Overview

This is an edited transcript from a video that shows how I use gravity to point a telescope at stars within an accuracy of a few arc minutes. The star finder was made from two Arduino boards. It sends gravity vector measurements to a mobile phone, which uses them to display the telescope pointer coordinates.

I used gravity sensors because six years ago I was looking for an equatorial telescope that could be taken on buses and trains and carried by hand along a kilometre or two of dirt road. It also had to point accurately in poor seeing conditions and have battery capacity for several days of photometry and spectroscopy.

A pushto telescope with a gravity-referenced star finder met these requirements. The star finder cost about $100. and was assembled and installed using a screwdriver, scissors, and 3M fasteners. It's not a commercial unit but may interest citizen scientists who: live in small apartments, use lucky imaging to manage cloudy skies, travel to cloud-free sites on public transport, or want to recycle or add PushTo capability to an old telescope.

This video describes the star finder, its assembly, and its performance. The appendices include a user manual, a calibration manual, and a maths background.

Portable astronomy

This slide shows the equipment. On the left is an image of the instrument box holding the telescope, mount, cameras, and spectroscope, on a foldup trolley. I'm carrying a tripod, and a backpack with supplies for the weekend.

The right-hand image shows the equipment set up. There is an equatorial telescope that is an unguided PushTo design. This choice removed the need for one or two motors, the guide scope, and a camera. It greatly reduced the size and weight of the instrument and power bank.

Two small black boxes, A and B, hold the gravity sensors. A is mounted on the declination plate, and B is on the hour angle plate. The EQ5 or Benro tripods connect to a Star Adventurer tracking motor and equatorial wedge, via a rotatable adaptor plate 'C'.

More compact Alt-Azimuth systems are available, but they don't yet have the flexibility and sensitivity of a compact, equatorial rig, or the ability to measure spectra. And this system has proven to be reasonably portable, rigid, and robust.

Packed for spectroscopy

- 2x recesses for eyepiece or camera
- ED80T 80 mm f/6 carbon fibre APO telescope
- Counterweight and rod
- Star Adventurer tracking motor
- Declination control
- Alpy 600 spectroscope and lamps
- Atik 314L+ camera

The portable astronomy equipment is contained in three alternative instrument cases, that hold a combination of specific, and shared, telescope and mount components. One case is for spectroscopy, the second is for photometry, and the third is for out-reach demonstrations.

This slide shows the spectroscopy instrument case. It contains a telescope, mount, and ancillary equipment, and particularly an Alpy 600 spectroscope, with calibration lamps and a variable slit mirror.

Packed for photometry

- 2x eyepieces or USB cameras
- Star Adventurer tracking motor
- Declination control
- Counterweight and rod
- Maksutov Cassegrain, 90 mm f/13.9
- Filter case with A Johnson V filter, narrow band filters and SA100 Star Analyser

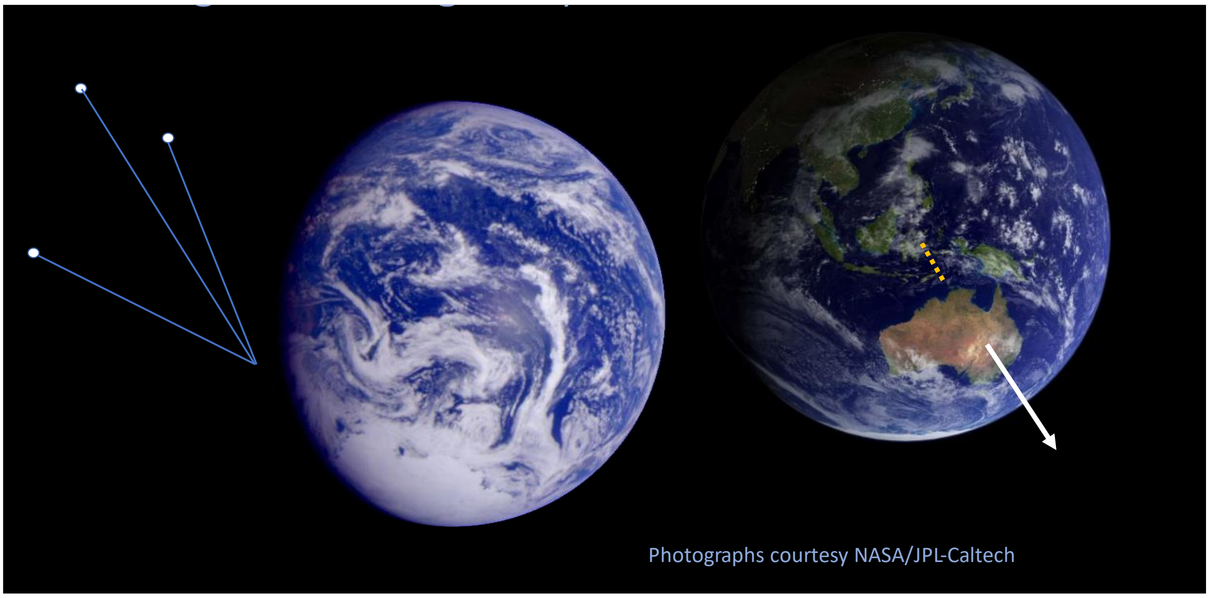
The photometry case shares basic equipment items with the spectrometer case. However, it has a 90 mm Maksutov telescope, a flip mirror, a filter wheel, a Johnson V filter, a Star Analyser grating, and a selection of narrow-band filters. There's also room for a computer above the declination control and tracking motor. It's shown in its foam tray to the left of the case.

Packed for outreach

- Takahashi 60 mm f/6 FS60CB telescope & flip mirror
- Counterweight rod (in recess beneath telescope)
- Counterweight
- Star Adventurer tracking motor
- Declination control
- 2x recesses for eyepiece or USB cameras
- Filter wheel with narrow band and Johnson V, filters, and an SA100 Star Analyser grating
- Atik 314L+ camera (beneath filter wheel)
- Red dot finder

The outreach case also holds the general-purpose equipment, a 60 mm Takahashi refractor telescope, and a flip mirror. It shares a filter wheel and filters with the photometry case. These are used with or without a computer to show brighter objects in the night sky and to demonstrate basic spectroscopy at outreach events.

Star alignment or gravity reference



Before going much further it's worth looking at the advantages and disadvantages of using gravity-referenced accelerometers, versus star alignment using optical encoders. One key difference was accuracy. The accelerometers I used were accurate to one or two arc minutes, whereas optical encoders are accurate to arc seconds. Optical encoders would be the essential option for fields of view much less than half a degree square, or for autoguiding a telescope.

The key advantages of accelerometers were: 1. stability, 2. ease of assembly, and 3. identification of mount defects. For example:

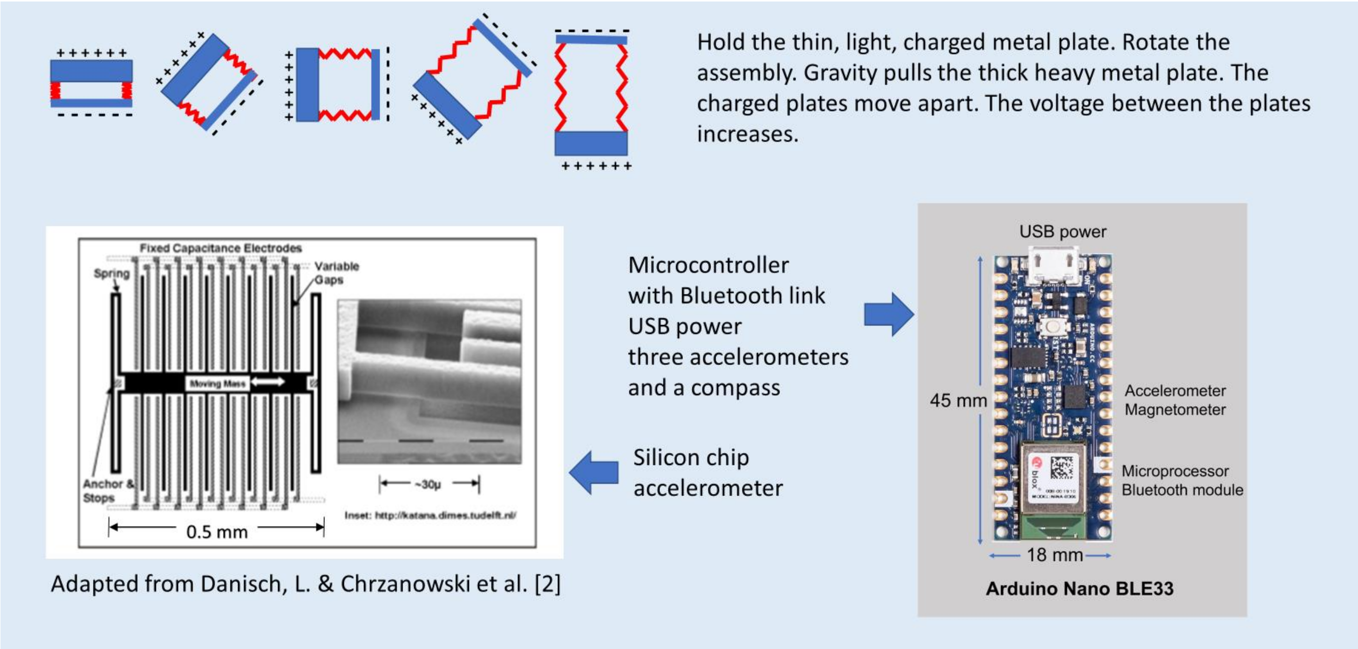
1. Gravity is extraordinarily stable, and clouds don't bother it. My gravity sensors are calibrated indoors and only need recalibrating after radical changes to a mount. Whereas the alignment of portable telescopes with optical encoders is weather-dependent and likely needs to be done at night, every time gear is set up.

