Archaeoastronomy and Ancient Technologies **2022**, 10(1), 79-90

Archaeoastronomy and Ancient Technologies

www.aaatec.org ***ISSN 2310-2144***

DOI: 10.24412/2310-2144-2022-1017990
УДК:[902.692]

A method for dating archaeological structures based on astronomical alignments

Adriano Gaspani[1], Stefano Spagocci[2]

[1]Società Italiana di Archeoastronomia, Via Brera 28, I20121 Milano
E-Mail: adriano.gaspani.astro@gmail.com
[2]SMS Consulting, via Cadore 25, I20092 Cinisello Balsamo (MI)
E-Mail: scimodsim@gmail.com

Abstract

A method for dating archaeological structures, based on their astronomical alignments, is presented. In this method, the number of alignments falling within a tolerance band is calculated in suitable time bins. These data are then converted into the probability for the alignments to be random. The time corresponding to the center of the (inverted) probability peak is taken as the structure dating, to which a confidence interval is attributed. Through the analysis of an elliptical enclosure in the Bergamo province (Lombardy, Northern Italy), more details of which were provided elsewhere, we show that the structure had two building phases and in each phase the structure was aligned. In particular, we respectively date the site to 510±20 BC and 340±20 BC.

Keywords: Celts, Cisalpine Gaul, dating, enclosure, sanctuary.

Introduction

Archaeoastronomical dating (see, e.g., Iwaniszewski, 2015, p. 320) is considered to be feasible in principle but not in practice. Indeed, in the last decade of the 19th century dating was attempted on Greek temples in Greece and Magna Grecia, with disappointing results. In particular, F.C. Penrose (Penrose, 1892; 1893; 1897) tried to astronomically date some temples, finding dates which were around 1000-1500 years earlier, with respect to the archaeological dates. In this paper, we describe the method we developed for dating archaeological structures, based on their alignments. As will be shown in the case study, archaeoastronomical dating can be successful, provided the right methodology is employed. We will also see that the poor performance of archaeoastronomical dating in the past can easily be explained.

The Algorithm: Alignment Probability

Let us first consider the case of lunar alignments. Due to the limited number of targets - eight, the extreme positions of the Moon - it is possible to manually check the alignments by using a (reliable) sky simulation program. A tolerance band for alignments is then defined, reflecting the ability of ancient observers. Ancient observers, in fact, due to the finite precision of their measures would have been unable to distinguish the extreme positions of the Moon from its position a few

DOI: 10.24412/2310-2144-2022-1017990
years earlier or later. The number of lunar alignments is then counted in a time bin centered on the year when the extreme position happens and whose width is given by a few years (the echoes), the number of which must be determined by simulation. Similar considerations, of course, apply to solar and stellar alignments.

Considering a given line l, the probability that the line, being oriented at random, hits one of the N_t astronomical targets is given by:

$$P_{rdl} = \frac{2\Delta\vartheta}{360} N_t \tag{1}$$

where $2\Delta\vartheta$ is the alignment tolerance band. Let us then consider the case of a number N_l of lines, whose alignments we want to check. We consider a site as astronomically aligned when at least one of the alignments is not random. With this definition, one has:

$$P_{rds} = 1 - (1 - P_{rdl})^{N_l} \tag{2}$$

If, as in our case, $P_{rdl} \ll 1$, one has:

$$P_{rds} = N_l \, P_{rdl} \tag{3}$$

which gives, for the expected number of random alignments in the site and taking echoes (N_e) into account:

$$N_{rds} = \frac{2\Delta\vartheta}{360} N_t \, N_l \, N_e \tag{4}$$

Eq. (4) gives the average number of alignments expected if the site's lines were randomly laid out. The probability of having (at date t) a number n of alignments greater than or equal to the number expected by chance is approximately described by a Poisson curve that, in turn, can be approximated by a Gaussian:

$$\mathrm{P}_{al}(\mathrm{t}) = \frac{1}{2}\left[1 - \mathrm{erf}\left(\frac{|\mathrm{n(t)} - \mathrm{N_{rds}}|}{\sigma_{\mathrm{al}}}\right)\right] \tag{5}$$

see (Taylor, 1997, ch. 12). In eq. 5, erf is the error function, tabulated in (Taylor, 1997, p. 286-289) and implemented in any calculation engine, including Excel:

$$\mathrm{erf}(z) = \frac{1}{\sqrt{2\pi}} \int_{-z}^{+z} \exp\left(-\frac{z^2}{2}\right) dz \tag{6}$$

The standard deviation of P_{al} is then approximately given by:

$$\sigma_{\mathrm{al}} = \sqrt{\mathrm{N_{rds}}} \tag{7}$$

According to the 95 percent confidence limit philosophy (Taylor, 1997, ch. 12), a peak at time t and having height n(t) above the noise level is deemed to be significant if:

$$\mathrm{P}_{al}(\mathrm{t}) \leq 5\% \tag{8}$$

DOI: 10.24412/2310-2144-2022-1017990

The Algorithm: Site Dating

In the case of a site not having intentionally been aligned to any azimuth, for any time bin there will be a number of unintentional alignments randomly distributed according to a Poisson distribution, with mean and standard deviation respectively given by eqs. 4 and 7. In other words, from time bin to time bin the number of unintentional alignments will fluctuate around a mean value. This will not happen for any time bin inside which an intentional alignment and its echoes are located. In fact, for every such time bin a number of alignments will be found, while the noise will fluctuate around its mean value and contribute with fewer or no alignments.

