

Celestial Mechanics for Archaeoastronomy Notes

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1. Introduction

These notes are a work in progress. They complement the Fieldwork Notes by giving the basics of celestial mechanics, “horizon astronomy”, and the celestial coordinates required to analyse the data gathered while on the field. With these notes, and the related spreadsheets you'll be able to compare your site orientations to certain astronomical events to test for alignments.

2. The Celestial Sphere, the Sky and the Horizon

The Celestial Sphere is an imaginary sphere of a very large radius, that has the Earth at its centre, and that rotates around the same axis as the Earth (figure 1). All the celestial objects can be thought of as inhabiting this sphere which, like the Earth, also has poles and an equator. These are extensions of the Earth's ones, as can be seen in the figure below.

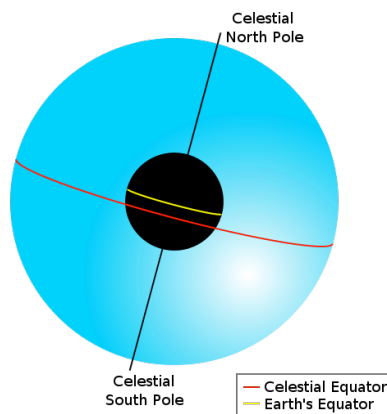


Figure 1. The Celestial Sphere (in blue) is an extension of the Earth's sphere (in black). The Celestial Poles are aligned with the Earth's poles, and the same is true of the Celestial Equator (in red).

Figure 2 shows a more complete view of the Celestial Sphere, set for the latitude of London. The Horizon, Ecliptic, Celestial Equator, Prime Vertical (connecting the Zenith with the Nadir) and Prime Meridian are all represented as well. Hopefully some of these will make some sense to you after you've gone through these notes, so feel free to refer back to this figure every once in a while.

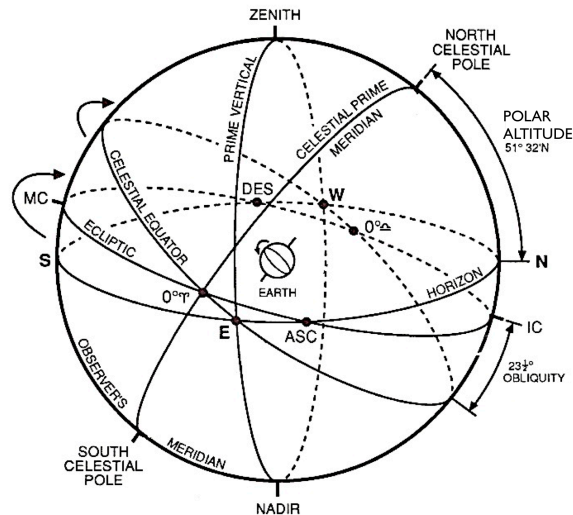


Figure 2. The Celestial Sphere with the most important great circles marked, namely the celestial equator and the ecliptic. These will make sense throughout these notes.

At any one place on Earth an observer will only see half of the Celestial Sphere, at most. This is because the Earth is so big that we don't see its curvature as in figure 1; locally it looks flat as this makes only a part of the sphere visible, a dome (figure 3). The same diagram can be represented in flat format, showing the great circles, like the celestial equator or the ecliptic, as they are perceived by an observer. This is shown in figure 3 and is the format adopted in most of the diagrams in these notes.

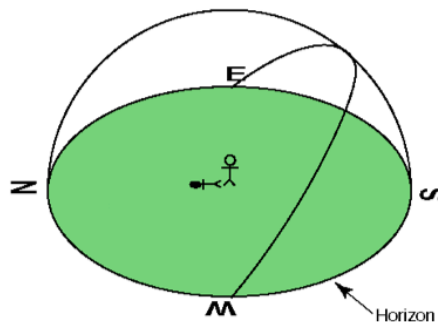


Figure 3. The sky as seen from a location on Earth. The local landscape is flat (in green) and terminates where the celestial dome begins: the horizon. The celestial equator (see following sections) is seen represented as a black line on the dome.

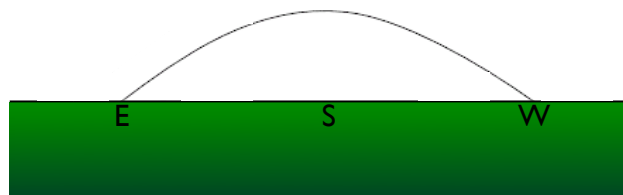


Figure 4. Same as figure 3 but on a flat format. The line represents the celestial equator, which also happens to be the path of the Sun on the Equinoxes.

To locate an object anywhere one needs a coordinate system. This is just a system for measuring a location, the coordinates being the numbers that give that location. Every system uses its own reference, a zero point if you will, from which one starts counting the coordinates. On Earth we use latitude and longitude and our references are respectively the equator and the Greenwich meridian. But when one is interested in pinpointing a location on the celestial sphere, there are other systems one can turn to, collectively known as Celestial Coordinates Systems.

3. Horizontal Coordinates: Azimuth and Altitude

The Horizontal coordinate system is quite straightforward. There are two coordinates: the azimuth and the altitude. The altitude is measured in degrees from the flat horizon towards the object in the sky (the green arrow in figure 5). The azimuth is measured along the flat horizon (blue arrow in the figure), from True North, which acts as reference, up to the point where a line perpendicular to the horizon passes through the object.

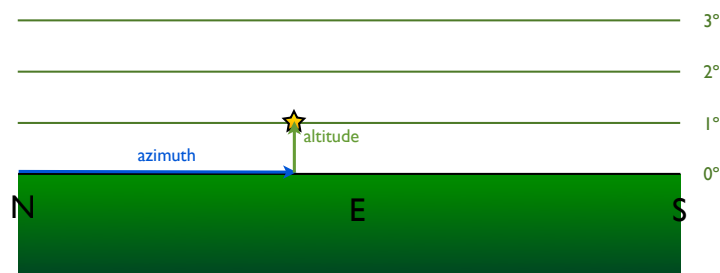


Figure 5. Horizontal coordinates: the azimuth (in blue) is measured along a flat horizon from True North (0° of azimuth); the altitude (in green) is measured perpendicularly to the azimuth.