2. Fitting optical encoders to a telescope requires significant instrument-making capacity. Whereas accelerometers can be stuck on, using industrial grade 3M fasteners.

3. An accelerometer system can highlight and help to correct important mount defects such as cone error.

Finally, it is hard to find a GoTo equatorial telescope, along with its observing equipment, that can be taken by hand on buses, trains, and along several kilometres of unsealed road.

Accelerometers and gravity

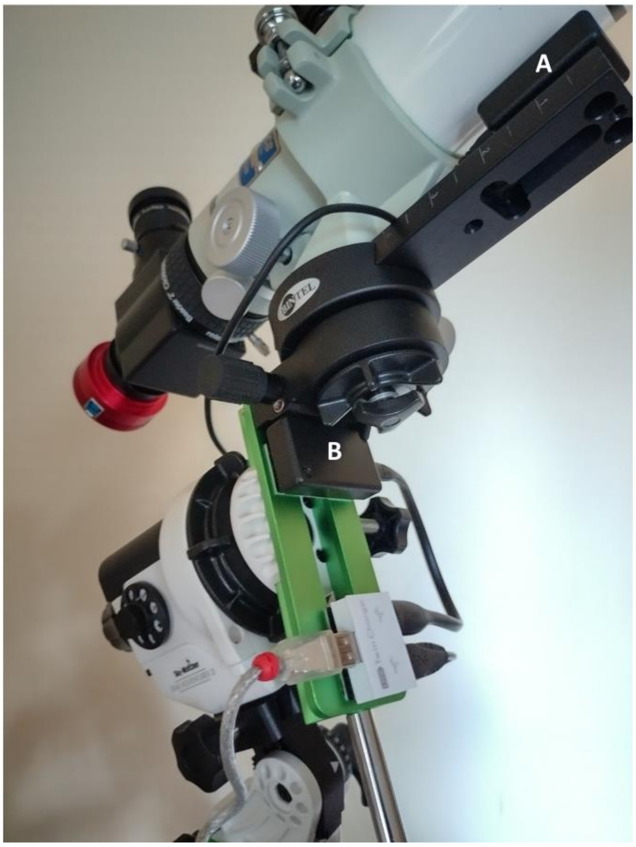


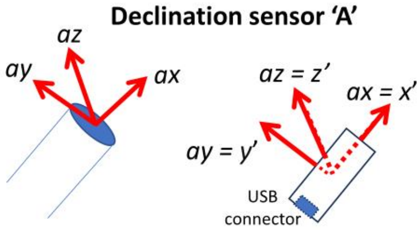
To quickly explain how an accelerometer works. The figure at the top left of this slide shows two blue metal plates separated by two red insulating springs, with an electric charge on the plates. On the left one plate is heavy and supported by the springs on top of a lighter one. As the assembly rotates to a position shown on the right, with the lighter plate on top, the distance between the plates increases. Consequently, the voltage needed to hold the charge across the two plates also increases. It's possible to use an equation to relate the voltage change as the plates move to the amount of rotation.

Silicon chip accelerometers are a microscopic version of this assembly, So, the bottom right of the slide shows a typical single-board microcontroller, and the accelerometer is just one of the chips on this board. The bottom left of the slide shows a schematic of how the accelerometer is made. It has two springs etched into the silicon, shown as double vertical black lines, on both the left-hand and the right-hand sides. These springs are connected to a weight shown as a thicker black horizontal bar, and to plates that move backward and forward, represented by vertical black lines. The vertical grey lines interlaced with the black lines represent stationary plates. The black plates are moved backward and forward between the stationary grey plates as the weight's direction changes with rotation.

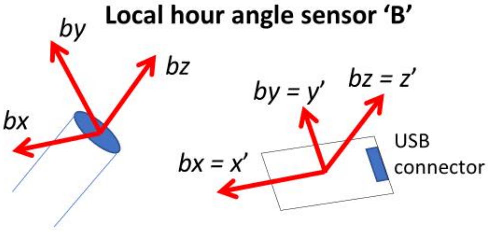
And that's how an accelerometer is constructed on a silicon chip. They are often used in phones to help control screen rotation. The same principle can be used to control how a telescope is rotated.

PushTo Dual sensor orientations





Sensor A beneath telescope.
ax ay is the reference rotation plane
x' y' is the sensor rotation plane
View from beneath IMU board A.



Sensor B on hour angle drive
bx by is the reference rotation plane
x' y' is the sensor rotation plane
Components face polar south.

This slide describes the reference configuration for the PushTo project. It uses two accelerometers, A for declination and B for local hour angle. The telescope declination reference frame is labelled *ax, ay,* and *az*, its hour angle reference frame is *bx, by,* and *bz,* and both follow the left-handed rotation convention. These axes have a one-to-one correspondence with the accelerometer axes, to simplify the transfer functions for alternative sensor mount orientations. Three equations at the end of the Arduino code define these orientations. The appendices provide more detailed explanations.

Assembling the gravity sensors

Each Arduino Nano 33 BLE board Includes:

- Computer
- Triaxial accelerometer
- Bluetooth Low Energy transceiver
- Power management

Cost - AUD100 for the two assemblies

Assembly time - 30 minutes

a) No soldering needed, just connect the USB port to a power bank

b) Two strips of foam mounting tape raise and hold the electronics board securely inside the enclosure half with screwholes.

c) Outside the enclosure half used in b) attach three Scotch Extreme fastener sections with centre section at right angles to outer two.

d) Enclosures with USB connector cutouts:

   i. Bud: USB-7201-C (thinnest, snug fit, requires hole drilled over reset button)

   ii. Hammond: 1551USB2BK (snug fit)

   iii. Hammond: 1551USB3BK (larger)

The star finders were assembled on a kitchen table in about half an hour using just a few hand tools. The electronics were purchased off the shelf as were all the necessary connectors. Small plastic boxes fitted with USB ports were available. These were well suited to holding the electronics. The electronic boards were held in place using double-sided foam adhesive tape to create support pads that dissipated vibration. The boxes were mounted on the telescope equipment using industrial grade 3M Extreme fasteners and could be readily removed.

The 3M fasteners were strong but rocked slightly along their grain boundaries. This was stabilised by cutting one strip of the fastener pair into three pieces and placing them side by side, with the centre piece at right angles to the outer two pieces, so the grain in the fasteners ran in two directions.

The accelerometers consumed just a few milliamps and were powered by a USB power bank. If it had an auto-off that couldn't be overridden, the power was taken from a hub supplying other devices on the telescope. Batteries were kept outside the boxes because changing batteries could upset the system alignment, also batteries close to the electronic board interfered with its magnetometer.

Installing the software

- Downloads: https://github.com/UltralightScopes/UsingGravityToFindStars
- Modifying and installing the mobile phone App:

  "Getting Started with MIT AppInventor"

  https://appinventor.mit.edu/explore/get-started
- Modifying and installing the accelerometer software:

  "Getting Started with the Arduino Nano 33 BLE"

  https://docs.arduino.cc/software/ide-v2/tutorials/getting-started-ide-v2

The mobile phone App provides the telescope pushto function, a semiautomated calibration, and a user-defined star catalog. It was written in MIT's programming language, 'App Inventor'. Coding for the electronic boards sends triaxial accelerometer and magnetometer data, via Bluetooth to a mobile phone and was written using Arduino. Both languages are well documented and supported by their developers and communities. The PDF version of this report provides links to the compilers, software downloads, and more detailed information.

To compile the PushTo mobile phone app: I log on to App Inventor, import the PushTo AIA code, press 'Build', and download the APK file to an Android phone using Google Drive. For the accelerometers, I import the Arduino compiler, paste the code text file into it, connect the accelerometer board to the computer USB port, and follow the Arduino compilation instructions.

Pointing to a star

Mobile phone screen

This video clip shows how to use the PushTo app for pointing a telescope. The demonstration is set up in my workshop and uses nominal star positions. The simplest method is to point at the target using the PushTo declination and right ascension readouts. This is fast, but only accurate to within half a degree. A second method is to jump from a reference star to the target. This takes more time but is typically accurate to within five arc minutes. To do this go to the database screen and select the target star and a nearby visible reference star.

Point the telescope at the reference star using the eyepiece or red dot finder. Then go back to the Main Screen and press the Set-Zero button. This will display just the target and reference differential values, which will drop to zero as the telescope is pushed from the reference to the target.

Ignore fluctuations in the declination display when adjusting the hour angle, for example using the counterweight and bar. These fluctuations are artifacts from combining filtering with the declination equation. For fine hour angle adjustments it can be helpful to use the tracking motor at about 12 times the tracking speed,

If the distance from the reference to the target is greater than a degree then large and rapid adjustments can be made. When the distance has dropped to about a degree start making small slow adjustments. This will allow the filter to cut in.

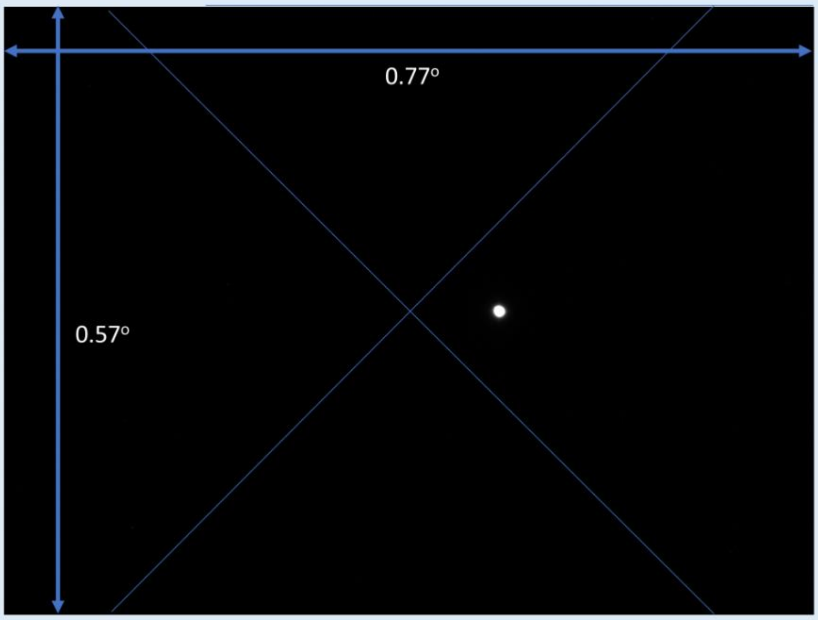
Fine adjustments do require practice. With fine adjustments backlash and the quality of the gearing will become evident and there may be a delay between the adjustment and the display and you will need to pause between adjustments to allow the displayed values to settle.