Intentional alignments are signalled by a peak in the number of events and an inverted peak in the randomness probability, eqs. 5, 6 and 7. To understand this, one has to consider that, besides a tolerance band around the true azimuth, another tolerance band "travels" together with the Moon. An approximate alignment will be registered when the two tolerance bands intersect. Indeed, eq. 4 has to be rewritten as:

$$N_{rds}(t) = \frac{2\Delta\vartheta(t)}{360}\, N_t\, N_l\, N_e \tag{9}$$

where Δϑ(t) is given by the intersection of the two tolerance bands and starts at zero, reaches a maximum and then goes back to zero.

The shape of Δϑ(t) depends on the apparent motion of the Moon or the relevant celestial body; however, we found that a Gaussian curve (which, in this case, has no statistical meaning) can fit the peaks in the number of events as a function of time. In particular, one could employ the following function:

$$N_{rds}(t) = \alpha \exp[\frac{(t-d_s)^2}{2{\sigma_s}^2}] \tag{10}$$

The site date is then quoted as:

$$d_s \pm 2\sigma_s \tag{11}$$

The Gaussian alignment peak can subsequently be converted into a randomness probability (inverted) peak, by employing eq. 5.

The Gaussian fit can be avoided if one considers that any (regular enough) function around its minimum or maximum can be approximated by a second-degree polynomial, so in our case one can employ the function:

$$N_{rds}(t) = \alpha - \beta\, (t - d_s)^2 \tag{12}$$

A "pseudo σ" can then be employed, which gives essentially the same results as the standard deviation of eq. 10. σ_p can in fact be approximated as the x-distance between the mean azimuth and the point where $N_{rds}(t)$ reaches the mean value, eq. 4, so that:

$$\sigma_s = \sqrt{\frac{\alpha - N_{rds}}{\beta}} \tag{13}$$

Rather than employing eqs. 4 and 7 to estimate the average number of alignments in a time bin and its standard deviation, it is more appropriate to "let the data speak by themselves" and calculate

DOI: 10.24412/2310-2144-2022-1017990

such quantities by making use of the "experimental" data, from which peaks have been removed. A consistency check, however, is that the standard deviation must be approximately equal to the square root of the mean.

If the site under investigation has different categories of alignments (e.g., lunar and stellar), for each category a randomness probability is obtained and the probabilities have to be combined into an overall randomness probability; the two dates, with their standard deviation, have to be combined, as well. This is done by applying standard statistical formulae, see (Taylor, 1997, ch. 7); in particular, the two probabilities are combined as:

$$\mathrm{P}_{al}(d_s) = \mathrm{P}_{al1}(d_s) + \mathrm{P}_{al2}(d_s) - \mathrm{P}_{al1}(d_s)\,\mathrm{P}_{al2}(d_s) \tag{14}$$

and the dates are combined as:

$$\mathrm{d}_s = \sum_i \frac{w_{si}}{w} d_{si} \tag{15}$$

$$w = \sum_i w_{si} \tag{16}$$

$$w_{si} = \frac{1}{\sigma_{si}{}^2} \tag{17}$$

Case Study: A Cisalpine Celtic Enclosure

The Mt Avaro Barec (fig. 1) is an elliptical enclosure in the Bergamo province (Lombardy, Northern Italy).

Figure 1. A view of the Mt Avaro Barec (Gaspani, Spagocci 2020, p. 127). (From Google Earth, image © 2020 Maxar Technologies).

DOI: 10.24412/2310-2144-2022-1017990

Thanks to previous studies by Gaspani (Gaspani, 2001), its inner structures (some components of which are engraved with cup-marks, which made the author think the alignments were intentional) were known to be astronomically oriented and probably date to the Iron Age but the enclosure was thought to be medieval. The structure was re-measured and analysed (Gaspani, Spagocci, 2018; 2020); the results, we will see, went beyond our expectations.

We checked both lunar and stellar alignments. Lunar alignments were checked by making use of the SkyMap simulation program, whose performance is such that the algorithms employed allow tracking the orbit of the Moon with an accuracy of 5 to 10 metres (Marriott, 1999, p. 288). As for stellar alignments, we checked 144 targets, the stars above the 3rd magnitude and visible from our latitudes, employing a Fortran program written by Gaspani.

