Navigation in the Ancient Mediterranean and Beyond

Background: The positions of celestial bodies

Cardinal directions

Cardinal directions are defined by astronomical processes like diurnal and annual apparent movements of the Sun and the apparent movements of the stars. In ancient and prehistoric times, the sky had a different significance than it does today. This is reflected in the many myths about the sky all around the world. As a result, we can assume that the processes in the sky have been watched and monitored closely. In doing this, the underlying cycles and visible phenomena were easy to observe.
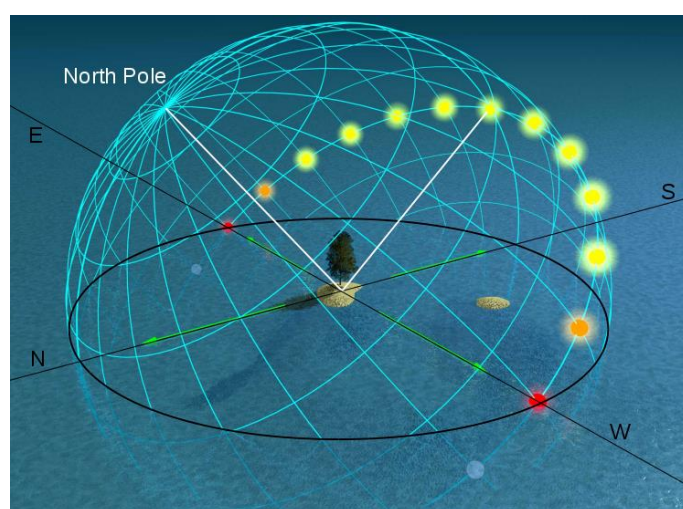

Figure 1: Apparent diurnal movement of the Sun in the Northern Hemisphere at equinox. The sun reaches its highest elevation above the horizon to the south. In the Southern Hemisphere, the Sun culminates to the north (Credit: Tau'olunga, https://commons.wikimedia.org/wiki/File:Equinox-50.jpg, 'Equinox-50', horizontal coordinate system and annotations added by Markus Nielbock, https://creativecommons.org/licenses/by-sa/3.0/legalcode).

For any given position on Earth except the equatorial region, the Sun always culminates towards the same direction (Figure 1). The region between the two tropics 23.5° north and south of the equator is special, because the Sun can attain zenith positions at local noon throughout the year. During night, the stars rotate around the celestial poles. Archaeological evidence from prehistoric eras like burial sites and the orientation of buildings suggest that the cardinal directions were common knowledge to a multitude of cultures many millennia ago. Therefore, it is obvious that it was applied to early navigation.

Latitude and longitude

Any location on an area is defined by two coordinates. The surface of a sphere is a curved area, so using coordinates like up and down does not make much sense, because the surface of a sphere has neither a beginning nor an end. Instead, we can use spherical polar coordinates originating from the centre of the sphere, where the radius is fixed by its size (Figure 2). Two angular coordinates remain, which for the Earth are called the latitude and the longitude, with the rotation providing the symmetry axis. The North Pole is defined as the point, where the theoretical axis of rotation meets the surface of the sphere and the rotation is counter-clockwise when looking at the North Pole from above. The opposite point is the South Pole. The equator is defined as the great circle half way between the two poles.
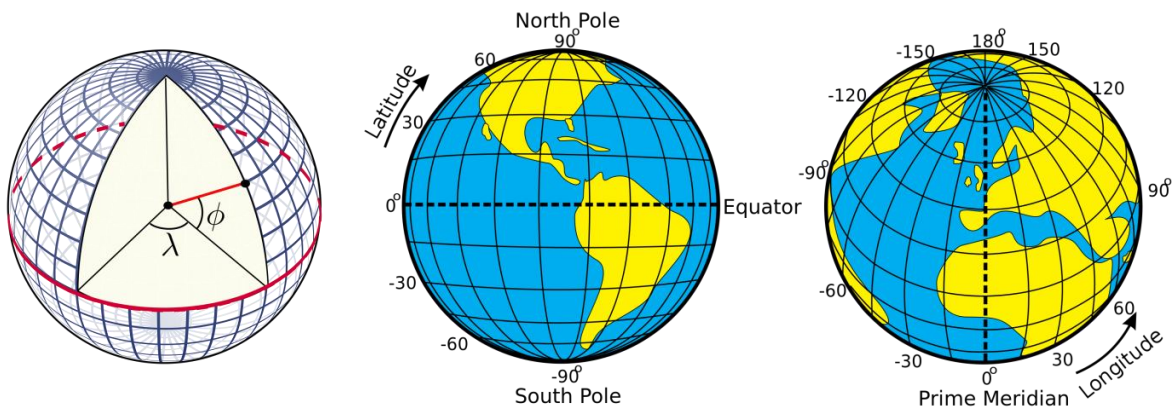
Figure 2: Illustration of how the latitudes and longitudes of the Earth are defined (Credits: Peter Mercator, djexplo, CC0).

The latitudes are circles parallel to the equator. They are counted from 0° at the equator to ±90° at the poles. The longitudes are great circles connecting the two poles of the Earth. For a given position on Earth, the longitude going through the zenith, the point directly above, is called the meridian. This is the line the Sun apparently crosses at local noon. The origin of longitudes is the Prime Meridian, and passes Greenwich, where the Royal Observatory of England is located. From there, longitudes are counted from 0° to ±180°.

Example: Heidelberg in Germany is located at 49.4° North and 8.7° East.