Note how adjusting the declination does not affect the hour angle results significantly. This further illustrates that the transient influence of the hour angle on declination is in part a property of the declination equation. Appendix 3 provides a more detailed explanation.

When the differential values are near zero the telescope should be pointing at the target. A third method is to point the telescope near the target using the declination and right ascension readouts; Use the plate solver to find an accurate value for the telescope's pointing direction, enter the solution as a reference, and move the telescope to the target. This can improve the accuracy to within `two arc minutes, which is the limit imposed by the accelerometer.

Alpha to Beta Centauri

Alpha and Beta Centauri		
Error	6	arc minutes
Hour angle distance	0.595	hours
Declination distance	0.449	degrees
Distance travelled	8.936	degrees
Apparent accuracy	1.16	%
Theoretical accuracy	0.37	%

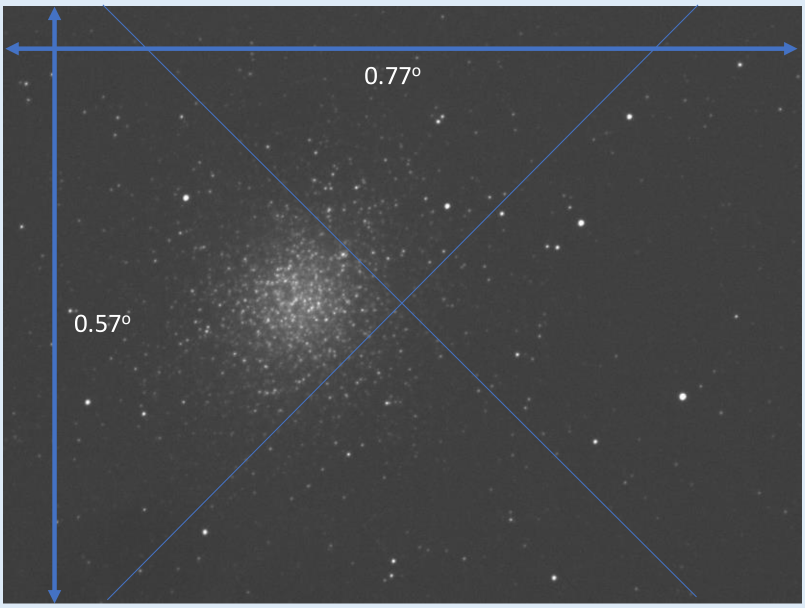


The next few slides show examples of stars that were located using PushTo. The images were taken from my backyard in Sydney, using a 60 mm Takahashi refractor telescope, a Star Adventurer mount, a ZWO ASI120 MM camera, and the live stacking software, SharpCap. I took this image while first testing the system by pointing backward and forward between Alpha and Beta Centauri.

The table on the left is worth explaining. The error value is the distance in arc minutes between the star and where it should be at the centre of the crosshairs. The apparent accuracy is the error as a percentage of the distance between the reference and target stars. Likewise, the theoretical accuracy is the two arc minute accuracy limit of the accelerometers.

Pointer accuracy – Epsilon Crucis to Omega Centauri

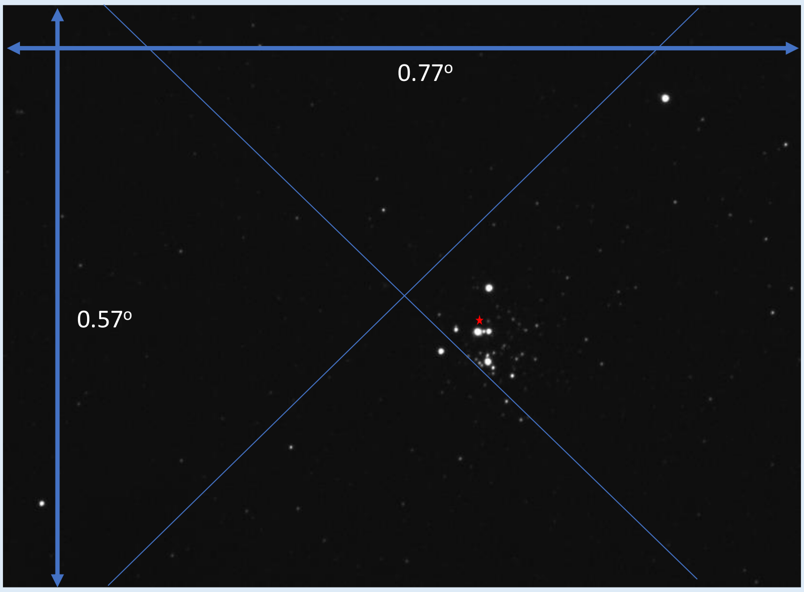
Epsilon Crucis and Omega Centauri		
Error	6.0	arc minutes
Hour angle distance	1.092	hours
Declination distance	12.928	degrees
Distance travelled	20.87	degrees
Apparent accuracy	0.45	%
Theoretical accuracy	0.16	%



This slide was one of the first invisible objects I found using the PushTo app and it required quite a long star hop of about 21 degrees from Epsilon Crucis to Omega Centauri.

Pointer accuracy – Jewel Box

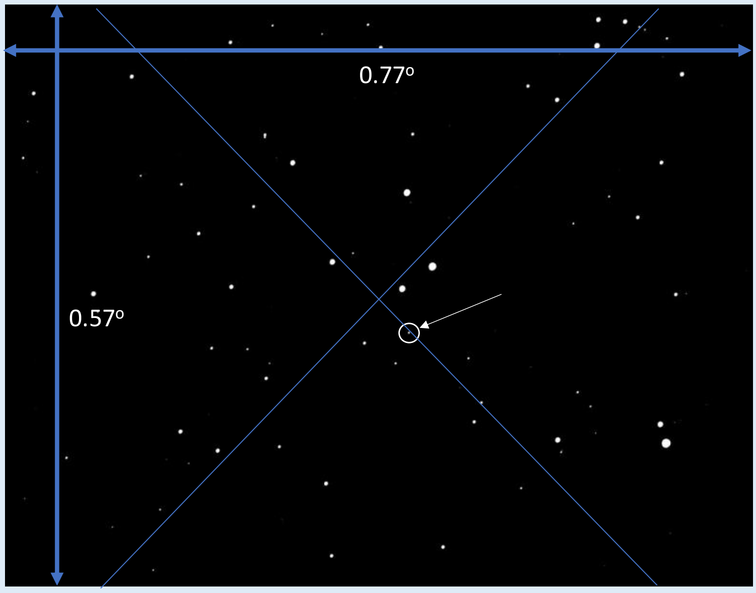
Becrux and Jewel Box		
Error	6	arc minutes
Hour angle distance	0.098	hours
Declination distance	-0.644	degrees
Distance travelled	1.63	degrees
Apparent accuracy	6.36	%
Theoretical accuracy	2.04	%



Here is another example, the Jewel Box. The target star has been coloured red. This required just a short star hop so although the positioning error is comparable with the previous examples the percent error is quite high.

Pointer accuracy – V.Y. Sculptoris

Fomalhaut and VY Sculptoris		
Error	3	arc minutes
Hour angle distance	0.523	hours
Declination distance	-0.158	degrees
Distance travelled	7.85	degrees
Apparent accuracy	0.6	%
Theoretical accuracy	0.42	%
Fomalhaut declination catalog	-29º	30'
Fomalhaut declination measured	-29º	37'



Here is the cataclysmic variable, V Y Sculptoris. Its magnitude is intermittently variable, so you can never be sure it will be visible. I was motivated to find this star by Alan Plummer's comment in Sky and Telescope, where he wrote that it was a tough find using star hopping. Alan was kind enough to validate my position for this star.

The image was taken using dark subtraction and stacking five, 30-second exposures. It was stretched, with a cut-off to remove sky-glow. Finding V Y Sculptoris, using Fomalhaut as a reference took one or two minutes. The star finder was calibrated four weeks prior to the session and pointing the mount south using drift alignment took seven minutes.

Pointer accuracy unmatched coordinates. – V Puppis

V **Puppis : Point A – Target coordinates**	
right ascension	07h 58m 55s
declination	-49º 16’ 21’’
V Puppis : Point B – Reference (centre) coordinates	
right ascension	07h 58m 13s
declination	-49º 14’ 41’’
PushTo pointer with platesolver J2000 error	
right ascension error	10.5 arc minutes
declination error	1.7 arc minutes

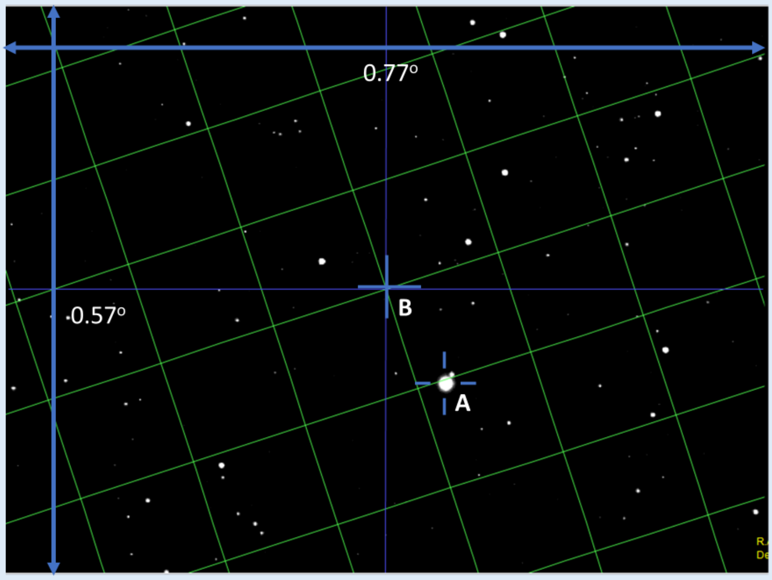


Plate solution reference coordinates: J2000 / target coordinates: apparent

This example shows an eclipsing binary star, V Puppis, at point A. It was located by pointing the telescope near the target, using SharpCap to access a plate solver, and then using the plate solution as the PushTo reference point B. However, there's an offset error of about ten arc minutes because the plate solver used J2000 coordinates, whereas the V Puppis target used apparent coordinates. The next slide shows how the offset was corrected in differential mode by using J2000 coordinates for the PushTo Target, to be compatible with the plate solver coordinates.

