Using gravity to find stars

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- Pleiades photograph iStock.com/Maik Thomas
- Downloads: github.com/UltralightScopes/UsingGravityToFindStars

Overview

Some years ago I was looking for an equatorial PushTo telescope that could be taken on buses and trains and then carried by hand along a kilometre or two of dirt road. Its battery capacity had to allow several days of photometry and spectroscopy and its mount had to point with an accuracy of a few arc minutes.

This document is a transcription of the video Using Gravity to Find Stars. It describes the telescope's PushTo star finder. It's based on two tiny Arduino boards that send gravity measurements to a mobile phone app to help point the telescope. The video shows how to assemble the star finder on your kitchen table, using just a scissors, screwdriver, and 3M extreme stickers, It takes about half an hour and costs about 100 dollars. There are also three appendices including an operating manual, a calibration manual, and the maths background.

Portable astronomy

So, portable astronomy. The left-hand image on this slide shows the equipment packed and carried. There's an instrument box on a foldup trolley that holds the telescope, mount, cameras, and spectroscope. On my shoulder is the tripod. And I'm carrying a backpack with enough supplies for a long weekend. There are more compact alt-azimuth systems available, but they don't yet have the flexibility and sensitivity of a compact equatorial rig, or the ability to measure spectra.

The right-hand image shows the implementation. I used an unguided equatorial push to telescope to reduce the instrument's size and weight. This removed one or two motors, the guide scope, and its camera, and greatly reduced the power bank size. Two small black boxes, A and B, hold the accelerometers that measure gravity to point the telescope at stars. Accelerometer A is mounted on the declination plate, and B on the hour angle plate. The tripods are either EQ5 or Benro units as both are rigid, portable, and robust. The EQ5 connects to a Star Adventurer tracking motor and equatorial wedge via a rotatable adaptor plate 'C'.

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

My system for portable astronomy is contained in three alternative instrument cases, with telescope attachments and mount components shared between them. One case is for spectroscopy, the second for photometry, and the third is for outreach.

Here’s a look at the contents of the spectroscopy instrument case. At the bottom left is a Star Adventurer tracking motor. On the bottom right is an Alpy 600 spectroscope with calibration lamps, a variable slit, and an Atik 314L+ camera. In the middle is the Star Adventurer declination control. Above that is a carbon fibre E D 80 triplet telescope and above that is a counterweight, and selection of eyepieces, or alternatively ASI 120 MM or ASI 5300 MM cameras.

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

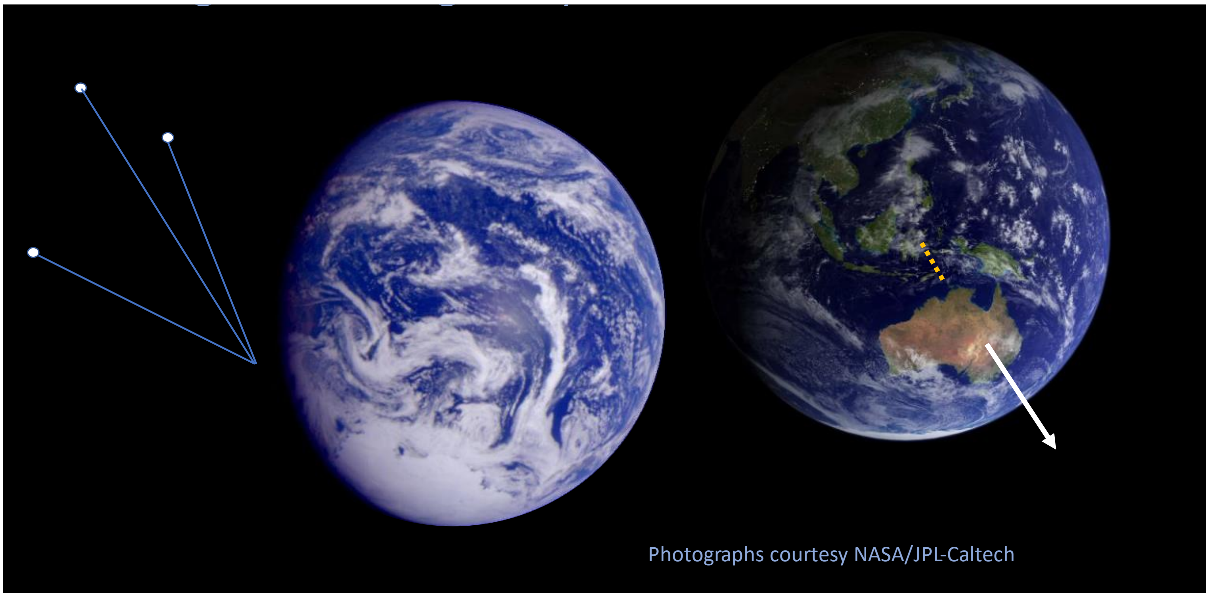
The photometry box is similar but with a 90 mm Maksutov telescope for fainter stars. There's a better view of the declination control near the bottom left and there's also room for a computer on top of the declination control and tracking motor. It's shown in its foam tray to the left of the case.

Packed for outreach

- Takahashi 60 mm f/6 FS60CB telescope
- Counter weight 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 holds general-purpose equipment including a 60 mm Takahashi FS60 CB telescope at the bottom of the case, and in a recess underneath it is the counterweight rod. The counterweight and an eyepiece are in recesses near the centre. At the middle left there is a filter wheel that holds a star analyser grating and narrow band filters. In a layer underneath this is an Atik 314L+ camera. Near the top left hand corner is an ASI585 MC camera and below to the left is a red dot finder. The declination control is in the middle at the top, and the tracking motor is in the right hand corner. This equipment is used with a small computer to show 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 is accuracy. Optical encoders are accurate to arc seconds, whereas accelerometers of the kind I'm using on small telescopes are accurate to one or two arc minutes. So if you're looking at fields of view much less than half a degree square, or need the pointer to automatically guide your telescope, then optical encoders and motors are essential.

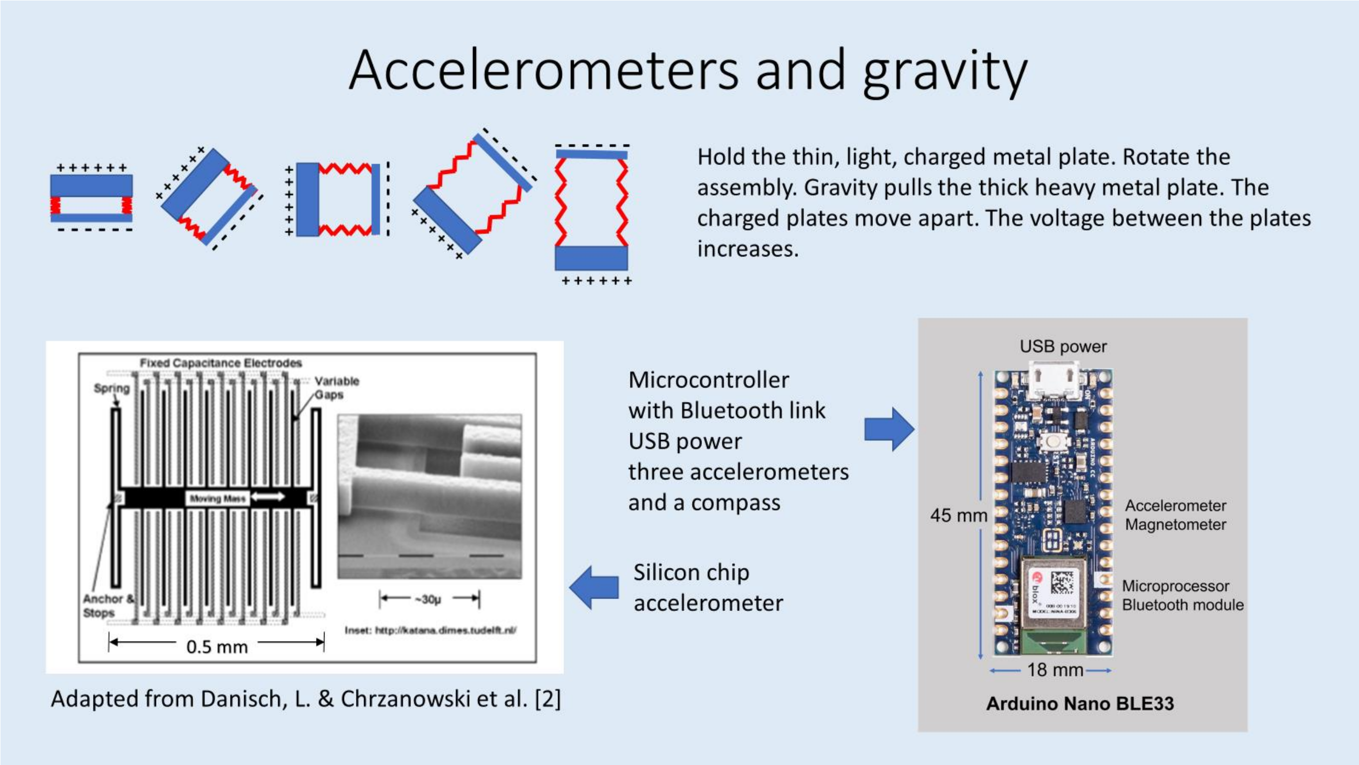
However, another key difference is stability. Gravity is extraordinarily stable, and clouds don't bother it, and a gravity-referenced telescope can be calibrated just once during the day in your study, and once calibrated generally only needs to be levelled and pointed south when you are on-site. Whereas the alignment of portable telescopes with optical encoders is weather dependent, and likely needs to be done at night, in the dark, every time you set the gear up.

