Motoscope

A portable & autonomous star-tracking telescope

Initial Design & Trades

Slides 4-7

Overarching design concept

A motorized, tracking, Newtonian telescope suitable for a variety of use cases: visual observing, planetary imaging, and deep-space object (DSO) imaging

Design goals:

- Sufficient tracking accuracy for 15 second long exposures (achieved!)
- Portable: lightweight and disassemblable, easy to set up (achieved!)
- High resolution: can see small objects (planetary imaging) (achieved!)
- High photon throughput: can see dim objects (DSO imaging) (achieved!)

Constraints:

- $1000 budget funded by MIT… rest comes from me
- Manufacturable with available tools (3D printing, laser cutting, CNC mill, CNC lathe, and various other common shop tools)

Initial trades: mirror size (0.32 m)

A larger mirror is more expensive and unwieldy, but both the signal-to-noise ratio (in the photon noise regime) and the resolution of the optics are directly proportional to the diameter of the mirror

The size of the mirror is chosen as 0.32 m since this corresponds to a Rayleigh criterion resolution of approximately 0.5 arcseconds, which is the best atmospheric seeing that can be expected for Cambridge, MA (i.e., beyond 0.32 m aperture, the resolution of the optics becomes atmospherically limited rather than diffraction limited)

A 0.32 meter mirror also corresponds well to the overall project budget and is about the largest size optics that can still be transported easily by a single person

Initial trades: focal ratio (f/5)

Planetary imaging favors high focal ratio to better match the optical resolution to the sensor’s pixel size (ideally would achieve the Nyquist spatial frequency), whereas DSO imaging favors low focal ratio for a higher photon flux on the sensor

Since focal ratio can be altered via the use of a barlow or focal reducer, the focal ratio is instead chosen to be as low as possible without exceeding the project budget, and without inducing excessive coma aberrations in the no-focal-reducer case

For the given sensor (Canon T7i, 2.23 x 1.49 cm sensor) and aperture size (32 cm), the coma on any corner of the sensor will be no larger than the diffraction limit of the optics at f/5, but will be larger than the diffraction limit below f/5 -- therefore f/5 is chosen

Initial trades: mount type (altitude-azimuth)

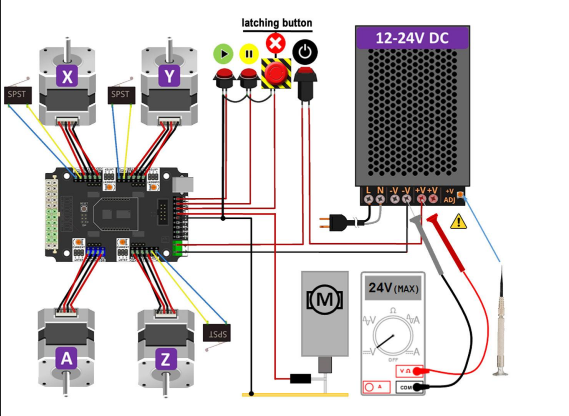
- Equatorial:
  - Advantages: tracking only requires constant rotation about one axis
  - Drawbacks: at 42 degrees latitude (Cambridge, MA), the telescope needs to be tilted from the vertical by 48 degrees, requiring a complicated counterweight system. Requires precise manual alignment upon every use.
- Altitude-azimuth:
  - Advantages: simpler mechanical design
  - Drawbacks: tracking requires varying rotation rates about both axes, and induces field rotation

I have chosen the alt-az mount type so as to reduce mechanical complexity at the expense of motorization and computational complexity. This is an uncommon choice for amateur tracking telescopes, but is in line with research-grade observatories. A key capability enabled by the alt-az mount is a software-based orientation determination / alignment system that takes advantage of plate solving astrometry code I previously wrote for an exoplanet detection project.

Subsystem: Electronics & Software

Slides 9-13

Electronics & driver software



- Stepper motor driver: CNC xPro
  - All-in-one board includes CPU and stepper drivers
  - Automatically microsteps (adjustable jumper)
  - CNC xPro software: Grbl… interprets GCodes and produces driving signals
  - GCodes: markdown language that commands stepper movement. GCodes generated by a python astrometry and tracking codebase I developed for this project, and sent from my laptop (see next slide)
- Stepper motors: Bipolar 400 steps/rev 9 watt stepper motors
  - Powered by 12v lead acid battery
  - Heavily geared down so as to meet required pointing accuracy

Validation of electronics and driver software

Successfully demonstrated at XFair 2019!