Elevation of the pole (pole height)

If we project the terrestrial coordinate system of the latitudes and longitudes on the sky, we get the celestial equatorial coordinate system. The Earth's equator becomes the celestial equator and the geographic poles are extrapolated to build the celestial poles. If we were to take a photograph with a long exposure of the northern sky, we would see from the trails of the stars that they all revolve around a common point, the northern celestial pole (Figure 3).

Figure 3: Trails of stars in the sky after an exposure time of approximately 2 hours (Credit: Ralph Arvesen, Live Oak star trails, **https://www.flickr.com/photos/rarvesen/9494908143**, **https://creativecommons.org/licenses/by/2.0/legalcode**)

Worksheets: Navigation in the Ancient Mediterranean and Beyond

In the Northern Hemisphere, there is a moderately bright star near the celestial pole, called the North Star or Polaris. It is the brightest star in the constellation the Little Bear, Ursa Minor (Figure 4). In our era, Polaris is less than a degree off. However, 1000 years ago, it was 8° away from the pole. Therefore, today we can use it as a proxy for the position of the celestial north pole. At the southern celestial pole, there is no such star that can be observed with the naked eye. Other methods have to be used to find it.
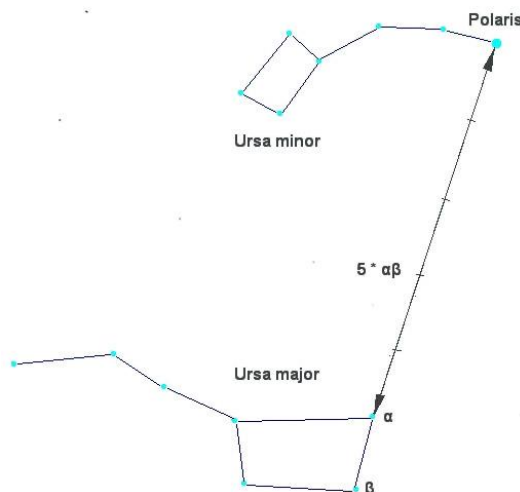

Figure 4: Configuration of the two constellations Ursa Major (Great Bear) and Ursa Minor (Little Bear) in the northern sky. Polaris, the North Star, which is close to the true celestial north pole, is the brightest star in Ursa Minor (Credit: Bonč, https://commons.wikimedia.org/wiki/File:Ursa_Major_-_Ursa_Minor_-_Polaris.jpg, 'Ursa Major – Ursa Minor – Polaris', based on https://commons.wikimedia.org/wiki/File:Ursa_Major_and_Ursa_Minor_Constellations.jpg, colours inverted by Markus Nielbock, https://creativecommons.org/licenses/by-sa/3.0/legalcode).

If we stood exactly at the geographic North Pole, Polaris would always be directly overhead. We can say that its elevation would be (almost) 90°. This information introduces the horizontal coordinate system (Figure 5). It is the natural reference we use every day. We, the observers, are the origin of that coordinate system located on a flat plane, whose edge is the horizon. The sky is imagined as a hemisphere above. The angle between an object in the sky and the horizon is the altitude or elevation. The direction within the plane is given as an angle between 0° and 360°, the azimuth, which is usually counted clockwise from North. In navigation, this is also called the bearing.
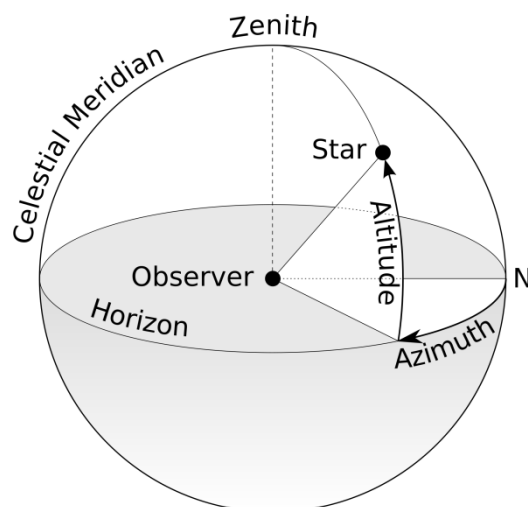

Figure 5: Illustration of the horizontal coordinate system. The observer is the origin of the coordinates assigned as azimuth and altitude or elevation (Credit: TWCarlson, https://commons.wikimedia.org/wiki/File:Azimuth-Altitude_schematic.svg, 'Azimuth-Altitude schematic', https://creativecommons.org/licenses/by-sa/3.0/legalcode).