The structure was measured by establishing a GPS base and referring compass measurements to it. In particular, the baseline endpoint geographical coordinates were measured by a GARMIN III+ GPS with external antenna, employing an integration time of one hour, and later converted into an azimuth; for this procedure, see e.g. (Cernuti, Gaspani, 2006, p. 112). The orientations of the site alignments and the baseline were then measured by Nikon PWCF 7x50 survey binoculars (with an embedded compass) and the two quantities were then subtracted, so as to obtain line azimuths relative to the baseline. Finally, the absolute azimuths of the site alignments were obtained by algebraically summing their relative azimuths to the absolute azimuth of the baseline; for the procedure see e.g. (Cernuti, Gaspani, 2006, ch. 6).

In Figure 2, the alignments found (Gaspani, Spagocci, 2018) are shown.

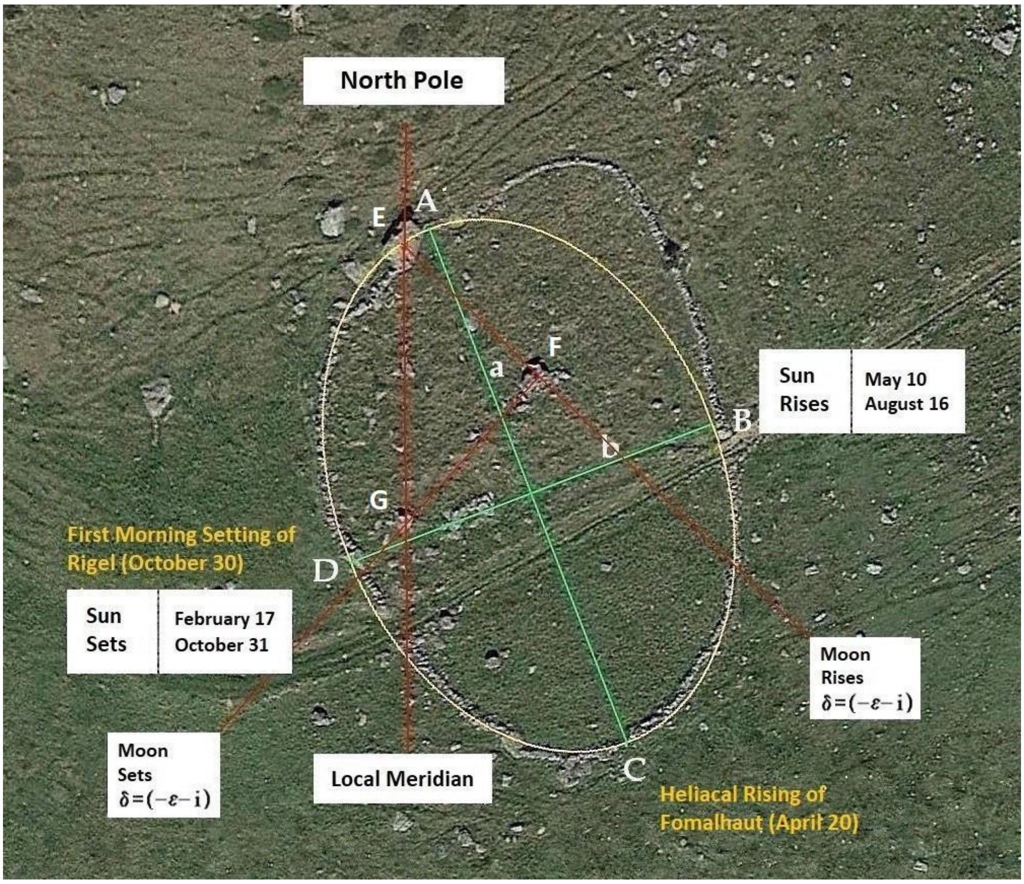

Figure 2. Alignments of the Mt Avaro Barec structures (Gaspani, Spagocci 2020, p. 127). (From Google Earth, image © 2020 Maxar Technologies).

DOI: 10.24412/2310-2144-2022-1017990

The geographical coordinates of the centre of the ellipse that approximates the profile turned out to be:

- Latitude: 46° 00’ 37.9” N
- Longitude: 09° 35’ 51.2” E
- Altitude: 1761 m

The profile of the enclosure was approximated by an ellipse:

- Semi-major axis: 32.3 metres
- Semi-minor axis: 23.4 metres
- Eccentricity: 0.69

The azimuths of the ellipse axes were measured onsite with the above-mentioned procedure and further checked with Google Earth, with the result:

- Semi-major axis (AC): (159.0 ± 0.4)°
- Semi-major axis (CA): (339.0 ± 0.4)°
- Semi-major axis (BD): (249.0 ± 0.6)°
- Semi-major axis (DB): (69.0 ± 0.6)°