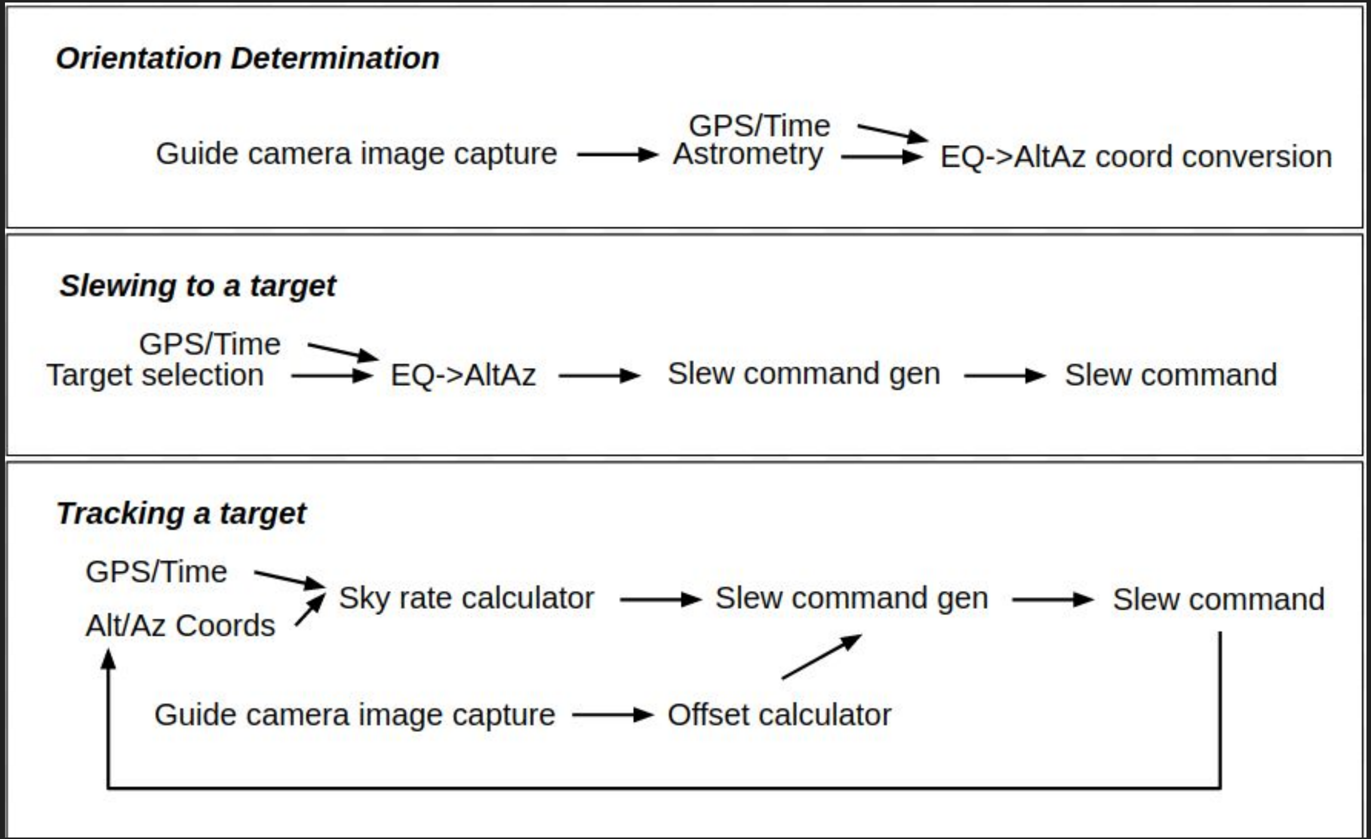
Caveats: Proper stepper motor gearing not yet in place, and the mechanical and optical system is a mockup just for the electronics demonstration

State of the test system at this point -- electronics simply rest on the floor...