Another issue is that fitting optical encoders to a telescope that doesn't have them requires significant instrument-making skills. Whereas accelerometers can be stuck on, using industrial grade 3M fasteners.

A significant additional benefit is that this accelerometer system on a small telescope will highlight defects such as cone errors and allow you to correct them.

Finally, it is hard to find a go to 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



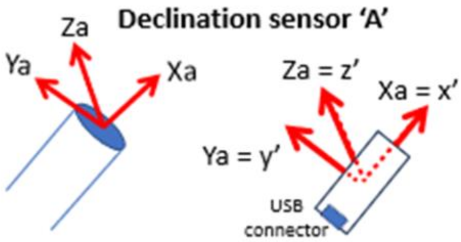
I should explain how an accelerometer works, Imagine two metal plates holding an electric charge and separated by two insulating springs, as shown in the figure at the top of this slide. On the left-hand side one plate is heavy and supported by the springs on top of a lighter one. As the assembly rotates to a position on the right-hand side with the lighter plate on top, the distance between the plates increases, consequently the voltage needed across the two plates, to hold that charge, also increases. Now it's possible to measure the voltage increase as the plates move apart and to use an equation to relate that voltage change 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.

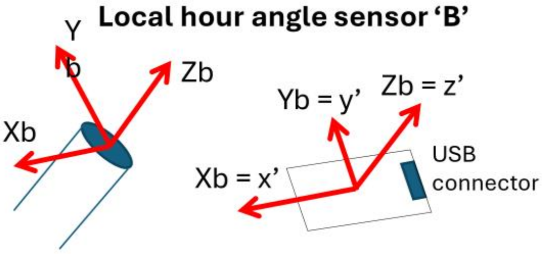
The bottom left of the slide shows a schematic of how the accelerometer is made. It has two springs etched into the silicon, shown as double vertical black lines, on both the left-hand and the right-hand sides. These springs are both connected to a weight shown as a thicker black horizontal bar, and 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 backwards and forwards 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.
XY is the reference rotation plane
x'y' is the sensor rotation plane
View from beneath IMU board A.



Sensor B on hour angle drive
XY 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 and local hour angle have separate reference frames. The declination reference frame is given as Xa, Ya, and Za. The hour angle reference frame is Xb, Yb, and Zb.

The accelerometer axes are labelled in lowercase letters and have a one-to-one correspondence with the telescope axes, which are labelled in uppercase. Declination and hour angle movements are given as rotations around their Z axes. Alternative orientations are possible and these are defined by three equations at the end of the Arduino accelerometer code listing. 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 system can be assembled on a kitchen table in about half an hour using just a few hand tools. The electronics can be purchased off the shelf as can all the necessary connectors, and there are small plastic boxes available and well suited to holding the electronics. The control board is held in place using two or three strips of a double-sided foam adhesive tape to make a support pad that may help to dissipate vibration. The box can be mounted on the telescope equipment using industrial grade 3M Extreme fasteners and is stable, secure and readily removed.

The 3M fasteners are strong but can rock slightly along their 'grain' boundaries. This is 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 that the grain in the fasteners runs in two directions.

The accelerometers are powered from a USB port and consume just a few milliamps so if the power supply has an auto-off that can't be overridden then take the usb power from a hub that is supplying other devices on the telescope. The power supply is kept outside the accelerometer boxes because changing batteries might upset the system alignment, also batteries can interfere with the magnetometer, which might otherwise be useful for pointing the telescope south.

Installing the software

- Downloads: github.com/pushtopete/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

If a project like this is to be widely accessible there's no point in using programming languages that require several months of intense training. So for the mobile phone App, I've used an educational language called App Inventor. It was developed by MIT for students and is simple to use, well-documented, and supported by the developers and community. Likewise, the accelerometer code uses Arduino, which is essentially the programming language 'C', and again it is well-documented and supported. The links are given in this slide, for the App Inventor and Arduino compilers, and they take you to their introductory pages. The code and support information can be found at the downloads link near the top of the slide.

To compile the PushTo mobile phone app: log on to app inventor, import the PushTo AIA code, press 'Build', and download the APK file to your phone using Google Drive. For the accelerometers, import the Arduino compiler, paste in the code text file, connect the accelerometer board to the computer USB port, and follow the Arduino instructions. The phone app and the accelerometer code compilations will each take a few minutes.

Pointing to a star

Mobile phone screen

There are several methods for pointing the telescope: The first is to point directly to the target coordinates. This is the fastest method but only accurate to within a degree. To use this method move the telescope until the display shows the desired declination and right ascension.

A second method is to jump to the target from a nearby reference star. This is slower but typically accurate to within five arc minutes. To do this go to the PushTo database screen. Select the target. Then select the reference. Press offset to calculate the distance between the target and the 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 button. This will highlight the reference to target differential coordinates, and they will drop to zero as the telescope is pushed from the reference to the target. Reduce the declination offset to about one degree with large adjustments to the declination control. Then make small adjustments until the offset is zero. When adjusting the declination and hour angle offsets allow each adjustment reading to stabilise,

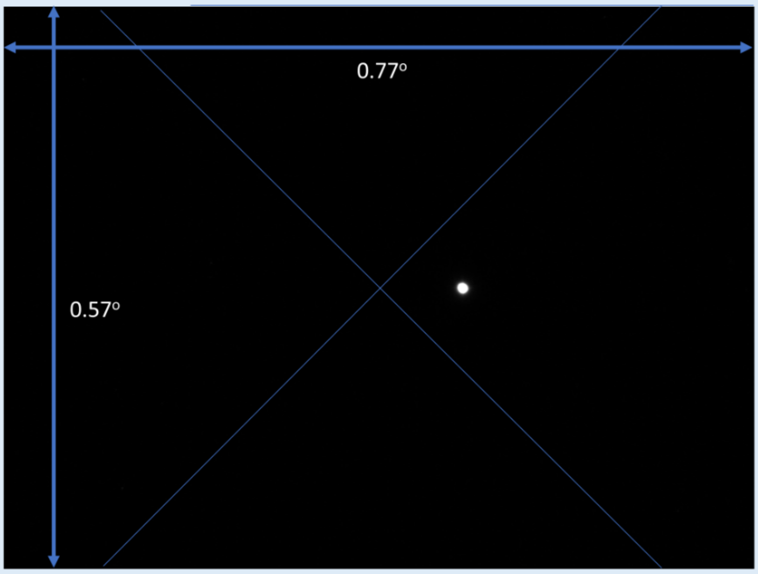
The adjustment filter responds to large changes immediately and has a ten-second time constant for small changes, so it's best to bring the declination offset to zero before moving to the hour angle adjustment. Now adjust the hour angle using the counterweight to rotate the telescope and bring the hour angle to one or two minutes. Ignore changes in the declination offset caused by the hour angle adjustment. Then engage and switch on the tracking motor and use the higher speed motor drive buttons to further reduce the hour angle. Once the hour angle is stable at zero, keep the tracking motor running and allow the declination to stabilise. When both the hour angle and declination are stable near zero the telescope should be pointing at the target. Press the Zero button to leave differential mode.