Pointer accuracy matched coordinates. – V Puppis

V **Puppis : Point A – Target coordinates**	
right ascension	07h 58m 14s
declination	-49º 14’ 42’’
V Puppis : Point B – Reference (centre) coordinates	
right ascension	07h 58m 19s
declination	-49º 13’ 20’’
PushTo pointer with platesolver differential error	
right ascension error	1.25 arc minutes
declination error	1.4 arc minutes

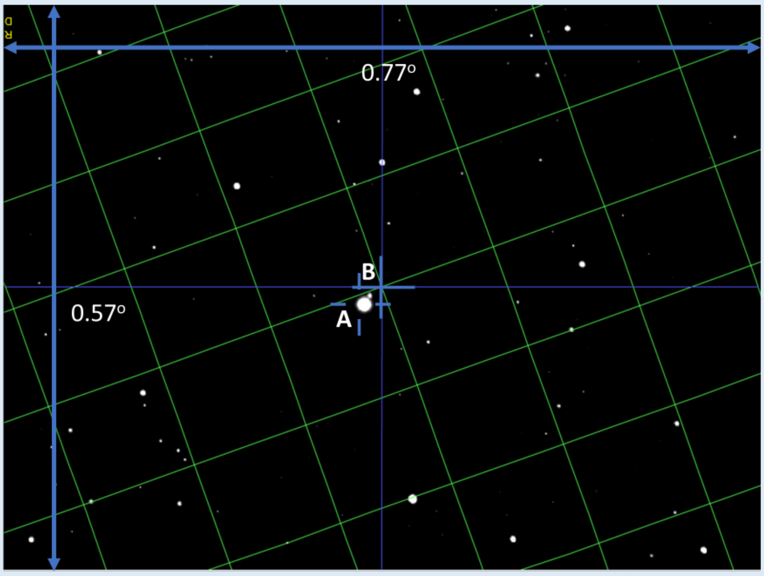


Plate solution reference coordinates: J2000 / target coordinates: J2000

This example located V Puppis using PushTo in differential mode and with the plate solver and target set to J2000 coordinates. The error is within two arc minutes, the limit imposed by the accelerometer resolution. However, Apparent coordinates account for the atmospheric, annual, and geographic corrections needed when using right ascension and declination readings to point a telescope. So, if possible, the plate solver and target should both be set to use Apparent coordinates.

Future work priorities

Finally, past and future work! The PushTo app was originally developed and demonstrated in 2018. Since then, I've improved its stability, accuracy, and functionality. I've also attempted to make it usable in the northern hemisphere, but this still needs testing. Nevertheless, there is potential for further improvement, as tabled below.

- Seek collaborator to test the PushTo algorithms in the northern hemisphere.
- Incorporate phone based live stack imaging with star coordinate identification, and data storage (e.g., by adding ZWO ASIAR, or Pegasus SmartEye units to the system).
- Incorporate phone based spectroscopy.
- Suppress hour angle induced fluctuations in the declination display.
- Calibrate and test the Arduino magnetometer function.
- Develop automatic compensation for cone error.
- Consider removing the temperature measurements as so far they have not been needed.

Conclusion

I've been using this system for several years now. On my telescopes: using the PushTo direct mode, the right ascension and declination readings point to within half a degree; the differential mode points within about three to six arc minutes; and, when using a plate solution instead of a reference star, the pointing accuracy improves to within two arc minutes.

It's worth noting that calibration may not be needed. If a camera and plate-solver are available I point the telescope near the target, obtain a plate solution, and use it as a reference for PushTo in differential mode. This is the simplest system to set up and the most accurate. However, accuracy is ultimately determined by the quality of the mount, its declination and hour-angle controls, backlash, and gear trains.

Finally, if you are interested in this system and have questions, please email ultralightscopes@gmail.com .

Acknowledgements

My thanks to the Sydney-City-Skywatchers, the Astronomical-Society-of-New-South-Wales, and the National-Australian-Convention-of-Amateur-Astronomers, for their encouragement. And the Massachusetts App Inventor power user group for all their advice while developing the phone App.

References

1. L. Meszaros et al, 2014, Accurate telescope positioning with MEMS accelerometers published by The Astronomical Society of the Pacific https://iopscience.iop.org/article/10.1086/677943/meta
2. Danisch, L. & Chrzanowski et al, 2022. Fusion of geodetic and mems sensors for integrated monitoring and analysis of deformations.
3. Gupta, S, 2024, SAF extension: App Inventor implementation of Storage Access Framework

Appendix 1. Operating Manual

The PushTo operating manual starts with a tour of the app's capability then describes in more detail how to use each of the app's four screens and finally shows two slides: one on how to rename the app sensors, and another on how to adjust the app and sensor firmware for different installation orientations. This appendix and the two that follow are also available in the video Using Gravity to Find Stars, which includes a few demonstrations on using the App.

PushTo App overview

Four screens provide the four PushTo functions:

1. Displays the telescope pointing direction and accelerometer values
2. Displays the changing distance as the telescope moves from a reference 'star' to a target 'star'.
3. Provides a database of target and reference stars.
4. Runs a semi-automated calibration.
   Note. Calibration may not be necessary. If you use a plate solver, just point the telescope near a target, plate solve the camera image, and enter the solution as a reference in the offsets page.

This is a tour of the PushTo app's capability and operation. The PushTo functions include:

1. Displaying the telescope pointing direction in both equatorial and horizontal coordinates.
2. Displaying the changing distance as the telescope moves from a reference point in the sky to a target star. The reference can be a star, or plate solver solution.
3. Setting up and managing a database of target and reference stars. And
4. Running a semi-automated calibration.

The PushTo app has separate screens for each function. They are accessed from the Main screen using a drop-down list, in the top right-hand corner. For example, choose the Star Offsets Screen where new targets and reference positions are entered.

To close Star Offsets press the Screen button and select Close screen. This will transfer the target and reference values to the Main screen. All screen buttons have a 'Return' option if no action is needed, and a 'Close application' option.

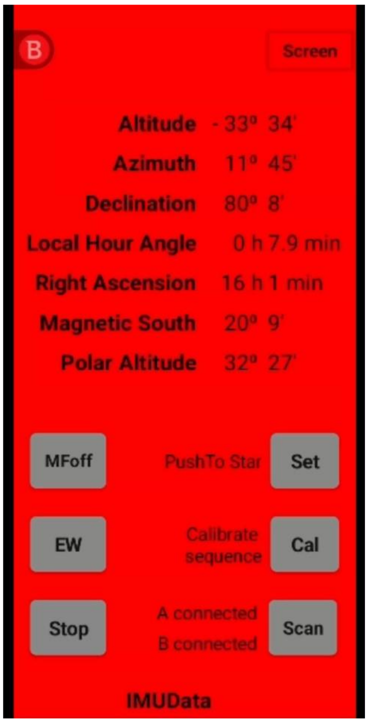
The main screen works as follows: Switch on the telescope sensors and press the Scan button to connect them to the PushTo app. When the display shows that the sensors are connected, press the Run button to display the telescope's altitude, azimuth, declination, local hour angle, right ascension, magnetic south, and polar altitude.

The sensor connections are reliable but can be lost if the internet is connected, or the phone is too far from the telescope. If the connections are lost, use the Stop button and then the Scan button to reconnect. After the connection has been made press the Run button.

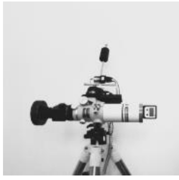
To calculate the telescope's azimuth indicate whether it is pointing east or west by pressing the E W button.

After a meridian flip, it is necessary to recalculate the right ascension and declination. This is carried out by pressing the M F button. The MF button and the right ascension algorithm have not yet been tested in the northern hemisphere. Feedback is welcome.

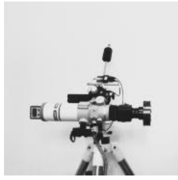
Calibration




CentreUpW


CentreDownE


CentreUpE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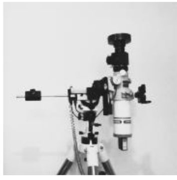
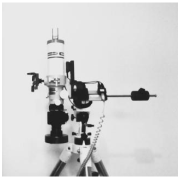
EUp


EN


EDown


ES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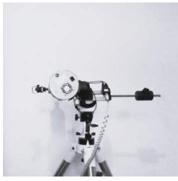
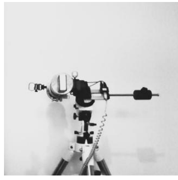

WN


WDown


WS

Be careful of the telescope and mount during the calibration and test procedures. They use positions not normally used, so make sure that, in each position, the telescope and mount are safe from damage due to collision, toppling, or cable entanglement. Take necessary precautions to prevent accidents or damage.