To measure using these coordinates one just needs to draw a line perpendicular to the horizon that passes through the celestial object one is measuring. Then measure the angle between the object and the flat horizon along this line (altitude), and the angular distance between True North and the point where this line crosses the flat horizon. On the field this means one just needs to point a clinometer to the object to measure its altitude and a compass to measure its azimuth (provided one takes magnetic declination and other anomalies into account, check Fieldwork notes for more on that).

4. Equatorial Coordinates: Declination and Right Ascension

Equatorial Coordinates have the celestial equator for reference. At a given latitude the celestial equator is inclined with respect to a flat horizon by 90° minus the latitude in degrees (figure 6, see also figure 2). This is because the whole celestial sphere is seen to be inclined (it is actually the observer that is inclined with respect to the celestial sphere).

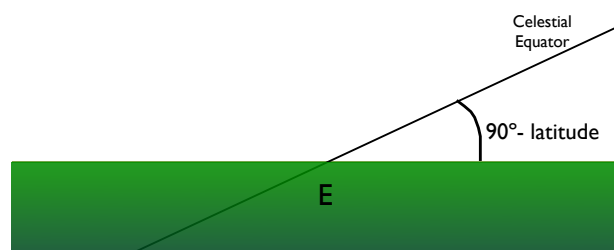


Figure 6. The celestial equator at a given location in the Northern Hemisphere. It always crosses East in a flat horizon, and its “inclination” is directly related to the latitude of the location.

The equatorial coordinates are the declination (Dec for short) and the right ascension (RA). The declination measures the angle of a point in the celestial sphere to the celestial equator (the red arrow in figure 5), whereas the RA measures an angle in the celestial equator from a reference point (the purple arrow). The reference point is the vernal equinox point, 0° Aries. Figure 7 also shows, in red, the lines of equal declination.

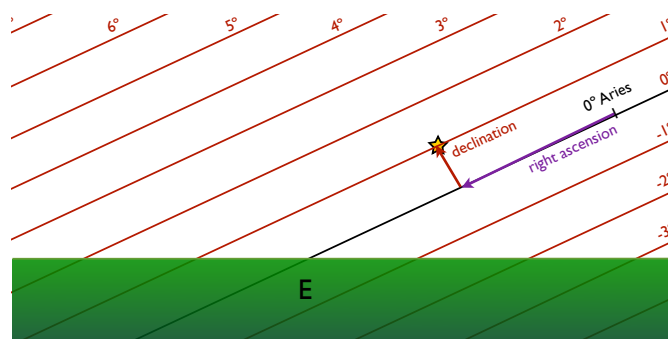


Figure 7. Equatorial coordinates: the right ascension (in purple) is measured along the celestial equator from the vernal equinox point (0° of Aries); the declination (in red) is measured perpendicularly to the equator.

To measure some object in equatorial coordinates one has to take a perpendicular to the celestial equator that passes through the object and then: i) measure the declination along this line and ii) measure the angle separation between 0° Aries and the point where this line crosses the equator to get the RA. This is not easy to do while on the field, as one would have to determine the celestial equator first, etc. It is much easier to measure everything in horizontal coordinates and then convert to equatorial ones.

5. Converting between Coordinates

The two coordinate systems described above can both be used to describe the same position in the celestial sphere. This is akin to using two rulers to measure the same thing, one in metres and the other in inches. They will both give completely different values for the same object, because they have two different references. This doesn't mean one of them is wrong: they are both right! So you can use whatever is more convenient to you, let's say it's the inch ruler, and convert the values to metres if you have to communicate the values to your European friends.

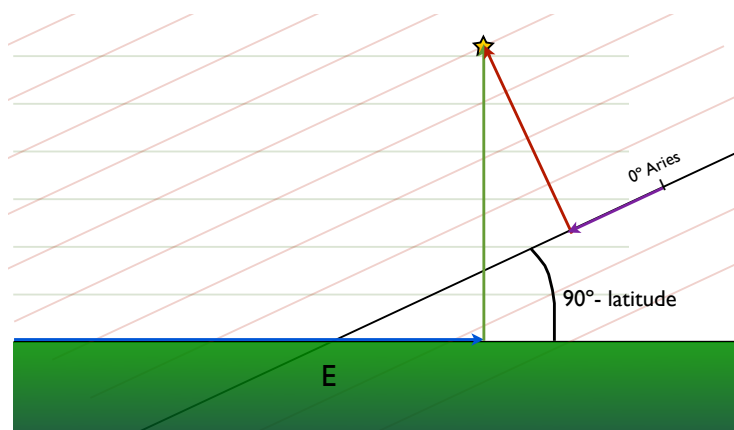


Figure 8. Horizontal and Equatorial Coordinates can both be used to describe the same point in the celestial sphere (in this case a star). This is the same as using two rulers, one in metres, one in inches, to measure the length and width of a table: we'll get very different values for each ruler, but they both describe the same object.

In Archaeoastronomy the situation is remarkably similar to the example just given. On the field it is much more convenient to use simple surveying tools, like a compass and clinometer, or a theodolite, to measure the horizontal coordinates. However, the azimuth and altitude of a given point in the celestial sphere, for example a star, will not be the same when seen from two points on Earth.

Figures 9 and 10 show this very well. The first figure shows the same case as figure 6 above, but when the sky is looked at from a latitude closer to the equator, i.e. a lower latitude. The whole of the celestial sphere is now more inclined relative to the horizon. (Look at the inclination of the celestial equator to the horizon. This will increase until you are on the equator, latitude 0° , for which the inclination will be 90° , and thus the equator is an arc that crosses the zenith and thus divides the sky in two equal parts.) As you can see from the figure, if one then measures the azimuth and altitude of the same star as before (which will still have the same equatorial coordinates, as it is the whole celestial sphere that is more inclined, not just the celestial equator) we will measure completely different values.

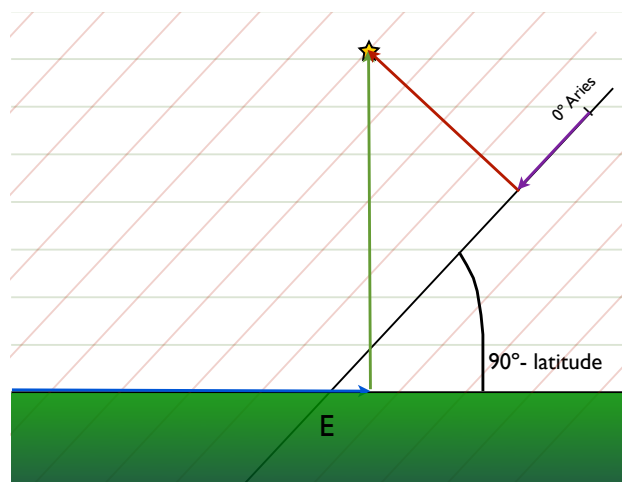


Figure 9. The same as figure 8 but in lower latitudes, which means that the celestial equator (the black line) is more inclined relative to the horizon. Note that the equatorial coordinates describing the same star (the red and purple arrows) are still the same (the arrows have the same lengths as in figure 8), whereas the horizontal coordinates (blue and green arrows) changed considerably.