The azimuths of the astronomically significant lines formed by the inner monoliths, measured onsite with the above-mentioned procedure, turned out to be:

- EF line: (141.7 ± 0.5)°
- FG line: (220.5 ± 0.8)°

The alignments above were determined by taking the local horizon into account (its average height for the sector of our interest turned out to be -1.2 degrees). The axes of the ellipse turned out to be oriented towards the following targets:

- AC: Heliacal rising of Fomalhaut (April 20)
- BD: First morning set of Rigel (October 30)

Solar alignments to dates compatible with the main Celtic festivals were also found:

- DB: Sunrise at Beltane and Lughnasad
- BD: Sunset at Imbolc and Samhain

Alignments to the 18.6-year extreme positions of the Moon (in particular, to the major lunar standstill) were found, as well:

- EF: Moon rising at $\delta=(-\varepsilon-i)$
- FG: Moon setting at $\delta=(-\varepsilon-i)$

The azimuth measurements achievable nowadays are not necessarily representative of the precision that an ancient observer might have achieved. In our analysis, we assumed $\Delta\vartheta=\pm 0.25°$. This is a reasonable value, as demonstrated by considering the angle subtended by a rod of 5 cm

DOI: 10.24412/2310-2144-2022-1017990

radius, placed at 10 metres from the observer, which is 1/200 radians or about 0.3 degrees. It can also be observed that a rod of 5 cm radius, placed at 11.4 metres, subtends an angle of 0.25°, which is the apparent radius of the Moon. An ancient observer, then, staying at a fixed distance from the rod, could keep the Moon centred and follow it till it sets under the local horizon. With this procedure, an even higher precision than ±0.25° might be achieved. In the following, we will explain why our method is largely independent on the assumed angular resolution, as far as the most probable value is concerned.

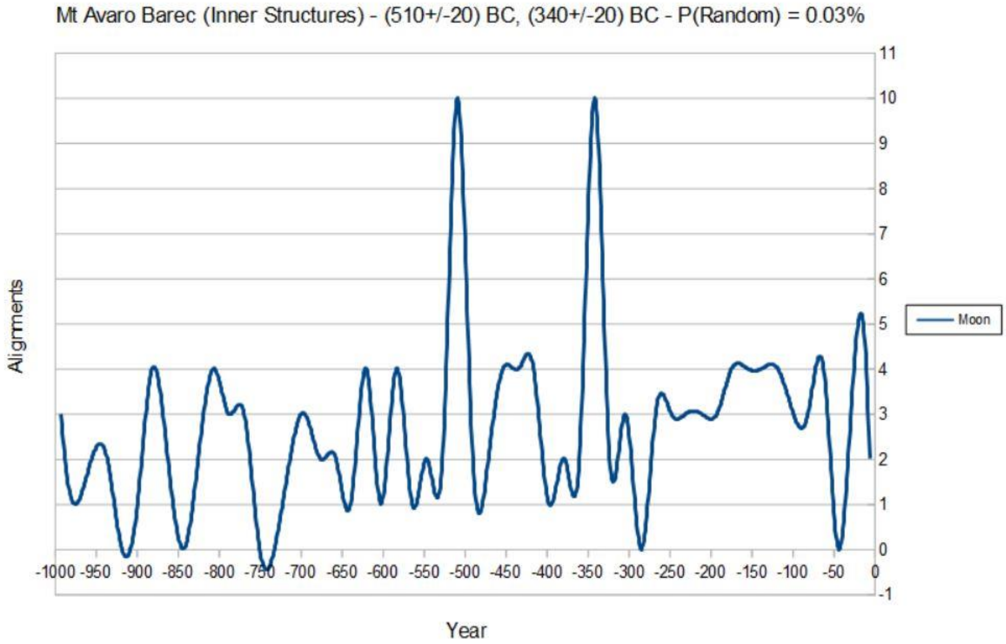

Figure 3. Dating curve, based on the number of alignments, for the Barec's inner structures, according to their lunar alignments (Gaspani, Spagocci 2020, p. 131).

