* firmware. If it finds a valid date and time, it is left unchanged otherwise it is set to Jan 1, 2020. Both the date/time and preferences are easily adjusted later using the normal Caveatron firmware under *UTILITIES->SETTINGS*.

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.

EEPROM Addresses

For reference, 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. Setup codes, calibration parameters and preference settings are all stored on the EEPROM.

Table 2. List of Caveatron parameters stored in EEPROM with their type, address, and size.

Parameter	Data Type	EEPROM Address (Hex bytes)	Data Size (# Bytes)
Hardware Code	12 characters	20	12
Touchscreen Calibration	3x10 character array	80	30
Accelerometer Calibration	3x4 float array	200	48
Magnetometer Alignment Calibration	8x1 float array	300	32
Magnetometer Hard & Soft Iron Calibration (User Calibration)	3x4 float array	400	48
Gyroscope Calibration	1x3 float array	600	12
LIDAR Module Corners	4x2 float array	700	32
LIDAR Orientation Calibration	1 float	800	4
LRF Range Calibration	1 float	860	4
LIDAR Rotation Speed Setting	1 byte	900	1
LIDAR Data Rate Setting	1 byte	900	1
LRF Rate Setting	1 byte	900	1
Auto-Shutdown Timer Setting	1 byte	900	1
Window Distortion Correction	362 or 722 bytes	A00	722

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