Figure 10 shows exactly the same for higher latitudes, closer to the poles. The celestial equator is now barely inclined at all. (If you are standing at the pole, latitude 90° , the celestial equator will have zero inclination, i.e. will be indistinguishable from the flat horizon circle, and the celestial north pole will lie at your zenith.) Again the measured azimuth and altitude, for the same star as before, will be very different from the values observed in the two previous figures.

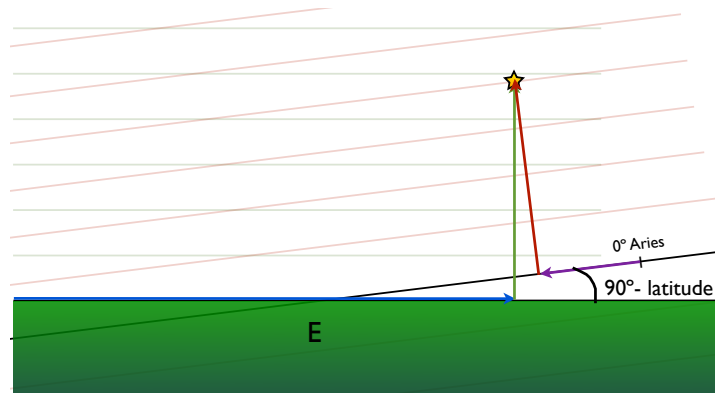


Figure 10. The same as figures 8 and 9 but in higher latitudes (the celestial equator is less inclined). Again the equatorial coordinates describing the star's position are still the same, but the horizontal coordinates are considerably different from the previous cases: the azimuth is now longer whereas the altitude is shorter.

Converting the measured horizontal coordinates to equatorial coordinates simplifies analysis considerably. A star's equatorial coordinates (RA and Dec) are always the same whether it is summer or winter, or whether you are seeing it from the Arctic Circle or the Tropics. The Sun and Moon have slightly more complicated movements (see next section) but their orbit in the sky at a particular day in the year can be described by the declination alone. The RA changes throughout time (for e.g. the Sun's yearly movement across the Zodiac) but, if one is interested in horizon events (risings and settings) alone, the declination is all that is needed. Also, you might be interested in comparing alignments across a range of sites located at different latitudes which, as seen above, can only be possible if one works in equatorial coordinates.

To convert horizontal to equatorial coordinates one needs a formula that comes straight from spherical trigonometry (i.e. trigonometry on a sphere, instead of on a plane). However, for the MA you are not required to know or directly handle the equations themselves. Instead there is a spreadsheet on Moodle that will help you with this task.

6. "Horizon Astronomy"

Having covered the basics about the systems of celestial coordinates involved in Archaeoastronomical research, the following sections now focus on the movements of the celestial bodies. This section will cover most aspects of what is unofficially termed "horizon astronomy", i.e. the focus on events, such as risings and settings, that occur at the local horizon. The local horizon is not always flat, and not in all directions. Which means that, in practice, risings and settings will not occur at a 0° altitude, but at the altitude of the horizon, which is what has to be measured on the field. See the Fieldwork notes for more information on this.

a. Stars

As mentioned above, any star is accurately described by a RA and Dec that do not change throughout the night or throughout the year, i.e. whether the star is above or below the horizon, it still has the same equatorial coordinates. Imagine that a star is either a hole in, or is glued to the celestial sphere (a "fixed star"). As the night goes by, it is the celestial sphere, as a whole, that is seen to be rotating around the earth, taking with it all the stars that are fixed to it. So the stars' position relative to the celestial equator (its equatorial coordinates) does not change. Because of this, on their daily movement, stars can be said to follow lines of constant declination (the red lines in figures 7 to 11). The implication of this for "Horizon Astronomy" is that one needs only the declination of a star to know its rise and set points on the horizon.

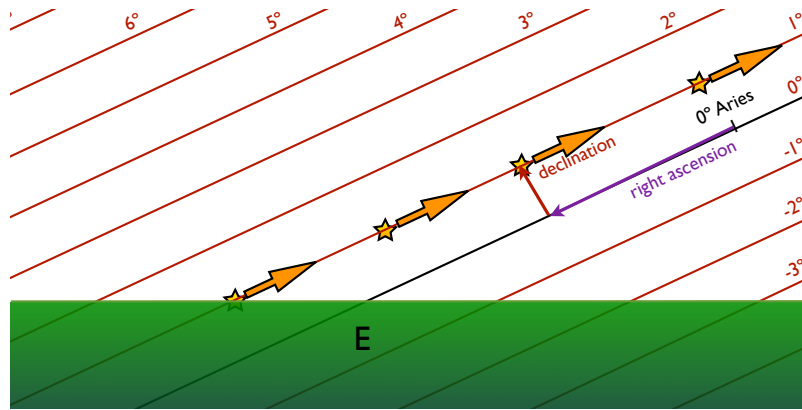


Figure 11. A star is seen here rising. As discussed in the text, throughout their nightly cycle, stars follow paths of constant declination, the red lines in the figure.

These values are easily found in tables (see Bernadette Brady's Notes), online or, using Planetarium software like Stellarium (freely available on www.stellarium.org), you can just point at any star and see its RA and Dec.

b. Sun

The Sun has a slightly more complicated movement. This is because the Sun actually moves on the ecliptic, which is inclined relative to the celestial equator.