A third method uses a plate solver to define a reference and is accurate to within two arc minutes. To use this, point the telescope near the target and use the plate solver to find its coordinates. Use the PushTo offset screen to either set up a target and reference from scratch or to replace the reference during one or two star hops. This is further described in the operating manual.

Alpha to Beta Centauri

Pointer accuracy – Alpha and 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%	



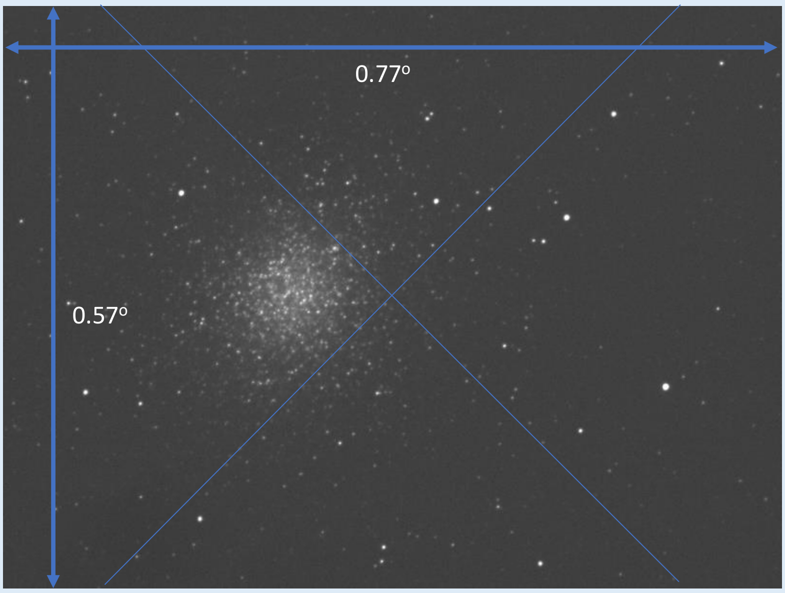
The next few slides show examples of stars that have been located using PushTo. The images were taken from my backyard in Sydney. I used a 60 mm Takahashi FS60 CB telescope. a Star Adventurer mount, ASI120 MM camera. And the live stacking software, SharpCap.

The first example is a result of working backward and forwards between Alpha and Beta Centauri. This is one of the trials I made when first testing the system.

The table on the left is worth explaining. The error value is the actual 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

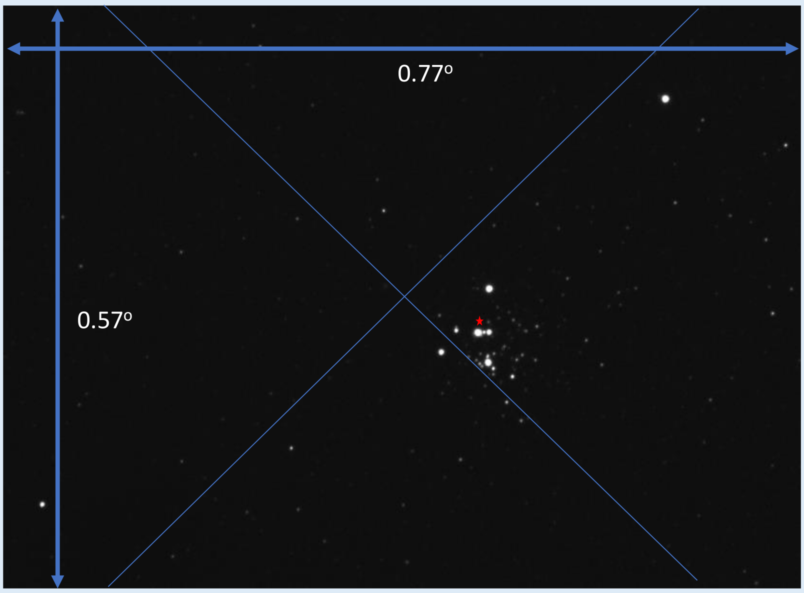
Epsilon Crucis and Omega Centauri		
Error	6.0	arc minutes
Hour angle distance	1.092	hours
Declination distance	12.928	degrees
Distance travelled	20.87	degrees
Apparent accuracy	0.45	%
Theoretical accuracy	0.16	%



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

Pointer accuracy - the Jewel Box

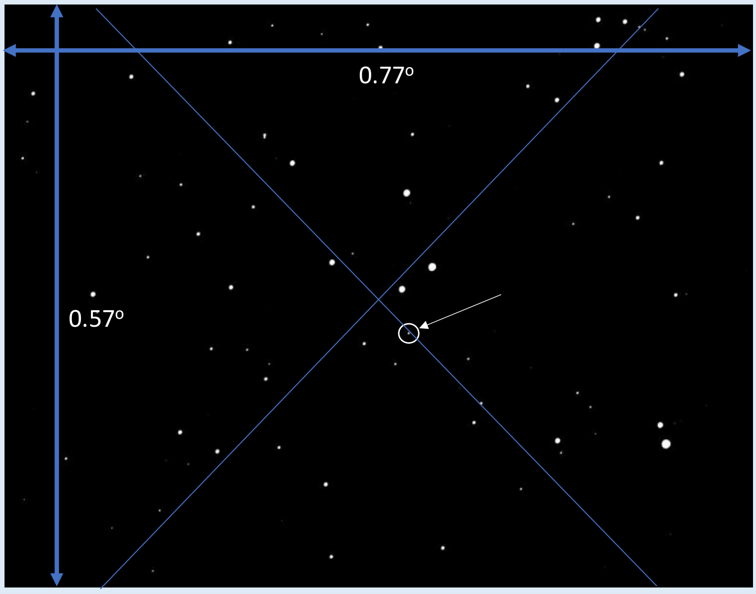
Becrux and Jewel Box		
Error	6	arc minutes
Hour angle distance	0.098	hours
Declination distance	-0.644	degrees
Distance travelled	1.63	degrees
Apparent accuracy	6.36	%
Theoretical accuracy	2.04	%



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	-29°	30'
Fomalhaut declination measured	-29°	37'



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

The image was made by stacking five, 30-second exposures. It was stretched, with a cut-off to remove sky glow, and dark subtraction to remove camera noise and hot pixels. Set up for this session took seven minutes to find true south, and then finding the star took one or two minutes to push the telescope from Fomalhaut to V Y Sculptoris. The last time the system was calibrated was about four weeks prior to this session.

Pointer accuracy unmatched coordinates. – V Puppis

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

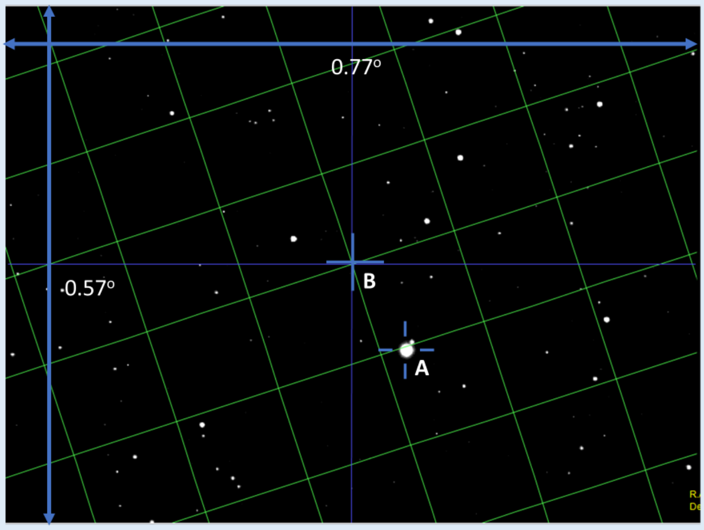


Plate solution reference coordinates: J2000 / target coordinates: apparent

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 shown at point B. This improves PushTo accuracy to within two arc minutes. However, there's an offset error of about ten arc minutes! This is because plate solvers use J2000 coordinates, whereas the V Puppis target has been set up here with apparent coordinates that include the atmospheric, annual, and geographic corrections needed when using right ascension and declination readings, and setting circles, to point a telescope. The offset can be removed in differential mode by using J2000 coordinates for the PushTo Target, to be compatible with the plate solver coordinates. This is demonstrated in the next example.