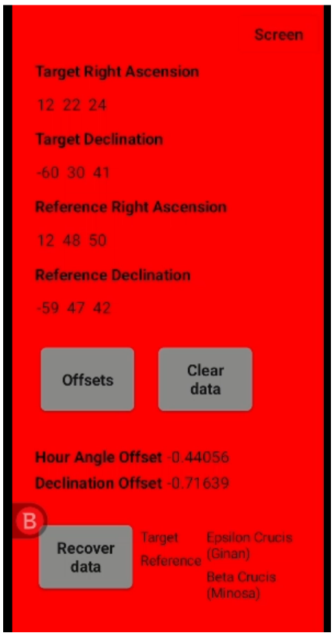
Calibration is carried out using the Main and Calibrate screens. It only needs to be done once and takes about half an hour. Pressing the Cal button on the main screen starts a sequence of calibration measurements at 12 telescope positions. Pressing Set acquires data from each position. For example:

- Centre Up West *(press Set then Cal)*
- Centre Down East *(press Set then Cal)*
- Centre Up East *(press Set then Cal)*
- Centre Down West *(press Set then Cal)*
- East Up *(press Set then Cal)*
- East North (*press Set then Cal)*
- East Down *(press Set then Cal)*
- East South *(press Set then Cal)*
- West Up *(press Set then Cal)*
- West North *(press Set then Cal)*
- West Down *(press Set then Cal)*
- West South *(press Set then Cal)*

Finally, to save the calibration press Set. To exit press Cal. The result is a New list of calibration values stored from the Calibration screen. Use the Read button in the Calibration screen to read the New calibration list. Use the Save button with the Local-Ext button to save it either in the PushTo app for immediate use or externally in the phone as a backup file. The calibration is now complete.

It's also possible to edit the calibration list using the main screen to check each adjustment against the IMU list of calibrated signals. A detailed procedure is described in the Calibration Appendix.

Target and Reference ‘Star’ Offsets



Target and Reference ‘Star’ Offsets

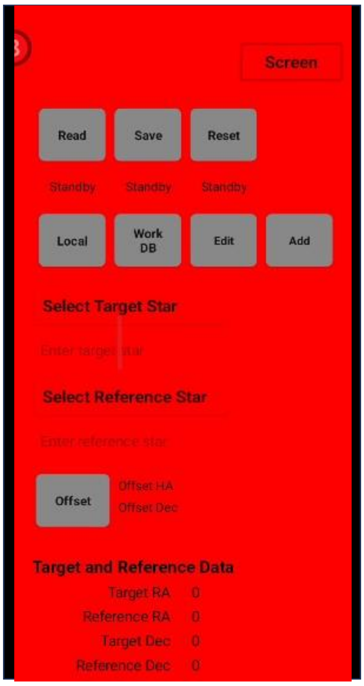
Manual offset entry and retrieval:

- The Star Offsets screen collects and manages the right ascension and declination values for target stars and reference stars or plate solver results.
- Enter a plate solver result instead of a reference star, to move to a target from wherever the telescope is pointing.
- The ‘Recover data' button recovers target and reference data from the last record sent to the Main Screen by either the Star Offsets or Star Database screens.

The Star Offsets page collects and manages the right ascension and declination values for target stars, and reference stars or plate solutions.

- To enter coordinate data use integers to enter hours, minutes, and seconds, or degrees, arc minutes, and arc seconds separating each unit value using spaces.
- The Offsets button calculates the local hour angle and declination offsets for moving the telescope to a target and sends the data to the Main Screen to use in the Push To Star function.
- The Clear button clears the target and reference data.
- The 'Recover data' button recovers target and reference data from the last record sent to the Main Screen by either the Star Offsets or Star Database screens. This is particularly useful for star hopping or using plate solver solutions.
- Scrolling down the screen shows text boxes holding: the target name, and comments, and the reference name and comments.
- Use the 'Save to DB' button to add or edit database record names and details and store the revised version in the database.

The Star Database



The data

- Automatically from the Offset screen or
- From CSV Excel files using the local/external and read or save buttons.

The database Edit button uses two files:

- The source file holds a database, which the PushTo app can't change,
- The work file holds records for calculating offsets and making drop-down lists.

Records containing a search term can be selected by:

- Adding single or multiple records with the search term
- Erasing all but the last record for multiple records with the search term
- Erasing a single record, e.g. the last remaining record with the search term

Now moving to the Star database screen, which collects and manages star coordinate data.

Use the target and reference drop-down lists or text boxes to select coordinates and press the Offsets button to calculate their offsets and transfer them to the Main screen

Use the Edit button and the add-erase button to prepare drop-down lists from the source file. Transfer star records from the Source file to the work file by toggling the Add-Erase button to Add. Alternatively, toggle to Erase to remove records from the work file.

For example, to add all the star records with Alpha prefixes

- Check the drop-down list to see if it already has any alpha-prefixed stars
- To transfer records toggle the Add-Erase button to Add.
- To enter the search term toggle the Edit button to EnterSearch.
- Enter the search phrase 'Alpha'
- Toggle the Enter-Search button to see how many records contain the search phrase.
- Use the 'Number of records ' drop-down list to set how these records will be selected.
    - adding multiple records selects all the available records containing the search term.
    - erasing multiple records with the search term erases all but the last record,
    - erasing one record with the search term erases the oldest record
- Toggle Select to add or erase the records and return from editing.
- The drop down list should now contain alpha prefixed star records

Naming the PushTo controller

Arduino IMU code

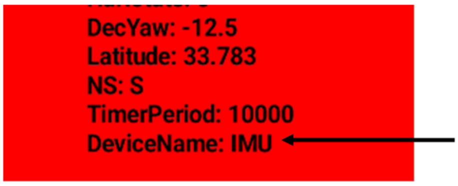
```
// Activate and initialize BLE peripheral
BLE.begin();
BLE.setLocalName("IMUB");
BLE.setAdvertisedService(imuService);
imuService.addCharacteristic(imuXYZChar);
imuService.addCharacteristic(imuTempChar);
imuService.addCharacteristic(imuSouthChar);
```

Change the default names for each accelerometer by modifying the line of Arduino code shown above, near the start of the accelerometer firmware listing.

The default name is IMUA or IMUB. This is the same as for the PushTo hand controller but with an A or B added. Just substitute the replacement name instead of IMU in the code line. Add the A or B to the end of the replacement name.

The name should be alphanumeric and end with an A for the declination board or B for the hour angle board.

Mobile phone hand control app



The PushTo hand controller default name is the same as for the Arduino board but without the 'A' or 'B' ending.

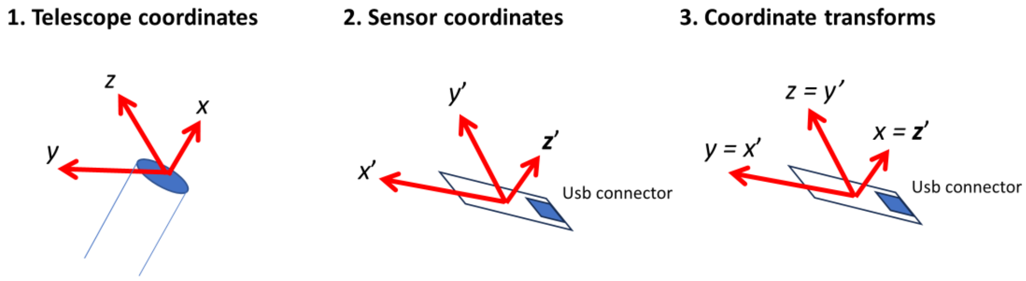
To change the device name substitute the replacement alphanumeric name instead of IMU in the last line at the bottom of the calibration file on the Calibration page.

If two or more PushTo systems are operating close together, then they should each have separate names, so that they don't interfere with each other.

Change the default names for each accelerometer by modifying the line of Arduino code near the start of the accelerometer firmware listing.

To change the matching PushTo hand control name edit the last line at the bottom of the calibration file on the Calibration page.

Changing sensor orientation code



4. Arduino sensor - lines of code for transforms

Set these three lines to match the required transform equations

```
void reOrient(int xyz[]){
  int x=xyz[0], y=xyz[1], z=xyz[2];
  xyz[0]=z; // reoriented X = z
  xyz[1]=x; // reoriented Y = x
  xyz[2]=y; // reoriented Z = y
}
```

EQ3 mount declination example

This slide shows how to change the sensor software to set the declination or local hour angle sensors in alternative orientations.

There are three lines of code at the end of the Arduino firmware that translate from sensor to telescope coordinates. The equations can be set up by comparing the telescope coordinates in Figure 1 to the sensor coordinates in Figure 2, to derive the equations in Figure 3. And the three lines of code in Figure 4.

This concludes the operating manual.

Appendix 2- Calibration Manual

Calibrating the accelerometers improves the PushTo finder accuracy but may be unnecessary if a camera and plate solver are available. Nevertheless, I calibrated my gravity sensors as it helped to uncover telescope alignment issues, also a camera is not always available, and plate solving can sometimes be slow,

The procedure I used is described in the next few slides, It took about half an hour and was conducted indoors during the day. The two systems I assembled were only recalibrated when the mount, drive, and sensors were radically altered. Telescope disassembly, transportation, and reassembly did not alter the calibration significantly.

Once the system was calibrated, the daytime preparation for each observing session was to level the telescope, set the mount altitude to the latitude angle within 0.1 degrees using a digital tilt meter, and align the telescope to the north or south celestial poles using a compass, or using drift alignment if long exposures were needed.

Preparation for calibrating the gravity sensors.

Be careful of the telescope and mount during the calibration and test procedures. They use positions not normally used, so make sure that, in each position, the telescope and mount are safe from damage due to collision, toppling, or cable entanglement. Take necessary precautions to prevent accidents or damage.