For any other position on Earth, the celestial pole or Polaris would appear at an elevation smaller than 90°. At the equator, it would just graze the horizon, i.e. be at an elevation of 0°. The correlation between the latitude (North Pole = 90°, Equator = 0°) and the elevation of Polaris is no coincidence. Figure 6 combines all the three mentioned coordinate systems. For a given observer, at any latitude on Earth, the local horizontal coordinate system touches the terrestrial spherical polar coordinate system at a single tangent point. The sketch demonstrates that the elevation of the celestial north pole, also called the pole height, is equal to the northern latitude of the observer on Earth.
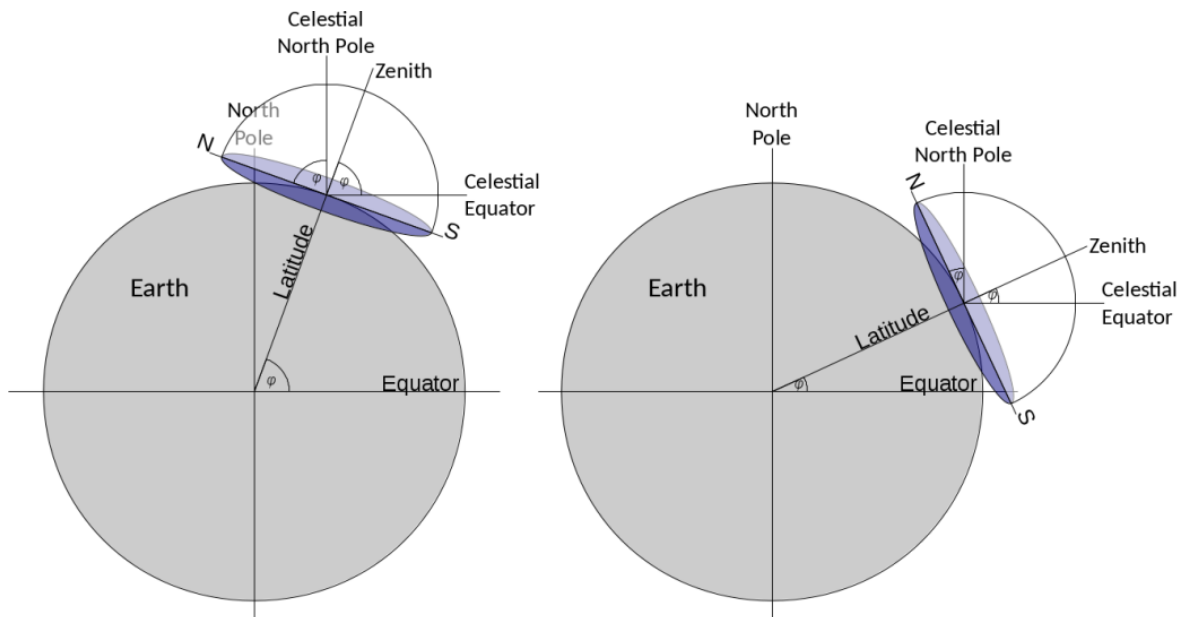

Figure 6: When combining the three coordinate systems (terrestrial spherical, celestial equatorial, local horizontal), it becomes clear that the latitude of the observer is equal to the elevation of the celestial pole, also known as the pole height (Credit: own work).

From this, we can conclude that if we measure the elevation of Polaris, we can determine our latitude on Earth with reasonable precision.
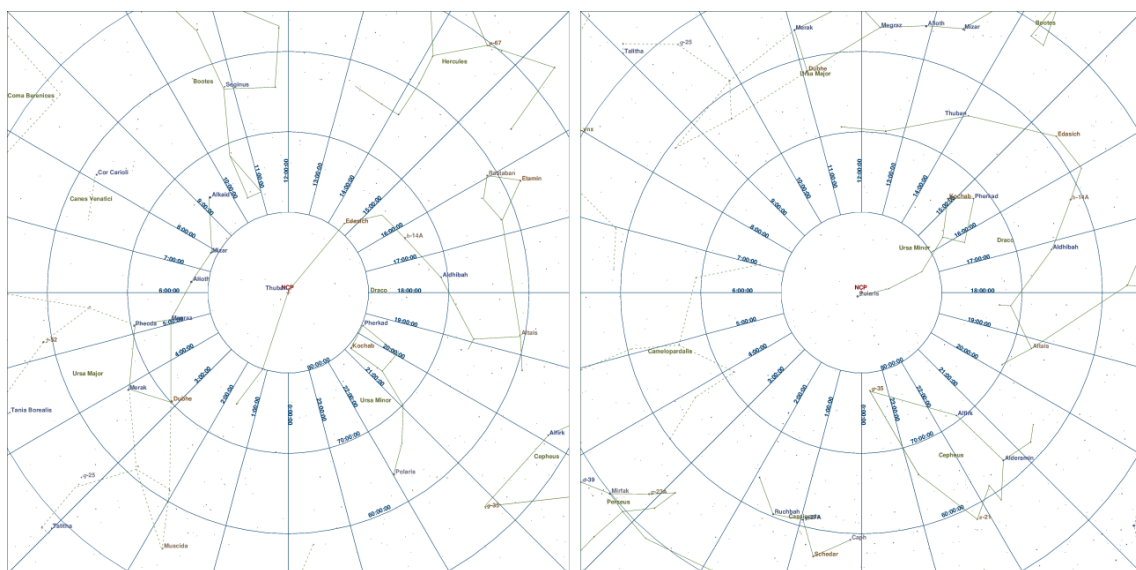

Figure 7: Star charts of the northern celestial pole region for the years 2750 BCE and 2016 CE (Credit: own work, created with XEphem Version 3.7.6, produced by Elwood C. Downey and distributed by the Clear Sky Institute Inc., Solon, Iowa, USA, http://www.xephem.com).

Circumpolar stars and constellations

In the Bronze Age, Polaris could not be used to determine north. Because of the precession of the axis of the Earth, it was about 30° away from the celestial north pole in 3500 BCE. Instead, the star Thuban (α Draconis) was more appropriate, as it was less than 4° off at that time. However, it was considerably fainter than Polaris and perhaps not always visible to the naked eye.

When looking at the night sky, some stars within a certain radius around the celestial poles never set; they are circumpolar (see Figure 3). Navigators were skilled enough to determine the true position of the celestial pole by observing a few stars close to it. This method also works for the southern celestial pole.

Please watch the two following videos that demonstrate the phenomenon of circumpolar stars and constellations for two locations on Earth. They show the simulated daily apparent rotation of the sky around the northern celestial pole for two cities: Heidelberg, Germany (49° North) and Lisbon, Portugal (23° North).

