## Experiencing Medieval Astronomy with an <br> Astrolabe

Michael Robinson


## What can you see from DC?

## Bortle 7:

 Many constellations visibleNote:
Shenandoah is Bortle 4 much better!
A

## Bortle 8:

Brighter constellations are visible, but often missing stars

My data were collected here

## Bortle 9:

Some bright stars, planets, not much else :(

Data source:
OpenStreetMap
David Lorenz's 2020

## From home... or even downtown



## From Shenandoah...



## Astro[nomyllogy] in antiquity



## Astro[nomyllogy] in antiquity



Figure: Wikipedia

## A scholar's necessary accessory!

## With an astrolabe, you can:

( - Measure elevations/heights of objects

- Tell the time
- Determine your latitude/longitude
- Measure the location of the planets
- Measure planetary orbits
- Measure compass directions
- Predict sunrise and sunset time
- Identify stars and constellations
- Compute basic trig functions
...Because it converts between geocentric fixed coordinates and azimuth/elevation

[^0]

Figure: Wikipedia

## Astrolabes, which you can make!



A wood and paper version


Laminated paper works OK, too!
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## Make one? How?

All the necessary files are on GitHub:

- https://github.com/kb1dds/large_astrolabe (my "daily driver")
- https://github.com/kb1dds/small_astrolabe (pocket size!)
- The files are ready for printing or laser cutting at DaBL!
- The graphics in this talk are from these files
- https://github.com/kb1dds/astrolabe_analysis (analysis in this talk)

If you want a different latitude or some other change...

- All the graphics are generated by a Jupyter notebook that emits SVG files
- It handles all the "math" and most of the labeling
- I extensively retouched the SVG files for aesthetics
- The most difficult part is aligning the thumb ring


## Anatomy of a DaBL astrolabe



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## When all else fails...

... read the manual!
Still the best book in English on astrolabes was written circa 1400 AD:

Geoffrey Chaucer*, A Treatise on the Astrolabe
My design follows his manual closely with a few small exceptions related to modern timekeeping preferences:

- Calendar months instead of Zodiak signs


Figure: Wikipedia

- I incorporate the sun's right ascension into the calendar scale... This is probably vanity!
- I don't need a trig table, so I include the modern equation of time instead on the back


## My dataset

- Collected from my home, mostly in the backyard
- Keyed to UTC time
- 773 observing sessions over 3 years
- 2264 elevation sightings
- 6 different astrolabes represented
- No optical aid with one exception: daytime sightings of Venus
- Calculated values using astrolabe:
- Local sidereal and solar time
- Planet right ascensions



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## Taking an elevation



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## Taking an elevation looks easy...

Astrolabe must hang freely from your finger

Use the "back" side

Object "next to" the center screw

Object "skims" the top of the pointer Don't touch the instrument here!

Alternate your focus between the instrument (close) and the object (far) until everything settles

## ... but takes practice!

You have to balance several tasks at once...

## How accurate are my sightings?

- Mean: - $0.8^{\circ}$, std dev: $2.6^{\circ}$
- Close to normally distributed! $95 \% \mathrm{CI}$ is $-0.95^{\circ}$.. $-0.65^{\circ}$


$n=1279$ total sightings of 12 stars
Elevations predicted using known locations and some spherical trig


## How accurate are my sightings?

- Mean: $-0.8^{\circ}$, std dev: $2.6^{\circ}$
- Contrary to Chaucer's warning, error does not grow tremendously* with elevation


$n=1279$ total sightings of 12 stars
Elevations predicted using known locations
*Not good enough for navigational purposes!


## Measure your latitude!

- All you need to do is find Polaris, the north star and take its elevation. (It's not exactly true north, but close enough...)
- You should get within a degree or so, based on the previous data



## Where are the stars, anyway?

- Very far away!
- They don't appear to deviate from their daily circuit around the poles
- We can assume
- They're "points at infinity"
- They don't move (but the Earth does)


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## The celestial sphere

- Project the stars onto the unit sphere
- The earth spins "inside this sphere"


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## The celestial sphere

- Project the stars onto the unit sphere
- Each star's position is given by two coordinates


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## A spherical astrolabe

- Project the stars onto the unit sphere
- Each star's position is given by two coordinates



## Stereographic projection

- To make a more convenient model, balance a plane on the north pole, project from the south pole


South pole

## Stereographic projection

- Circles and lines on the sphere become circles (and lines) in the projection
- These form curves of constant elevation and compass direction (azimuth)



## Stereographic projection

Given a set of stars, it's easy to project them all! Data from: Hipparcos catalog


## Star chart in stereographic projection



## Star chart (just the most visible stars)

The earth's equator is roughly $22.5^{\circ}$ offset from the ecliptic (causing the tropics!)