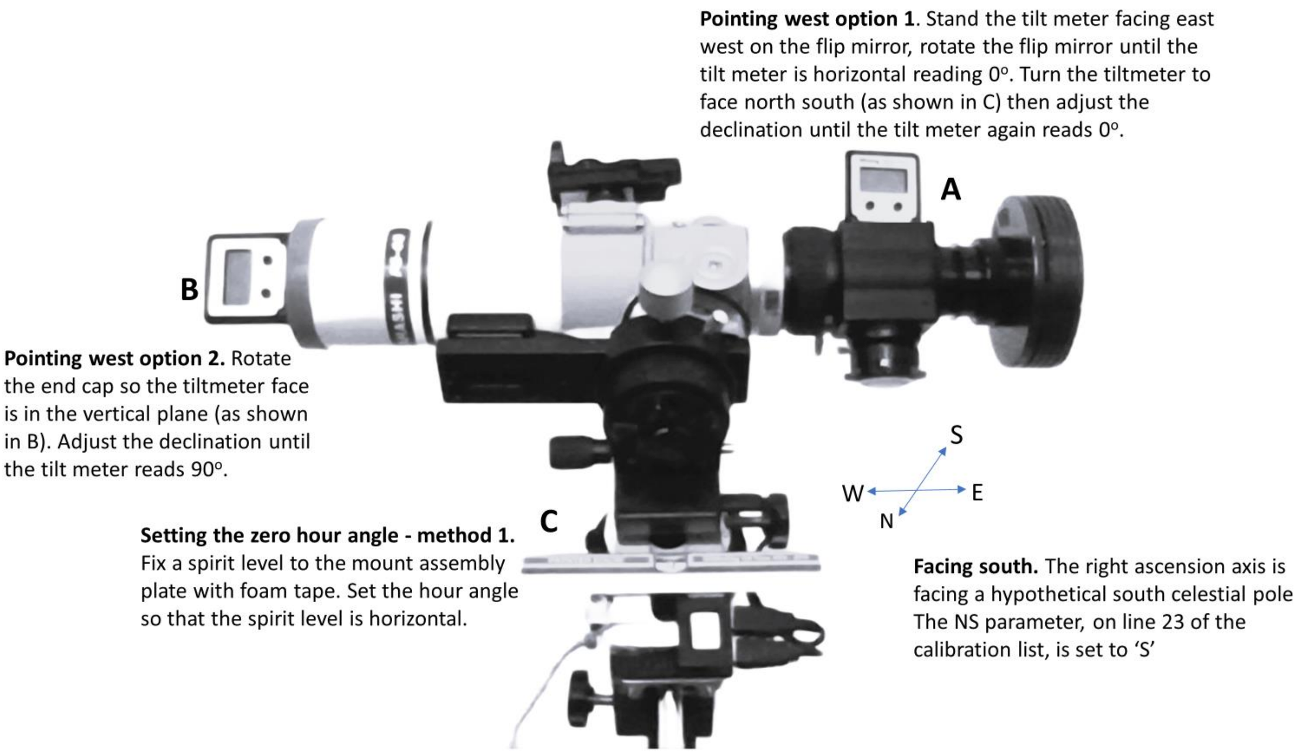
The calibration tool was a digital tilt meter, also known as an inclinometer, carpenter level, or angle gauge. It had a resolution of 0.1 degrees.

One or two of the calibration steps measured tilt in a non-vertical plane, for example when setting the hour angle for the calibration start position. If a digital tiltmeter didn't measure properly in non-vertical planes a spirit level was used instead. An example is given later in this appendix.

At each calibration step the tilt meter should be supported securely and be easily reoriented. A rotatable flip mirror box, with at least one flat side, was used to support the tilt meter, for all orientations, except pointing to the zenith or nadir, when the tilt meter was placed on the telescope or flip mirror end caps.

An alternative method was also tried using old or homemade rotatable telescope endcaps. The tiltmeter was attached to end caps using removable double-sided sponge tape, or 3M stick-on fasteners. This worked quite well, though care was needed to ensure the end cap rotated easily on the telescope without falling off or creating scuff marks. For my telescopes, the rotatable flip mirror box was a much more convenient and accurate option.

The starting position: Centre up pointing 'west'



The starting position for calibration is with the telescope's local hour angle set to zero, and the telescope pointing to the assumed west.

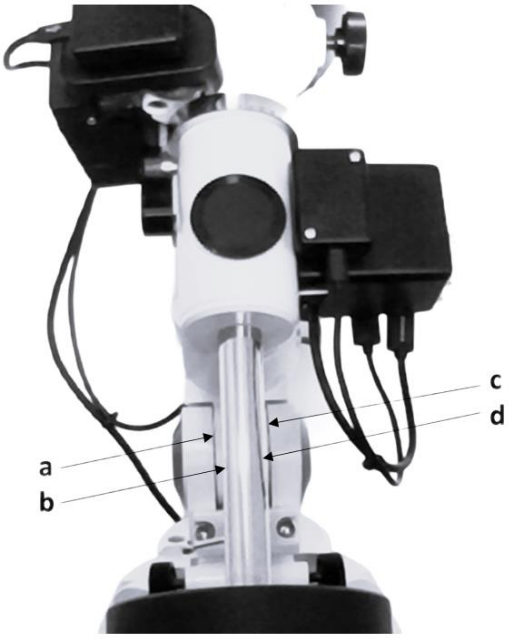
Before starting the calibration, set the equatorial wedge to the latitude angle, and point the right ascension axis to a hypothetical south or north celestial pole. It doesn't need to be the actual pole; it is just an assumption used as a reference for the calibration procedure.

The example shown here uses the Star Adventurer mount. It has been set up for the southern hemisphere, so the telescope points left to the assumed west. For northern hemisphere calibration, the telescope points right to the assumed west.

Once in the starting position, the tiltmeter needs to be set up. This slide demonstrates two ways to support it. My preferred method is to stand it on the flat surface of a rotatable flip mirror as shown in option A. Alternatively, you can fasten it to a telescope end cap as shown in option B, which was described in previous slides.

There are also two ways to set the hour angle to zero. The first, shown in image C, uses a spirit level attached to the right ascension plate to measure the hour angle's zero value in the non-vertical equatorial plane. The second, displayed in the next slide, uses surface edges on the mount as references to align the right ascension plate at the hour-angle's zero value.

Starting the calibration



Point the right ascension axis at hypothetical north or south celestial pole as appropriate. The direction is hypothetical because the azimuth setting doesn't affect accelerometers. Set the NS parameter in the calibration list to N or S as appropriate.

Set the zero hour angle - method 2 for for an EQ3 mount: Align the equatorial mount edges a and c, with the counterweight shaft edges b and d.

Point the telescope west using the methods described in the previous slide

Switch off mobile phone internet

Press the Cal button to step through each orientation, step. Press Set to store the measurement for each step

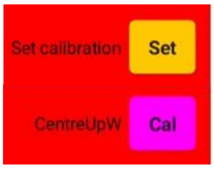
This slide describes how to start the calibration. It also uses an EQ3 mount to illustrate the second method for setting the hour angle to zero by aligning the equatorial mount edges a and c, with the counterweight shaft edges b and d.

Once the starting position has been set up, switch off the phone's Wi-Fi to stop internet messages or pop-ups from interfering.

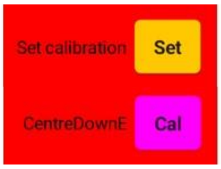
The calibration has three stages, each with four orientation steps. Press the Cal button to step through each orientation, and for each orientation step press Set to store the measurement after the IMU values have stabilised.

Stage 1 calibration- hour angle and altitude sensors

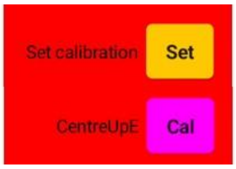
Step 1.
Centre up pointing west



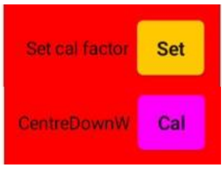
Step 2.
Center down pointing east



Step 3.
Centre up pointing east



Step 4.
Centre down pointing west



Stage 1 has four steps. For step 1. With the telescope in the starting position and with the Cal button label showing Centre Up W, press Set then Cal.

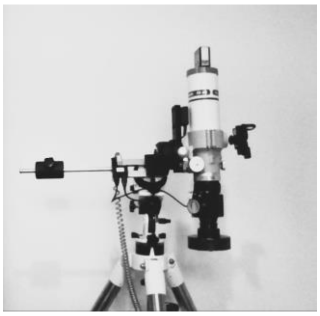
Step 2. With the Cal button showing Centre Down E, rotate the telescope 180 degrees around the hour angle axis, The telescope should then be pointing east. Press Set, then Cal.

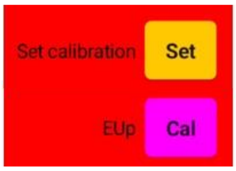
Step 3. With the Cal button label showing Centre Up E rotate the telescope back through 180 degrees of hour angle and 180 degrees of declination so that the telescope points east. Press Set, then Cal.

Step 4. Finally, with the Cal button label showing Centre Down W, rotate the telescope 180 degrees around the hour angle axis. The telescope should then be pointing west. Press Set, then Cal.

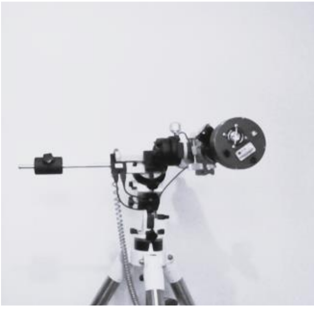
Stage 2 calibration- declination sensors, east side measurements

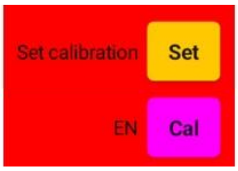
Step 1.
East pointing up





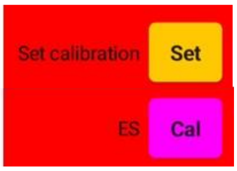
Step 2.
East pointing north





Step 3.
East pointing down

Step 4.
East pointing south



This slide describes the Stage 2 measurements.