CircumpolarStars Heidelberg 49degN (Duration: 0:57)
https://youtu.be/uzeey9VPA48

CircumpolarStars Habana 23degN (Duration: 0:49)
https://youtu.be/zggfQC_d7UQ

You will notice the following:
1. There are always stars and constellations that never set. Those are the circumpolar stars and constellations.
2. The angle between the celestial pole (Polaris) and the horizon depends on the latitude of the observer. In fact, these angles are identical.
3. The circumpolar region depends on the latitude of the observer. It is bigger for locations closer to the pole.

If you are familiar with the use of a planisphere, you can study the same phenomenon by watching the following two videos. They show the rotation of the sky for the latitudes 20° and 45°. The transparent area reveals the visible sky for a given point in time. The dashed circle indicates the region of circumpolar stars and constellations.

CircumPolarStars phi N20 (Duration: 0:37)
https://youtu.be/Uv-xcdqhV00

CircumPolarStars phi N45 (Duration: 0:37)
https://youtu.be/VZ6RmdzbpPw

When sailing north or south, sailors observe that with changing elevation of the celestial pole, the circumpolar range is altered. Therefore, whenever navigators see the same star or constellation culminating – i.e. passing the meridian – at the same elevation, they stay on the 'latitude'. Although the educated ancient Greeks were familiar with the concept of latitude of a spherical Earth, common sailors were probably not. For them, it was sufficient to realise the connection between the elevation of stars and their course. Ancient navigators knew the night sky very well. They utilised the relative positions of constellations to determine their position in terms of latitude.

Early navigation in the Mediterranean

Ancient navigators realised that celestial objects, especially stars, can be used to keep the course of a ship. Such skills have been mentioned in early literature like Homer's Odyssey, which is believed to date back to 8th century BCE. The original sources are thought to originate from the Bronze Age, in which the Minoans of Crete were a particularly influential people. They lived between 3,650 and 1,450 BCE in the northern Mediterranean region and sailed the Aegean Sea. Since many of their sacral buildings were aligned with the cardinal directions and astronomical phenomena like the rising sun and the equinoxes, it is reasonable to believe that they used this knowledge for navigation, too. The Minoans sailed to the island of Thera and Egypt, which would have taken them several days on open water.

Figure 8: The night sky with bearing from Crete to Alexandria for 22 September 2000 BCE, 21:30 UT (Credit: own work, created with Stellarium, free GNU GPL software).

The Greek poet Aratos of Soli published his *Phainomena* around 275 BCE, describing in detail the positions of constellations and their order of rising and setting. This was vital information for any navigator to maintain a given course. He would simply have pointed his ship at a bearing and be able to keep it, with the help of stellar constellations that appeared towards that heading. The azimuth of a given star when rising or setting remains constant throughout the year, except for a slow variation over 26,000 years caused by the precession of the Earth axis. Interestingly, Aratos' positions did not fit the Late Bronze and Early Iron Age but suited the era of the Minoan reign some 2,000 years earlier.

Pytheas

A very notable and well documented long distance voyage has been described by ancient authors and scholars like Strabo, Pliny and Diodorus of Sicily. It is the voyage of Pytheas (ca. 380 – 310 BCE), a Greek astronomer, geographer and explorer from Marseille who at around 320 BCE apparently left the Mediterranean, travelled along the European west coast and made it up north until the British Isles and beyond the Arctic Circle, during which he possibly reached Iceland or the Faroe Islands that he called Thule.

Massalia (or Massilia), as Thule was called then, was founded by Phocean Greeks around 600 BCE, and it quickly evolved into one of the biggest and wealthiest Greek outposts in the western Mediterranean with strong trade relations to Celtic tribes who occupied most of Europe. Pytheas was born in the Late Bronze Age, when the trade with regions in northern Europe was flourishing.

Not much was known in Greek geography about this part of the world, except that the barbarians living there mined tin ore and delivered the precious amber that the whole Mediterranean so desperately sought. Perhaps, it was out of pure curiosity that Pytheas set out to explore these shores.

His voyage was a milestone, because Pytheas was a scientist and a great observer. He used a gnomon or a sundial, which allowed him to determine his latitude and measure the time during his voyage. He also noticed that in summer the sun shone longer at higher latitudes. In addition, he was the first to notice a relation between the tides, which are practically absent in the Mediterranean, and the lunar phases.

Figure 9: Statue of Pytheas erected at the Palais de la Bourse in Marseille in honour of his achievements (Credit: Rvalette, https://commons.wikimedia.org/wiki/File:Pythéas.jpg, 'Pythéas', https://creativecommons.org/licenses/by-sa/3.0/legalcode).

Figure 10: The journey of Pytheas of Massalia according to Cunliffe (2003) (Credit: ESA/Cunliffe, http://www.esa.int/spaceinimages/Images/2005/09/The_journey_of_Pytheas, http://www.esa.int/spaceinimages/ESA_Multimedia/Copyright_Notice_Images).

Further reading about Pytheas

B. Cunliffe, 'The Extraordinary Voyage of Pytheas the Greek', Penguin Books

Activity 1: Circumpolar constellations and stars

Materials needed:
- Worksheet
- Pair of compasses
- Pencil
- Ruler
- Calculator

In the absence of a bright star at the celestial poles, ancient navigators were able to find the celestial poles by observing a few circumpolar stars. These navigators were experienced enough to determine the true north by recognising the relative position of such stars and by their paths around it.