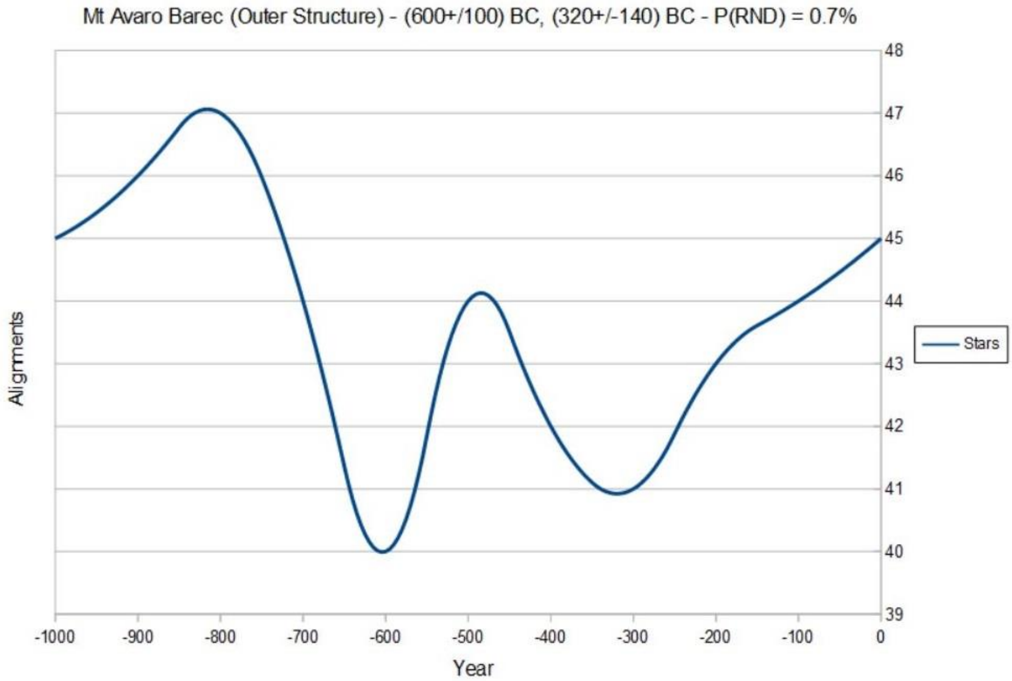

Figure 4. Dating curve, based on the number of alignments, for the Barec's outer structures, according to their stellar alignments (Gaspani, Spagocci 2020, p. 131).

DOI: 10.24412/2310-2144-2022-1017990

The inner structure dating curve (see Figure 3 for the number of alignments and Figure 5 for the randomness probability) shows two peaks at 510±20 BC and 340±20 BC, the randomness probability of which is 0.03%. The outer structure dating curve (see Figure 4 for the number of alignments and Figure 6 for the randomness probability) shows one peak at 600±100 BC and another one at 320±140 BC, having a randomness probability of 0.7%.

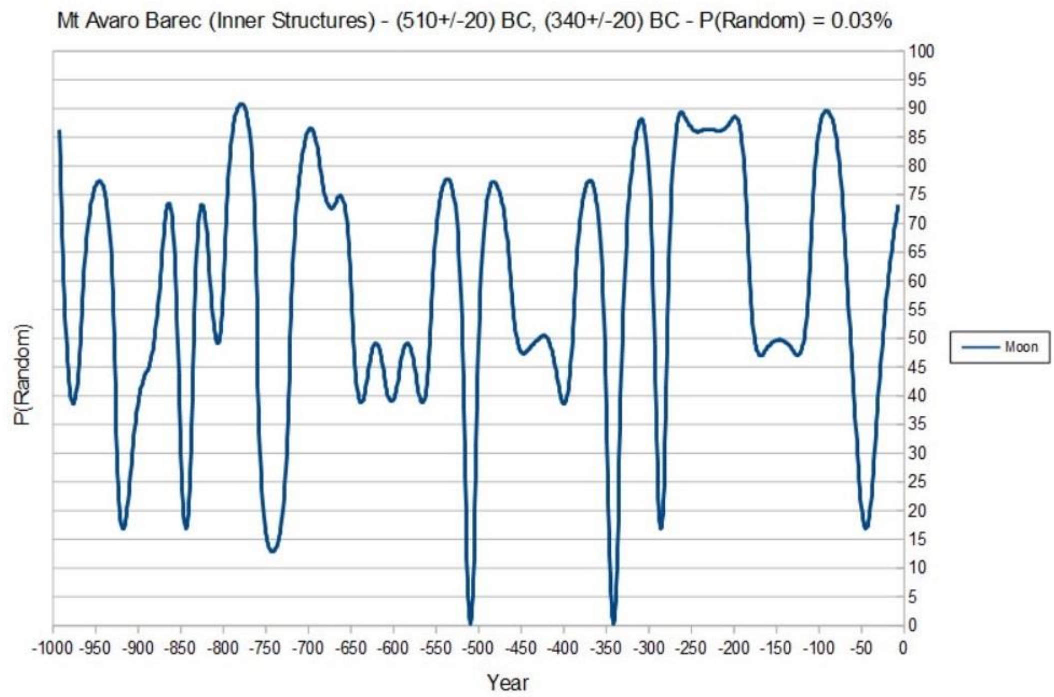

Figure 5. Dating curve, based on randomness probability, for the Barec's inner structures, according to their lunar alignments (Gaspani, Spagocci 2020, p. 131).