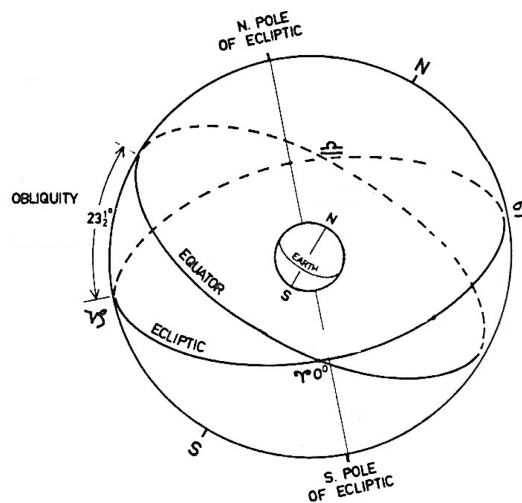


Figure 12. Celestial Sphere with the celestial equator and ecliptic marked. As you can see the ecliptic makes a certain angle, the obliquity, with the celestial equator.

This inclination, known as obliquity or axial tilt, is currently of 23.44° but sometimes rounded to 23.4° , 23.5° or even 24° , depending on the source. This means that the ecliptic takes the Sun on a yearly trajectory that moves it from 23.4° to -23.4° of declination, corresponding respectively to the Summer and Winter Solstices. The mid-points, where the ecliptic crosses the celestial equator and thus has 0° of declination, mark the equinoxes. Figures 13-14 below shows the daily path of the Sun on these dates. The different values in the declination at different dates give different azimuths for both sunrise and sunset.

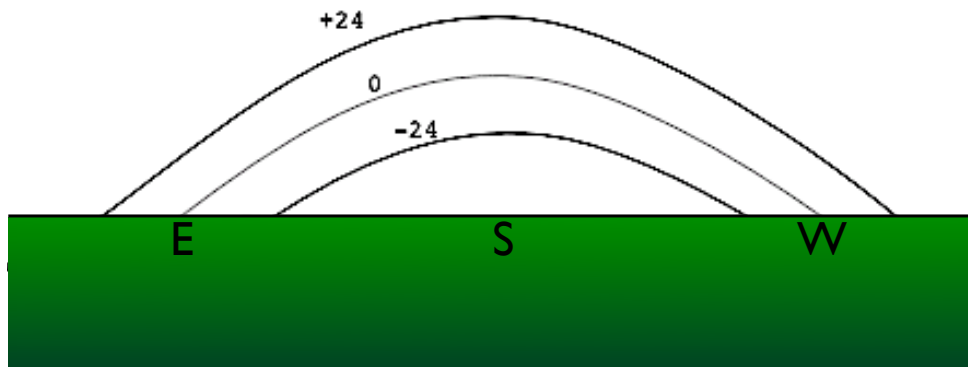


Figure 13. The path of the Sun in the daily sky. The path changes throughout the year, three of which are represented: Summer Solstice ($+24^\circ$ of declination), equinoxes (0° of declination) and Winter Solstice (-24° of declination).

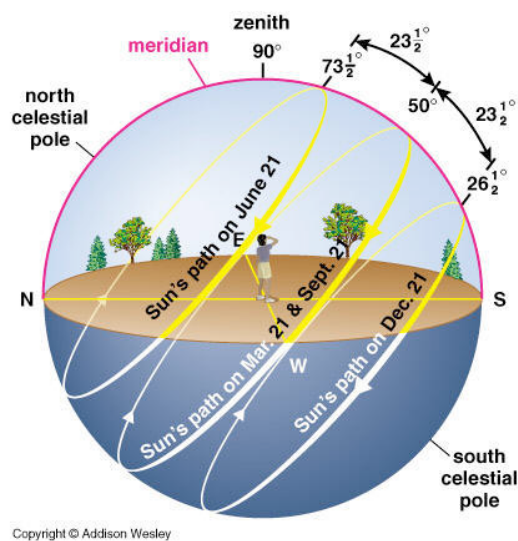


Figure 14. Sun's path at the Solstices and the Equinoxes on the Celestial Sphere, as seen for a Northern Hemisphere observer.



Figure 15. Sunrise points at the Solstices. Note that, unlike figure 13 one is now looking due East, towards the sunrise. It takes the Sun six months to travel from one extreme to the other.

c. Moon

The Moon is neither fixed to the celestial sphere nor does it move along the ecliptic. It moves on its own orbit, which is inclined with respect to the ecliptic 5.15° . This means that, in a situation similar to the solar one above, the maximum, and minimum, declinations possible for the Moon are $23.4^\circ + 5.15^\circ = 28.55^\circ$, and $-23.4^\circ - 5.15^\circ = -28.55^\circ$. However, there is an added layer of complication here: the Moon's orbit around the Earth is rotating (or precessing) with a period of 18.6 years. This gives rise to two other limit declinations: $23.4^\circ - 5.15^\circ = 18.25^\circ$ and $-23.4^\circ + 5.15^\circ = -18.25^\circ$. These four declinations correspond to the so-called Lunar Standstills. To get a better idea of what's happening let us look at the Moon's behaviour along the horizon.

Let's look at the moonrise, even though the same is true for moonset. The moonrise point does the same kind of movement on the horizon as the sunrise one, but instead of taking a year, it takes only one month to move between its extremes. When the Moon is Dark (New Moon is modern parlance) it is closest to the Sun, so the Moon will rise close to sunrise (even though it will be very difficult to observe it). On the other hand, if the Moon is Full it will be farthest away from the Sun, both in time (rising when the Sun is setting) and in space: the full-moonrise point is the moonrise point farthest from sunrise of the whole month.

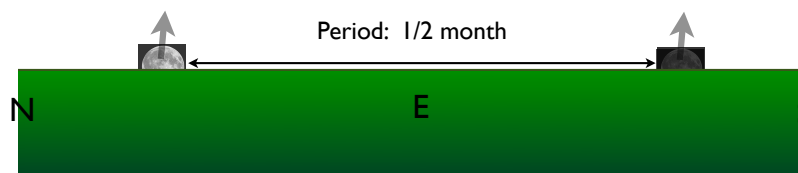


Figure 16. Moonrise points (looking towards East) at the month closest to the Winter Solstice, i.e. when the sun is rising closest to South (see figure 15). It takes the Moon half a synodic period, that is half a month, to travel between the two lunistics. Notice the phases on the two lunistics: dark when closest to the sunrise point and Full when farthest apart.

But, because of the precession of the lunar orbit (not to confuse with axial precession, see below), these limits in moonrise also vary in an 18.6 year period. They vary between two extreme points, marked by the declinations calculated above, which are called the major Lunar Standstill (if the declinations are beyond the Solstice limits) and minor Lunar Standstills (if they are within the solar limits). The figure below shows these four points on a flat horizon, with the Solstice sunrise points marked as well. The monthly moonrise extremes (called lunistics) will then be moving between their major and minor limits over a 18.6 year period, 9.3 years from the major limit to the minor limit, and the same amount of time going back. These four declinations then mark extremes in the moon's movement on the horizon, which might have been regarded as significant. The major Standstills, for example, mark points on the horizon that only the Moon "touches", as the Sun never rises (or sets) at such declinations.