Pointer accuracy matched coordinates. – V Puppis

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

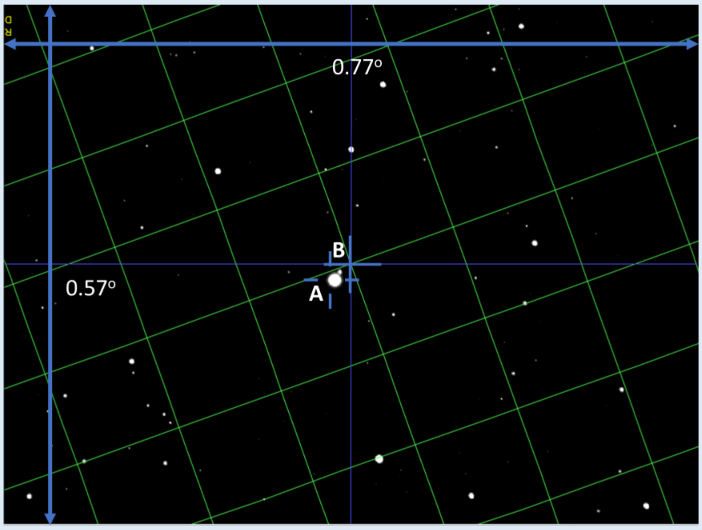


Plate solution reference coordinates: J2000 / target coordinates: J2000

This example locates V Puppis with PushTo in differential mode and both the plate solver and target positions are given using J2000 coordinates. This has greatly reduced the apparent vs. J2000 coordinate error and PushTo can now locate stars to within the two arc minute accelerometer resolution

Conclusion and future work

Future work in priority order

- Seek collaborator to test the right ascension algorithm in the northern hemisphere.
- Seek phone based live stack imaging and spectroscopy software.
- Reduce the anti-vibration filter response time delay (currently a two pole adaptive filter).
- Calibrate and test the Arduino magnetometer function for stage 1 polar alignment.
- Develop automatic compensation for cone error.
- Consider removing the temperature compensation measurements as so far, they have not been needed.

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.

Contact for questions and advice on building the system: UltralightScopes@gmail.com

In conclusion, the PushTo direct mode, using the right ascension and declination readings, points to within half a degree. The differential mode points within about three to six arc minutes. And if a plate solution is used instead of a reference star, the pointing accuracy improves to within two arc minutes. However, accuracy is ultimately determined by the quality of the declination and hour-angle controls' backlash and gear trains.

It's worth noting that calibration is not essential if you have access to a plate solver. Just point the telescope near the object you're looking for, plate solve the camera image, and enter the solution as a reference into the offsets page. SharpCap provides an excellent tool for live stacking images and accessing plate solvers.

Finally, there's still quite a bit of work that could be done. While the PushTo app is by no means a commercial system, it might, nevertheless, be of interest to citizen scientists living in small apartments, in cloud-covered light-polluted cities, or to anyone wanting to recycle or add PushTo capability to an old telescope. And if any of you are interested in this system and have questions, please don't hesitate to send a note to UltralightScopes@gmail.com .

Thank you for listening and the Sydney-City-Skywatchers, the Astronomical-Society-of-New-South-Wales, and the National-Australian-Convention-of-Amateur-Astronomers, for their encouragement, The Massachusetts App Inventor power user group for all their advice while developing the phone App, and Sunny Gupta for making available the App Inventor extension that provides the PushTo App with user accessible mobile phone data storage.

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. The 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,
4. Running a semi-automated calibration.

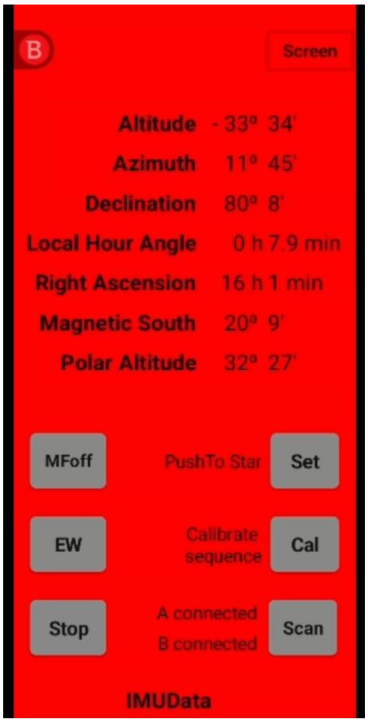
The PushTo app has separate screens for each function. They are accessed from the Main screen using a drop-down list in the top right-hand corner. For example, choose the Star Offsets screen to enter new targets and reference positions. To close Star Offsets press the Screen button and select Close screen. This will transfer the target and reference values to the Main screen and open it. 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 running, or the phone is a long way from the telescope. If the connections are lost, use the Stop button and then the Scan and Run buttons to reconnect.

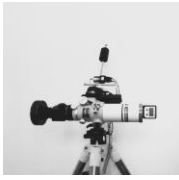
Accelerometers can't measure in the horizontal plane, so press the EW button to indicate if the telescope is pointing in an eastern or western hemisphere for the azimuth value calculation. This isn't necessary for equatorial coordinates.

Finally, the MF button is used to manage a meridian flip. It's switched on when the telescope has moved from pointing east to pointing west. The MF button is only needed if tracking past the meridian will cause a collision and to keep tracking the star you need to carry out a meridian flip, i.e., rotate the telescope through the hour angle by 180 degrees, and through declination by twice its displacement from plus or minus 90 degrees.

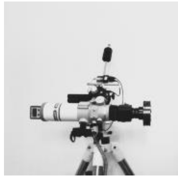
Calibration




CentreUpW


CentreDownE


CentreUpE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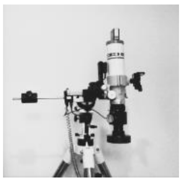
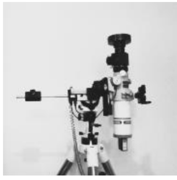
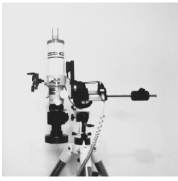

EUp


EN


EDown


ES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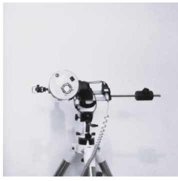
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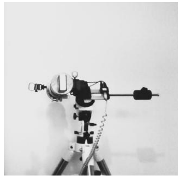
WDown


WS

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:

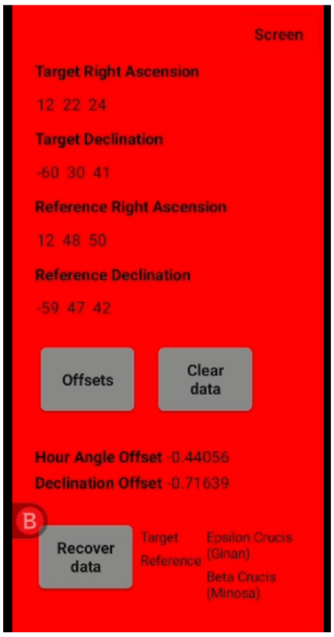
- Centre Up West
- Centre Down East
- Centre Up East
- Centre Down West
- East Up
- East North
- East Down
- East South
- West Up
- West North
- West Down
- West South

If you wish to save the calibration press Set. To exit press Cal. The result is a 'New' list of calibration values available in the Calibration screen by toggling the Cal/New button. Use the Read button on 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 at the bottom of the Main screen.