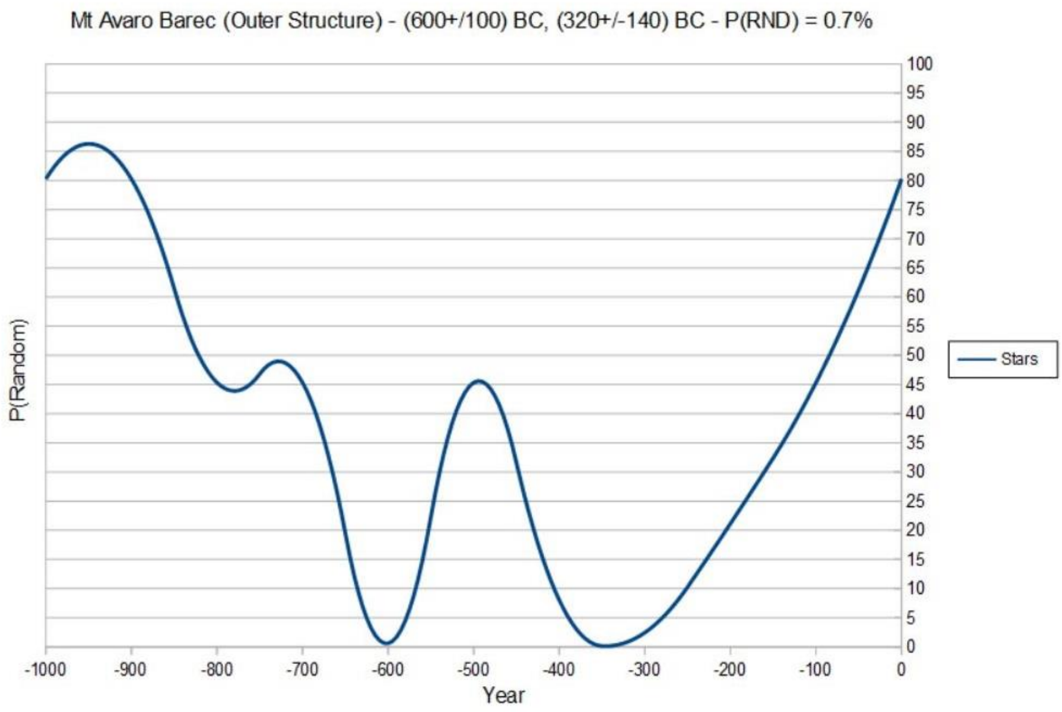

Figure 6. Dating curve, based on randomness probability, for the Barec's outer structures, according to their stellar alignments (Gaspani, Spagocci 2020, p. 131).

DOI: 10.24412/2310-2144-2022-1017990

Having combined the dates for peaks one and two (Gaspani, Spagocci, 2020, p. 130), we claim that the whole site is astronomically significant and underwent two building phases. In the first phase, in 510±20 BC, the inner structure was erected and aligned. In the second phase, in 340±20 BC, the inner structure was realigned and the outer structure erected and aligned. The site randomness probability, derived from the combination of the inner and outer structure randomness probabilities (eq. 14), turned out to be 0.7%.

Why the Method Works

As previously mentioned, in a series of papers published in the 1890's F.C. Penrose proposed foundation dates for a number of Greek temples (Penrose, 1892; 1893; 1897), based on their astronomical orientation. In the 1930's, W.B. Dinsmoor reanalysed Penrose's data, comparing the archaeological and astronomical dates for the temples. It turned out (Dinsmoor, 1939, p. 104) that Penrose's astronomical dates were off by -1000/-1500 years, with respect to the archaeologically established dates.

Why, then, do we claim that our method is able to provide reliable dates for archaeological sites? We have previously shown that our method, applied to the Mt Avaro's Barec, gave two dates (VI and IV cent. BC) for the structure's building phases, as shown in Figure 3 to 6. In order to date the structure, we considered both lunar and stellar alignments and found that the dates for the two building phases, obtained by the two independent methods, are in excellent statistical agreement. This testifies in favour of the reliability of our method.

With regards to Penrose's dates, it has to be considered that the author's approach was to look for a star whose heliacal rising happened in the direction of the temple's axis; the day and year when this happened were deemed to be the day and year of the temple's foundation. F.C. Penrose did not calculate the probability for his alignments to be due to chance, put no time limits to his search and looked for one single event (the heliacal rising) with hundreds of possible candidates (the stars visible to the naked eye). On the contrary, we limited our search to the Iron Age, considered events for which there is one only possible target (the Sun, the Moon) or, in the case of stars, considered the 144 brightest ones together, and determined the probability for our alignments to be due to chance. This explains the success of our method, as shown by the fact that the dates obtained by considering lunar and stellar alignments are statistically compatible.