Step 1. With the Cal button label showing E Up move the telescope to the east side of the mount and point it towards the zenith. Check the orientation with the tilt meter supported upright on the end cap. It should face south or north while adjusting the local hour angle and east or west while adjusting the declination. Press Set, then Cal.

For the next three orientation steps, the local hour angle should remain constant. At each step secure the tilt meter on the flip mirror or the telescope endcap and position it so its face stays in a vertical plane as the declination is adjusted.

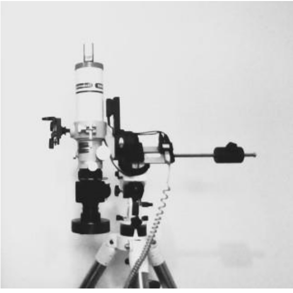
Step 2. With the Cal Label showing E N, move from East Up to East North by adjusting the declination until the tilt meter shows the telescope is horizontal pointing north. Press Set, then Cal.

Step 3. With the Cal label showing E Down, move from East North to East Down by adjusting the declination until the tilt meter shows the telescope is vertical pointing to the nadir. Check the orientation using the tilt meter supported upright on the camera or flip mirror end cap, or upside down and attached to the telescope end cap. Press Set, then Cal.

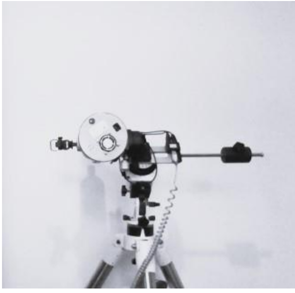
Step 4. With the Cal label showing E S, move from East Down to East South by adjusting the declination until the tilt meter shows the telescope is horizontal pointing south. Press Set, then Cal.

Stage 3 calibration- declination sensors, west side measurements

Step 1.
West pointing up

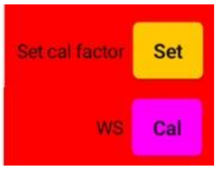


Step 2.
West pointing north



Step 3.
West pointing down

Step 4.
West pointing south



This slide describes the Stage 3 measurements.

These are essentially the same as for stage 2 except the telescope is on the west side of the mount.

Step 1. With the Cal button label showing W Up, move the telescope to the west side of the mount, and point it towards the zenith. Check the orientation with the tilt meter supported upright on the telescope end cap. It should face south or north while adjusting the hour angle and east or west while adjusting the declination. Press Set, then Cal.

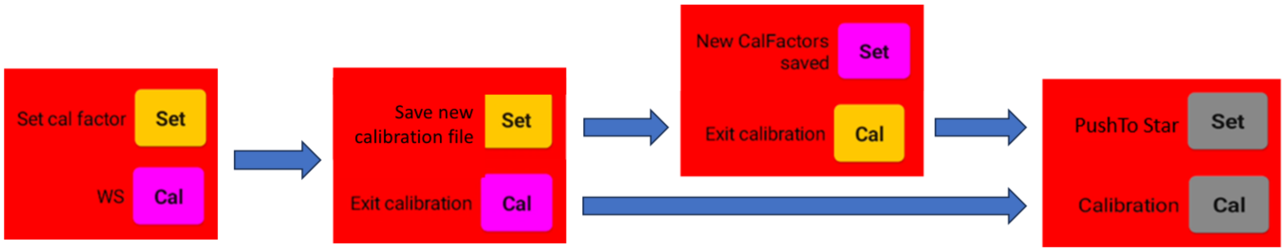
For the next three orientation steps, the local hour angle should remain constant. At each step secure the tilt meter on the flip mirror or the telescope endcap and position the tilt meter so its face stays in a vertical plane as the declination is adjusted.

Step 2. With the Cal label showing W N, move from West Up to West North by adjusting the declination until the tilt meter shows the telescope is horizontal pointing north. Press Set, then Cal.

Step 3. With the Cal label showing W Down, move from West North to West Down by adjusting the declination until the tilt meter shows the telescope is vertical pointing to the nadir. Check the orientation using the tilt meter supported upright on the camera or flip mirror end cap, or upside down and attached to the telescope end cap. Press Set, then Cal

Step 4. With the Cal label showing W S, move from West Down to West South by adjusting the declination until the tilt meter shows it is horizontal pointing south. Press Set, then Cal.

Save the calibration file and exit



Step 1.
Last calibration step

Step 2.
Choose exit or save

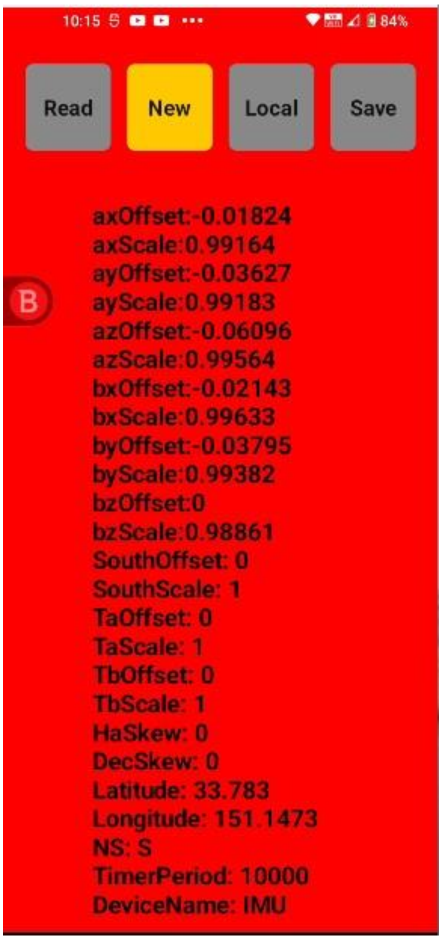
Step 3.
Exit after save

Step 4.
Calibration complete

This flow diagram shows how to manage the calibration data.

At Step 1, the calibration measurements are now complete. In Step 2, if you wish to save the new calibration factors, press the Set Button. Its label will then show New CalFactors saved. In Step 3, press the Cal button to exit the program. The button labels will turn grey, and the screen will return to normal monitoring as shown in Step 4.

Using the new calibration values



The following steps replace the current values for finding stars with the new calibration factors:

- Move to the PushTo 'Calibration' screen.
- Toggle the 'New-Cal' button to 'New'.
- Press the 'Read' button.
- Toggle the 'New-Cal' button back to 'Cal'.
- Press the 'Save' button.

You can now read the new calibration values by moving to the calibration screen, toggling the New-Cal button to New, and pressing the Read button. Then toggle back to 'Cal' and press the Save button to replace the current values for finding stars.

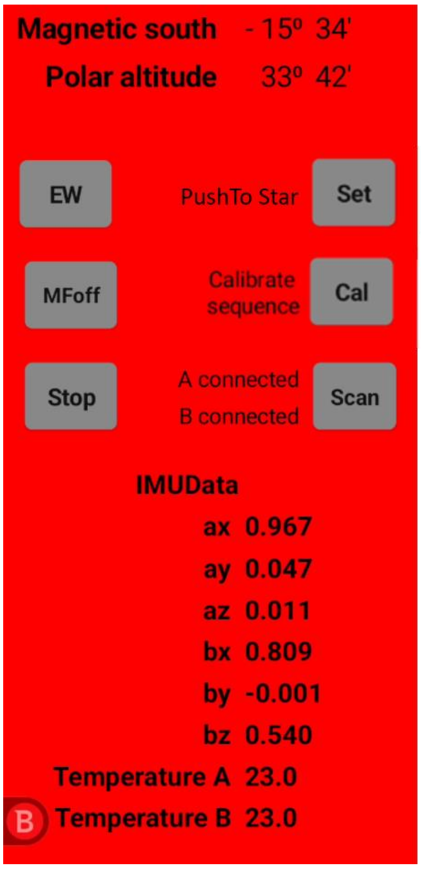
Declination and hour offset angle/yaw adjustments.

There won't always be horizontal or vertical planes to support the declination or hour-angle gravity sensors. An example is given here of an EQ3 mount with a declination sensor supported on the declination motor box, which is offset by ten degrees from the telescope's optical axis. In this case, it should be possible to manage the calibration stages two and three by fastening the tiltmeter to the declination sensor rather than the telescope endcap or flip mirror. After calibration, correct the offset by setting the Dec Skew parameter in the calibration list to minus the offset angle, which is approximately ten degrees in this example.

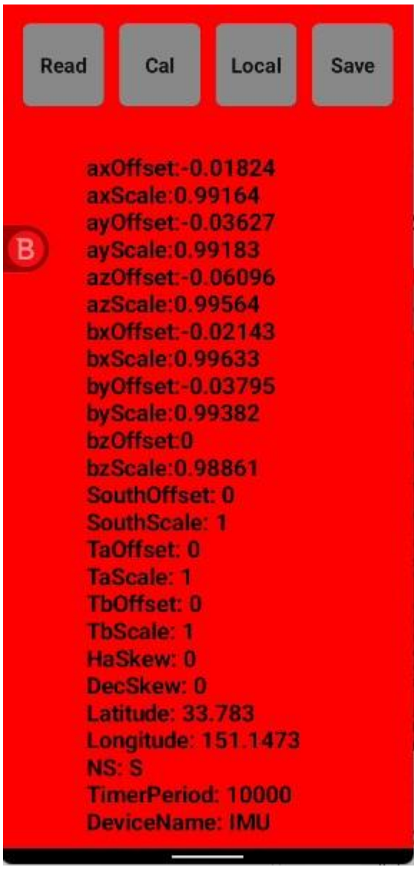
I have not had a chance to test this procedure with field measurements but it does produce a sensible calibration list and passes the calibration tests described in this appendix.