A detailed procedure is described in the Calibration appendix.

Target and Reference ‘Star’ Offsets



Target and Reference ‘Star’ Offsets

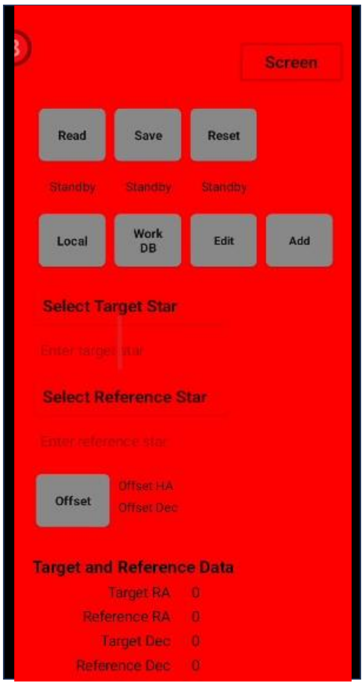
Manual offset entry and retrieval:

- 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 screen collects and manages the right ascension and declination values for target stars, and reference stars or plate solutions. 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.

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. These units are also displayed as greyed-out text in the text boxes when they are not holding data.

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

The Star database screen collects and manages star coordinate data.

Use the Select Target and Select 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 again 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 Target/Reference Star drop down lists should now contain alpha prefixed star records

Naming the PushTo controller

Arduino IMU code

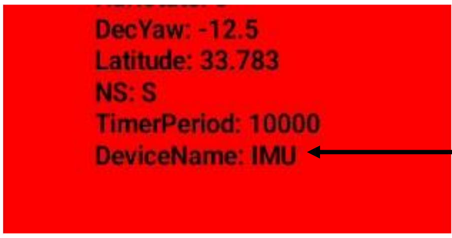
```
// Activate and initialize BLE peripheral
BLE.begin();
BLE.setLocalName("IMUB");
BLE.setAdvertisedService(imuService);
imuService.addCharacteristic(imuXYZChar);
imuService.addCharacteristic(imuTempChar);
imuService.addCharacteristic(imuSouthChar);
```

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



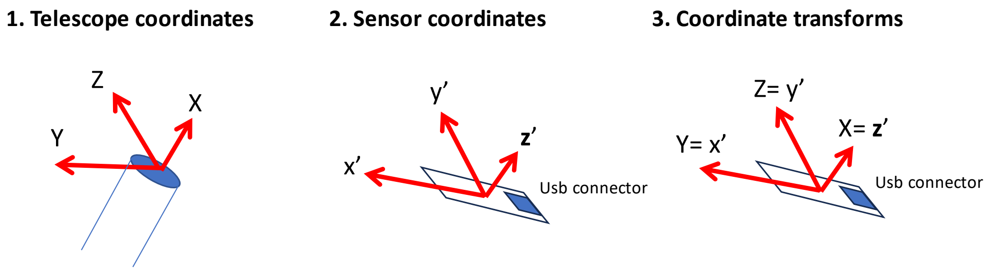
The PushTo hand controller default name is ‘IMU’, without the ‘A’ or ‘B’ ending. To change the device name edit the last line at the bottom of the calibration file on the Calibration page.

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 shown above, near the start of the accelerometer firmware listing. The name is the same as for the PushTo hand controller but with an A or B added. The name should be alphanumeric and end with an A for the declination board or B for the local hour angle board.

The matching PushTo hand control name is the same as for the sensors but without the A or B ending. To change the 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 figure 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 sketch 1, to the sensor coordinates in sketch 2, to derive the equations in sketch 3. And adjust these equations in the three lines of code shown in sketch 4.

This concludes the operating manual.

Appendix 2- Calibration Manual

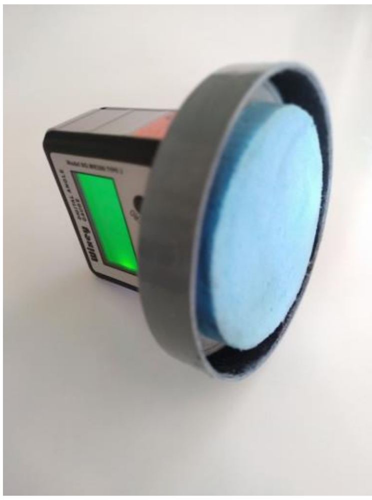
This appendix shows how to use the PushTo app to calibrate gravity sensors as digital setting circles on an equatorial telescope.

Calibrating the accelerometers will improve the speed and accuracy of the PushTo finder. But you may not need to calibrate if your telescope is fitted with a camera and you have access to a plate solver. If so you could try just pointing the telescope near the object you're looking for, plate solve the resulting image, and enter the solution as a reference into the offsets page. SharpCap provides an excellent tool for live stacking images and accessing plate solvers.

Calibration takes about half an hour and can be conducted indoors during the day. It's only needed once unless the mount, drive, and sensors are radically altered. Telescope disassembly, transportation, and reassembly should not make any difference to the calibration.

Once the system is calibrated, the only preparation needed for each observing session is 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 pole. Use drift or polar alignment of the mount azimuth if long exposures are needed,

Preparation for calibrating the gravity sensors.



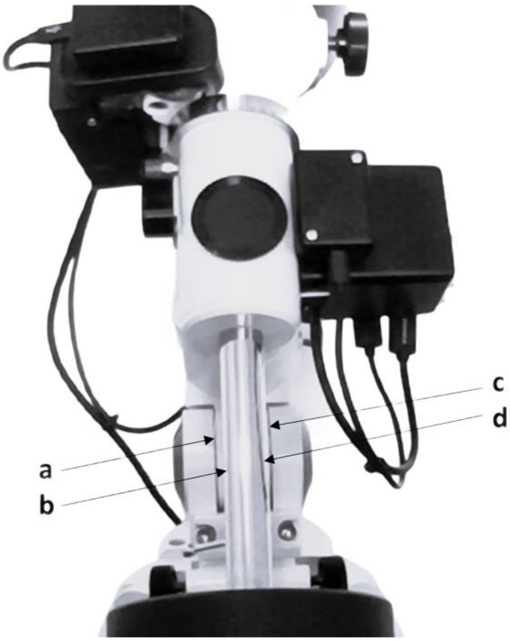
The primary calibration tool is a digital tilt meter, also known as an inclinometer, carpenter level, or angle gauge. It should have a resolution of 0.1 degrees.

If the tilt meter can only measure accurately in a vertical plane, use a spirit level to set the hour angle for the calibration start position.

The tilt meter should be supported securely during calibration, but it should also be easily reoriented at each calibration step. . Most of the images in this presentation show the tilt meter fastened to a telescope end cap. However, it can also stand on the top side of a rotatable flip mirror box for all orientations, except pointing to the zenith or nadir when it can stand on the telescope or flip mirror end caps.

If a rotatable flip mirror box is not available, then fasten the tiltmeter to an old or homemade rotatable telescope endcap. I've used double-sided adhesive foam tape to hold the tilt meter on the outside of the end cap. Or, for tilt meters that have a magnetic base, I've glued a magnet inside the end cap to hold a tilt meter centrally on the outer side. I protected the lens or mirror by fixing a soft pad over the magnet in case it fell off and made sure the glue was well cured and not outgassing in case this affected the telescope or lens mirror.

Setting the zero-hour angle position, method 1



The starting position for calibration is with the mount set to the zero hour angle. The azimuth setting doesn’t affect accelerometers and is irrelevant for calibration.

The calibration images were all prepared as if the mount was either:

- facing south in the southern hemisphere, or
- facing north in the northern hemisphere.