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## Star chart (just the most visible stars)



## Star chart (just the most visible stars)



Declination (measured in degrees from the equator)

## Finding the sun


... trace through the north pole to the ecliptic

Find the date...
-2
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## Finding the planets

Luckily for us, the planets (and the moon) all lie within a few degrees of the ecliptic.

This isn't true in other solar systems!

The astrolabe can measure right ascensions for them using only elevation sightings!


The astrolabe cannot predict planet right ascensions...

Many astronomers tried to remedy this.

Ultimately, they had to wait for Kepler to amass enough data to find the true pattern.

## Elevation and Azimuth



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## The curves depend on latitude!



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## The curves depend on latitude!



## Kinds of time

- Keeping time using a big spinning ball of rock is annoying, but works well if you keep consistent
- There are several kinds of time:
- Mean solar, timezone time (what our clocks use)

One day is
24 hours

- Mean local solar time (no one uses this in practice, but it serves as an approximate One day is 24 hours since we're near a $15^{\circ}$ increment in longitude)
- Apparent local solar time (sundial time)
- Local sidereal time (governs where stars appear in our sky)

Day length varies $\pm 20$ minutes or so
One day is
~23.93 hours

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Need to know your longitude

My astrolabe has a scale to fix this.
Chaucer's didn't

Directly displayed on astrolabe

## Solving for sidereal time

- Suppose we sight Sirius at $20^{\circ}$ elevation.
- Start by finding the elevation contour



## Solving for sidereal time

- Suppose we sight Sirius at $20^{\circ}$ elevation
- Find Sirius on the star chart



## Solving for sidereal time

- Suppose we sight Sirius at $20^{\circ}$ elevation
- Both parts of the astrolabe fit together and rotate...

Rotate just the star chart (clear plastic)

## Solving for sidereal time

- ... Rotate Sirius to align with the elevation contour
- There are two possibilities. We need another star!


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## Solving for sidereal time

## - ... Suppose we also sight Rigel at $37^{\circ}$ elevation

Rigel is here, close to the correct elevation contour


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## Solving for sidereal time

- Then you can read off the sidereal time from the right ascension ring



## Solving for solar time

- If we additionally know the date: Feb 15 , we can read off the solar time off the penultimate ring



## Solving for solar time using the sun

- Start by placing the sun on the ecliptic using the calendar scale



## Solving for solar time using the sun

- Suppose we sight the afternoon sun at $25^{\circ}$ elevation
- Turn the star chart to align the sun* with that contour


Read the local time: 15:05

## Does solar time agree with clock time?



It's usually within 25 minutes... but
There is some squiggly variation going on!

This is due to two effects of the earth's orbit:

1. It's not quite circular
2. The earth's rotation axis isn't perpendicular to the ecliptic
$\rightarrow$ A modern correction can be applied to handle these effects. (Not on Chaucer's instrument)

## Correction: the equation of time



## Mean error yields Longitude

- Local time at my house is behind EST by 7.4 minutes
- Timezones are rounded* to the nearest hour, that is $15^{\circ}$ longitude
- EST is local time at $75^{\circ}$ longitude
- So, 7.4 minutes behind $=1.85^{\circ}$ longitude offset westerly
- By this, my house is at $76.85^{\circ} \mathrm{W}$
- It's actually nearly $77^{\circ} \mathrm{W}$ (on the button), so that's not bad at all!
Mean $=-7.4$ minutes
$n=765$, sd $=57 \mathrm{~min}$,
so $95 \%$ CI is $-11.4 \ldots 3.4$ minutes...

*Mostly true. But very wrong in places...


## How do you do this correction?

## Flip over the astrolabe. <br> ... it's just a date-based compensation of a few minutes <br> 

The astrolabe's solar time is currently reading 14 minutes slow compared to standard time
Add 14 minutes to the local time displayed on the front of the astrolabe to get clock time


## Does it matter if we use stars/sun?

- Not really!
- Stellar time estimates seem to have less bias
- Means are within $1 \sigma$ of each other (ANOVA: $p>0.9$ )



## Solving for right ascension

- On Jan 27, I sighted Venus at $15^{\circ}$ elevation
- Since Venus is a planet in our solar system, it's always close to the ecliptic
- But we don't know where on the ecliptic it is...
- We need another piece of information:
- Sidereal time!
- Get that from some stars...