Fine calibration adjustments

A



B



The calibration list shown in screenshot A can be edited. Starting from the top of the list are the accelerometer offsets and scale factors that can all be adjusted. Likewise, near the bottom of the list, it's possible to set the observer's latitude and longitude; change the controller operating hemisphere by setting the NS parameter to North, or South; adjust the number of seconds allowed to find a star; and change the sensor Bluetooth name,

The calibration zero offsets and scale factors can be adjusted while checking them in real-time against the IMU list shown in screenshot B. However, I've only ever had to correct the Az and Bz scale factors for altitude and polar altitude respectively, and with the telescope pointing at the south pole I sometimes correct the A offset with the hour angle at zero hours and the Bx offset with the hour angle at plus or minus six hours. These approaches to fine-tuning would need to be modified where accelerometer mounts are skewed, for example in the EQ3 mount.

To test these alignments go to the main screen. Test the local hour angle alignment by pointing the telescope to the zenith. The local hour angle should read six hours on the west side of the mount and minus six hours on the east side. These values were accurate to within 0.5 minutes for my Star Adventurer mount.

Test the declination by pointing the telescope to the north or south pole and read the declination while moving the local hour angle from minus to plus six hours. The declination values were typically accurate to within 0.5 degrees for my Star Adventurer mount.

Despite these errors, declination and right ascension readings were useful for locating visible reference stars or pointing the telescope near a target ready for a plate solver reference. However, differential measurements using a reference star typically reduced the error to between three and six arc minutes; and when plate solutions were used for the reference position, the star finder accuracy approached its theoretical limit of two arc minutes, and accelerometer calibration wasn't needed.

This concludes the description of the calibration process. I'd welcome your feedback and suggestions for improvement.

Appendix 3 – Math background

This Appendix outlines the frames of reference and key equations for evaluating the absolute and differential coordinates.

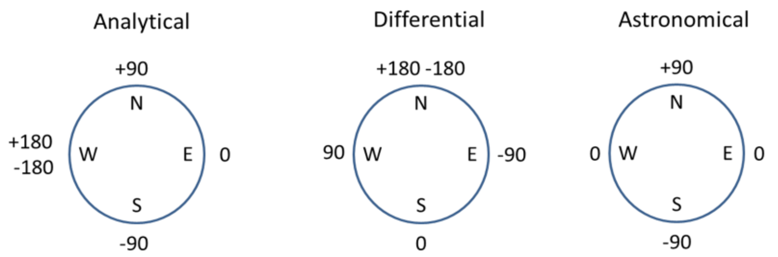
Hybrid coordinates

h local hour angle
δ declination
ϕ_0 latitude
a declination accelerometer vector
b local hour angle accelerometer vector

$$\mathrm{h} = \frac{\pi}{2} + \operatorname{atan2}\left(\frac{bx.\cos(\emptyset_0)}{by}\right)$$

$$\delta = \operatorname{atan2}\left(\frac{ay.\cos(\emptyset_0).\cos(h) - ax.\sin(\emptyset_0)}{ax.\cos(\emptyset_0).\cos(h) + ay.\sin(\emptyset_0)}\right)$$ Adapted from Meszaros et al [1]

Coordinate systems for declination



Astronomers, who use equatorial mounts, describe the position of a star using two axes: declination and right ascension. These are analogous to latitude and longitude but are spread across the sky rather than the earth.

The reference zero for declination is the celestial equator, and for right ascension, it's the vernal equinox for the year 2000. The local-hour-angle reference zero is derived from the right ascension and local time and it's at the local meridian.

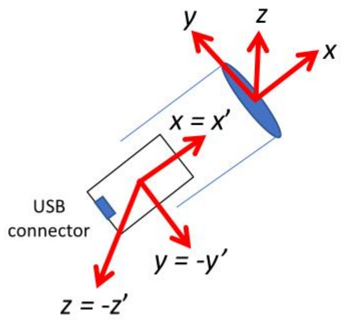
The Earth's gravity vector works well to measure rotation around equatorial axes because it has components in both the declination and local hour-angle planes. These gravity vector components can be used to point a telescope at a star. The equations here use the gravity component A, to describe declination, and the gravity component B to describe local hour angle.

The equations shown here provide a very stable solution, but it's important to note the hour angle term, h, in the expression for declination. This apparent dependence is nulled by the equation, provided the tracking motor altitude is well aligned with latitude and the telescope is stationary. However, rapid changes to the hour angle can produce fluctuations in the declination display, as the equation is thrown out of balance due to filter delays when responding to transient changes in the hour angle.

The declination is evaluated using analytical coordinates, then transformed into differential coordinates to determine changes in declination as the telescope moves from the reference to the target position. The transform also moves a discontinuity from west to north; this allows a greater range of telescope movement that can be useful in deciding when to carry out a meridian flip. The discontinuity is due north because I'm in Australia. In the northern hemisphere, the discontinuity is at due south. Finally, the differential coordinate values are transformed into astronomical coordinates to convert the measured values into easily recognisable results.

Single sensor reference orientation

Adapted from Meszaros et al [1]



Sensor A: x and z rotate around the declination axis and y rotates around the hour angle axis to give a partial solution for hour angle and declination.

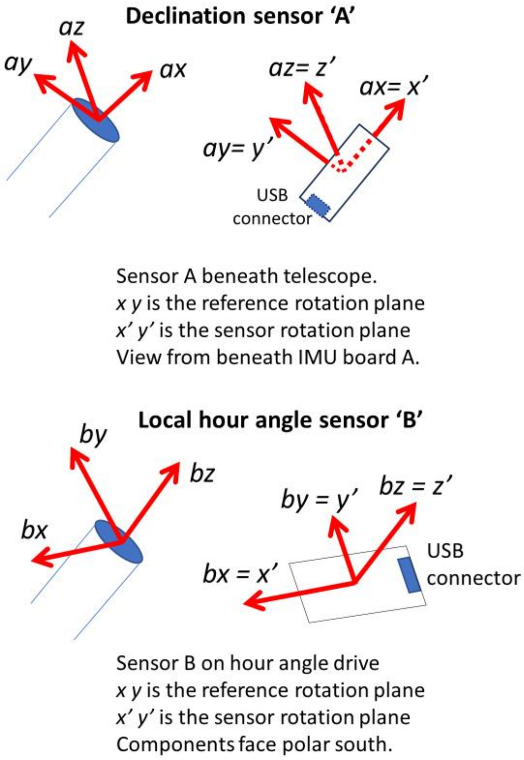
Sensor B on the hour angle drive axis determines east or west to complete the solution.

In this and the examples that follow:
x, y, z are telescope coordinates
x′ y′ z′ are sensor coordinates

The configuration shown here was used by researchers from the HUN-REN Research Centre for Astronomy and Earth Sciences. It's an important example of measuring local hour angle and declination using accelerometers. While it's not the primary configuration for the PushTo project, the declination equation based on their work has proven to be a very stable solution.

This slide shows an Arduino board with a triaxial accelerometer whose x and zed axes rotate in the declination plane, while the y axis rotates in the hour angle plane. A separate accelerometer or tilt switch is needed to resolve a bimodality in the declination equation.

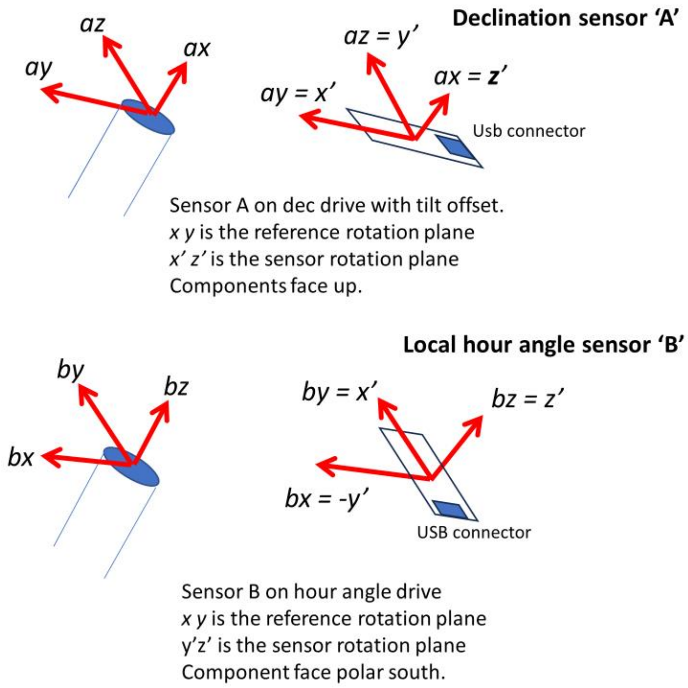
PushTo dual sensor reference orientation



This slide describes the reference configuration for the PushTo project. It uses separate accelerometers to measure the declination and local hour angle. This resolves the bimodality mentioned in the previous slide, provides a more stable and accurate value for hour-angle, and enables cone error reporting.

The telescope's declination and local hour angle are assigned separate left-handed coordinates; Ax, Ay, Az, and Bx, By, Bz, and these have a one-to-one correspondence with the accelerometer coordinates. The next slide demonstrates how this simplifies the derivation of equations, for alternative sensor mount orientations.

Alternative dual sensor orientations and transforms



The PushTo system is not restricted to the previous slide's reference configuration. The accelerometers can be mounted in six orthogonal orientations and can also have offsets in the declination and hour angle values.

The orientations can be changed by swapping axes using a table of three equations at the end of the accelerometer firmware listing. The examples shown here derive these equations by comparing the required accelerometer orientations against the declination or the local hour angle reference frames as shown in this slide. Instructions for setting up the tables in the firmware are provided in the operating manual.

The EQ3 mount is an example where surfaces for mounting the accelerometers are not orthogonal. They have rotation angle offsets around the declination and local hour angle axes. These are not accounted for in the axis swapping table but can be set to zero using the Dec-Yaw, and HA-Yaw entries in the PushTo firmware calibration tables. The calibration manual describes an approach for managing such offsets.

This concludes the description of the PushTo math background. It also concludes the full presentation. Thank you for listening and if you have any questions or comments please send an email to ultralightscopes@gmail.com.