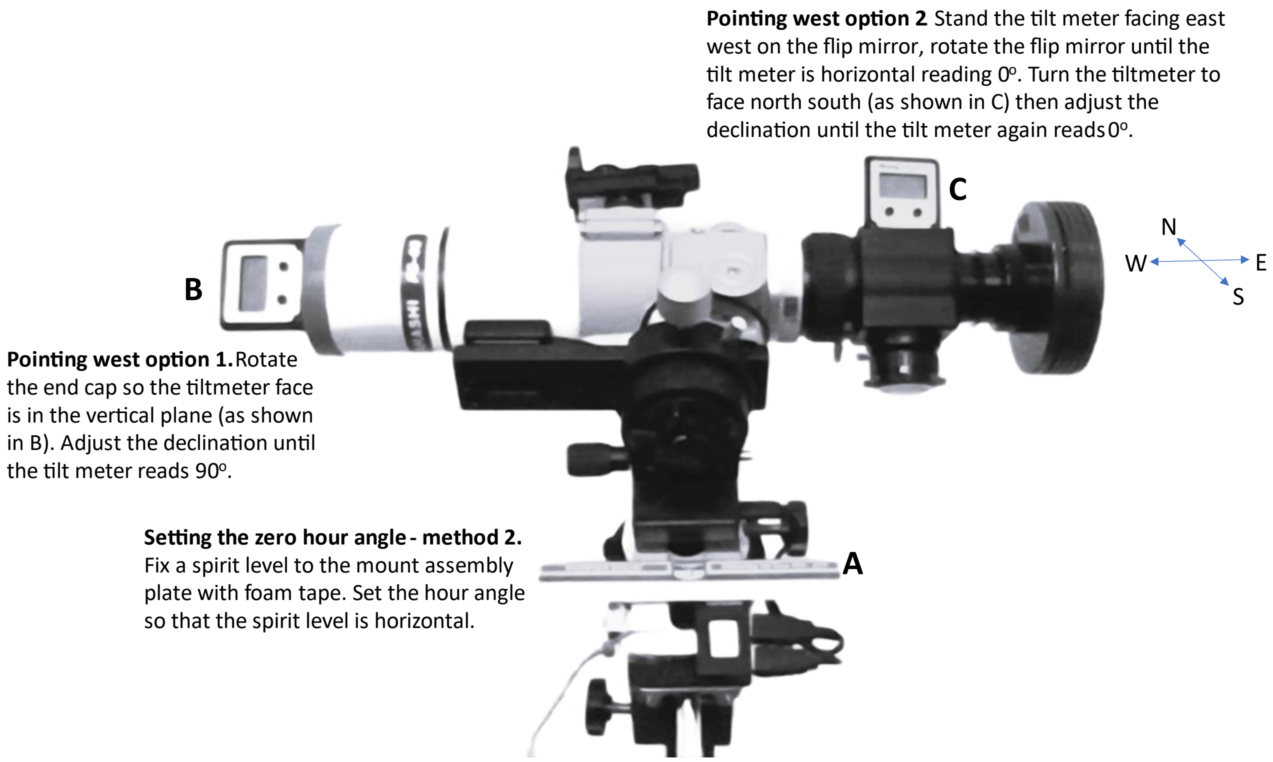
The NS parameter, on line 23 of the calibration file, should be set to ‘S’ or ‘N’ as appropriate.

To start the calibration set the telescope's local hour angle to zero and point it due west.

There are two methods for setting the local hour angle to zero. Method 1 aligns vertical or horizontal surface edges on the mount’s tracking motor and static assemblies. Method 2 uses a tiltmeter or spirit level fastened to the tracking motor assembly.

This slide illustrates method one. It uses the EQ3 mount as an example and shows how to align the wedge support edges ‘a’ and ‘c’, with the counterweight shaft edges ‘b’ and ‘d’, to set the local hour angle to zero.

The starting position: Centre up pointing 'west'



This figure illustrates method two for setting the hour angle to zero. It uses the Star Adventurer mount as an example.

First set the tracking motor mounting plate to the latitude angle. Use double-sided foam tape to fasten the tilt meter to the plate. Substitute a spirit level 'A' if the tilt meter can only measure in a vertical plane.

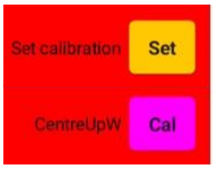
The slide also shows how to support the tilt meter when pointing the telescope west, either by fastening it to the telescope end cap, 'B', or by standing it on the top side of a rotatable flip mirror box, 'C'.

The calibration has three stages, each with four orientation steps. For each orientation wait for the PushTo app IMU values to stabilise, then press Set, then press Cal.

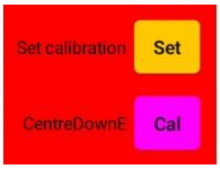
To start the calibration, first switch off the phone's Wi-Fi to stop internet messages or pop-ups from interfering, then press Cal. Cal, steps through the sequence for each orientation, and Set, stores the measurement for each orientation step.

Stage 1 calibration- hour angle and altitude sensors

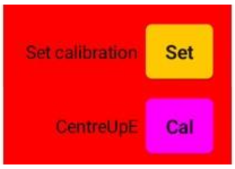
Step 1.
Centre up pointing west



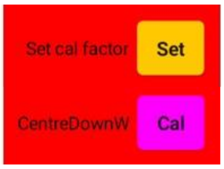
Step 2.
Center down pointing east



Step 3.
Centre up pointing east



Step 4.
Centre down pointing west



Stage 1 has four steps.

Step 1. With the telescope in the starting position and with the Cal button label showing Centre Up W, press Set then Cal.

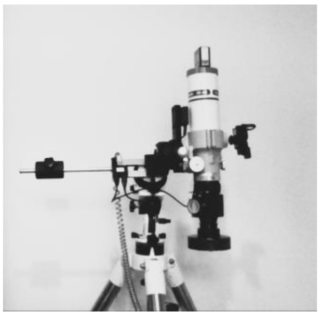
Step 2. With the Cal button showing Centre Down E, rotate the telescope 180 degrees around the hour angle axis without altering the declination. Press Set, then Cal.

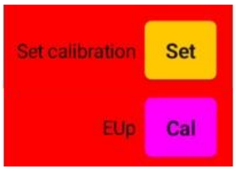
Step 3. With the Cal button label showing Centre Up E rotate the telescope back through 180 degrees of hour angle and 180 degrees of declination. Press Set, then Cal.

Step 4. Finally, with the Cal button label showing Centre Down W and without altering the declination, rotate the telescope 180 degrees around the hour angle axis. Press Set, then Cal.

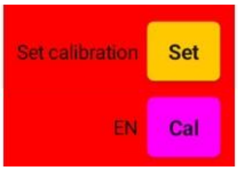
Stage 2 calibration- declination sensors, east side measurements

Step 1.
East pointing up



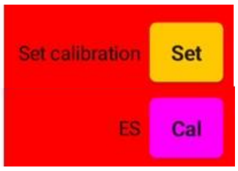


Step 2.
East pointing north



Step 3.
East pointing down

Step 4.
East pointing south



This slide describes the Stage 2 measurements with the telescope on the east side of the mount.

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 shouldn't be changed. Secure the tilt meter on the telescope endcap or the flip mirror and position it so its face stays in a vertical plane as the declination is adjusted.

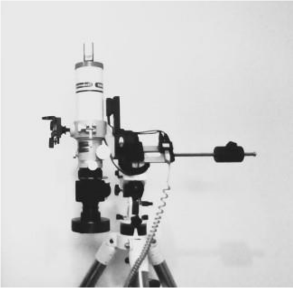
Step 2. With the Cal Label showing EN, move from East Up to East North by adjusting the declination until the tilt meter shows the telescope is horizontal pointing north. Press Set, then Cal.

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 if these are not available then upside down and attached to the telescope end cap. Press Set, then Cal.

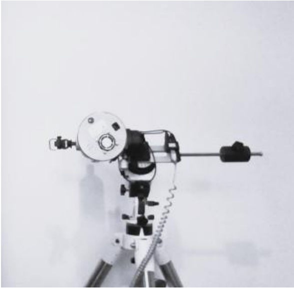
Step 4. With the Cal label showing ES, move from East Down to East South by adjusting the declination until the tilt meter shows the telescope is horizontal pointing south. Press Set, then Cal.