Astrometry and tracking software

The telescope is built with a secondary guide telescope (“guide scope”) that piggybacks the main telescope. The guide scope has a camera hooked up to it, which sends pictures to my laptop to be used to determine the center of the image by using plate solving software (astrometry.net’s software, wrapped in my own python code for running it automatically with this specific optical setup, and feeding the output to the GCode generator for the stepper motors). This feature is necessary (1) to determine the orientation of the telescope upon initial setup when a precise orientation is unknown, and (2) to continuously update orientation knowledge when tracking a target so as to achieve better tracking accuracy and thus longer exposures. The primary telescope+camera cannot be used because it is reserved for imaging (could actually use an off-axis guide camera rather than a guide scope+camera but that would have been a more expensive option).

Astrometry and tracking software (visual overview)



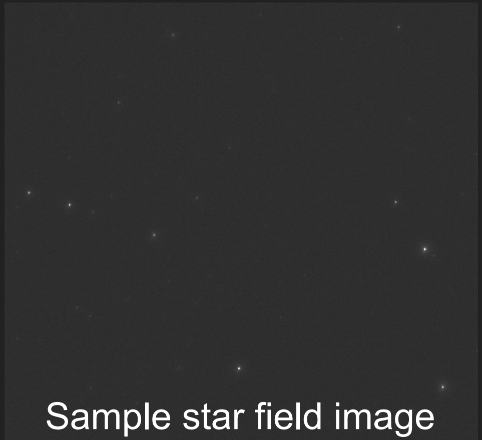
Validating astrometry+tracking software on test setup

First demonstrated on a 3D printed arduino barn door mount in Jan 2020

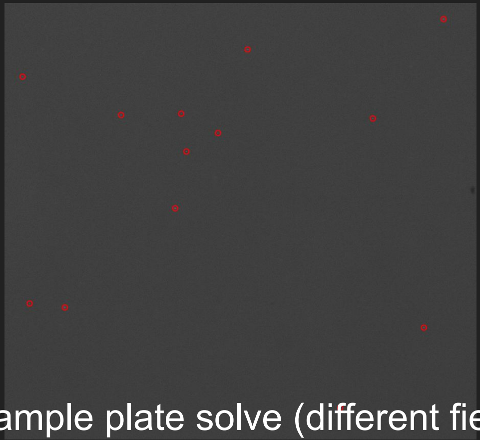
Guide camera: ZWO ASI 120MM Mini (mono)

Guide scope: SVBONY SV106 50mm

Validated to 0.5 arcsecond accuracy (sub-pixel positioning!)



Sample star field image



Sample plate solve (different field)

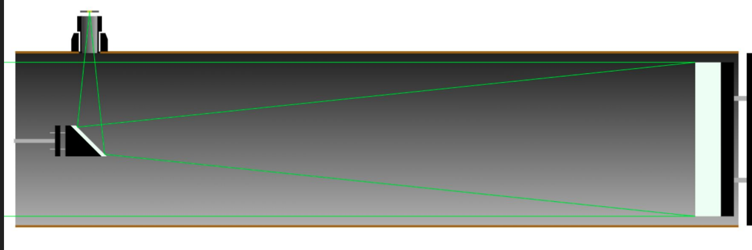
Subsystem: Optical assembly

Slides 15-18

Optical design notes

The optical tube assembly design is relatively simple. I performed the relevant calculations to ensure there was no light clipping on the focus tube and the appropriate distance to the focal plane was achieved. I offset the secondary mirror to account for the fact that the leading edge of the secondary mirror is closer to the primary mirror than the trailing edge, and so it should have a small (but significant) radial offset to account for that difference.

Since I do not own a low-profile 2” focuser, I made sure there is enough length adjustment in the primary mirror position to achieve the required difference in focal plane height from the central optical axis when using a DSLR vs. an eyepiece.



Mirror specs verification

Verified primary mirror diameter and focal ratio BEFORE building the optical tube assembly… measure twice, cut once!