In addition, they used circumpolar constellations and stars to infer their latitude. They never rise or set – they are always above the horizon. While today we can simply measure the elevation of Polaris above the horizon, ancient navigators saw Polaris many degrees away from the celestial north pole. In the Southern Hemisphere, there is no such stellar indicator anyway. So, instead of measuring the elevation of Polaris, they observed the stars and constellations that were still visible above the horizon when they attained their lowest elevation above the horizon (lower culmination) during their apparent orbit around the celestial pole.
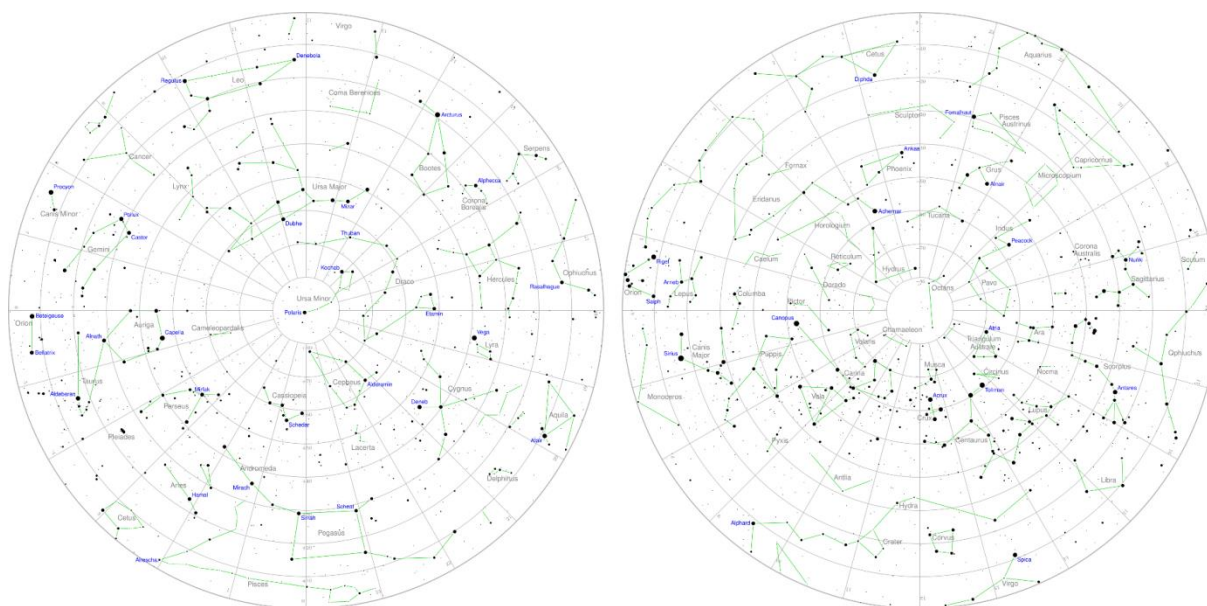

Figure 11: Star charts of the Northern and the Southern Hemisphere (Credit: Markus Nielbock, https://commons.wikimedia.org/wiki/File:NorthernCelestialHemisphere.png, https://commons.wikimedia.org/wiki/File:SouthernCelestialHemisphere.png, https://creativecommons.org/licenses/by/4.0/legalcode, created with PP3, http://pp3.sourceforge.net)

Exercise

Your task is now to walk in the footsteps of a navigator that lived around 5000 years ago. Based on those skills, you will determine the constellations that are circumpolar when observed from given positions on Earth.

The table below contains the names of six cities along with their latitudes φ. Negative values indicate southern latitudes. The seventh row is empty, where you can add the details of your home town. From this, you will have to calculate the angular radii ϱ from the celestial pole. The calculation is simple, because it is the same as the pole height and the latitude:

$$\varphi = \varrho$$

Then select the map that matches the hemisphere. Use the compass to draw circles of those radii around the corresponding pole. The constellations inside that circle are circumpolar. List the constellations that are just fully or partially visible for a given city.

| City	Latitude (°)	Radius in map (cm)	Constellations
Tunis (ancient Carthage, Tunisia)	36.8		
Cape Town (South Africa)	-33.9		
Plymouth (UK)	50.4		
Wellington (New Zealand)	-41.3		
Mumbai (India)	19.0		
Grytviken (South Georgia)	-54.3		