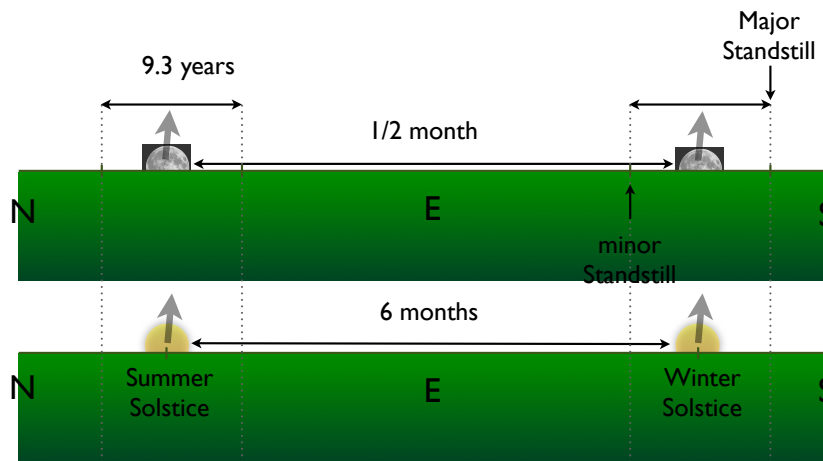


Figure 17. Standstill moonrise points compared to the Solstice sunrise points along the Eastern side of the horizon.

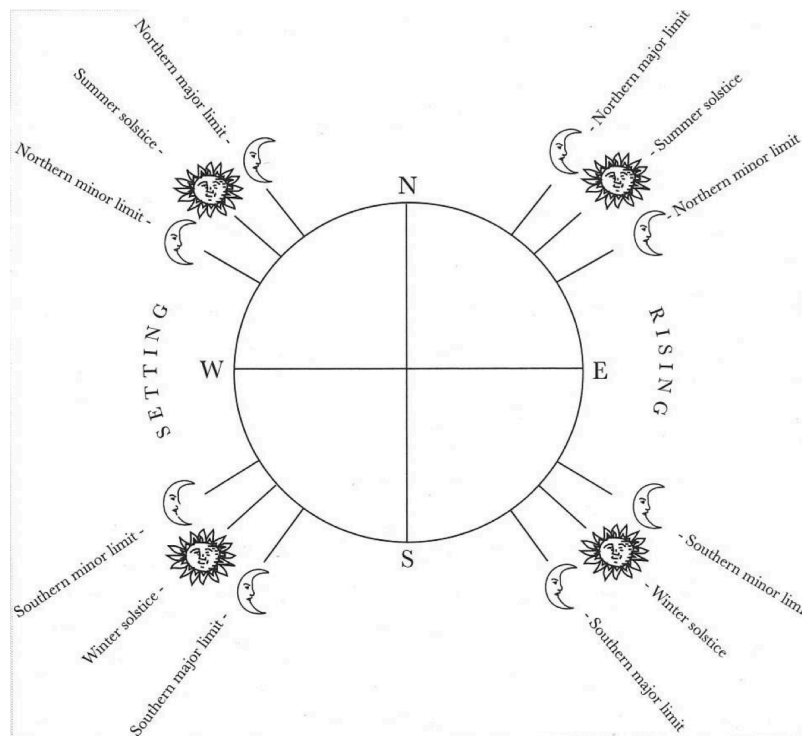


Figure 18. Standstill and Solstice points along the horizon as seen from above. Taken from Ruggles (1999).

Northern		Southern	
minor	major	minor	major
18.25	28.55	-18.25	-28.55

Table 1. Declination values for Lunar Standstills, both minor and major, both northern and southern. These values need to be adjusted for past epochs, see sections on obliquity and lunar parallax.

Equinoctial Full Moons

Other particular points in the lunar cycle that are only now starting to take hold of the archaeoastronomical community, and for which there is increasing evidence for alignments, are the Equinoctial Full Moons. These are the Full Moons closest to the equinoxes, and are marked by a crossover between the positions of the Sun and the Full Moon. During winter, the Sun travels low in the sky (the lowest path in figures 13 and 14), whereas the Full Moon, as discussed, will always be very high in the sky as it will be far from the Sun. The situation is reversed for the summer season. The point in time at which the Sun and Full Moon are seen to swap places is always the Full Moon closest to the Equinoxes, which also means the sunrise and full-moonrise points will be very close to each other, and to the East point.

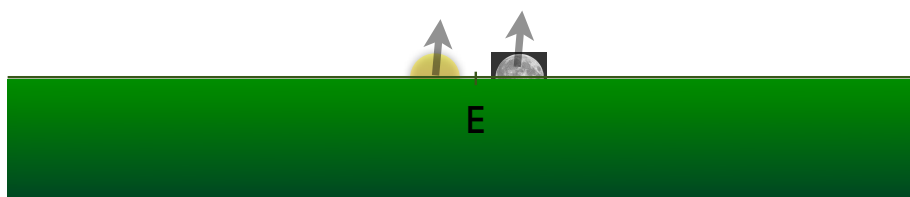


Figure 19. Typical Spring Full Moon sunrise and moonrise points. Just after Winter Solstice the Sun's rise point moves north each day, whereas the Full Moon's rise point, every month, moves south. The rise points crossover at the Spring Full Moon, even though the two luminaries rise with a twelve hour difference. The same situation happens for an Autumn Full Moon, but the relative position of the two celestial bodies would be swapped.