Test setup: mirror placed opposite from a point source in a dark room. Vary the distance to the point source until its reflection converges back into a point source exactly at the same distance -- this distance is twice the focal length

1/(object distance) + 1/(image distance) = 1/(focal length)

For object distance = image distance, focal length = object distance/2

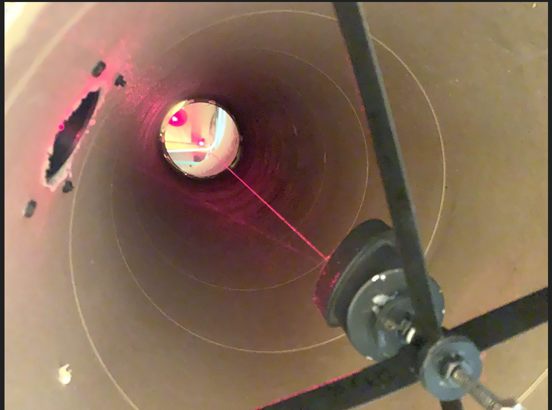
Measured focal ratio came out to actually be 4.75, not 5 as advertised… an 80 mm difference in focal length! Would have been a critical error for a system that requires focusing precision on the order of the wavelength of visible light

Optical collimation

Primary mirror and secondary mirror must be adjustable in order to achieve sufficient alignment of the optical train (from experience, must collimate about once per month)

The secondary mirror spider vane mount comes with screws for adjustment

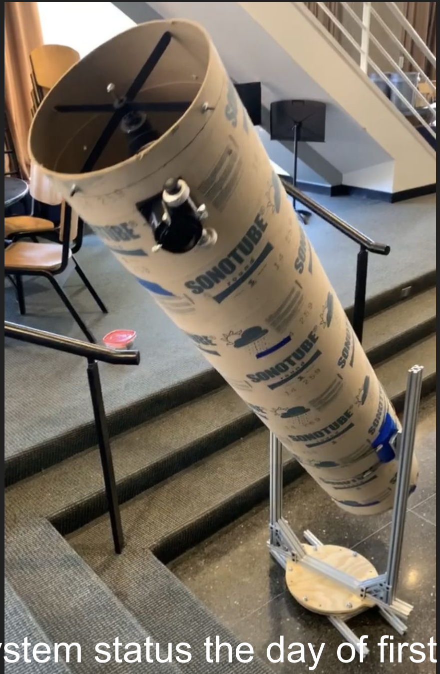
Primary mirror mount designed with 3 springs and bolt+wing nut pairs to be able to rotate the mirror in any axis by manually turning the wing nuts



Left: laser collimation… successful test! Fall 2019
Right: primary mirror mount

First light

At this point, I had yet to integrate the electronics and gearing onto the mount (not to mention the guide scope), but since the mount and optical tube assembly were complete, I took it outside for its first light!



system status the day of first light

first light! :)

Subsystem: Mount

Slides 19-20

Gearing ratio

The telescope may have a 0.5 arcsec resolution limit, but the stepper motors only have 6400 steps/resolution with 16x microstepping, which corresponds to slightly over 200 arcseconds per step assuming 1:1 gearing. Therefore a gearing ratio of at least 400:1 is necessary to obtain 0.5 arcseconds per step. Ideally, the system would achieve a small fraction of an arcsecond per step. I ended up choosing a gearing ratio of 600:1 which was limited by maximum size gear I could cut on the available laser cutter.

Mount:OTA connection

The position of the optical tube assembly must be adjustable to account for the different possible centers of gravity depending on the camera/eyepieces used. Furthermore, the bearing must be smooth and able to handle heavy transverse loads. I settled on the following design for the bearing:

And for the bearing-OTA connection:

Backup Slides

Resources

- Budgeting: https://docs.google.com/spreadsheets/d/1dmXDCCLsYOh-nMCJdEJgjl8lIT31fcioC-TbfYWwn_0/edit?usp=sharing
- Timeline: https://docs.google.com/spreadsheets/d/1BiiixqL2wlUgnTPEhaZDRdtd30U4GTe0fZrdaG_7an0/edit#gid=0
- Steppers: https://www.amazon.com/gp/product/B00PNEQZNY/ref=oh_aui_detailpage_o02_s00?ie=UTF8&psc=1
- XPro wiki: https://github.com/Spark-Concepts/xPRO/wiki/2.-Connecting-CNC-xPRO