Further possible doubts concern the nature of the dating error and the dependence of the dating algorithm on the precision achievable by ancient observers. As for the former, we again point out that there are algorithms, such as the ones employed in SkyMap (Marriot, 1999, p. 288), that allow tracking the Moon with an accuracy better than 10 metres, so that they are not sources of errors. The dating errors, such as the ones quoted above, are due to the fact that any observer, even more so naked-eye observers, has a finite precision; as previously pointed out, then, an ancient observer might have observed "pseudo major standstills" some years after the real ones, whence the dating errors.

As for the dependence of the performance of our algorithm on the pointing accuracy achievable by ancient naked-eye observers, one has to consider that, as long as the accuracy is smaller than the range of variation of the azimuths to be measured, the amplitude of the peak tends to worsen as bin size increases but, since the peak is symmetrical with respect to the mean value, the mean value tends not to vary with bin size.

DOI: 10.24412/2310-2144-2022-1017990

Why it is Possible to Date with Stars

Due to the precession of the equinoxes, the right ascension and declination of a star tend to vary by an appreciable quantity in one millennium. In fact, by applying the standard Euler formulae (Gaspani, 2017) we calculated the following approximate expression:

$$\varepsilon(\delta) = 1^\circ \frac{Y - Y_0}{26000} \quad (18)$$

where δ is the star declination and Y_0 is the reference year as far as coordinates are concerned (+2000, in our case). The error in azimuth (Gaspani, 2017, p. 3) is given by:

$$\varepsilon(Az) = -\frac{\cos\delta}{\cos\varphi \sin Az}\varepsilon(\delta) \quad (19)$$

where φ is the observer's latitude.

Considering the brightest non-circumpolar stars, a latitude of about +46° and the first millennium BC, by employing standard Euler formulae (Gaspani, 2017) we found an azimuth variation of -6° to +4°, which is appreciable with the angular resolution of ±0.25° we adopted, as the peaks of Figure 4 and 6 testify.

Why it is Possible to Date with the Moon

One might be tempted to say that dating with the Moon is not feasible, since the azimuth of the Moon at a given date does not appreciably vary over one millennium. The fact that we were able to obtain sharp peaks (fig. 3, fig. 5) that, in addition, are statistically comparable to those obtained by star dating, testifies otherwise.

In Figure 7 we show the azimuth of Moon setting in each year of the first millennium BC in the day when the major standstill happened.

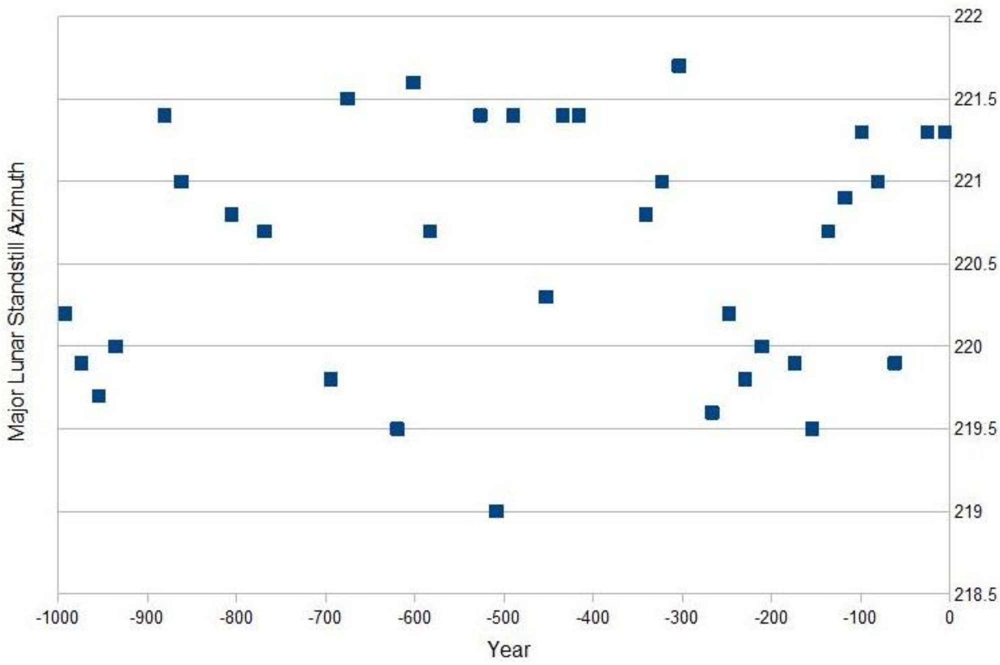

Figure 7. Moonset azimuths at the dates of the major lunar standstills.

DOI: 10.24412/2310-2144-2022-1017990

The reader may be surprised to see that the graph looks like random noise with an amplitude of ~2°, which is appreciable with an angular resolution of ±0.25°. In order to explain this strange result, one has to consider that in the first millennium BC the declination of the Moon varied from -29° to +29° in 27.5 days, which implies $\varepsilon(\delta)=1.96°$ per day. If in eq. 19 one considers $\varphi=46°$, $\delta=-29°$, Az=221°, the azimuth of the Moon is found to vary by 4.03° per day.