However the Equinoctial Full Moons (both Spring Full Moon and Autumn Full Moon) do not occur on the same date every year (think about Easter/Passover) which means that there isn't a single declination value for this event, but a distribution of possibilities. Simulations show that these distributions encompass a considerable breadth of the horizon, with very well defined minimum and maximum points, but are much more likely to occur around the distribution's peak. The distributions are shown in the figure below and the values are given in the table, for both Spring and Autumn Full Moons for the current epoch (Silva, 2011)

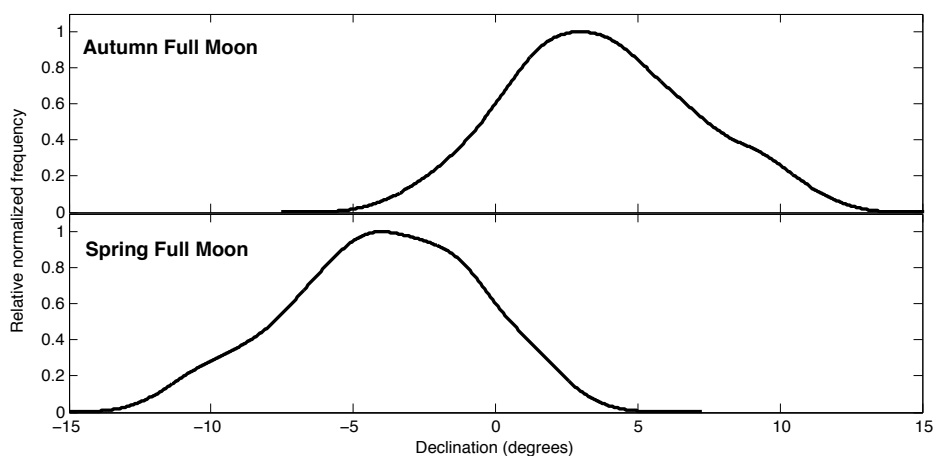


Figure 20. Equinoctial Full Moon for moonrise. The vertical axis represents the likelihood that an EFM will occur at a given declination, the highest the more likely. The declination values for the peaks and the limits are given in the table below.

Spring Full Moonrise			Autumn Full Moonrise		
Minimum	Peak	Maximum	Minimum	Peak	Maximum
-14.44	-3.67	6.21	-6.05	3.27	14.60

Table 2. Declination values for both Equinoctial Full Moons. These values need to be adjusted for past epochs and for moonsets. See section on obliquity and Silva (2011) for more details.

Lunar Parallax

When dealing with the moon one has to take parallax into account. Parallax occurs because the moon is closer to the Earth than the sun, the planets or the stars and, on the other hand, because the Earth's size is not negligible. If you look at figures 1 and 2, the celestial sphere with the Earth at its centre, you will realize that the declination and RA are measured with respect to the centre of the celestial sphere, i.e. the centre of the Earth. These are called geocentric coordinates. However, figure 1 is more realistic in that the Earth's size is considerable. Looking at this figure one now realizes that, an observer on the surface of the Earth is quite far from the centre and thus would measure different angles. The angles would also be different on different locations. These angles are the ones one gets when converting field data into equatorial coordinates, and they are called topocentric.

For the Sun, planets or stars, the topocentric and geocentric coordinates will be essentially the same (even though there is such a thing as stellar parallax, but that is because of the Earth's orbit around the Sun). The Moon however is close enough to the Earth to produce this effect. What is parallax then? Parallax is an apparent displacement of an object relative to some background, when viewed from two different viewpoints. Consider figure 21 below, where an object that is closer to the observer than the coloured background, is seen from two viewpoints. What the observer would see at the two viewpoints is shown in the bottom part. Essentially the object is seen to be in different positions. You can try yourself by putting a finger in front of your nose and looking at it using just one eye. Then try with the other eye. It will appear to have moved relative to the background. If you put your finger further away from your eyes the effect will be reduced. In astronomy, the distant background are the fixed stars, and, in figure 22, the Moon is seen to be in different positions relative to the Pleiades when it is observed from different locations on Earth.

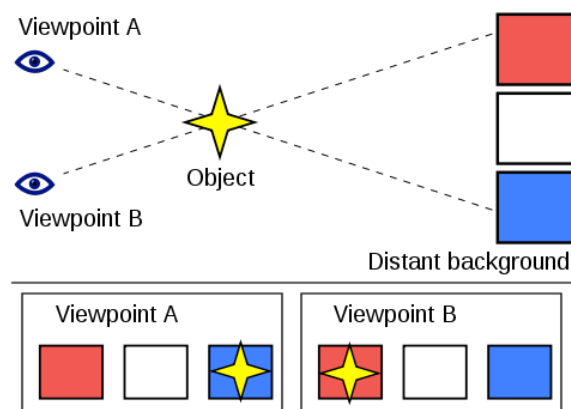


Figure 21. Simple example of parallax. When the nearby object is seen from two viewpoints it seems to have moved relative to a distant background.

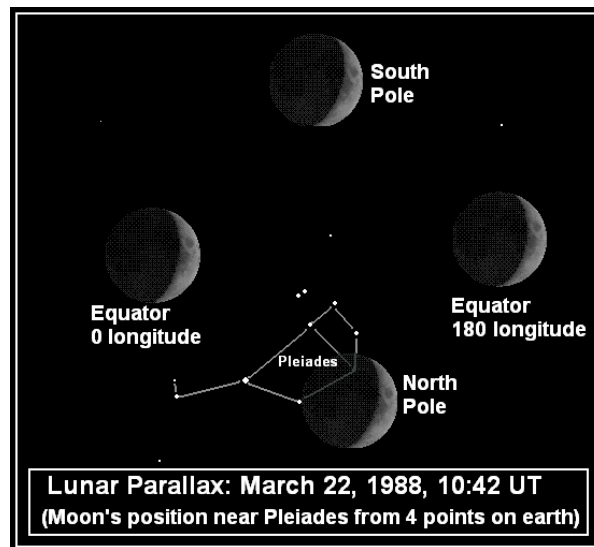


Figure 22. Lunar parallax for a given date and time, as observed from four different locations on Earth. The position of the Moon relative to the Pleiades is quite different in each case.

Lunar parallax thus depends heavily on the observer's location on Earth and will affect all lunar (geocentric) declinations given above (whether standstill or EFM values). The best way to deal with it is to use the US Naval Observatory [LINK!] to get the values for the topocentric lunar declinations for your own site(s), or use planetarium software.

d. Planets

The planets are similar to the Moon: they have their own orbits. However they are not as inclined as the Moon's, and thus they all travel very close to the ecliptic. They, however, do not behave exactly as the Sun, or Moon, because we are neither orbiting around them, nor are they orbiting around us. This gives rise to an assortment of behaviours, depending on whether they are closer to the Sun (Mercury and Venus) or more distant (Mars, Jupiter, Saturn, Uranus and Neptune).