Detailed instructions
1. Determine the map scale. The angular scale is 90° from the poles to the outer circle, i.e. the celestial equator.
2. Convert the latitudes in the table into radii in the scale of the maps and add them to the table.
3. For each of the cities:
   a. Select the suitable map.
   b. Use the compass to draw a circle with a radius that was determined for that city.
   c. Find and note the visible circumpolar constellations. If they are too many, just select the most prominent ones.
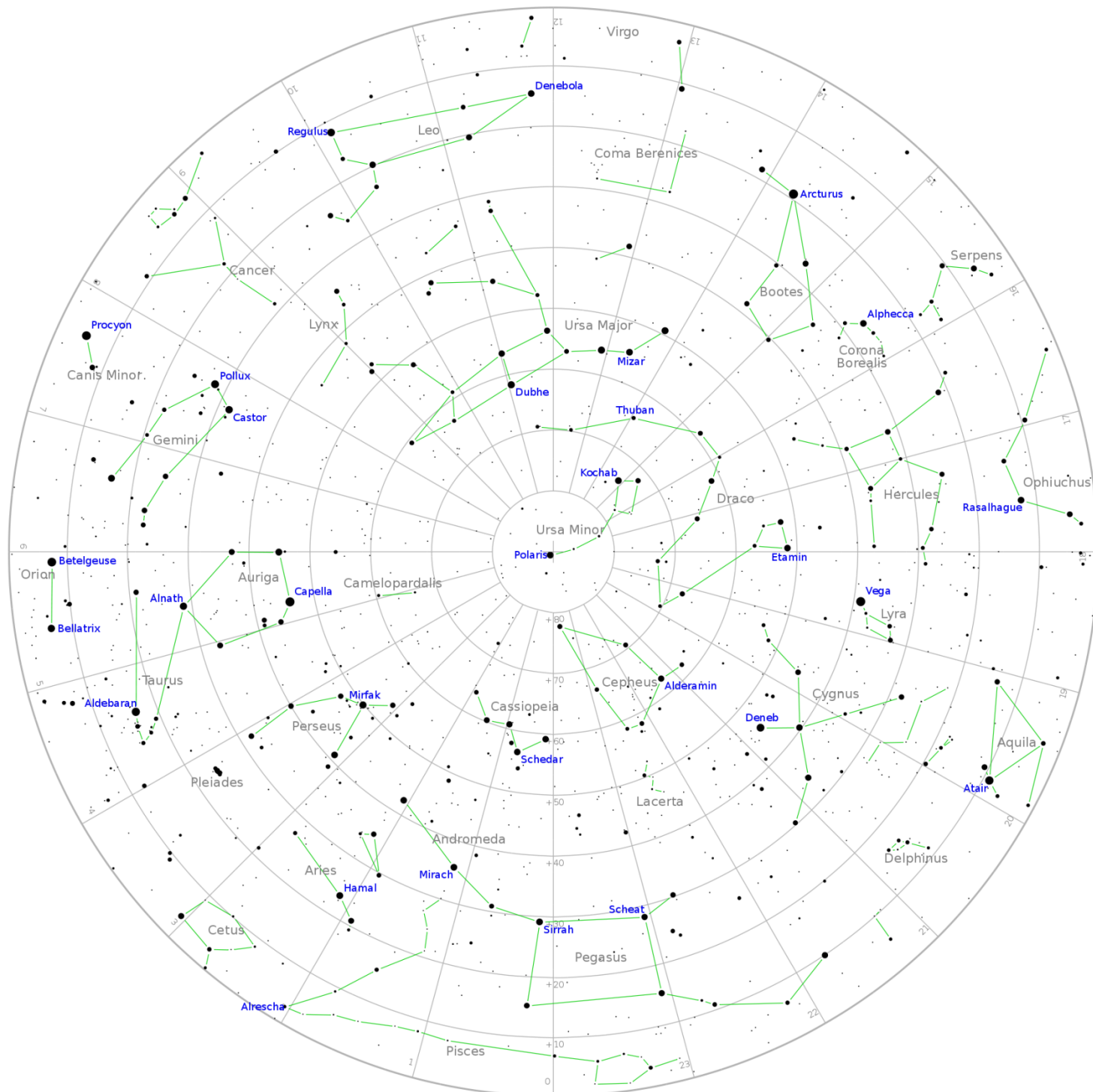
Map scale:

Map of the Southern Hemisphere
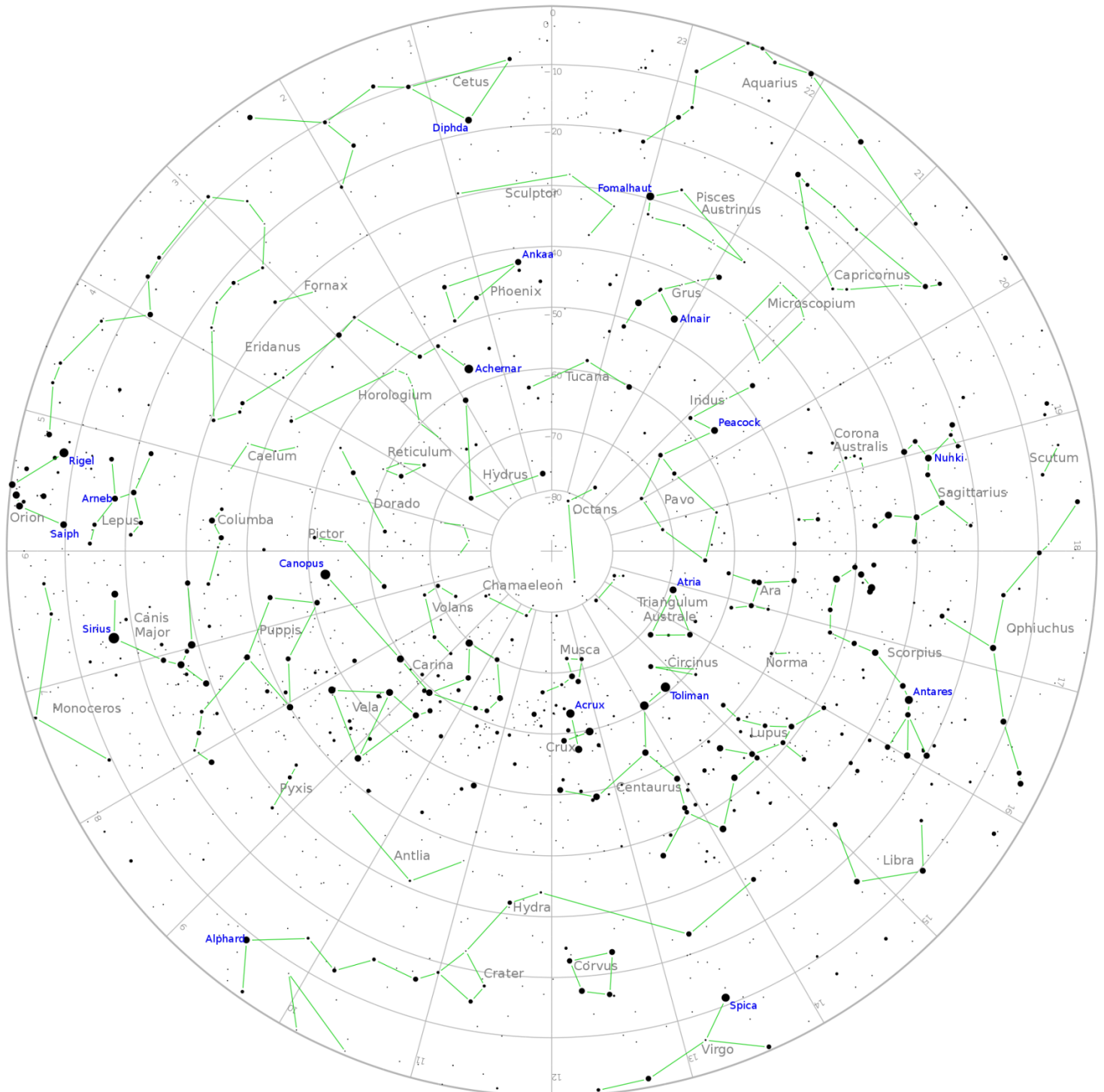
Map scale:

Activity 2: Stars guide the way

Materials needed:

- Worksheet
- Pencil
- Protractor
- Computer with MS Excel installed
- Excel spreadsheet 'AncientMediterranean_BrightStars_EUSPACE-AWE_Navigation.xlsx'

In the absence of a star like Polaris that indicates a celestial pole, ancient navigators used other stars and constellations to determine cardinal directions and their ship's course. They realised that the positions where they appear and disappear at the horizon (the bearings) do not change during a lifetime. Experienced navigators knew the brightest stars and constellations by heart.
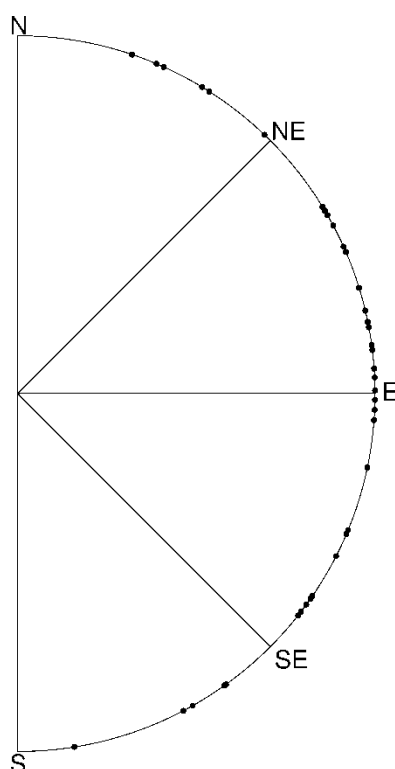

Figure 12: Bearings of selected rising bright stars for latitude 45° at an elevation of 10° above the horizon (own work).

Exercise

You will produce a stellar compass similar to Figure 12. The calculations that are needed to convert the sky coordinates of the stars into horizontal coordinates, i.e. azimuth and elevation, are quite complex. Therefore, this activity comes with an Excel file that does it for you. It consists of 57 bright stars plus the Pleiades, which is a very prominent group of stars.

All you have to do is enter the latitude of your location and the elevation of the stars in the corresponding line at the bottom of the spreadsheet. For the elevation, 10° is a good value. This means, you will get the azimuths of the stars when observed at an angle of 10° above the horizon. You can also use different values, but note that this exercise is meant for finding stars that just rise or set. The azimuth is an angle along the horizon, counting clockwise from north.

The last two columns (AZ1, AZ2) then display two angles, the azimuths, one when the star is rising and one when the star is setting. Note that the distribution of azimuths for rising and setting stars is

symmetric relative to the meridian, i.e. the line that connects North and South. The cells that show #NA do not contain valid numbers. These stars never rise or set. They are either circumpolar or below the horizon.

Then translate the values into the stellar compass below. Note that 0° is North and angles run clockwise. Use a protractor and indicate the position of each star on the circle. Write its name next to it.