The time when the Moon sets at the major standstill differs by up to 24 hours from the time of the major standstill, so that it might seem that the azimuth variation would be 4.03°. However, around the major standstill the azimuth of the Moon first grows, then inverts its course and goes back to essentially the same value as the day before, so that the 4.03° have to be multiplied by a factor of ~0.5; the result is that the azimuth of the Moon around the major standstill varies by approximately 2°, as observed. Figure 7 also shows that the moonset azimuth wildly varies between adjacent major standstills, whence its "noisy" appearance.

Conclusions

In this paper, we presented an algorithm for dating archaeological structures, based on astronomical alignments. In our algorithm a time interval, chosen on the bases of the archaeology of the site, is explored with a suitably chosen sampling rate and the number of alignments, within a reasonable tolerance band, is calculated. We then calculate the probability that the alignments are due to chance; intentional alignments then correspond to peaks in the number of events and the randomness probability. Probable alignment dates are then found.

Having calculated dates of an Iron Age sanctuary with two different methods, respectively based on lunar and stellar alignments, we found statistically compatible dates, which validates our method. As a bonus, we obtained two separated Iron Age dates, which shows that the enclosure was realigned about two centuries after its first building date.

At least in lucky cases, then, the method allows to date different building phases of an archaeological structure or site. According to our experimental results, then, archaeoastronomical dating, when feasible, gives errors at the same level as such methods as radiocarbon dating. Furthermore, and contrary to expectations, dating with the Moon turns out to be as feasible as dating with the stars.

Acknowledgments

The authors would like to thank the team of amateur astronomers who, together with them, performed the measurements on the Mt Avaro Barec.

References

Cernuti, Gaspani, 2006 – Cernuti, S.; Gaspani, A. Introduzione all'Archeoastronomia - Nuove tecniche di analisi dei dati. Tassinari: Florence, Italy, 2006.

Dinsmoor, 1939 – Dinsmoor, W.B. Archaeology and Astronomy. *Proceedings of the American Philosophical Society*. Vol. 80. Philadelphia, 1939. – pp. 95-173.

Gaspani, 2001 – Gaspani, A. I Barec del Monte Avaro: Semplici Recinti di Pastori? *Terra Insubre*, 2001, *18*, pp. 14-17.

DOI: 10.24412/2310-2144-2022-1017990

Gaspani, 2017 – Gaspani, A. *La propagazione degli errori in Archeoastronomia*. www.academia.edu/10247080/La_propagazione_degli_errori_in_Archeoastronomia, 2017.

Gaspani, Spagocci, 2018 – Gaspani, A.; Spagocci, S. Il Barec dei Piani di Monte Avaro. *Terra Insubre*, 2018, *85*, pp. 36-43.

Gaspani, Spagocci, 2020 – Gaspani, A.; Spagocci, S. Archaeoastronomical "Stratigraphy": Investigations on a Cisalpine Celtic Enclosure. *SEAC Publications*, 2020, *1*, pp. 126-134.

Iwaniszewski, 2015 – Iwaniszewski, S. Cultural Interpretation of Archaeological Evidence Relating to Astronomy. In *Handbook of Archaeoastronomy and Ethnoastronomy*. Springer Science Media: New York NY, USA, 2015, pp. 315-324.

Marriott, 1999 – Marriott, C. *SkyMap Pro – Version 6*. World Wide Software Publishing: Bloomington, MN, USA, 1999.

Penrose, 1892 – Penrose, F.C. A Preliminary Statement of an Investigation of the Dates of Some of the Greek Temples as Derived from Their Orientation. *Nature*, Vol. 45, Number 1165. 1892, pp. 395-397.

Penrose, 1893 – Penrose, F.C. On the Results of an Examination of the Orientations of a Number of Greek Temples with a View to Connect these Angles with the Amplitudes of Certain Stars at the Time the Temples were founded, and an Endeavour to Derive therefrom the Dates of Their Foundation by consideration of the Changes produced upon the Right Ascension and Declination of the Stars by the Precession of the Equinoxes *Philosophical Transactions of the Royal Society of London*. *Series A.* Vol. 184. 1893, pp. 805-834.

Penrose, 1897 – Penrose, F.C. On the Orientation of Certain Greek Temples and the Dates of Their Foundation Derived from Astronomical Considerations, Being a Supplement to a Paper on the Same Subject Published in the Transactions of the Royal Society in 1893. *Philosophical Transactions of the Royal Society of London. Series A. Containing Papers of a Mathematical or Physical Character.* Vol. 190. 1897, pp. 43-65.

Taylor, 1997 – Taylor, J.R. *An Introduction to Error Analysis*. University Science Books: Sausalito CA, USA, 1997.