Planets that are interior to the Earth's orbit are always close to the solar orb and exhibit a morning/evening star behaviour: they sometimes act as the first "star" to show up at dusk, or the last "star" to disappear at dawn. Throughout the year they form quite complex patterns. Fabian (2001, p.70) reproduces one for the first appearance of Venus as morning star, but there are four other distinct ones.

All planets exhibit periods of retrograde motion, as will be well known to all Sophia Centre students. But apart from these periods, the outer planets tend to follow a well known orbit close to the ecliptic.

7. Beyond "Horizon Astronomy"

Not all astronomical events happen around the horizon. There are plenty of other interesting stuff happening elsewhere on the celestial sphere at any one time: there are stars culminating all the time; certain stars that are visible throughout the whole year, and that are seen to move around one of the poles; the Sun, Moon or planets also culminate and, depending, on location, might also cross the zenith, ... The possibilities are truly endless and this is why, wherever possible, alignments should be substantiated with archaeological, historical or ethnographical data.

Because there are so many possibilities we will only cover a few here. The best approach to explore an idea that is not developed here, is to use planetarium software to find the event you are interested in, at the location of your site, and retrieve the declination of the celestial object at that time, which you can then compare to your field data. Bear in mind that although some events might be conceptually very well defined they might not occur every single year/month/day (i.e. have different periods) or they might not occur at the same location (i.e. declination) every time. An example of the former are the Lunar Standstills, which have a period of 18.6 years, and of the latter are the Equinoctial Full Moons, which occur on different dates every year.

a. Culmination

A celestial object is said to culminate when it reaches its maximum altitude (due South of the observer) or, in other words, when it crosses the local meridian (the Prime Meridian of figure 2). The local meridian is defined as a line on the celestial sphere that goes from the observer's true north towards the south point. It divides the sky in two equal parts, an eastern and a western one. Because the sky is a sphere, the local meridian is actually a circle which means any object crosses the meridian again at its minimum altitude (negative), but this event is not observable so the so-called lower culmination is of no interest to us.

As an example the Sun always culminates at local noon and herein lies the first problem: local noon is not 12 o'clock sharp everywhere. It will only be 12 o'clock if you are situated on your timezone meridian (for example, along the Greenwich meridian), but otherwise it will occur slightly before or after. Daylight saving time should also be taken into account. For all these reasons the easiest way to proceed is to use planetarium software to find out when the object culminates (some software packages find it automatically).

When an object culminates it is at its maximum altitude for that day, but this may vary throughout the year (see figures 13 and 14 for the sun's path in different days, notice the difference in maximum altitude). It also varies, as seen in the previous section, for different locations. However, you still only need to retrieve the declination of the object. When on the field, you'll need to get both the azimuth and the altitude (not of the horizon anymore) of whatever you think might be indicating the culmination point, then convert it to declination and compare.

b. Poles

The celestial sphere is seen to rotate around the poles of which, unless you're exactly on the equator and with a very flat horizon, only one can be seen from any point on Earth. Whether one is in the North or South Hemisphere, the stars are seen to rotate around one of these points (see figure 23). In some cases a star might be marking this place (Polaris), but this is not necessarily true for all epochs (see next section).



Figure 23. Long exposure photograph of the night sky in Tikal, Guatemala. The stars rotate around the pole.

The declination of the poles is, by definition, 90° and their altitude is directly related to the latitude, just like the inclination of the celestial equator. If an observer is located on the terrestrial North Pole, then the celestial North Pole will be at the zenith, that is will have an altitude of 90° . On the other hand, if one observes it from the Equator it will have an altitude of 0° . From this it becomes obvious that the altitude of the Poles is given by the latitude. If one is in the Southern Hemisphere then we just have to neglect the negative sign of the latitude.

c. Circumpolar Stars

Circumpolar Stars are stars that do not touch the horizon on figure 23. This means that they never rise, nor do they set, and are always visible in the night sky throughout the year (just like the poles themselves). At higher latitudes, the poles are higher in the sky, which means that more stars will be circumpolar. As a rule of thumb, all stars with declination higher than 90° minus the latitude will be circumpolar. For Southern Hemisphere observers all stars with declination lower than $-(90^\circ - \text{latitude})$ are circumpolar, this is because declinations are negative in the Southern Celestial Hemisphere.

8. The Sky in the Past

It is typical in Archaeoastronomy to work on sites that were built in past epochs, whether historical or pre-historic. The sky then is not exactly the same as it is now, and this is truer the farther back into the past one goes. The differences must then be taken into account.

a. Axial Precession / Precession of the Equinoxes

Axial Precession, or Precession of the Equinoxes, is a circular movement of the Earth's axis around a centre point. This movement is very slow, it has a period of roughly 26,000 years (figure 24). This secular movement has a number of observable effects, most of which will be well known to Sophia Centre students.

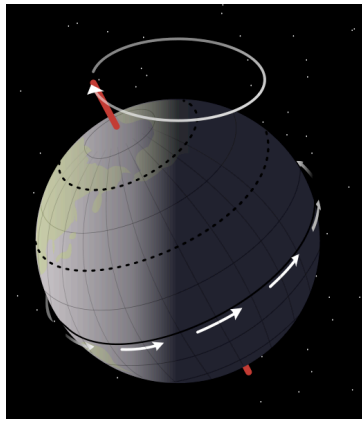


Figure 24. Axial Precession. The Earth's axis, and thus the poles, are seen to move around in a circle every 26,000 years.

For our purposes the most important one is the fact that the celestial poles shift. This impacts on two things: i) pole stars come and go, depending on epoch; ii) the equatorial coordinates, most notably the declination, change for different epochs. Figure 25 shows the trajectory of both North and South poles at different epochs given by their dates. The left picture represents the North Pole in 2000CE (+2000 in the figure) close to Polaris. The orange circle represents the trajectory of the celestial pole through it's 26,000 year cycle. If one moves along the orange line towards the beginning of the Christian Era (marked with a 0), one notices that Polaris get farther and farther away from the pole, which would now be where the tick corresponding to year 0 is. If one continues to move back into the past (clockwise) one sees that another star becomes polar around the year 3000BCE, this is Thuban, of the constellation Draco. Many other stars, for both North and South poles, can be said to have been, or that they will become, polar stars, some brighter than others (brightness is represented by the star's area in the figure).