Stage 3 calibration- declination sensors, west side measurements

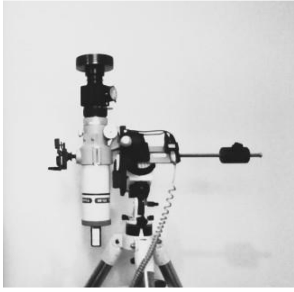
Step 1.
West pointing up



Step 2.
West pointing north



Step 3.
West pointing down



Step 4.
West pointing south

The Stage 3 measurements 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.

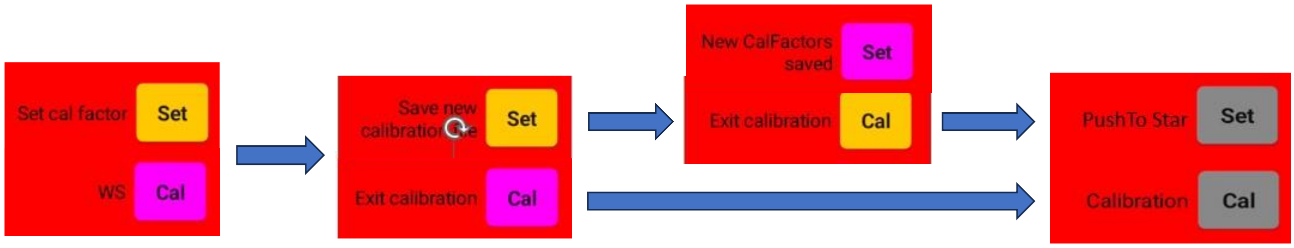
For the next three orientation steps, the local hour angle shouldn't be changed. Secure the tilt meter on the telescope endcap or flip mirror and position the tilt meter so its face stays in a vertical plane as the declination is adjusted.

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 if these are not available then 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

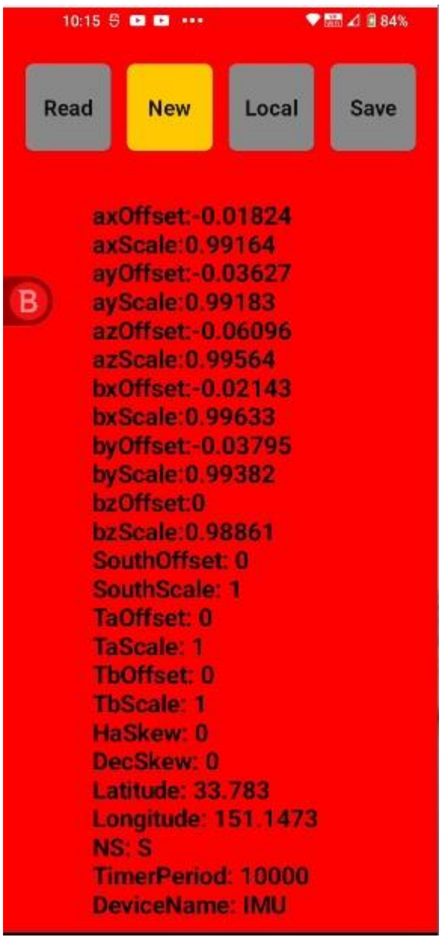
Step 2.
Choose exit or save

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.

Reading 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.

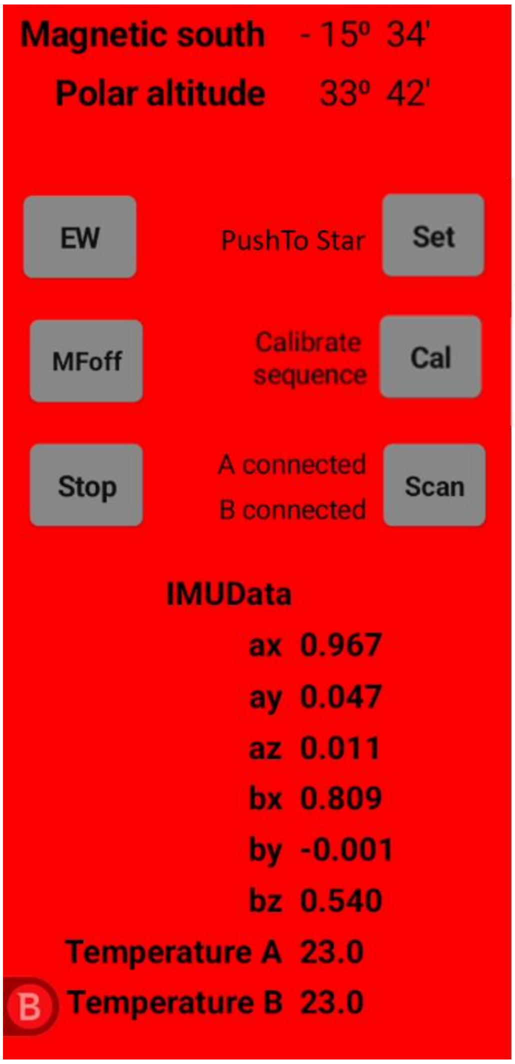
Declination and hour offset angle/yaw adjustments.

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 vertical and horizontal planes. In this case, it should be possible to manage the calibration stages two and three by fastening the tiltmeter to the declination motor box 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.

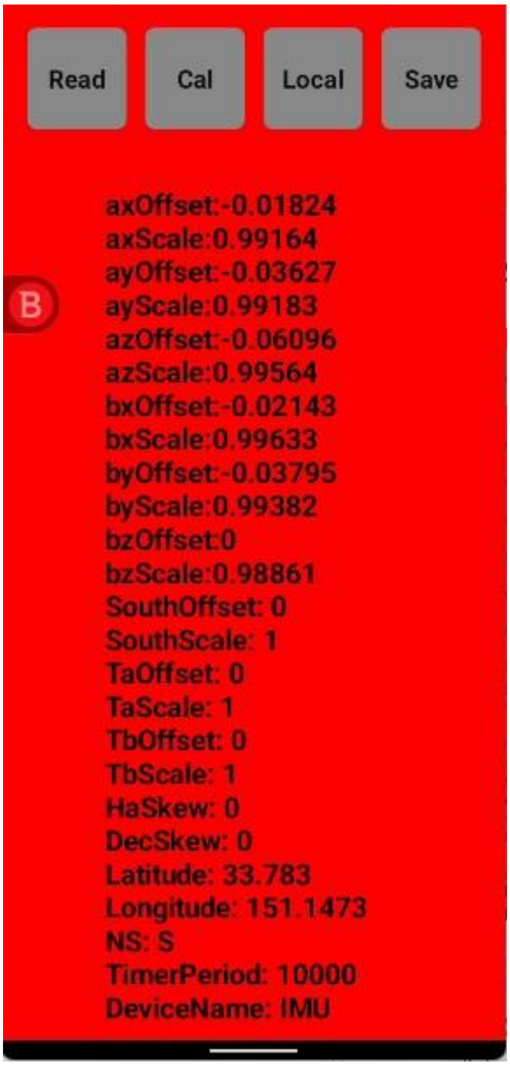
I have not had a chance to test this procedure with field measurements but it does produce a sensible calibration list and passes the calibration tests described in this appendix.

Fine calibration adjustments

A



B



The calibration list can be edited to fine-tune the offset zero calibration factors or set skew values that correct the hour angle and declination sensor misalignments as described previously. It can also be used: to set the observer's latitude and longitude; change the controller operating hemisphere by setting the NS parameter to North (N), or South (S); adjust the number of seconds allowed to find a star; or change the sensor Bluetooth name.

I've found that fine-tuning scale factors is only necessary to correct the altitude values. This is done by adjusting the az and bz scale factors for altitude and polar altitude respectively.

Fine-tuning the offsets requires some detailed explanation. I've included all the offset zero calibration parameters in the next fine-tuning section for completeness. But, in practice, I've only ever had to fine-tune the ay offset parameter, with the telescope at zero hour angle, and pointing at the south pole.