N

W   E

+

S
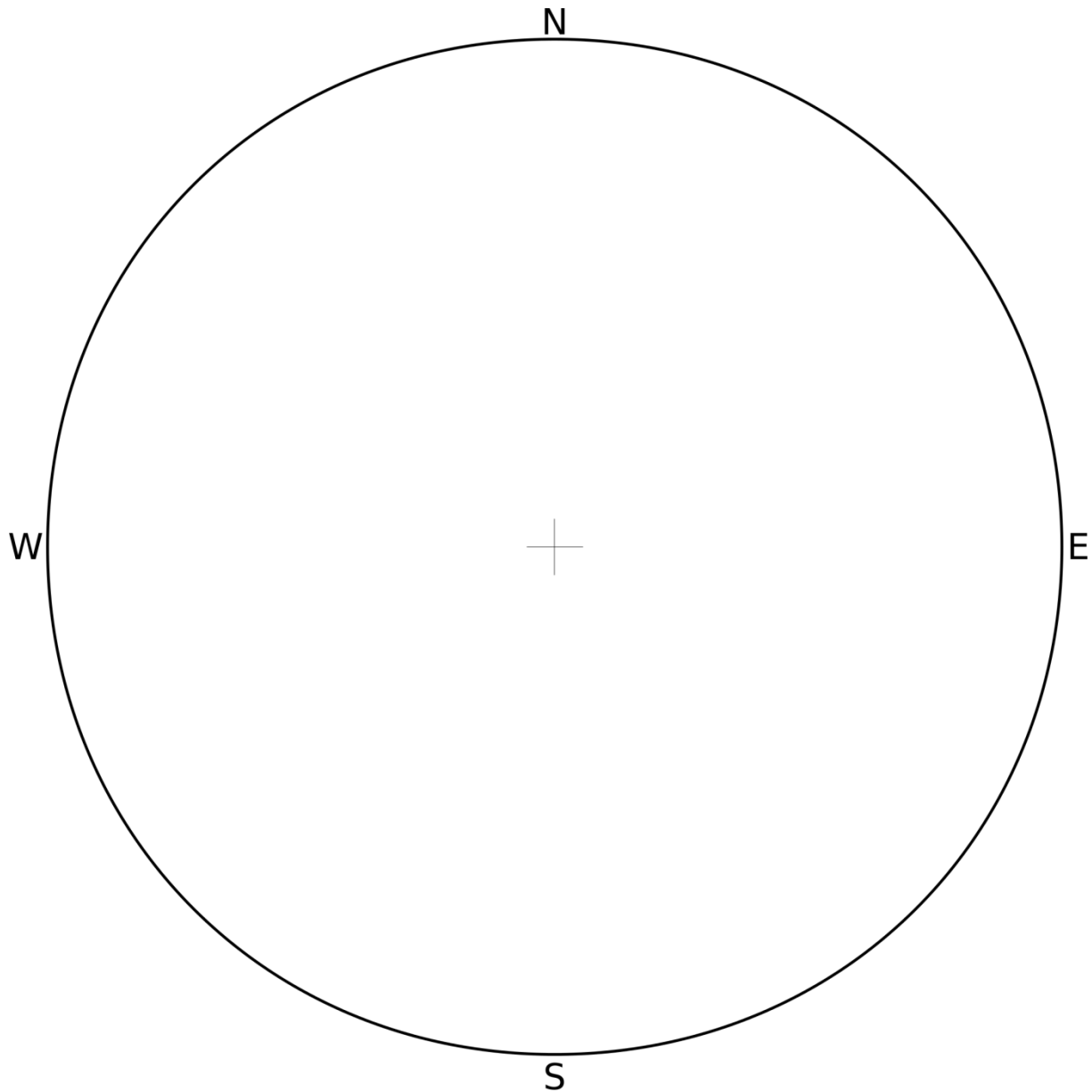
Activity 3: Do it yourself! (Supplemental)

Materials needed:
- Results of the previous activities
- Portable red lamp like e.g. a dimmed torch or a torch covered with a red filter
- A magnetic compass if available

Nothing is more instructive than applying what has been learned and exercised in theory to real conditions. Therefore, the results from the previous two activities can be tested in the field by observing the night sky.

Exercise
You can carry out this activity alone at home or as a group event with the class.

Select a clear evening and a site with a good view of the horizon. Once it is dark enough to see the stars, use the dimmed torch to inspect the maps with the circumpolar ranges from activity 1. A dimmed torch – better still, a red one – helps to keep the eyes adapted to the dark.

After identifying the brightest stars, inspect your stellar compass from activity 2. Point the markers of one or some of the stars to the stars at the sky. Identify north (or south, depending on which celestial pole is visible from your location). If in the Northern Hemisphere, does this match the direction of the North Star, Polaris? In the Southern Hemisphere, a magnetic compass might be needed.

Identify the constellations you see in the sky on your map. Look north (south in the Southern Hemisphere) and name the stars and constellations that are just above the horizon. Does this coincide with the map? Note that there should be a circle that indicates the circumpolar range for the local latitude.

In doing this activity, you are working like the navigators from 4,000 years ago.

Glossary

Apparent movement
Movement of celestial objects, which is in fact caused by the rotation of the Earth.

Cardinal directions
Main directions, i.e. North, South, West, East

Circumpolar
Property of celestial objects that never set below the horizon.

Culmination
Passing the meridian of celestial objects. These objects attain their highest or lowest elevation there.

Diurnal
Concerning a period that is caused by the daily rotation of the Earth around its axis.

Elevation
Angular distance between a celestial object and the horizon.

Great circle
A circle on a sphere, whose radius is identical to the radius of the sphere.

Meridian
A line that connects North and South at the horizon via the Zenith.

Pole height
Elevation of a celestial pole. Its value is identical to the latitude of the observer on Earth.

Precession
Besides the rotation of a spinning body, the rotation axis often also moves in space. This is called precession. As a result, the rotation axis constantly changes its orientation and points to different points in space. The full cycle of precession of the Earth's axis takes roughly 26,000 years.

Spherical polar coordinates
The natural coordinate system of a flat plane is Cartesian and measures distances in two perpendicular directions (ahead, back, left, right). For a sphere, this is not very useful, because it has neither a beginning nor an end. Instead, the fixed point is the centre of the sphere. When projected outside from the central position, any point on the surface of the sphere can be determined by two angles with one of them being related to the symmetry axis. Such axis defines two poles. In addition, there is the radius that represents the third dimension of space, which permits determining each point within a sphere. This defines the spherical polar coordinates. When defining points on the surface of a sphere, the radius stays constant.

Sundial
A stick that projects a shadow cast by the sun. The orientation and length of the shadow helps determine time and latitude.

Zenith
Point in the sky directly above.