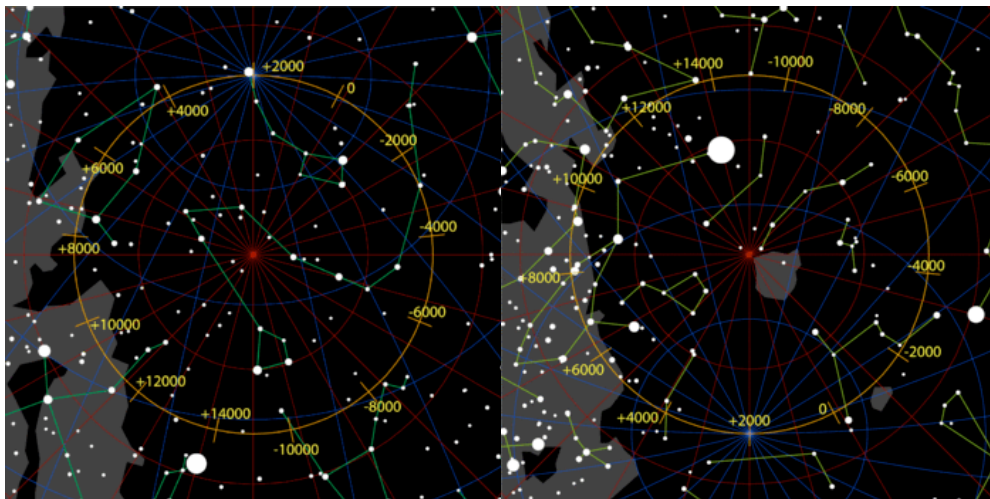


Figure 25. Axial Precession. The North (left picture) and South (right picture) poles move in a circle with a period of 26,000 years. These pictures show their current locations as well as their future and past trajectories. The numbers indicate dates, positive being CE, and negative being BCE.

Because the poles shift, the equatorial coordinates will also shift, most notably declination (which is always to be 90° at the poles). This means that the same star will have different declinations whether one is observing it nowadays or in the past. Think of Polaris again: nowadays it's quite close to the pole so it has a

declination of roughly 90° . However, as one moves back into the past, its declination decreases, and the declination of Thuban increases until it becomes the pole star in 3000BCE.

Precession is a complex movement but one that is easily modeled mathematically. You can easily get the declinations of stars in the past in appropriate star tables, but you can also use planetarium software package to get more accurate values for the epoch you are interested in. Precession doesn't affect the Sun or the moon's movements (but see below for nutation).

b. Stellar Proper Motion

There is an added complication with the stellar declinations in the past. Stars were once thought to be fixed, but they in fact move very slowly, some faster than others, in what is called proper motion. These effects have been measured and are taken into account in star tables and planetarium software.

c. Obliquity Decrease

Another very important secular movement is the change of the Earth's obliquity. Because the obliquity is slowly decreasing the angle between the ecliptic and the celestial equator is also decreasing, which means the Sun, the Moon and the planets' path is slowly changing. Luckily this is also easily modeled, and the changes have been quite slow in the past millennia. Ruggles (1999, p.57) gives a list of Solstice and Lunar Standstill declinations for different epochs. Below we transcribe the Solstice ones. The Lunar Standstills in his list should not be used, as they are topocentric declination for north Scotland only!

Date	Summer Solstice	Winter Solstice
2000 CE	23.45	-23.45
1000 BCE	23.8	-23.8
1500 BCE	23.85	-23.85
2000 BCE	23.95	-23.95
2500 BCE	24.0	-24.0
3000 BCE	24.05	-24.05
3500 BCE	24.05	-24.05
4000 BCE	24.1	-24.1
4500 BCE	24.15	-24.15

Table 3. Declination values for the Solstices on different epochs. From Ruggles (1999,p.57).

d. The Moon

The lunar orbital parameters did not change much in the past, so the model for calculating lunar standstill geocentric declinations given in the section is valid for the past as well, as long as you take the change in the obliquity into account. For example, if one is interested in obtaining the standstill declinations for 4000 BCE, looking at table 3, one gets an obliquity of 24.1° . Then one just needs to add and sum the lunar inclination of 5.15° to it and get the four values of the Lunar Standstill: 29.25° / 18.95° and -29.25° / -18.95° .

The Equinoctial Full Moons also need a slight adjustment. In these cases it is a shift of the whole distribution corresponding to the shift in obliquity. So, to calculate the values for, again, 4000BCE, one needs to get the obliquity difference between 4000BCE and 2000CE, which is 0.65° , then subtract it from all the Spring Full Moon values, and add it to all the Autumn Full Moon values of table 2, yielding peak values of -4.32° and 3.92° .

Remember that these values will still be geocentric declinations and that you need topocentric declinations to compare with your field data. Just get the lunar parallax by taking the difference between the geocentric and the topocentric values you got from the US Naval Observatory website, and add them to the Lunar Standstill and EFM values.

9. Frequently Asked Questions

This section presents some of the questions that might have popped up while reading these notes or while on the field. This section will be constantly updated with answers and more questions.

- a. How do I know which direction the Sun (or Moon) rises in on a particular date at a particular latitude?
- b. Why should I work in declination again?
- c. What's the best planetarium software available?
- d. What's the cheapest planetarium software available?
- e. How far into the past can I trust the calculations of my planetarium software?
- f. What happens to all the equations and figure if my site(s) are in the Southern Hemisphere?

10. References

Included below are some references for those interested in particular aspects mentioned in this set of notes.

Fabian, S., 2001. *Patterns in the Sky*. Long Grove: Waveland Press.

--- Solid introduction to movement patterns in the sky, for ethnoastronomical purposes, with a singular omission: Lunar Standstills (EFMs are also missing, but these are relatively new concepts).

Morrison, L.V., 1980. On the Analysis of Megalithic Lunar Sightlines in Scotland. *Journal for the History of Astronomy*, xi, pp.S65-77.

--- Good for an in-depth understanding of what a Lunar Standstill is in term of the celestial mechanics.

Da Silva, C. M., 2004. The Spring Full Moon. *Journal for the History of Astronomy*, xxxv, pp.475-8.

--- First definition of Spring Full Moon and analysis of data from southern Iberia dolmens.

Silva, F., 2011 (submitted). Equinoctial Full Moons and Non-Gaussianity: Portuguese Dolmens as a Test Case. In Rappenglueck, M., Rappenglueck, B. and Campion, N. *Astronomy and Power (Proceedings of the SEAC2010 conference)*.

--- Generalization to Equinoctial Full Moon and in-depth analysis of declination distribution. Short mention of ethnographic support for EFMs.