To fine-tune the accelerometer offset factors you could read their x, and y values from the IMU list shown in screenshot A. The ax and ay values correspond to the declination, and the bx and by values correspond to the local hour angle. Read these IMU values for orientations that should display zero for the appropriate x or y parameter. This could include orientations with declinations of 0 degrees and 90 degrees, and hour angles of 0 hours, plus six hours, and minus six hours. Then, using the display shown in screenshot B, correct the ax, ay, bx, and by, offset factors in the calibration list, so that their IMU list values read zero for the appropriate orientations.

Note these approaches to fine-tuning would need to be modified where accelerometer mounts are skewed, for example in the EQ3 mount

Test the accuracy of 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. I found these values were accurate to within 0.5 minutes for a Star Adventurer mount.

To test the declination accuracy, point the telescope to the north or south pole, and read the declination while adjusting the local hour angle from minus to plus six hours. The declination values were typically accurate to within 0.5 degrees for a Star Adventurer mount.

These are significant errors and seem inevitable, given the machining tolerances available to small amateur telescopes. Despite their errors, direct readings of declination and right ascension can help to locate visible reference stars or to point the telescope near a target ready for a plate solver reference. Differential measurements can typically reduce the star location error to between three and six arc minutes. And if plate solutions are used for the reference position then the star finder accuracy can approach its theoretical limit of two arc minutes, and accelerometer calibration may not be needed.

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

Appendix 3 – Math background

This Appendix provides the background and equations that are essential if you wish to modify the PushTo algorithms. It also shows how to reorient the sensors to work on non-orthogonal surfaces such as those found on an EQ3 motorised mount.

Hybrid coordinates

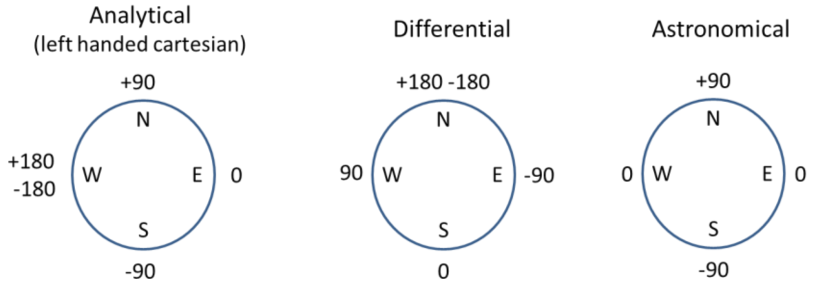
h local hour angle
δ declination
ϕ_0 latitude
a1 local hour angle accelerometer vector
a2 declination accelerometer vector

$$\mathrm{h} = \frac{\pi}{2} + \mathrm{atan2}\left(\frac{\mathrm{a1x}\,.\cos(\emptyset_0)}{a1y}\right)$$

$$\delta = \mathrm{atan2}\left(\frac{(a2x.\sin(\emptyset_0) - a2z.\cos(\emptyset_0)\,.\cos(h + pi/2))}{a2x.\cos(\emptyset_0)\,.\cos(\mathrm{h}) + az.\sin(\emptyset_0))}\right)$$

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 given here use the gravity component A1. to describe the local hour angle, and the other component, A2, to describe the declination.

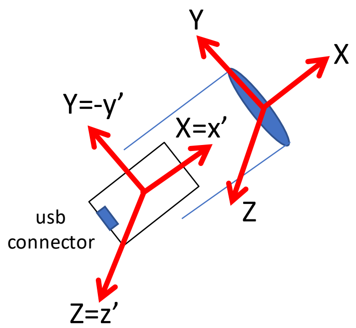
The equations shown here provide a very stable solution, but it's important to note the hour angle term, h, in the expression for declination. This apparent dependence is nulled by the equation, provided the tracking motor altitude is well aligned with latitude and the telescope is stationary. However, rapid changes to the hour angle can produce fluctuations in the declination display, so it's advisable to adjust the declination first and ignore fluctuations when adjusting the hour angle.

The declination is evaluated using analytical coordinates, then transformed into differential coordinates to determine changes in declination as the telescope is moved from the reference to the target position. This includes moving a discontinuity from the west to the north to allow a greater range of telescope movement. The discontinuity is at 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 on the side of the telescope rotates around the Y and X axes 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 represent the telescope coordinates
x'y'z' represent the 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. However, it's not the primary configuration for the PushTo project. The two slides following this one, describe the PushTo configurations.

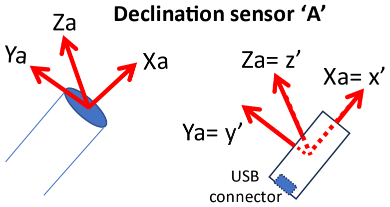
I've used the Arduino, Nano 33 BLE board, to illustrate the coordinate configurations shown in this and the following two slides. In the configuration shown here, a single triaxial accelerometer measures the local hour angle and declination and a separate accelerometer or tilt switch resolves a bimodality in the hour angle equation.

The telescope axes are labelled with upper case X, Y, and Z letters as right-handed coordinates. The X and Z axes measure rotation around the Y axis, that is the declination. The Y and Z axes measure rotation around the X axis, that is the local hour angle. The accelerometer axes are labelled in lowercase letters and three equations indicate how they move in the telescope reference frame.

PushTo dual sensor reference orientation

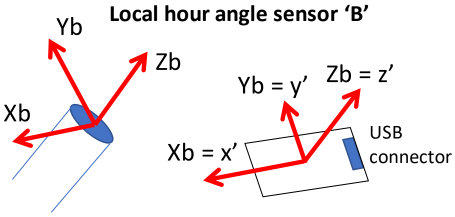
PushTo dual sensor reference orientations

Declination sensor 'A'



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

Local hour angle sensor 'B'



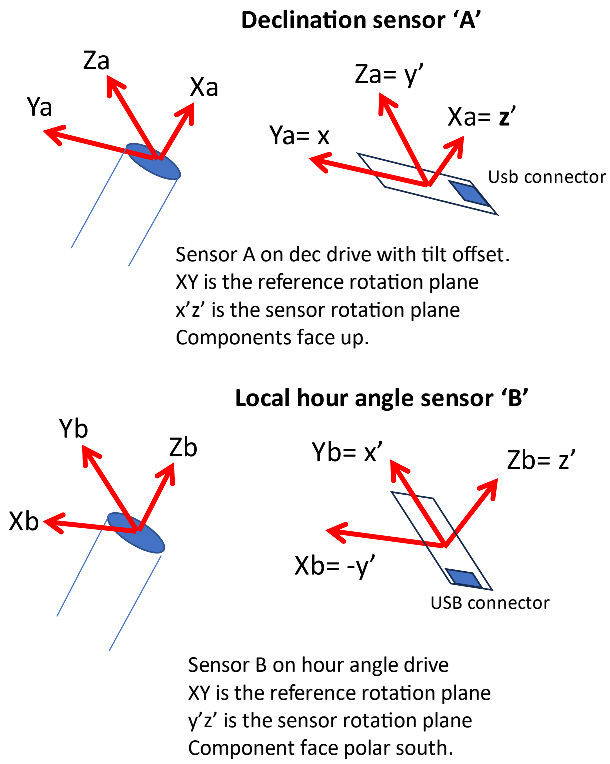
Sensor B on hour angle drive
XY is the reference rotation plane
x'y' is the sensor rotation plane
Components face polar south.

This figure describes the reference configuration for the PushTo project. It uses separate accelerometers for the declination and local hour angle, and the local hour angle equation has been modified. This removes the bimodality mentioned in the previous slide and provides a more stable solution for local hour angle and declination. It's also useful for reporting the cone error.

The telescope declination and local hour angle planes are described in separate reference frames with left-handed coordinates, This simplifies the generation of equations for different accelerometer orientations.

The accelerometer axes are labelled in lowercase letters and have a one-to-one correspondence with the telescope axes, which are labelled in uppercase. The declination reference frame is given as Xa, Ya and Za. The local hour angle reference frame is Xb, Yb, and Zb. Declination and local hour angle movements are given as rotations around their Z axes.

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 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 provides a detailed description 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 .