## Solving for right ascension

- Without belaboring the point*: that $15^{\circ}$ Venus observation was at 15:15 sidereal time
- Two possibilities...

I knew I was looking east-ish, so this one is correct!


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## Solving for right ascension

- Without belaboring the point*: that $15^{\circ}$ Venus observation was at 15:15 sidereal time
- Read off RA!

Right ascension: 18:10

*Arcturus \& Vega used to obtain the sidereal time. Also it was super early morning... pre-dawn, anyway

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## Repeat 813 more times...planet data!



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## Kepler's third law

- The square of the orbital period of a planet is directly proportional to the cube of its semi-major axis of its orbit
- Kepler derived this empirically (polynomial regression!)
- Newton provided a theoretical derivation from his laws (it's not actually easy to do; there are some "tricks"...)
- Larger orbits have longer orbital periods
- If we can determine the periods, we can measure the orbits!
- Things get complicated when you're observing from Earth... it helps to constrain the geometry


## Oppositions and conjunctions



## Oppositions and conjunctions

Object in solar opposition


Object in solar conjunction
(appears "right on top of" the sun)
Don't look for these without safety equipment!!

## Kepler in action

- The square of the orbital period of a planet is directly proportional to the cube of its semi-major axis of its orbit

$R=$ semimajor axis in earth orbital radii (astronomical units, AU)
$T=$ time between oppositions or conjunctions in Earth days (synodic period)


## Kepler in action

## Using the Earth's orbital radius and period as a yardstick


"Outer" planets: Mars, Jupiter, Saturn

$$
R^{3}=\left[\frac{T}{T-365}\right]^{2}
$$

$$
R^{3}=\left[\frac{T}{T+365}\right]^{2}
$$

$R=$ semimajor axis in earth orbital radii (astronomical units, AU)
$T=$ time between oppositions or conjunctions in Earth days (synodic period)

## My planetary data (again)



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## Time between Jupiter oppositions

year
2019
2020


Estimates of Jupiter's orbital radius:
408 days $\rightarrow 4.43 \mathrm{AU}$
402 days $\rightarrow 4.91 \mathrm{AU}$
810 days $\rightarrow 4.65 \mathrm{AU}$
Accepted figure is 399 days $\rightarrow 5.16 \mathrm{AU}$

## Time between Saturn oppositions



Estimates of Saturn's orbital radius:
398 days $\rightarrow 5.22 \mathrm{AU}$
386 days $\rightarrow 6.92 \mathrm{AU}$
784 days $\rightarrow 5.91 \mathrm{AU}$
Accepted figure is 378 days $\rightarrow 9.45 \mathrm{AU}$

## Fitting Venus data



## Coda: Mars data



We don't even have oppositions/conjunctions, and we really can't easily fit a sinusoid or a line due to missing data...

But there is a repeat in right ascension difference, which can serve the same role for a circular orbit...

Let's use that!
Estimate of Mars's orbital radius:
Period 800 days $\rightarrow 1.50 \mathrm{AU}$
Accepted figure is 780 days $\rightarrow 1.51 \mathrm{AU}$ (but orbit is fairly far from circular!)

## Summary

An astrolabe is a powerful instrument even if you don't have dark skies!

## You can meaure:

- Your latitude and longitude (to around $1^{\circ}$, if you are careful and patient)
- The time to within 30 minutes consistently, often much better
- The current locations of objects in the sky
- The size of the orbits of the nearby planets

You can even suggest (based on Venus) that some planets orbit the sun, and not the Earth!

## What's next? For you!

- Go outside at night and look at the sky!
- Make an instrument! You can go to DaBL or you can use other materials



## To learn more...

Plans for laser cutting:
https://github.com/kb1dds/large_astrolabe https://github.com/kb1dds/small_astrolabe https://github.com/kb1dds/sundials Data and Analysis Script: https://github.com/kb1dds/astrolabe_analysis

Usage instructions:
(easy) https://www.youtube.com/watch?v=tt-_GKmX8dk
(advanced) https://www.youtube.com/watch?v=n1VhfexY0ys


[^0]:    fxed coordinates and azimuth/elevation

